ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

FAKULTA LESNICKÁ A DŘEVAŘSKÁ

DISERTAČNÍ PRÁCE

2021 **Ing. Adam SIKORA**

ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE
FAKULTA LESNICKÁ A DŘEVAŘSKÁ

ZÁKLADNÍ MECHANICKÉ CHARAKTERISTIKY KOMPOZITNÍCH MATERIÁLŮ NA BÁZI DŘEVA A NEDŘEVNÍCH KOMPONENTŮ

DISERTAČNÍ PRÁCE

Studijní program:	Zpracování dřeva a technika v lesním hospodářství
Pracoviště (katedra/ústav):	Katedra zpracování dřeva a biomateriálů
Vedoucí disertační práce:	doc. Ing. Milan Gaff, PhD.

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ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

Fakulta lesnická a dřevařská

ZADÁNÍ DISERTAČNÍ PRÁCE

Ing. Adam Sikora

Lesní inženýrství
Zpracování dřeva a technika v lesním hospodářství

Název práce

Základní mechanické charakteristiky kompozitních materiálů na bázi dřeva a nedřevních komponentů

Název anglicky

Basic mechanical characteristics of wood-based composite materials and non-wood components

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Cíle práce

Práce je zaměřena na analýzu vlivu vybraných faktorů na ohybové charakteristiky vrstvených materiálů na bázi dřeva a nedřevních komponentů. Syntézu poznatků je následně vede k inovovanému a optimalizovanému návrhu vrstevnických materiálů v závislosti na jejich účelu použití a trvanlivosti.

Cílem práce je:

(1) Analyzovat vybrané ohybové charakteristiky vrstveného kompozitního materiálu na bázi dřeva v závislosti na (a) materiálovém modelu kompozitního materiálu a (b) okrajových podmínkách (zátěžových stavech). Materiálový model zahrnuje modifikaci vlastností dřeva a zpevňování/ztužování kompozitu.

(2) Stanovit vybrané ohybové charakteristiky (a) experimentálně a (b) analyticky. Experimentální přístup je založen na standardním ohybu; analytický výpočet vychází z teorie mechaniky deformovatelného tělesa resp. laminární teorie.

(3) Vytvořit a ověřit inovovaný postup vyhodnocení modulu pružnosti v ohybu u vrstveného kompozitu a to jak v elastické tak i plastické oblasti silově-průhybového diagramu.

(4) Navrhnout metodu optimalizace kompozitního materiálu na bázi dřeva na základě kvantifikace vlivu faktorů na ohybové charakteristiky.

Metodika

Pro naplnění uvedených cílů možno metodiku rozdělit do několika bodů:

A. Získat literární poznatky z oblasti tvorby vrstvovitých materiálů a na základe získaných poznatků:

a. Implementování nových vědeckých poznatků (ve formě matematických modelů) a přístupů k jejich identifikaci, na základě, kterých je možné důležité materiálové charakteristiky správně a rychle identifikovat a kvantifikovat.

b. Otestovaní implementovaných poznatků a jejich zavedeni do praxe.

B. Identifikace a kvantifikace faktorů působících na vlastnosti vrstvovitých materiálů na bázi dřeva a nedřevních komponentů na jejich vlastnosti při ohýbání.

V této části pryč je třeba:

a. Sledovat vliv vybraných faktorů na ohybové charakteristiky vrstvovitých materiálů.

b. Navrhnout vliv rozdílných skladeb s důrazem na charakteristiky popisující elastickou a plastickou oblast silově – průhybového diagramu.

C. Návrh a odzkoušení metody pro tvorbu vrstevnických materiálů specifických vlastnosti pro daný účel použití.

Doporučený rozsah práce

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Klíčová slova

mechanické vlastnosti, kompozitní materiály, vrstvené materiály, zhušťování dřeva, vyztužování dřeva

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Vedoucí ústavu

Elektronicky schváleno dne 12. 1. 2021
doc. Ing. Milan Gaff, PhD.
Předseda oborové rady

Elektronicky schváleno dne 12. 1. 2021
prof. Ing. Róbert Marušák, PhD.
Děkan

V Praze dne 12. 01. 2021

"Prohlašuji, že jsem disertační práci na téma Základní mechanické charakteristiky kompozitních materiálů na bázi dřeva a nedřevních komponentů vypracoval samostatně s použitím uvedené literatury a na základě konzultací a doporučení školitele. Souhlasím se zveřejněním disertační práce dle zákona č. 111/1998 Sb. o vysokých školách v platném znění, a to bez ohledu na výsledek její obhajoby."

V Praze dne 5. 2. 2021 Ing. Adam Sikora

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Abstrakt ve státním jazyce

V práci se zabývám zjišťováním vybraných mechanických vlastností, jako jsou ohybová práce, ohybový potenciál, tangentové moduly, sečnicový modul a modul pružnosti vrstvených materiálů na bází zhušťovaného dřeva (v rozsahu zhuštění od 10 % do 40 %, vzhledem ke vstupní tloušťce lamel) vyztužovaného vysokopevnostními komponenty na bázi uhlíkových a skelných vláken a také dalšími faktory vstupujícími do procesu vrstvení dřeva. Hlavním cílem práce je ověření hypotéz o možnosti využitelnosti zhušťovaného dřeva ve skladbě vrstvených materiálů a vyztužování těchto materiálů na základě kvantifikace vybraných vlastností v ohybu. Dalšími cíli práce je vývoj vhodného nástroje pro přesné stanovení ohybových charakteristik, dále pak vytvoření matematické metody stanovení teoretického modulu pružnosti více vrstvých materiálů jako nástroje pro navrhování vrstvených materiálů na základě jejich geometrických parametrů a jejich tuhosti.

Byly potvrzeny hypotézy o vlivu zhušťování dřeva ve skladbě vrstvených materiálů a stejně tak byla potvrzena hypotéza ohledně vyztužování dřeva, vhodnou kombinací zhušťování a vyztužování lze dosáhnout významného zlepšení sledovaných vlastností. Co se týče hypotézy ohledně vytvoření matematické metody stanovení modulu pružnosti vrstvených materiálů, přístup předkládaný v práci se dá používat s dostatečnou přesností pouze na materiály bez výztužných komponentů, což je dané zjednodušeným charakterem tohoto matematického přístupu.

Klíčová slova: mechanické vlastnosti, kompozitní materiály, vrstvené materiály, zhušťování dřeva, vyztužování dřeva.

Abstrakt v cizím jazyce

The thesis deals with the determination of selected mechanical properties, such as bending work, bending potential, tangent modules, chord modulus and modulus of elasticity of laminated wood-based materials with densified wood (densification ranging from 10 % to 40%, due to lamella thickness) reinforced with high-strength carbon and glass fibres based components and last but not least, other factors entering the wood layering process. The main goal of this thesis is to verify hypotheses about the possibility of usability of densified wood in the composition of laminated materials and reinforcement of these materials based on the quantification of selected bending properties. Other goals are the development of a suitable tool for accurate determination of bending characteristics, and creating a mathematical method for determining the theoretical modulus of elasticity of multiple layed materials as a tool for designing layered materials based on their geometric parameters and their stiffness.

Hypotheses about the influence of wood densification in the composition of laminated materials were confirmed, as well as the hypothesis regarding wood reinforcement was confirmed, a suitable combination of compaction and reinforcement can achieve a significant improvement of the observed properties. Regarding the hypothesis of creating a mathematical method for determining the modulus of elasticity of layered materials, the approach presented in the thesis can be used with sufficient accuracy only for materials without reinforcing components, it is given by the simplified nature of this mathematical approach.

Keywords: mechanical properties, composite materials, laminated materials, wood densification, wood reinforcement.

Cíle práce

Základním cílem práce je kvantifikace vybraných ohybových charakteristik (ohybová práce, ohybový potenciál, tangentové moduly, sečnicový modul a modul pružnosti) vrstveného materiálu z hlediska zhušťování, vrstvení a vyztužování vysoko pevnostními prvky jakožto i jejich společnou interakcí. Cíle budou naplněny analýzou průběhu namáhání těchto materiálů ve statickém ohybu, v rámci této analýzy jsou stanoveny dílčí cíle jako je vytvoření vhodného nástroje pro přesné stanovení ohybových charakteristik, a dále pak vytvoření matematické metody stanovení teoretického modulu pružnosti více vrstvých materiálů jako nástroj pro navrhování vrstvených materiálů.

Hypotézy

1. Zhušťováním jednotlivých vrstev ve skladbě vrstveného materiálu lze významnou měrou zvýšit vybrané mechanické vlastností vrstvených materiálů s ohledem na stupěn zhuštění.
2. Kombinací dřevních vrstev s vysoko pevnostními komponenty ve skladbě vrstvených materiálů lze významnou měrou zvýšit vybrané mechanické vlastností vrstvených materiálů s ohledem na typ vysokopevnostního komponentu.
3. Za účelem přesnějšího stanovení ohybových vlastností materiálů je možné využívat silově průhybové diagramy s využitím interpolace chybějících hodnot s přesným stanovením hraničních bodů.
4. Možnost aplikace matematické metody vycházející z laminární teorie pro stanovení teoretického modulu pružnosti vrstvených materiálů.

Obsah

Seznam ilustrací

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1 Úvod

Charakteristiky dřeva dělají z tohoto materiálu unikátní přírodní materiál (Bodig a Jayne 1982). Již v minulosti i současnosti to byl běžně používaný a velmi univerzální materiál v dřevo zpracujícím průmyslu (Požgaj *et al.* 1993). V současné době procházejí materiály používané v dřevozpracujícím průmyslu určitými změnami. Tyto změny se týkají zejména zlepšení vlastností nejčastěji používaných nebo nově vytvořených materiálů se specifickými vlastnostmi (Zemiar *et al.* 1999, Sandberg *et al.* 2018). Hranice tvorby materiálů výhradně na bázi přírodní dřevní substance mají své omezení. I přesto, že se neustále posouvají, ukazuje se, že výraznější pokroky je možné dosáhnout zušlechťováním dřeva různými metodami, anebo jeho vrstvením v kombinaci s jinými, rozdílnými látkovými komponenty (Lukowsky 2015, Bal 2016, Niemz 2016). Vrstvené dřevěné materiály lze modifikovat upravením vybraných vlastností jednotlivých vrstev například zhušťováním nebo kombinacemi jednotlivých vrstev s nedřevěnými komponenty (Nelson 1997, Gašparík *et al.* 2016). Vrstvení dřeva je technika výroby materiálů z několika vrstev s výsledným zlepšením vybraných vlastností. Proces vrstvení je velmi důležitý v průmyslovém využití jak ve stavebnictví, tak i v dřevozpracujícím průmyslu (Glos *et al.* 2004). Možnosti zvýšení pevnosti a tuhosti dřeva spočívají v jeho kombinaci s nedřevními komponenty na různých materiálových bázích. Při vrstvených materiálech ve stavebních konstrukcích jsou to ocelová, skelná, uhlíková vlákna a další (Dai 2006, Parvez 2009), ale také různé ocelové spojovací prostředky. Můžou se aplikovat v lepeném lamelovém dřevě (GLULAM), ale také ve vrstvených masivních deskách. Zvýšené pevnostní vlastnosti vrstvených materiálů je možné dosáhnout spolupůsobením materiálů předepsaných kvalitativních parametrů. Výzkumy poukazují na aspekty zvýšení požadavků na kvalitu dřeva a způsobů spojování (Florek *et al.* 2009, Stöd a Herajarvi 2010, Steiger a Gehri 2010, Sandoz 2009).

Z hlediska zaměření práce byla řešena problematika statického ohybu. Mezi nejdůležitější faktory ovlivňující ohybové vlastnosti jsou druh dřeva, tloušťky jednotlivých vrstev a metoda modifikace dřeva (Ellis a Steiner 2002, Yoshihara a Itoh 2003, Wang a Cooper 2005, Frese a Blaß 2006). Hlavním účelem zhušťování jednotlivých vrstev je zvýšení vybraných mechanických vlastností. Toto tvrzení je založeno na vědomostech, že dřevo s vyšší hustotou dosahuje vyšších napěťově-deformačních charakteristik při statickém namáhání (Kamke 2006, Weber a Krug 2008). V práci je řešena problematika zhušťování dřeva bez úplné plastifikace, jedná se o technologii při zhušťování dřeva v kontinuálních výrobních procesech, kdy úplná plastifikace je časově poměrně náročná a snižuje pružnost samotné výroby. Různé vlastnosti vrstvených materiálů lze dosáhnout také kombinacemi dřeva s rozdílnou hustotou (Gaff *et al.* 2017). Z hlediska aplikovatelnosti musí kompozitní materiály dosahovat určitých mechanických vlastností. Je potřeba rozlišovat ohybové charakteristiky v pružné a plastické oblasti pracovního diagramu (Brandt a Fridley 2001). Namáhání kompozitních materiálů ohybem je velmi aktuální otázkou. Z hlediska využití kompozitních materiálů v exteriéru a interiéru jsou tyto ohybové charakteristiky velmi důležité.

Protože se u vrstvených kompozitů předpokládá, že vzájemná spojitost komponentů různého látkového složení bude zabezpečovaná hlavně lepením, do jejich vzájemného vztahu vstupuje lepidlo jako další komponent. Při lepení dřeva s nedřevními materiály je důležité zohledňovat strukturu dřeva, dřevo je pórovitou látkou polárního charakteru a heterogenního organického složení. Pro dobrou adhezi lepidla ke dřevu a druhému materiálu a dostatečnou soudržnost a houževnatost lepidlového filmu v lepidlovém spoji se vyžaduje čistý povrch, vhodně vysušené a hladce opracované dřevo. Zvyšování pevnosti spoje lepených materiálů je trvalým cílem v procesu lepení (Sedliačik 2005). Kvalita lepeného spoje závisí nejen na druhu lepených materiálů a lepidla, ale také na vlastním procesu lepení (Shukla a Kamdem 2008). Produkce vrstvených materiálů vyžaduje určitou ekonomickou náročnost, kterou je nevyhnutelné kvantifikovat z hlediska nákladovosti navrhnutých variant řešení. Každý výrobek má mnoho kvalitativních a kvantitativních vlastností, z kterých má každá svoji vlastní hodnotu. Finální kvalita výrobku je daná synergií účinku těchto vlastností a rozptylem jejich hodnot (Nenadál 2008).

V posledních letech se objevila řada nových matematických modelů a matematických analýz, jejichž výsledky pomáhají rozšířit poznatky o ohybových charakteristikách materiálů na bázi dřeva a nedřevních komponentů (Gaff *et al.* 2016, Gaff *et al.* 2017). Tvorba nových typů materiálů specifických vlastností pro daný účel použití je vědecké a průmyslové odvětví, které je na špičce celosvětového zájmu téměř každé průmyslové oblasti. Vyvíjejí se inteligentní materiály, na které jsou kladeny různé požadavky jejich „potenciálních“ zpracovatelů. Velkým nedostatkem při zkoumání jejich vlastností je to, že mnohokrát metody vyhodnocení vycházejí z přístupů zavedených v dobách, kdy nebyly takové možnosti, jaké v současné době přinášejí moderní informační technologie.

Neméně podstatným přínosem je implementovaní nových vědeckých poznatků (ve formě matematických modelů) a přístupů k jejich identifikaci, na základě, kterých je možné důležité materiálové charakteristiky správně a rychle identifikovat a kvantifikovat.

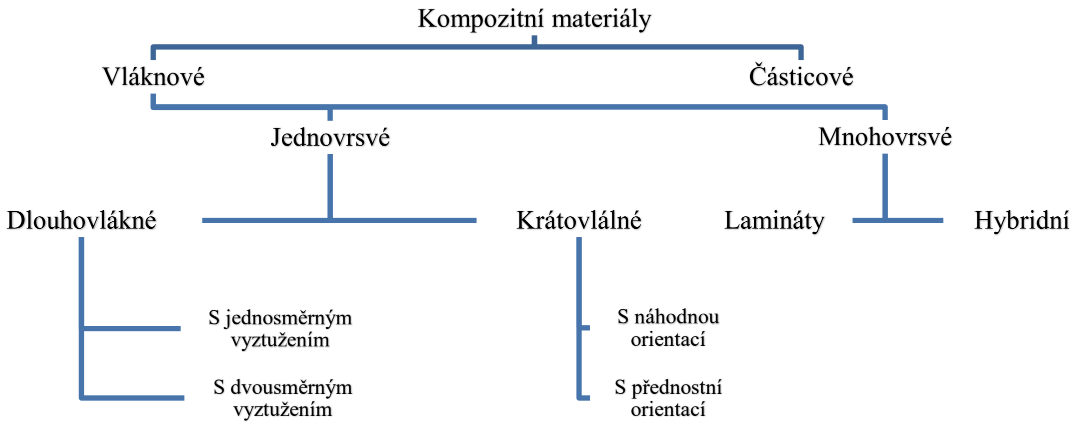
Výsledky práce poskytnou podklady pro tvorbu specifických vrstvených materiálů na bázi dřeva s ohledem na jejich skladbu a tím pádem i na lepší využívání dřevní suroviny na základě přesné kvantifikace vybraných ohybových vlastností vrstveného materiálu z hlediska zhušťování, vrstvení a vyztužování vysokopevnostními prvky jakožto i jejich společnou interakcí. V Práci se také zaobírám novou tvorbou matematické metody pro stanovení teoretického modulu pružnosti specifických vrstvených materiálů na základě vlastností jednotlivých vrstev. Tato metoda má potenciální využití při tvorbě specifických vrstvených materiálů pro daný typ užití v rámci požadovaných vlastností.

2 Kompozitní materiály

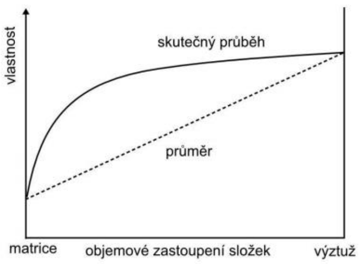
Kompozitní materiály se objevily v polovině 20. století jako slibná třída inženýrských materiálů poskytující nové vyhlídky na moderní technologie. Obecně lze říci, že jakýkoli materiál sestávající ze dvou nebo více složek s různými vlastnostmi a odlišnými rozhraními mezi složkami může být označen jako kompozitní materiál. Myšlenka kombinovat několik komponentů k výrobě materiálu s vlastnostmi, které nejsou dosažitelné s jednotlivými komponentami, byla člověkem používána po tisíce let (Vasiliev a Morozov 2018).

Kompozitní materiály lze tedy definovat jako kombinovaný materiál složený z dvou nebo více typů materiálů (výztužné elementy, výplně, spojovací matrice) lišících se v makroměřítku tvarem nebo složením. Každá složka v kompozitních materiálech může být fyzikálně identifikována spolu s rozhraním mezi jednotlivými složkami. Kompozity jsou materiály, ve kterých jsou délkové nehomogenity v rozměrech mnohem větších, než jsou atomární (což umožňuje využívat pro tyto nehomogenity rovnice klasické fyziky), které jsou ale v makroskopickém měřítku přirozeně (statisticky) homogenní (Milton 2002).

Kompozitní materiály lze kategorizovat dle povahy matice, podle druhu zpevňující fáze, podle geometrického tvaru zpevňující fáze a podle finálního použití. Kompozitní materiály z hlediska druhu zpevňující fáze lze ve všeobecnosti rozdělit na vláknové a částicové. Z hlediska charakteru práce bude výzkum zaměřen na vláknové kompozitní materiály, jejichž rozdělení lze vidět na obrázku 1.



Obr. 1 Kategorizace kompozitních materiálů z hlediska typu zpevňující fáze



Obr. 2 Schématické znázornění synergického efektu (převzato z Daďourek 2007)

Při tvorbě kompozitních materiálů je nutné brát v potaz takzvaný synergický efekt, pod kterým se rozumí, že vysledné složení pozitivních vlastností by měl být vyšší než poměrný součet. Synergický účinek je možné vyjadřit jako 1 + 1 = 3 (Daďourek 2007). Grafické vyjádření synergického účinku je zobrazeno na obrázku 2.

2.1 Kompozitní materiály na bázi dřeva a jejich kategorizace

Snižování kvality lesních surovin a poptávka po dřevěných prvcích s přesněji definovanými vlastnostmi zvyšuje zájem o kompozitní materiály na bázi dřeva. Dřevo, navzdory oceli a betonu zůstává posledních 150 let významnou surovinou užívanou ve stavebních aplikacích, jakožto jeden z mála obnovitelných zdrojů. Rozvoj techniky v posledních letech výrazně zlepšuje využívání dřevní suroviny v různých aspektech využití ať už z hlediska jeho funkčnosti či trvanlivosti. Novými způsoby zpracování přírodního dřeva lze dosáhnout pozitivní změny jeho vstupních rozměrových parametrů či jeho fyzikálních a mechanických vlastností. Současně lze využívat výrobní zbytky a dřevo nižší kvality k výrobě všestranně využitelných a účelných výrobků. Jednou z klíčových vlastností zpracování dřeva je, že technickými prostředky lze překonat omezení dané rozměry kmene a vyrábět kompozitní materiály s definovanými vlastnostmi a rozměry přizpůsobenými účelu použiti. Díky tomuto vývoji je možné odstraňovat vliv přirozených vad struktury dřeva za účelem zvýšení jeho pevnostních charakteristik, ale také potlačení nepříznivého vlivu anizotropie dřeva a jeho nehomogenity (Král a Hrázský, 2005, Sandberg *et al.* 2018).

2.2 Specifikace a možnosti uplatnění vybraných kompozitních materiálů na bázi dřeva v praxi

Vzhledem k charakteru práce jsou v této kapitole popsány pouze vybrané skupiny kompozitních materiálů na bázi dřeva, a to lepené lamelové dřevo, dřevo zpevněné vysoko pevnostními vlákny, vrstvené dýhové dřevo a vrstvené zhuštěné dýhové dřevo.

2.2.1 Lepené lamelové dřevo

Lepené lamelové dřevo, běžně označováno jako GLULAM, představuje konstrukční nosné prvky z tloušťkově slepovaných přířezů s rovnoběžně orientovanými vlákny ve směru nosníku nebo přířezů s určitým zakřivením. V Evropě i v jiných částech světa se lepené vrstvené dřevo používá v široké škále aplikací, od nosných trámů po hlavní konstrukční prvky, jako jsou nosníky, sloupy apod. Tyto prvky se běžně používají pro stavbu kancelářských budov a škol, jakož i pro průmyslové stavby pro stavbu mostů K výrobě se používá jehličnaté i listnaté dřevo, nejobvyklejší jsou ale smrk ztepilý, douglaska tisolistá, modřín, borovice lesní, borovice bahenní, borovice montereyská a liliovník. Pro konstrukce, kde se předpokládá dlouhodobý vliv vlhkosti, se používá řezivo ošetřené ochrannými prostředky. Hlavní výhodou lepeného lamelového dřeva je jeho vysoká pevnost a tuhost, což znamená, že může být použita k výrobě konstrukcí pro široké rozpětí a zvýšenou únosnost. K výrobě lepeného vrstveného dřeva se zásadně používá dřevo pevnostní třídy, které výrobek odlišuje od jiných typů tloušťkově lepených výrobků. Pro maximální využití pevnosti výrobku se dřevo s vysokou pevností často používá na vnější části, kde je namáhání největší „kombinované lepené lamelové dřevo“, nicméně existují i „homogenní“ typy lepeného lamelového dřeva využívající prvky o přibližně stejné pevnosti. K výrobě lepeného vrstveného dřeva se používají výhradně lepidla se zaručenou vysokou pevností a odolností vůči dlouhodobému zatížení a lepidla, s nimiž mají výrobci dlouhodobě praktické zkušenosti (Obucina *et al.* 2017, Sandberg *et al.* 2018).

Vzhledem k běžně využívaným materiálům ve stavebnictví jako je beton a ocel má lepené lamelové dřevo množství výhod, např.:

- lepené lamelové dřevo je více ekologicky přátelštější než beton a ocel, je plně recyklovatelné a má menší energetické nároky na výrobu,
- výhodou lepeného lamelového dřeva vzhledem k betonu a oceli je také lepší

jeho uhlíková stopa,

- velkou výhodou těchto materiálů je jejich hmotnost, při porovnání nosníku tohoto typu materiálu při stejných rozměrech s betonovými prvky dosahuje lepené lamelové dřevo jen 1/6 hmotnosti betonového prvku, v případě oceli se jedná až o 2/3,
- významnou výhodou lepeného lamelového dřeva je jeho chování při vystavení ohni, kdy nedochází k přímému selhání nosníku,
- možnost výroby nosníků o široké škále tvarů a rozměrů.

Vlastnosti lepeného lamelovéh dřeva dle tříd pevnosti je možné vidět v tabulce 1.

Tab. 1 Vlastnosti lepeného lamelového dřeva dle ČSN EN 14080 (2013)

Třídy pevnosti kombinovaného lepeného lamelového dřeva

Vlastnost [MPa]	**20c**	**22c**	**24c**	**26c**	**28c**	**30c**	**32c**
Pevnost v ohybu	20	22	24	26	28	30	32
Modul pružnosti	10 400	10 400	11 000	12 000	12 500	13 000	13 500

Třídy pevnosti homogeního lepeného lamelového dřeva

Vlastnost [MPa]	**20h**	**22h**	**24h**	**26h**	**28h**	**30h**	**32h**
Pevnost v ohybu	20	22	24	26	28	30	32
Modul pružnosti	8 400	10 500	11 500	12 000	12 600	13 600	14 000

Tabulka udává základní vlastností jako je pevnost v ohybu a modzl pružnosti pro třídy pevnosti kombinovaného nebo homogenního lamelového dřeva.

2.2.2 Dřevo zpevněné vysokopevnostními vlákny

Dřevěné prvky zpevněné polymerním kompozitním systémem vyztuženým vlákny jsou využitelné pro konstrukční nosné aplikace, jako lepené lamelové dřevo v konstrukci staveb, mostů, železničních pražců a při opravách dřevěných sloupků. Také překližky lze zpevňovat vložením vláken nebo textilie mezi dýhové vrstvy. Existuje celá řada postupů pro vyztužení dřevěných dílců pomocí polymerních kompozitů vyztužených vlákny, jako je vyztužování dřevěných prvků mokrým procesem nebo lepení prefabrikovaných listů materiálů na dřevěné prvky (John a Lacroix 2000, Fiorelli a Dias 2003, Borri *et al*. 2005). Velmi často se používají skelná vlákna, pro speciální účely také uhlíková a aramidová vlákna. Nejvhodnějším zpevňovacím materiálem pro dřevěné konstrukce je E-sklo díky rovinné aplikaci ve dvou vrstvách. Vrstvy mohou být ukládány paralelně, nebo v úhlu 45° vůči podélnému směru textilie. Vlákna z E-skla se používají také v netkaných textiliích. E-sklo je sklolaminát vyrobený z běžného hlinito-vápnito-borito-křemičitého skla, vlákna, které nabízí vysokou pevnost, tuhost, odolnost proti korozi, nízkou elektrickou vodivost a podstatné izotropní vlastnosti. Vlastnosti E-skelných vláken značnou měrou závisí na obsahu oxidu boritého (Sandberg *et al.* 2018).

2.2.3 Vrstvené dýhové dřevo

Vrstvené dýhové dřevo (LVL) například Microllam® se vyrábí z dýh tloušťky 2-4 mm, slepených dohromady se stejnou orientací vláken jednotlivých vrstev do velkoformátových panelů nebo trámů. Nosníky Microllam® dosahují modulu pružnosti kolem 14 000 MPa a pevnosti v ohybu cca 85 MPa. Někdy se používá uložení vybraných vnitřních dýh s kolmou orientací vláken pro konstrukční zpevnění. Výrobní postup je velmi podobný překližce, finální výrobek má vysokou pevnost, dobrou rozměrovou stabilitu a homogenitu fyzikálních a mechanických vlastností v celé ploše. Dýhy se vrství systematicky, dýhy nejnižší kvality tvoří vnitřní vrstvy, dýhy nejvyšší kvality jsou v povrchových vrstvách, čímž se zlepšuje pevnost v ohybu a modul pružnosti. Vrstvené dýhové dřevo lze využívat ve velkoplošných podlahových a střešních panelech, na stěny, ale i sloupy a nosníky. Vrstvené dýhové dřevo se může kombinovat s jinými kompozitními materiály na bázi dřeva, využívat na duté podlahové a střešní kazety pro vytvoření konstrukčního průřezu s dobrými možnostmi překlenutí. Počet dýh užívaných ve vrstveném dýhovém dřevě závisí na rozměrech jednotlivých desek. Vrstvené dýhové dřevo se používá v tloušťkách do 275 mm, v šířkách kolem 2 m a délkou do 25 m kvůli omezeným dopravním možnostem (Sandberg *et al.* 2018). Účelem konstrukce vrstveného dýhového dřeva je odstranit vady snižující pevnost a tím dosáhnout vysoké pevnosti, zlepšené rozměrové stálosti a homogenity fyzikálních i mechanických vlastností. Dýhy jsou odstupňovány tak, aby do jádra byla umístěna méně kvalitní dýha, a jako vnější vrstvy se používá vysoce kvalitní dýhy, čímž se zlepšuje jak pevnost v ohybu, tak i modul pružnosti (Obucina *et al.* 2017).

2.2.4 Vrstvené zhuštěné dýhové dřevo

Desky ze zhuštěných vrstvených dýh jsou materiálem, který je zlisován v příčném směru, aby se zvýšila jeho hustota. Tento proces se obvykle nazývá zhušťování. Fyzikální a mechanické vlastnosti materiálu závisí na použité teplotě, tlaku a čase lisování. Jedním z důvodů zhušťování dřeva v příčném směru bylo vytvoření vysoce kvalitních komponentů ze dřeva nízké kvality. Zhuštěné dřevo má však nežádoucí vlastnost, kdy při vystavení vlhkosti mají zhuštěné prvky tendenci významných rozměrových změn. Za určitých výrobních podmínek lze dosáhnout spojení mezi vrstvami materiálu bez použití lepidla, což zlepšuje ekologickou charakteristiku výrobku. Pro zabezpečení rozměrové stability výrobku jsou obvykle dýhy impregnovány pryskyřicí o nízké molekulární hmotnosti, která je pak částečně vytvrzována teplem. Trámy se lisují za tepla na hustotu cca 1 300 kg/m^3. Mezi další aplikace pryskyřicí impregnovaných dýh patří ochranné otěrové díly strojů a dopravních vozidel, strojní modelářské formy, neprůstřelné ochranné bariéry, zásobníky na zemní plyn (LNG) a související pomocné prvky. Desky ze zhuštěných vrstvených dýh nelze zaměňovat s lisovanými vrstvenými lamináty, které jsou z melaminem impregnovaných dekorativních povrchů podložených vícevrstvým sulfátovým papírem impregnovaným fenolickou pryskyřicí a sloučeny do pevného listu fólie pomocí vysoké teploty a tlaku (Obucina *et al.* 2017, Sandberg *et al.* 2018).

3 Modifikace dřeva za účelem zvýšení mechanických vlastností

3.1 Modifikace dřeva a jeho kategorizace

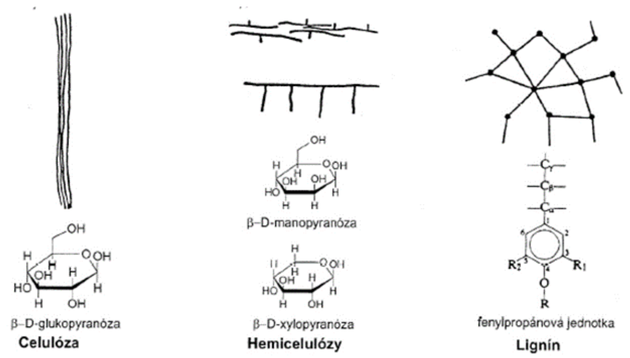
Pod pojmem modifikace dřeva lze chápat proces řízené změny přírodních vlastností dřeva za účelem zlepšení požadovaných vlastností a současně eliminace některých nedostatků dřevní suroviny (Hill 2006). Modifikací dřeva se zvyšuje jeho užitná cena, jelikož umožňuje aplikaci dřeva i v takových aplikacích, kde by to za přirozených okolností nebylo možné, ať už z hlediska zlepšení fyzikálních nebo mechanických vlastností. Nicméně modifikace jako taková je všeobecně spojena s vyšší cenou dřeva, která se odvíjí od náročnosti technologických operací využitých v tomto procesu. Ať už se jedná o vysoké energetické nároky procesu anebo náklady na recyklaci či likvidaci modifikovaného dřeva (Hill 2006, Hájek *et al.* 2018).

Z hlediska časového působení účinků modifikace lze modifikaci rozdělit na dvě základní skupiny, a to na přechodné modifikace, které se vyznačují tím, že vzhledem k působení času se účinky modifikace snižují, popřípadě úplně ruší. Druhou skupinou jsou modifikace trvalé, kdy se efekt modifikace v čase nemění (Hájek *et al.* 2018).

3.2 Modifikace struktury dřeva zhušťováním

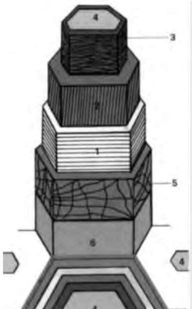
3.2.1 Strukturální hladiny dřeva

Všeobecná definice kompozitních materiálů je kombinace dvou a více materiálů za účelem vytvoření nového materiálu vykazujícího vlastnosti všech kombinovaných materiálů (Vasiliev a Morozov 2018). Dřevo se skládá z vláken uspořádaných jako vrstvený kompozit. Na molekulární úrovni je dřevo složeno ze tří hlavních složek, a to z celulózy, hemicelulóz a ligninu (obrázek 3). Páteř dřeva na molekulární úrovni je vysoce uspořádána krystalická celulóza, což je polysacharid tvořený výhradně glukózovými jednotkami. O ligninu lze hovořit jako o lepidlu, jež spojuje hemicelulózy a celulózu dohromady a tím zvyšuje celkovou mechanickou pevnost (Ek *et al.* 2009, Reinprecht 2012).



Obr. 3 Chemické složky dřeva (Reinprecht 2012)

Z hlediska anatomické struktury ve dřevě lze definovat stavbu buňkových stěn na základě jejich vrstevnatosti a podílů a lokalizace chemických složek Stavba buňkových stěn závisí na typu buněk a druhu dřeva (Niemz, 2016). Základní stavební jednotkou buňkových stěn dřeva jsou elementární fibrily, které jsou složeny obvykle ze 40 makromolekul celulózy. 20–60 těchto elementárních fibril obvykle vytvářejí mikrofibrily s minimálním podílem hemicelulóz a ligninu. Hemicelulózové výplně a ligninové mikro vrstvy se podílejí hlavně na tvorbě složené střední lamely, která lepí jednotlivé buňky do komplexu dřeva. Složená sekundární stěna je základním stavebním kamenem buňkové stěny dřeva (Reinprecht 2012). Vnější stěna představuje vrstvu primární buněčné stěny, na které jsou tři sekundární vrstvy S1, S2 a S3. Orientace celulózových mikrofibril je v každé vrstvě znázorněna čarami (obrázek 4). Nejvnitřnější vrstva buněčné stěny je zanedbatelná ve svém příspěvku k fyzickým vlastnostem Bodig a Jayne (1982). Přičemž vrstva S2 má díky úhlu uložení mikrofibril nejvýznamnější příspěvek k pevnosti a tuhosti, nežli je tomu u vrstev S1 a S3. Vyšší úhly uložení mikrofibril májí za následek nižší hodnoty modulu pružnosti dřeva, jakož i nižší hodnoty pevnosti v tahu (Požgaj *et al.* 1993).

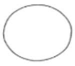


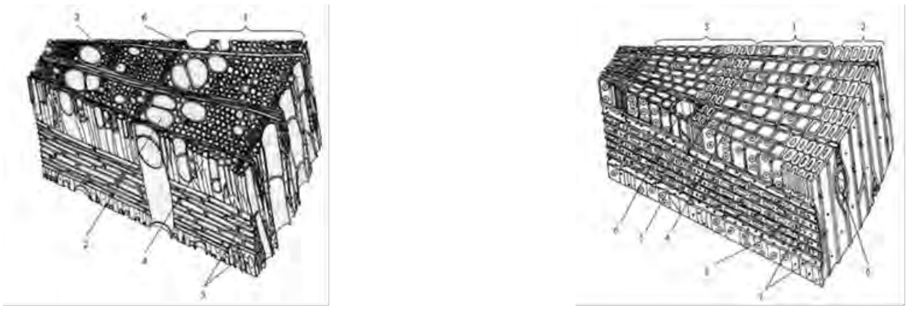
Obr. 4 Schématické znázornění složení buněčné stěny (Bowes 1996)

1 – vnější vrstva sekundární stěny, 2 – střední vrstva buněčné stěny, 3 – vnitřní vrstva sekundární stěny, 4 – lumen, 5 – primární stěna, 6 – střední lamela

Při pohledu na morfologickou strukturu dřeva je možné identifikovat izolované buňkové elementy a buňky seskupené do pletiv. Izolované buňkové elementy dřeva rozeznáváme podle typu, tvaru, rozměru, osové orientace vzhledem ke dřeni, tloušťky buněčné stěny, a přítomnosti a lokalizace typů ztenčením v buňkových stěnách. Typ buněk ve dřevě se také rozlišuje podle druhu dřeviny. Dřevo jehličnatých dřevin je vývojově starší než listnaté dřevo a mají jednodušší anatomickou stavbu. Přibližně 90 % morfologické struktury jehličnatého dřeva je tvořeno tracheidami, které mají vodivou i mechanickou funkci. Dalším elementem ve struktuře jehličnatého dřeva jsou parenchymatické buňky dřeňových paprsků, jejichž funkce je rozvádět organické zásobní látky. Největší rozdíl mezi buňkovými elementy dřeva jehličnatých a listnatých dřevin je v tom, že v případě dřeva listnatých dřevin jsou jednotlivé typy buněk úžeji specifikované a tím pádem více morfologicky přizpůsobené svému účelu. Pro vodivou funkci jsou v listnatém dřevě tracheje (jarní, letní). V morfologické struktuře listnatého dřeva se také vyskytují tracheidy (cévovité, vazicentrické, vláknité). Pro mechanické účely jsou v listnatém dřevě libriformní vlákna (trubkovité, vřetenovité, s náhlým rozšířením ve středu vlákna), jejichž zastoupení je v jednotlivých typech dřeva listnatých dřevin velmi odlišné. Parenchymatické buňky v morfologické struktuře dřeva listnatých dřevin je výrazněji více zastoupený než v případě dřeva jehličnatých dřevin a jedná se o axiální dřevní parenchym a radiální parenchym (Požgaj *et al.* 1993, Dinwoodie 2000, Reinprecht 2012). Pro jednodušší přehlednost jednotlivých typů buněčných elementů je možné vidět jejich přehled v tabulce 2. Uspořádání jednotlivých buňkových elementů jehličnatého a listnatého dřeva je možné vidět na obrázku 5.

Tab. 2 Funkce a tloušťka buněčné stěny buněk jehličnatého a listnatého dřeva (převzato z Dinwoodie 2000)

Typ buněk	*Jehličnaté dřevo*	*Listnaté dřevo*	*Funkce*	*Tloušťka buněčné stěny*
Parenchym	Ano	Ano	Úložná, vodivá	
Tracheidy	Ano	Ano	Podpůrná, vodivá	
Vlákna	-	Ano	Podpůrná	
Trachee	-	Ano	Vodivá	



a) b)

Obr. 5 Uspořádání buňkových elementů v a) listnatém, b) jehličnatém dřevě (Požgaj *et al.* 1993)

5 a) 1 – letokruh, 2 – jarní céva, 3 – letní céva, 4 – libriformní vlákno, 5 – dřeňový paprsek, 6 – podélný parenchym.

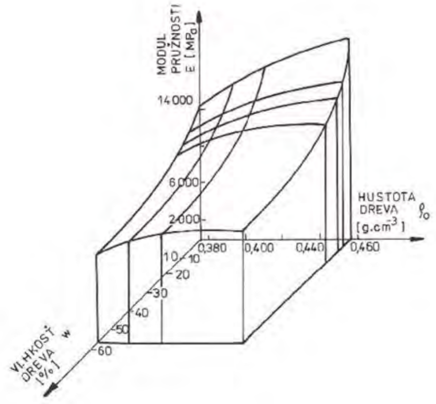
5 b) 1 – jarní dřevo, 2 – letní dřevo, 3 – letokruh, 4 – jarní tracheida s dvojtečkami, 5 – letní tracheida, 6 – pryskyřičný kanálek, 7 – dřeňový paprsek, 8 – příčná tracheida.

Takto uspořádané buňkové elementy tvoří makro strukturu dřeva, která definuje prostorové tvary, podíl bělové a jádrové části (respektive zralého dřeva), podíl jarního a letního dřeva v jednotlivých letokruzích a vzájemný poměr tangenciálních, radiálních a příčných ploch (Reinprecht 2012). Z hlediska makroskopických znaků je možné pozorovat rozdíl mezi jádrovým dřevem a bělovým dřevem, které se nachází na vnějším okraji blíže ke kůře. Jádrové dřevo má obvykle tmavší barvu a je vysoce nepropustné pro vlhkost vzhledem k sousední běli (Hoffmeyer a Pedersen 1995). Dalším znakem ovlivňujícím makroskopickou strukturu dřeva je přítomnost, početnost a stav makroskopických nehomogenností. Jedná se o makroskopické znaky, jež se dají považovat za chyby dřeva (suky, tlakové nebo tahové dřevo, nepravé jádro, pryskyřičné kanálky apod.). Vnímání makroskopické struktury dřeva je závislé na několika faktorech. V první řadě na prostorovém rozmístění buňkových elementů a pletiv ve dřevě. Dále je závislá na výskytu růstových chyb a dalších anomáliích. A v neposlední řadě je velmi závislá na způsobu opracování dřeva (Dinwoodie 2000, Reinprecht 2012).

3.2.2 Vliv struktury dřeva na jeho mechanické vlastnosti

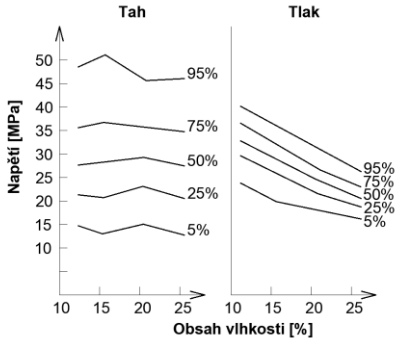
Vlastnosti dřeva jsou ovlivněny uspořádáním jednotlivých složek dřeva ve všech strukturálních hladinách. Do značné míry je také ovlivněna přítomností přírodních defektů vyskytující se ve struktuře dřeva, ale také defekty vzniklými při zpracování dřevní suroviny. Tyto defekty se projevují změnou venkovního vzhledu, porušením pravidelnosti stavby dřeva, celistvosti jeho pletiv a změnami v anatomické stavbě (Požgaj *et al.* 1993). Vlivem struktury dřeva se v průběhu posledních let zabývala spousta výzkumných týmů. Výsledné mechanické vlastnosti dřeva se velmi výrazně odvíjejí už od chemického složení a vlastností buněčné stěny. Touto problematikou se zabývali Bezazi a Salmén (2002). Ve studii byl zkoumán vliv elastických konstant dřevních polymerů na elastický modul buněčné stěny. Bylo zjištěno, že celulóza dominuje vlastnostem v podélném směru, přičemž v příčném směru byl účinek vlastností hemicelulózy výraznější. Výsledky ukazují, že je možné do značné míry snížit nesoulad mezi experimentálními a modelovanými hodnotami příčného modulu snížením předpokládaných hodnot elastických konstant hemicelulózy a ligninu. Tloušťka a úhly fibril vrstvy S1 a S3 byly také shledány důležitými parametry pro příčné vlastnosti buněčné stěny. Tyto dvě vrstvy by neměly být zanedbávány, pokud příčné elastické vlastnosti souvisejí se strukturou buněčné stěny. Dřevo je materiál s hierarchickou buněčnou strukturou se specifickou pevností a specifickým modulem pružnosti. Každá buňka dřeva se obvykle skládá z celulózových makromolekul, respektive fibril, které se točí kolem směru makroskopického vlákna. I když je přirozené předpokládat vztah mezi úhlem mikrofibril a mechanickými vlastnostmi, dobrá korelace byla dosud stanovena pouze pro jednotlivá vlákna. Vlivem uložení mikrofibril v buněčné stěně se zabýval kolektiv Reiterer *et al.* (1998), kde popisují tento vztah pro tenké (200 μm) části dřeva, což poskytuje silný důkaz pro skutečnost, že úhel mikrofibril optimalizuje roztažitelnost dřeva. V kombinaci tahových zkoušek se strukturálními zkouškami pomocí malého úhlu rentgenového rozptylu bylo zjištěno výrazné zvýšení maximálního napětí se zvyšujícím se úhlem mikrofibril a také změnu elastických modulů.

Množství dřevní hmoty přímo závisí na podílu rozměrů mechanických elementů dřeva jako i od podílu letního dřeva a šířky letokruhů. Jedná se o parametry, jež můžou být ovlivněny rychlostí růstu dřevin. Závislost mezi hustotou dřeva a mechanickými vlastnostmi je složitější, protože pevnost dřeva závisí nejen na množství dřevní hmoty v objemové jednotce, ale také na přítomnosti odchylek od standardní struktury dřeva (Požgaj *et al.* 1993). Otázkou vlivu hustoty v důsledku změny rychlosti růstu na mechanické vlastnosti dřeva jehličnatých a listnatých dřevin se zabýval Zhang (1995). Prokázal, že v případě jehličnatého dřeva se obecně mechanické vlastnosti výrazně snižují se snižující se hustotou. U některých druhů jehličnatého dřeva jsou mechanické vlastnosti méně ovlivněné vlivem snížené hustoty. Ve srovnání se studovaným dřevem listnatých dřev jsou fyzikálně-mechanické vlastnosti studovaného dřeva pozoruhodně méně ovlivněny. U druhů roztroušeně pórovitého dřeva listnatých dřevin má rychlost růstu obecně velmi malý vliv jak na hustotu, tak na mechanické vlastnosti. U kruhovitě pórovitého dřeva listnatých dřevin se zdá, že fyzikálně-mechanické vlastnosti s rychlostí růstu neklesají a u některých druhů dokonce mají tendenci se zvyšovat. Vlastnosti pevnosti a tuhosti dřeva jsou velmi závislé také na obsahu vlhkosti. BS EN 1995-1-1:2004+A2:2014, část Eurokódu 5 (EC5), kategorizoval obsah vlhkosti do tří tříd kategorií pro dřevěné prvky. První kategorie se vztahuje na obsah vlhkosti menší než 12 %, druhá kategorie je charakterizována obsahem vlhkosti od 12 % do 20 %. Kategorie 3 se vztahuje pro obsah vlhkosti nad 20 %. Snížení obsahu vlhkosti vede k vyšším hodnotám modulu pružnosti dřeva. Tuhost v ohybu (EI) je však téměř neovlivněna klesajícím obsahem vlhkosti. To je přímý důsledek sníženého druhého momentu plochy, který je funkcí smrštění průřezu po sušení (Madsen 1992). Závislost modulu pružnosti na vlhkosti a hustotě je možné vidět na obrázku 6.



Obr. 6 Model závislosti modulu pružnosti na hustotě a vlhkosti (Požgaj *et al.* 1993).

Charakteristiky pevnosti v tahu jsou méně ovlivněny kolísáním vlhkosti než charakteristiky pevnosti v tlaku (obrázek 7). Celkově není tahová pevnost dřeva při různých obsazích vlhkosti ovlivněna. Pevnost v tlaku však dramaticky klesá v závislosti na zvyšování obsahu vlhkosti (Madsen 1992, Požgaj *et al.*1993). Větší objemy dřeva obsahují více defektů než menší objemy a vlastnosti se mohou lišit podle rozměrů materiálu. Zejména tahová pevnost dřeva bude klesat v závislosti na rostoucí délce (Green *et al.* 1999).



Obr. 7 Tlaková a tahová pevnost jako funkce různé úrovně obsahu vlhkosti (Madsen 1992)

Negativnímu účinku defektů a kolísání vlhkosti lze čelit výrobou dřevěných kompozitů, které snižují vlastní heterogenitu dřevěných prvků. Toho je často dosaženo lepením a laminováním dřeva. Jedná se o kompozitní materiály komerčně dostupné jako vrstvené řezivo a lepené vrstvené dřevo (Alam 2004).

3.2.3 Změna struktury dřeva zhušťováním a jeho vývoj

Proces zhušťování masivního dřeva nelze v žádném případě považovat za novou metodu modifikace dřeva. Je podloženo, že v první čtvrtině 20. století bylo ve Spojených státech amerických vydáno množství patentů zabývající se zhušťováním dřeva (Kutnar *et al.* 2015, Blomberg 2006, Sandberg *et al.* 2013, Neyses 2016). První výskyt na trhu takto upraveného masivního dřeva s obchodním názvem „Lignostone" se datuje do roku 1930 (Neyses 2016). Jednalo se v podstatě o dřevo zhuštěno v hydraulickém lisu při teplotě 140 °C při tlaku 25 MPa (Kollmann 1936). V tabulce 3 je možné vidět stučné popisy prvních metod zhušťování dřeva s definovanými parametry samotného zhušťování (vstupní vlhkost dřeva, tlak a teplota samotného lisování).

Tab. 3 Historicky využívané metody zhušťovaní dřeva podle Blomberg 2006

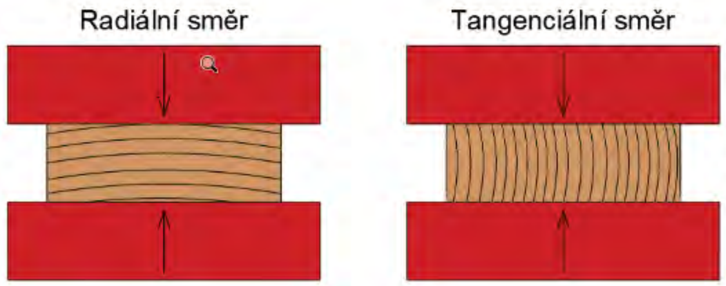
Název metody	*Vlhkost [%]*	*Tlak [MPa]*	*Teplota [°C]*	*Popis metody*
Lignostone (1940)	10		Zvýšená	Biaxiální zhuštění ohřátého dřeva
Staypak (1948)	6–12	13,8	160–180	Zhuštění tenkých dýh, lepené
Compreg (1951)	8	8,5	140–150	Zhuštění dýh, in situ polymerizovaný fenol-formaldehyd teplem a tlakem
Impreg (1943)				Stejný jako Compreg, ale bez stlačení
Lignofol (1940)	3–8	34	Zvýšená	Stejný jako Compreg

V prvním výzkumným příspěvku zabývající se problematikou zhušťování dřeva bylo prováděno zhušťování březové dýhy při tlaku v rozmezí od 10 do 17 MPa s výslednou hustotou až 1 300 kg.m^{-3}. Podmínky při zhušťování byly nastaveny tak, aby byla dřevní hmota dostatečně plastifikována (Seborg *et al.* 1945). Cílem takto modifikovaného dřeva bylo výrazné zvýšení mechanických vlastností, což by umožnilo použití ve vysoce namáhaných aplikacích. Nicméně velkou nevýhodou takto modifikovaného dřeva byla nízká rozměrová stabilita v případě vystavení vlhkosti.

V průběhu následujících desetiletí přibývalo výzkumných studií zabývajících se problematikou zhušťování dřeva se zvláštním zaměřením na vhodnou volbu technologických parametrů umožňující eliminaci nízké rozměrové stability způsobené odpružením dřevních buněk tzv. „spring-back“ efekt a vlhkostí způsobenou regenerací zhuštěných dřevních buněk. Kollman *et al.* (1975) přišli na metodu eliminace zpětného odpružení zhuštěných dřevních buněk ochlazením zhuštěného materiálu teplotou pod 100°C. Dalšími metodami zvýšení rozměrové stability zhuštěného dřeva se zabývali Inoue *et al.* 1993 a Dwianto *et al.* 1997, kteří se snažili eliminovat regeneraci zhuštěných dřevních buněk vystavením páře při 180 °C v uzavřeném v lisovacím systému, ve kterém byla kontrolována teplota, vlhkost a tlak.

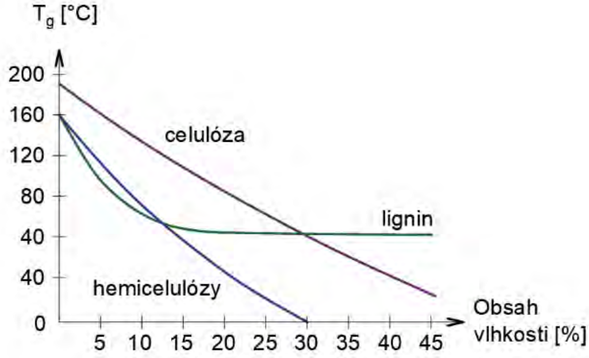
3.2.4 Základní principy zhušťování struktury dřeva

Dřevo lze zhušťovat v rozdílných směrech, buď v podélném, nebo příčném. Z hlediska využitelnosti v aplikaci vrstveného dřeva tato disertační práce řeší v rámci modifikací dřeva jeho příčné zhušťování. Příčné zhušťování lze rozdělit dále na zhušťování v radiálním nebo tangenciálním směru (obrázek 8).



Obr. 8 Schematické znázornění radiálního a tangenciálního zhušťování

Z hlediska zhušťování dřeva je nutné brát v potaz interakce mezi teplotou a vlhkostí dřeva za účelem vytvoření vhodných podmínek pro proces zhušťování z hlediska deformace buněk. Na obrázku 9 jsou izolovaně zachyceny teploty skelného přechodu tří hlavních složek dřeva v závislosti na obsahu vlhkosti ve dřevě. Tyto tři složky dřeva jsou chemicky spojeny, z toho důvodu se z hlediska správné deformace buněk musí dbát na to, aby byla chemická matrice dřeva v plastickém stavu (Neyses 2016).



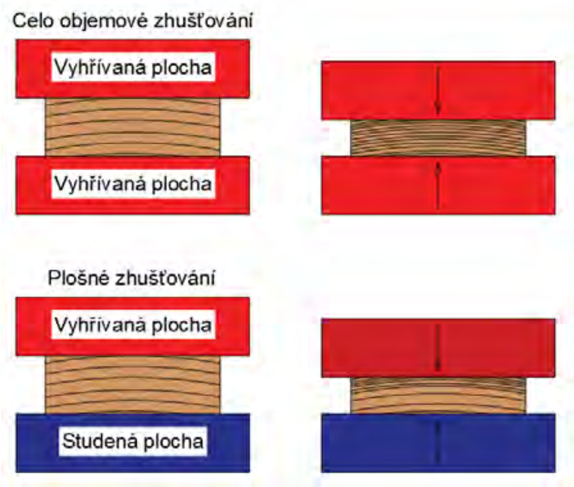
Obr. 9 Teploty skelného přechodu pro základní chemické komponenty dřeva (převzato z Neyses 2016)

Z hlediska samotného zhuštění je nutno dbát na zpětné odpružení buněk ve snaze o návrat ke svému původnímu tvaru a rozměrům. Po zhuštění dřeva je nutné buňky dřeva klimatizovat při zatížení za účelem stabilizace rozměrů. Tímto krokem ovšem nelze zabránit „spring-back“ efektu po odstranění zatížení užitého pro zhuštění kdy se projevují elastické vlastnosti dřeva. V případě dostatečné re-plastifikace zhuštěného dřeva bez přítomnosti zátěže může dojít k téměř úplnému navrácení buněk zhuštěného dřeva do původního stavu. Tomuto jevu je možné se vyhnout využitím vhodné dodatečné úpravě.

V případě celkového zhuštění dřevěných prvků je nutné určit kompresní poměr určený zhuštěnou tloušťkou k počáteční tloušťce zhušťovaného dřevěného prvku. Jelikož se jedná o rovnoměrné zhuštění v celém průřezu dřevěného prvku a hustotní profil by měl být rovnoměrný, je možné aplikovat kompresní poměr na rozdíl od povrchového zhuštění. Při povrchovém zhušťování by došlo ke zvýšení hustoty povrchových oblastí až na dvounásobnou hodnotu původní hustoty, ovšem při menší změně tloušťky (Neyses 2016).

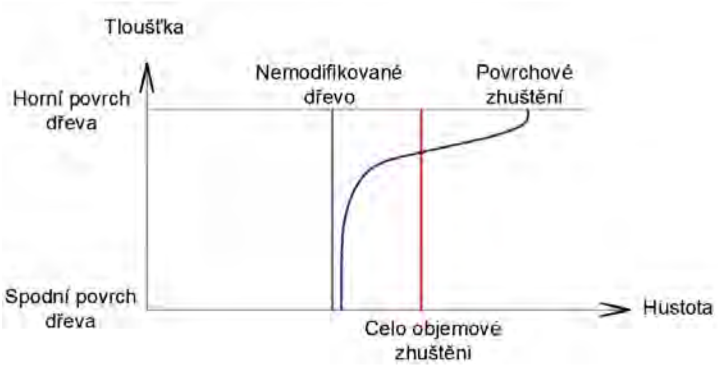
3.2.5 Metody zhušťování dřeva

Ačkoliv je zhušťování poměrně dlouhou dobu známá metoda modifikace dřeva, větší vědecké pozornosti se jí dostalo až v průběhu posledních let s důrazem na vývoj nových metod zhušťování. Většina výzkumných týmů se zaměřila na vývoj termo mechanické, nebo termo-hydro mechanické metody modifikace zhušťováním. Zhuštění dřeva se používá, k dosažení trvalé deformace buněk, která má za následek zvýšení hustoty celého nebo části objemu zhuštěného materiálu. Obecně je hlavním cílem zhuštění dřeva zvýšit jeho tvrdost a odolnost proti oděru povrchu a v některých případech také zvýšit jeho pevnost a tuhost. Zhušťovací proces se obvykle provádí v lisu za horka, popřípadě hybridním způsobem za účelem povrchového zhuštění (obrázek 10). Tento proces můžeme rozdělit na termomechanické nebo termo-hydro mechanické. Termomechanické zhušťování se provádí v otevřeném systému s kombinací tepla a tlaku, ale bez kontroly vlhkosti prostředí. V případě termo-hydro mechanického procesu je zhušťování provádí uzavřeném systému za podmínek regulované atmosféry (Sandberg *et al.* 2013, Neyses 2016).



Obr. 10 Schematické znázornění celo objemového zhušťování a povrchového zhušťování (převzato z Neyses 2016)

Rozdílem mezi výše zmíněnými typy zhušťování je rozdílný hustotní profil. V případě celoobjemového zhuštění se hustotní profil jeví stejně jako u nezhuštěného dřeva, ale v případě povrchového zhuštění je evidentní výkyv hustoty v povrchových vrstvách zhušťovaného dřeva (obrázek 11). V obou případech zhušťování dochází ke zvýšení modulu pružnosti a meze pevnosti, které umožňují potenciální využití v oblasti dřevařského průmyslu (Kutnar *et al.* 2008).



Obr. 11 Změna hustotního profilu v důsledku celo objemového a povrchového zhušťování (převzato z Neyses 2016)

3.2.5.1 Termo mechanické zhušťování

Technologickými parametry termomechanické metody v otevřeném systému zhušťování dřeva s důrazem na změnu mechanických vlastností se zabývali Ulker *et al.* (2012). Zvýšení mechanických vlastností pramenilo ze snížení poměru lumenů při procesu zhušťování, což také vedlo ke zvýšení prvků buněčné stěny, které mají nosné vlastnosti na jednotku objemu. Zvýšením teploty zhuštění se snižovaly pevnostní vlastnosti. Pokles hodnot pevnosti byl vysvětlen zvýšením chemické degradace se zvýšením teploty. Nejvhodnější teplotní úroveň byla 120 °C pro vyšší ohybovou, střihovou a pevnost v tlaku a 140 °C pro vyšší radiální a tangenciální tvrdost při zhušťování borovice. Po zhuštění bylo dosaženo 42% zvýšení pevnosti v ohybu, 20% ve smykové pevnosti, 47% v pevnosti v tlaku, 242% v radiální tvrdosti a 268% v tangenciální tvrdosti.

Účinky termomechanického zhušťováním se zabývali Bekhta *et al.* (2017). Experiment byl prováděn na široké škále dýh s nízkým obsahem vlhkosti (~ 5 %). Jednalo se o dýhy z olše, buku, břízy a borovice (~ 5 %). Dýhové desky byly zhuštěny za použití tlaků 4, 8 a 12 MPa při teplotách: 100 °C, 150 °C a 200 °C po dobu 4 minut. Výsledky byly porovnány s výsledky u nezhuštěných dýh. Získané výsledky ukazovaly, že zhuštění dýh termomechanickým procesem způsobuje nevratné změny jejich vlastností. Bylo zjištěno, že rovnoměrné zhuštění dýh termomechanickým procesem poskytuje stabilní vlastnosti za normálních podmínek atmosféry, což je důležité pro potencionální průmyslové aplikace.

Pelit *et al.* (2015) zkoumali účinky termomechanického zhuštění s následným tepelným zpracováním na hustotu a Brinellovu tvrdost borovice lesní (*Pinus sylvestris* L.) a východního buku (*Fagus orientalis* L.) Zhuštění probíhalo při kompresních poměrech

20 a 40 % a při teplotě 110 °C a 150 °C. Po zhuštění bylo aplikováno tepelné zpracování při 3 různých teplotách. K určení, zda ke změnám došlo z důvodu technologických vlastností, byly provedeny zkoušky tvrdosti podle Brinella. Hustota borovice a buku byla zvýšena od 35 % do 42 %. Po zhušťovacím procesu bylo dosaženo zvýšení hodnot radiální a tangenciální tvrdosti. Bylo pozorováno snížení hodnot hustoty a tvrdosti zhušťovaného dřeva z důvodu zvýšení teploty během tepelného zpracování. Po tepelném zpracování došlo k 4% a 5% snížení příslušných hodnot hustot borovice a buku a snížení jejich radiální a tangenciální tvrdosti.

3.2.5.2 Termo-hydro mechanické zhušťování

Jedním z prvních výzkumných týmů zabývajících se termo-hydro mechanickým zhušťováním byl tým z EPFL Lausanne ve Švýcarsku, které vedl Parviz Navi. Publikovali několik publikací zabývající se termo-hydro mechanickým procesem zhušťování. Jejich metoda spočívala v kombinaci tepla, nasycené páry a tlaku v uzavřeném systému (Navi *et al.* 1997, Navi a Sandberg, 2012). Tento postup lze rozdělit do 4 stupňů. Prvním stupněm je plastifikace, kdy je dřevo vystaveno zvýšené teplotě kolem 160 °C v nasycené páře. Druhým stupněm je samotné zhušťování ve stejných podmínkách jako v prvním stupni procesu. V následném stupni zhušťování se vykonáváno ošetření po zhušťování, kdy lis zůstává ve stejné poloze a teplota se zvyšuje, zatímco podmínky nasycené páry jsou udržovány po dobu několika minut. V konečném stupni nastává ochlazení zhušťovaného dřeva na teplotu 60 °C a poté otevření lisu.

Výzkumná skupina vedená Frederickem Kamkem získala patent na viskoelastické tepelné zhuštění (Kamke a Sizemore 2004). Viskoelastické tepelné zhuštění je podobný proces jako v případě termo-hydro mechanického procesu, protože ke zhuštění dřeva používá kombinaci tepla, páry a tlaku. V prvním kroku dřevo překračuje svou teplotu skelného přechodu při zvýšených teplotách a vlhkosti, poté se dřevo dále plastifikuje vyvoláním rychlé dekomprese par a odstraněním vázané vody z buněčné stěny. Krok dekomprese par je rozhodující pro úspěšnou plastifikaci dřevěných buněk a spoléhá se na rychlý pohyb vody z buněčné stěny. K dosažení optimálního změkčovacího účinku je třeba dobře načasovat proces a sled kroků. Dřevo je stlačeno v tomto změkčeném stavu. Poté následuje fáze stabilizace a chlazení před otevřením lisovacího zařízení.

Odlišný způsob byl zvolen kolektivem Pizzi *et al.* (2005), kdy plastifikace povrchových vrstev bylo dosaženo třením dvou kusů dřeva proti sobě za nízkého tlaku. Svaření obou kusů k sobě bylo zabráněno využitím vrstvy slunečnicového oleje, když se kusy pohybovaly vůči sobě po dobu 8 až 14 sekund za nízkého tlaku, vzniklo tření které zapříčinilo plastifikaci povrchové části dřeva. Jakmile byly povrchové části dřeva plastifikovány, pohyb vytvářející tření byl zastaven a byla použita další tlaková síla, aby se dosáhlo skutečné zhuštění. Tlak byl udržován, dokud nebylo dřevo ochlazeno pod 100 °C.

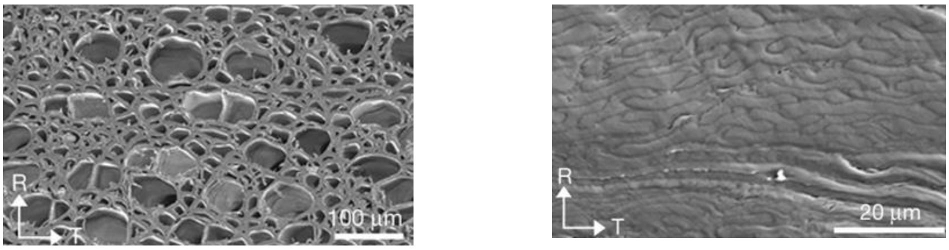
3.2.6 Mechanické vlastnosti zhuštěného dřeva

Zhušťování ovlivňuje širokou škálu mechanických vlastností dřeva, nicméně nejvíce ovlivněnými statickými mechanickými vlastnostmi zhuštěného dřeva je v závislosti na změně hustoty tvrdost, modul pružnost a pevnost v ohybu. Zaměření na oblast ohýbání zhuštěného dřeva lze pozorovat prakticky u všech výzkumných týmů zabývajících se zhušťováním dřeva.

Efekt příčného zhušťování dřeva s využitím PF pryskyřic na změny hustoty, modulu pružnosti a pevnosti v ohybu byl zaznamenán kolektivem Yano *et al.* (1997), kdy bylo dosaženo až dvojnásobného zvýšení jak v modulu pružnosti, tak v pevnosti v ohybu. Tento výzkumný tým v průběhu dalších let publikoval několik publikací (Navi a Giradet 2000, Heger *et al.* 2004, Shams *et al.* 2006, Kutnar *et al.* 2008, Pařil *et al.* 2013, Rautkari *et al.* 2013, Laine *et al.* 2016, Kariz *et al.* 2017, Song *et al.* 2018), v nichž tento proces zhušťování vylepšili a dosáhli ještě výraznějšího zvýšení mechanických vlastností. Možnost až desetinásobného zvýšení smykové pevnosti ve směru vláken byla zkoumána při využití termo-hydro mechanické modifikace, kde dřevo bylo zhušťováno v atmosféře nasycené páry při zvýšené teplotě po dobu cca 30 min (Navi a Giradet 2000, Heger *et al.* 2004, Shams *et al.* 2006). Ve všeobecnosti je možné říct, že modul pružnosti a pevnost v ohybu se zvyšuje s nárůstem hustoty (Kutnar *et al.* 2008). Od začátku roku 2010 skupina z Mendelovy univerzity v České republice, často spolupracující s vědci z univerzity Sopron v Maďarsku, zveřejnila několik studií o bukovém dřevu plastifikovaném amoniakem před zhuštěním produkt zvaný Lignamon. Ve srovnání s termo-hydro mechanicky zhuštěným bukem vykazoval Lignamon vyšší modul pružnosti, zatímco mez pevnosti zůstala zhruba stejná (Pařil *et al.* 2013).

Vliv zhuštění v otevřeném systému (termomechanickou metodou) na mechanické vlastnosti byly studovány hlavně Rautkariho skupinou na Aalto University a několika dalšími, méně aktivními skupinami po celém světě. Skupina vedená Lauri Rautkari se zaměřila hlavně na Brinellovu tvrdost a méně na další mechanické vlastnosti, při jejich výzkumu bylo zaznamenáno dvojnásobné zvýšení tvrdosti podle Brinella po zhuštění borovice o tloušťce 22, 20 a 18 mm na cílovou tloušťku 15 mm (Rautkari *et al*. 2013). To ukázalo, že tvrdost je téměř výhradně ovlivněna hustotou povrchové vrstvy, pokud je zhuštěná plocha dostatečně silná. Následné hydro-termické ošetření vedlo ke ztrátě hmotnosti, ale neovlivnilo hustotu ani tvrdost. Studie smrku se stejnou metodou vedla k mírně nižšímu zvýšení tvrdosti a zvýšení modulu pružnosti a pevnost v ohybu nebylo úměrné zvýšení hustoty (Kariz *et al.* 2017). Ve studii celoobjemového zhuštění s využitím v podstatě stejné metody – za použití horkého lisu při teplotě 150 °C se zjistil nárůst tvrdosti úměrný zvýšení hustoty (Laine *et al.* 2016). Tepelné dodatečné ošetření opět nemělo škodlivý účinek na tvrdost.

Novou metodou celoobjemového zhušťování za účelem dosažení vysoce výkonného konstrukčního materiálu se velmi podrobně zabývali Song *et al.* 2018. Kolektiv poukázal na to že, při zhušťování s předúpravou párou, teplem, amoniakem nebo válcováním za studena dochází k neúplnému zhuštění a nedostatečné rozměrové stabilitě v reakci na vlhké prostředí. Při aplikaci jejich metody zhušťování je možné dosažení zvýšení pevnosti až desetinásobně. Díky částečnému odstranění ligninu pomocí vaření ve směsi NaOH a Na_2SO_4 s následným lisováním za horka až do bodu úplného zhroucení buněk (obrázek 12). Tímto postupem bylo možné vytvoření materiálu s výší specifickou pevností než v případě většiny strukturálních kovů a slitin. Dřevo upravenou touto metodou se vykazuje až 11,5násobnou pevností v tahu v porovnání s neupraveným nativním dřevem. V případě elastické tuhosti byl pozorován až deseti násobný nárůst hodnot. Pří rázové zkoušce Charpyho kladivem byl pozorován až osminásobný nárůst hodnot vzhledem nativnímu dřevu. V případě ohybové pevnosti lze vidět nárůst hodnot v rozsahu od 6 do 18násobku (Song *et al.* 2018).



a) b)

Obr. 12 Snímek ze skenovacího elektronového mikroskopu a) (SEM) příčného řezu vzorku rostlého dřeva b) SEM analýza zhuštěného dřeva v příčné rovině (Song *et al.* 2018).

Vytváření laminovaných kompozitů se zesílenou jádrovou vrstvou a zhuštěnými vrstvami vedlo ke zvýšení modulu pružnosti a meze pevnosti ve srovnání s nezhuštěným dřevem, ale v tomto případě s konstantou proporcionality menší než 1 ve vztahu ke zvýšení hustoty povrchové vrstvy. Pod nasycenou parou byl nárůst hodnot úměrný zvýšení hustoty, ale za podmínek přehřáté páry byl nárůst menší (Kutnar a Kamke 2012a). Následné ošetření nasycenou parou při 200 °C po dobu 13 minut nevedlo ke zhoršení ohybových vlastností zhutněného dřeva (Kutnar a Kamke 2012b). Výzkumem zabývajícím se vlivem zhuštění válcováním jednotlivých dýh ve struktuře vrstveného dřeva se zabývali Gaff a Gašparík (2015). Jejich výsledky ukazují, že vrstvené dřevo tvořené zhuštěnými a nezhuštěnými dýhami, případně s PVC fólií, dosáhlo vyšších hodnot pevnosti v ohybu ve srovnání s tradičním složením sestávajícím z nezhuštěných dýh. Zhušťování mělo silný vliv na pevnost v ohybu.

Pro stručné shrnutí otázky vlivu zhuštění dřeva na mechanické vlastnosti lze říct, že obecně dochází ke zvýšení mechanických vlastností úměrně se změnou hustoty vlivem zhuštění. Při porovnání různých metod zhušťování je nutno konstatovat, že zhušťováním v uzavřeném systému lze dosáhnout patrnějších zlepšení mechanických vlastností. V případě povrchového zhuštění je vztah mezi profilem hustoty a nárůstem modulu pružnosti a mezí pevnosti méně jasný a několik studií uvádí méně úměrné zvýšení mechanických vlastností vzhledem k hustotě. Při využití zhuštěných dřevěných prvků ve vrstvovité struktuře je také možné pozitivně ovlivnit mechanické vlastností vrstvených materiálů.

4 Vrstvení dřeva a nedřevních komponentů

O kompozitech se obvykle uvažuje, jako o dvoufázovém systému, kde jsou jednotlivé prvky propojené pojivem, dřevěné kompozity jsou však vícefázové systémy, kde je potřeba počítat s vlhkostí, přítomností dutin a aditiv. Popisy různých prvků této skupiny zdůrazňují jejich složený charakter (Bodig a Jayne 1982). Vrstvené kompozitní materiály na bázi dřeva lze kategorizovat do 5 základních skupin, viz tabulka 4.

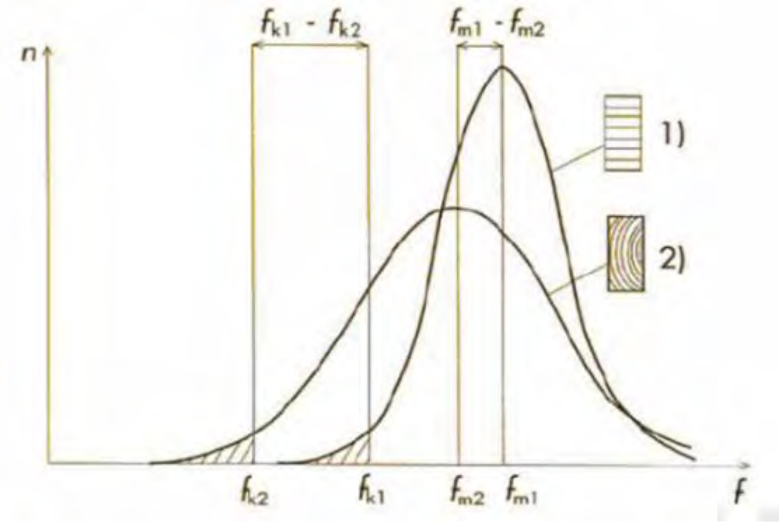
Tab. 4 Kategorizace vrstvených kompozitních materiálů na bázi dřeva

1) Paralelně vrstvené	- Lepené vrstvené dřevo - Vrstvené dýhy
2) Křížově vrstvené	- **Překližované materiály** - **Dýhované desky s orientovanými třískami**
3) Vyztužené dřevo	
4) Sendvičové panely	
5) Mechanicky spojené lamináty	

4.1 Lepené vrstvené dřevo

V této disertační práci bylo řešeno paralelní vrstvení s následnou aplikací vyztužujícího prvku. Paralelně vrstvené kompozitní materiály na bázi dřeva dosahují vlastností podobných rostlému dřevu. Vrstvením dřeva je snaha o dosažení zlepšení makroskopických ukazatelů dřeva vzhledem k rostlému dřevu. Vrstvením dřeva dosahujeme stejných často zlepšených vlastností v zatěžování, s vrstvením je také spojeno zvýšení rozměrové stability. Vrstvené kompozitní materiály se vykazují širokou škálou využití od stavebnictví až po nábytkové komponenty vzhledem ke tloušťce jednotlivých vrstev, což má vliv z hlediska jak statického tak dynamického namáhní těchto materiálů v ohybu. Je potřeba také rozlišovat krátkodobé a dlouhodobé zatížení z hlediska pružné a plastické oblasti namáhání. Dřevo se ve své přírodní podobě vyznačuje výskytem odchylek od struktury dřeva, jež zvyšují jeho heterogenitu a snižují nosnou kapacitu nosníku. Rozříznutím toho nosníku na tenké vrstvy (lamely) a jeho následným slepením s náhodným uspořádáním odchylek lze dosáhnout nosník s vyšší pevností nicméně ne nutně se zvýšenou tuhostí. Uspořádáním lamel tak, aby lamely s vyšším počtem odchylek byly ve středové části nosníku, lze zlepšit jeho vlastnosti. Možností, jak ještě výrazněji zlepšit vlastnosti vrstveného nosníku, je odstranění všech vad a následně vrstvit spojované lamely. Nejvyššího zlepšení lze dosáhnout kombinováním vrstveného dřeva s prvkem se zvýšenou pevností a tuhostí (Bodig a Jayne 1982).

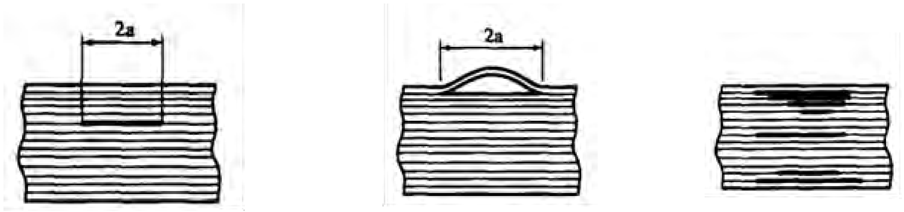
Distribuce pevnosti lepeného vrstveného dřeva je proto užší a vyšší než distribuce u masivního dřeva. Hodnota pátého percentilu, která se používá k navrhování dřevěných konstrukcí, se posune doprava, stejně jako průměrná hodnota pevnosti (obrázek 13).



Obr. 13 Distribuce pevnosti lepeného vrstveného dřeva (1) porovnané s distribucí pevnosti rostlého dřeva (2) převzato z Carling 2001

4.1.1 Delaminace vrstvených materiálů na bázi dřeva

Pod pojmem delaminace rozumíme oddělení jednotlivých vrstev v laminátech na bázi dřeva z důvodů selhání lepidla buďto přímo v lepidlu nebo na rozhraní mezi lepidlem a lepeným prvkem (Bucur 2014). Delaminace se týká strukturálních vrstvených produktů zahrnující kompozity na bázi dřeva, jako je například vrstvené dřevo, lepené vrstvené dřevo a lepené vrstvené dřevo vyztužené vysoko pevnostními polymerními vlákny. Kritériem klasifikace delaminace je poloha delaminace v průřezu prvku, jako například: vnitřní delaminace (14a), delaminace v blízkosti povrchu (14b) a delaminace, které způsobují vícenásobné porušení lepených prvků (14c). Růst delaminace může významně ovlivnit pevnost, tuhost a stabilitu kompozitu. Výskyt delaminace vyplývá z mnoha zdrojů, jako jsou výrobní vady, poškození lepených materiálů nebo poškození místním nárazem (Kim *et al.* 1997, Bucur 2014).



a) b) c)

Obr. 14 Pozice delaminace ve vrstvených kompozitních materiálech (Bolotin 1996), a) vnitřní delaminace, b) delaminace poblíž povrchové vrstvy, c) multi-násobná delaminace

Vnitřní delaminace je označována jako delaminace pozorovaná za vzniku vnitřní praskliny a studována pomocí lomové mechaniky. Vnitřní delaminace může být detekována jak u masivního dřeva, tak u kompozitů na bázi dřeva v submikroskopickém, mikroskopickém a makroskopickém měřítku. Například: v masivním dřevu mezi střední lamelou a ostatními vrstvami buněčné stěny nebo mezi vrstvami S1 a S2 nebo mezi vrstvami S3 a G, jak je často pozorováno u tlakového dřeva nebo tahového dřeva. V makroskopickém měřítku dochází k delaminaci v ročním kruhu mezi zónami s různými hustotami (Clair 2001, Bucur 2014). Delaminace v blízkosti povrchu je situována těsně u povrchu prvku a je vždy doprovázena vzpíráním povrchového prvku, jako jsou puchýře v překližce vzniklé v průběhu výrobního procesu. Jeho růst je pozorován jako mezi laminární poškození. Delaminace, která způsobuje multinásobné praskání po celé tloušťce prvku, bez oddělení vrstev, je typická u masivního dřeva v průběhu vysychání. U vláknitých kompozitů je tato vada velmi častá a je způsobená nejčastěji během výrobního procesu indukována tepelnými faktory. U konstrukčních vrstvených materiálů na bázi dřeva lze pozorovat multinásobné praskliny u LVL nebo v GLULAMU, používaných ve stavebnictví. Lokální nestabilita a růst trhlin v lepeném vrstveném dřevě může způsobit globální nestabilitu velkých konstrukčních prvků, které v extrémních případech mohou dokonce vést k selhání celé struktury (Bolotin 1996, Reiter *et al.* 2002, Bucur 2014). Při namáhání lepených nosníků jsou z hlediska normálových napětí jako kritické body označovány povrchové vrstvy nosníku, kde dochází k nejvyšším normálovým tahovým a tlakovým napětím (obrázek 15). Nicméně z hlediska delaminace jsou kritické lepené spáry, kde je velmi důležité smykové napětí. Za předpokladu obdélníkového průřezu je smykové napětí parabolické podél výšky nosníku, s nejvyšším smykovým napětím v neutrální ose (Babiak *et al.* 2018), viz obrázek 15.

Obr. 15 Rozložení normálových a smykových napětí po výšce lepeného nosníku

Klíčovým faktorem z hlediska delaminace u vrstvených materiálů je rozložení napětí aplikace vhodného adhezivního systému.

4.1.2 Adheziva využívaná při tvorbě vrstvených materiálů na bázi dřeva

Lepidla jsou nekovové materiály, které se používají ke spojení dvou nebo více součástí dohromady přitažlivými (adhezivními a kohezivními) silami působícími přes rozhraní (Belgacem a Pizzi 2016). Jedním z hlavních rysů všech lepidel je relativně malé množství potřebné k vytvoření spoje mezi dvěma spojovanými materiály ve srovnání s hmotností finálního produktu. Výběr typu a formy lepidla závisí na povaze adherentů, požadavcích na konečné použití a na procesech lepení (Pizzi 1989). Pro dřevěné kompozity se používá řada různých lepidel. Mezi nimi termosetová lepidla založená na použití formaldehydových pryskyřic získaných polykondenzací dominovala v dřevozpracujícím průmyslu po mnoho let. V dřevozpracujícím průmyslu se využívají lepidla na bázi formaldehydu, která dnes stále představují většinu z lepidel využívaných při lepení kompozitů na bázi dřeva, a dalších produktů, jako jsou akrylátové a polyvinylacetátová lepidla, které jsou v dřevozpracujícím průmyslu osvědčenými lepidly již dlouhou dobu, jakož i na novější produkty, které byly v tomto průmyslu nedávno přijaty relativně rychle, jako jsou izokyanátové a jednosložková polyuretanová lepidla atd. (Belgacem a Pizzi 2016).

Pokud má být lepidlo použito k lepení dřeva na dřevo, musí být zvážena vhodnost dřeva pro lepení: pokud jde o tvrdé dřevo, je výhodnější PVAc než v případě měkkého dřeva. PVAc lepidla se využívají hlavně na dynamicky zatěžované prvky hlavně z důvodů jejich pružnosti (Pizzi 1989). PVAc lepidla se obecně nepoužívají pro spoje, které jsou pod stálým zatížením (v důsledku termoplastického tečení za studena) nebo vystavené vysoké teplotě (ztrácí soudržnost se zvyšující se teplotou) a vysoké vlhkosti, nejsou ani strukturální, mohou být upraveny tak, aby měly za těchto podmínek lepší efektivitu. Přidání malých podílů solí chromu jako zesíťovacího činidla je nejjednodušší formou ze síťovacího systému pro tato adheziva, i když se často používají i praktikovatelné komonomery (Belgacem a Pizzi 2016).

4.1.2.1 Charakteristika polyvinyl acetátových (PVAc) adheziv

Polyvinyl acetátová adheziva (PVAc) jsou stabilní suspenze/emulze ve vodě polymeru vytvářejícího film. Vyrábějí se emulzní polymerací, mechanismem přidávání volných radikálů k polymeraci monomeru v přítomnosti vody a stabilizátorů. Jsou to termoplastické polymery, které si v průběhu let získaly široké přijetí jako surovina lepidel na dřevo. Modifikované nebo nemodifikované a jako homopolymery nebo kopolymery vykazují univerzálnost, díky které jsou velmi vhodné pro lepení široké škály materiálů (Belgacem a Pizzi 2016). Hlavními výhodami PVAc jsou snadná a široká aplikace, elasticita, odolnost proti stárnutí, nízká cena a dostupnost, odolnost proti bakteriálním a fungicidním útokům a netoxicita. Hlavní nevýhody PVAc lepidel je nízká odolnost vůči povětrnostním vlivům a vlhkosti, špatná odolnost vůči většině rozpouštědel, pomalé vytvrzování a rychlost tuhnutí a dotvarování při zvýšené statické zátěži (Kim *et al.* 2007, Šedivka *et al.* 2015).

4.1.2.2 Chemizmus polyvinyl acetátových (PVAc) adheziv

Monomer vinylacetátu je průmyslově polymerizován radikálovou emulzní polymerizací. Polymerizační reakce je iniciována volnými radikály vytvořenými rozpadem organických hydroperoxidů nebo podobných iniciátorů. Polymerizace je čistě exotermický proces přidáním, při němž nedochází k eliminaci malých molekul. Spolu s vodou, vinyl acetátovým monomerem, peroxidem nebo hydroperoxidovými iniciátory, ko-monomery a vodou, počáteční reakční médium obsahuje stabilizační koloid nebo povrchově aktivní látku, polyvinyl alkohol je nejčastěji používaný jako stabilizační koloid. V některých lepidlech je druhý monomer kopolymerován s vinylacetátem, aby se modifikovaly jeho vlastnosti. Obvykle se jedná o změkčení polymeru nebo ke zlepšení jeho odolnosti vůči alkáliím (Pizzi 1989, Belgacem a Pizzi 2016). Jakýkoli emulzní polymer ve vlhkém stavu má formu suspenze nespojitých částic polymeru. Toto sušení musí odstranit vodu, aby se tyto částice spojily dohromady, a tak vytvořily souvislý film přemosťující povrch, který má být spojen. Teplota, při které se vytváří souvislý film, ale pod kterou se voda vypaří a zanechá prachový depozit nepoužitelný pro lepení, se nazývá minimální teplota pro tvorbu filmu. Minimální teplota tvorby filmu je nejdůležitějším parametrem tohoto typu lepidel a je silně ovlivněna teplotou skelného přechodu (Tg) polymeru. Homopolymer PVAc má Tg 28 °C. Každý polymer má charakteristickou Tg vztahující se k jeho flexibilitě hlavního řetězce a velikosti skupin postranních řetězců. Proto má methylmethakrylát vyšší Tg než methylakrylát, protože má nižší flexibilitu svého hlavního řetězce. Existuje mnoho obyčejných látek, které se používají v PVAc, jako je di-butylmaleát, methylmethakrylát a VeoVA 10, všechny se obvykle používají ke zvýšení tvrdosti polymeru a ke změně jeho minimální teploty tvorby filmu. Kopolymery vinylacetátu také získaly v posledních desetiletích rostoucí komerční význam. To je způsobeno účinností ethylenu pro zlepšení pružnosti hlavního polymerního řetězce, a tím se snižuje jeho minimální teplota pro tvorbu filmu (Down *et al*. 1996, Qiao a Easteal 2001, Belgacem a Pizzi 2016).

4.2 Vyztužování vrstvených materiálů

4.2.1 Výztužné nedřevní prvky

4.2.1.1 Skelná vlákna

Skelná vlákna jsou nejpoužívanější výztuží v kompozitech z polymerní matrice. Skelné vlákno je výsledkem smíchání písku, kaolinu, vápence a colemanitu. Změna podílu každé složky vede k různým druhům skleněných vláken (A, E, C, AR, S). Každý z nich má různé použití a následně různé vlastnosti. Směs se poté podrobí vysoké teplotě (1 600 °C), což vede k tvorbě tekutého skla. Kapalina se následně nasává a chladí současně malými otvory (průměr 5 až 24 μm). Extrudovaná vlákna získaná tímto způsobem se spojí do malých svazků. Takto spojené svazky se využívají pro vytvořené skelné tkaniny. Velmi často se používají skelná vlákna typu E kvůli jejich dobrým mechanickým vlastnostem a relativně nízkým nákladům (André 2007). Přehled vlastností nejpoužívanějších skelných vláken lze vidět v tabulce 5.

Tab. 5 Vlastnosti základních typů skelných vláken (André 2007)

	Pevnost v tahu [GPa]	*Modul pružnosti E_m [GPa]*	*Relativní prodloužení ε [%]*	*Specifická hmotnost [g/cm^3]*
Skelní vlákna typu E	3,5	73,5	4,8	2,52
Skelní vlákna typu AR	3,5	175	2	2,68
Skelní vlákna typu S	4,6	86,8	5,4	2,46

4.2.1.2 Uhlíková vlákna

Uhlíková vlákna se vyrábějí oxidací, karbonizací a grafitizací při vysoké teplotě z prekurzorových materiálů s vysokým obsahem uhlíku. Nejčastěji používán je polyakrylonitril z důvodu nejvyšších mechanických vlastností uhlíkových vláken. Uhlíková vlákna mají průměr mezi 5 a 15 μm. Změnou teploty během grafitizačního procesu z 2 600 °C na 3 000 °C lze vyrobit vlákna s vysokou pevností nebo s vysokým modulem pružnosti (Oqawa, 2000, Chung, 2017). Uhlíková vlákna jsou dražší než skleněná vlákna, ale mají také vyšší mechanické vlastnosti (tabulky 5-6). Jejich použití je dlouhodobě omezeno na oblasti, jako je letectví, ale v posledních letech bylo rozšířeno na další aplikace. Pevnost v tahu a modul pružnosti jsou však stále pouze 7 % a 65 % teoretických odhadovaných hodnot, kterých by uhlíková vlákna mohla dosáhnout. Vlastností základních typů uhlíkových vláken lze vidět v tabulce 6.

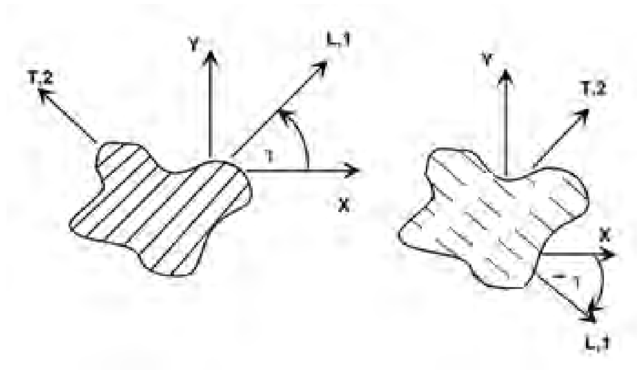
Tab. 6 Vlastnosti základních typů uhlíkových vláken (SIKA s.r.o., 2020)

	Pevnost v tahu [GPa]	*Modul Pružnosti Em [GPa]*	*Relativní prodloužení ε [%]*	*Specifická hmotnost [g/cm^3]*
Uhlíková vlákna s vysokou pevností	4,3–4,9	230–240	1,9–2,1	1,8
Uhlíková vlákna s vysokým modulem pružnosti	2,7–5,4	294–329	0,7–1,9	1,78–1,81
Uhlíková vlákna s ultra vysokým modulem pružnosti	2,6–4	540–640	0,4–0,8	1,91–2,12

4.3 Mechanické vlastnosti laminy a laminátů

4.3.1 Elastické chování laminy

Ortotropní lamináty jsou vrstvy s jedinečnými a předvídatelnými vlastnostmi a sestávají ze souboru vláken ležícího v rovině drženého na místě maticí. Vrstva může být složena z kontinuálních nebo diskontinuálních vláken (obrázek 16).



a) b)

Obr. 16 Typy značení laminy s kontinuálními (a) a diskontinuálními vlákny (b)

V teorii laminování se užívá označování m = cos (θ) a n = sin (θ), kde θ je orientace vlákna v laminátu. Transformační matice [T] (1) z lokálního souřadného systému (L-T) do globálního souřadného systému (x-y), (2):

$$[T] = \begin{bmatrix} m^2 & n^2 & +2mn \\ n^2 & m^2 & -2mn \\ -mn & +mn & m^2 - n^2 \end{bmatrix} \tag{1}$$

$$\begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \gamma_{LT} \end{Bmatrix} = [T] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad ; \quad \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix} = [T] \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} \tag{2}$$

Zevšeobecnění Hookova zákona pro kontinuální vláknité kompozity v lokálním souřadnicovém systému (L-T) lze vidět na vzorci (3):

$$\{\varepsilon\}_{LT} = [S]\{\sigma\}_{LT} \quad \text{a} \quad \{\sigma\}_{LT} = [Q]\{\varepsilon\}_{LT}, \tag{3}$$

kde $[S]$ je maticí shody. $[S]=[Q]^{-1}$, kde $[Q]$ je matice tuhosti pro ortotropní materiály (4, 5):

$$[Q] = \begin{bmatrix} \frac{E_L}{1-\nu_{LT}\nu_{TL}} & \frac{\nu_{LT}E_T}{1-\nu_{LT}\nu_{TL}} & 0 \\ \frac{\nu_{LT}E_T}{1-\nu_{LT}\nu_{TL}} & \frac{E_T}{1-\nu_{LT}\nu_{TL}} & 0 \\ 0 & 0 & G_{LT} \end{bmatrix} \quad (4)$$

$$[S] = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{TL}}{E_T} & 0 \\ \frac{\nu_{LT}}{E_L} & \frac{1}{E_T} & 0 \\ 0 & 0 & G_{LT} \end{bmatrix} \quad (5)$$

Obecný Hookův zákon v globálním souřadnicovém systému je stejný, s tím rozdílem, že $[S]$ je nahrazen $[\bar{S}]$.(6):

$$[\bar{S}] = [T]^T[S][T] \quad (6)$$

Využitím technických konstant laminátu lze vyjádřit $[\bar{S}]$ (7):

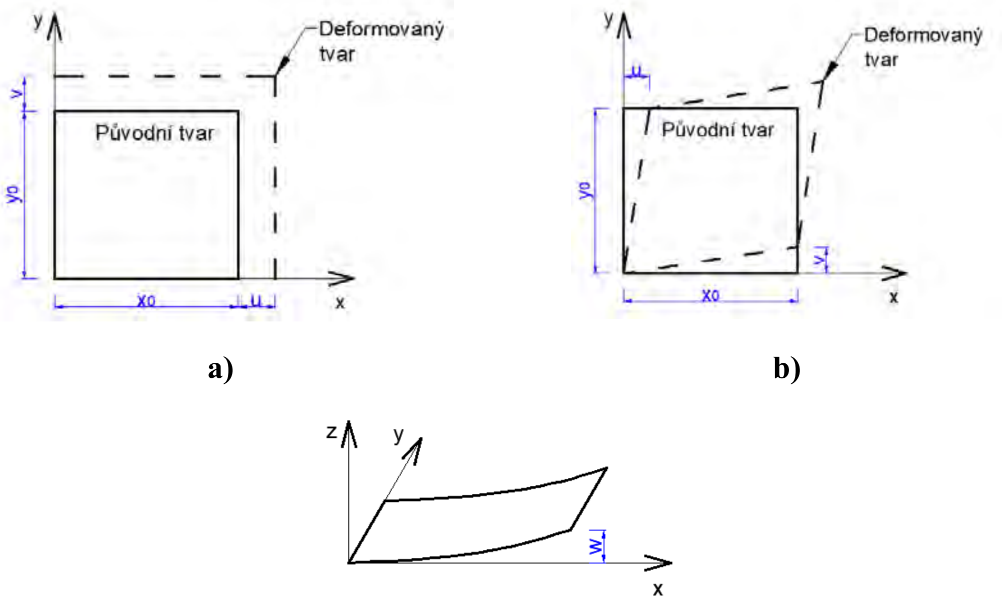
$$[\bar{S}] = \begin{bmatrix} \frac{1}{E_x} & \frac{\nu_{xy}}{E_x} & -\frac{m_x}{E_L} \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{m_y}{E_L} \\ -\frac{m_x}{E_L} & -\frac{m_y}{E_L} & \frac{1}{G_{xy}} \end{bmatrix}; \; m_i = -\frac{\varepsilon_i . E_L}{\gamma_{xy} . G_{xy}} \quad (7)$$

4.3.2 Mechanika vrstvených kompozitů

Laminární teorie je popsána v práci Nettles (1994) a vychází z několika předpokladů. Prvním předpokladem je, že tloušťka laminátu je velmi nízká vzhledem k ostatním rozměrům materiálu. Dalším předpokladem této teorie je, že jednotlivé vrstvy laminátu jsou perfektně spojené. Třetím předpokladem je, že kolmice k povrchu laminátu zůstávájí rovné a kolmé i po deformaci. Dalším předpokladem je, že jak jednotlivé laminy tak laminát jako celek jsou lineárně elastické. Uvedené předpoklady platí, pokud není laminát poškozen a je vystaven malým průhybům.

4.3.2.1 Napětí a deformace

Je potřeba rozlišovat osové a momentové namáhání, níže popsaná teorie platí pro obecné vrstvené materiály. Podle teorie (Nettles 1994) deformace desky ve směru *x* je označena jako *u*. Pro směr *y* je deformace označena jako *v* a pro směr *z* jako *w*. Obrázek 17 ukazuje tyto deformace. Napětí lze tedy definovat jako:



a) **b)**

c)

Obr. 17 a) Normálové deformace, b) Smykové deformace, c) Ohybové deformace, převzato z Nettles 1994

$$\varepsilon_x \overset{\text{def}}{=} \frac{\partial_u}{\partial_x}\ ;\ \ \varepsilon_y \overset{\text{def}}{=} \frac{\partial_v}{\partial_y}\ ;\ \gamma_{xy} \overset{\text{def}}{=} (\frac{\partial_u}{\partial_y} + \frac{\partial_v}{\partial_x}) \tag{8}$$

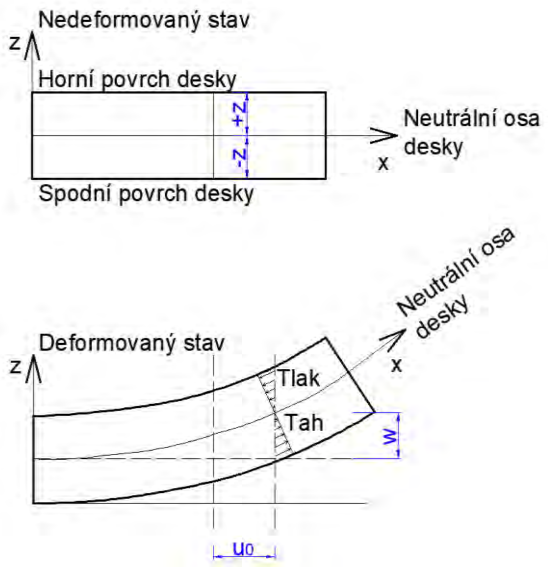
V případě ohybu desky lze sklon vyjádřit jako:

$$\frac{\partial_w}{\partial_x}\ \textit{podél směru } x \tag{9}$$

$$\frac{\partial_w}{\partial_y}\ \textit{podél směru } y$$

Celková deformace *v* rovině v kterémkoli bodě desky je součet normálových deformací spolu s deformacemi způsobenými ohýbáním. Označení deformace střední roviny desky pro směr *x* a *y* jako *u*, respektive *v*, jsou zobrazeny na obrázku 18, z čehož lze odvodit celkovou deformaci.

$$u = u_0 - z\ \frac{\partial_w}{\partial_x}; v = v_0 - z\ \frac{\partial_w}{\partial_y} \tag{10}$$



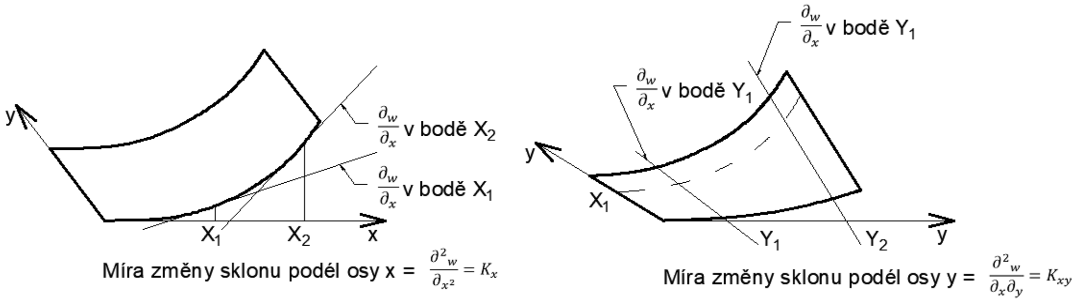
Obr. 18 Totální posunutí ohybem převzato z Nettles 1994

Pro obrázek 18 platí, že x může být nahrazeno y (tzn. pohled, může být z libovolné strany desky). Předpokládá se, že ve směru tloušťky nedochází k žádnému namáhání, pouze k deformacím.

Rovnice 8 a 9 lze vyjádřit v maticovém stavu jako:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} + z \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \tag{11}$$

Na obrázku 19 je vidět, že zakřivení desky K_x nebo K_y je míra změny sklonu ohýbané desky ve směru x nebo y. Zakřivení desky K_{xy} je velikost ohybu ve směru x podél osy y.



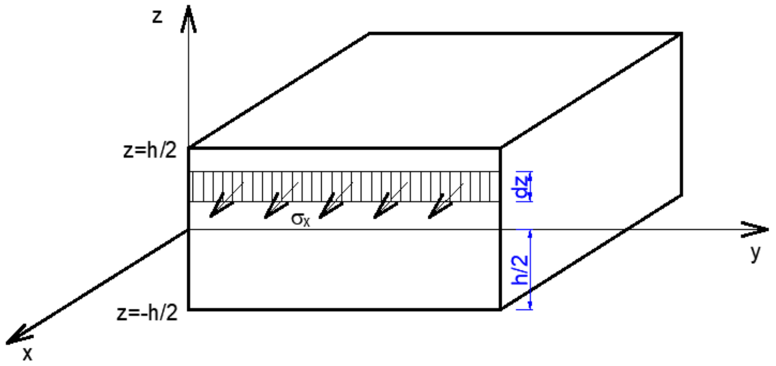
Obr. 19 Definice zakřivení desky převzato z Nettles 1994

Napětí v každé vrstvě laminátu lze tedy vyjádřit v maticovém stavu pomocí rovnice 12:

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}=\begin{bmatrix}\overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}}\\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}}\\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}}\end{bmatrix}\begin{bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \varepsilon_{xy}^0\end{bmatrix}+z\begin{bmatrix}\overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}}\\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}}\\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}}\end{bmatrix}\begin{bmatrix}K_x\\ K_y\\ K_{xy}\end{bmatrix} \tag{12}$$

4.3.2.2 Definice silových a momentových výslednic

Protože napětí v každé vrstvě se mění v závislosti na tloušťce laminátu, je výhodné definovat napětí jako ekvivalentní síly působící na střední povrch. Na obrázku 20 je vidět, že napětí působící na hranu lze rozdělit na přírůstky a sečíst je. Výsledný integrál je tedy definován jako silová výslednice a je označen N_i (13–15), kde index E' označuje směr. Tato silová výslednice má jednotky síly na šířku a působí ve stejném směru (Nettles 1994).



Obr. 20 Definice silových a momentových výslednic převzato z Nettles 1994

Ze scématu na obrázku 20, lze také vyjádřit napětí ve směru y a smykové napětí. Výsledkem jsou tedy tři napěťové výslednice:

$$N_x \overset{\text{def}}{=} \int_{-h/2}^{h/2} \sigma_x \, dz \tag{13}$$

$$N_y \overset{\text{def}}{=} \int_{-h/2}^{h/2} \sigma_y \, dz \tag{14}$$

$$N_{xy} \overset{\text{def}}{=} \int_{-h/2}^{h/2} \tau_{xy} \, dz \tag{15}$$

Jak je vidět na obrázku 20, napětí působící na hranu vytváří moment kolem střední roviny. Síla je σ_x (dz) (y). Rameno momentu je ve vzdálenosti z od střední roviny.

Stejným postupem jako u výslednic napěťových faktorů lze momentové výslednice definovat jako:

$$M_x \overset{\text{def}}{=} \int_{-h/2}^{h/2} \sigma_x \, z \, dz \tag{16}$$

$$M_y \overset{\text{def}}{=} \int_{-h/2}^{h/2} \sigma_y \, z \, dz \tag{17}$$

$$M_{xy} \overset{\text{def}}{=} \int_{-h/2}^{h/2} \tau_{xy} \, z \, dz \tag{18}$$

Tyto momentové výslednice mají jednotky točivého momentu na jednotku délky.

4.3.2.3 Fyzikální rovnice pro lamináty

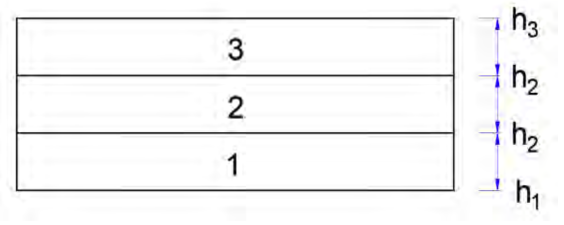
Maticový stav rovnic 13–15, lze zapsat ve formě:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \tag{19}$$

Stejně tak lze v maticovém stavu vyjádřit rovnice 16-18:

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} z \, dz \tag{20}$$

Integrály v rovnicích 19 a 20 musí být provedeny na každé vrstvě a sečteny, protože diskontinuity v napětí mohou nastat na rozhraní vrstev. Při použití schématu laminátu na obrázku 21 musí být rovnice 19 a 20 psány jako.



Obr. 21 Označení jednotlivých vrstev v průžezu laminátu

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \, ; \begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} z \, dz \tag{21}$$

Rovnice 11 může být nahrazena rovnicemi 21, za účelem získání rovnic 22 a 23.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \left\{ \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} dz \right. \\ \left. + \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} z\, dz \right\} \tag{22}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \sum_{k=1}^{n} \left\{ \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} z\, dz \right. \\ \left. + \int_{h_{k-1}}^{h_k} \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} z^2\, dz \right\} \tag{23}$$

Protože deformace a zakřivení neutrální osy (ε^0a K) nejsou funkcí z (protože tyto hodnoty jsou vždy na neurální ose $z = 0$), nemusí být zahrnuty do integrace. Matrice tuhosti laminátu je také konstantní pro danou vrstvu, takže také bude konstantní po integraci tloušťky vrstvy. Vyjádřením těchto konstatnt před integrál v rovnicích 22 a 23 lze získat zápis v podobě rovnic 24 a 25:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \left\{ \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} \int_{h_{k-1}}^{h_k} dz \right. \\ \left. + \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \int_{h_{k-1}}^{h_k} z\, dz \right\} \tag{24}$$

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \sum_{k=1}^{n} \left\{ \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} \int_{h_{k-1}}^{h_k} dz \right. \\ \left. + \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix}_K \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix} \int_{h_{k-1}}^{h_k} z\, dz \right\} \tag{25}$$

Protože deformace a zakřivení neutrální osy nejsou součástí sumací, matice tuhosti laminátu a h_k termíny mohou být kombinovány za vzniku nových matric. Z rovnic (24) a (25) je lze definovat jako:

$$A_{ij} = \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \left[\bar{Q}_{ij}\right]_k (h_k - h_{k-1}) \tag{26}$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \left[\bar{Q}_{ij}\right]_k (h_k^2 - h_{k-1}^2) \tag{27}$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{n} \int_{h_{k-1}}^{h_k} \left[\bar{Q}_{ij}\right]_k (h_k^3 - h_{k-1}^3) \tag{28}$$

V maticové podobě můžou být fyzikální rovnice zapsány ve formě jako:

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ — \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & | & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & | & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & | & B_{16} & B_{26} & B_{66} \\ — & — & — & — & — & — & — \\ B_{11} & B_{12} & B_{16} & | & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & | & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & | & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ — \\ K_x \\ K_y \\ K_{xy} \end{bmatrix}. \tag{29}$$

Ve zkráceném tvaru lze tuto rovnici uvést jako:

$$\begin{bmatrix} N \\ — \\ M \end{bmatrix} = \begin{bmatrix} A & | & B \\ — & — & — \\ B & | & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ — \\ K \end{bmatrix}. \tag{30}$$

Tento zkracený tvar zápisu lze částečně převrátit do tvaru:

$$\begin{bmatrix} \varepsilon^0 \\ — \\ M \end{bmatrix} = \begin{bmatrix} A^* & | & B^* \\ — & — & — \\ C^* & | & D^* \end{bmatrix} \begin{bmatrix} N \\ — \\ K \end{bmatrix}, \tag{31}$$

kde platí:

$$\begin{gathered} [A^*] = [A]^{-1}, \\ [B^*] = -[A]^{-1}[B], \\ [C^*] = [B][A]^{-1}, \\ [D^*] = [D] - [B][A]^{-1}[B]. \end{gathered} \tag{32}$$

Plně převrácený zápis lze tedy vyjádřit jako:

$$\begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ \text{—} \\ K_x \\ K_y \\ K_{xy} \end{bmatrix} = \begin{bmatrix} A'_{11} & A'_{12} & A'_{16} & | & B'_{11} & B'_{12} & B'_{16} \\ A'_{12} & A'_{22} & A'_{26} & | & B'_{12} & B'_{22} & B'_{26} \\ A'_{16} & A'_{26} & A'_{66} & | & B'_{16} & B'_{26} & B'_{66} \\ \text{—} & \text{—} & \text{—} & \text{—} & \text{—} & \text{—} & \text{—} \\ C'_{11} & C'_{12} & C'_{16} & | & D'_{11} & D'_{12} & D'_{16} \\ C'_{12} & C'_{22} & C'_{26} & | & D'_{12} & D'_{22} & D'_{26} \\ C'_{16} & C'_{26} & C'_{66} & | & D'_{16} & D'_{26} & D'_{66} \end{bmatrix} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ \text{—} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix}, \tag{33}$$

kde platí:

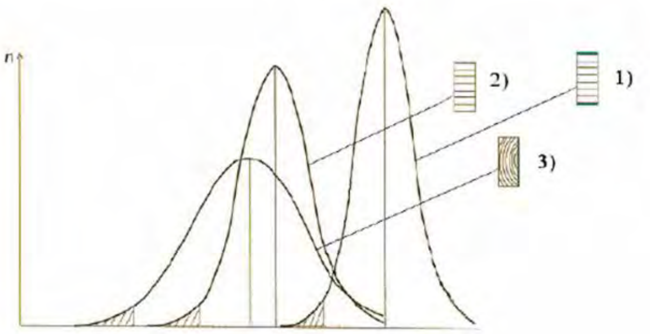
$$\begin{aligned} [A'] &= [A^*] - [B^*][D]^{-1}[C^*], \\ [B'] &= [B^*][D]^{-1}, \\ [C'] &= [D]^{-1}[C^*], \\ [D'] &= [D]^{-1}. \end{aligned} \tag{34}$$

Z hlediska symetrie lze lamináty rozdělit na symetrické a nesymetrické. U symetrických laminátů (lamináty, které jsou konfigurovány tak, že geometrický střed je zrcadlový obraz konfigurací vrstev nad a pod neutrální rovinou), geometrická střední rovina je také neutrální rovinou desky a matice $[B]$ bude mít všechny prvky rovná nule. Pokud je však laminát nesymetrický, tj. pokud jsou vrstvy poblíž spodní části desky mnohem tužší ve směru x, pak geometrická střední rovina nebude neutrální rovinou desky; a neutrální rovina bude blíže ke spodní části desky ve směru x. S tím se také počítá ve fyzikálních rovnicích, protože matice $[B]$ bude mít některé nenulové prvky, což znamená, že ohybové napětí (zakřivení desky) způsobí napětí v neutrální rovině. Podobně bude napětí v neutrální rovině působit ohybový moment (Nettles 1994).

4.3.3 Vyztužování vysoko pevnostními vlákny

Možností vyztužování dřevěných lepených nosníků se zabývaly výzkumné týmy již více než 45 let. Na začátku byly pro účely vyztužování používány tradiční vyztužovací materiály, jako je hliník a ocel. Z důvodů poklesu cen se však začaly využívat právě vysoko pevnostní vlákna jako materiál možný pro účely vyztužování. Ve srovnání těchto materiálů s tradičně používanými materiály je pravděpodobně nižší hustota. Hlavní rolí vyztužujících materiálů s vysokými mechanickými vlastnostmi je poskytovat místní přemostění namáhání v místech kde jsou defekty materiálu, omezí místní lom a zpomalí jeho otevření a v neposlední řadě lokálně zvýší mechanické vlastnosti nosníku.

S využitím těchto nedřevních vysoko pevnostních komponentů lze také snižovat rozměry použitého dřevěné prvku ve skladbě lepeného vrstveného dřeva (Kellogg a Wangaard 1964, Ehsani *et al*. 2004).

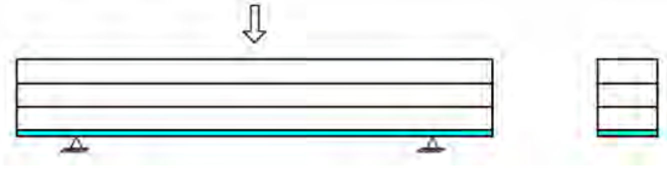


Obr. 22 Charakteristika vrstveného vyztuženého dřeva (1) porovnané s distribucí pevnosti vrstveného dřeva (2) a rostlého dřeva (3) převzato z André 2007

Na obrázku 22 je možné vidět předpokládané výsledky lepených vrstvených nosníků vyztužených vysoko pevnostními vlákny. Z tohoto modelu je zřejmé, že lepené vrstvené nosníky vyztužené nedřevními vysoko pevnostními vlákny by měly poskytovat menší odchylky mezi vlastnostmi vyztuženého vrstveného dřeva a lepšími mechanickými vlastnostmi. Navržená hodnota vyztužených lepených nosníků poukazuje na nové možnosti využití těchto nosníků pro tvorbu konstrukcí, jež dokážou udržet vyšší zatížení.

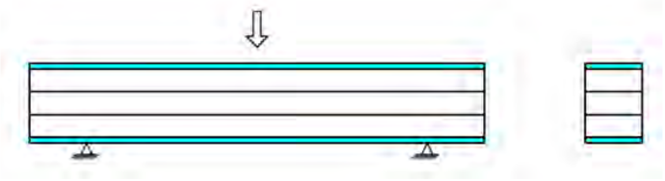
4.3.3.1 Ohybové vyztužování a vlastnosti vyztužených kompozitů na bázi dřeva

Z hlediska namáhání lepených nosníků v ohybu, nosníky často selhávají na tahové straně, z tohoto důvodu má praktické využití v největší míře vyztužování tahové strany nosníku. Vyztužením tahové strany dojde k přesunutí části napětí na kompresní stranu, což pozitivně ovlivní celkové ohybové vlastnosti dřeva. Běžné možnosti vyztužování vrstvených nosníku za účelem zvýšení ohybových vlastností lze vidět na obrázcích 23–28.



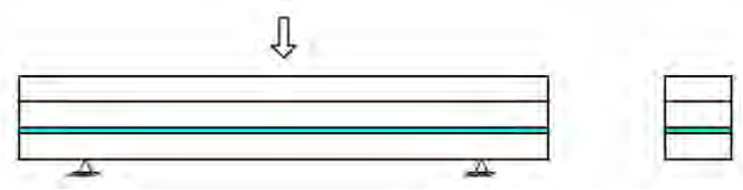
Obr. 23 Vyztužení nosníku vrstvou vysokopevnostními vlákny na tahové straně vrstveného nosníku

Selhání dřeva v ohybu tahovým napětím je náhodné, a tudíž velmi obtížné přesně předvídat. V důsledku toho je vhodné vyztužovat tahovou stranu vrstvených nosníků (obrázek 23) vrstvou vysoko pevnostních vláken (John a Lacroix 2000, Fiorelli a Dias 2003, Borri *et al*. 2005). John a Lacroix 2000 se zabývali vyztužováním dřeva lepením vysoko pevnostních vláken na tahem namáhanou stranu. Při této aplikaci vláken zjistili zvýšení pevnosti v ohybu v rozmezí od 40 % do 70 %. Podobný způsob zvolili Fiorelli a Dias (2003), jako výztužné vrstvy nastavili skelné a uhlíkové vysoko pevnostní vlákna. Při namáhání bylo pozorováno porušení ve dvou stupních, první porušení bylo způsobeno na kompresní straně s následným smykovým a tahovým porušením. Touto aplikací bylo dosaženo zvýšení ohybové tuhosti o 15 % až 30 %. Aplikací předpjatých vláken v epoxidové vrstvě na tahovou stranu namáhaných nosníků se zabývali Borri *et al.* 2005. Touto aplikací bylo zvýšeno maximální zatížení v ohybu o 40–60 %, spolu se zvýšením tuhosti o 22–29 %. Aplikace předpjatých vláken neměla výrazný vliv v porovnání s aplikací nepředpjatých vláken.



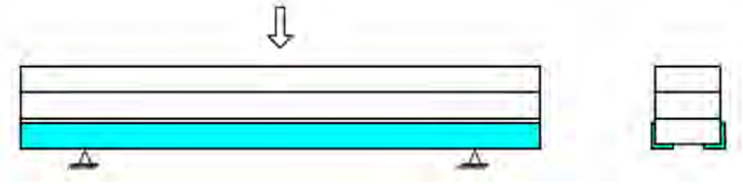
Obr. 24 Vyztužení nosníku vrstvami vysokopevnostních vláken na tahové a tlakové straně vrstveného nosníku

U vyztužení nosníku vrstvami vysokopevnostních vláken na tahové a tlakové straně vrstveného nosníku (obrázek 24) se očekává kromě zlepšení ohybových charakteristik namáhaného nosníku také zlepšení trvanlivosti dřeva. Využitím polyesterových a skelných vláken s objemovým poměrem 2,1 % se zabývali Lopez-Anido a Xu (2002). Ve výzkumu byly použity jednosměrné lamináty a ±45° lamináty. Při použití jednosměrných laminátů bylo sledováno zvýšení mezního zatížení o cca 47 % a změna poruchového režimu byla sledována se zvýšenou tažností. V případě využití laminátů s vlákny pod 45° nedošlo k výraznému zvýšení ohybových charakteristik, poruchový režim byl řízen lomem dřeva v tahu jako v případě nevyztužených nosníků. Vyztužováním vysoko pevnostních uhlíkových vláken na tahovou a tlakovou plochu namáhaného nosníku za účelem zvýšené ohybových charakteristik a požární odolností se zabýval také Ogawa (2000). Ve své práci uvádí vyztužování modřínového dřeva uhlíkovými vlákny s objemovým podílem v rozsahu od 0,08–1,3 %. Pro zajištění zvýšené požární odolnosti byla využita nová fenolická pryskyřice. Aplikací této fenolické pryskyřice byla také mimo zvýšení požární odolnosti také zvýšena mezilaminátová smyková pevnost. Z hlediska ohybových charakteristik došlo k jejich zvýšení bez ohledu na použitý druh dřeva a množství navázaných uhlíkových vysoko pevnostních vláken.



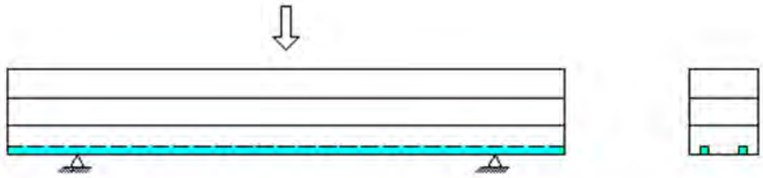
Obr. 25 Vyztužení nosníku vrstvou vysokopevnostních vláken mezi posledními dvěma vrstvami lepeného nosníku

Méně efektivní metodou vyztužení lepených nosníků za pomocí vysoko pevnostních vláken je aplikace mezi poslední dvě vrstvy lepené dřevěného nosníku (obrázek 25). Výzkumem této metody vyztužení lepených nosníku se zabývali například Dagher *et al.* (1996). Cílem tohoto výzkumu bylo zjištění vlivu vyztužení vysoko pevnostními vlákny v interakci na kvalitu vrstev lepeného nosníku. Na jednotlivé vrstvy bylo využito dřevo o nízké, střední a vysoké kvalitě, pro vyztužení byly využité vysoko pevnostní vlákna o objemovém podílu 1,1 a 3,1 %. Při této aplikací byl pozorován pozitivní vliv vyztužení jen lepených nosníků složených vrstev o nízké kvalitě naopak u vysoce kvalitních vrstev nebylo sledováno téměř žádné zlepšení ohybových charakteristik. Problematikou aplikace této metody se také zabývali Romani a Blaß (2001). Tento výzkum byl zaměřen na vyztužování aramidovými a skelnými vysoko pevnostními vlákny aplikovány mezi dvě poslední vrstvy lepeného nosníku. Ve většině případů docházelo k selhání ve vrstvě nad vlákny, v některých případech došlo k selhání pod vyztužením (většinou tahové selhání).



Obr. 26 Vyztužení nosníku vysokopevnostními vlákny na boční a tahové ploše

Metoda vyztužení vysoko pevnostnímu vlákny, kdy jsou vlákna aplikována z části na boční a zčásti na tahové ploše (obrázek 26), není příliš běžná, byla zkoumána výzkumným týmem Borri *et al.* (2005), kdy byly pro vyztužení využity uhlíkové vysoko pevnostní vlákna. Touto metodou lze dosáhnout zvýšení maximálního zatížení až o 55 % a tuhosti o 30 % což je prakticky identické s ohybovými vlastnostmi nosníků vyztužených vysoko pevnostními vlákny o vysoké hustotě na tahové straně.



Obr. 27 Vyztužení nosníku vysokopevnostními vlákny zapuštěnými v tahové ploše

Další možností vyztužování pomocí vysokopevnostních vláken je zapuštěním těchto vláken v tahové ploše (obrázek 27). Výzkumem této aplikace vysoko pevnostních vláken umístěných podél nosníku v několika drážkách se zabývali Gentile *et al.* (2002). Uložení dvou výztužných prvků o průřezu 13 mm byly uloženy ve dvou podélných drážkách na tahové straně namáhaného nosníku. Objemový podíl výztužných elementů byl 0,42 %. Touto metodou vyztužení bylo dosaženo zlepšení ohybových charakteristik nosníku až o 46 %. Přibližně 60 % sledovaných nosníků selhalo v režimu ohybové komprese.

Obr. 28 Vyztužení nosníku vysokopevnostními vlákny zapuštěnými v boční ploše tahové zóny

V případě vyztužení nosníku vysoko pevnostními vlákny zapuštěnými v boční ploše tahové zóny (obrázek 28) se jedná o podobnou metodu vyztužování jako v předchozím případě. Kdy jsou vyztužující prvky zapuštěny podélně v boční ploše tahové zóny. Touto metodou se zabývali podobně jako u předchozího způsobu Borri *et al.* (2005), kdy byl výzkum zaměřen na sledování vlivu umístění a počtu výztužných elementů z vysoko pevnostních uhlíkových vláken. V prvním případě se jednalo o umístění výztužného elementu ve středu nosníku, kdy bylo pozorováno zvýšení maximálního zatížení o cca 29 % a tuhost o 22 %. V druhém případě se jednalo o symetrické uložení dvou výztužných elementů z vysoko pevnostních uhlíkových vláken po výšce nosníku. U toho vyztužení bylo pozorováno zvýšení maximálního zatížení o cca 52 % a tuhost 25,5 %. Podobný přístup k této metodě vyztužování zkoumali Johnsson *et al.* (2007), kteří vyztužovali lepené nosníky pomocí výztužných vysoko pevnostních uhlíkových vláken v matici s průřezem 10×10 mm. V tomto výzkumu sledovali stejné uložení jako v předchozím výzkumu, které byly rozšířené navíc o zkrácené výztužné elementy umístěné ve středu nosníku. Všechny testované nosníky prokazovaly zlepšené ohybové charakteristiky. Nosnost těchto nosníků byla v průměru zvýšena o 44–63 %. Jako u ostatních studií bylo pozorováno selhání nosníku na tlakové straně.

4.3.3.2 Smykové vyztužování a vlastnosti vyztužených kompozitů na bázi dřeva

Dřevo má poměrně nízkou smykovou pevnost kolmo k vláknům, což může mít v některých případech za následek kritickou smykovou odolnost v podélném směru. Pro smykové vyztužování nosníků se v minulosti používaly hliníkové a ocelové desky (Triantafillou 1998). Studie zabývající se smykovým vyztužováním vysoko pevnostními vlákny jsou omezené, protože smykové porušení dřevěných nosníků je poměrně vzácné (André 2007). Radford *et al.* (2002) uvedli, že dřevo může být výrazně zesíleno ve smyku smykovými deskami s vlákny orientovanými na ± 45° pro maximalizaci smykové tuhosti. Tuhost se zvýšila z průměrné hodnoty 2,6 GPa (nevyztužené nosníky) na 9,8 GPa (vyztužené nosníky). Svecova a Eden 2004 testovali mostní nosníky vyztuženy tyčemi složených z vysoko pevnostních skelných vláken. Byly testovány tři různé typy vyztužení (se změnou vzdálenosti mezi tyčemi, s dispozicí po celé délce nebo jen po smykové délce). Ve srovnání s kontrolními nosníky byla zvýšená mez pevnosti ve smyku z 10 GPa na 21 GPa.

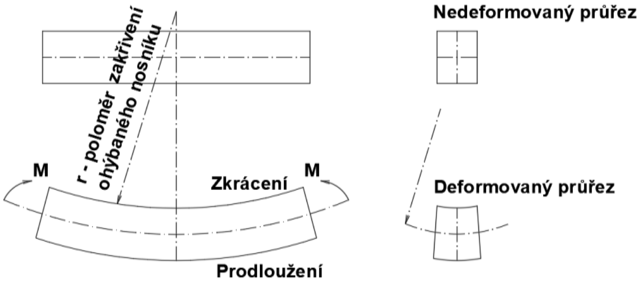
4.3.3.3 Kombinované vyztužování a vlastnosti vyztužených kompozitů na bázi dřeva

Kombinace smykového a ohybové vyztužování je další možností zlepšení mechanických vlastností dřevěných nosníků. Jednou z možností takového vyztužování za využití vysoko pevnostních vláken je využití kolíků orientovaných pod úhlem 60° od podélné roviny pro smykové vyztužení a tyčí z vysoko pevnostních skelných vláken pro ohybové vyztužení (Amy a Svecova 2004). Kontrolní nosník (nevyztužený, ale ve srovnání s vyztuženými nosníky vyšší kvality) vykazuje ve všech případech režim selhání smyku. Použití ohybových tyčí z vysoko pevnostních skelných vláken a kolíků vedlo ke zvýšení maximálního zatížení o 22 % a odlišnému typu selhání (stlačení kolmo k vláknům). Další možností smykového a ohybového vyztužování se zabývali Buell a Saadatmanesh 2005. V tomto výzkumu byla pro vyztužení použita tkanina z vysoko pevnostních uhlíkových vláken. Tato tkanina byla aplikována na tahovou plochu, obě boční plochy a dvě třetiny kompresní plochy. Orientace vláken v tkanině byla 45° z důvodů optimalizace smykové tuhosti. Takto vyztužené nosníky byly testovány v ohybu a smyku. Bylo zaznamenáno zvýšení v ohybové pevnosti o cca 53 % a zvýšení modulu pružnosti o 17 %. Bylo také zaznamenáno zvýšení smykové pevnosti o cca 68 %. Buell a Saadatmanesh 2005 testovali principiálně podobnou metodu s využitím na rozdíl od předchozí metody několik separovaných tkanin z vysoko pevnostních uhlíkových vláken. Účelem bylo prozkoumat účinek překrývání tkanin. Bylo zjištěno zvýšení pevnosti v ohybu o 43 % a modulu pružnosti o 27 %. Většina nosníků zaznamenala selhání na tahové straně. Smyková pevnost se také zvýšila, a to o cca 23. Podobnou metodu testoval také John a Lacroix (2000), kdy pro vyztužení byla použita tkanina z vysokopevnostních vláken aplikovaná na tahovou stranu v U tvaru s částečným přesahem na bočních plochách nosníků. Touto aplikací bylo dosaženo všeobecného zvýšení ohybových charakteristik.

4.4 Jednoduchý ohyb dřeva a vrstvených kompozitů na bázi dřeva

Aplikace ohybové teorie na dřevě se uplatňuje hlavně pro konstrukční účely, nicméně také při jeho tvarování ohybem apod. Při zjednodušeném pohledu na problematiku ohybu dřevěného prutu, je možné vnímat namáhaný prvek jako soubor nekonečného počtu prutů s podélnou orientací vzhledem k podpěrám. Při zatěžování je možné pozorovat dva typy namáhání, a to tlakové (konkávní plocha prvku) a tahové (konvexní plocha prvku). Při řešení stavu napětí a deformace takto namáhaného dřevěného prvku je nutné přijímat jisté zjednodušení jako například že je prvek přímý, venkovní zatížení působí v jedné rovině a současně je rovinou souměrnosti průřezu prvku. Tato rovina je v nedeformovatelném stavu kolmá na neutrální rovinu, během ohýbání prvku je rovina zatížena rovinou ohybové čáry (Požgaj *et al.* 1993).

V prutu namáhaném v ohybu způsobuje ohybový moment deformaci a změnu tvaru (obrázek 29). Kromě tahového a tlakového napětí se zde vyskytuje také smykové napětí. Deformace je tedy výsledkem normálového a smykového napětí v průřezu paprsku (Bodig a Jayne 1982). Na tlakové straně namáhaného prvku dochází ke zkracování, kdežto na tahové straně dochází k prodlužování, čímž se projevují negativní vlastnosti dřeva při ohybu, kdy deformace při zatížení v tahu jsou výrazně menší než deformace při zatížení v tlaku ve stejném směru. Z tohoto důvodu existuje snaha posouvat neutrální osu směrem k tahové zóně za účelem zvýšení podílu tlakové zóny. Na základě těchto poznatků je možné uvést, že poměrná deformace v ohybu při uvedeném zatížení přímo závisí od vzdálenosti od neutrální osy a je nepřímo úměrná poloměru zakřivení.



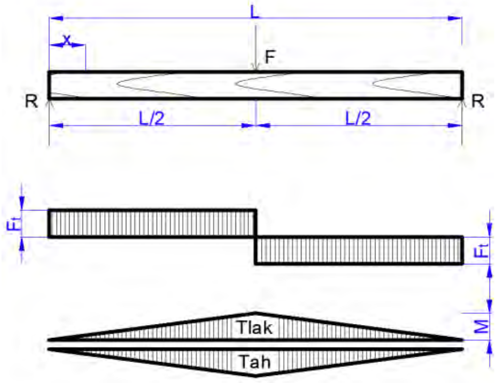
Obr. 29 Deformace dřevěného prvku vystavenému ohybovému momentu (Babiak *et al.* 2018)

U krátkých nosníků vystavených ohybu je možné často pozorovat porušení ve smyku, zejména u nosníků s vyšší výškou (Požgaj *et al.* 1993, Blomberg *et al.* 2005, Chao *et al.* 2017). Je-li průřez nosníku obdélníkový, je rozdělení smykového napětí parabolické podél výšky nosníku (obrázek 30).

Obr. 30 Rozložení napětí v průřezu namáhaného prvku (Babiak *et al.* 2018)

Je-li dřevěný nosník zatížen příčnými silami, vytvoří se v průřezu nosníku posuvné síly „Ft“ a ohybový moment „M“ (obrázek 31). Ohybový moment způsobuje v průřezu normálové napětí. Změna točivého momentu vede k posuvným silám, které se snaží posunout jednu část dřevěného nosníku k druhé, což má za následek smykové napětí v průřezu. Kromě toho se během ohybu vytváří smykové napětí, které se snaží posunout jednotlivé vrstvy vláken postupně ve směru podpěr (Bodig a Jayne 1982, Požgaj *et al.*

1993, Eilmann *et al.* 2014, Bezazi a Scarpa 2007).

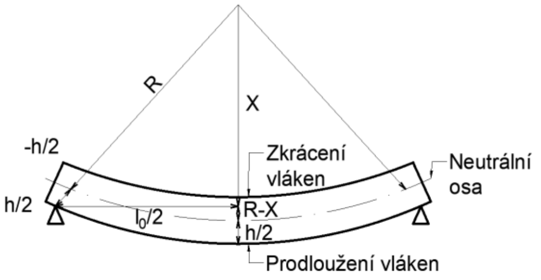


Obr. 31 Posuvné síly vzniklé tří bodovým ohybem (Babiak *et al.* 2018)

Velikost příčných posuvných sil lze vyjádřit pomocí rovnice (35):

$$F_t = \frac{dM}{dx} \tag{35}$$

kde Ft je příčná posuvná síla, příčná smyková síla a pravá strana se tedy rovná změně ohybového momentu *dM* v určité vzdálenosti *dx*.



Obr. 32 Schéma ohybu jednovrstvého tělesa

Na základě schématu jednoduchého ohybu (obrázek 32), je možné matematicky vyjádřit deformace a napětí dle vztahu Eq. 36–37

$$\varepsilon = \frac{l' - l_0}{l_0} = \frac{\pi \cdot (R + x) - \pi \cdot R}{\pi \cdot R} \tag{36}$$

$$\varepsilon = \frac{x}{R} \tag{37}$$

$$\sigma = \frac{E \cdot x_2}{\mathrm{R}}$$

Základní rovnice ohybu, ze které vychází náš předpoklad matematické predikce celkové tuhosti vrstveného materiálu, celkový moment síly, moment setrvačnosti pro obdélníkové průřezy je zachycen rovnicemi 38–40.

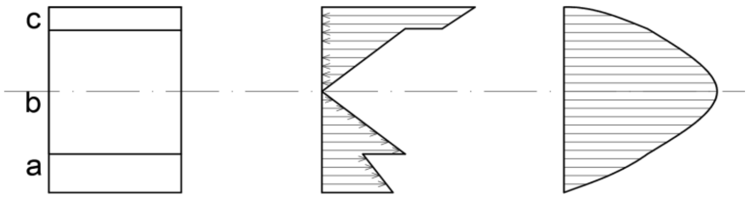
$$\frac{1}{R} = \frac{M}{E \cdot I} \tag{38}$$

$$M = \int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} \sigma \cdot x_2 \cdot dx_2 \cdot dx_3 \tag{39}$$

$$I = b \cdot \int_{-\frac{h}{2}}^{\frac{h}{2}} x_2^2 \cdot dx_2 = \frac{bh^3}{12} \tag{40}$$

kde, *R* vyjadřuje poloměr ohybu vzhledem k neutrální ose (mm), *M* vyjadřuje celkový moment síly vyjadřující míru otáčivého účinku síly, *I* je moment setrvačnosti vyjadřující míru setrvačnosti tělesa o obdélníkovém průřezu při otáčivém pohybu, *E* vyjadřuje celkový modul pružnosti tělesa (MPa), *h* je tloušťka materiálu (mm), a *b* je šířka materiálu (mm).

Z hlediska ohybu nesymetrických vrstvených kompozitů na bázi dřeva dochází ke změně distribuce normálových a smykových napětí ve vztahu k parametrům a vlastnostem jednotlivých vrstev. U vrstvených materiálů složených z více typů materiálů s rozdílnými vlastnostmi je také důležitá vzdálenost jednotlivých vrstev od neutrální osy. Vzhledem ke zvýšené vzdálenosti vrstvy od neutrální osy se u vrstvy s vyšší tuhostí vytvoří vlivem ohybu vyšší napětí než v případech vrstvy s nižší tuhostí. Tímto uspořádáním vznikne nejvyšší smykové napětí v neutální ose jak je možné vidět na obrázku 33 (Bodig a Jayne 1982).



a) b) c)

Obr. 33 Distribuce napětí v ohybu vrstveného nesymetrického kompozitu a) příčný průřez, b) ohybové napětí, c) smykové napětí (převzato z Bodig a Jayne 1982)

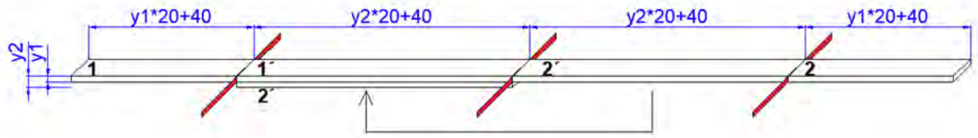
5 Metodika disertační práce

5.1 Použité materiály

V této kapitole jsou uvedeny použité materiály pro tvorbu vrstveného kompozitního materiálu na bázi zhuštěného bukového dřeva vyztuženého vysoko pevnostními skelnými a uhlíkovými vlákny.

5.1.1 Specifikace bukových lamel

Vstupním materiálem pro tvorbu vrstvených materiálů byl zvolen buk s důrazem na jeho ohybové charakteristiky. Bukové radiální lamely byly vyrobeny standardními technologickými postupy o nominální šířce 35 mm. Jednotlivé lamely byly vyrobeny o dvou typech tlouštěk a to 5 mm a 9 mm. Lamely o těchto příčných rozměrech byly vyrobeny v délkách od 1 000–2 000 mm. Z takto připravených lamel byly vymanipulovány nominální lamely, tak aby byly vymanipulovány vady snižující mechanické vlastnosti v ohybu dle přiloženého schématu viditelného na obrázku 34.



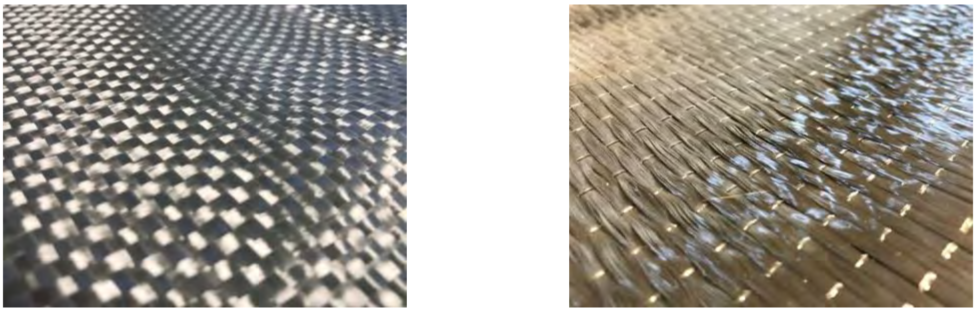
Obr. 34 Schematické znázornění pořezu lamel a jejich rozměrových charakteristik

Jednotlivé lamely byly vyráběny párovým způsobem tak aby bylo možné testovat mechanické vlastnosti v ohybu jednotlivých vrstev lepeného vrstveného kompozitu pro následné využití při numerickém modelování za účelem porovnání experimentálně získaných a vymodelovaných dat. Ze schématu pořezu lamel je možné vidět, že délka jednotlivých lamel byla vyráběna s ohledem na tloušťku jednotlivých lamel a tloušťkou lepených vrstvených lamel.

5.1.2 Specifikace výztužných elementů

Skelná vlákna využita jako vyztužující element byla ve formě tkané výztuže (KITTFORT) tkané jako plátno v poměru 1:1 (obrázku 35). Tato skelná tkanina je vyrobena ze sklo vláknitých pramenů, které jsou opatřeny povrchovou úpravou na bázi

UPE. Použitá skelná tkanina je složena ze skelných vláken typu E.



a) b)

Obr. 35 Využitá a) skelná vlákna ve formě tkaniny, b) uhlíková vlákna ve formě tkaných uhlíkových pramenů

Dalším použitým výztužným elementem byla využita jednosměrná tkaná prošívaná a lehčená tkanina z uhlíkových vláken typu SikaWrap 150C/30 (obrázek 36). Tato tkanina je vyrobena z uhlíkových vláken s vysokou pevností a hustotou 1,81 g/cm^3.

5.1.3 Adhezivní prostředky využity pro lepení

Pro spojování jednotlivých komponentů v lepené struktuře bylo využito jedno složkové vodě odolné polyvinyl acetátové lepidlo (PVAc) AG-COLL 8761/L D3. Technické parametry použitého PVAc lepidla je možné vidět v tabulce 7. Lepidlo bylo aplikováno manuálně za pomocí nanášecího válečku jednostranným nátěrem s nánosem lepidla v rozmezí od 150–180 g/m^2. Lepené materiály byly lisovány za studena pomocí mechanických svorek po dobu 20 minut.

Tab. 7 Technické parametry PVAc lepidla AG-COLL 8761/L D3

Technické parametry pro lepidla AG-COLL 8761/L D3	
Viskozita (MPa)	5000–7000 (při 23 °C)
Pracovní čas (min)	15–20
Hustota (g/cm^3)	0,9–1,1 (při 23 °C)
Otevřený čas (min)	15
Obsah sušiny (g)	49–51
pH	do 4,5
Smyková pevnost podle EN 205 (MPa)	11,9

5.2 Modifikace zhušťováním

Pro zhušťování lamel byla použita termo mechanická metoda celoobjemového zhušťování v tangenciálním směru. Jednotlivé lamely byly zhušťovány v oboustranně vyhřívaném hydraulickém lisu TOS Rakovník, při teplotě vyhřívaných desek 140 C° (±5°C). Pro zajištění dostatečných podmínek zajišťující skelný přechod základních složek dřeva byly do lisu vkládány lamely o vlhkosti 12 % (± 1 %). Vlhkost dřeva byla vypočítána dle normy ISO 13061-1 (2014) dle vzorce 41. Technické parametry lisovacího procesu jednotlivých lamel v závislosti od stupně zhuštění a počáteční tloušťky lze vidět v tabulce 8.

$$w = \frac{m_w - m_0}{m_0} \cdot 100 \tag{41}$$

kde w je obsah vlhkosti v (%), m_w je hmotnost dřeva ve vlhkém stavu (g), m_0 je hmotnost vysušeného dřeva na o vlhkost (g). Sušení na 0 % vlhkost, bylo provedeno v souladu s normou ISO 13061-1 (2014).

Tab. 8 Technické parametry lisování lamel v závislosti od stupně zhuštění

Stupeň zhuštění z hlediska tloušťky	***Bukové lamely 5 mm***		***Bukové lamely 9 mm***	
	Tlak (MPa)	Čas (min)	Tlak (MPa)	Čas (min)
10 %	30,2	5	37,7	9
20 %	31,5	6	39,3	10
30 %	34,2	7	42,7	11
40 %	36,3	8	43,4	12

Hustota (42) před a po zhušťování byla vypočítána dle normy ISO 13061-2 (2014).

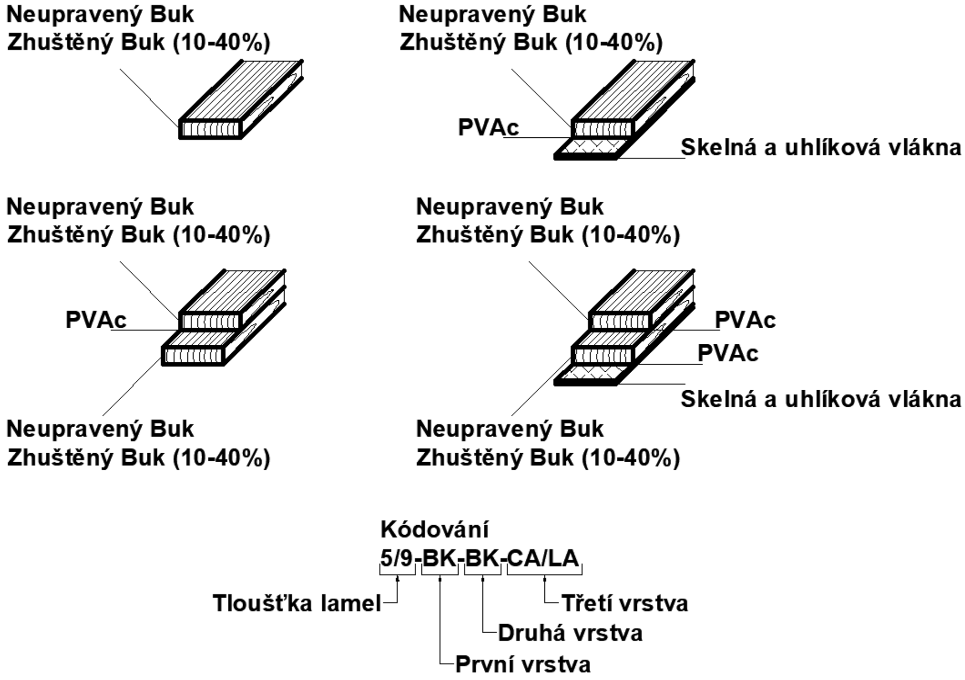
$$\rho_w = \frac{m_w}{V_w} \tag{42}$$

kde ρ_w je hustota dřeva při konkrétní vlhkosti (kg/m^3) m_w je hmotnost dřeva při konkrétní vlhkosti w (kg), a V_w je objem dřeva při konkrétní vlhkosti w (m^3).

5.3 Tvorba zkušebních těles

Z nezhuštěných a zhuštěných lamel byly vyrobeny zkušební tělesa dle schématu na obrázku 36. Principiálně lze rozdělit zkušební soubory do 4 následujících skupin:

- jednotlivé nezhuštěné a zhuštěné lamely (určené pro teoretické výpočty),
- vyztužené nezhuštěné a zhuštěné lamely vysoko-pevnostními vlákny,
- slepené vrstvené nezhuštěné a zhuštěné lamely,
- vyztužené slepené vrstvené nezhuštěné a zhuštěné lamely vysoko-pevnostními vlákny.



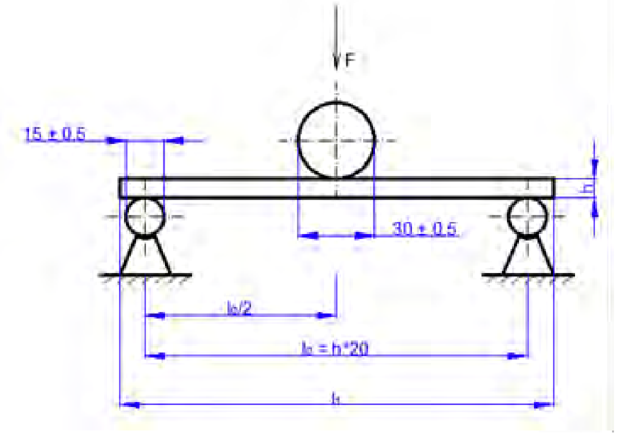
Obr. 36 Rozdělení zkušebních souborů z hlediska vrstvené skladby

Tyto čtyři zkušební skupiny (obrázek 37) byly složeny dohromady z 60 zkušebních souborů. Z hlediska statistického vyhodnocení bylo v každém zkušebním souboru 30 zkušebních těles.

5.4 Metodika mechanického testování v ohybu

5.4.1 Mechanické testování

Všechny testované soubory byly testovány tří bodovým ohybem dle normy EN 310 (1993). Zkušební tělesa byla zatížena jednou izolovanou silou dle schématu uvedeného na obrázku 37. Pro samotné testování byl využit univerzální testovací stroj FPZ 100. Rychlost zatěžování byla stanovena na 3 mm/min tak, aby testování nepřekročilo dobu testování stanovenou v příslušné normě. Dalším relevantním nastavením univerzálního testovacího zařízení byla rozteč spodních podpěr, tato rozteč byla u všech zkušebních těles nastavena tak aby odpovídala 20 násobku průměrné tloušťky testovaného zkušebního tělesa. Využití méně vhodné metody z hlediska tvorby smykového napětí 3bodovým ohybem bylo využito z technických důvodů. Při testování s vyšším stupněm zhuštění by nebylo v případě využití čtyř bodového ohybu možné dodržovat stanovené rozpětí spodních podpěr na 20 násobek tloušťky testovaného prvku.



Obr. 37 Schéma testování tříbodovým ohybem dle EN 310 1993

5.4.2 Výpočet základních mechanických charakteristik

Pro výpočet všech ohybových charakteristik z pracovního diagramu byl použit software MATESS, jenž pracuje na bázi identifikace a kvantifikace hraničních bodů pracovního diagramu. Pro svůj chod tento software pracuje v pěti krocích. V prvním kroku vyčistí datové sady s následnou interpolací chybějících hodnot. Po tomto kroku následuje krok místního vyhlazování pracovního diagramu. V následných krocích probíhá detekce meze pevností a meze úměrnosti. V posledním pátém kroku proběhne kvantifikace charakteristik pracovního diagramu.

Pro výpočet meze pevnosti v ohybu “MOR” v tříbodovém ohybu byl využit vzorec 43, dle ISO 13061-3 (2014).

$$MOR = \frac{3F_{max}l_0}{2bh^2} \tag{43}$$

kde, MOR je mez pevnosti (MPa), F_{max} je síla potřebná pro zlomení testovaného zkušebního tělesa (N), l_0 je rozpětí spodního suportu testovacího zařízení (mm), a b

(šířka) a h (tloušťka) jsou průřezové rozměry testovaného zkušebního tělesa (mm).

Pro výpočet ohybového modulu pružnosti, vyjadřující vnitřní odolnosti proti pružné deformaci byl využit vzorec 44, dle normy EN 310 (1993).

$$E = \frac{l_0^3(F_2 - F_1)}{4bh^3(y_2 - y_1)} \tag{44}$$

kde, E je modul pružnosti (MPa), l_0 je rozpětí spodního suportu testovacího zařízení (mm), b (šířka) a h (tloušťka) jsou průřezové rozměry testovaného zkušebního tělesa (mm), $F_2 - F_1$ je přírůstek zatížení v lineární části pracovního diagramu (F_1 je 10 % a F_2 je 40 % z maximálního zatížení (N)), a $y_2 - y_1 je$ přírůstek průhybu (mm) pod zatěžující sílou (odpovídající $F_2 - F_1$).

Pro výpočet meze úměrnosti byl použit vzorec (45) podle normy EN 310 (1993).

$$LOP = \frac{3F_E l_0}{2bh^2} \tag{45}$$

kde, LOP je mez úměrnosti (MPa), l_0 je rozpětí spodního suportu testovacího zařízení (mm), F_E je síla na mezi úměrnosti (N) b (šířka) a h (tloušťka) jsou průřezové rozměry testovaného zkušebního tělesa (mm).

Pro výpočet tangentových modulů a sečnicového modulu byly použity vzorce 46–49. Vzorce jsou převzaté z práce Sikora *et al.* (2018).

$$E_E = \frac{F_E}{\mathrm{y}_E} \cdot \frac{l_0^3}{48I} \tag{46}$$

$$E_{MV} = \frac{F_{MV}}{\mathrm{y}_{MV}} \cdot \frac{l_0^3}{48I} \tag{47}$$

$$E_P = \frac{F_P}{\mathrm{y}_P} \cdot \frac{l_0^3}{48I} \tag{48}$$

$$CH_M = \frac{F_P - F_E}{\mathrm{y}_P - y_E} \cdot \frac{l_0^3}{4bh^3} \tag{49}$$

kde, F_P je síla na elastickém limitu (N), F_E je síla na mezi úměrnosti (N), y_P je průhyb na elastickém limitu (mm), y_E je průhyb na mezi pevnosti (mm), y_{MV} je průhyb vyjádřený jako průměr mezi y_E a y_P (mm), l_0 je rozpětí spodního suportu testovacího zařízení (mm), b (šířka) a h (tloušťka) jsou průřezové rozměry testovaného zkušebního tělesa (mm).

Pro výpočet elastického a plastického potenciálu byly využity vzorce 50–51 převzaty z prací Gaff *etl al.* (2017a) a Gaff *et al.*(2017b).

$$P_E = \frac{3\mathrm{F}y_E}{2bhl_0} \tag{50}$$

$$P_P = \frac{\overline{W_A}}{bhl_0} \tag{51}$$

kde, P_E je elastický potenciál (MPa), P_P je plastický potenciál (MPa), F je síla (N), y_E je průhyb na mezi úměrnosti, W_A je práce ve vizko-plastické oblasti (mJ), l_0 je rozpětí spodního suportu testovacího zařízení (mm), b (šířka) a h (tloušťka) jsou průřezové rozměry testovaného zkušebního tělesa (mm).

Plastická práce může být vypočítana pomocí regresní rovnice (52) nebo zjednodušenou variantou pomocí lineární aproximace (53). Na základě těchto přístupů lze vyjádřit chybu aproximace (54), viz vzorec 51:

$$\overline{W_A} = \frac{a}{3}(y_P^3 - y_E^3) + \frac{b}{2}(y_P^2 - y_E^2) + c(y_P - y_E) \tag{52}$$

$$\overline{W_B} = \frac{(F_P + F_E)}{2}(y_P - y_E) \tag{53}$$

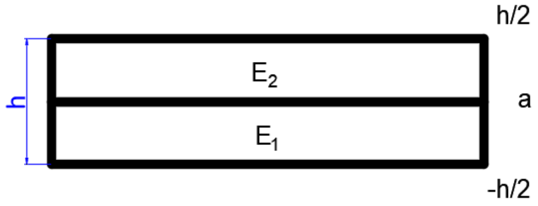
$$\Delta W = \frac{\overline{W_A} - \overline{W_B}}{\overline{W_A}} 100 \tag{54}$$

kde: $\overline{W_A}$ je práce (mJ), $\overline{W_B}$ je aproximovaná práce (mJ), ΔW je chyba aproximace (%), y_E je průhyb na mezi úměrnosti (mm), y_P je průhyb na mezi pevnosti (mm), F_E síla na mezi úměrnosti (N), F_P síla na mezi pevnosti (N).

5.5 Analytická metoda predikce ohybových vlastností na základě tuhosti

5.5.1 Teoretický výpočet tuhosti dvouvrstvého materiálu

Při aplikaci poznatků o jednovrstvých prutech v ohybu lze matematicky vyjádřit tuhost heterogenního dvou vrstveného materiálu na základě základní rovnice ohybu. Schématické znázornění dvouvrstevného tělesa lze vidět na obrázku 38.



Obr. 38 Schéma pro odvození modulu pružnosti dvou vrstvého systému na základně parametrů jednotlivých vrstev

Ze základní rovnice ohybu lze vyjádřit teoretickou celkovou tuhost dvouvrstvého prvku dle vzorce odvozeného ze základní rovnice tuhosti (55).

$$E \cdot I = b_T \cdot \left\{ \int_{-\frac{h}{2}}^{a} E_1 \cdot x_2^2 \cdot dx_2 + \int_{a}^{\frac{h}{2}} E_2 \cdot x_2^2 \cdot dx_2 \right\} \tag{55}$$

S následným odvozením do podoby vzorce umožňující výpočet celkového modulu pružnosti v ohybu dvou vrstvého kompozitního materiálu na bázi dřeva (56).

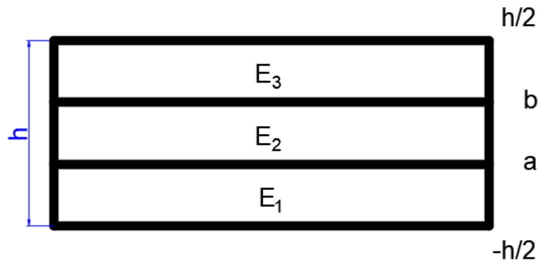
$$\bar{E} = \frac{1}{2}(E_1 + E_2) + 4\left(\frac{a}{h}\right)^3 (E_2 - E_1) \tag{56}$$

$$E_2 < E_1$$

kde, $\bar{E}$ představuje celkový modul pružnosti vrstveného materiálu (MPa), E_1 je modul pružnosti první vrstvy (MPa), E_2 je modul pružnosti druhé vrstvy (MPa), a představuje tloušťku první vrstvy (mm), *h* (x_2) představuje celkovou tloušťku vrstveného materiálu (mm), a *b* (x_3) představuje celkovou šířku prvku (mm).

5.5.2 Teoretický výpočet tuhosti trojvrstvého materiálu

Při aplikaci poznatků o jednovrstvých prutech v ohybu lze matematicky vyjádřit tuhost heterogenního tří vrstveného materiálu na základě základní rovnice ohybu. Schématické znázornění tří vrstvého tělesa lze vidět na obrázku 39.



Obr. 39 Schéma pro odvození modulu pružnosti tří vrstvého systému na základně parametrů jednotlivých vrstev

V případě tří vrstvých materiálů lze využít vzorec pro vypočet tuhosti který je založen na parametrech jednotlivých vrstev (57).

$$E \cdot I = b_T \cdot \left\{ \int_{-\frac{h}{2}}^{a} E_1 \cdot x_2^2 \cdot dx_2 + \int_{a}^{b} E_2 \cdot x_2^2 \cdot dx_2 + \int_{b}^{\frac{h}{2}} E_3 \cdot x_2^2 \cdot dx_2 \right\} \tag{57}$$

S následným odvozením do podoby vzorce umožňující výpočet celkového modulu pružnosti v ohybu tří vrstvého materiálu (Eq. 58).

$$\bar{E} = \frac{4}{h^3} \cdot [a^3 \cdot (E_1 - E_2) + b^3 \cdot (E_2 - E_3)] + \frac{E_1 + E_3}{2} \tag{58}$$

kde, $\bar{E}$ představuje celkový modul pružnosti vrstveného materiálu (MPa), E_1 je modul pružnosti první vrstvy (MPa), E_2 je modul pružnosti druhé vrstvy (MPa), E_3 je modul pružnosti třetí vrstvy vrstvy (MPa), a představuje tloušťku první vrstvy (mm), b představuje tloušťku první vrstvy (mm), h představuje celkovou tloušťku vrstveného materiálu (mm), a b_T představuje šířku prvku (mm).

5.5.3 Kvantfikace rozdílů mezi reálně měřeným a vypočítaným modulem pružnosti

Na základě výpočtů uvedených v kapitole 5.5.1 a 5.5.2 (vzorce 54 a 55) byly provedeny výpočty teoretických hodnot tuhosti pro dvou a tří vrstvé materiály. Z této teoretické tuhosti byly vyjádřeny teoretické moduly pružnosti dle vzorců 55 a 57. Tyto teoretické moduly pružnosti byly porovnány s moduly pružnosti získanými pomocí destruktivní zkoušky tříbodovým ohybem dle oddílu 5.4.1. Procentuální rozdíl mezi teoretickými a naměřenými hodnotami modulu pružnosti bylo vyjádřeno za pomocí vzorce 59.

$$\Delta E = \frac{E_T - E_M}{E_T} 100 \quad (59)$$

kde, ΔE vyjadřuje rozdíl mezi E_T a E_M (%), E_T vyjadřuje teoretický modul pružnosti (MPa) a E_M vyjadřuje měřený modul pružnosti (MPa).

5.6 Statistické vyhodnocení

Ke zhodnocení výsledků a jejich interakcí byl vybrán Duncanův test, s hladinou významnosti α = 0,05. Tento test určuje na základě hladiny významnosti „P“, zda je sledovaný faktor statisticky významný a v jaké míře.

Podle velikosti P se hodnotí sledovaný faktor dle následujících kritérií:

- P = 0 – pravděpodobnost, že faktor nepůsobí, je nulová,
- P = (0; 0,001) – vliv faktorů je statisticky velmi významný,
- P = (0,001; 0,1) – vliv faktorů je středně významný,
- P < 0,05 – vliv faktoru je statisticky významný,
- P < 0,01; 0,05) – vliv faktorů je statisticky málo významný,
- P = 0,05 – vliv faktoru je na hranici statistické významnosti,
- P > 0,05 – vliv faktoru není statisticky významný.

6 Syntéza výsledků publikovaných článků

V této kapitole jsou představeny souhrné výsledky disertační práce publikované v odborných publikacích v průběhu doktorského studia. Jednotlivé separáty článků a manuskriptů jsou uvedeny v kapitole 9.

Vlastnosti vrstveného dřeva lze ovlivnit různými způsoby, například kombinací vrstev je možné vytvořit vrstvené dřevo s jinými vlastnostmi než vlastnosti masivního dřeva. Vhodný výběr lepidel nebo kombinace lepidel může umožnit změny vlastností vrstveného dřeva, čímž se vytvoří materiál se specifickými požadovanými vlastnostmi. V článku číslo 1 (Adhesive as a Factor Affecting the Properties of Laminated Wood) jsme se zaměřili na zkoumání vlivu lepidel na ohybové vlastnosti vrstveného dřeva. Dřevo lepené PVAc lepidlem bylo pružnější než masivní dřevo, což dokazují jeho vyšší koeficienty ohýbatelnosti (o 43 % vyšší) společně s touto vlastností bylo u PVAc lepidel zjištěna vyšší trvanlivost lepeného spoje vzhledem k cyklickému namáhání.

Tab. 9 Vliv lepidla na vybrané charakteristiky rostlého a vrstveného dřeva

	Rostlé dřevo	***Vrstvené dřevo***		
		UF	**PVAc**	**PUR**
Maximální síla (N)	1 284.2 (8,2)	1 721 (7,5)	1 351 (4,3)	2 035 (3,3)
Maximální průhyb (mm)	13,3 (8,4)	9,9 (4,6)	10,7 (9,6)	13.0 (7,3)
Min. ohybový poloměr (mm)	594 (9,2)	467,7 (5,7)	374,6 (4,3)	491,4 (9,8)
Koeficient ohývatelnosti	0,0168 (10,5)	0,0191 (6,3)	0,0240 (6,7)	0,0203 (5,4)

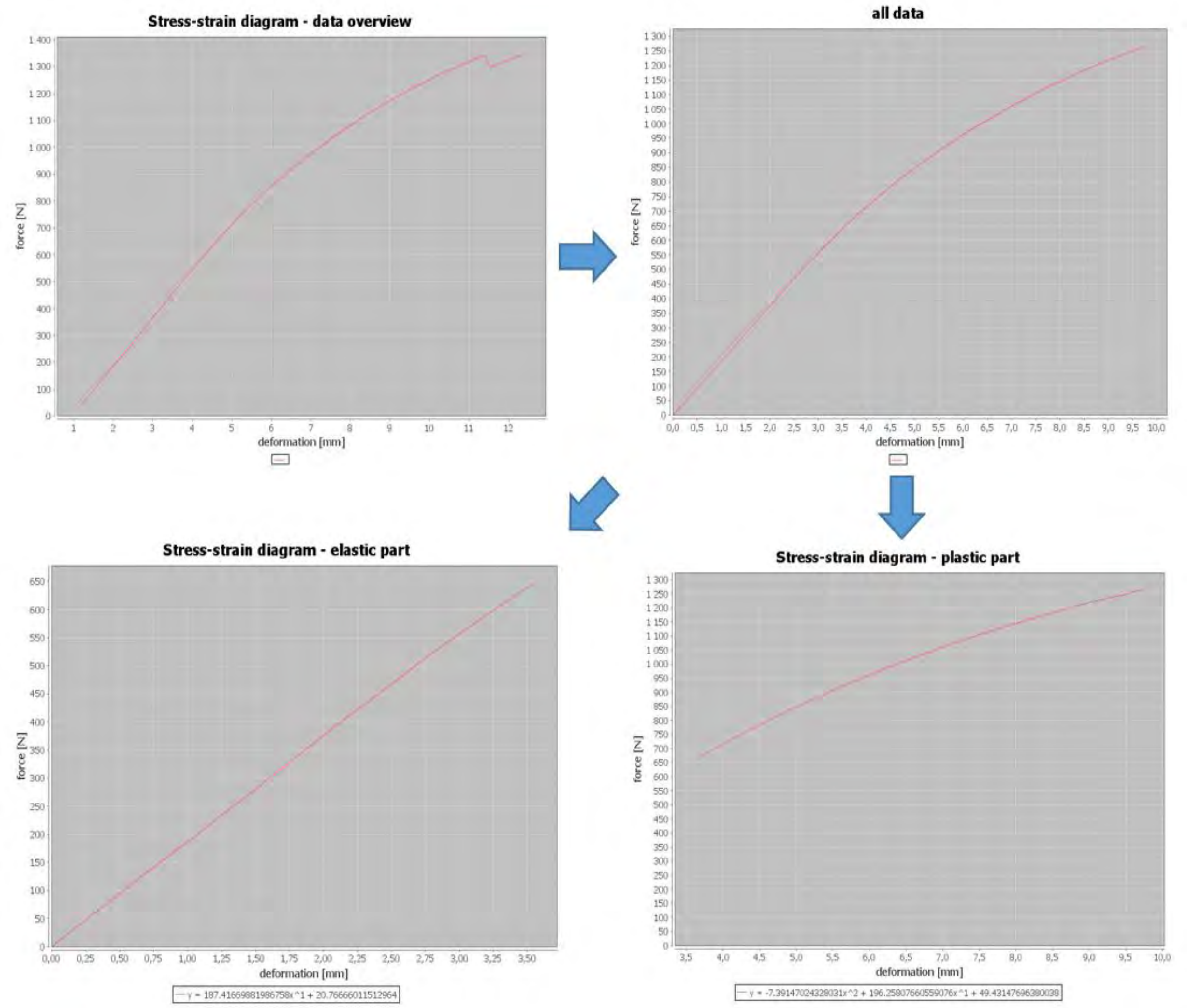
Hodnoty v závorkách jsou variační koeficienty (%)

Vzhledem ke zhušťování jednotlivých vrstev ve skladbě testovaného vrstveného materiálu, kdy vlivem samotného zhušťování dochází také k významným morfologickým změnám, dochází hlavně ke změnám drsnosti lepeného povrchu. Tato problematika byla řešena v článcích 2-3 (The Influence of Thermomechanical Smoothing on Beech Wood Surface Roughness, Shear Bond Strength of Two-Layered Hardwood Strips Bonded with Polyvinyl Acetate and Polyurethane Adhesives), kdy jsme došli k závěru, že vlivem zhušťování ve všeobecnosti dochází ke snižování smykové pevnosti. Mírného nárustu symkové pevnosti bylo dosaženo u lepených prvků s vyšší tloušťkou, ačkoliv tento nárust byl pouze mírného charakteru. Z hlediska použitého adheziva byla vyšší smyková pevnost zjištěna u prvků lepených PVAc lepidlem, ačkoliv rozdíl mezi PVAc a PUR lepidlem byl pouze 1,7% ve prospěch PVAc lepidla. Z hlediska lepení zhuštěnych prvků bylo zjištěno, že v případě kombinací různě zhuštěných prvků byla dosažena nižší smyková pevnost než v případě lepení prvků o stejném stupni zhuštění. V případě lepení zhuštěných prvků se prokázaly PUR lepidla jako efektivnější, což je opačný trend než v případě nezhušteného dřeva. Při lepení PUR lepidlem byla smyková pevnost ve všeobecnosti vyšší o 9,1%.

Z hlediska bližší analýzy změny drsnosti ovlivňující kvalitu lepeného spoje při využití modifikace zhušťováním byl řešen článek 2 (The Influence of Thermomechanical Smoothing on Beech Wood Surface Roughness). Z hlediska zhušťování a jeho dopadu na změnu drsnoti povrchu je nutné brát v potaz vícero faktorů jako je tlak, teplota, doba stabilizace v lisu. Výsledky tohto článku poukazují na vliv těchto faktorů na změny drsnosti skrz charakteristiku (R_a) tedy aritmetický průměr odchylky od vyhodnocovaného profilu. Vzhledem k dosaženým výsledkům, můžeme řící, že vlivem zhušťování se R_a snížila v obou sledovaných směrech vzhledem k orientaci dřevních vláken. V podélnémé směru vláken se R_a snižovalo v rozsahu od 15–40 % a ve směru kolmém k průběhu vláken bylo dosaženo podobného procentuálního poklesu 15–43 %. Vlivem zvýšení teploty nedocházelo ke staticky významné změně drsnosti povrchu vyjádřené parametrem R_a. Naopak zvyšováním tlaku bylo dosaženo výraznějšího poklesu hodnot R_a. Tyto změny vysvětlují výslednou kvalitu lepených spojů, kdy do určité míry může být zhušťování dřeva ve skladbě lepeného materiálu pozitivním faktorem ovlivňujícím kvalitu lepeného spoje, nicméně při vyšších stupních zhuštění z důvodů přílišného vyhlazování se tento proces modifikace dřeva jeví kontraproduktivně vzhledem ke kvalitě lepeného spoje.

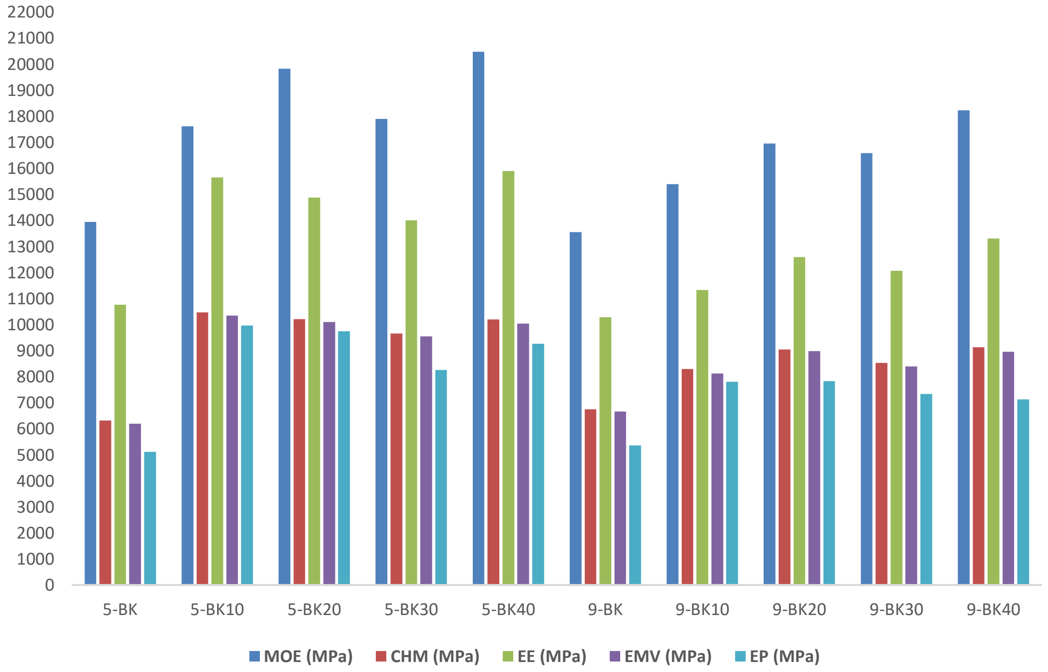
Výsledné analýzy průběhu namáhání vrstvených materiálů ze zhuštěných lamel a jejich kombinací s vysokopevnostním komponenty jsou podrobně popsány v článcích 4-7. (Deflection of Densified Beech and Aspen Woods as a Function of Selected Factors, Impact of Selected Factors on the Bending Forces at the Proportionality Limit and Yield Point in Laminated Veneer Lumber, Effect of Selected Factors on the Bending Deflection at the Limit of Proportionality and at the Modulus of Rupture in Laminated Veneer Lumber, Laminated Venner Lumber with Non-Wood Components and the Effects of Selected Factors on Its Bendability) a odeslných manuskriptech 1-3 (Properties of Wood-Based Composites Manufactured of Densified Beech Wood in Viscoelastic and Plastic Region Force – Deflection Diagram (FDD), Bending Work of Laminated Materials Based on Desnsified Wood and Reinforcing Components, Densification and Reinforcement of

Layerd Wood and its Influence on Bending Potential). V rámci vyhodnocování sledovaných ohybových mechanických charakteristik, byl tento výzkum z části využit pro vytvoření nástroje pro přesnou analýzu silově průhybového diagramu, čímž tato práce přispěla ke vzniku softwaru MATESS, který byl primárně výstupem projektu programu GAMA Technologické agentury ČR (GAMA TAČR TG03010020). Kdy tento software pracuje v několika krocích (čištění dat a interpolace chybějících hodnot, místní vyhlazování pracovního diagramu, detekce meze pevnosti a meze úměrnosti a následné vyhodnocení zbývajících charakteristik) viz obrázek 40.



Obr. 40 Proces zpracování pracovních diagramů softwarem MATESS

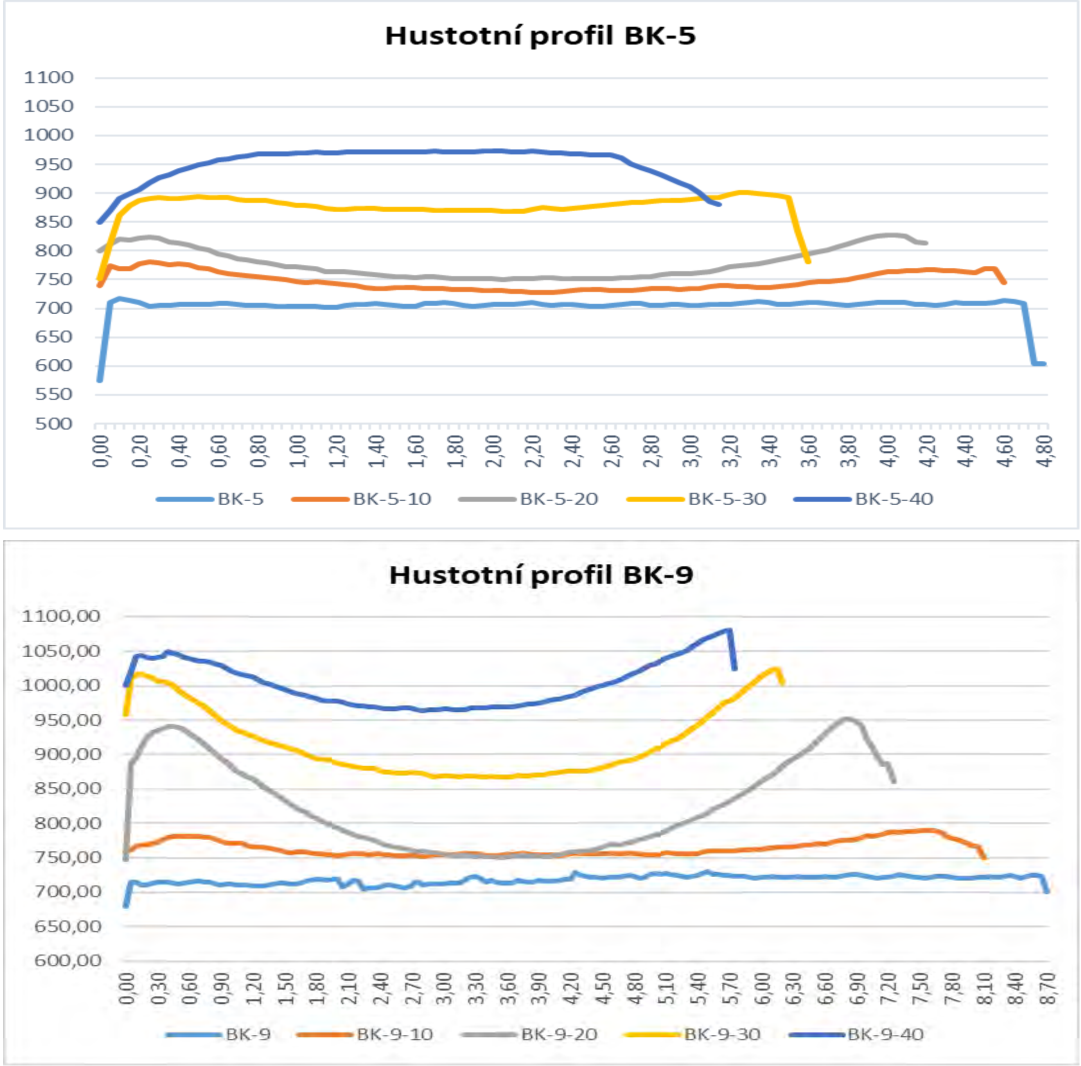
Při výpočtu modulu pružnosti a pevnosti dřeva se bere v úvahu zejména zatížení a odpovídající průhyby v mezích úměrnosti a pevnosti. Tvar křivky silově průhybového diagramu v plastické oblasti je však velmi důležitý pro zjištění analýzu chování materiálů v plastické oblasti namáhání. Byly zjišťovány hodnoty tangentových modulů a sečnicového modulu, protože tyto hodnoty poskytují důležité informace o chování dřeva v případě náhodného přetížení, když zatížení přesáhne lineární oblast namáhání. Zhuštění lamel má za následek zvýšení hodnot tangentových modulů. Mezi stupni zhuštění vykazovaly nejlepší výsledky lamely zhuštěné o 10 % své tloušťky. Se zvyšujícím se stupněm zhuštění, zejména při zhuštění o 30 a 40 %, došlo k mírnému poklesu hodnot tangentových modulů ve srovnání s lamelami zhuštěnými o 10%, a to navzdory skutečnosti, že zhuštění vedlo k téměř lineárnímu zvýšení hustoty. Podobný trend byl sledován také u modulu pružnosti. U lamel s vyšší tloušťkou byly nárusty tangentových modulů a sečnicivého modulu nižší než v případě nížší tloušťky lamel.



Tyto výsledky je možné vidět na obrázku 41.

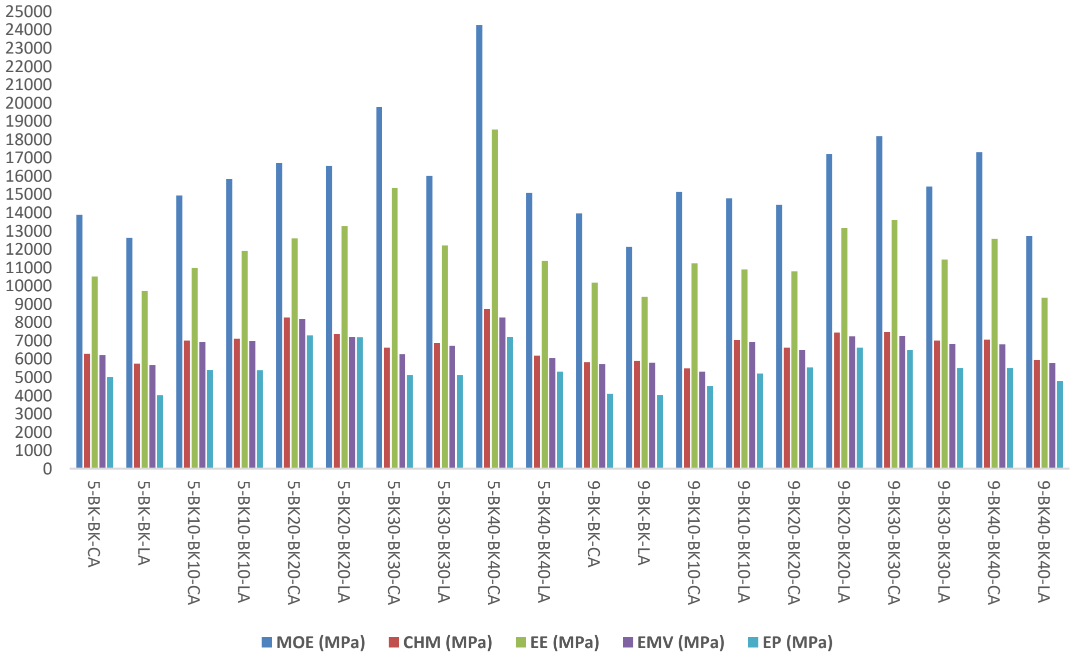
Obr. 41 Změna modulu pružnosti, tangentových modulů a sečnicivého modulu dřeva vlivem zhušťování

Vliv hustoty změněné procesem zhušťování je evidentní. Nicméně je také možné pozorovat neefektivní zušťování při vyšších stupních zhuštění (30-40%), což je dané zvolenou metodou zhušťování. Je možné pozorovat mírně odlišné trendy změn tangentových modulů při 5 mm a 9 mm zhuštěných lamelách. Změny hustotních profilů vysvětlující odlišné změny tangentových modulů jednotlivých typů lamel je možné vidět na obrázku 42.



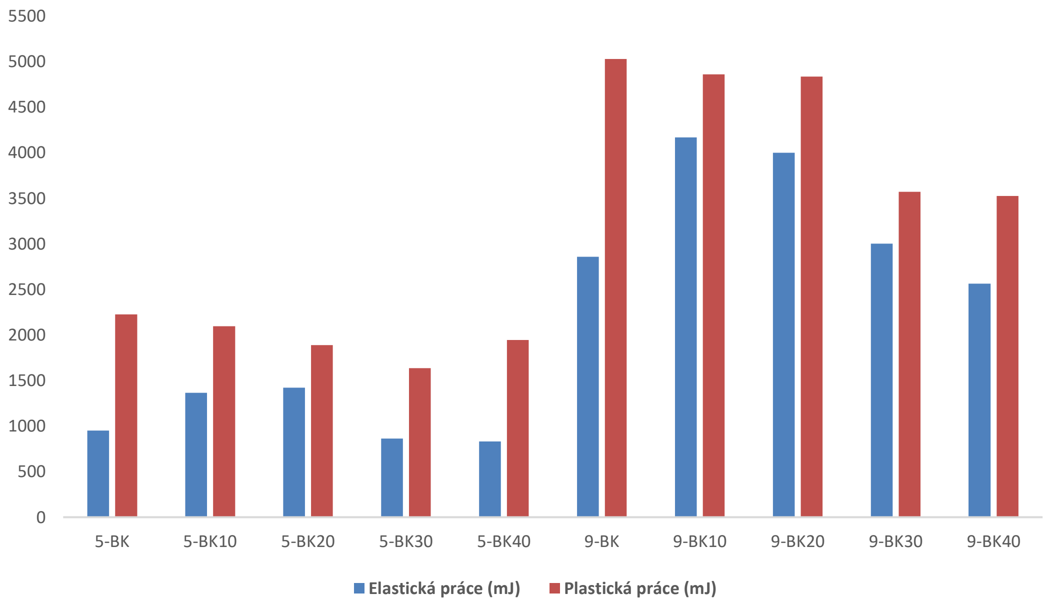
Obr. 42 Změna tangentových modulů a sečnicivého modulu dřeva vlivem zhušťování

Lze konstatovat, že při aplikaci vysoko pevnostních komponentů ve vrstvené skladbě materiálu (obrázek 43) existuje silná závislost na změně hodnot tangentových modulů a sečnicového modulu a na základě výsledků lze konstatovat, že při aplikaci vysokopevnostních komponentů ve skladbě s lamelami zhuštěnými do 20% neexistuje statisticky významný rozdíl mezi aplikaci skelných a uhlíkových vláken, zatímco vysoko pevnostní komponenty na bázi uhlíkových vláken mají lepší výsledky v případě skladby vrstveného materiály skládajícího se z lamel zhuštěných o 30 % a 40%. Tento trend je možné vysvětlit morfologickými změnami povrchu dřeva vlivem zhuštění a změnou afinity jednotlivých vrstev, které byly popsány výše.



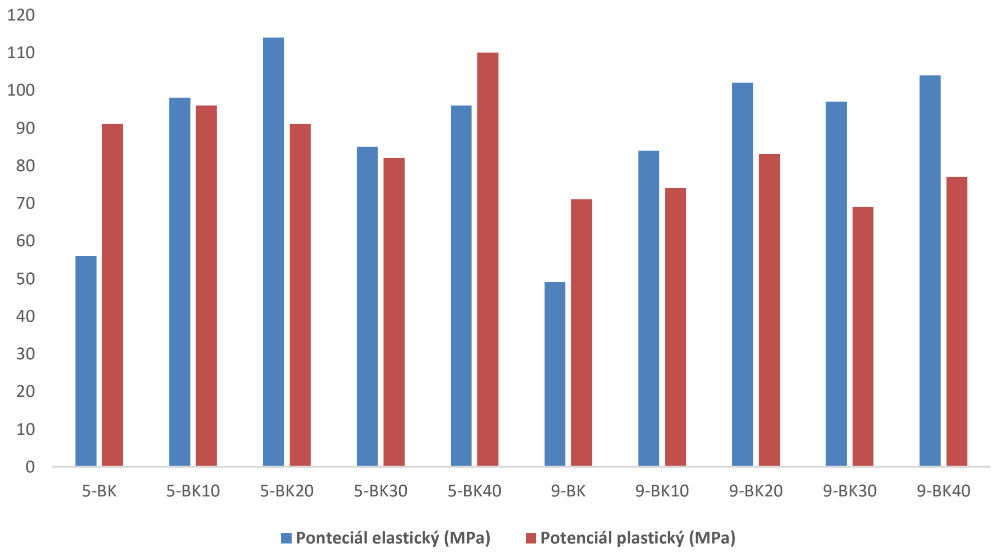
Obr. 43 Změna tangentových modulů a sečnicivého modulu vrstvených materiálů na bázi dřeva a vysokopevnostních komponentů

V rámci stanovených mechanických vlastností byla také řešena problematika ohybové práce a potenciálu. Výsledky ohybové práce poukazující na množství energie potřebné pro ohyb daného materiálu je možné vidět na obrázku 44. Jelikož se jedná o charakteristiku vztahující se k celkovému objemu je možné vidět značné rozdíly mezi 5 mm a 9 mm vstupními lamelami. U obou tloušťěk se ovšem prokazuje stejný trend změn hodnot vlivem zhušťování. Nárust práce v pružné oblasti je možný pozorovat u lamel zhuštěných o 10 % a 20 % a naopak jeho pokles při vyšších stupních zhuštění. Plastická práce se snižuje u všech stupňu zhuštění, ale v případě 30% a 40% zhuštění je pokles výraznější. Hustota materiálu má tedy významný vliv jak na elastickou, tak na plastickou práci, vztah však nebyl lineární pro celou zkoušenou oblast zhušťování. Bylo také zjištěno, že úroveň zhuzhuštění o 10% je optimální, pokud jde o zlepšení pružné, plastické a celkové ohybové práce v obou zkoušených tloušťkách (5 a 9 mm). Zvýšení celkové práce v důsledku zhuštění je způsobeno hlavně zvýšením ohybové práce v elastické oblasti, protože zhušťování způsobovalo mírné snižování plastické práce při ohýbání.



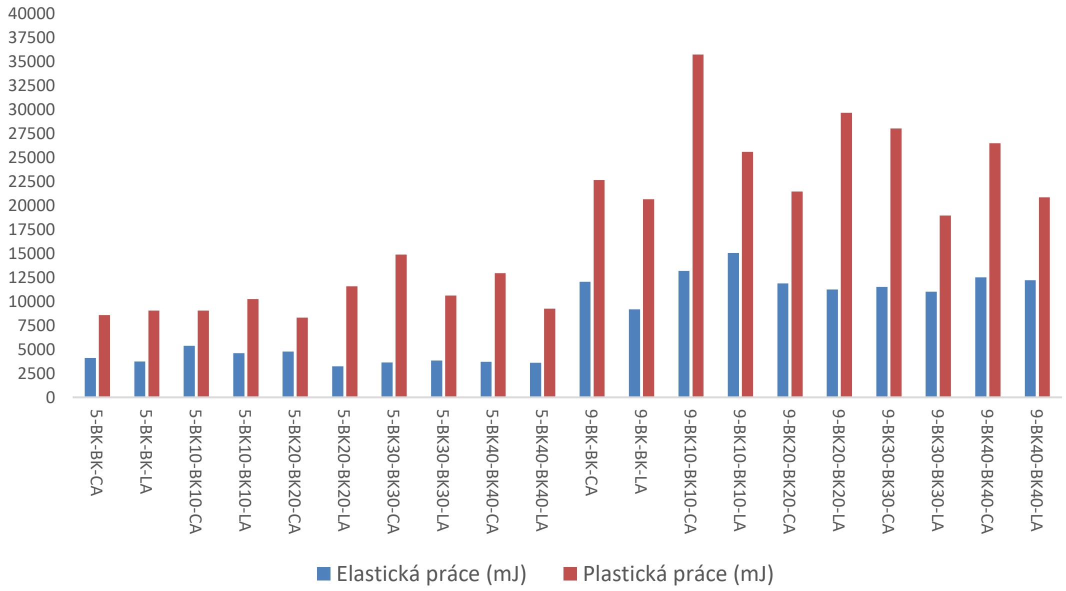
Obr. 44 Vliv stupňů zhušťování dřeva na ohybovou práci

Výsledky změn ohybového potenciálu vlivem zhuštění (obrázek 45) ukazují na významný účinek zhuštění a korelují tedy s výsledky stanovení ohybové práce. Hustota materiálu má významný vliv na elastický i plastický potenciál, vztah však nebyl lineární pro celou zkoušenou oblast zhušťování. U jednotlivých lamel byl nejvyšší účinek prokázán při 20% zhuštění jak u 5 mm, tak u 9 mm lamel. Se zvyšujícím stupňem zhuštění, zejména o 30 % a 40%, lze pozorovat pokles hodnot ohybového potenciálu vzhledem k hodnotám získaných při 20% zhuštění. U jednotlivých lamel nebyla u plastického potenciálu pozorována žádná významná závislost na zhuštění. Nicméně je možné vidět, že celkový potenciál a potenciál elastický mají prakticky stejný trend změn vzhledem k jednotlivým stupňům zhuštění. Bylo zjištěno, že úroveň 20% zhuštění je optimální, pokud jde o zlepšení elastického, plastického a celkového ohybového potenciálu v obou zkoušených tloušťkách lamel (5 a 9 mm). Zvýšení celkového potenciálu v důsledku zhuštění je způsobeno hlavně zvýšením ohybového potenciálu v elastické oblasti. Důležitým poznatkem je také změna poměru mezi elastickým a plastickým ohybovým potenciál, kdy vlivem zhušťování docházelo ke zlepšení tohoto poměru ve prospěch elastické ohybového potenciálu.



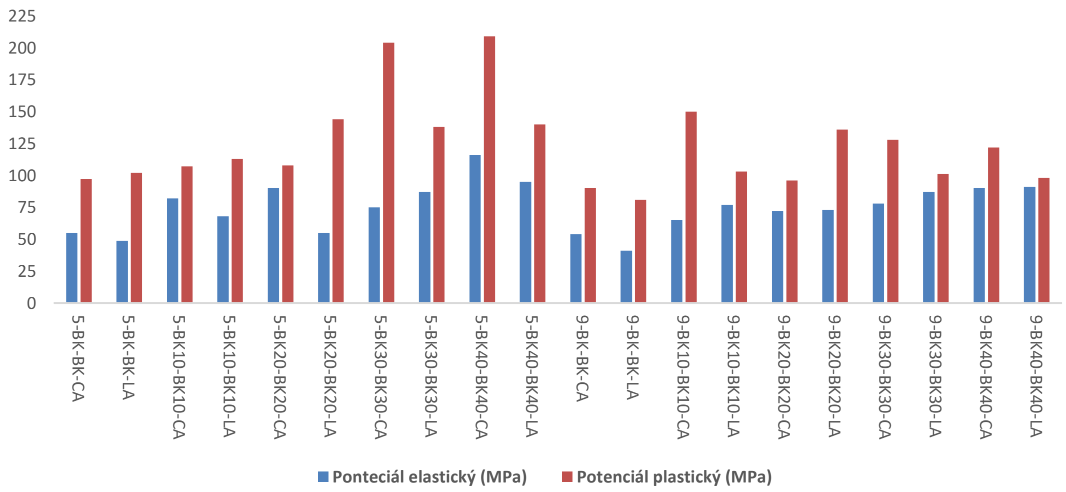
Obr. 45 Vliv stupňů zhušťování dřeva na ohybový potenciál

U vrstveného zhušťovaného dřeva s aplikací vysokopevnostních komponentů je možné z hlediska ohybové práce pozorovat rozdílné trendy při aplikaci skelných a uhlíkových vláken (obrázek 46). Ve většině případů se projevily uhlíkové vlákna jako vhodnější výztužný komponent jak pro elasticou tak pro plastickou práci, kromě materiálu složeného z lamel zhuštěných o 20%. Rozdíly mezi uhlíkovými a sklenými vlákny u materiálů složených z 5 mm lamel byly u elastické práce statisticky nevýznamné. U plastické práce se statistická významnost projevila ve prospěch uhlíkových vláken hlavně u vyšších stupňu zhuštění. Významnější statistické rozdíly mezi aplikací skelných a uhlíkových vlaken, hlavně u plastické práce byly zaznamenány u vrstvených materiálů složených z 9 mm vstupních lamel. Podobně jako u vrstvených materiálů z 5 mm lamel bylo i u materiálů složených z 9 mm lamel zhuštěných o 20 % dosaženo vyšší plastické práce v případě aplikace skelných vláken. Když ale budeme sledovat kombinovaný efekt zhušťování a vyztužování, lze uvést, že z hlediska zhušťování je optimálním stupněm zhuštění jak z pohledu elastické tak plastické práce 10% zhuštění bukových lamel.



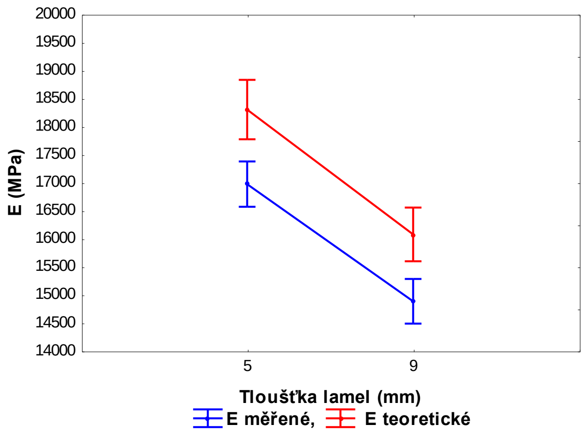
Obr. 46 Vliv vrstvení zhušťovaného dřeva a vysokopevnostních komponentů na ohybovou práci

Z hlediska elastického potenciálu (obrázek 47) u vrstvených materiálů na bázi zhuštěného dřeva a vysokopevnostních komponentů lze pozorovat odlišný trend změn hodnot s ohledem na vstupní tloušťku lamel. Obecně lze říct, že v případě elastického potenciálu u materiálu se vstupní tloušťkou lamel 5 mm se projevoval vysokopevnostní komponent na bázi uhlíkových vláken lépe než komponent na bázi skelných vláken. Naopak u materiálu se vstupními lamelami 9 mm vidíme postupné zvyšování hodnot v důsledku zhuštění a obecně lze říci, že při aplikaci skelných vláken byly zaznamenány vyšší hodnoty elastického potenciálu, s výjimkou materiálu složeného z nezhuštěných lamel. V případě plastického potenciálu lze pozorovat také měnící se trend, pokud jde o vstupní tloušťku lamel. Lze však říci, že vyšší hodnoty plastického potenciálu lze obecně pozorovat při aplikaci uhlíkových vláken (s výjimkou materiálů složených z lamel zhuštěných o 20 %). Trend změn hodnot plastického potenciálu se výraznou měrou podepisuje na celkovém potenciálu. Nejvyšší hodnoty celkového potenciálu byly zaznamenány u materiálu sestávajícího z lamel zhušťěných o 40% při aplikaci uhlíkových vláken. Je tedy možné vidět výrazné rozdíly v chování samotného zhuštěného dřeva a vrstveného dřeva na bázi zhuštěných lamel kombinovaného s vysoko pevnostními komponenty. Při kombinaci jak zhuštění, tak vyztužování, byl výkon vyztužených vzorků zhuštěných o 10% shledán optimálním z hlediska elastického i plastického potenciálu, i když se výztužné komponenty jevily efektivněji při vyšších stupních zhuštění.



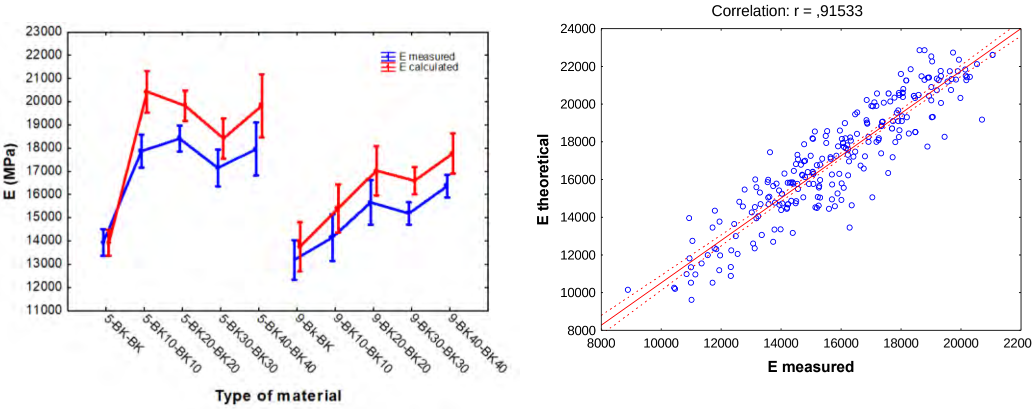
Obr. 47 Vliv vrstvení zhušťovaného dřeva a vysokopevnostních komponentů na ohybový potenciál

V rámci cílů této disertační práce byl také záměr vytvořit a ověřit matematický přístup pro stanovení teoretického modulu pružnosti, který by mohl sloužit jako nástroj pro optimalizaci skladby vrstvených materiálů vzhledem k požadovaným vlastnostem. V rámci tohoto cíle byl také vyhodnocován modul pružnosti vrstvených materiálů na bázi zhušťovaného dřeva. Obrázek 48 ukazuje účinek vstupní tloušťky lamel bez ohledu na stupně zhuštění na měřené (E_m) a teoretické (E_t) hodnoty modulů pružnosti. Výsledky ukazují, že vyšších hodnot modulu pružnosti lze dosáhnout použitím lamel s menší tloušťkou. To bylo také statisticky podloženo. Jednotný rozdíl mezi naměřeným a předpovězeným modulem pružnosti (ΔE) zjištěným statistickým hodnocením naznačuje, že tloušťka jednotlivých lamel nemá vliv na přesnost matematického přístupu pro dvou vrstvé materiály.



Obr. 48 Vliv tloušťky vstupních lamel na hodnoty modulu pružnosti (E_m a E_t)

Výsledky celkového účinku typu testovaného materiálu na charakteristiky E_m a E_t lze vidět na obrázku 49. Tyto výsledky naznačují, že u lepených lamel se vstupní tloušťkou 5 mm jednotlivých lamel došlo k velmi významnému zvýšení naměřených hodnot modul pružnosti (o 22 %) s 10% zhuštěním vzhledem k nezhuštěným lepeným lamelám stejné tloušťky. U lepených 5 mm lamel zhuštěných o 20% bylo zvýšení modulu pružnosti kolem 24 %. Další stupně zhuštění (30% a 40%) u materiálů se vstupními 5 mm lamelami však ukázalo pokles modulu pružnosti, i když hodnoty byly významně vyšší, pokud jde o nezhuštěné lepené lamely. Mírně odlišný trend v hodnotách měřeného modulu pružnosti byl dosažen u materiálů se vstupní lamelou o tloušťce 9 mm, kde byl nárůst hodnot ovlivněn zhuštěnými lamelami. Materiály vytvořené z 10% zhuštěných lamel vykazovaly 7% nárůst v modulu pružnosti ve srovnání s materiály složenými z nezhuštěných lamel. Nárůst modulu pružnosti dosáhl 16 % s lamelami zhuštěnými o 20%. Nejvyššího nárůstu modulu pružnosti o 19 % bylo dosaženo u materiálů složených z lamel zhutněných o 40 %. Hodnoty vypočítaného toretického modulu pružnosti ve všech případech nadhodnocovaly reálně měřené hodnoty modulu pružnosti.



Obr. 49 Vliv vrstvení zhušťovaného dřeva na hodnoty modulu pružnosti (E_m a E_t)

Obrázek 49 ukazuje také korelaci mezi naměřeným a teoretickým modulem pružnosti bez ohledu na tloušťku materiálu a stupeň zhutnění s 95% intervalem spolehlivosti. Výsledky (r = 0,915) naznačují velmi silný vztah mezi naměřeným a vypočítaným modulem pružnosti vrstvených dřeva, což naznačuje, že model může být použit ke stanovení modulu pružnosti dvou vrstvových materiálů na bázi dřeva. Při aplikaci tohoto modelu na skladby materiálů s vysokopevnostními komponenty docházelo k vysokému nadhodnocování modulu pružnosti vzhledem k reálně měřeným hodnotám. Tento negativní výsledek se dá vysvětli neefektivním přenosem vlastností vysokopevnostních komponentů.

7 Závěry a přínosy

Hlavní přínos disertační práce je komlexní popis chování specifických paralelně vrstvených materiálů na bázi zhušťovaného dřeva a vysokopevnostních komponentů při namáhání ohybem. Předkládaný výzkum obsahuje data o vlivech jednotlivých faktorů, jako jsou stupně zhušťování dřevní substance, tloušťky jednotlivých vrstev a aplikace vysokopevnostních komponentů na sledované ohybové charakteristiky. Konkrétně se jedná o stupně zhušťování v rozmezí od 10 % do 40 % vzhledem k původní tloušťce materiálu. Z hlediska vstupních tloušťěk byly řešeny lamely o tloušťkách 5 a 9 mm. Jako vysoko pevnostníkomponenty byly použity materiály na bázi uhlíkových a skelných vláken.

Kromě hlavních přínosů týkajících se stanovení vlivů jednotlivých faktorů na sledované vlastnosti bylo v rámci této práce řešeno vytvoření nástroje pro přesnou identifikaci ohybových vlastností. Tento nástroj vznikl z části právě díky experimentální části této disertační práce, jedná se o software MATESS, který byl hlavním výstupem projektu programu GAMA Technologické agentury ČR (GAMA TAČR TG03010020). Dalším přínosem je také vytvoření a ověření matematické metody stanovení teoretického modulu pružnosti pro vrstvené materiály pomocí geometrických parametrů jednotlivých vrstev a také pomocí tuhosti jednotlivých vrstev ve skladbě paralelně vrstvených materiálů. Z disertační práce mohou být na základě výsledků experimentální části práce vyvozeny následující hlavní závěry:

1. Významným faktorem ovlivňujícím výsledné mechanické vlastnosti paralelně vrstvených materiálů je volba adhezivního prostředku a jeho afinita k danému lepenému povrchu. V rámci lepení zhuštěných lamel dochází s vyššími stupní zhušťování k vyhlazování povrchu jak v podélném tak příčném směru vzhledem k orientaci vláken, kdy do určité míry může být zhušťování dřeva pozitivním faktorem ovlivňující kvalitu lepeného spoje, nicméně při vyšších stupních zhuštění se tento proces modifikace dřeva jeví kontraproduktivně. V rámci změny povrchových vlastností vlivem zhušťování byl také ovlivněn vztah mezi lepenými dřevními prvky a vysokopevnostními komponenty.
2. Z hlediska samotného zhušťování, kdy docházelo téměř k lineárnímu nárustu hustoty vzhledem k jednotlivým stupňům zhuštění (10–40% zhuštění vzhledem k původní tloušťce) daným způsobem zhušťování, můžeme uvést, že nejefektivnějšími stupni pro 5 mm lamely bylo hlavně zhuštění o 10 %, kdy

při vyšších stupních zhuštění byly sledované mechanické charakteristiky zlepšené vzhledem k referenci, ale statisticky nevýznamně k lamelám zhuštěných o 10%. V případě 9 mm lamel byl tento trend podobný s rozdílem, že se jako efektivní způsob prokázal kromě 10% zhuštění také 20% zhuštění. V případě vyšších stupňů zhuštění byly sice dosaženy vyšší hodnoty, ale ze statistického pohledu bylo toto zvýšení nevýznamné.

3. Aplikace vysokopevnostních komponentů na bázi skelných a uhlíkových vláken se prokázala jako významný faktor ovlivňující sledované ohybové charakteristiky. Při vyztužování zhuštěných prvků do 20% je možné uvést, že nebyla sledována žádná statistická významnost mezi jednotlivými vysokopevnostními komponenty. Ve všeobecnosti je možné uvést, že mírně vyšší vlastnosti byly pozorovány při aplikaci sklených vláken. Nicméně při vyztužování dřeva zhuštěného o 30-40% se z pohledu statistické významnosti jevila lépe uhlíková vlákna.
4. V rámci hodnocení sledovaných mechanických vlastností, vznikl z části díky této disertační práci software MATESS, který umožňuje velmi přesnou a rychlou identifikace hraničních bodů a následný výpočet vybraných mechanických charakteristik v ohybu na základě reálného průběhu silově průhybových diagramů.
5. V případě vytvoření a ověření matematického způsobu stanovení teoretického modulu pružnosti vrstvených materiálů na základě jejich geometrických parametrů a jejich tuhosti, může být na závěr uvedeno, že lze poměrně přesně využívat pro dvou vrstvé materiály čistě na bázi dřeva, kdy na základě statistického hodnocení lze říci, že mezi reálně měřenými a vypočítanými teoretickými moduly pružnosti není statisticky významný rozdíl, ve všech případech dochází k mírnému nadhodnocení materiálu. U materiálů využívající výztužné vysokopevnostní komponenty byly zaznamenány statisticky velmi významné rozdíly mezi reálně získanými moduly pružnosti a vypočítanými teoretickými moduly pružnosti, kdy ve všech případech docházelo k velmi významnému nadhodnocení modulu pružnosti. Z tohoto pohledu bude nutné v případě využívání vysokopevnostních komponentů upravit matematický přístup a zohlednit objemový podíl vláken vzhledem k celkovému objemu materiálu a zohlednit vzákemnou afinitu rozdílných materiálů.

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9 Seperáty článků a manuskriptů

9.1 Článek číslo 1., Adhesive as a Factor Affecting the Properties of Laminated Wood

Adhesive as a Factor Affecting the Properties of Laminated Wood

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This study focuses on changing wood's bending properties using several types of adhesives. The strength, flexibility, and durability (service life) of laminated wood, glued with four types of adhesives, were examined. The results were compared with solid beech wood, conditioned to 9% moisture content. Depending on the adhesive used, the results indicate that laminated (layered) wood improved the strength and bending characteristics in comparison to the intact wood. Gained knowledge about materials properties have practical applications in the area of dynamic stress (*e.g.*, as components of vibrating machinery mechanisms or in constructing beds, chairs, and sports equipment).

Keywords: Beech; Solid wood; Laminated wood; Lamination; MOR; Cyclic bending; Bendability coefficient; Minimum bend radius

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INTRODUCTION

People have long favored wood on account of its technical and aesthetic properties. Wood has many beneficial mechanical properties, which are utilized in a broad range of products. In certain cases, its properties need to be modified to better suit a product's specific requirements. One modification possibility is the production of layered (laminated) wood with better strength or bending properties. Laminating is a technique that substantially improves the value of the wood material while enabling changes in the wood's properties. The characteristics of laminated wood can be altered in various ways.

From an environmental perspective, wood is a clean and renewable material held in high regard for its usefulness to society. Wood has had a place in people's lives since ancient times, and it continues to be a widely utilized material. Wood is a strong, elastic, and light material that can bear heavy burdens. Additonally, it is easy to process and can be joined, allowing for added versatility. Untreated wood's low flexibility and the related problems regarding shaping (especially in larger dimensions) are factors motivating the development and application of lamination (Aydin *et al.* 2004). Laminated wood comprises multiple layers of wood, most frequently in the form of veneers (thin slices), glued and pressed together, as shown in Fig. 1. A material's stratification is very important in industrial practice, both in civil engineering and the wood processing industry (Dubovský *et al.* 1998; Glos *et al.* 2004; Frese and Blaß 2006).

In the wood processing industry, material stratification provides greater homogenity, thereby reducing the portion of critical areas that cause damage to the material when under stress. This process also allows for the utilization of lower-rated wood species in the middle layers of the material, with more valued wood species (or those with better mechanical properties) in the outer layers (Gáborík and Dudas 2008; Gaff and Zemiar 2008). Laminated wood can be modified by altering the properties of the individual layers of the structure according to the required purpose (Gaff and Gašparík 2013). This results in a product that can maintain untreated wood's positive properties while suppressing its negative properties (Zemiar *et al.* 2000).

Lamination should be viewed as a technique that substantially improves the value of wood material (Zemiar and Gáborík 1997). Laminated wood is especially utilized in manufacturing chairs and beds. Laminated wood's properties are affected primarily by the type of wood and its subsequent physical and mechanical properties (Gaff and Gáborík 2014). The material is also affected by the type of adhesive and technology used (Sviták *et al.* 2014). The present study focused on the adhesive's effect on selected properties of laminated wood while comparing laminated wood's bending properties with those of solid wood. Almost all types of adhesives are used to produce laminated wood. Gluing mixtures (adhesives) used to produce laminated wood must form strong and elastic bonds between the individual layers (Konnerth *et al.* 2006).

EXPERIMENTAL

Materials and Characterization

Based on the study's defined objective, one batch of samples was prepared from solid wood and four batches were prepared from laminated wood, consisting of five layers or slats. Layers of veneers were glued together with the parallel orientation for each layer. The tests utilized beech wood (*Fagus sylvatica* L.) and veneers by peeling. Each individual layer was composed of beech veneer, each 2 mm thick (Fig. 1). The experiment used four types of adhesive. Diakol F, (Diakol Strážske, Ltd., Slovakia) was selected to represent urea–formaldehyde adhesives and Duvilax LS-50 (Diakol Strážske, Ltd., Slovakia) represented polyvinyl acetate adhesives. A mixture of the two adhesives was also employed, to combine their favorable properties. The ratio of these adhesives (Diakol F:Duvilax LS-50) in the mixture was 4:1. The ratio was determined on the basis of our preliminary experimental works. The fourth batch was composed of laminated wood glued with JOWAPUR 687.40 (Diakol Strážske, Ltd., Slovakia) polyurethane adhesive. The adhesive was layered on one side at 180 g/m^2. There were five veneer layers per laminated batch. In our concept we investigated laminated venner lumber LVL, which are layered in parallel orientation (Fig. 1).

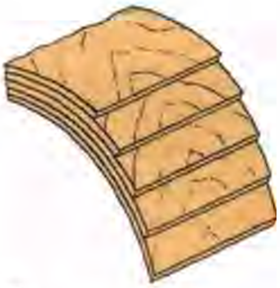

Fig. 1. Laminated sample preparation

Wood was pressed cold at a pressure of 1.2 MPa for a duration of 40 min. Adhesive was applied at 150 to 200 g/m^2. After the wood was removed from the press, it was stabilized for 24 h in a compressed state using a manual press (0.8 MPa). After stabilization, the wood was divided into samples for individual tests according to the diagram in Fig. 2. Samples for static bending measured 45 × 250 x 10 mm (width × length x thickness) (10 pieces), samples for the durability test of dynamic bending measured 45 × 600 x 10 mm (width × length x thickness), (10 pieces), and samples for determining adhesiveness had dimensions of 20 × 150 x 10 mm (width × length x thickness) (10 pieces).

The samples were conditioned to 12% moisture. To achieve the required moisture level, the test samples were placed in a heating chamber APT Line II (Binder, Germany), at the following conditions: relative humidity (ϕ) = 65 ± 3% and temperature (t) = 20 ± 2 °C. Moisture content verification was carried out in accordance with ISO 13061-1 (2014).

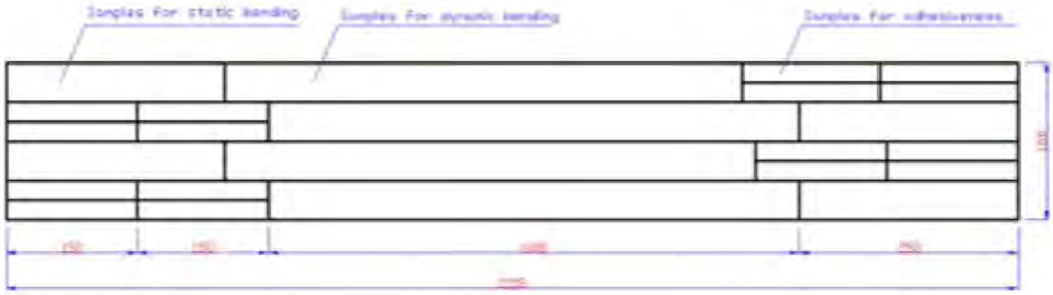

Fig. 2. Distribution of samples from pressed wood

Methods

The samples were bent by the three-point bending principle. Bending was carried out in a FPZ 100/1 testing loading machine (HECKERT, Germany) according to EN 310 (1993); the machine contained a special jig for flexural tests and an ALMEMO 2690-8 data logger (AHLBORN, Germany) for recording the loading forces and maximum deflection.

The adhesiveness test measured the quality of the gluing process. The testing of adhesives' effects on laminated wood's properties focused on the bending properties during static bending as well as cyclic (dynamic) stress. Bending strength (MOR) and modulus of elasticty (MOE) characteristics of layered beech wood were determined through testing at a bend using a single axis of stress (Fig. 3).

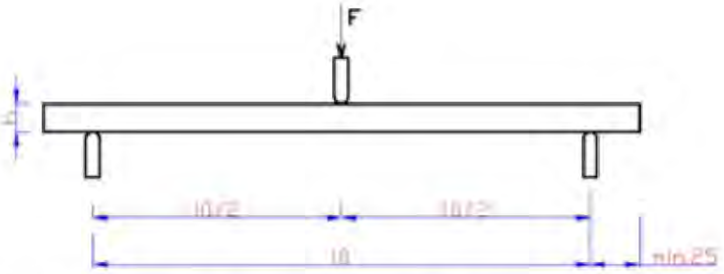

Fig. 3. Stress method for static bending; l_0 is distance between supports ($l_0 = 20 \times h$) (mm), l is sample length (mm), and h is sample thickness (mm)

Measured values were used to calculate bending strength (σ_{bend}) according to Eq. 1, modulus of elasticity (E_m) according to Eq. 2, minimum bend radius (R_{min}) according to Eq. 3, and bendability coefficient (k_{bend}) according to Eq. 4.

Bending Strength (MOR)

The bending strength was calculated in accordance with EN 310 (1993) and Eq. 1,

$$\sigma_{\text{bend}} = \frac{3 \times F_{\max} \times l_0}{2 \times b \times h^2} \qquad \text{(MPa)} \qquad (1)$$

where σ_{bend} is the (ultimate) bending strength of wood (MPa), F_{max} is the maximum (breaking) force (N), l_l is the distance between supporting pins (mm), b is the width of the sample (mm), and h is the height (thickness) of the sample (mm).

Modulus of Elasticity (MOE)

The modulus of elasticity was calculated in accordance with EN 310 (1993) and Eq. 2,

$$E_m = \frac{l_1^3 (F_2 - F_1)}{4bh^3 (a_2 - a_1)} \qquad \text{(MPa)} \qquad (2)$$

where E_m is the modulus of elasticity perpendicular to fibers in radial direction (MPa), l_1 is the supports distance (mm), b is the width of sample (mm), h is the thickness of sample (mm), $F_2 - F_1$ is the loading increment in the proportional section of the load *vs.* deflection diagram, where F_1 must represent approximately 10% and F_2 is approximately 40% of the breaking load (N), and $a_2 - a_1$ is the deflection increment in the half of the sample length corresponding to the loading increment ($F_2 - F_1$).

Minimum Bend Radius

The value of the minimum bend radius is given by,

$$R_{\min} = \frac{l_0^2}{8 \times y_{\max}} + \frac{y_{\max}}{2} \qquad \text{(mm)}, \qquad (3)$$

where y_{max} is the maximum bend (mm).

Bendability Coefficient

$$k_{\text{bend}} = \frac{h}{R_{\min}} \qquad (4)$$

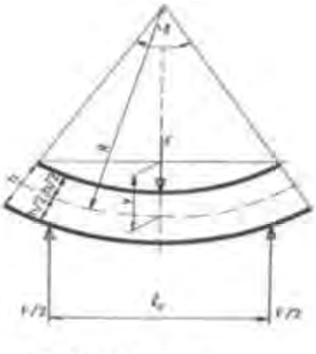

Fig. 4. Measuring the monitored variables in bend tests

The cyclic bend stress test also characterizes the examined materials' elasticity. Laminated wood was placed under repeated cyclical bending stress, increasing from zero to the selected maximum (Fig. 5). The cycle frequency was 22 cycles per min. For testing purposes and based on expected safety, it was decided to stress the laminated wood only up to 50% of the maximum bend, calculated according to Eq. 5,

$$y_{\mathrm{d}} = \frac{l_d^2}{8 \times R_{\mathrm{min}}} \tag{5}$$

where y_{d} is cyclic bend stress and l_d is the distance between supports in the cyclic test (490 mm).

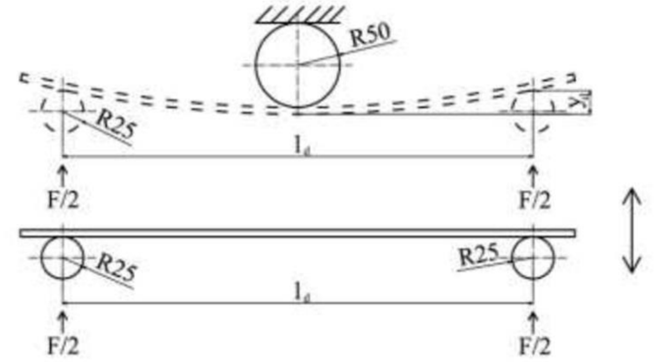

Fig. 5. Cyclic bending of slats

RESULTS AND DISCUSSION

The acquired results indicate that laminated (layered) wood had better bending characteristics than (solid) wood. The results indicate that the choice of adhesive substantially affected the laminated wood's overall strength properties (Table 1). Urea – (UF) adhesives are the most widely used in producing laminated wood for furniture because of their good strength properties and acceptable price.

MOR is a property monitored primarily for sizing cross-sections of materials used to construct products. Materials glued with UF and polyurethane (PUR) adhesives recorded higher strength values than solid wood. With the application of UF adhesive, the MOR was 4.6% higher than that of solid wood. For the PUR adhesive, the figure was 12% higher with σ_{bend} = 148.5 MPa (Table 1). The strength of beech wood varies depending on the origin of the wood, as well as the method of its determination. Požgaj *et al.* (1993) reported MOR of beech wood σ_{bend} = 124 MPa and MOE 12,966 MPa, similar to the MOR results of 117 MPa found by Gašparík and Barcík (2014). Dubovský (1998) reported σ_{bend} = 94 ± 18 MPa and Gáborík (1995) stated σ_{bend} = 77.6 MPa.

The results show that the greatest difference was in durability, where wood glued with UF adhesive recorded only one-quarter the durability of laminated wood glued with PUR adhesive.

Table 1. Bending Properties of Solid and Laminated Beech Wood

Properties		Solid beech wood (9% moisture)	Laminated wood (9% moisture)			
			Adhesive			
			UF	PVAc	Mixture (UF + PVAc)	PUR
MOR	σ_{bend} (MPa)	130.2 (9.8)	136.2 (8.7)	101.7 (6.4)	111.2 (7.1)	148.5 (4.8)
MOE	E_m (MPa)	11,654 (7.6)	13,060 (9.4)	10,102 (8.5)	11,709 (7.3)	14,268 (4.2)
Durability	(number of cycles)	-	9,923 (10.7)	16,882 (10.8)	13,394 (8.0)	40,136 (9.3)
Loading force	F_{max} (N)	1,284.2 (8.2)	1,721 (7.5)	1,351 (4.3)	1,446 (7.7)	2,035 (3.3)
Maximal deflection	y_{max} (mm)	13.3 (8.4)	9.9 (4.6)	10.7 (9.6)	8.75 (9.7)	13.0 (7.3)
Minimum bend radius	R_{min} (mm)	594 (9.2)	467.7 (5.7)	374.6 (4.3)	436.5 (10.9)	491.4 (9.8)
Bendability coefficient	k_{bend}	0.01684 (10.5)	0.0191 (6.3)	0.0240 (6.7)	0.0200 (7.2)	0.0203 (5.4)

Values in parentheses are coefficients of variation (CV) in %

Using a polyvinyl acetate (PVAc) dispersion adhesive or a mixed adhesive (UF + PVAC) when gluing laminated wood can increase the wood's flexibility and durability (service life), while decreasing its MOR and MOE. The MOR was 23% lower for the PVAc adhesive and 14.6% lower for the mixed adhesive than it was for solid wood. In comparison to PUR adhesive, the MOR was 31% and 25% lower, respectively (Fig. 6).

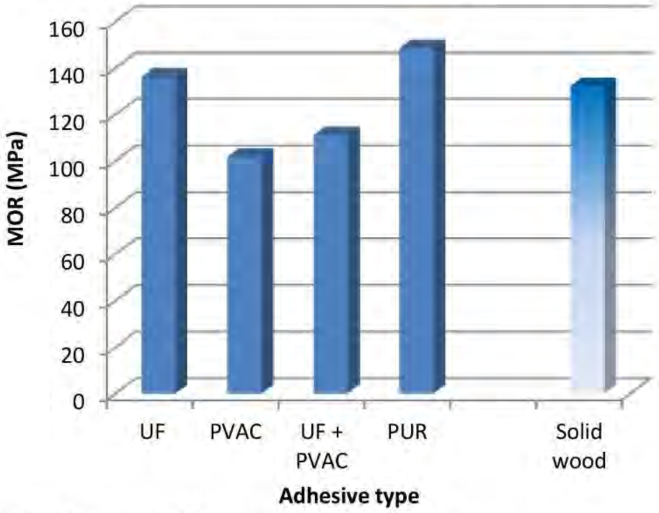

Fig. 6. MOR of solid and laminated beech wood

One may explain these findings based on the fact that PVAc glues hardened physically by evaporation of water. Such evaporative curing can be expeted to create "micro-dowell" connections. UF glues make hard but brittle joints. A suitable combination of UF and PVAc adhesives enables the modification of laminated wood's properties. Specifically, increasing the proportion of UF adhesive increases the laminated wood's MOR and MOE while decreasing flexibility and durability. In contrast, increasing the proportion of PVAc adhesive in a mixture produces the opposite changes for these properties.

Even changing the type of UF adhesive can produce a change in properties, as confirmed by the findings of Olekšák (1996), who used a different type of UF adhesive for a similar laminated wood composition and recorded higher MOR (σ_{bend} = 153 MPa) and modulus (E_m = 14,373 MPa) than the present study. The MOE expresses the material's internal resistance to elastic deformation. As the modulus increases, increasing amounts of stress are required to induce deformation (Požgaj *et al.* 1993). The highest value was recorded by laminated wood glued with PUR adhesive, at E_m = 14,268 MPa, which was 22% higher than the solid wood. Similar results have also been obtained by Farkašovský (2010), with E_m = 14,560 MPa, and Pavlík (2009), with E_m = 15,494 MPa.

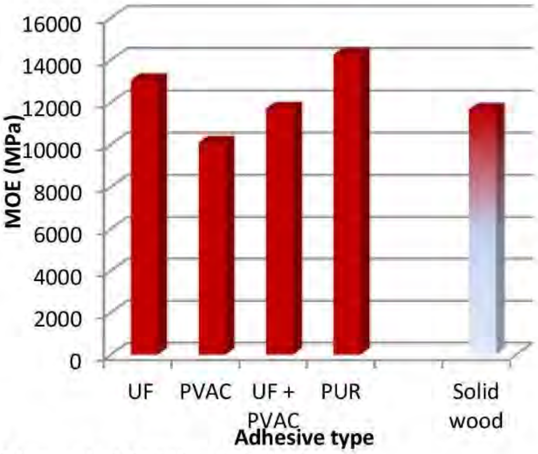

Fig. 7. MOE of solid and laminated beech wood

The bendability coefficient characterizes material in terms of how it is shaped by bending. As exhibited by the irregular shape of bentwood chairs, solid beech wood has high malleability. Laminated wood can be sufficiently shaped after it is glued. The present study recorded durability 13% to 43% higher than that for solid wood. The best malleability was demonstrated by laminated wood glued with PVAc adhesive. Dudas and Gáborík (2006) also recorded improved flexibility for laminated wood.

Durability was evaluated within this study *via* cyclic bend stress. The results showed laminated wood glued with PUR adhesive to have the highest values. Durability with PUR adhesive was four times higher than UF adhesive and 2.4× higher than PVAc adhesive (Table 1, Fig. 8). PUR glues were cured chemically by connection on the free OH groups of the wood, and create the best elastic joints, but UF glues make hard but brittle joints. Dynamic loading is not suitable for UF glues, because at the vibrations disrupt the brittle joints.

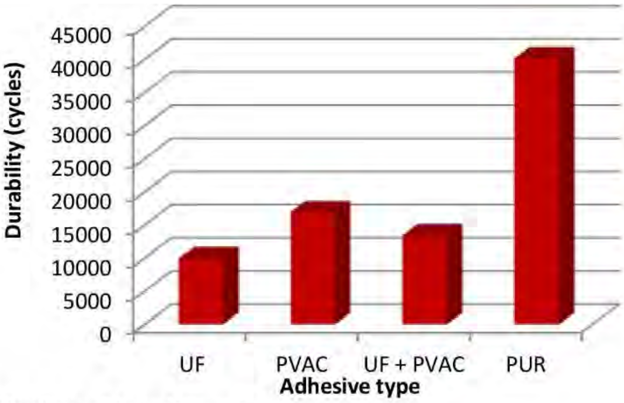

Fig. 8. Durability of laminated beech wood

CONCLUSIONS

1. Laminated wood's properties can be influenced through various means. By combining layers, for example, it is possible to create laminated wood with properties different than those of solid wood. This study focused on examining the effect of altering adhesives on the bending properties of laminated wood. Urea–formaldehyde adhesives create stronger but more brittle bonds, as was confirmed by the results. In this study, the MOR was 4.6% higher for wood glued with such an adhesive than it was for solid wood. In contrast, wood glued with a PVAc adhesive was more flexible than solid wood, as demonstrated by its higher bendability coefficients (43% higher) and high durability/service life (*i.e.*, cyclical bending of up to 16,882 cycles).
2. Suitable selection of adhesive or a combination of adhesives can enable changes to laminated wood's properties, thus creating a material (laminated wood) with specific required properties. The PUR adhesive substantially improved the monitored properties in comparison to both solid wood and laminated wood glued with UF and PVAc adhesives. In comparison to solid wood, the given compositions demonstrated improved strength (by 12% to 31%) and flexibility (by 18% to 43%). The specific adhesive type also affected the final properties as well.

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9.2 Článek číslo 2., The Influence of Thermomechanical Smoothing on Beech Wood Surface Roughness

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The Influence of Thermomechanical Smoothing on Beech Wood Surface Roughness

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This paper deals with the change of roughness of compressed beech wood. Effects of temperature, pressure, and time on the results of pressing were examined. The surface roughness of beech wood in longitudinal and transversal directions was evaluated. Roughness was described by R_a. A contact method was applied. The results show that by increasing pressure, time, or temperature, the surface roughness of beech wood decreases. The highest roughness reduction occurred at the temperature of 150 °C, pressure 4 MPa, and time 20 min.

Keywords: Beech; Roughness; Temperature; Pressure; Time

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INTRODUCTION

Wood is a material that can be treated using various technologies to create altered and improved final products. Every product has different surface quality requirements, when considering its function and aesthetic appearance. The quality of an individual product surface represents the output of certain production technology.

Each technological operation leaves characteristic irregularities on the surface, affecting the integrity and usage of the treated surface of the specimen. It is necessary to regard these irregularities both in their macrogeometric and microgeometric aspects (Kvietkova *et al.* 2015a).

Macroscopic and microscopic irregularities are very minor deviations from an ideal flat surface, which form on the wood surface (Prokeš 1982). The wood surface is a border region which divides the wood substance from the surrounding environment (Požgaj *et al.* 1997). To obtain a more complete idea of wood surfaces, it is necessary to know information regarding many of its properties, such as morphology, chemical composition, optical properties, thermodynamic properties, *etc.* (Kurjatko *et al.* 2010). It is also necessary to be familiar with the effects of a whole range of factors on the surface properties. These factors include methods of wood surface treatment, moisture, temperature, *etc.*

With real wood surfaces, it is always necessary to take into account the effect of the operating instrument on the geometry of the surface (Liptáková *et al.* 1995).

The geometry of the wood surface results from a combination of its anatomical structure and the selected treatment method. The principle of evaluating the surface geometry of solid materials lies in the classification and quantification of deviations, corresponding to the actual surface from the base surface.

In technological practice, researchers differentiate between three deviations of geometric surfaces, which consider the range of rough irregularities:

- Order 1: Deviation represents major macrogeometric defects on the whole surface. This deviation is mostly considered a deviation from the geometrical shape.
- Order 2: Deviation is a waviness. It is given mainly by the method of treatment and by technological operations.
- Order 3: Deviation of higher orders, included in the common name of roughness (Liptáková and Sedliačik 1989; Liptáková and Kudela 2000).

Surface roughness is a geometric property that is determined by the material type, and also by the method of treatment (Kvietkova *et al.* 2015b). During evaluation, the same criteria are used for solid materials with a certain degree of irregularity. The examination of surface roughness is the most utilized method of surface quality evaluation.

Roughness can be expressed by several parameters (*e.g.*, R_a - arithmetical mean deviation of the assessed profile, R_z - maximum height of the profile, R_p - maximum profile peak height, R_v - maximum profile valley depth). According to the norm STN EN ISO 4287 (1997), the R_a characteristic is considered one of the main evaluation criteria for evaluating roughness, and it is appropriate to supplement the characteristic with the other aforementioned parameters.

Roughness and waviness are determined either by contact or optical profilometers. It is necessary to correctly choose the sampling length, as the (R) and (W) parameters of roughness are established (Kúdela 2010). The treated surface quality is determined by treatment with an appropriate instrument, by which the irregularities on the wood surface are removed. The most utilized method of final wood surface treatment is sanding, and to a lesser extent, milling. The slowness and dustiness of the sanding process poses many problems. That is why new methods of decreasing the roughness of a wood surface utilizing mechanical, or more precisely, thermomechanical treatment are being researched (Gáborík and Dudas 2008; Gáborík and Žitný 2010).

Several authors have attempted to increase the smoothness of a sample's material surfaces in their works (Sandig 1998; Kneist and Raatz 2001; Raatz 2002; Wieloch 2004; Rehm and Raatz 2005). The authors engaged in a thermomechanical method of wood surface treatment, namely thermal-smoothing by rolling and hot pressing. Thermal-smoothing is considered a final treatment for the wood surface. By the use of temperature and pressure, a so called thermo-effect develops, which plasticizes the surface fibers, pressing them into the surface. As a result of lignin melting, which floods the irregularities of wood, the treated surface becomes smoother and shinier (Mýtny 1995; Wieloch 2004).

During this work, the researchers focused on wood surface treatment by hot pressing (thermal-smoothing). This study investigated the effect of pressing factors (*i.e.*, temperature, pressure and duration) on the roughness of the wood surface, in relation to the direction of the wood fibers. The purpose of this paper was to evaluate the effect of the examined factors on the surface roughness of the beech wood, *i.e.*, the increase in surface smoothness by thermal-smoothing.

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica* L.) originated from the Poľana region of central Slovakia. Logs were cut into planks. Heartwood planks were cut into samples with dimensions of 16 x 60 x 100 mm. The number of samples was 10 for each measurement. They were cut from the same batch of material. The samples were conditioned in a HCP 108 humidity chamber (Memmert, Schwabach, Germany) to a moisture content of 7%, which was determined using the weighting method in accordance with STN 490103 (1979). This moisture content corresponds to the equilibrium moisture content of furniture elements according to EN 942 (2007) and STN 91 0001/Z3 (1998).

After all the tests the samples were dried in a lab drier KBC-G-100/250 (Premed; Warsaw; Poland) at 103 ± 2 °C in order to achieve zero moisture content. The density of beech wood at its absolute driest state was $\rho_0 = 650$ kg/m^{-3}. The surface of the samples before hot compression was treated *via* milling. Hot pressing with stabilization (thermal-smoothing) was conducted in the radial direction, *i.e.*, the tangential surfaces of the samples were treated. The researchers evaluated the quality of the surface based on roughness observations. The roughness was determined using the Mahr Pocket Surf (Rapp Industrial Sales, Pennsylvania, United States) contact profile meter, with a sampling length of $L = 5$ mm. The roughness was measured in 5 areas, parallel to the wood fibers and perpendicular to the fibers (Fig. 1).

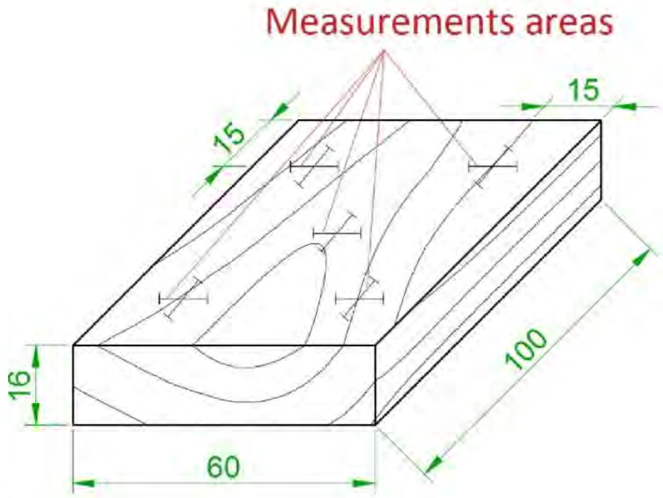

Fig. 1. Measurements areas of roughness by contact method

Methods

The researchers measured the arithmetic mean deviation of the evaluated profile (R_a). This is defined by STN EN ISO 4287 (1999) as a bidirectional roughness irregularity relating to the mean line on a sampling length, denoted as L (Fig. 2). For the purpose of scanning the surface irregularities, a scanning stylus with a 5 microns tip radius was mounted in the instrument. The measurement range of the instrument, for the arithmetical mean deviation – R_a, was 0.03 μm to 6.35 μm.

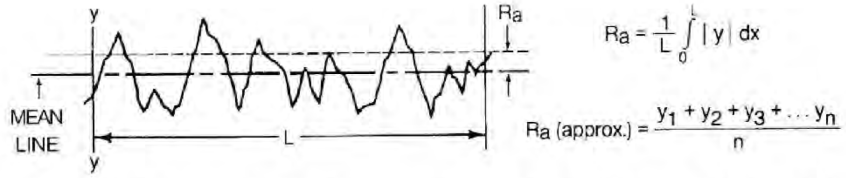

Fig. 2. Arithmetical mean deviation of the assessed profile Ra STN EN ISO 4287 (1999)

The samples were molded and planed between heated plates in a ZD 10/90 (VEB TIR RAUENSTEIN; Germany) tensile testing machine. There were polished steel sheets on the surface of the plates. The plates were heated resistively, with their own temperature regulators. Two temperatures and three pressures (each pressure with its own duration) of hot pressing were selected. The actual pressing parameters are listed in Table 1.

Table 1. Pressing Parameters

Temperature (°C)	Pressure (MPa)	Duration of compression – stabilization (min)
120	1	5
	2	10
	4	20
150	1	5
	2	10
	4	20

Based on the values of roughness (Ra) measured before and after compression, the changes in surface roughness were evaluated.

Illustrated below is the decrease of roughness, on the molded – planed surface, as opposed to the milled surface, expressed as a percentage, according to Eq. 1,

$$R_x = \frac{R_a(F) - R_a(L)}{R_a(F)} \times 100 \qquad (1)$$

where R_x is the roughness change (%), $R_a(F)$ is the value of roughness after the milling (μm), and $R_a(L)$ is the value of roughness after the hot compression (μm).

RESULTS AND DISCUSSION

At the chosen thermal-smoothing conditions, the beech wood was pressed by 2.5% of its thickness. The determined values of roughness (the arithmetic mean deviation of the evaluated profile (R_a) of the wood before and after pressing) are listed in Tables 2 to 6. The input roughness achieved by plane milling reached an average value of 1.62 μm along the length of the fibers, and 2.73 μm crosswise against the fibers. Based on the ascertained data, the researchers concluded that the roughness of the milled wood surface varies depending on the fibers' direction. Extrapolating from the data, it can be concluded that the direction perpendicular to the wood fibers was 71% rougher than the direction parallel to the fiber for the beech wood. Žitný (2010) achieved similar results, listing a roughness equal to 2.86 μm lengthwise and 5.06 μm crosswise (this is 77% rougher than the direction parallel to the fiber), and 2.4 μm lengthwise and 4.7 μm crosswise (96 % rougher). After milling the radial surfaces, Rešetka (2013) found the roughness along the length of the fibers was 3.78 µm and 7.54 µm when oriented crosswise against the fibers (99.5% rougher). Wieloch (2004) found that roughness oriented crosswise across the fibers of beech wood was 3.32 µm.

After the process of thermal-smoothing by hot pressing, the roughness decreased and the average value of roughness was 1.3 µm for the lengthwise orientation, and 2.15 µm for the crosswise orientation (Table 2). Even after hot pressing, the wood roughness measured perpendicular to the fibers was 65% higher than the parallel direction. By thermal-smoothing, this difference decreased by only 6%.

Table 2. Mean Values of Roughness Before and After Hot Pressing

Surface treatment	Roughness * R_a (µm)	
	Parallel to the fibers	Perpendicular to the fibers
Milling before hot pressing	1.62	2.73
After hot pressing	1.30	2.15

Note: * the value represents the average of all values measured on the samples

The effects of the factors, *i.e.*, a temperature of 120 °C, the pressure, and the duration of hot pressing, are listed in the Tables 3 and 4. From the results, it can be extrapolated that by the gradual increasing of the pressure and the duration of stabilization in the press, a 17 to 31% decrease in the wood surface roughness in the direction parallel to the fibers, and a 15 to 40% decrease in the direction perpendicular to the fibers, can be expected.

More distinct improvements in the surface smoothness were exhibited in the direction perpendicular to the wood fibers (Table 4). A similar tendency of decreasing roughness was also exhibited on the surface of wood molded at a temperature of 150 °C. From the data in Tables 3 and 4, it can be deduced that a decrease in wood surface roughness of 20 to 39% in the direction parallel to the fibers, and 15 to 43% in the direction perpendicular to the fibers, had occurred. The increase of temperature by 30 °C yielded only a slight improvement in the examined surfaces' smoothness.

It can be concluded that a 30 °C increase in temperature (considering the marginal difference from 120 °C) did not significantly decrease the surface roughness. The contribution to the roughness decrease was only 3 to 8%.

A higher temperature, pressure, and duration of thermal-smoothing improved the smoothness of the wood surface. The improvement of wood smoothness by thermal-smoothing is also evident in the works of other authors. For example, Žitný (2010) achieved a surface improvement of 11 to 23%, Wieloch (2004) by 31%, and Kiššák (2009) by 30 to 70%. Rešetka (2013) found an improvement of the surface quality (*i.e. a* decrease of roughness) of beech wood hot pressed at 160 °C, 40% compression and 6 minutes duration. He found an average roughness 1.75 µm (a 54% decrease) in the direction parallel to the fibers and 3.25 µm (a 57% decrease) perpendicular to the fibers. It can be concluded that in these conditions, almost the same surface smoothness improvement was achieved for both directions.

Table 3. Influence of Pressing Temperature 120 °C and 150 °C, Pressure, and Time on Roughness

Temperature (°C)	Pressure (MPa)	Duration of hot pressing (min)	Roughness before hot pressing $R_a(F)$ (μm)		Roughness after hot pressing $R_a(L)$ (μm)	
			∥	⊥	∥	⊥
120	1	5	1.72	2.73	1.26	2.31
		10	1.81	2.99	1.48	2.53
		20	1.57	2.68	1.31	2.11
	2	5	1.55	2.65	1.28	2.17
		10	1.72	2.70	1.29	2.19
		20	1.69	2.84	1.14	2.08
	4	5	1.44	2.81	1.04	1.67
		10	1.59	2.62	1.17	1.91
		20	1.72	2.89	1.19	1.93
	Average		**1.65**	**2.77**	**1.24**	**2.10**
150	1	5	1.55	2.65	1.28	2.17
		10	1.72	2.70	1.29	2.19
		20	1.69	2.84	1.14	2.08
	2	5	1.51	2.73	0.98	1.83
		10	1.60	2.60	1.28	2.02
		20	1.66	2.63	1.22	2.03
	4	5	1.79	2.88	1.34	2.16
		10	1.55	2.67	1.23	1.87
		20	1.63	2.87	1.00	1.64
	Average		**1.63**	**2.73**	**1.20**	**2.00**

Wieloch (2004) and Móza (2010) decreased the roughness by 12.5% to a value of 2.1 μm, by hot pressure with the parameters of 140 °C temperature and stabilization 2 min. During the surface treatment by gradual sanding, the researchers achieved a 33.3% decrease in the R_a value, resulting in a roughness value of 1.6 μm. In this case, the moistening of the surface by water, with the addition of urea-formaldehyde glue, facilitated a better smoothness. Moistening was conducted between the first and second sanding. Gurau *et al.* (2004) achieved a surface roughness of 1.8 to 2.1 μm by sanding beech.

The mentioned data corresponds with the results of Wieloch (2004) and Žitný (2010).

Table 4. Influence of Pressing Temperature 120 °C and 150 °C, Pressure, and Time on Decrease of Roughness

Temperature (°C)	Pressure (MPa)	Duration of hot pressing (min)	Decrease in roughness *Rx* (%)	
			Parallel to the fibers (‖)	Perpendicular to the fibers (⊥)
120	1	5	26.9	15.4
		10	18.2	15.1
		20	16.6	21.3
	2	5	16.8	18.1
		10	25.0	18.6
		20	30.7	26.8
	4	5	27.3	40.6
		10	25.9	27.1
		20	30.9	33.2
150	1	5	19.7	15.0
		10	21.5	18.5
		20	22.8	15.9
	2	5	35.1	32.7
		10	20.1	22.7
		20	26.5	22.8
	4	5	24.7	25.0
		10	20.1	30.1
		20	38.6	43.2

CONCLUSIONS

1. Many different technologies can be used to treat wood and achieve the desired quality on all surfaces. Thermal-smoothing by hot pressing can be considered a viable method of wood surface treatment. The main factors of hot pressing affecting the result of planing are pressure, temperature, and duration of stabilization in the press. During the observation of these parameters, this study found that their mutual interaction has an effect on the change in roughness (R_a (μm) - arithmetical mean deviation of the assessed profile), or more precisely, the increase in the surface smoothness of beech wood.
2. Based on the achieved results, one can conclude that after beech wood pressing, a decrease in roughness occurred in both directions, considering the structure of the wood fibers. In the direction parallel to the fibers, the roughness decreased by 15 to 40 %, and in the direction perpendicular to the wood fibers it decreased by 15 to 43 %.
3. An increase in temperature of 30 °C did not produce significant changes in the surface roughness measured by the Ra parameter.
4. The increase of the pressure and the increase of duration showed positive effects on the surface smoothness of the tangential planes of beech wood.
5. By pressing the wood, some technological operations can be excluded from the wood surface preparations, *e.g.* sanding. Surfaces treated in a better way by thermal-

smoothing undergo shorter surface treatment processes by excluding inter-operational sanding for water-soluble coating substances or by excluding the filling of the pores during treating into a closed surface. This means a decrease in coating substance usage can be achieved.

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9.3 Článek číslo 3., Shear Bond Strength of Two-Layered Hardwood Srips Bonded with Polyvinyl Acetate and Polyurethane Adhesives

Shear Bond Strength of Two-Layered Hardwood Strips Bonded with Polyvinyl Acetate and Polyurethane Adhesives

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This article deals with the effects of various parameters on the shear bond strength (SBS) of glued wood. A four-factor analysis showed that the combination of only non-densified wood pieces achieves higher shear bond strength values than densified ones. In this case, only the piece combination was a significant factor. The other factors (glue type, wood species, and number of loading cycles) had no significant effect. Although the differences were not large, a higher SBS was achieved in beech wood glued with polyvinyl acetate (PVAc) glue. Glued wood consisting of the combination of densified and non-densified pieces had slightly lower SBS values. In this case, all the factors were statistically significant. Beech wood had a more significant impact on the SBS than aspen wood. The effect of the type of glue showed an opposite trend than that in the previous variant, *i.e.*, a higher SBS was achieved with polyurethane (PUR) glue. Wood subjected to cyclic loading had slightly higher SBS values than non-cyclically loaded wood. The degree of densification had no significant effect. Glued wood composed entirely of densified pieces showed greater SBS variation between versions.

Keywords: Shear bond strength; Beech; Aspen; Densification; PVAc; PUR; Cyclic loading

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INTRODUCTION

Although wood is an exceptional material, people are still trying to improve its desirable properties and eliminate its shortcomings. This is why new materials are created either by modifying the properties of the wood, or by combining wood materials of different properties. The mentioned combination of materials creates widespread wood-based composites that are applied in the most common spheres of the timber industry, such as in the production of furniture and wooden buildings (Stoeckel *et al*. 2013).

Wood-based composites are one of the core materials in the woodworking industry. In general, wood-based[a] composites are formed by layering wood materials (plies, strips, veneers, strands, pieces, fibres, *etc*.) (Cai and Ross 2010) and then pressing the material to a final shape with the desired properties. In the construction industry, where these types of composites are most commonly applied, they are divided into two subgroups: structural composite lumber materials (LVL, PSL, LSL, OSL, glulam), and other materials (OSB, fibreboard, plywood, particleboard). Structural composite lumber materials are used for load-bearing elements in buildings and structures, such as rafters, headers, beams, joists, studs, and columns (Stark *et al.* 2010). Other materials are used for non-load bearing applications, such as tiling, floors, formwork, and thermal and sound insulating layers. In the furniture industry, wood-based composites are used a little differently. Structural composite lumber is not used at all, but some principles of its formation are used in other elements (*e.g.*, LVL and bed piece component). Most materials that are intended for non-load bearing use in construction are used to manufacture load-bearing elements in the furniture industry, with the exception of OSB (not used at all) and fiberboards.

Gluing wood is one of the basic methods of bonding wood, known since ancient times. In terms of gluing wood, both the bonding strength and the properties of the glue are important. These characteristics are affected by the gluing conditions (open time, curing method, moisture content of wood, and necessary ambient temperature), as well as the length of the entire production process and the strength of the final product. Today, the most widely used adhesives in the furniture and construction industries are polyvinyl acetate (PVAc) and polyurethane (PUR), which are both defined as elastic polymers (Stoeckel *et al*. 2013). PVAc glues (most often dispersed in the form of an emulsion) are thermoplastics characterized by the need for an absorbent surface, and their glass-transition temperature (T_g) is close to room temperature (Motohashi *et al*. 1984; Minelga *et al*. 2010). Their mechanical properties are closely linked to changes in temperature, which is why even the slightest change in their T_g affects their mechanical properties under specified usage conditions (Motohashi *et al*. 1984). The advantage of PVAc glue is its water solubility, low curing temperature, non-toxic composition, transparent adhesive joints, and its ease of use. PUR glues are thermoplastics most often cured using the wood's moisture content, which reacts with the glue's isocyanate groups (Ren and Frazier 2012). PUR glue for wood creates strong joints with good flexibility, cures at a normal ambient temperature, and is more water resistant than PVAc glue, but it requires a higher moisture content of the glued material or air (Vick and Okkonen 1998).

The bonding quality of glued wood-based composites is affected by various factors. First of all, there are the basic physical and structural properties of the adherent wood, such as moisture content, density, porosity, properties of the cell wall, lumen, and extracellular spaces, which can sometimes change when the wood is modified (impregnation, grinding, and surface treatment). Another group of factors are the properties of the glue in its application (*e.g.*, penetration behavior and surface free energy) and curing (*e.g.*, creep and stiffness) states (Follrich *et al*. 2007; Li *et al*. 2015). Finally, the gluing parameters (adhesive spread, pressing time and temperature, and applied pressure) determine the final properties of the glue and therefore the entire glued wood-based composite (Follrich *et al*. 2007).

The suitability of an adhesive for bonding wood under certain conditions can be determined by various characteristics. The most commonly used reference parameter for the bond strength of the glued wood is its shear bond strength (Serrano 2004; Burdurlu *et al*. 2006; Konnerth *et al*. 2006; Raftery *et al*. 2009; Derikvand *et al*. 2014). The bond strength is the ability of the bonded wood to hold the wood-based composite elements together, ensuring its overall strength. If the bond has a low strength, then the wood-adhesive interface fails; the elements stop sharing the load and the entire composite will have poor characteristics (Le and Nairn 2014).

This research focuses on examining the shear bond strength of beech and aspen wood consisting of pieces bonded with PVAc and PUR adhesives. The main goal was to determine the effects of wood densification, combination of pieces, wood species, and number of cycles on the shear bond strength values.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) and European aspen (*Populus tremula* L.) woods were used for testing. Thin wood pieces of three thicknesses (3, 5, and 9 mm), 25 mm in width and 600 mm in length were produced. These pieces were conditioned to an equilibrium moisture content (EMC) of 8% (ϕ = 40 ± 3% and t = 20 ± 2 °C). The EMC represented the final moisture content of furniture and wooden joinery (flooring and cladding) for interior use, according to EN 942 (2007) and ČSN 91 0001 (2007). The pieces of both wood species were divided into two groups: the first group consisted of non-densified pieces, and the second group consisted of pieces designed for densification.

Densification

Pieces intended for densifying were cold-pressed in a UPS 1000 hydraulic press (RK MFL Prüfsysteme GmbH, Germany) without previous plasticizing. The press was closed for 5 min, and gradual densification of the pieces began. The pieces were kept densified for 2 min. In the last stage, which lasted 3 min, the press was opened and the pressure was released. Subsequently, the pieces relaxed for 5 min.

Table 1 shows all the individual densities of the non-densified and densified pieces for each combination.

Table 1. Average Density Values of Pieces at Moisture Content of 12%

			Density (kg/m^3)		
	Pieces Combination	**Wood Species**	Before Densification (original)	After Densification by 10%	After Densification by 20%
I. group	Non-densified + Non densified	Beech N	679	-	-
		Aspen N	451	-	-
II. group	Densified + Densified	Beech D	704	734	766
		Aspen D	471	503	508
	Non-densified + Densified	Beech N	715	-	-
		Aspen N	505	-	-
		Beech 10% D	703	745	-
		Beech 20% D	702	-	769
		Aspen 10% D	474	490	-
		Aspen 20% D	473	-	514

N – non-densified, D – densified pieces

Sample preparation

The one-component dispersion water-proof polyvinyl acetate (PVAc) adhesive AG-Coll 8761/L D3 (Agglu SK Ltd., Slovakia) and moisture-curing one-component polyurethane (PUR) adhesive Neopur 2238R (Neoflex S.L., Spain) were used for the gluing of pieces. According to EN 204 (2001) these PVAc and PUR adhesives belong to durability classes D3 and D4, respectively. The adhesive properties are shown in Table 2.

Table 2. Adhesives Properties

Glue Type	**Dry Matter Content** (%)	**Viscosity** (mPas)	**Density** (g/m^3)	**pH**	**Working Time** (min)	**Pressing Force at 20 °C** (MPa)	**Wood Moisture Content** (%)
PVAc	49-51	7,000-13,000	0.9-1.1	3.8-4.5	15	0.2-0.8	8-12
PUR	-	2,000-4,000	1.13	-	20-25	-	6-12

A toothed spatula was used for the glue application, laying a thin film of glue at the recommended level of 160 g/m^2. The samples were pressed in an industrial press GS 6/90 (SCM GROUP S.p.A., Italy) under 0.6 MPa at a temperature 20 °C during 20 min. Subsequently, the samples were conditioned in the humidity chamber HCP 108 (Memmert, Germany) to a moisture content of 8% (ϕ = 40 ± 3% and t = 20 ± 2 °C). Lastly, the 2-layered samples were cut to final dimensions of 600 × 35 × h mm^3 (thickness was dependent on the combination of pieces).

Table 3 shows samples with various combinations of pieces. One group consisted of 120 glued samples made of non-densified pieces and the second group consisted of 480 glued samples created by various combinations of densified and non-densified pieces. One half of the samples were intended for cyclic loading testing.

Table 3. Marking and Parameters of Samples

Sample Marking	**Description**
3NN	The sample includes a pair of non-densified pieces with thickness 3 mm
5NN	The sample includes a pair of non-densified pieces with thickness 5 mm
9NN	The sample includes a pair of non-densified pieces with thickness 9 mm
3DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 2.7 mm
3DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 2.4 mm
5DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 4.5 mm
5DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 4 mm
9DD10	The sample includes a pair of pieces, after densification by 10%, with thickness 8.1 mm
9DD20	The sample includes a pair of pieces, after densification by 20%, with thickness 7.2 mm
3ND10	The sample includes a non-densified (3 mm) piece and piece densified by 10% (2.7 mm)
3ND20	The sample includes a non-densified (3 mm) piece and piece densified by 20% (2.4 mm)
5ND10	The sample includes a non-densified (5 mm) piece and piece densified by 10% (4.5 mm)
5ND20	The sample includes a non-densified (5 mm) piece and piece densified by 20% (4 mm)
9ND10	The sample includes a non-densified (9 mm) piece and piece densified by 10% (8.1 mm)
9ND20	The sample includes a non-densified (9 mm) piece and piece densified by 20% (7.2 mm)

3, 5, and 9 are the original thicknesses of the pieces in millimeters
N – non-densified pieces, D – densified pieces

Cyclic loading

At least 24 h after bonding, cyclic loading was carried out. Cyclic loading testing, based on uniaxial bending stress, was carried out using a cycling machine (designed by Milan Gaff at the Faculty of Forestry and Wood Sciences, CULS Prague) with a distance between supporting pins of 490 mm. Cyclic loading was based on bending loading with repetitive loading and releasing. The cyclic loading rate was 60 cycles/min. Maximum load was set to 90% of the limit of proportionality. The limit of proportionality was found during the preliminary tests. Its value is important for avoiding the sample overloading during the cyclic loading. Therefore, the loading value was set up to 90% of the proportionality limit. Subsequently, the samples underwent 10,000 cycles and were compared with non-cyclic loaded samples (0 cycles).

Many of glued furniture parts are loaded cyclically during their use (*e.g.* lamellar grid of chairs and bed furniture). Therefore, the impact of cyclic loading should be examined for glued wood designed for such furniture components.

Shear bond strength

After cyclic loading, the clear samples were cut to 110 × 25 × h mm^3 (sample thickness according to Table 3) and were conditioned to an equilibrium moisture content (EMC) of 12% ($\phi = 65 \pm 3\%$ and $t = 20 \pm 2$ °C). The shear bond strength (SBS) was represented by tensile-shear strength using a lap joint test according to EN 205 (2003) (Fig. 1). Tensile-shear strength was determined using the universal testing machine UTS 50 (TIRA, Germany). The constant loading speed was set to 5 ± 0.5 mm/min such that the time required to reach failure was between 30 s and 50 s. Maximum loading force was directly recorded into the computer software.

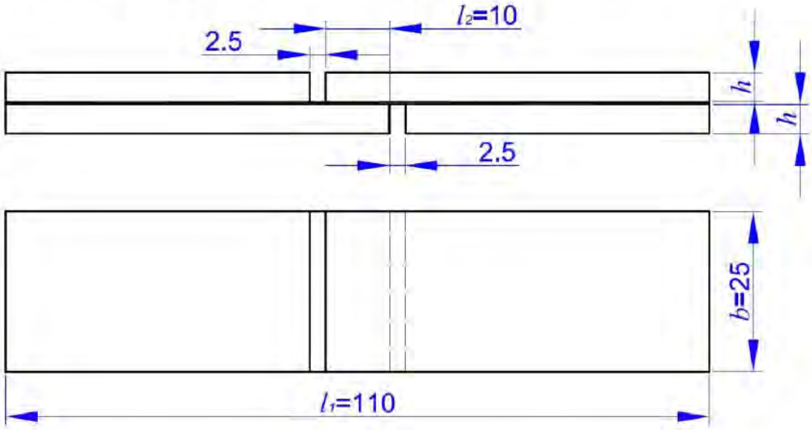

Fig. 1. Testing sample dimensions
Note: l_1 – sample length (mm), l_2 – shear area length (mm), b – sample width/shear area width (mm), h – piece thickness (mm).

Evaluation and Calculation

The shear bond strength values were evaluated using MANOVA, specifically utilizing Fisher's F-test in STATISTICA 13 software (Statsoft Inc., Tulsa, Oklahoma, USA). The results were evaluated using a 95% confidence interval, which reflects a probability of 0.05 ($P < 0.05$).

The tensile-shear strength was calculated according to EN 205 (2003) and Eq. 1:

$$\tau = \frac{F_{\max}}{l_2 . b} \tag{1}$$

where τ is the tensile-shear strength parallel to the fibers (MPa), $F_{\max}$ is the maximum loading force recorded at the breaking point (N), l_2 is the length of the shear area (mm), and b is the width of the shear area/sample (mm).

The wood density was determined according to ISO 13061-2 (2014) and Eq. 2,

$$\rho_w = \frac{m_w}{V_w} \tag{2}$$

where ρ_w is the density of the sample at moisture content w (kg/m^3), m_w is the weight of the sample at moisture content w (kg), and V_w is the volume of the sample at moisture content w (m^3).

The moisture content of the samples was determined according to ISO 13061-1 (2014) and Eq. 3,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{3}$$

where w is the moisture content of the sample (%), m_w is the weight of the sample at moisture content w (kg), and m_0 is the weight of the oven-dry sample (kg). Oven-drying was carried out according to ISO 13061-1 (2014).

RESULTS AND DISCUSSION

Combination of Non-Densified Pieces

Table 4 presents a statistical evaluation of the influence of factors on the shear bond strength of the samples with non-densified piece combination. Only the piece combination was statistically significant ($P < 0.04$). The wood species, glue type, number of cycles, as well as the interaction of all factors, did not significantly influence the shear bond strength.

Table 4. Statistical Evaluation of the Shear Bond Strength for Combinations of Non-densified Pieces

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F - test	*p*-value
Intercept	15,974.13	1	15,974.13	1,117.206	0.001
Wood species (1)	24.20	1	24.20	1.692	0.196
Glue type (2)	1.04	1	1.04	0.073	0.788
Piece combination (3)	165.70	2	82.85	5.794	0.004
Number of cycles (4)	0.42	1	0.42	0.029	0.865
1*2*3*4	43.23	2	21.61	1.512	0.226
Error	1,372.64	96	14.30		

The mean shear bond strength value for beech wood (12 MPa) was approximately 8.1% higher than that of aspen (11.1 MPa; Fig. 2). The differences in shear bond strength values between the different wood species were probably caused by the different anatomical structures (length of wood fibers, porosity, water absorption, and surface roughness), which affect the adhesion of the glue to the surface of the wood pieces.

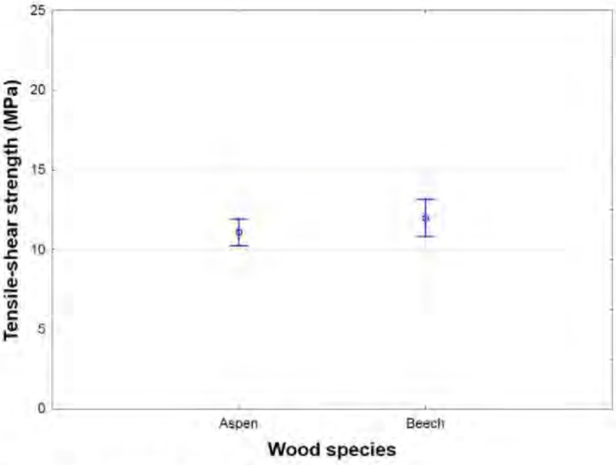

Fig. 2. Influence of wood species on tensile-shear strength

Shear bond strength also depends on the type of adhesive used. It is generally believed that PUR adhesives achieve slightly higher strength values. In this research, no significant differences between PUR and PVAc were observed. However, the shear bond strength found using PVAc glue was 1.7% higher than that with PUR glue (Fig. 3), which is the opposite of the general assumption.

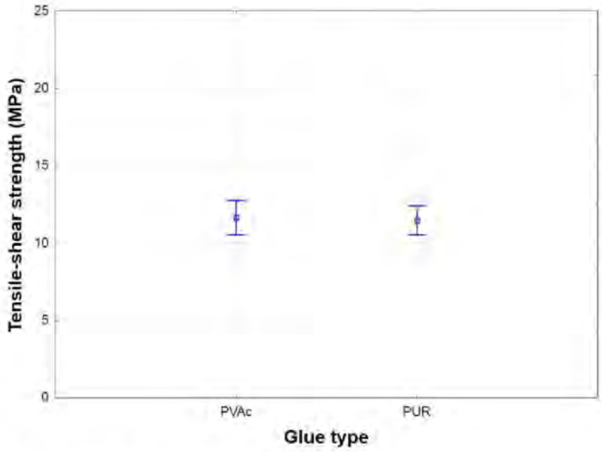

Fig. 3. Influence of glue type on tensile-shear strength

The effect of piece combinations proved to be the only statistically significant factor. Although the area for finding the shear bond strength was the same for all combinations (10 × 25 mm), the thickness of individual pieces changed, which also changed the overall thickness of the samples. The shear bond strength values increased with the increase in sample thickness (Fig. 4).

While the samples composed of 3 mm pieces achieved shear bond strength of 9.9 MPA, the samples composed of 5 mm pieces achieved shear bond strength of 11.9 MPa. The highest value of shear bond strength, 12.6 MPa, was found in the samples composed of 9 mm pieces.

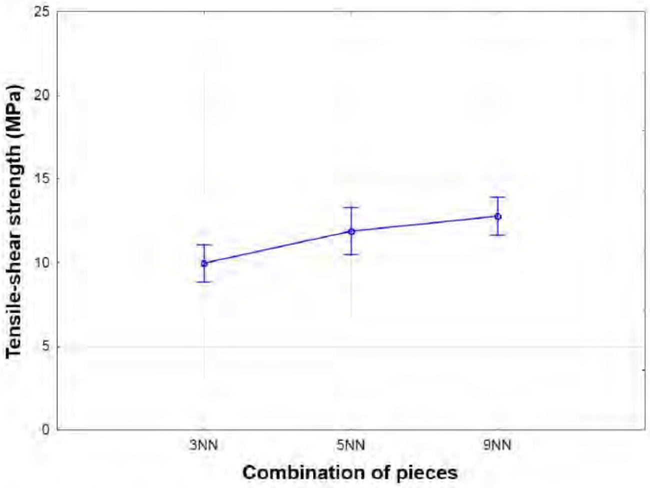

Fig. 4. Influence of pieces combination on tensile-shear strength

Cyclic loading had almost no effect on the shear bond strength. The shear bond strength in the samples without cyclic loading were slightly higher, but only by 1.1%, in comparison to the cyclically-loaded samples (Fig. 5). Both adhesives created a sufficiently flexible bond that could withstand cyclic loading, and the bonded sample therefore remained intact.

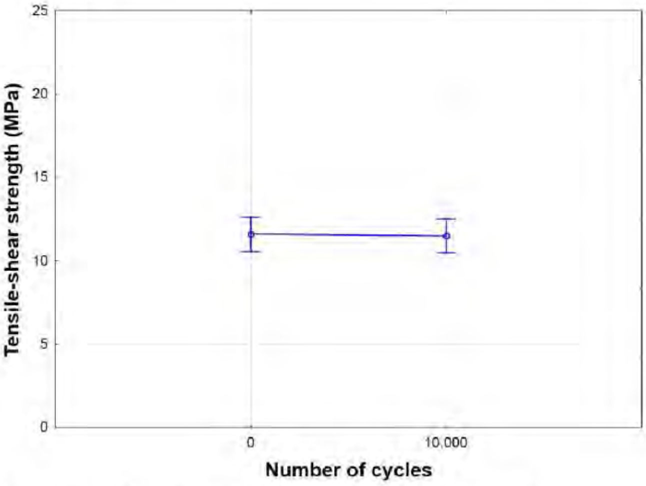

Fig. 5. Influence of number of loading cycles on tensile-shear strength

Figure 6 shows the combined effect of piece combination, glue type, and wood species on the samples without cyclic loading. The shear bond strength is only clear in one case: in beech pieces bonded by PVAc glue. In this case, the shear bond strength increased in proportion to the increase in the thickness of the pieces, or samples. Other cases did not confirm this relationship. It can be concluded that slightly higher shear bond strength values were achieved with PVAc glue.

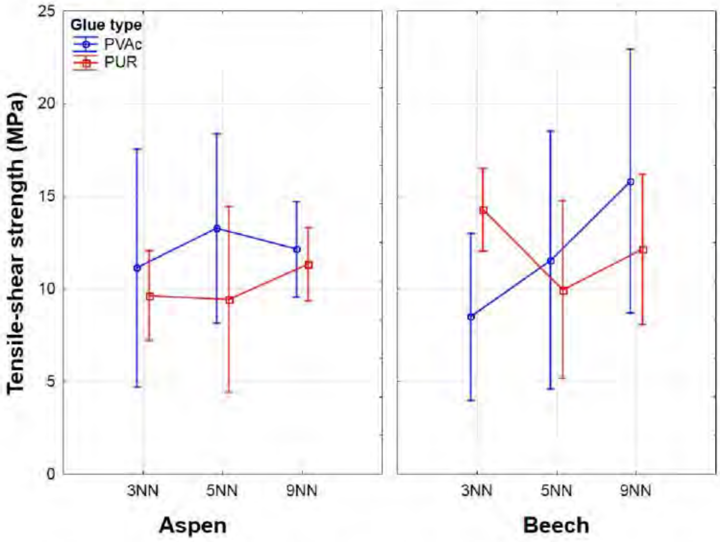

Fig. 6. Influence of piece combination, glue type, and wood species on the tensile-shear strength without cyclic loading

The combined effect of piece combination, glue type, wood species, and cyclic loading had a different character than that in the case of wood without cyclic loading (Fig. 7). This case is characterized by a distinctive trend in the shear bond strength dependency on the piece combination.

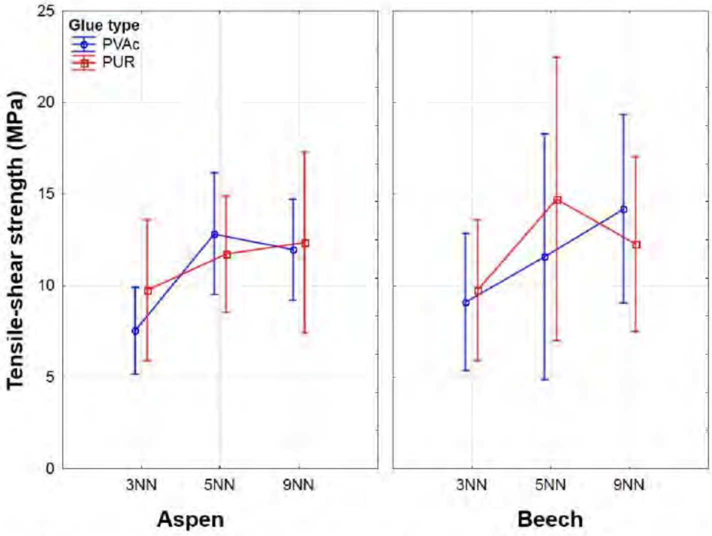

Fig. 7. Influence of piece combination, glue type, and wood species on the tensile-shear strength after cyclic loading by 10,000 cycles

Large differences between different wood species were also found, where higher shear bond strength was measured in beech wood samples. The influence of the glue type exhibited smaller differences than in the previous case.

Comparing these results with other studies, it is clear that the SBS values are similar in most cases (Table 5).

For example, Konnerth *et al.* (2006) reported an SBS value in laminated beech wood of 10.8 MPa using PVAc glue, and 9.7 MPa using PUR glue.

On the other hand, Derikvand and Pangh (2016) found higher SBS values using PUR glue (13.4 MPa) than using PVAc glue (12.3 MPa) to bond Oriental beech (*Fagus orientalis* Lipsky).

Král *et al.* (2015), who investigated plasma surface treatment and subsequent bonding of beech wood with polyvinyl acetate glue, reported a relatively lower SBS value of 8.2 MPa.

Tiryaki *et al.* (2015) reported an even lower SBS value, 6.9 MPa, in the bonding of Oriental beech wood (*Fagus orientalis* Lipsky) using PVAc glue.

Özçifçi and Yapici (2008) reported an even lower SBS value for aspen wood bonded with PUR glue – a value of 4.9 MPa.

The differences in SBS values among various studies are caused by the different physical and mechanical properties of the wood (surface roughness, porosity, density, *etc.*), the variability of the adhesives used (viscosity, open time, fillers and hardeners, water resistance D1 – D4, *etc.*), as well as the gluing conditions (temperature, pressure, and pressing time).

Table 5. Mean Values of the Tensile-shear Strength for Combination of Non-densified Pieces

Combination of Pieces	Glue Type	Number of Cycles	Tensile-Shear Strength (MPa)	
			Beech	Aspen
3NN	PVAc	0	8.9 (3.65)	11.1 (5.18)
3NN	PVAc	10,000	9.1 (3.01)	7.5 (1.90)
3NN	PUR	0	14.3 (1.81)	9.6 (1.95)
3NN	PUR	10,000	9.8 (3.08)	9.7 (3.08)
5NN	PVAc	0	11.5 (5.61)	13.3 (4.11)
5NN	PVAc	10,000	11.6 (5.41)	12.8 (2.67)
5NN	PUR	0	9.9 (3.86)	9.4 (4.03)
5NN	PUR	10,000	14.7 (6.22)	11.7 (2.54)
9NN	PVAc	0	15.8 (5.72)	12.1 (2.09)
9NN	PVAc	10,000	14.2 (4.13)	11.9 (2.22)
9NN	PUR	0	12.1 (3.28)	11.3 (1.60)
9NN	PUR	10,000	12.3 (3.85)	12.3 (3.98)

*Values in parentheses are standard deviations

Combination of Non-Densified and Densified Pieces

Table 6 contains a statistical evaluation of factors that affect the shear bond strength. All individual factors and their combined effect were statistically significant (P <0.05; Table 6).

Table 6. Statistical Evaluation of the Shear Bond Strength for Combinations of Densified and Non-Densified Pieces

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F - test	*p*-value
Intercept	31,136.12	1	31,136.12	3,208.876	0.001
Pieces combination (1)	835.49	11	75.95	7.828	0.001
Wood species (2)	434.14	1	434.14	44.742	0.001
Glue type (3)	59.83	1	59.83	6.166	0.013
Number of cycles (4)	39.54	1	39.54	4.075	0.044
1*2*3*4	296.89	11	26.99	2.782	0.002
Error	3,726.00	384	9.70		

As in the previous case of the combination of non-densified pieces, in the combination of densified and non-densified pieces the shear bond strength was higher in beech wood than in aspen wood (Fig. 8). The average value for the glued wood consisting of beech pieces was 26.8% higher than in aspen pieces.

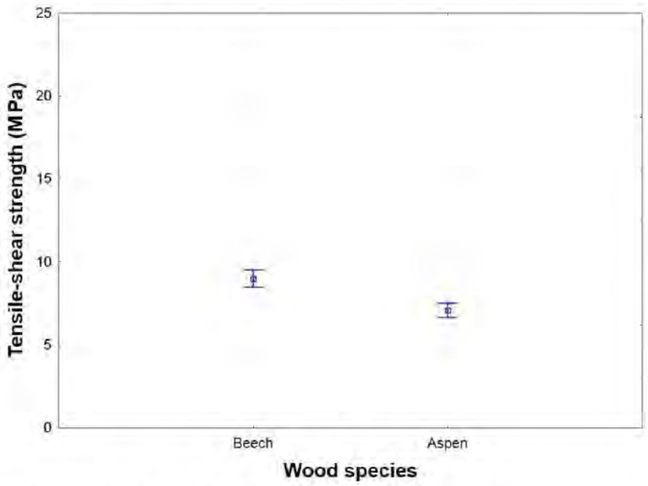

Fig. 8. Influence of wood species on tensile-shear strength

The type of adhesive used had an opposite effect on the shear bond strength (Fig. 9) than in the combination consisting only of non-densified pieces. The shear bond strength of the wood glued with PUR glue was 9.1% higher than that with PVAc glue. The smoother surface of the pieces, as a result of densification, had a positive effect on the adhesion of the glue. The works of Özçifçi (2006), Özçifçi and Yapici (2008), as well as Frihart and Hunt (2010) confirm that higher surface smoothness increases the shear bond strength of wood.

Figure 10 shows the shear bond strength for different combinations of non-densified and densified pieces. Based on the course of the curves in the graph, it can be concluded that the combination of only densified pieces exhibits the greatest differences in shear bond strength values.

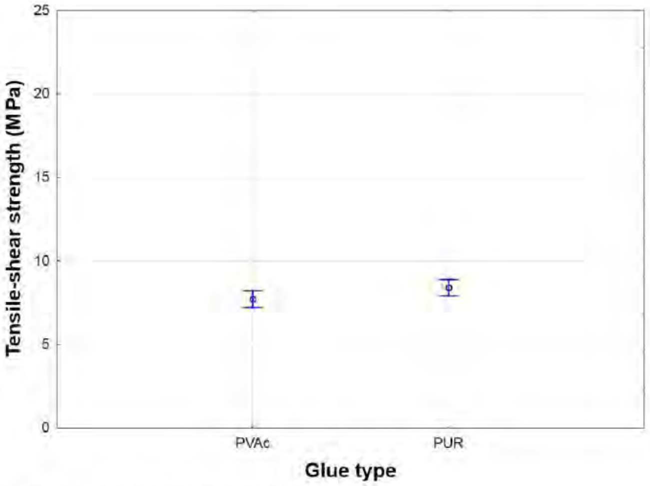

Fig. 9. Influence of glue type on tensile-shear strength

Paradoxically, the glued wood consisting of pieces densified by 20% achieved lower shear bond strength values in all cases, whereas the thickness of the individual pieces had no significance. However, glued wood consisting of densified and non-densified pieces showed smaller differences, and as the thickness of the pieces increased, there was a gradual increase in the shear bond strength.

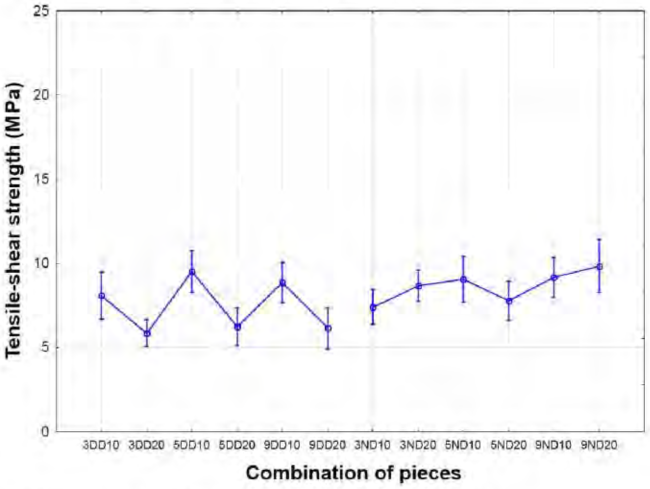

Fig. 10. Influence of piece combination on tensile-shear strength

Although cyclic loading was a statistically significant factor, its probability $P < 0.04$ was close to $P < 0.05$. Based on this result, it can be concluded that the number of cycles had the smallest effect on the shear bond strength of all the factors. The shear bond strength of the glued wood subjected to cyclic loading was 7.4% higher than that of wood without cyclic loading (Fig. 11).

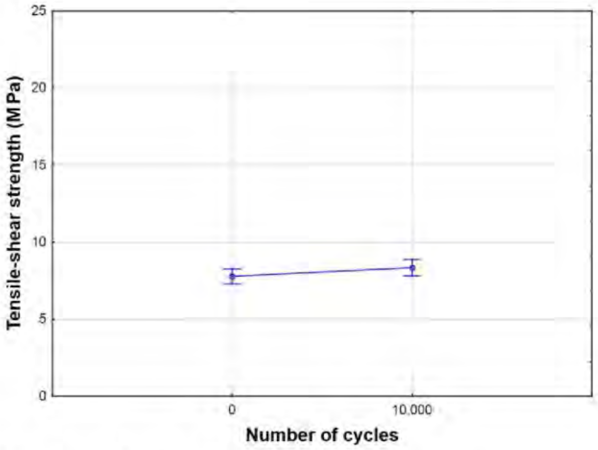

Fig. 11. Influence of number of cycles on tensile-shear strength

The assessment of the effect of all the factors on the SBS of wood not subjected to cyclic loading is shown in Fig. 12. The glued wood consisting of both wood species did not achieve a clear trend in SBS values for any combination of densified and non-densified pieces. A clear dependence on the piece thickness or their combination in terms of densification was not confirmed. The use of PUR glue resulted in greater fluctuations in SBS values in beech wood. These results confirmed the assumption that the glued beech wood achieved higher SBS values than the aspen wood with the use of both types of adhesives.

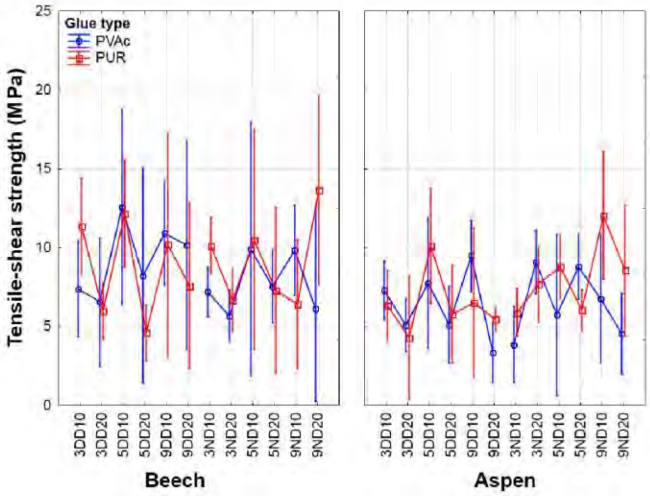

Fig. 12. Influence of piece combination, glue type, and wood species on the tensile-shear strength without cyclic loading

The effect of the combination of all the factors (wood species, glue type, combination of pieces, and cyclic loading) on the SBS is shown in Fig. 13. In this case, there were greater differences between the combinations of densified and non-densified pieces in glued beech wood. Glued wood consisting of both densified and non-densified pieces achieved significantly higher SBS values but a dependence on the piece thickness was not confirmed in compariosn with the combination of densified pieces. Glued beech wood without cyclic loading also achieved higher SBS values than those of aspen wood. The SBS of aspen wood did not have a definite dependence on the combination of pieces or their thickness in any of the cases.

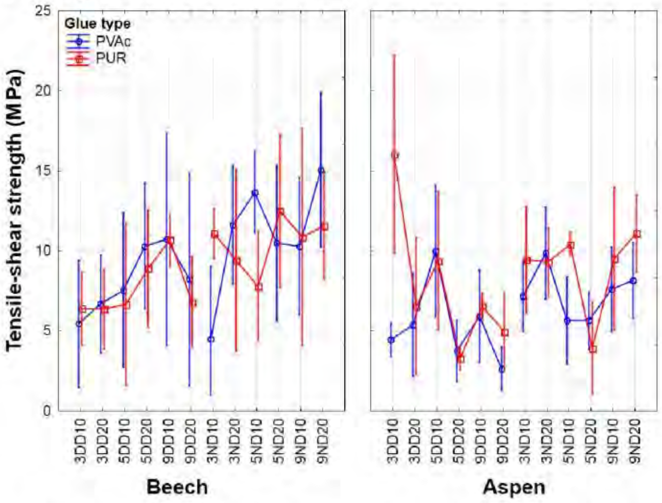

Fig. 13. Influence of piece combination, glue type, and wood species on the tensile-shear strength after cyclic loading by 10,000 cycles

The SBS values obtained have some similarities with other studies (Table 7) as stated previously. Similar values were reported by Özkaya *et al.* (2015), who found the SBS value of 8.1 MPa in beech LVL glued with PVAc glue. Slightly higher values were found by Kläusler *et al.* (2014), who reported an SBS value of 12.5 MPa for beech wood glued with single-component PUR glue. Shukla and Kamden (2008), who studied LVL consisting of thin aspen veneer and PVAc glue, found SBS values in the range of 2.1 to 3 MPa. In this case, the densification of the pieces played a certain role in the results, which was most clearly demonstrated in the gluing of the pieces densified by 20%. The combination of densified and non-densified pieces balanced the SBS values of the glued wood. Similar studies indicate that densification has no significant effect on SBS values. For example, Kurowska *et al.* (2010) found that densification of veneers has no significant effect on the SBS value of plywood glued with UF glue.

Wood, as a natural heterogeneous material, is affected by many factors during gluing. The quality of the adhesive bond depends primarily on the properties of the wood, as well as the gluing parameters. One of the most basic wood properties, that affect the gluing process, is density. Generally speaking, the shear bond strength increases along with the density. However, increasing density requires higher compression pressure, depending on the surface flatness. Hardwood species with higher density require a smoother surface for bonding, while softwood species require a rougher surface. Excessive compression pressure has a negative effect, because it densifies the wood and pushes the glue out of the glue line (Seldiačik and Sedliačik 2000). Densification or pressing of wood can eliminate surface roughness to a certain extent, but it also causes a decrease in the wood's porosity (Schneider and Wagner 1974, Patyakin et al. 2008, Plötze and Niemz 2011), which limits the ability of the adhesive to bind to its surface.

Table 7. Mean Values of the Tensile-shear Strength for Combinations of Densified and Non-Densified Pieces

Combination of Pieces	Tensile-Shear Strength (MPa)		Glue Type	Number of Cycles	Tensile-Shear Strength (MPa)		Combination of Pieces
	Beech	Aspen			Beech	Aspen	
3DD10	7.4 (2.44)	7.4 (1.51)	PVAc	0	7.2 (1.26)	3.8 (1.93)	3ND10
3DD10	5.4 (3.19)	4.5 (0.84)	PVAc	10,000	4.5 (4.44)	7.2 (1.74)	3ND10
3DD10	11.4 (2.43)	6.3 (1.82)	PUR	0	10.1 (1.42)	5.9 (1.22)	3ND10
3DD10	6.4 (1.84)	16.0 (4.97)	PUR	10,000	11.1 (1.26)	9.4 (2.67)	3ND10
3DD20	6.6 (3.27)	5.1 (1.33)	PVAc	0	5.7 (1.30)	9.1 (1.64)	3ND20
3DD20	6.7 (2.45)	5.4 (2.60)	PVAc	10,000	11.6 (2.99)	9.9 (2.31)	3ND20
3DD20	6.0 (1.43)	4.3 (3.13)	PUR	0	6.7 (1.60)	7.7 (1.92)	3ND20
3DD20	6.4 (1.99)	6.6 (3.42)	PUR	10,000	9.4 (4.57)	9.3 (1.73)	3ND20
5DD10	12.6 (4.97)	7.8 (3.31)	PVAc	0	9.9 (6.47)	5.7 (4.15)	5DD10
5DD10	7.6 (3.87)	10.0 (3.32)	PVAc	10,000	13.7 (2.05)	5.7 (2.19)	5DD10
5DD10	12.2 (2.70)	10.1 (2.93)	PUR	0	10.5 (5.61)	8.8 (1.62)	5ND10
5DD10	6.7 (4.07)	9.4 (3.46)	PUR	10,000	7.8 (2.77)	10.4 (0.58)	5ND10
5DD20	8.2 (5.48)	5.1 (1.96)	PVAc	0	7.5 (1.84)	8.8 (1.63)	5ND20
5DD20	10.3 (3.17)	3.7 (1.53)	PVAc	10,000	10.5 (3.91)	5.7 (1.46)	5ND20
5DD20	4.6 (1.42)	5.8 (2.49)	PUR	0	7.3 (4.21)	6.0 (1.05)	5ND20
5DD20	8.9 (2.95)	3.3 (0.60)	PUR	10,000	12.5 (3.85)	3.9 (2.29)	5ND20
9DD10	10.9 (2.65)	9.5 (1.83)	PVAc	0	9.8 (2.27)	6.7 (3.24)	9ND10
9DD10	10.7 (5.36)	5.9 (2.30)	PVAc	10,000	10.3 (3.46)	7.6 (2.11)	9ND10
9DD10	10.2 (5.67)	6.5 (3.82)	PUR	0	6.4 (3.29)	12.0 (3.26)	9ND10
9DD10	10.7 (1.31)	6.5 (0.65)	PUR	10,000	10.8 (5.46)	9.5 (3.59)	9ND10
9DD20	10.2 (5.32)	3.3 (1.51)	PVAc	0	6.1 (6.75)	4.6 (2.05)	9ND20
9DD20	8.2 (5.34)	2.6 (1.08)	PVAc	10,000	15.1 (3.88)	8.2 (1.91)	9ND20
9DD20	7.6 (4.24)	5.5 (0.58)	PUR	0	13.7 (4.82)	8.6 (3.34)	9ND20
9DD20	6.8 (2.26)	4.9 (1.98)	PUR	10,000	11.6 (2.70)	11.1 (1.94)	9ND20

Values in parentheses are standard deviations
3, 5, and 9 are the original thicknesses of the pieces in millimeters

The outer and inner surface of the wood is considered. The outer surface, which consists of the wood's anatomical structure (porosity, differences between spring and summer wood, the width of annual rings, etc.), and the type of machining tool, is measured by the surface roughness and waviness. The surface roughness of the wood is strictly dependent on the method of processing. A milled surface does not require high pressure for gluing in order to achieve higher shear bond strength. In a sanded surface, the higher the compression pressure, the higher the shear strength. The inner surface is the set of all capillary cavities from wood fiber lumens, the spaces between the fibrils and submicroscopic areas between microfibrils and micelles (Sedliačik and Sedliačik 2000). The wood surface affects the penetration of the adhesive into its structure, and therefore the adhesion between the wood and the glue.

Based on these facts, it is important to further examine the various effects on the interaction between wood and glue. It is necessary to examine wood as an adherend with certain anatomical properties (porosity, surface roughness, waviness) and changes to these properties through technological operations (densification, machining, modifications) based on the properties of the adhesive and gluing parameters.

CONCLUSIONS

1. In general, glued wood consisting only of non-densified pieces achieved higher SBS values in both wood species. As expected, higher SBS values were found in glued beech wood. However, statistical probability was only confirmed for the pieces combination ($P > 0.04$), where there was a slight increase in SBS values as the piece thickness increased. The other factors had no significant effect on the SBS. The difference in the SBS between PUR and PVAc glue was only 1.7% in the favor of PVAc. The comparison of SBS values of glued wood subjected to cyclic loading and wood not subjected to cyclic loading showed a difference of only 1.1%.
2. Glued wood consisting of a combination of densified and non-densified pieces had lower SBS values. All the factors were statistically significant. The SBS of glued beech wood was 26.8% higher than that of aspen wood. The combination of non-densified and densified pieces achieved lower SBS values than those of glued wood consisting only of densified pieces. PUR glue ensured 9.1% higher SBS as compared to PVAc glue, which was the opposite of the trend as in the previous variant (combination of NN pieces). Cyclic loading of glued wood increased the SBS by 7.4% compared to wood not subjected to cyclic loading.

ACKNOWLEDGMENTS

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9.4 Článek číslo 4., Deflection of Densified Beech and Aspen Woods as a Function of Selected Factors

Deflection of Densified Beech and Aspen Woods as a Function of Selected Factors

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Effects of selected factors (wood species (Beech, Aspen), degree of densification (10%, 20%), material thickness (4 mm, 6 mm, 10 mm, and 18 mm), and number of loading cycles (0, 10,000)) were analyzed relative to the bendability of densified wood. The monitored characteristics were the deflection at proportional limit (Y_E), deflection at maximum limit (Y_P), and their ratio (Y_E:Y_P). One of the main causes of unfavorable wood bending is its low deflection under tensile stress parallel to the fiber in comparison to compressive stress in the same direction. From the results it is clear that the deflection at the proportionality limit depended on all monitored factors. The deflection at the yield point was not influenced by cyclic loading, and the ratio of deflection was influenced by material thickness only. Based on this ratio, the moulding properties of material can be identified. There was a strong correlation between the two deflection limits. The results are an important foundation for progress in the production of laminated materials with specific properties for intended use.

Keywords: Cyclic loading; Laminated wood; Bending strength; Modulus of elasticity; Elasticity deflection at proportional limit; Deflection at maximum limit; Ratio of elastic and maximum deflection

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INTRODUCTION

Wood is a flexible, strong, and yet lightweight material that has good thermal insulation properties, can bear heavy loads, absorb vibrations, and is easily machined with cutting tools (Efe *et al*. 2007). When evaluating the technical characteristics of furniture, the strength, stability, functionality, durability, and quality of each piece of furniture is primarily assessed (Gaff *et al*. 2017).

This article considers selected indicators of the bending strength of wood, the knowledge of which is essential to expand the possibilities of its use in bentwood furniture. For this reason, it is necessary to obtain theoretical knowledge of the positive and negative factors that affect the bending of densified wood.

There has been minimal in-depth research on the bending strength of densified wood conducted in the past, as well as a lack of knowledge of the behavior of the components in the process. The respective knowledge could bring additional technical, technological, and economical benefits. The efficiency of bentwood furniture production is improved with the use of low-grade wood compared to the currently used species, and by the omission of certain technological steps (steaming) in the bending process (Wagenführ 2000; Blomberg *et al*. 2005; Kamke 2006; Boonstra and Blomberg 2007).

Wood properties can be altered chemically, physically, and mechanically, as well as a combination of those methods (Gaff *et al*. 2015a). This article investigates a densification of wood in the radial direction and subsequent bending. Bending is a non-cutting method of shaping wood based on its ability to deform plastically (Sandberg and Navi 2007). The shape is changed by external forces, causing deformation in materials (Schellberg 2012). These deformations are very small in wood with standard processing for furniture that has a moisture content of 8% ± 4% and a temperature of 20 °C. Wood deformability can be significantly increased by plasticizing the wood (Glos *et al*. 2004) *via* higher humidity and temperature to achieve plasticity of the material for the time necessary for bending. Chemical treatments to promote bending have not found a wider application due to ecological and economic reasons (Wagenfuhrer *et al*. 2006; Gaff *et al*. 2015b; Gaff *et al*. 2015c; Gaff *et al*. 2016). There are two primary bending methods typically used. Shaping that uses the moulding form (free bending) is used for shaping parts with a slight bend. Bending is based on the principle patented in 1841 by M. Thonet, on changing the wood properties by plasticizing it and the effect of frontal pressure, using a bending strap that improves the formability of the wood and enables bending with smaller bend radii (Frese and Blaß 2006). Previous authors (Sandberg and Navi 2007; Fortino *et al*. 2013; Laine *et al*. 2014) have indicated that densification improves the mechanical properties of wood. However, the effect of densification on the bendability of wood is unknown. In bending, the neutral layer is moved to the side with higher stiffness (modulus of elasticity MOE) (Fortino *et al*. 2013). However, densification is not uniform across the cross-section. The density of the densified wood typically decreases from the surface layers to the central ones. Increasing the density of the surface layers and therefore increasing the stiffness could theoretically lead to increased flexibility. The main advantage of bending, in comparison with injection molding of parts, is primarily the substantially higher stiffness and strength of bent parts. The parallel course of fibers is maintained in bending, and it does not result in a complicated grain pattern as it does in molding. Wood bending is also associated with a higher yield from the wood, classifying this technology as waste-free (Gaff *et al*. 2017).

Wood bendability is a feature that characterizes its bending potential. It can be expressed by various characteristics, such as the size of elastic deflection (deflection at the proportional limit- Y_E), the level of maximum deflection (deflection at the maximum limit- Y_P), the coefficient of bendability (ratio of the thickness of the bent material h to the minimum bending radius r- has a more practical nature), or the ratio of elastic and maximum deflection and stress (Y_E:Y_P). Each of these characteristics has its advantages and highlights a specific purpose of the future use of the material.

Knowledge on the bendability of densified wood is modest. Thus, this study focused on the analysis of its essential characteristics, such as the size of elastic deflection and the size of maximum deflection.

Elastic deflection shows the material's ability to deform under external mechanical forces and return to its original state after their removal (Požgaj *et al*. 1997). Maximum deflection is the deflection at the modulus of rupture. Part of this deflection remains after the removal of the mechanical force and the material takes a new shape (Yamashita *et al*. 2009). In practical terms, the maximum limit during bending shows the deflection size that the material can be exposed to without causing permanent deflection.

With the ratio of the characteristics described above, namely the deflection at the proportional limit and deflection at the maximum limit, the material can be assessed. When the beam (panel) is loaded by bending, the bending moment causes deformation and the shape of the bent beam is changed (Fig. 1). The resulting deformation is the result of stresses over the cross-section of the beam.

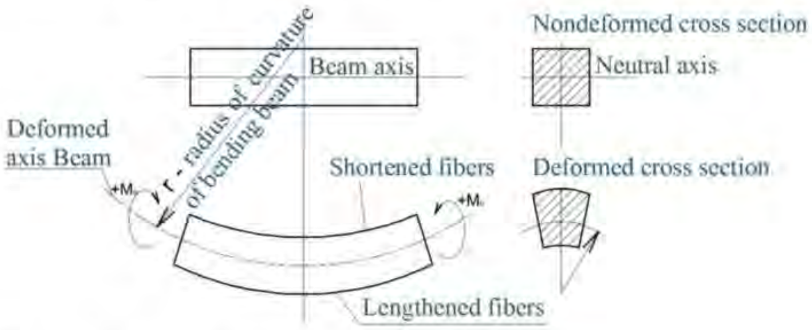

Fig. 1. Deformation of beam loaded by bending moment

However, the size of the deformation achieved through the loading of the beam may not be the same in different materials (M1, M2), or in materials with various treatments (*e.g.*, plasticized and nonplasticized wood, densified and non-densified, *etc.*). In this case, identical load-stress (σx) can result in different deformation of the materials (Y_{E1}, Y_{E2}, Y_{P1}, Y_{P2}), and varying degrees of deformation in materials with different treatments may result in an equal stress. The difference in deformation (bending) caused by stress in these materials is reflected in their linear (elastic), and non-linear (plastic) region (Fig. 2). In material molding the objective is to achieve the highest proportion of plastic deformation, which is why materials with a high proportion of plastic deformation (bending), or ductile materials, are suitable from this point of view (Fig. 2). With an increase of plastic bending in relation to elastic bending, the resulting ratio decreases. The lower the achieved percentage ratio, the greater the proportion of plastic deformation. The ratio increases with a decrease in plastic deformation in relation to elastic deformation. Such materials are characterized by a higher capacity to resist elastic deformation, elastic material, and are also characterized by a low ductile capacity in the plastic region, making them unsuitable for molding, or so-called fragile materials.

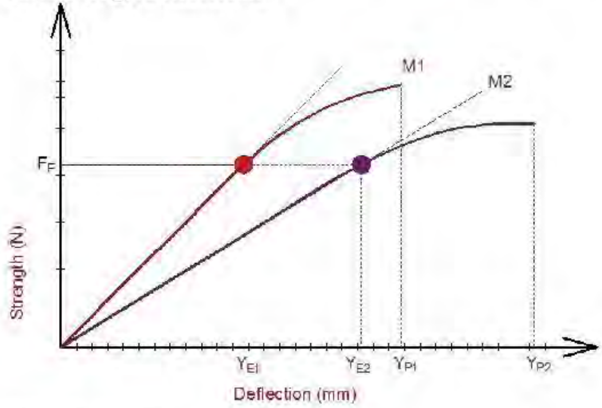

Fig. 2. Deformation of beam under bending moment

Another good example is the stress-strain diagram of the beam subjected to bending (Fig. 3) in an unmodified state (M1) and after plasticization (M2). The figure shows that the proportion of plastic deformation (D) increased several fold due to the effect of plasticization in relation to wood that was not plasticized (C). The increase in the proportion of plastic deformation implies that the material is suitable for molding.

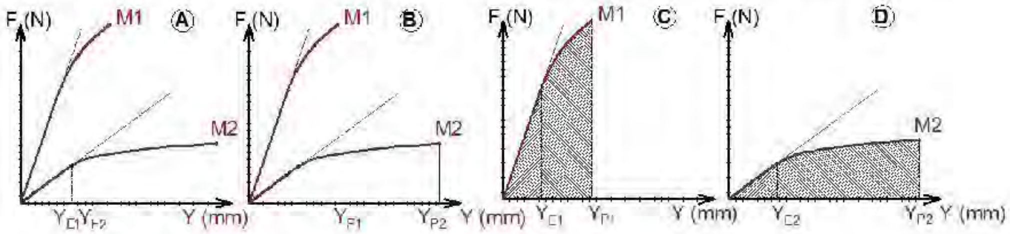

Fig. 3. Deformation of beam under bending moment

Based on the ratio of deformations, the properties of the material can be determined for its further use. Materials with a low deformation ratio are suitable for the purposes of molding. Materials with a high proportion of elastic deformation have the capacity to withstand high levels of stress in the elastic region.

The objective of this study was to assess the properties of these materials based on the knowledge given above, with regard to their future application in the production of wood-based materials and non-wood components. These innovations in increasing process efficiency guarantee knowledgeable decisions represented by innovative wood products. These research results can improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

EXPERIMENTAL

Materials

European beech (*Fagus sylvatica* L.) and aspen (*Populus tremula* L.) wood from the Polana region in Slovakia was used as the test specimens.

Wood species with the dimensions of 4 mm, 6 mm, 10 mm, and 18 mm thickness, 35 mm width and 600 mm length were prepared from the selected wood species. The samples were conditioned to the moisture content of 8% in a climate chamber Binder (ED, APT Line II; Binder, Tuttlingen, Germany) with 40% relative humidity and temperature of 20 °C. For these test specimens, the impact of selected factors (wood species, degree of densification, material thickness, and number of loading cycles) on the monitored characteristics was analyzed before cyclic loading (number of cycles = 0) and after cyclic loading (number of loading cycles = 10,000). For the study, Y_E is the deflection at the proportional limit, Y_P is the maximum deflection, and $Y_E{:}Y_P$ is the ratio of deflections.

The results were compared with results measured on test specimens that were subjected to 10% to 20% densification. Ten test samples were used for each set of test specimens.

Methods

Densification of test specimens

The test specimens that were intended for densification were pressed in a hydraulic press (RK Prüfsysteme MFL 1000, Keyx, Leipzig, Germany). The temperature during densification was 20°C, and the time after pressing was 48 hours.

The values of spring back deformation were measured and will be evaluated separately in the part devoted to rheology.

The densification process of each set of test specimens is shown in Table 1.

Table 1. Compressive Load on Each Set of Test Specimens

Specimen Thickness (mm)	Densification 10%		Densification 20%	
	Beech (kN)	Aspen (kN)	Beech (kN)	Aspen (kN)
4	3550	1080	3950	1500
6	2100	1850	3900	2100
10	3750	2150	4500	2500
18	3650	1720	3680	1800

Determination of values of bending characteristics

After the cyclic loading, the support span was adjusted to L1 = 20 × h ; the support span was changed in relation to the thickness of specimens. The samples were bent using 3-point bending with a universal testing machine FPZ 100 (TIRA, Schalkau, Germany) in accordance with EN 310 (1993). The bending characteristics were measured perpendicular to the fibers in radial direction; the tests were carried out according to the standard EN 310 (1993).

The loading speed was set to 3 mm/min so that the test duration would not exceed 2 min. Maximum breaking forces of samples were measured using the data logger ALMEMO 2690-8 (Ahlborn GmbH, Braunschweig, Germany).

Evaluation and calculation

To determine the effect of the individual factors on the bending characteristics, an analysis of variance (ANOVA) and the Fischer F-test were performed using Statistica 12 (Statsoft Inc., Tulsa, USA) software. The wood density was determined before and after testing according to ISO 13061-2 (2014) and Eq. 1,

$$\rho_w = \frac{m_w}{V_w} \tag{1}$$

where ρ_w is the density (kg*m^{-3}) of the sample at moisture content w (%), m_w is the mass of the sample (kg) at moisture content w (%), and V_w is the volume of the sample (m^{-3}) at moisture content w (%).

The moisture content of the samples was determined and verified before and after testing. These calculations were performed according to (ISO 13061-1 2014) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{2}$$

where w is the moisture content (%) of the samples, mw is the mass of the sample (g) at moisture content w (%), and m_0 is the mass of the oven-dry sample (g). Drying to an oven-dry state was also performed according to ISO 13061-1 (2014).

Next, the deflection at the proportional limit in static bending was determined in accordance with EN 310 (1993). First, limit of proportionality from the force-deflection diagram was determined. The limit of proportionality was on the end of the linear part of the curve. The deflection at the maximum limit corresponds to the deflection at the modulus of rupture. Deflection at the maximum limit and deflection at the proportionality limit was determined from the stress-strain diagram recorded in the bending of test specimens.

Cyclic bend loading

The cyclic loading was performed on a cycler machine with cyclic bending of the test pieces using single-axis loading. The following numbers of cycles were selected for testing: 0 and 10,000. During the preliminary experimental testing, the specimens were loaded with static bending to determine the breaking strength and proportionality limit because the test pieces had to be loaded up to 90% of the proportionality limit.

RESULTS AND DISCUSSION

Deflection at the Limit of Proportionality and at the Maximum Limit

Based on the values of the level of significance *P* and the results of Fisher's F-test, the authors can conclude that each of the monitored factors and their mutual interaction were shown to have a statistically significant effect (Table 2). The respective model explains approximately 92% of the total sum of squares. Table 3 shows the average values of the monitored characteristics, average density values measured for each set of test specimens, and the corresponding coefficient of variation.

Table 2. Statistical Evaluation of the Effect of Factors and their Interaction on Deflection at the Limit of Proportionality

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	3962.363	1	3962.363	15373.74	***
1) Wood species "WS"	22.605	1	22.605	87.71	***
2) Material thickness "MT"	460.795	3	153.598	595.95	***
3) Degree of densification "DOD"	1.686	2	0.843	3.27	***
4) Number of cycles "NC"	2.216	1	2.216	8.60	***
WS * MT	9.951	3	3.317	12.87	***
WS * DOD	7.306	2	3.653	14.17	***
MT * DOD	6.651	6	1.108	4.30	***
WS * NC	1.443	1	1.443	5.60	***
MT * NC	9.982	3	3.327	12.91	***
DOD * NC	2.573	2	1.286	4.99	***
WS * MT * DOD	7.418	6	1.236	4.80	***
WS * MT * NC	3.550	3	1.183	4.59	***
WS * DOD * NC	0.460	2	0.230	0.89	NS
MT * DOD * NC	7.526	6	1.254	4.87	***
1*2*3*4	4.382	6	0.730	2.83	***
Error	49.485	192	0.258		

NS- not significant, *** - significant P < 0.01

Table 3. Average Values of Bending Characteristics, Density, and Coefficient of Variance

Wood Species	Material Thickness (mm)	Degree of Densification (%)	Number of Cycles	Y_E (mm)	Y_P (mm)	Y_E:Y_P (%)	Density (Kg/m^3)
Beech	**4**	**0**	**0**	2.8 (3.4)	4.8 (10.2)	58 (11.5)	693 (4.6)
Beech	**4**	**0**	**10,000**	3.0 (18.2)	4.6 (5.2)	65 (16.6)	680 (9.5)
Beech	**4**	**10**	**0**	2.6 (9.7)	4.8 (3.8)	46 (11.2)	725 (8.6)
Beech	**4**	**10**	**10,000**	2.2 (8.0)	3.7 (7.4)	45 (25.6)	739 (6.6)
Beech	**4**	**20**	**0**	2.7 (3.7)	4.8 (3.3)	38 (26.3)	784 (4.0)
Beech	**4**	**20**	**10,000**	2,0 (16.1)	3.8 (8.8)	54 (10.7)	766 (4.7)
Beech	**6**	**0**	**0**	3.5 (6.8)	7.6 (11.2)	36 (16.3)	665 (3.4)
Beech	**6**	**0**	**10,000**	3.1 (19.1)	7.0 (7.0)	37 (17.0)	692 (4.4)
Beech	**6**	**10**	**0**	3.2 (15.3)	7.2 (12.9)	55 (10.0)	703 (4.8)
Beech	**6**	**10**	**10,000**	3.6 (6.9)	7.3 (12.3)	60 (9.7)	749 (5.0)
Beech	**6**	**20**	**0**	2.5 (17.6)	6.7 (16.6)	45 (17.8)	751 (5.6)
Beech	**6**	**20**	**10,000**	3.7 (5.2)	7.6 (10.8)	49 (13.0)	750 (5.3)
Beech	**10**	**0**	**0**	4.4 (14.4)	12.0 (15.7)	42 (25.0)	694 (4.7)
Beech	**10**	**0**	**10,000**	5.1 (3.4)	9.6 (9.0)	49 (10.0)	690 (5.8)
Beech	**10**	**10**	**0**	4.8 (4.1)	11.9 (18.6)	38 (17.4)	733 (3.7)
Beech	**10**	**10**	**10,000**	7.4 (25.7)	14.9 (17.3)	33 (18.8)	719 (5.6)
Beech	**10**	**20**	**0**	4.6 (6.7)	11.7 (13.2)	55 (4.2)	788 (3.5)
Beech	**10**	**20**	**10,000**	5.1 (4.0)	10.5 (2.1)	53 (9.3)	726 (2.5)
Beech	**18**	**0**	**0**	6.6 (17.9)	18.3 (16.6)	38 (17.0)	735 (8.1)
Beech	**18**	**0**	**10,000**	6.3 (9.3)	17.2 (7.6)	49 (13.6)	698 (8.2)
Beech	**18**	**10**	**0**	6.4 (6.3)	17.5 (17.4)	40 (14.9)	744 (3.9)
Beech	**18**	**10**	**10,000**	6.4 (3.9)	19.6 (17.2)	48 (4.4)	749 (4.6)
Beech	**18**	**20**	**0**	6.2 (3.5)	18.9 (15.7)	34 (18.4)	747 (6.8)
Beech	**18**	**20**	**10,000**	6.7 (5.0)	25.4 (12.3)	27 (15.9)	757 (8.6)

Values in parentheses are coefficients of variation (CV) in %

Wood Species	Material Thickness (mm)	Degree of Densification (%)	Number of Cycles	Y_E (mm)	Y_P (mm)	Y_E:Y_P (%)	Density (Kg/m^3)
Aspen	**4**	**0**	**0**	2.4 (8.2)	4.7 (15.6)	53 (9.9)	400 (4.1)
Aspen	**4**	**0**	**10,000**	1.5 (19.4)	3.3 (13.5)	45 (12.8)	416 (8.4)
Aspen	**4**	**10**	**0**	2.2 (6.2)	5.0 (17.9)	53 (19.3)	421 (9.3)
Aspen	**4**	**10**	**10,000**	1.7 (47.0)	3.6 (21.1)	51 (16.8)	404 (3.6)
Aspen	**4**	**20**	**0**	2.7 (8.4)	5.7 (7.7)	48 (27.1)	488 (5.7)
Aspen	**4**	**20**	**10,000**	2.9 (27.7)	4.0 (13.1)	48 (36.2)	476 (14.1)
Aspen	**6**	**0**	**0**	3.1 (13.5)	6.0 (13.9)	42 (20.6)	533 (8.7)
Aspen	**6**	**0**	**10,000**	3.1 (13.8)	6.1 (4.7)	32 (14.3)	539 (4.4)
Aspen	**6**	**10**	**0**	2.9 (16.3)	6.1 (6.8)	46 (22.8)	557 (6.6)
Aspen	**6**	**10**	**10,000**	3.4 (9.4)	6.6 (6.8)	47 (48.7)	584 (7.9)
Aspen	**6**	**20**	**0**	2.7 (14.2)	6.8 (14.9)	47 (11.2)	620 (9.6)
Aspen	**6**	**20**	**10,000**	3.5 (2.6)	6.8 (6.7)	52 (12.0)	580 (6.5)
Aspen	**10**	**0**	**0**	3.8 (6.7)	8.2 (21.6)	38 (6.0)	528 (4.2)
Aspen	**10**	**0**	**10,000**	4.0 (13.7)	8.7 (22.2)	45 (23.7)	536 (8.4)
Aspen	**10**	**10**	**0**	3.7 (4.4)	9.8 (6.3)	39 (28.5)	564 (1.3)
Aspen	**10**	**10**	**10,000**	4.2 (6.9)	9.6 (18.5)	35 (20.6)	560 (5.8)
Aspen	**10**	**20**	**0**	4.5 (12.7)	11.2 (15.0)	48 (6.9)	604 (1.8)
Aspen	**10**	**20**	**10,000**	4.3 (9.7)	10.8 (11.7)	74 (27.1)	628 (13.9)
Aspen	**18**	**0**	**0**	5.3 (8.3)	13.1 (25.4)	40 (19.8)	529 (2.1)
Aspen	**18**	**0**	**10,000**	5.0 (9.4)	16.1 (21.9)	52 (5.3)	519 (12.7)
Aspen	**18**	**10**	**0**	5.7 (12.6)	15.5 (29.6)	40 (8.9)	568 (4.8)
Aspen	**18**	**10**	**10,000**	5.6 (5.6)	16.6 (16.5)	40 (17.4)	581 (4.0)
Aspen	**18**	**20**	**0**	5.8 (6.5)	18.4 (8.5)	32 (4.7)	589 (7.0)
Aspen	**18**	**20**	**10,000**	6.1 (4.1)	15.6 (21.2)	40 (19.6)	594 (6.2)

Values in parentheses are coefficients of variation (CV) in %

Based on the results of Duncan's test (Table 4), the factor species was significant at the level P = 0.0001. Densification of 10% showed the effect at the level P = 0.29 in comparison with not densified specimens. Densification of 20% in comparison with 10% was not determined to be significant (P = 0.863). The increase of material thickness showed in all cases statistical significance at the level P = 0.0001. The number of loading cycles was not a significant factor.

Table 4. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Limit of Proportionality

Wood Species		(1) 4.371	(2) 3.7563
1	Beech		0.000
2	Aspen	0.000	

Degree of Densification (%)		(1) 0.021	(2) 0.021	(3) 0.020
1	0		0.029	0.034
2	10	0.029		0.863
3	20	0.034	0.863	

Material Thickness (mm)		(1) 2.3974	(2) 3.1897	(3) 4.6556	(4) 6.0102
1	4		0.000		0.000
2	6	0.000		0.000	
3	10		0.000		0.000
4	18	0.000		0.000	

Number of Cycles		(1) 3.9671	(2) 4.1593
1	0		0.029
2	10000	0.029	

The deflection values at the maximum limit were significantly affected by all of the monitored factors with the exception of cyclic loading, which has shown to be an insignificant factor based on the level of significance P (Table 5). Based on these results, the interaction of all the monitored factors can be considered a combination of statistically significant values affecting deflection at the maximum limit. The nonsignificant interactions were WS * DOD, WS * NC, DOD * NC, WS * MT * NC, and MT * DOD * NC. The respective model explained approximately 92% of the total sum of squares.

The results of Duncan's test of the influence of all factors on the deflection values at the maximum limit are displayed in Table 6. The results show a statistically significant influence of species at the level P = 0.0001. A significant influence was confirmed for a densification of 10% (P = 0.007) and 20% (P = 0.0001). The thickness showed in all cases statistical significance at the level P = 0.0001. The statistical significance of cyclic loading was not proven (P = 0.665).

Table 5. Statistical Evaluation of Factors and their Interaction on Deflection at the Maximum Limit

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	23583.82	1	23583.82	7121.682	***
1) Wood species	160.10	1	160.10	48.346	***
2) Material thickness	6057.26	3	2019.09	609.710	***
3) Degree of densification	71.32	2	35.66	10.769	***
4) Number of cycles	0.62	1	0.62	0.187	NS
WS * MT	108.03	3	36.01	10.874	***
WS * DOD	4.05	2	2.03	0.612	NS
MT * DOD	89.89	6	14.98	4.524	***
WS * NC	6.57	1	6.57	1.985	NS
MT * NC	50.94	3	16.98	5.128	***
DOD * NC	5.86	2	2.93	0.885	NS
WS * MT * DOD	54.53	6	9.09	2.744	**
WS * MT * NC	11.67	3	3.89	1.175	NS
WS * DOD * NC	44.25	2	22.13	6.682	***
MT * DOD * NC	15.07	6	2.51	0.758	NS
1*2*3*4	95.29	6	15.88	4.796	***
Error	635.82	192	3.31		

NS- not significant, *** - significant P < 0.01

Table 6. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Maximum Limit

Wood Species		(1) 10.730	(2) 9.0962
1	Beech		0.000
2	Aspen	0.000	

Degree of Densification (%)		(1) 9.2104	(2) 9.9892	(3) 10.539
1	0		0.007	0.000
2	10	0.007		0.056
3	20	0.000	0.056	

Material Thickness (mm)		(1) 4.4055	(2) 6.8227	(3) 10.739	(4) 17.684
1	4		0.000	0.000	0.000
2	6	0.000		0.000	0.000
3	10	0.000	0.000		0.000
4	18	0.000	0.000	0.000	

Number of cycles		(1) 9.8621	(2) 9.9637
1	0		0.665
2	10000	0.665	

The average deflection values at the limit of proportionality in aspen wood (3.75 mm) were lower compared to beech wood (4.8 mm) by 21.87% (Fig. 4). This was confirmed by the results shown in Table 3, which revealed a statistically significant effect of the wood species on the monitored characteristic. Beech is a typical example of bendable wood; it has long fibers and a uniform width of annual growth rings that predisposes it to achieve higher values of bending at the proportional limit (Higashihara *et al.* 2000). Although aspen is also a porous wood, its fibers are much shorter, which is why it achieved a 22% lower value of bending at the proportional limit.

The average deflection values at the maximum limit (Fig. 4) measured in aspen wood (9.1 mm) were 15.47% lower than the values measured in beech wood (10.8 mm). Again, the higher values measured in beech wood could be attributed to its longer fibers in comparison to the fibers in aspen wood. These results confirmed the results of multiple authors work (Požgaj *et al.* 1997; Wagenführ 2000; Schellberg 2012; Fortino *et al.* 2013).

It can be generally concluded that elastic deflection increased with the increasing material thickness (Fig. 5). The average elastic deflection in material with a 4 mm thickness was 2.4 mm; in material with a thickness of 6 mm an average value of 3.2 mm was recorded, which was 33.33% higher. The average bending value in material with a thickness of 10 mm (4.6 mm) was 91.67% higher than in lamellas with a thickness of 4 mm, and 43.75% higher than in lamellas with a thickness of 6 mm. The highest values of elastic deflection was measured in materials with a thickness of 18 mm. In the above case, the values were 150% higher than in lamellas with a thickness of 4 mm, 87.5% higher than in lamellas with a 6 mm thickness, and 30.43% higher than in lamellas with a 10 mm thickness.

As in the deflection at the proportional limit, the material thickness could also be considered to be a factor that significantly affected the values of deflection at the maximum limit (Fig. 5). It was evident from the above results that deflection at the maximum limit increased with an increase in the material thickness. In material with a thickness of 6 mm 68.29% higher values of deflection at the maximum limit were measured than in materials with a thickness of 4 mm. In material with a thickness of 10 mm the measured values of deflection at the maximum limit (10.8 mm) were 163.41% higher, and in material with an 18 mm thickness (17.9) they were 336.59% higher than in material with a 4 mm thickness.

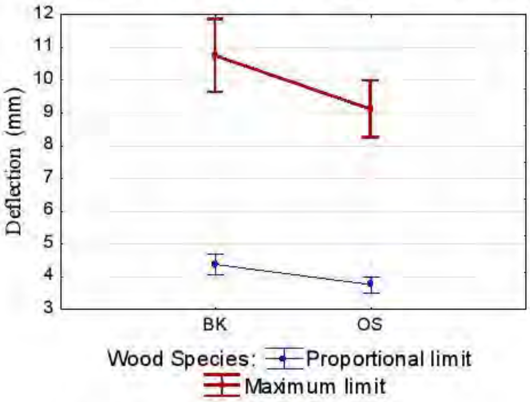

Fig. 4. Effect of the wood species on deflection at the proportional limit and at the maximum limit

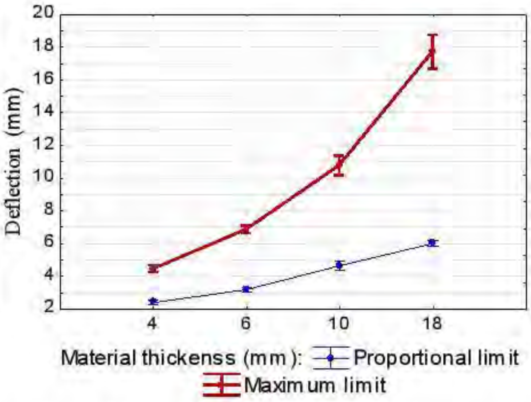

Fig. 5. Effect of the material thickness on deflection at the proportional limit and at the maximum limit

Based on the results, the degree of densification could be considered a moderately significant factor that affected the deflection at the proportional limit (Fig. 6). With 10% and 20% densification, a 9.21% increase in the monitored characteristic was measured in comparison to non-densified wood. There was no statistically significant difference between the average values of the densified wood (10% and 20%). In bending, the neutral layer shifts to the side with the higher stiffness (modulus of elasticity, *E*) (Fortino *et al.* 2013). Increasing the density of surface layers of the wood and therefore increasing the stiffness could theoretically lead to an increase in its bendability.

With the densification of wood, the values of deflection at the maximum limit increased with medium significance (Fig. 6). In comparison with deflection values at the proportional limit (where there was no significant difference between 10% and 20% densification), the monitoring of deflection at the maximum limit showed a medium significant difference between 10% and 20% densification. By a 10% densification a 5.6% to 5.7% increase in density was achieved in both wood species, and the values of the maximum limit increased 7.53% as a result of the densification. By 20% densification of beech wood a 3.6% increase in density was achieved, and in aspen wood an 8.6% increase in density was achieved; the average increase in maximum limit values was 5%.

Due to the effect of cycling loading, the average value of deflection at the proportional limit increased 6.41% in comparison to test specimens that were not subjected to cyclic loading. The authors believe that hydrogen bonds were weakened in the monitored number of loading cycles and the wood became more flexible. As a result the elastic deflection reached higher average values. It is believed that cyclic loading led to the development of plastic deformations, which resulted in a reduction in the nonlinear region. In the results of previous work (Gaff and Gašparík 2015), the cyclic loading (3,000, 6,000, and 7,000 cycles) had no significant effect. The authors expect that with a higher number of loading cycles the difference should be reflected more strongly. The results of previous work indicated that the effect of the monitored number of cycles (10,000) caused an increase in the limit of proportionality and a significant increase in elastic potential, which confirms the current hypothesis about the effect of the monitored number of cyclic loads.

While the assessment of the effect of cyclic loading on deflection at the proportional limit showed that cyclic loading can be considered to be a factor of medium significance (Fig. 7), the assessment of the effect of cyclic loading on deflection at the maximum limit illustrated that this was a factor of low significance (Fig. 7).

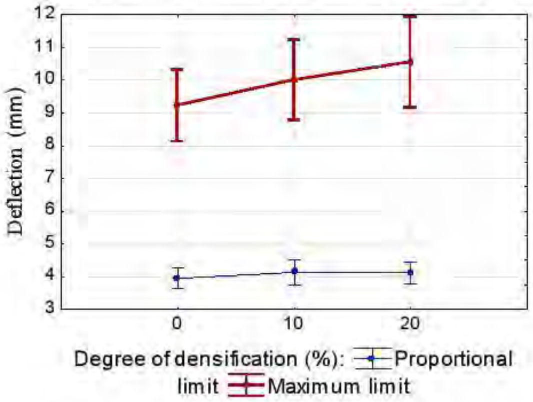

Fig. 6. Effect of the degree of densification on deflection at the proportional limit and at the maximum limit

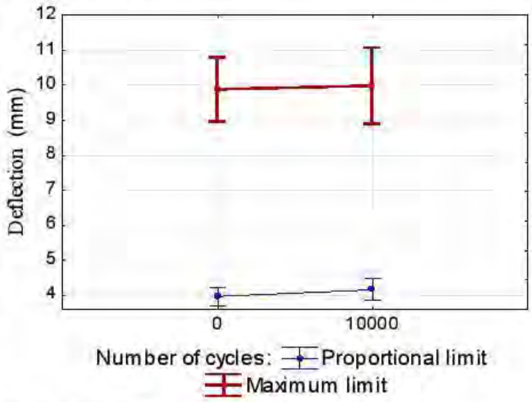

Fig. 7. Effect of the number of cycles on deflection at the proportional limit and at the maximum limit

The results illustrating the synergistic effect of all of the monitored factors suggest that the wood species and material thickness had the most significant impact on the deflection at the proportional limit (Figs. 8 and 9).

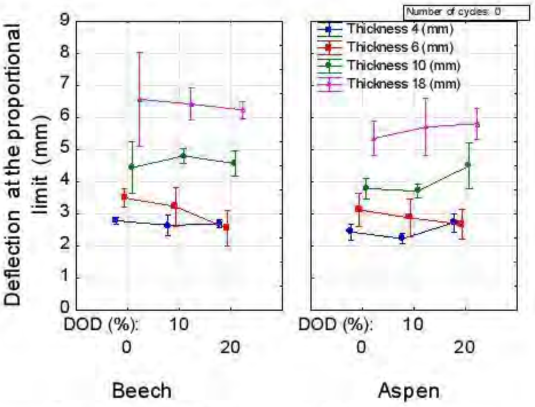

Fig. 8. Synergistic effect of the studied factors on the deflection at the proportional limit

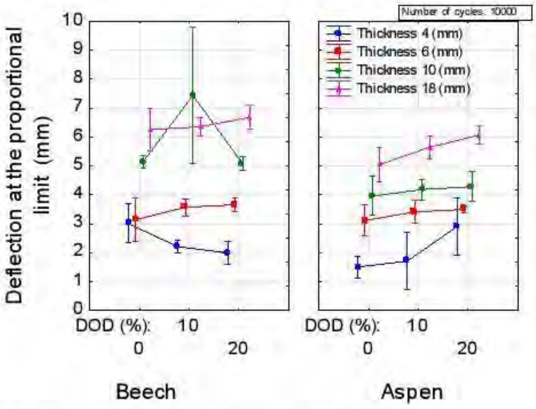

Fig. 9. Synergistic effect of the studied factors on the deflection at the proportional limit

The synergistic effect of all the monitored factors on values of deflection at the maximum limit is shown in Figs. 10 and 11. The values point to the fact that the material thickness, wood species and degree of densification have the most significant effect on the monitored characteristic.

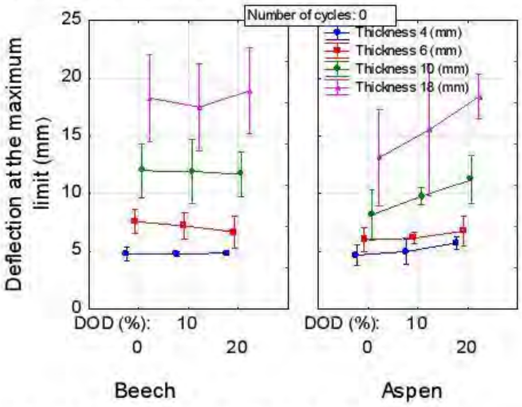

Fig. 10. Synergistic effect of the studied factors on the deflection at the maximum limit

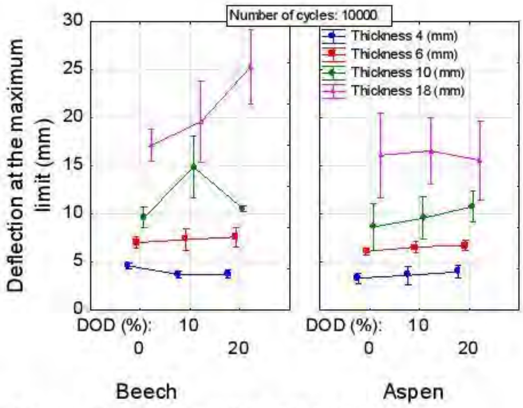

Fig. 11. Synergistic effect of the studied factors on the deflection at the maximum limit

The Ratio of Deflection at the Proportional Limit and at the Maximum Limit

The results of a multi-factor variance analysis evaluating the effect of individual factors and their mutual interaction on the values of the ratio of deflection are shown in Table 7. Based on the results of Fisher's F-test and the level of significance *P*, it can be concluded that only material thickness and number of cycles had a significant effect on the ratio of deflection. The effect of other factors and their interaction was shown to be insignificant.

The interactions WS * DOD, MT * DOD, WS * NC, DOD * NC, WS * MT * NC, and MT * DOD * NC, as well as the interaction of all factors are not significant. The respective model explains roughly 58% of the total sum of squares.

Table 7. Statistical Evaluation of Factors and their Interaction on Ratio of Deflection

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F- Test	Significance Level *P*
Intercept	495717.4	1	495717.4	6695.953	***
1) Wood species	5.6	1	5.6	0.076	NS
2) Material thickness	11604.6	3	3868.2	52.250	***
3) Degree of densification	328.1	2	164.1	2.216	NS
4) Number of cycles	647.5	1	647.5	8.746	***
WS * MT	822.8	3	274.3	3.704	***
WS * DOD	315.2	2	157.6	2.129	NS
MT * DOD	593.3	6	98.9	1.336	NS
WS * NC	3.3	1	3.3	0.045	NS
MT * NC	777.6	3	259.2	3.501	***
DOD * NC	449.6	2	224.8	3.037	NS
WS * MT * DOD	1091.3	6	181.9	2.457	***
WS * MT * NC	320.1	3	106.7	1.441	NS
WS * DOD * NC	963.2	2	481.6	6.505	***
MT * DOD * NC	459.1	6	76.5	1.034	NS
1*2*3*4	865.8	6	144.3	1.949	NS
Error	14214.2	192	74.0		

NS - not significant, *** - significant P < 0.01

The results of Duncan's test (Table 8), confirmed the results shown in Table 7. The species had no influence on the ratio of deflection ($P = 0.783$). A densification of 10% was not statistically significant ($P = 0.130$) and a densification of 20% was close to being insignificant ($P = 0.055$). Cyclic loading significantly influenced the tested property at the level $P = 0.003$.

Table 8. Comparison of the Effects of Individual Factors using Duncan Test on the Values of the Deflection at the Maximum Limit

Wood Species		(1) 45.601	(2) 45.294
1	Beech		0.783
2	Aspen	0.783	

Degree of Densification (%)		(1) 47.052	(2) 44.992	(3) 44.299
1	0		0.130	0.055
2	10	0.130		0.610
3	20	0.055	0.610	

Material Thickness (mm)		(1) 54.833	(2) 47.245	(3) 44.304	(4) 35.408
1	4		0.000	0.000	0.000
2	6	0.000		0.061	0.000
3	10	0.000	0.061		0.000
4	18	0.000	0.000	0.000	

Number of Cycles		(1) 43.805	(2) 47.090
1	0		0.003
2	10000	0.003	

The results evaluating the effect of the wood species on the monitored characteristic are shown in Fig. 12. They confirm the results in Table 5, based on which it can be concluded that the wood species had no significant effect on the monitored characteristic, and the ratio of deflection did not change by the effect of the wood species.

As the material thickness increased, the ratio of deformation significantly decreased (Fig. 13). The results show that the proportion of plastic deformation increased along with the material thickness. Thicker materials were capable of achieving a larger proportion of plastic deformation and were more suitable for shaping by bending. In the bending method, 3-point bending was applied and the shear stress was not taken into account. Greater material thickness with the same width resulted in higher shear stress. Shear stress leads to higher bending values compared to bending measured in pure bending (Esendemir 2009).

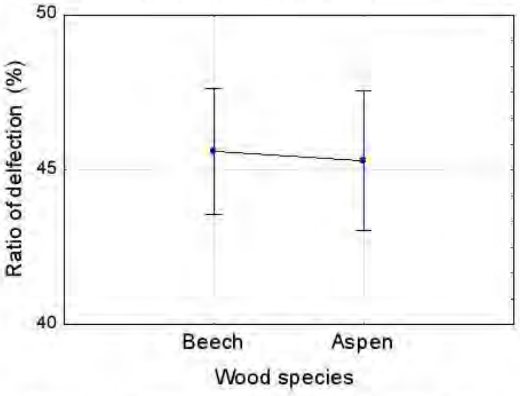

Fig. 12. Effect of the wood species on the ratio of deflection

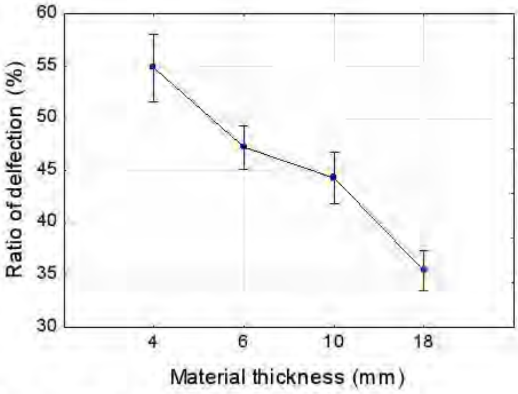

Fig. 13. Effect of the material thickness on the ratio of deflection

The ratio of deformation increased with material thickness. The deformation at the proportional limit increased far more intensively than the deformation at the maximum limit, due to increased material thickness. A thicker material was capable of achieving a large proportion of plastic deformation and was more suitable for shaping with bending. In the 3-point bending that was applied, the shear stress was not taken into account. Greater material thickness with the same width resulted in higher shear stress. Shear stress led to higher deflection values compared to bending measured in pure bending.

Based on the level of significance *P* given in Table 5, the effect of densification could be considered as a factor that significantly affected the ratio of deflection. Figure 14 clearly shows that the ratio of deflection increased with an increase in the degree of densification.

With cyclic loading, a significant increase of the values of elastic deformation in relation to plastic deformation was achieved (Fig. 15), which resulted in an increase in the ratio of deformation. It was most likely possible to achieve higher elastic deformation of material within the monitored range of cyclic loading. In the sets of test specimens not subjected to cyclic loading, the average deflection ratio was 43.6%, whereas in specimens subjected to cyclic loading it was 47%. It was likely that the cyclic loading caused the development of plastic and viscoelastic deformation. For this reason, the plastic deformations in the bending test after cyclic loading were smaller, *i.e.* the deflection ratio increased. Cyclic loading could affect the deflection at the proportional limit and result in an increased proportion of elastic deflection, due to the loosening of hydrogen bonds. The ratio of deformation decreased under cyclic loading, in which plastic and viscoelastic deformations developed. For this reason, the plastic deformations in the bending test after cyclic loading were smaller, *i.e.* the deflection ratio increased. The level of dependence between the deflection at the proportional limit and the deflection at the maximum limit was 90%. The ratio of deflection was 70% at the proportional limit and at the maximum limit only 38%.

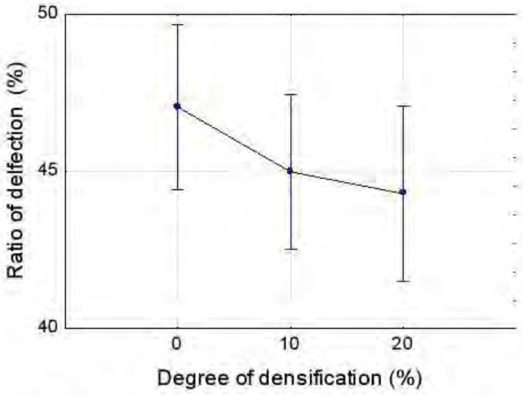

Fig. 14. Effect of the degree of densification on the ratio of deflection

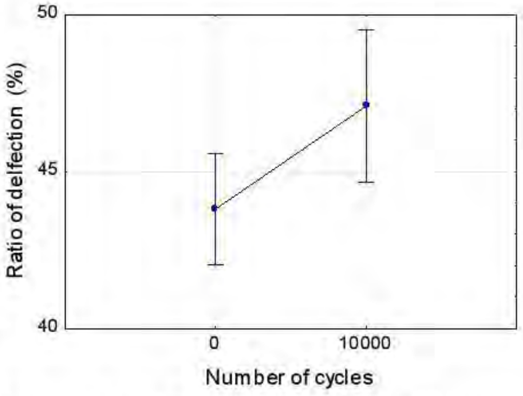

Fig. 15. Effect of the number of cycles on the ratio of deflection

The interaction of the effect of all monitored factors is shown in Figs. 16 and 17. It was apparent that the material thickness had the most significant effect on the monitored characteristic, resulting in an increased deflection ratio.

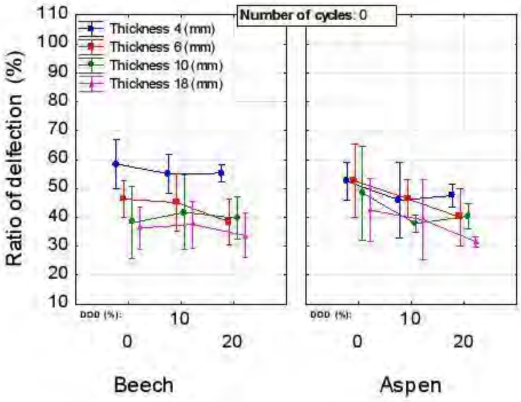

Fig. 16. Synergistic effect of the studied factors on the ratio of deflection

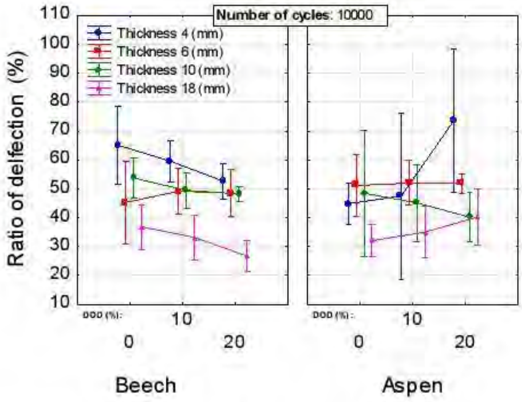

Fig. 17. Synergistic effect of the studied factors on the ratio of deflection

Correlation Analysis

The level of dependence between the deflection at the proportional limit and the deflection at the maximum limit was 91% (Table 9), which indicated a close level of dependence between the monitored characteristics.

The level of significance of the ratio of deflection and deflection at the proportional limit was only 69.5%, which indicated a close level of dependence between the monitored characteristics. The level of dependence between the ratio of deflection and deflection at the maximum limit was 37.7%. It was apparent that the limit of proportionality had a significant effect on this characteristic on the ratio of deflection, whereas the maximum limit had an insignificant effect on this characteristic.

Table 9. Spearman's Correlation

Variable	Y_E (mm)	Y_P (mm)	Y_E:Y_P (mm)
Y_E (mm)	1.000	0.908	-0.694
Y_P (mm)	0.908	1.000	-0.377
Y_E:Y_P (%)	-0.694	-0.377	1.000

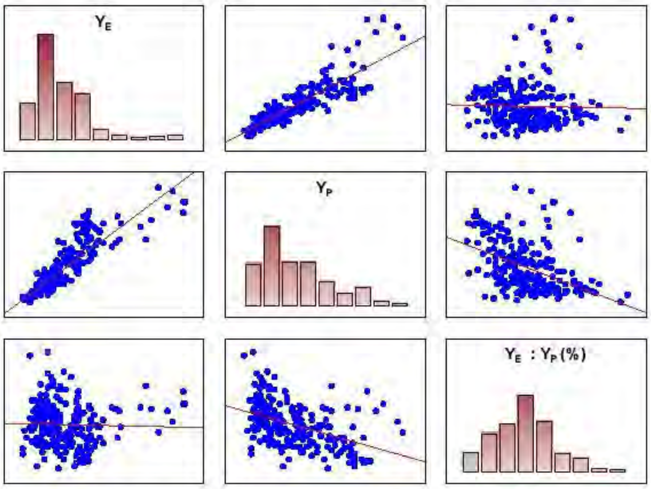

Fig. 18. Correlation matrix of the level of dependence of monitored characteristics

CONCLUSIONS

1. Each of the monitored factors (wood species, material thickness, degree of densification, and number of loading cycles), as well as their synergistic effect significantly affected the deflection at the proportional limit. In wood species with longer fibers, a higher deflection at the proportional limit during bending was achieved. A significant effect of the degree of densification within the monitored parameters was not observed.

2. The effect of the monitored factors on deflection at the proportional limit substantially coincided with the effect of the monitored factors on the deflection at the maximum limit. Only cyclic loading was shown to be insignificant, which had no effect on the deflection at the proportional limit.

3. The ratio of deflection was not affected by the type of material; there was no significant difference between the values measured in beech wood and aspen wood. The ratio of deformation increased with material thickness.
4. The degree of densification also had a significant effect on the monitored characteristic, and in turn the ratio increased significantly.

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9.5 Článek číslo 5., Impact of Selected Factors on the Bending Forces at the Proportionality Limit and Yield Point in Laminated Veneer Lumber

Impact of Selected Factors on the Bending Forces at the Proportionality Limit and Yield Point in Laminated Veneer Lumber

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Knowledge of the force required to overcome deformation at the proportionality limit, yield point, as well as knowledge of the effect of selected factors on the characteristics during bending stress, have scientific and practical significance. They are the basis for designing tools for bending and accurately determining the stresses to which products and their parts may be subjected during use. This study analyzed the effect of selected factors on the selected characteristics, including the forces at the proportionality limit (F_E) and yield point (F_P). The chosen factors of this study were the wood species (*Fagus sylvatica* L. and *Populus tremula* L.), non-wood component (carbon and fiberglass), non-wood component position in the composition matrix (up and down), material thickness (6 mm, 10 mm, and 18 mm), and adhesive used (polyvinyl acetate and polyurethane), as well as their combined interaction. The results contributed to the advancement of knowledge necessary for the study and development of new materials with specific properties for their intended use. The results could improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

Keywords: Product innovations; Laminated wood; Force at the proportionality limit; Force at the maximum limit

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INTRODUCTION

From an environmental point of view, wood is a renewable material, which makes it important. Wood has always been present in the lives of people, and it is still widely used today. A great advantage of wood is its elasticity in relation to its density. However, it is characterized by a low flexibility and difficulty in molding, especially in bigger material sizes. These negative properties motivate the development and application of lamination (Aydın *et al.* 2004).

Wood-based laminated veneer lumber (LVL) materials consist of several components, but the basic component is wood. The composition design and production of LVL materials is primarily geared to the intended use of the material. Therefore, to create LVL, it is necessary to understand the proposed composition under the influence of various factors. The individual layers of this material can be modified or unmodified. The properties of these materials can be monitored and assessed on the basis of a force-deflection diagram, in which the forces required to achieve deflection at the proportionality limit and yield point can be determined (Fig. 1).

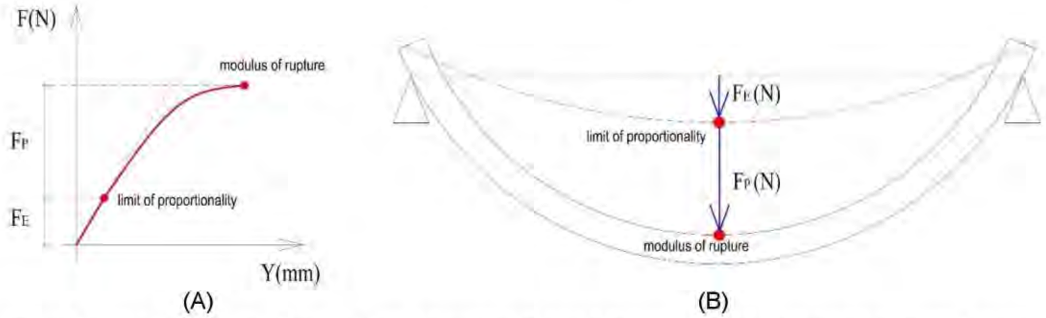


Fig. 1. Force-deflection diagram during bending (A) and determining the proportionality limit and yield point (modulus of rupture) (B) (Svoboda *et al.* 2017)

The force at the proportionality limit F_E can be defined as the force required to achieve deflection at the proportionality limit, and the force at the yield point F_P is characterized as the force required to achieve deflection at the yield point. In a deeper analysis of the force-deflection diagram up to the proportionality limit, it can be found that deflection only causes elastic deformation (Gaff *et al.* 2016; Gaff *et al.* 2017a; Babiak *et al.* 2018; Hýsek *et al.* 2018). Once the proportionality limit has been reached and the external forces are released, the deformation returns to its original state. From this assumption it can be concluded that only elastic deformation occurs and stress is evenly distributed in the wood up to the proportionality limit. Stress above the proportionality limit is no longer even (Požgaj *et al.* 1997) and plastic deformation occurs (Gaff *et al.* 2017b; Gaff and Babiak 2018a,b; Sikora *et al.* 2018).

The strength and stiffness of wood can be increased by combining it with non-wood components based on different materials and also by obtaining adhesive joints (Blomberg and Persson 2007; Corigliano *et al.* 2016). In the 1960s, technologists and manufacturers became interested in improving the mechanical properties of wood, which led to the production of composite fibers. Composite materials include carbon fiber, aramid fiber, basalt fiber, fiberglass, asbestos fiber, polyvinyl alcohol (PVA), and others (Plevris and Triantafillou 1995; Redon *et al.* 2001; Sviták and Ruman 2017). An important factor in the use of these materials, in addition to their mechanical properties, is the location in the laminate material composition (Mosallam 2016). Experimental research has shown that by correctly locating the non-wood component on the stressed tensile zone, it is possible to significantly improve bending properties of layered materials (Raftery and Harte 2013).

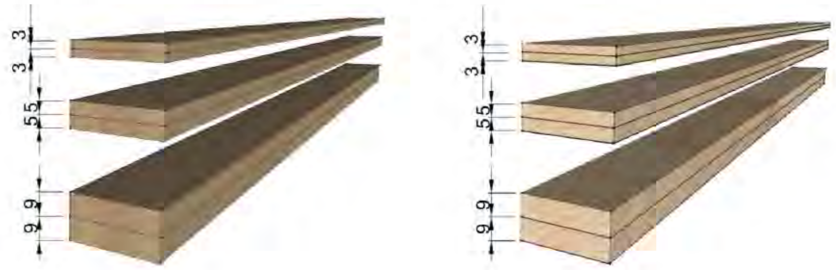
The literature points to increasing requirements for wood quality and methods of joining individual layers (Florek *et al.* 2009; Sandoz 2009; Steiger and Gehri 2010; Stöd and Heräjärvi 2010). Another important factor when gluing laminated wood-based materials or laminated materials based on wood and non-wood components is the type of adhesive used. Glued structural elements are characterized by improved properties compared with solid wood (Lorenzo 2010; Vallée *et al.* 2015). As a result of poor spreading of the adhesive, improper pressing, or an uneven surface of the glued components, the load bearing capacity may decrease because of incorrect bonding. Wood, as a hygroscopic material, continuously absorbs and releases moisture from and into the atmosphere, which results in changes in the moisture stress, and hence dimensional changes. These changes may cause the adhesive to separate from the wooden element. This can be prevented by using a suitable adhesive for the specific purpose of the bonded element (Saracoglu 2011; Khorasan 2012).

The aim of this study was to determine the effect of the laminated wood structure (wood type, non-wood component type, non-wood component position in the structure, material thickness, and adhesive type) on the main strength characteristics of the force-deflection diagram (forces at the proportionality limit and yield point).

EXPERIMENTAL

Materials

The experiments were conducted on lamellas with a thickness of 6 mm, 10 mm, and 18 mm (thickness of non-wood component was 0.15 mm), width of 35 mm, and length of 600 mm (Fig. 2). Lamellas were made from beech wood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.) from the Polana region of Slovakia. Each test group was represented by 20 replicate samples.



(A) **(B)**

Fig. 2. Test samples: beech (A) and aspen lamellas (B)

The effect of the non-wood component on the monitored characteristics was evaluated by comparing the values measured using carbon or fiberglass cloth. The effect of the non-wood component position within the lamella structure was also studied. The non-wood component was positioned as the top (orange color for carbon and red color for fiberglass in Fig. 3) or bottom layer (dark blue for carbon and light blue for fiberglass in Fig. 3). The effect of the adhesive was evaluated by comparing the test results obtained from the lamellas glued using polyvinyl acetate (PVAc) (green in Fig. 3) and polyurethane (PUR) adhesive (yellow in Fig. 3). The samples were conditioned to a moisture content of 8% in a climate chamber (ED, APT Line II, Binder, Tuttlingen, Germany) at a relative humidity of 40% and temperature of 20 °C.

Methods

Determination of the selected characteristics

During testing, the support span length for three-point bending was set to 20 times the thickness (*i.e.*, the support span length was changed in relation to the thickness of the lamellas). The samples were subjected to flexural testing using an FPZ 100 universal testing machine (TIRA, Schalkau, Germany), according to EN 310 (1993), Eilmann *et al.* (2014), and ISO 13061-2 (2014).

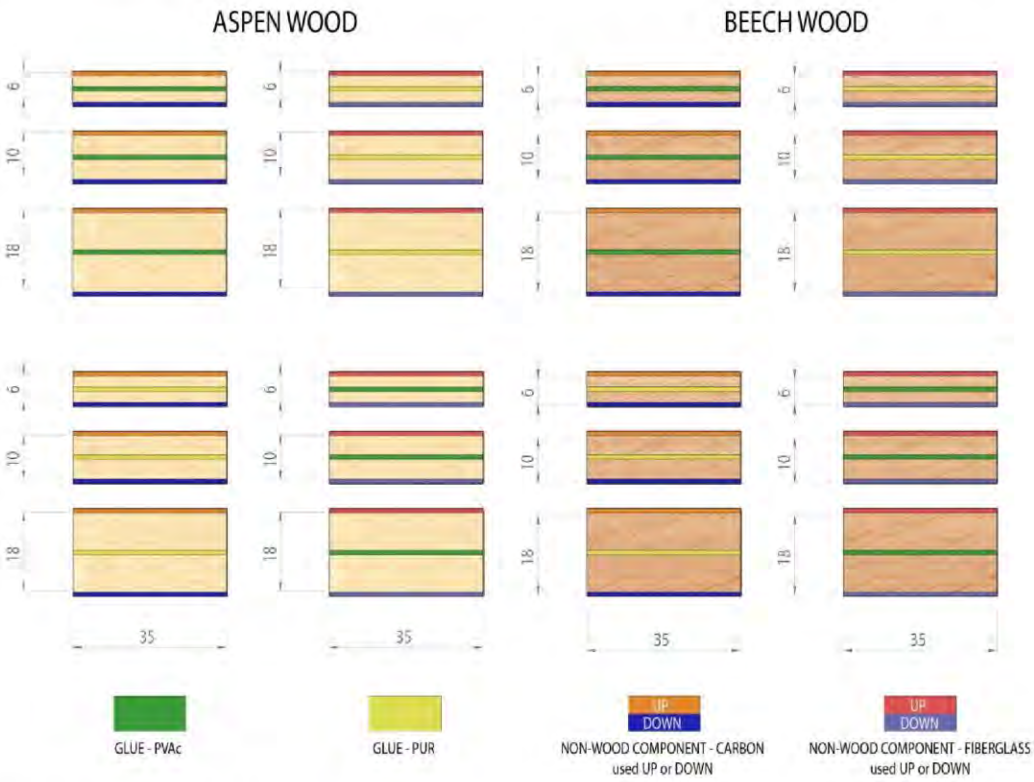


Fig. 3. Arrangement of the test specimens

The cross-head speed was set to 3 mm/min so that the duration of the test did not exceed 2 min. The forces that exceeded the proportionality limit and yield point of the samples were recorded using an ALMEMO 2690-8 datalogger (Ahlborn GmbH, Braunschweig, Germany).

Evaluation and calculation

To determine the influence of the individual factors on the bending characteristics, an analysis of variance (ANOVA) and Fischer's F-test were performed using Statistica 12 software (Statsoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Table 1 shows the average values and variation coefficients (in parentheses) of the forces at the proportionality limit (F_E) and yield point (F_P) of the aspen laminated materials reinforced with non-wood components (carbon fiber and fiberglass) and glued with PVAc and PUR adhesives. The largest force at the proportionality limit (1094 N) was measured with the 18-mm-thick test specimens with fiberglass on the convex side glued with PUR adhesive. The largest force at the yield point (2112 N) was measured with the test specimens that had a total thickness of 18 mm and carbon fibers glued on the convex side with PUR adhesive. The importance of the quality of the bottom layer of laminated wood has been examined in detail in the work (Raftery and Harte 2013). The effect of the non-wood component was verified after comparison with the results of Svoboda *et al.* (2017), who determined the forces at the proportionality limit and yield point for laminated materials without non-wood components.

Table 1. Mean Values of the Forces at the Proportionality Limit and Yield Point, and the Coefficient of Variance of the Aspen Wood

WS	NWC	NWC Location	Glue	T (mm)	Code	F_E (N)	F_P (N)
A	CA	U	PUR	6	A-CA-U-PUR-6	419 (18.8)	614 (17.4)
A	CA	U	PUR	10	A-CA-U-PUR-10	650 (19.0)	1078 (18.8)
A	CA	U	PUR	18	A-CA-U-PUR-18	850 (15.4)	2087 (9.4)
A	CA	U	PVAc	6	A-CA-U-PVAc-6	249 (7.5)	622 (8.9)
A	CA	U	PVAc	10	A-CA-U-PVAc-10	339 (17.7)	707 (18.6)
A	CA	U	PVAc	18	A-CA-U-PVAc-18	783 (12.2)	1536 (12.2)
A	LA	U	PUR	6	A-LA-U-PUR-6	219 (17.8)	441 (20.8)
A	LA	U	PUR	10	A-LA-U-PUR-10	531 (15.2)	965 (18.1)
A	LA	U	PUR	18	A-LA-U-PUR-18	958 (7.4)	1454 (7.8)
A	LA	U	PVAc	6	A-LA-U-PVAc-6	183 (18.0)	462 (19.4)
A	LA	U	PVAc	10	A-LA-U-PVAc-10	459 (13.4)	946 (19.5)
A	LA	U	PVAc	18	A-LA-U-PVAc-18	817 (10.2)	1417 (13.1)
A	CA	D	PUR	6	A-CA-D-PUR-6	572 (19.2)	869 (7.7)
A	CA	D	PUR	10	A-CA-D-PUR-10	916 (20.5)	1632 (18.1)
A	CA	D	PUR	18	A-CA-D-PUR-18	987 (11.0)	2112 (19.0)
A	CA	D	PVAc	6	A-CA-D-PVAc-6	557 (15.9)	782 (10.3)
A	CA	D	PVAc	10	A-CA-D-PVAc-10	672 (4.6)	1204 (17.9)
A	CA	D	PVAc	18	A-CA-D-PVAc-18	724 (15.8)	1528 (13.1)
A	LA	D	PUR	6	A-LA-D-PUR-6	340 (15.2)	554 (16.2)
A	LA	D	PUR	10	A-LA-D-PUR-10	617 (20.0)	1090 (15.2)
A	LA	D	PUR	18	A-LA-D-PUR-18	1094 (14.9)	1515 (14.6)
A	LA	D	PVAc	6	A-LA-D-PVAc-6	344 (4.7)	512 (6.2)
A	LA	D	PVAc	10	A-LA-D-PVAc-10	488 (11.5)	1049 (2.6)
A	LA	D	PVAc	18	A-LA-D-PVAc-18	928 (14.0)	1517 (16.1)

WS – wood species; NWC – non-wood component; T – thickness; F_E – force at the proportionality limit; F_P – force at the yield point; A – aspen; CA – carbon; LA – fiberglass; U – up; D – down

Table 2 shows the average values and variation coefficients (in parentheses) of the forces at the proportionality limit (F_E) and yield point (F_P) for the laminated beech materials reinforced with non-wood components and glued with PVAc and PUR. The largest force at the proportionality limit (1419 N) was measured in the test specimens with an overall thickness of 18 mm and carbon fibers glued with PVAc on the convex side relative to the load direction. The largest force at the yield point (2405 N) was measured on the 18-mm-thick test specimens with fiberglass glued on the convex side with PVAc adhesive. After comparing the results with those of Svoboda *et al.* (2017), the same conclusions were reached as for the laminated aspen materials. The effectiveness of the type of adhesive is determined by the surface structure of the bonded surface, as has been shown in the research by Vallée *et al.* (2015). The results of this research were used to verify the effects of the adhesive on all the characteristics observed for both beech and poplar layered wood.

Table 2. Mean Values of the Forces at the Proportionality Limit and Yield Point, and Coefficient of Variance of the Beech Wood

WS	NWC	NWC Location	Glue	*T* (mm)	Code	F_E (N)	F_P (N)
B	CA	U	PUR	6	B-CA-U-PUR-6	658 (18.8)	1011 (11.4)
B	CA	U	PUR	10	B-CA-U-PUR-10	687 (16.6)	1447 (18.3)
B	CA	U	PUR	18	B-CA-U-PUR-18	926 (11.7)	1472 (11.9)
B	CA	U	PVAc	6	B-CA-U-PVAc-6	342 (8.3)	815 (9.0)
B	CA	U	PVAc	10	B-CA-U-PVAc-10	841 (12.2)	1858 (6.7)
B	CA	U	PVAc	18	B-CA-U-PVAc-18	1372 (18.3)	1982 (12.6)
B	LA	U	PUR	6	B-LA-U-PUR-6	201 (12.4)	464 (10.5)
B	LA	U	PUR	10	B-LA-U-PUR-10	758 (14.4)	1638 (18.3)
B	LA	U	PUR	18	B-LA-U-PUR-18	1271 (19.1)	2253 (14.4)
B	LA	U	PVAc	6	B-LA-U-PVAc-6	341 (9.2)	841 (9.0)
B	LA	U	PVAc	10	B-LA-U-PVAc-10	763 (11.9)	1724 (18.3)
B	LA	U	PVAc	18	B-LA-U-PVAc-18	1074 (19.1)	2189 (20.6)
B	CA	D	PUR	6	B-CA-D-PUR-6	874 (21.0)	1418 (11.9)
B	CA	D	PUR	10	B-CA-D-PUR-10	968 (12.1)	1546 (15.2)
B	CA	D	PUR	18	B-CA-D-PUR-18	1076 (8.0)	1508 (16.8)
B	CA	D	PVAc	6	B-CA-D-PVAc-6	641 (17.0)	1119 (8.5)
B	CA	D	PVAc	10	B-CA-D-PVAc-10	1316 (20.3)	2320 (7.7)
B	CA	D	PVAc	18	B-CA-D-PVAc-18	1419 (16.3)	2117 (19.1)
B	LA	D	PUR	6	B-LA-D-PUR-6	293 (26.4)	586 (11.0)
B	LA	D	PUR	10	B-LA-D-PUR-10	781 (14.6)	1733 (16.0)
B	LA	D	PUR	18	B-LA-D-PUR-18	1249 (14.1)	2399 (15.9)
B	LA	D	PVAc	6	B-LA-D-PVAc-6	499 (14.8)	860 (10.6)
B	LA	D	PVAc	10	B-LA-D-PVAc-10	781 (14.7)	1668 (15.5)
B	LA	D	PVAc	18	B-LA-D-PVAc-18	1119 (17.9)	2405 (20.8)

WS – wood species; NWC – non-wood component; *T* – thickness; F_E – force at the proportionality limit; F_P – force at the yield point; B – beech; CA – carbon; LA – fiberglass; U – up; D – down

All of the measured data was statistically evaluated using a single-factor analysis, in which the test specimen type was chosen as the default factor. The evaluation was based on the significance level *p*, which was less than 0.005.

Tables 3 and 4 show the statistical evaluation of the effect of the test specimen type on the force at the proportionality limit in the aspen laminated materials with the non-wood component placed on the top or bottom side with respect to the direction of the stress. The results clearly showed that the test specimen type had a significant effect on the force at the proportionality limit.

Table 3. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Aspen and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	46153050	1	46153050	4765.727	***
1) Type of Sample	4295507	11	390501	40.323	***
Error	1045912	108	9684		

NS – not significant, *** – significant at $p < 0.005$

Table 4. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Aspen and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	28234194	1	28234194	4206.166	***
1) Type of Sample	8009036	11	728094	108.467	***
Error	677970	101	6713		

NS – not significant, *** – significant $p < 0.005$

Tables 5 and 6 show the statistical evaluation of the effect of the test specimen type on the force at the proportionality limit in the beech laminated materials with the non-wood component placed on the top or bottom side with respect to the direction of the stress. These results showed that the test specimen type had a significant effect on the force at the proportionality limit.

Table 5. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Beech and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	101134235	1	101134235	3397.933	***
1) Type of Sample	12696908	11	1154264	38.781	***
Error	3214453	108	29763		

NS – not significant, *** – significant $p < 0.005$

Table 6. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Proportionality Limit for Beech and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	63365377	1	63365377	2105.246	***
1) Type of Sample	21213860	11	1928533	64.073	***
Error	3431262	114	30099		

NS – not significant, *** – significant $p < 0.005$

The statistical evaluation of the effect of the test specimen type on the force at the yield point in the layered aspen materials with the non-wood component on the top or bottom side in relation to the direction of the stress is shown in Tables 7 and 8. The results clearly showed that the test specimen type had a significant effect on the force at the yield point.

Table 7. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Aspen and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	171984002	1	171984002	4192.093	***
1) Type of Sample	25344583	11	2304053	56.161	***
Error	4430787	108	41026		

NS – not significant, *** – significant $p < 0.005$

Table 8. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Aspen and NWC Up

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	131628796	1	131628796	4477.039	***
1) Type of Sample	62616662	11	5692424	193.614	***
Error	2969487	101	29401		

NS – not significant, *** – significant $p < 0.005$

The results of the statistical evaluation of the effect of the test specimen type on the force at the yield point in the layered beech materials with the non-wood component on the top or bottom side in relation to the direction of the stress are shown in Tables 9 and 10. These results clearly showed that the test specimen type had a significant effect on the force at the yield point.

Table 9. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Beech and NWC Down

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	322747426	1	322747426	4281.145	***
1) Type of Sample	39241711	11	3567428	47.321	***
Error	8141916	108	75388		

NS – not significant, *** – significant $p < 0.005$

Table 10. Statistical Evaluation of the Effect of the Factors and their Interaction on the Force at the Yield Point for Beech and NWC Up

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level
Intercept	282099740	1	282099740	2095.762	***
1) Type of Sample	103786852	11	9435168	70.095	***
Error	15344954	114	134605		

NS – not significant, *** – significant $p < 0.005$

Table 11. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Aspen and NWC Down

No.	Sample Type	(1) 572	(2) 915	(3) 986	(4) 557	(5) 672	(6) 723	(7) 340	(8) 517	(9) 694	(10) 344	(11) 488	(12) 628
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.108										
4	A-CA-D-PVAc-6	0.740	0.000	0.000									
5	A-CA-D-PVAc-10	0.032	0.000	0.000	0.017								
6	A-CA-D-PVAc-18	0.002	0.000	0.000	0.001	0.275							
7	A-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8	A-LA-D-PUR-10	0.244	0.000	0.000	0.363	0.001	0.000	0.000					
9	A-LA-D-PUR-18	0.011	0.000	0.000	0.005	0.615	0.508	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.000	0.000	0.000	0.926	0.000	0.000			
11	A-LA-D-PVAc-10	0.084	0.000	0.000	0.141	0.000	0.000	0.002	0.512	0.000	0.002		
12	A-LA-D-PVAc-18	0.201	0.000	0.000	0.129	0.323	0.049	0.000	0.021	0.161	0.000	0.004	

Table 12. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Aspen and NWC Up

No.	Sample Type	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.000	0.000	0.000									
5	A-CA-D-PVAc-10	0.050	0.000	0.000	0.027								
6	A-CA-D-PVAc-18	0.000	0.051	0.005	0.000	0.000							
7	A-LA-D-PUR-6	0.000	0.000	0.000	0.455	0.005	0.000						
8	A-LA-D-PUR-10	0.009	0.004	0.000	0.000	0.000	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.129	0.000	0.000	0.386	0.000	0.000			
11	A-LA-D-PVAc-10	0.330	0.000	0.000	0.000	0.005	0.000	0.000	0.076	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.000	0.416	0.000	0.000	0.033	0.000	0.000	0.001	0.000	0.000	

Table 13. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Beech and NWC Down

No.	Sample Type	(1) 874	(2) 967	(3) 1076	(4) 640	(5) 1316	(6) 1419	(7) 293	(8) 781	(9) 1248	(10) 498	(11) 781	(12) 1119
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.228											
3	B-CA-D-PUR-18	0.014	0.162										
4	B-CA-D-PVAc-6	0.006	0.000	0.000									
5	B-CA-D-PVAc-10	0.000	0.000	0.004	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.186							
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8	B-LA-D-PUR-10	0.260	0.027	0.001	0.072	0.000	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.001	0.035	0.000	0.384	0.038	0.000	0.000				
10	B-LA-D-PVAc-6	0.000	0.000	0.000	0.068	0.000	0.000	0.009	0.001	0.000			
11	B-LA-D-PVAc-10	0.232	0.023	0.000	0.088	0.000	0.000	0.000	0.999	0.000	0.001		
12	B-LA-D-PVAc-18	0.003	0.065	0.581	0.000	0.016	0.000	0.000	0.000	0.095	0.000	0.000	

Table 14. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Proportionality Limit for Beech and NWC Up

No.	**Sample Type**	**(1) 658**	**(2) 687**	**(3) 1225**	**(4) 342**	**(5) 841**	**(6) 1371**	**(7) 201**	**(8) 757**	**(9) 1470**	**(10) 341**	**(11) 763**	**(12) 1753**
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.749											
3	B-CA-D-PUR-18	0.000	0.000										
4	B-CA-D-PVAc-6	0.001	0.000	0.000									
5	B-CA-D-PVAc-10	0.075	0.127	0.000	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.113	0.000	0.000							
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.147	0.000	0.000						
8	B-LA-D-PUR-10	0.307	0.442	0.000	0.000	0.394	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.000	0.011	0.000	0.000	0.278	0.000	0.000				
10	B-LA-D-PVAc-6	0.001	0.000	0.000	0.992	0.000	0.000	0.127	0.000	0.000			
11	B-LA-D-PVAc-10	0.299	0.437	0.000	0.000	0.396	0.000	0.000	0.951	0.000	0.000		
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.262	0.000	0.000	

Table 15. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Aspen and NWC Down

No.	Sample Type	(1) 869	(2) 1631	(3) 2112	(4) 782	(5) 1203	(6) 1527	(7) 554	(8) 1090	(9) 1514	(10) 512	(11) 1048	(12) 1517
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.339	0.000	0.000									
5	A-CA-D-PVAc-10	0.001	0.000	0.000	0.000								
6	A-CA-D-PVAc-18	0.000	0.253	0.000	0.000	0.001							
7	A-LA-D-PUR-6	0.001	0.000	0.000	0.013	0.000	0.000						
8	A-LA-D-PUR-10	0.022	0.000	0.000	0.002	0.214	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.245	0.000	0.000	0.001	0.894	0.000	0.000				
10	A-LA-D-PVAc-6	0.000	0.000	0.000	0.005	0.000	0.000	0.646	0.000	0.000			
11	A-LA-D-PVAc-10	0.050	0.000	0.000	0.006	0.109	0.000	0.000	0.647	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.237	0.000	0.000	0.001	0.909	0.000	0.000	0.978	0.000	0.000	

Table 16. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Aspen and NWC Up

No.	**Sample Type**	**(1) 613**	**(2) 1078**	**(3) 2286**	**(4) 621**	**(5) 707**	**(6) 1535**	**(7) 441**	**(8) 964**	**(9) 2451**	**(10) 461**	**(11) 946**	**(12) 1715**
1	A-CA-D-PUR-6												
2	A-CA-D-PUR-10	0.000											
3	A-CA-D-PUR-18	0.000	0.000										
4	A-CA-D-PVAc-6	0.922	0.000	0.000									
5	A-CA-D-PVAc-10	0.299	0.000	0.000	0.313								
6	A-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000							
7	A-LA-D-PUR-6	0.055	0.000	0.000	0.051	0.004	0.000						
8	A-LA-D-PUR-10	0.000	0.183	0.000	0.000	0.004	0.000	0.000					
9	A-LA-D-PUR-18	0.000	0.000	0.049	0.000	0.000	0.000	0.000	0.000				
10	A-LA-D-PVAc-6	0.075	0.000	0.000	0.075	0.008	0.000	0.808	0.000	0.000			
11	A-LA-D-PVAc-10	0.000	0.144	0.000	0.000	0.006	0.000	0.000	0.826	0.000	0.000		
12	A-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.035	0.000	0.000	0.000	0.000	0.000	

Table 17. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Beech and NWC Down

No.	Sample Type	(1) 1418	(2) 1545	(3) 1508	(4) 1119	(5) 2320	(6) 2117	(7) 586	(8) 1732	(9) 2398	(10) 860	(11) 1667	(12) 2405
1	B-CA-D-PUR-6		0.332	0.464	0.017	0.000	0.000	0.000	0.022	0.000	0.000	0.065	0.000
2	B-CA-D-PUR-10	0.332		0.761	0.001	0.000	0.000	0.000	0.154	0.000	0.000	0.322	0.000
3	B-CA-D-PUR-18	0.464	0.761		0.003	0.000	0.000	0.000	0.098	0.000	0.000	0.225	0.000
4	B-CA-D-PVAc-6	0.017	0.001	0.003		0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000
5	B-CA-D-PVAc-10	0.000	0.000	0.000	0.000		0.101	0.000	0.000	0.524	0.000	0.000	0.519
6	B-CA-D-PVAc-18	0.000	0.000	0.000	0.000	0.101		0.000	0.002	0.031	0.000	0.001	0.032
7	B-LA-D-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.028	0.000	0.000
8	B-LA-D-PUR-10	0.022	0.154	0.098	0.000	0.000	0.002	0.000		0.000	0.000	0.599	0.000
9	B-LA-D-PUR-18	0.000	0.000	0.000	0.000	0.524	0.031	0.000	0.000		0.000	0.000	0.958
10	B-LA-D-PVAc-6	0.000	0.000	0.000	0.037	0.000	0.000	0.028	0.000	0.000		0.000	0.000
11	B-LA-D-PVAc-10	0.065	0.322	0.225	0.000	0.000	0.001	0.000	0.599	0.000	0.000		0.000
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.519	0.032	0.000	0.000	0.958	0.000	0.000	

Table 18. Comparison of the Effects of the Sample Type Using Duncan's Test on the Force at the Yield Point for Beech and NWC Up

No.	Sample Type	(1) 1011	(2) 1647	(3) 2471	(4) 815	(5) 1857	(6) 2582	(7) 464	(8) 1638	(9) 2552	(10) 840	(11) 1723	(12) 3989
1	B-CA-D-PUR-6												
2	B-CA-D-PUR-10	0.002											
3	B-CA-D-PUR-18	0.000	0.000										
4	B-CA-D-PVAc-6	0.341	0.000	0.000									
5	B-CA-D-PVAc-10	0.000	0.308	0.002	0.000								
6	B-CA-D-PVAc-18	0.000	0.000	0.592	0.000	0.001							
7	B-LA-D-PUR-6	0.009	0.000	0.000	0.071	0.000	0.000						
8	B-LA-D-PUR-10	0.002	0.963	0.000	0.000	0.306	0.000	0.000					
9	B-LA-D-PUR-18	0.000	0.000	0.674	0.000	0.001	0.878	0.000	0.000				
10	B-LA-D-PVAc-6	0.378	0.000	0.000	0.893	0.000	0.000	0.066	0.000	0.000			
11	B-LA-D-PVAc-10	0.001	0.692	0.000	0.000	0.489	0.000	0.000	0.679	0.000	0.000		
12	B-LA-D-PVAc-18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Duncan's test was performed for a detailed comparison of the differences between the forces at the proportionality limit and yield point for the different types of aspen and beech laminate materials, and the results are shown in Tables 11 to 18.

Figure 4 shows that the largest force required to reach the proportionality limit for the aspen lamellas was found with the 18-mm-thick samples that had the fiberglass cloth component on the bottom of the laminated material. These lamellas were glued with PUR adhesive. In contrast, the smallest force needed to reach the proportionality limit was found with the 6-mm-thick lamellas, especially those with fiberglass on top. Moreover, this material reached only 16.7% of force at the proportionality limit in comparison to the above-mentioned material.

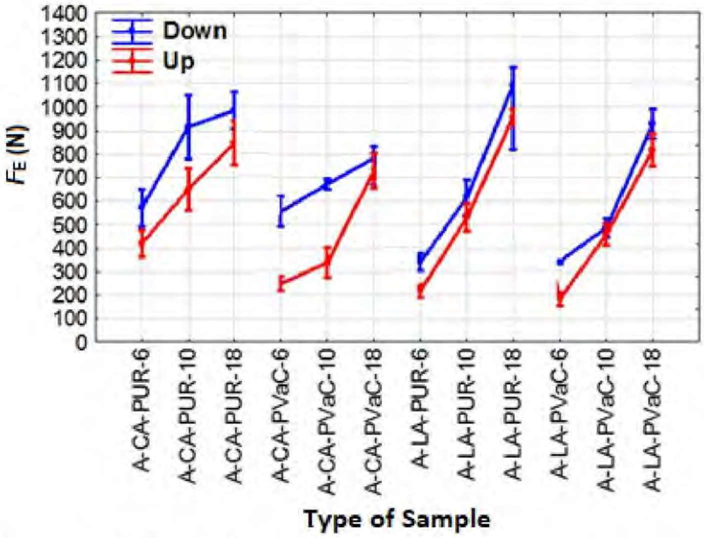


Fig. 4. Effect of aspen on the force at the proportionality limit

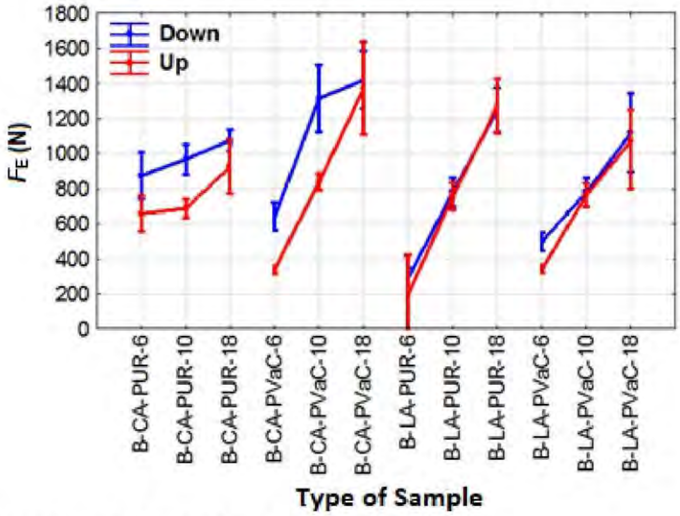


Fig. 5. Effect of beech on the force at the proportionality limit

For the beech lamellas, the results were different (Fig. 5). The largest force needed to reach the proportionality limit for the beech lamellas was found with the 18-mm-thick specimens with carbon on the bottom of the lamella, unlike the aspen lamellas. These lamellas were glued with PVAc adhesive. As with the aspen lamellas, the 6-mm-thick beech lamellas glued with PUR reinforced with carbon fibers located on the top required the smallest force to reach the proportionality limit. This material reached only 14.2% of force at the proportionality limit compared to the above-mentioned material.

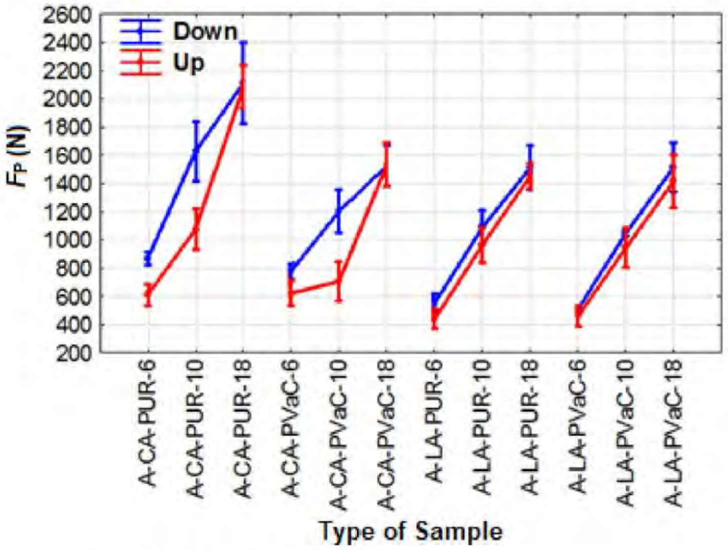


Fig. 6. Effect of aspen on the force at the yield point

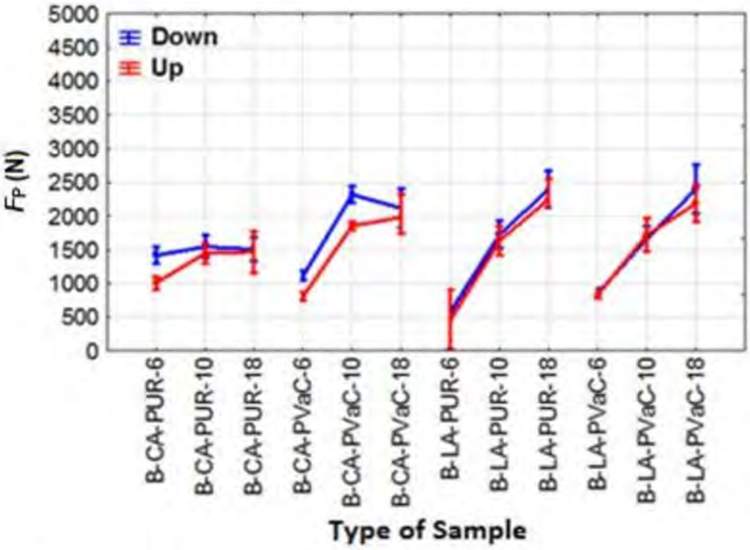


Fig. 7. Effect of beech on the force at the yield point

Figure 6 clearly shows that the largest force required to reach the yield point for the aspen lamellas was found with the 18-mm-thick samples with carbon on the bottom of the lamella. These lamellas were glued with PUR adhesive. The smallest force needed to reach the yield point was found with the 6-mm-thick lamellas with fiberglass on the top, this material reached only 20.9 % of the force at the yield point in comparison to the above-mentioned material. The trend was therefore similar to that of the proportionality limit for the aspen lamellas.

As was the case for the proportionality limit, the results for the yield point for the beech lamellas were different (Fig.). The largest force needed to reach the yield point for the beech lamellas was found with the 18-mm-thick specimens that had fiberglass on the bottom of the lamella, unlike the aspen lamellas. These lamellas were glued with PVAc adhesive. The smallest test values were recorded with the beech lamellas bonded with PVAc adhesive and reinforced with fiberglass on the top. This material reached only 22.7% of force at the yield point relative to the above-mentioned material.

CONCLUSIONS

1. It was generally found that the monitored characteristics, namely the forces at the proportionality limit and yield point, reached higher values in the laminated beech wood modified with a non-wood component than in the laminated aspen wood modified with a non-wood component.
2. For the aspen laminated wood with a non-wood component, it can be safely said that the largest values of the monitored characteristics were measured in the test specimens with a non-wood component glued on the convex side with respect to the stress. These materials showed that the largest forces at the proportionality limit and yield point were achieved when the individual layers were glued with PUR adhesive. The results for the effect of the non-wood component in the aspen laminates on the force at the proportionality limit showed that fiberglass glued to the convex side had the greatest effect. For the force at the yield point, the opposite trend was found, *i.e.*, larger values were achieved using carbon fibers glued to the convex side.
3. In the case of the laminated wood with beech and non-wood components, an opposite trend was found with regards to the effect of the adhesive compared with the aspen specimens. The PVAc glue was shown to be the most effective adhesive for the monitored characteristics. As for the effect of the non-wood component, an opposite trend compared with that of the laminated aspen specimens was also seen. For the force at the proportionality limit, modification with carbon fibers was shown to be the best, and for the force at the yield point, modification with fiberglass was the best.
4. As was expected, the material thickness proved to be a significant factor that affected the forces at the proportionality limit and yield point for all of the materials.

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9.6 Článek číslo 6., Effect of Selected Factors on the Bending Deflection at the Limit of Proportionality and at the Modulus of Rupture in Laminated Veneer Lumber

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Effect of Selected Factors on the Bending Deflection at the Limit of Proportionality and at the Modulus of Rupture in Laminated Veneer Lumber

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Abstract: The deflection of a test material occurs under bending stress that is caused by force. In terms of plasticity and elasticity, the deflection can be quantified at two main areas, which are the limit of proportionality and the modulus of rupture. Both of these deflections are of great importance in terms of the scientific and practical use. These characteristics are particularly important when designing structural elements that are exposed to bending stress in terms of the size of the deflection in their practical application. This study analyzed the effect on the size of the deflection at the limit of proportionality and at the modulus of rupture. Wood species (*Fagus sylvatica* L. and *Populus tremula* L.), material thickness (6 mm, 10 mm, and 18 mm), non-wood component (glass and carbon fiber), position of the non-wood component in the layered material (up and down side with respect to the loading direction), and adhesive used to join the individual layers (polyurethane and polyvinyl acetate) were the observed factors. Glass fiber reinforcement proved to be a better option; however, the effect of correctly selected glue for individual wood species was also apparent. For the aspen laminated materials, polyurethane adhesive (PUR) adhesive was shown to be a more effective adhesive and PVAc adhesive was better for the beech-laminated materials. These results are of great importance for the production of new wood-based materials and materials were based on non-wood components, with specific properties for their intended use.

Keywords: technological and product innovations; cyclic loading; laminated wood; deflection at the limit of proportionality; deflection at the modulus of rupture; wood-processing industry performance

1. Introduction

The composition design and production of Laminated Veneer Lumber materials is primarily focused on the intended use of the material. Therefore, it is necessary to know the proposed composition under the influence of various factors in order to create such a material.

The basic component of LVL materials is wood component, however non-wood component can be also used. The single layers of LVL material could be modified or unmodified. The modification can be carried out in a variety of ways, such as high temperature, chemical, impregnation, pressure, microwave irradiation, lamination, etc. The possibilities of increasing the strength and the stiffness of wood lie in its combination with non-wood components at various material bases [1]. These are steel, glass, and carbon fibers in building materials [2–4]. Authors [5] conducted research with the effect of embedded carbon fiber fabric in the bonded joint of five-layer plywood to increase the flexural strength.

Flexibility is a technical property of wood that expresses its ability to bend. It is a material property that may be classified as either a positive or negative characteristic, depending on the purpose. In the case of materials that are intended for bending, this property is desirable [6–8], whereas it is undesirable in materials that are intended for construction [9,10].

Bending is defined as a torque that acts on a material perpendicular to the cross section, which results in normal and tangential stress that causes stress through bending or twisting [11]. Each change in a beam subjected to bending is the result of work that is directly dependent on the force that is used and the resulting deformation [12,13]. The range of external forces doing the work changes in bending within the maximum boundary. The internal forces that are caused by deformation are also displaced [14]. Potential energy accumulates in an elastically deformed object, and then the energy is converted into work that is consumed after release to enable the object to return to its original shape [15–17].

The deflection at the limit of proportionality of wood is characterized as the boundary after which deformation becomes elastic over time and plastic. It is necessary to use the force at the limit of proportionality to achieve deflection at the limit of proportionality [18]. Up to this point, the wood is loaded with a force that only causes elastic deformation and it is therefore only flexibly loaded [19–21]. This deflection can be achieved without any apparent permanent deformation of its size or shape. The deflection at the modulus of rupture is characterized as the deflection when the material breaks. It is necessary to use force at the modulus of rupture to achieve this deflection (Figure 1) [20,22,23].

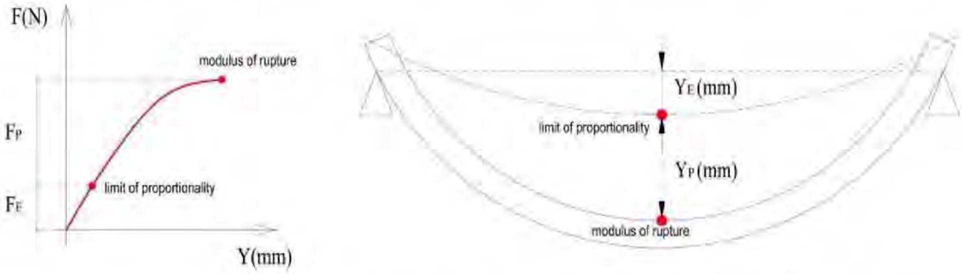

Figure 1. Force-deflection diagram of the bending stress and determining the limit of proportionality and the modulus of rupture [24].

The bending characteristics of the wood can be improved by reinforcing it with non-wood components on a different basis [1,25]. Carbon fibers, aramid fibers, basalt fibers, fiberglass, and polyvinyl alcohol (PVA), and others, are suitable non-wood components that can be used for wood reinforcement [26–28]. In addition to synthetic fiber reinforcement, natural fiber reinforcement may also be used, e.g., in the form of a nonwoven fabric. Experimental research has shown that correctly locating the reinforcement component has the potential to increase the bending characteristics of laminated wood in the case of application on the stressed tensile zone [21,29,30].

The literature points to the influence of surface structure on the properties of the bonded surface joint [31,32]. In view of this, the selection of a suitable adhesive for joining wood-based materials and non-wood components is very critical [33]. Wood itself is a hygroscopic material and, as such, it continually absorbs and releases moisture, which, among other things, causes a change in size. These changes can cause the adhesive to separate from the wood component. This effect can be avoided by appropriately selecting an adhesive for a specific bonded element [34].

The objective of this study was to determine the effect of the composition of laminated wood (wood species, type of non-wood component, position of the component in the structure, thickness of the material, and the type of adhesive used for bonding individual layers) on the deflection characteristics of the force-deflection diagram (deflection at the limit of proportionality and at the modulus of rupture).

2. Materials and Methods

2.1. Material

For the experiment, layered beech (*Fagus sylvatica* L.) and aspen (*Populus tremula* L.) wood (Polana, Slovakia), with a non-wood reinforcing component (glass and carbon fibers), were used. The test specimens were made with three thicknesses of 6 mm, 10 mm, and 18 mm, with a lamella width of 35 mm and length of 600 mm. The test specimens were divided into 48 test groups, with respect to the thickness and species of wood component, the type of non-wood component, and the position of the non-wood component relative to the load direction. Figure 2 shows the categorization of the test specimens. The individual wood and non-wood components were glued while using two types of adhesive, which were single-component waterproof polyvinyl acetate adhesive (PVAc) (AG-COLL 8761/L D3, EOC, Oudenaarde, Belgium) and single-component polyurethane adhesive (PUR) (NEOPUR 2238R, NEOFLEX, Madrid, Spain). Table 1 lists the detailed parameters of these adhesives. The test specimens were climatized at a 12% equilibrium moisture content (EMC) in a climatic chamber (Binder ED, APT Line II, Tuttlingen, Germany) at set relative humidity (65%) and temperature values (20 °C).

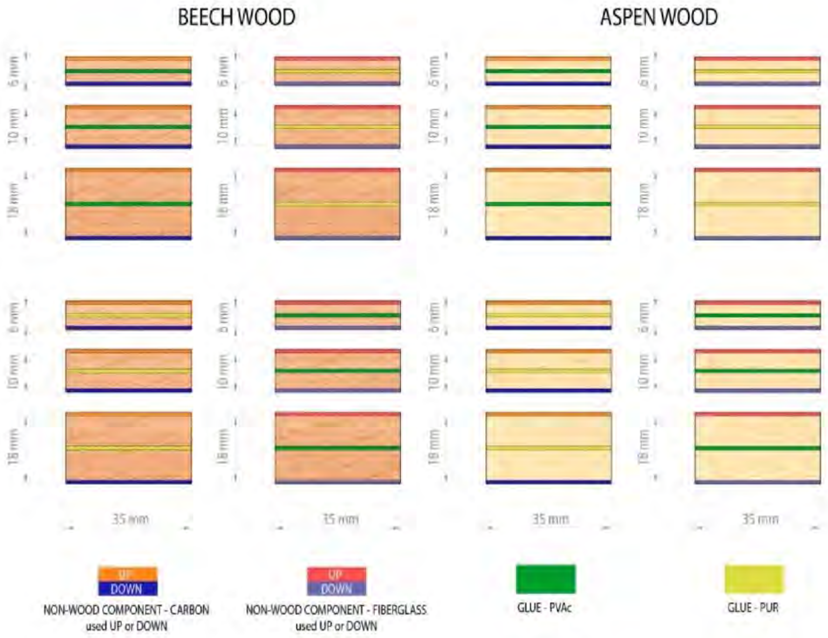

Figure 2. Categorization of the test specimens.

Table 1. Parameters of the polyvinyl acetate adhesive (PVAc) and polyurethane adhesive (PUR) Adhesives.

Technical Data	AG-COLL 8761/L D3	NEOPUR 2238R
Viscosity (mPa)	5000 to 7000 by 23 °C	2000 to 4500 by 25 °C
Working Time (min)	15 to 20	60
Density (g/cm^3)	0.9 to 1.1 by 23 °C	approx. 1.13
NCO Content (%)	-	approx. 15.5 to 16.5
Color	White, milk	Brown
Open Time (min)	15	approx. 20 to 25
Dry Matter Content	49 to 51	100
pH	3.8 to 4.5	-

2.2. Methods

2.2.1. Determining Selected Characteristics

The three-point bending test was performed according to the predetermined conditions. The lower support span was set to 20 times the thickness of the test specimen (this span varied, depending on the thickness of the test specimens). The bending tests were performed on a universal testing machine (FPZ 100, TIRA, Schalkau, Germany), according to [35–37]. To adhere to the duration limit for the test (2 min.), the top support feed rate was set to 3 mm/min. The deflections at the limit of proportionality and at the modulus of rupture were measured using an ALMEMO 2690-8 datalogger (Ahlborn GmbH, Braunschweig, Germany).

A force-deflection diagram was used to determine the limit of proportionality and the modulus of rupture. To identify all of the necessary characteristics, a program was developed for identifying data that can be obtained from the force-deflection diagram.

2.2.2. Evaluation and Calculation

To determine the influence of the sample type on the bending characteristics, an analysis of variance (ANOVA) and a Fischer's F-test were performed using Statistica 12 software (Statsoft Inc., Tulsa, OK, USA).

For the determination of deflection at the limit of proportionality and at the modulus of rupture, it was necessary to calculate the limit of proportionality and the modulus of rupture.

We calculate the limit of proportionality "*LOP*" in three point bending according to EN 310 [35] and Equation (1):

$$LOP = \frac{3F_E l_0}{2bh^2} \tag{1}$$

where *LOP* is the limit of proportionality of material (MPa), F_E is force at the limit of proportionality (N), l_0 is the distance between supporting span (mm), b is width of test samples (mm), and h is the height (thickness) of the sample (mm).

The bending strength "modulus of rupture (*MOR*)" in three point bending was calculated in accordance with ISO 13061-3 [38] and Equation (2):

$$MOR = \frac{3F_{max} l_0}{2bh^2} \tag{2}$$

where *MOR* is (bending strength) of material (MPa), F_{max} is maximum (breaking) force (N), l_0 is the distance between supporting span (mm), b is width of test samples (mm), and h is the height (thickness) of the sample (mm).

3. Results and Discussion

Tables 2 and 3 show the average value and the coefficients of variation for the deflection at the limit of proportionality (Y_E) and deflection at the modulus of rupture (Y_P) in the laminated aspen and beech materials reinforced with a non-wood component (glass and carbon fiber) that is glued with PUR and PVAc adhesives. For the aspen wood (Table 2), the highest deflection at the limit of proportionality (4.89 mm) was measured on the 18-mm-thick test specimens that were glued with PVAc adhesive and reinforced with carbon fibers on the underside of the loaded specimen with respect to the loading direction. The greatest deflection at the modulus of rupture (16.70 mm) was measured on the 18-mm-thick laminated material that was glued with PUR adhesive and reinforced with glass fibers placed on the underside with respect to the loading direction. A comparison with the results of Sikora et al. verified the effect of the use of a non-wood material reinforcement to improve the deflection characteristics [39], and it was concluded that the use of a non-wood component significantly affected the deflection characteristics.

Table 2. Mean Values of the Deflection at the Limit of Proportionality and the Deflection at the Modulus of Rupture, and Coefficient of Variance of the Aspen Wood.

WS	NWC	NWC Location	Glue	T (mm)	Code	Y_E (mm)	Y_P (mm)
A	CA	U	PUR	6	A-CA-U-PUR-6	1.59 (14.0)	3.00 (18.1)
A	CA	U	PUR	10	A-CA-U-PUR-10	2.06 (16.8)	8.01 (16.6)
A	CA	U	PUR	18	A-CA-U-PUR-18	2.45 (13.0)	9.32 (13.2)
A	CA	U	PVAc	6	A-CA-U-PVAc-6	2.10 (9.0)	7.97 (3.3)
A	CA	U	PVAc	10	A-CA-U-PVAc-10	2.81 (17.7)	11.32 (5.5)
A	CA	U	PVAc	18	A-CA-U-PVAc-18	3.29 (21.0)	12.24 (16.8)
A	LA	U	PUR	6	A-LA-U-PUR-6	1.98 (17.9)	7.46 (14.4)
A	LA	U	PUR	10	A-LA-U-PUR-10	2.73 (15.4)	7.74 (15.9)
A	LA	U	PUR	18	A-LA-U-PUR-18	3.81 (8.0)	8.74 (17.1)
A	LA	U	PVAc	6	A-LA-U-PVAc-6	2.28 (5.7)	9.07 (13.6)
A	LA	U	PVAc	10	A-LA-U-PVAc-10	2.70 (7.7)	9.68 (19.5)
A	LA	U	PVAc	18	A-LA-U-PVAc-18	3.32 (16.5)	9.90 (11.0)
A	CA	D	PUR	6	A-CA-D-PUR-6	1.54 (20.2)	5.11 (19.4)
A	CA	D	PUR	10	A-CA-D-PUR-10	2.97 (7.4)	9.07 (19.9)
A	CA	D	PUR	18	A-CA-D-PUR-18	3.22 (16.4)	13.30 (16.9)
A	CA	D	PVAc	6	A-CA-D-PVAc-6	3.82 (15.0)	8.46 (20.4)
A	CA	D	PVAc	10	A-CA-D-PVAc-10	4.09 (20.6)	12.95 (6.9)
A	CA	D	PVAc	18	A-CA-D-PVAc-18	4.89 (19.1)	14.48 (17.9)
A	LA	D	PUR	6	A-LA-D-PUR-6	3.21 (18.5)	8.23 (19.3)
A	LA	D	PUR	10	A-LA-D-PUR-10	3.56 (7.7)	10.33 (16.4)
A	LA	D	PUR	18	A-LA-D-PUR-18	4.93 (8.8)	16.70 (18.7)
A	LA	D	PVAc	6	A-LA-D-PVAc-6	3.48 (9.5)	9.21 (6.2)
A	LA	D	PVAc	10	A-LA-D-PVAc-10	4.05 (12.9)	10.51 (16.3)
A	LA	D	PVAc	18	A-LA-D-PVAc-18	4.22 (14.3)	13.62 (21.1)

WS—wood species; NWC—non-wood component, T—thickness, Y_E—deflection at the limit of proportionality, Y_P—Deflection at the modulus of rupture, A—aspen, CA—carbon, LA—fiberglass, U—up, and D—down

Table 3. Mean Values of the Deflection at the Limit of Proportionality and the Deflection at the Modulus of Rupture, and Coefficient of Variance of the Beech Wood.

WS	NWC	NWC Location	Glue	T (mm)	Code	Y_E (mm)	Y_P (mm)
B	CA	U	PUR	6	B-CA-U-PUR-6	2.11 (20.1)	5.13 (17.6)
B	CA	U	PUR	10	B-CA-U-PUR-10	2.22 (14.4)	6.81 (19.8)
B	CA	U	PUR	18	B-CA-U-PUR-18	2.45 (8.7)	7.38 (8.8)
B	CA	U	PVAc	6	B-CA-U-PVAc-6	2.59 (19.8)	7.85 (9.3)
B	CA	U	PVAc	10	B-CA-U-PVAc-10	2.87 (8.1)	9.48 (9.7)
B	CA	U	PVAc	18	B-CA-U-PVAc-18	3.48 (14.4)	10.39 (9.5)
B	LA	U	PUR	6	B-LA-U-PUR-6	1.85 (12.6)	5.42 (10.3)
B	LA	U	PUR	10	B-LA-U-PUR-10	2.85 (18.5)	7.80 (17.0)
B	LA	U	PUR	18	B-LA-U-PUR-18	4.39 (18.7)	9.25 (16.8)
B	LA	U	PVAc	6	B-LA-U-PVAc-6	2.37 (20.2)	7.14 (4.8)
B	LA	U	PVAc	10	B-LA-U-PVAc-10	3.20 (17.6)	10.25 (11.2)
B	LA	U	PVAc	18	B-LA-U-PVAc-18	4.03 (7.6)	11.69 (19.3)
B	CA	D	PUR	6	B-CA-D-PUR-6	2.83 (19.5)	7.26 (8.4)
B	CA	D	PUR	10	B-CA-D-PUR-10	3.04 (19.6)	7.72 (14.9)
B	CA	D	PUR	18	B-CA-D-PUR-18	7.07 (20.1)	15.12 (15.7)
B	CA	D	PVAc	6	B-CA-D-PVAc-6	3.00 (19.0)	8.99 (12.9)
B	CA	D	PVAc	10	B-CA-D-PVAc-10	3.71 (16.1)	10.07 (18.9)
B	CA	D	PVAc	18	B-CA-D-PVAc-18	6.69 (19.0)	12.70 (16.1)
B	LA	D	PUR	6	B-LA-D-PUR-6	4.36 (17.9)	11.38 (7.4)
B	LA	D	PUR	10	B-LA-D-PUR-10	5.33 (20.5)	12.45 (17.4)
B	LA	D	PUR	18	B-LA-D-PUR-18	5.63 (12.4)	15.33 (15.6)
B	LA	D	PVAc	6	B-LA-D-PVAc-6	2.87 (20.7)	7.52 (8.1)
B	LA	D	PVAc	10	B-LA-D-PVAc-10	4.07 (19.3)	11.84 (17.9)
B	LA	D	PVAc	18	B-LA-D-PVAc-18	6.77 (19.7)	20.01 (18.9)

WS—wood species, NWC—non-wood component, T—thickness, Y_E—deflection at the proportionality limit, Y_P—deflection at the modulus of rupture, B—beech, CA—carbon, LA—fiberglass, U—up, and D—down.

Table 3 shows the deflection characteristics (Y_E and Y_P) of the layered beech materials that were reinforced with non-wood components. The greatest deflection at the limit of proportionality (7.07 mm) was measured on the 18-mm-thick test specimens that were bonded with PUR adhesive and reinforced with carbon fibers placed on the underside of the loaded test specimen relative to the loading direction. In the case of deflection at the modulus of rupture, the highest values (20.01 mm) were measured on the 18-mm-thick test specimens that were glued with PVAc adhesive and reinforced with glass fibers placed on the underside with respect to the loading direction. The effect of the adhesive was verified while using the results of Gáborík et al. [40], who presented results of the deflection of beech lamellas that were glued using PUR and PVAc adhesives. Regarding the effect of using a non-wood component to reinforce the layered material, the results of the present study were compared with the results of Sikora et al. [39], with the same conclusion as for the layered aspen materials.

The measured data were statistically evaluated using one-factor analyses (ANOVA), where the factor was the type of test specimen. The code of test samples includes the wood species that are used in the laminated material, type of non-wood component and its position in the structure relative to the loading direction, type of adhesive, and total thickness of the test sample. The evaluation was based on the p significance level, which was $p = 0.005$. Table 4 shows the results of the statistical evaluation of the effect of the aspen and beech test sample type on the deflection at the limit of proportionality and deflection at the modulus of rupture of the laminated materials with a non-wood component on the underside and topside. It was clear from these results that the type of test sample had a significant effect on the deflection at the limit of proportionality and on the deflection at the modulus of rupture.

From Figure 3 and Table 4, it was clear that it was more beneficial to apply the reinforcing material to the down side of the laminated aspen material for the deflection at the limit of proportionality. Higher values were achieved in all of the cases, except one, where the values were almost equal. The values of the reinforced material glued on the down side were approximately 41.32% higher than the average values when it was glued on the top. When evaluating the material that was used for reinforcing solid wood, the average values with glass fiber were 15.62% higher than those measured with carbon fiber. The last important factor was the adhesive used to connect the individual elements together. The average values measured using PVAc adhesive were 20.56% higher than those measured with PUR adhesive.

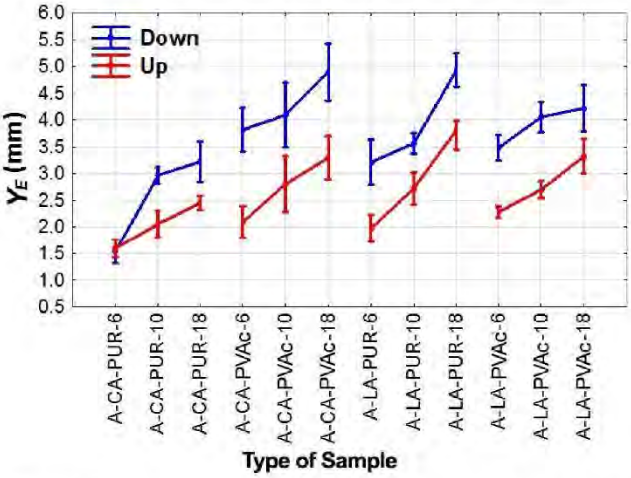

Figure 3. Effect of the aspen wood species on the deflection at the limit of proportionality.

The ANOVA test results in Figure 4 and Table 4 confirmed the same trend in the deflection at the limit of proportionality in the reinforced laminated beech material, as in the deflection at the limit of proportionality in the laminated aspen material. Higher values were achieved when the reinforcing material was glued on the down side. The average values in this case were up to 60.91% higher. The reinforcing materials were evaluated in the same way. The glass fiber had 13.46% higher deflection values than the carbon fiber. As for the adhesive used, there were no major differences. Expressed as a percentage difference of the mean values, the difference between PVAc and PUR was approximately 3.5%, where PVAc had higher deflection values at the limit of proportionality.

Table 4. Statistical Evaluation of the Effect of Type of Samples on the Deflection at the Limit of Proportionality and Deflection at the Modulus of rupture.

Deflection at the Limit of Proportionality of Aspen and NWC Down					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level p**
Intercept	1469.556	1	1469.556	5410.635	***
(1) Type of Sample	76.586	11	6.962	25.634	***
Error	29.333	108	0.272		-
Deflection at the Limit of Proportionality of Aspen and NWC UP					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level p**
Intercept	469.9151	1	469.9151	5033.475	***
(1) Type of Sample	19.7016	11	1.7911	19.185	***
Error	9.4292	101	0.0934		-
Deflection at the Modulus of Rupture of Aspen and NWC Down					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level p**
Intercept	2373.329	1	2373.329	2497.682	***
(1) Type of Sample	298.265	11	27.115	28.536	***
Error	102.623	108	0.950		-
Deflection at the Modulus of Rupture of Aspen and NWC Up					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level p**
Intercept	5186.339	1	5186.339	4235.214	***
(1) Type of Sample	288.155	11	26.196	21.392	***
Error	139.602	114	1.225		-
Deflection at the Limit of Proportionality of Beech and NWC Down					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level p**
Intercept	13,863.51	1	13,863.51	3716.494	***
(1) Type of Sample	1281.94	11	116.54	31.242	***
Error	402.87	108	3.73		-
Deflection at the Limit of Proportionality of Beech and NWC Up					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level P**
Intercept	6405.696	1	6405.696	4427.627	***
(1) Type of Sample	373.911	11	33.992	23.495	***
Error	146.122	101	1.447		-
Deflection at the Modulus of Rupture of Beech and NWC Down					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level P**
Intercept	15,277.64	1	15,277.64	4198.613	***
(1) Type of Sample	1739.17	11	158.11	43.451	***
Error	392.98	108	3.64		-
Deflection at the Modulus of Rupture of Beech and NWC Up					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F-test**	**Significance Level P**
Intercept	5186.339	1	5186.339	4235.214	***
(1) Type of Sample	288.155	11	26.196	21.392	***
Error	139.602	114	1.225		-

NS—not significant, ***—significant at $p < 0.005$.

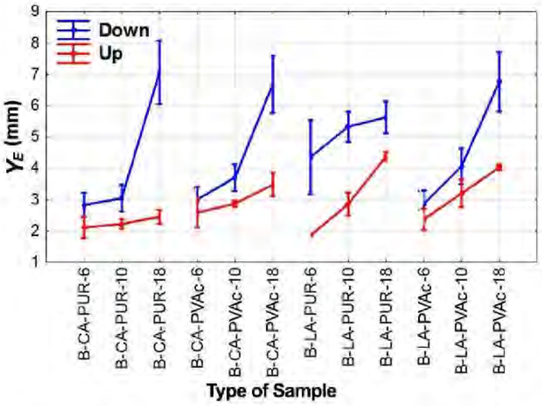

Figure 4. Effect of the beech wood species on the deflection at the limit of proportionality.

Figure 5 graphically depicts a comparison of the factors that were focused on the deflection at the modulus of rupture in the aspen wood. The dependencies were similar to those of the deflection at the limit of proportionality, as seen in Table 4. A greater deflection was observed when the reinforcing material was glued opposite to the loaded side (by 26.35% in this case). The average deflection values were 5.17% higher when glass fiber. The adhesive used was the last important factor. With PVAc glue, the deflection at the modulus of rupture was 20.93% higher.

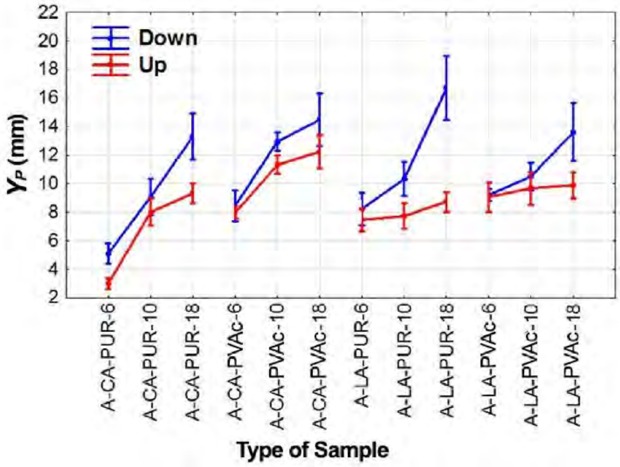

Figure 5. Effect of the aspen wood species on the deflection at the modulus of rupture.

As for all of the previous cases, higher deflection at the modulus of rupture values was achieved in the reinforced laminated beech materials by gluing the reinforcing material to the down side relative to the loading direction (Figure 6). These values were approximately 36% higher than these measured in the materials with the non-wood component glued on the top (Table 4). With glass fibers, the deflection at the modulus of rupture values increased by approximately 20% when compared with carbon fibers. A further increase in the deflection values can be achieved by using the correct adhesive; in this study, the deflection values for the samples with PVAc were 15.2% higher.

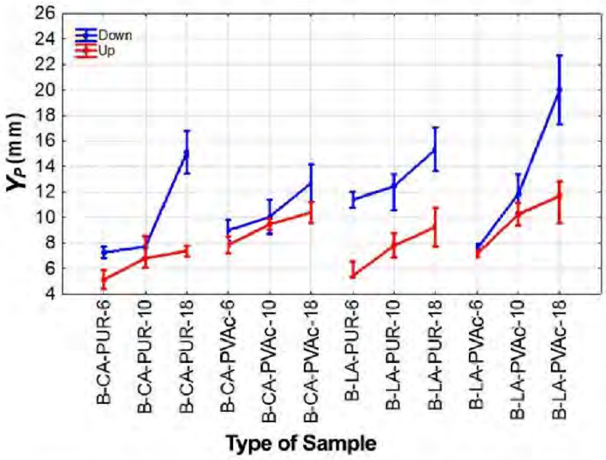

Figure 6. Effect of the beech wood species on the deflection at the modulus of rupture.

4. Conclusions

1. For the laminated aspen and beech materials that were reinforced with non-wood components, the lowest deflection values were measured in the test specimens with the non-wood component on the up side with respect to the loading direction, and the highest deflection values were measured in the test specimens with the non-wood component on the down side with respect to the loading direction.
2. Glass fiber was proven to be better non-wood component for both the laminated beech and aspen materials with regard to the deflection at the limit of proportionality and at the modulus of rupture in terms of the non-wood component itself.
3. In the case of the adhesive used, it cannot be clearly stated which adhesive was the most effective. However, higher average values of deflection at the limit of proportionality and at the modulus of rupture were measured with the PVAc adhesive.
4. As was expected, the thickness of the material proved to be an important factor that affected the deflection at both the limit of proportionality and at the modulus of rupture.
5. In the case of aspen composition for better bendability, we suggest gluing with PUR adhesive and reinforcement with glass fiber on the down side with respect to the loading direction. In addition, in the case of beech composition, we suggest gluing with PVAc adhesive and reinforcement with glass fiber on the down side with respect to the loading direction.

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9.7 Článek číslo 7., Laminated Veneer Lumber with Non-Wood Components and the Effects of Selected Factors on Its Bendability

forests

Article

Laminated Veneer Lumber with Non-Wood Components and the Effects of Selected Factors on Its Bendability

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Abstract: Knowledge of the coefficients of wood bendability (K_{bendC} and K_{bendB}) and of the effects of selected factors on the listed characteristics in bending stress has both scientific and practical significance. It forms a foundation for designing tools for bending and determines the stress that products and their parts can be exposed to during use. This study analyzes the effects of selected factors on the selected characteristics, such as the coefficients of wood bendability (K_{bendC} and K_{bendB}). The selected factors of this study were wood species (WS) (*Fagus sylvatica* L. and *Populus tremula* L.), non-wood component (carbon fiber and glass fiber), position of the non-wood component in the laminated material (top and bottom), material thickness (T) (6 mm, 10 mm, and 18 mm), and adhesive (polyvinyl acetate and polyurethane), as well as their combined interaction on the monitored characteristics described above. The results contribute to the advancement of knowledge necessary for the study and development of new materials with specific properties for their intended use. The measured values of laminated structures can be compared with the values measured on the samples from the wood. The results can improve the innovative potential of wood processing companies and increase their performance and competitiveness in the market.

Keywords: coefficient of wood bendability; laminated wood; technological and product innovations; minimal curve radius

1. Introduction

The effective use of wood and its by-products has gained increased attention in recent years due to limited natural resources [1,2]. It is in society's general interest to efficiently utilize our limited forest resources and improve recycling [2].

Because composite material production uses materials of varying characteristics, it is necessary to verify their quality to ensure good product performance and market competitiveness. Composite production is a complex process [3]; it requires immediate consideration of various parameters (cutting geometry, production volume, matrix types, machine requirements, market economy, etc.). One of the main aspects limiting the structural use of high-strength composites is their weak interlaminar resistance [4]. Several strategies for enhancing the resistance of composites have been proposed [4–6], such as using a harder resin for hybrid composites, harder adhesive layers, and others.

Material stratification is very important in industrial practice, both in construction and in the manufacturing industry [7,8]. In the woodworking industry, homogeneity leads to better performance, thereby reducing the possible negative properties of wood that could lead to material failures. In environmental modification of wood, a number of studies have focused on thermal modification [9–15]. Densification of wood is also one of the ways to modify the basic properties

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of wood. It is a process whereby wood is pressed, for example, by rolling or by the action of various presses, thereby reducing its volume and increasing density. Such wood is then harder, firmer, and darker to look at. Densification of wood reduces the porosity and moisture content of the wood [16]. Gaff et al. [17] examined the effect of densification on bond strength. They found that the effect of the densification on bond strength is statistically very significant.

Another way to modify the properties of wood elements is through the use of non-wood reinforcing materials to form wood-based composite materials [18]. Such reinforcing materials include carbon, aramid, basalt, and glass fibers [19–21]. The application of non-wood components in a wood-based laminated veneer lumber material is usually intended to strengthen the material, increase its resistance to stress, and reduce bending values [22,23]. Such materials are characterized by different specific properties for their intended uses [24–27]. The intended use is a determining factor of the desired characteristics in a given material [22,28–30]. In some cases, emphasis is placed on materials with high strength values, while other cases see the creation of materials with high elasticity values [23] or high bendability values [22].

Bendability is a characteristic that has recently attracted great interest. The effect of the placement of a non-wood component in such a material has not yet been given much attention, and the interactions of different types of materials with other factors influencing this characteristic have also not been studied. A mathematical interpretation of the bending coefficient [17] was only recently established for the correct description of bendability.

The bending coefficient (K_{bend}) is a quantitative characteristic that is defined as the ratio of the thickness (h) of the bent material to the minimum bend radius (R) (Figure 1). For most types of wood, the limit ratio is h:R = 1:35 to 1:45. The critical area for bending wood is the tensile zone. The maximum tensile deformation of wood in its original unmodified state is 0.75% to 1%. This can be increased with plasticization to 1.5% to 2%. By contrast, the compressibility of wood is greater at optimum humidity and temperature; if its porosity allows it, it reaches up to 40% [31].

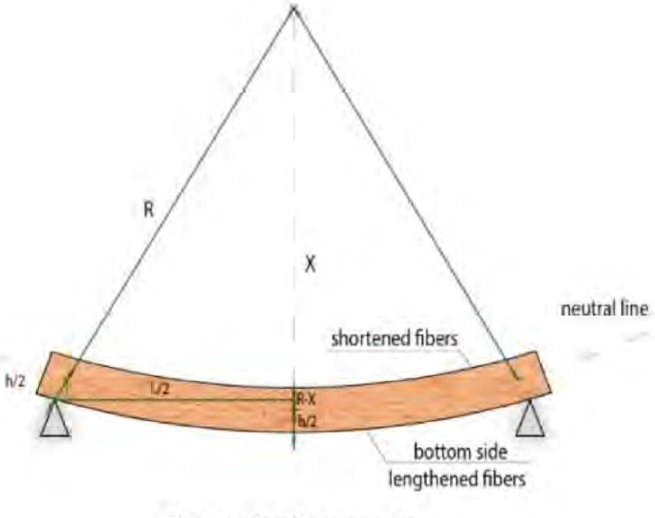

Figure 1. Bending geometry.

There is very little scientific knowledge about the minimum bend radius and bending coefficient. The aim of our work is therefore to deepen the knowledge of the bending coefficient of wood (K_{bendC} and K_{bendB}), namely beech and aspen, under three-point bending. Gaff et al. [32] showed that as the material thickness increases, the value of the bending coefficient decreases, and the force needed for bending increases. Gaff et al. [17] created a model for analyzing bendability, with which it is possible to define the correct relations for determining the minimum bend radius (R_{min}), which can then be used to calculate the bending coefficient (K_{bend}).

2. Materials and Methods

2.1. Material

The wooden lamellas used in this experiment were made of beech wood (*Fagus sylvatica* L.) and aspen wood (*Populus tremula* L.) with thicknesses of 3 mm, 5 mm, and 9 mm, widths of 35 mm, and lengths of 600 mm. The beech and aspen wood came from Polana, Slovakia. Polyvinyl acetate (PVAc) and polyurethane (PUR) adhesives were used to produce laminated wood using the above lamellas. Carbon fibers (SikaWrap-150 C/30, 155 $g/m^2 \pm 5$ g/m^2) and glass fibers (Kittfort, 355 g/m^2) were used as the reinforcing materials, which were first glued on the convex sides and then on the concave sides with respect to the direction of loading. Categorization of the test specimens is shown in Figure 2.

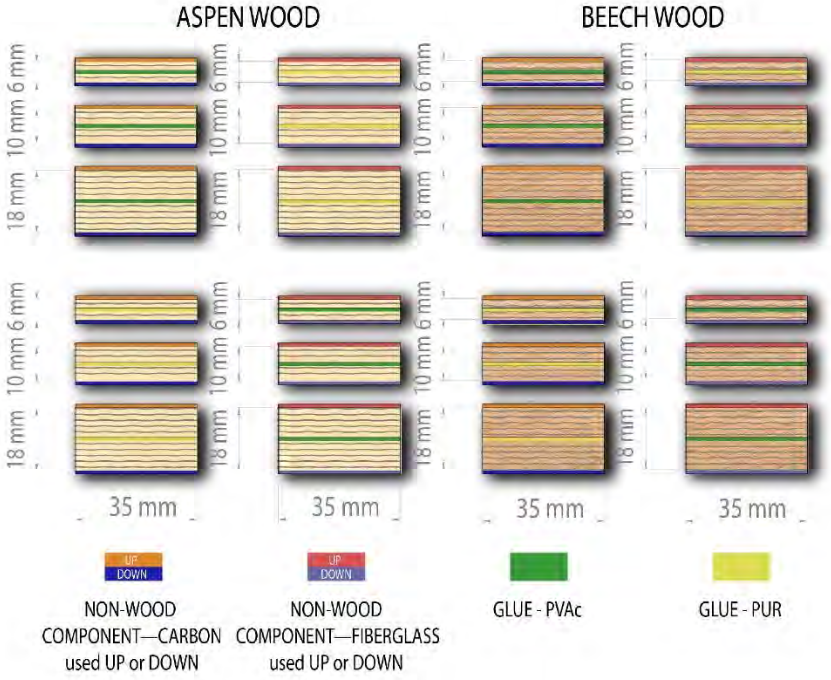

Figure 2. Categorization of test specimens.

After all test specimens were created, they were climatized in a climatic chamber (ED, APT Line II, Binder, Tuttlingen, Germany) to 12% moisture content at 65% relative humidity and 20 °C.

2.2. Methods

2.2.1. Determining Selected Characteristics

Testing was performed with three-point bending (Figure 3), with the bottom support span set to 20 times the total thickness of the test specimen. The top support crossbeam was set in a center position relative to the distance of the bottom support crossbeam. Testing was performed according to EN 310 (1993) [33] using a universal testing machine (FPZ 100, TIRA, Schalkau, Germany). Testing took place in the tangential direction relative to the fiber direction. The feed rate of the top support was set to 3 mm/min due to the duration of the test. An ALMEMO 2690-8 datalogger (AhlbornGmbH, Braunschweig, Germany) was used to record all the forces during the test.

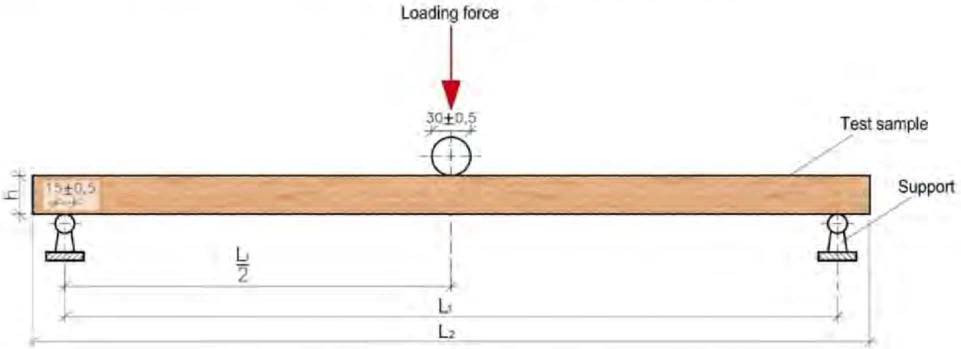

Figure 3. Principle of the three-point bending test [33].

Before the measurement was performed, the densities and humidities of the used wooden components were measured according to ISO 13061-1 (2014) [34] and ISO 13061-2 (2014) [35]. After the tests were completed, all test specimens were dried to 0% moisture content, as necessary to calculate the moisture content at the time of the test.

2.2.2. Evaluation and Calculation of K_{bend} and R_{min}

Based on data obtained from the stress–strain diagram, exact identification of the boundary points between the linear and non-linear parts of the diagram was used to determine forces at the limit of proportionality (F_{E}) and at the yield point (F_{P}), along with the deflections at the limit of proportionality (Y_{E}) and at the yield point (Y_{P}). These characteristics were identified using the MATESS program, which is currently being developed by the Czech University of Life Sciences in Prague.

In the next step, the bendability of the tested material was evaluated based on the minimum bend radius (R_{minB} and R_{minC}) and the bending coefficient (K_{bendB} and K_{bendC}). Two approaches were used to evaluate the bendability. The first approach was based on bending geometry (Equations (1) and (2)), while the second approach was based on the simple bending equations (Equations (3) and (4)), which were used in the work of Gaff et al. [17]:

$$R_{\text{minB}} = \frac{l_0^2}{8\,Y_{\text{P}}} + \frac{Y_{\text{P}}}{2} - \frac{h}{2} \tag{1}$$

$$K_{\text{bendB}} = \frac{h}{R_{\text{minB}}} = \frac{h}{\frac{l_0^2}{8\,Y_{\text{P}}} + \frac{Y_{\text{P}}}{2} - \frac{h}{2}} \tag{2}$$

$$R_{\text{minC}} = \frac{l_0^2}{12\,Y_{\text{P}}} \tag{3}$$

$$K_{\text{bendC}} = \frac{h}{R_{\text{minC}}} = \frac{h}{\frac{l_0^2}{12\,Y_{\text{P}}}} \tag{4}$$

where R_{minB} is the minimum bend radius based on bending geometry (mm), R_{minC} is the minimum bend radius based on the simple bending equations (mm), K_{bendB} is the bending coefficient based on bending geometry, K_{bendC} is the bending coefficient based on the simple bending equations, Y_{P} is the deflection at the yield point (mm), l_0 is the bottom support span (mm), and h is the total material thickness (mm).

The results were statistically evaluated with an analysis of variance (ANOVA), specifically Fisher's F-test, with STATISTICA 12 software (Statsoft Inc., Tulsa, OK, USA). The results were evaluated using a 95% confidence interval, which represents a significance level of 0.05 ($p < 0.05$). Duncan's test was also used for deeper analysis to compare all sets of test specimens.

3. Results and Discussion

Tables 1 and 2 show the average values and coefficients of variation (in parentheses) of the monitored characteristics, the average density values measured in individual sets of test specimens, and the corresponding coefficients of variation. Table 1 shows the average values of K_{bendC}, K_{bendB}, R_{minC}, and R_{minB} measured in the aspen test specimens.

Table 1. Values of bending characteristics and the coefficients of variance of layered aspen material.

WS	NWC	Location	Glue	T (mm)	Code of Test Sample	K_{bendC}	K_{bendB}	R_{minC} (mm)	R_{minB} (mm)
A	CA	U	PUR	6	A-CA-U-PUR-6	0.014 (17.0)	0.012 (13.5)	519.28 (9.4)	717.76 (11.9)
A	CA	U	PUR	10	A-CA-U-PUR-10	0.024 (13.3)	0.015 (16.8)	526.38 (14.9)	693.13 (20.4)
A	CA	U	PUR	18	A-CA-U-PUR-18	0.012 (8.4)	0.007 (7.8)	1616.03 (14.7)	2448.28 (13.5)
A	CA	U	PVAc	6	A-CA-U-PVAc-6	0.039 (4.1)	0.026 (4.1)	150.72 (3.3)	227.08 (3.3)
A	CA	U	PVAc	10	A-CA-U-PVAc-10	0.034 (5.0)	0.023 (5.1)	280.19 (12.0)	406.81 (17.0)
A	CA	U	PVAc	18	A-CA-U-PVAc-18	0.013 (14.0)	0.008 (13.6)	1279.40 (15.5)	1651.62 (11.4)
A	LA	U	PUR	6	A-LA-U-PUR-6	0.031 (11.3)	0.021 (17.5)	159.95 (14.3)	238.00 (18.0)
A	LA	U	PUR	10	A-LA-U-PUR-10	0.024 (16.0)	0.015 (14.4)	511.83 (18.5)	671.01 (16.6)
A	LA	U	PUR	18	A-LA-U-PUR-18	0.015 (17.2)	0.010 (17.2)	1233.71 (14.0)	1848.16 (14.0)
A	LA	U	PVAc	6	A-LA-U-PVAc-6	0.043 (14.7)	0.028 (14.1)	134.11 (11.4)	202.81 (11.0)
A	LA	U	PVAc	10	A-LA-U-PVAc-10	0.022 (11.3)	0.015 (17.6)	401.48 (10.8)	628.74 (9.6)
A	LA	U	PVAc	18	A-LA-U-PVAc-18	0.016 (10.3)	0.011 (8.9)	1220.28 (10.8)	1688.32 (13.4)
A	CA	D	PUR	6	A-CA-D-PUR-6	0.026 (19.4)	0.019 (17.9)	248.51 (19.1)	355.31 (16.0)
A	CA	D	PUR	10	A-CA-D-PUR-10	0.022 (17.9)	0.014 (15.4)	379.73 (18.4)	570.20 (18.3)
A	CA	D	PUR	18	A-CA-D-PUR-18	0.020 (19.6)	0.013 (20.4)	878.98 (13.2)	1365.45 (18.2)
A	CA	D	PVAc	6	A-CA-D-PVAc-6	0.036 (19.2)	0.026 (21.0)	165.21 (11.8)	253.26 (7.4)
A	CA	D	PVAc	10	A-CA-D-PVAc-10	0.037 (15.7)	0.024 (15.3)	280.82 (16.4)	427.67 (15.8)
A	CA	D	PVAc	18	A-CA-D-PVAc-18	0.024 (17.2)	0.014 (18.3)	884.80 (12.0)	1454.81 (11.9)
A	LA	D	PUR	6	A-LA-D-PUR-6	0.031 (15.6)	0.024 (20.4)	144.14 (15.0)	218.42 (14.7)
A	LA	D	PUR	10	A-LA-D-PUR-10	0.032 (16.5)	0.021 (16.3)	330.58 (16.3)	495.74 (16.2)
A	LA	D	PUR	18	A-LA-D-PUR-18	0.028 (18.7)	0.019 (18.5)	670.60 (21.4)	1004.97 (21.3)
A	LA	D	PVAc	6	A-LA-D-PVAc-6	0.036 (7.2)	0.027 (12.1)	143.00 (14.7)	225.48 (15.4)
A	LA	D	PVAc	10	A-LA-D-PVAc-10	0.027 (16.6)	0.018 (16.5)	402.30 (18.6)	602.38 (18.5)
A	LA	D	PVAc	18	A-LA-D-PVAc-18	0.023 (19.2)	0.014 (19.9)	886.44 (17.9)	1322.03 (18.0)

WS—wood species; NWC—non-wood component; T—thickness; K_{bendC}—bending coefficient based on simple bending equations; K_{bendB}—bending coefficient based on bending geometry; R_{minC}—minimum bend radius based on simple bending equations; R_{minB}—minimum bend radius based on bending geometry; A—aspen; CA—carbon; LA—glass fiber; U—top; D—bottom.

Table 2. Average values of bending characteristics and the coefficients of variance of layered beech material.

WS	NWC	Location	Glue	T (mm)	Code of Test Sample	K_{bendC}	K_{bendB}	R_{minC} (mm)	R_{minB} (mm)
B	CA	U	PUR	6	B-CA-U-PUR-6	0.024 (17.6)	0.016 (17.6)	231.20 (12.9)	340.25 (8.4)
B	CA	U	PUR	10	B-CA-U-PUR-10	0.026 (15.4)	0.017 (18.6)	459.30 (20.7)	663.96 (17.4)
B	CA	U	PUR	18	B-CA-U-PUR-18	0.011 (6.0)	0.006 (19.4)	2262.89 (18.2)	3288.95 (16.4)
B	CA	U	PVAc	6	B-CA-U-PVAc-6	0.037 (9.1)	0.024 (8.8)	153.98 (8.9)	232.03 (8.7)
B	CA	U	PVAc	10	B-CA-U-PVAc-10	0.031 (9.6)	0.021 (9.6)	354.65 (9.5)	531.16 (9.5)
B	CA	U	PVAc	18	B-CA-U-PVAc-18	0.014 (16.9)	0.009 (9.7)	1416.71 (12.4)	1804.00 (21.0)
B	LA	U	PUR	6	B-LA-U-PUR-6	0.044 (5.1)	0.030 (0.8)	134.43 (11.2)	169.19 (8.5)
B	LA	U	PUR	10	B-LA-U-PUR-10	0.025 (16.4)	0.016 (16.3)	439.62 (18.5)	657.95 (18.4)
B	LA	U	PUR	18	B-LA-U-PUR-18	0.008 (19.3)	0.005 (17.2)	2442.86 (20.3)	3391.53 (14.3)
B	LA	U	PVAc	6	B-LA-U-PVAc-6	0.033 (5.6)	0.022 (5.5)	168.33 (4.7)	253.25 (4.6)
B	LA	U	PVAc	10	B-LA-U-PVAc-10	0.032 (11.8)	0.022 (10.8)	317.76 (16.7)	476.68 (16.4)
B	LA	U	PVAc	18	B-LA-U-PVAc-18	0.013 (19.2)	0.008 (19.2)	1451.32 (18.4)	2171.66 (18.4)
B	CA	D	PUR	6	B-CA-D-PUR-6	0.034 (7.7)	0.023 (7.6)	166.27 (8.6)	250.18 (8.4)
B	CA	D	PUR	10	B-CA-D-PUR-10	0.025 (17.9)	0.015 (17.9)	427.22 (18.8)	644.19 (18.5)
B	CA	D	PUR	18	B-CA-D-PUR-18	0.015 (12.3)	0.015 (18.5)	1232.78 (15.1)	1488.03 (17.2)
B	CA	D	PVAc	6	B-CA-D-PVAc-6	0.042 (14.0)	0.028 (13.6)	135.40 (12.5)	204.75 (12.2)
B	CA	D	PVAc	10	B-CA-D-PVAc-10	0.030 (14.9)	0.021 (19.5)	296.37 (16.9)	489.47 (19.4)
B	CA	D	PVAc	18	B-CA-D-PVAc-18	0.021 (18.9)	0.014 (18.8)	793.45 (18.4)	1248.23 (11.0)
B	LA	D	PUR	6	B-LA-D-PUR-6	0.046 (7.4)	0.030 (7.0)	105.94 (7.5)	162.18 (7.0)
B	LA	D	PUR	10	B-LA-D-PUR-10	0.024 (13.0)	0.015 (17.9)	426.66 (13.0)	683.36 (19.0)
B	LA	D	PUR	18	B-LA-D-PUR-18	0.026 (18.4)	0.016 (16.7)	663.54 (18.5)	1209.10 (14.0)
B	LA	D	PVAc	6	B-LA-D-PVAc-6	0.035 (8.5)	0.023 (8.3)	160.41 (7.9)	241.58 (7.7)
B	LA	D	PVAc	10	B-LA-D-PVAc-10	0.034 (19.3)	0.024 (13.5)	296.34 (19.6)	459.85 (13.9)
B	LA	D	PVAc	18	B-LA-D-PVAc-18	0.033 (17.3)	0.022 (17.0)	526.61 (16.3)	795.58 (16.4)

WS—wood species; NWC—non-wood component; T—thickness; K_{bendC}—bending coefficient based on simple bending equations; K_{bendB}—bending coefficient based on bending geometry; R_{minC}—minimum bend radius based on simple bending equations; R_{minB}—minimum bend radius based on bending geometry; B—beech; CA—carbon; LA—glass fiber; U—top; D—bottom.

The highest average values of R_{minC} (1616 mm) and R_{minB} (2448 mm) were measured in the material with a thickness of 18 mm glued with PUR adhesive and reinforced with carbon fibers placed on the top side with respect to the direction of loading. The lowest average values of R_{minC} (134 mm) and R_{minB} (202 mm) were measured in the material with a thickness of 6 mm glued with PVAc adhesive and reinforced with glass fibers placed on the top side with respect to the direction of loading.

Higher average values for the bending coefficient were obtained in calculations based on the simple bending equation K_{bendC} (0.01 to 0.04) than in calculations based on bending geometry K_{bendB} (0.01 to 0.03), which corresponds with the results reported in the work of Gaff et al. [17], who also studied the bending coefficient of unmodified aspen wood.

Table 2 shows the average values of K_{bendC}, K_{bendB}, R_{minC}, and R_{minB} calculated in beech test specimens. The layered beech materials showed the same tendency of the bending coefficient as the laminated aspen materials. In the laminated beech materials, K_{bendC} values (0.01 to 0.05) were greater than K_{bendB} values (0.01 to 0.03). Comparing these results with those of Gaff et al. [17] confirms the trend of greater K_{bendC} values.

The greatest average value of R_{minB} (3391 mm) was measured in the material with a thickness of 18 mm glued with PUR adhesive and reinforced with glass fibers on the top side with respect to the direction of loading. The lowest value of R_{minB} (162 mm) was measured in the material with a total thickness of 6 mm bonded with PUR adhesive and reinforced with glass fiber on the bottom side of the test specimen relative to the direction of loading. The greatest (2442 mm) and lowest (105 mm) average values of R_{minC} were measured in the same materials as the greatest and lowest values of R_{minB}.

All the measured data were statistically evaluated using a single-factor analysis in which the test specimen type was chosen as the default factor. The evaluation was based on the significance level p, which was less than 0.005. Tables 3–6 show the statistical evaluation of the effect of the test specimen type on the bending coefficient based on the simple bending equations (K_{bendC}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom side with respect to the direction of loading.

Table 3. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for aspen and non-wood component (NWC) on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.101015	1	0.101015	4182.484	***
1) Type of Sample	0.003778	11	0.000343	14.220	***
Error	0.002608	108	0.000024		

NS—not significant, ***—significant at $p < 0.005$.

Table 4. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.058817	1	0.058817	5814.366	***
1) Type of Sample	0.010364	11	0.000942	93.141	***
Error	0.001022	101	0.000010		

NS—not significant, ***—significant at $p < 0.005$.

Table 5. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.114036	1	0.114036	5587.265	***
1) Type of Sample	0.008469	11	0.000770	37.724	***
Error	0.002204	108	0.000020		

NS—not significant, ***—significant at $p < 0.005$.

Table 6. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendC}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.055837	1	0.055837	5566.564	***
1) Type of Sample	0.011935	11	0.001085	108.163	***
Error	0.001144	114	0.000010		

NS—not significant, ***—significant at $p < 0.005$.

Tables 7–10 show the statistical evaluation of the effect of the test specimen type on the bending coefficient based on bending geometry (K_{bendB}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 7. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.046953	1	0.046953	3654.379	***
1) Type of Sample	0.002775	11	0.000252	19.633	***
Error	0.001388	108	0.000013		

NS—not significant, ***—significant at $p < 0.005$.

Table 8. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.026766	1	0.026766	5122.907	***
1) Type of Sample	0.004369	11	0.000397	76.012	***
Error	0.000528	101	0.000005		

NS—not significant, ***—significant at $p < 0.005$.

Table 9. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.052061	1	0.052061	5814.871	***
1) Type of Sample	0.003206	11	0.000291	32.553	***
Error	0.000967	108	0.000009		

NS—not significant, ***—significant at $p < 0.005$.

Table 10. Statistical evaluation of the effect of the factors and their interaction on the coefficient of wood bendability (K_{bendB}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	0.024553	1	0.024553	5158.266	***
1) Type of Sample	0.005388	11	0.000490	102.915	***
Error	0.000543	114	0.000005		

NS—not significant, ***—significant at $p < 0.005$.

Tables 11–14 show the statistical evaluation of the effect of the test specimen type on the minimum bend radius based on the simple bending equations (R_{minC}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 11. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	24436158	1	24436158	3264.754	***
1) Type of Sample	9717956	11	883451	118.032	***
Error	808363	108	7485		

NS—not significant, ***—significant at $p < 0.005$.

Table 12. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	44421882	1	44421882	2710.337	***
1) Type of Sample	28160468	11	2560043	156.197	***
Error	1655370	101	16390		

NS—not significant, ***—significant at $p < 0.005$.

Table 13. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	22802737	1	22802737	2892.018	***
1) Type of Sample	12097814	11	1099801	139.485	***
Error	851549	108	7885		

NS—not significant, ***—significant at $p < 0.005$.

Table 14. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minC}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	58491893	1	58491893	1178.097	***
1) Type of Sample	81191097	11	7381009	148.662	***
Error	5660040	114	49649		

NS—not significant, ***—significant at $p < 0.005$.

Tables 15–18 show the statistical evaluation of the effect of the test specimen type on the minimum bend radius based on bending geometry (R_{minB}) in laminated aspen and beech materials with the non-wood component placed on the top or bottom with respect to the direction of loading.

Table 15. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for aspen and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	57349324	1	57349324	2933.356	***
1) Type of Sample	24093243	11	2190295	112.031	***
Error	2111481	108	19551		

NS—not significant, ***—significant at $p < 0.005$.

Table 16. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for aspen and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	89797468	1	89797468	2744.915	***
1) Type of Sample	61286334	11	5571485	170.308	***
Error	3304126	101	32714		

NS—not significant, ***—significant at $p < 0.005$.

Table 17. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for beech and NWC on the bottom.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	51699287	1	51699287	2759.401	***
1) Type of Sample	22194201	11	2017655	107.690	***
Error	2023455	108	18736		

NS—not significant, ***—significant at $p < 0.005$.

Table 18. Statistical evaluation of the effect of the factors and their interaction on the minimum bend radius at the yield point (R_{minB}) for beech and NWC on top.

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-Test	Significance Level
Intercept	118241938	1	118241938	1681.398	***
1) Type of Sample	159214450	11	14474041	205.821	***
Error	8016889	114	70324		

NS—not significant, ***—significant at $p < 0.005$.

Duncan's test was performed for a detailed comparison of the differences in the bending coefficients (K_{bendC} and K_{bendB}) among individual types of laminated aspen and beech materials, and the results are shown in Tables 19–26.

Table 19. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for aspen and NWC on the bottom.

No.	Type of Sample	(1) 0.026	(2) 0.022	(3) 0.020	(4) 0.036	(5) 0.037	(6) 0.024	(7) 0.031	(8) 00.32	(9) 0.028	(10) 0.036	(11) 0.027	(12) 0.023
1.	A-CA-D-PUR-6												
2.	A-CA-D-PUR-10	0.048											
3.	A-CA-D-PUR-18	0.007	0.414										
4.	A-CA-D-PVAc-6	0.000	0.000	0.000									
5.	A-CA-D-PVAc-10	0.000	0.000	0.000	0.973								
6.	A-CA-D-PVAc-18	0.261	0.331	0.092	0.000	0.000							
7.	A-LA-D-PUR-6	0.049	0.000	0.000	0.032	0.035	0.003						
8.	A-LA-D-PUR-10	0.016	0.000	0.000	0.085	0.096	0.001	0.595					
9.	A-LA-D-PUR-18	0.445	0.008	0.001	0.001	0.001	0.077	0.182	0.078				
10.	A-LA-D-PVAc-6	0.000	0.000	0.000	0.943	0.965	0.000	0.036	0.100	0.001			
11.	A-LA-D-PVAc-10	0.895	0.040	0.005	0.000	0.000	0.238	0.057	0.019	0.494	0.000		
12.	A-LA-D-PVAc-18	0.213	0.403	0.120	0.000	0.000	0.840	0.002	0.000	0.056	0.000	0.187	

Table 20. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for aspen and NWC on top.

No.	Type of Sample	**(1)** **0.014**	**(2)** **0.024**	**(3)** **0.012**	**(4)** **0.039**	**(5)** **0.034**	**(6)** **0.013**	**(7)** **0.031**	**(8)** **0.024**	**(9)** **0.015**	**(10)** **0.043**	**(11)** **0.022**	**(12)** **0.016**
1.	A-CA-U-PUR-6												
2.	A-CA-U-PUR-10	0.000											
3.	A-CA-U-PUR-18	0.198	0.000										
4.	A-CA-U-PVAc-6	0.000	0.000	0.000									
5.	A-CA-U-PVAc-10	0.000	0.000	0.000	0.002								
6.	A-CA-U-PVAc-18	0.886	0.000	0.221	0.000	0.000							
7.	A-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.075	0.000						
8.	A-LA-U-PUR-10	0.000	0.935	0.000	0.000	0.000	0.000	0.000					
9.	A-LA-U-PUR-18	0.603	0.000	0.086	0.000	0.000	0.535	0.000	0.000				
10.	A-LA-U-PVAc-6	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000			
11.	A-LA-U-PVAc-10	0.000	0.242	0.000	0.000	0.000	0.000	0.000	0.240	0.000	0.000		
12.	A-LA-U-PVAc-18	0.264	0.000	0.022	0.000	0.000	0.228	0.000	0.000	0.502	0.000	0.000	

Table 21. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for beech and NWC on the bottom.

No.	Type of Sample	**(1)** **0.034**	**(2)** **0.025**	**(3)** **0.015**	**(4)** **0.042**	**(5)** **0.030**	**(6)** **0.021**	**(7)** **0.046**	**(8)** **0.024**	**(9)** **0.026**	**(10)** **0.035**	**(11)** **0.034**	**(12)** **0.033**
1.	B-CA-D-PUR-6												
2.	B-CA-D-PUR-10	0.000											
3.	B-CA-D-PUR-18	0.000	0.000										
4.	B-CA-D-PVAc-6	0.000	0.000	0.000									
5.	B-CA-D-PVAc-10	0.029	0.032	0.000	0.000								
6.	B-CA-D-PVAc-18	0.000	0.042	0.009	0.000	0.000							
7.	B-LA-D-PUR-6	0.000	0.000	0.000	0.107	0.000	0.000						
8.	B-LA-D-PUR-10	0.000	0.655	0.000	0.000	0.012	0.089	0.000					
9.	B-LA-D-PUR-18	0.000	0.702	0.000	0.000	0.061	0.020	0.000	0.438				
10.	B-LA-D-PVAc-6	0.861	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000			
11.	B-LA-D-PVAc-10	0.910	0.000	0.000	0.000	0.027	0.000	0.000	0.000	0.000	0.941		
12.	B-LA-D-PVAc-18	0.592	0.000	0.000	0.000	0.078	0.000	0.000	0.000	0.001	0.516	0.544	

Table 22. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendC}) for beech and NWC on top.

No.	Type of Sample	**(1)** **0.024**	**(2)** **0.026**	**(3)** **0.011**	**(4)** **0.037**	**(5)** **0.031**	**(6)** **0.014**	**(7)** **0.044**	**(8)** **0.025**	**(9)** **0.008**	**(10)** **0.033**	**(11)** **0.032**	**(12)** **0.013**
1.	B-CA-U-PUR-6												
2.	B-CA-U-PUR-10	0.174											
3.	B-CA-U-PUR-18	0.000	0.000										
4.	B-CA-U-PVAc-6	0.000	0.000	0.000									
5.	B-CA-U-PVAc-10	0.000	0.006	0.000	0.001								
6.	B-CA-U-PVAc-18	0.000	0.000	0.062	0.000	0.000							
7.	B-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8.	B-LA-U-PUR-10	0.689	0.296	0.000	0.000	0.000	0.000	0.000					
9.	B-LA-U-PUR-18	0.000	0.000	0.060	0.000	0.000	0.000	0.000	0.000				
10.	B-LA-U-PVAc-6	0.000	0.000	0.000	0.017	0.304	0.000	0.000	0.000	0.000			
11.	B-LA-U-PVAc-10	0.000	0.001	0.000	0.005	0.581	0.000	0.000	0.000	0.000	0.585		
12.	B-LA-U-PVAc-18	0.000	0.000	0.313	0.000	0.000	0.333	0.000	0.000	0.006	0.000	0.000	

Table 23. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for aspen and NWC on the bottom.

No.	Type of Sample	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		0.019	**0.014**	**0.013**	**0.026**	**0.024**	**0.014**	**0.024**	**0.021**	**0.019**	**0.027**	**0.018**	**0.014**
1.	A-CA-D-PUR-6												
2.	A-CA-D-PUR-10	0.004											
3.	A-CA-D-PUR-18	0.003	0.936										
4.	A-CA-D-PVAc-6	0.000	0.000	0.000									
5.	A-CA-D-PVAc-10	0.004	0.000	0.000	0.124								
6.	A-CA-D-PVAc-18	0.003	0.996	0.937	0.000	0.000							
7.	A-LA-D-PUR-6	0.005	0.000	0.000	0.105	0.859	0.000						
8.	A-LA-D-PUR-10	0.112	0.000	0.000	0.005	0.153	0.000	0.181					
9.	A-LA-D-PUR-18	0.918	0.005	0.004	0.000	0.003	0.004	0.005	0.110				
10.	A-LA-D-PVAc-6	0.000	0.000	0.000	0.808	0.093	0.000	0.074	0.003	0.000			
11.	A-LA-D-PVAc-10	0.503	0.021	0.020	0.000	0.001	0.018	0.001	0.034	0.540	0.000		
12.	A-LA-D-PVAc-18	0.005	0.844	0.795	0.000	0.000	0.837	0.000	0.000	0.006	0.000	0.022	

Table 24. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for aspen and NWC on top.

No.	Type of Sample	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		0.012	**0.015**	**0.007**	**0.026**	**0.023**	**0.008**	**0.021**	**0.015**	**0.010**	**0.028**	**0.015**	**0.011**
1.	A-CA-U-PUR-6												
2.	A-CA-U-PUR-10	0.002											
3.	A-CA-U-PUR-18	0.000	0.000										
4.	A-CA-U-PVAc-6	0.000	0.000	0.000									
5.	A-CA-U-PVAc-10	0.000	0.000	0.000	0.005								
6.	A-CA-U-PVAc-18	0.004	0.000	0.393	0.000	0.000							
7.	A-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.153	0.000						
8.	A-LA-U-PUR-10	0.003	0.820	0.000	0.000	0.000	0.000	0.000					
9.	A-LA-U-PUR-18	0.071	0.000	0.056	0.000	0.000	0.242	0.000	0.000				
10.	A-LA-U-PVAc-6	0.000	0.000	0.000	0.024	0.000	0.000	0.000	0.000	0.000			
11.	A-LA-U-PVAc-10	0.002	0.997	0.000	0.000	0.000	0.000	0.000	0.810	0.000	0.000		
12.	A-LA-U-PVAc-18	0.480	0.000	0.003	0.000	0.000	0.024	0.000	0.000	0.226	0.000	0.000	

Table 25. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for beech and NWC on the bottom.

No.	Type of Sample	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
		0.023	**0.015**	**0.015**	**0.028**	**0.021**	**0.014**	**0.030**	**0.015**	**0.016**	**0.023**	**0.024**	**0.022**
1.	B-CA-D-PUR-6												
2.	B-CA-D-PUR-10	0.000											
3.	B-CA-D-PUR-18	0.000	0.973										
4.	B-CA-D-PVAc-6	0.000	0.000	0.000									
5.	B-CA-D-PVAc-10	0.455	0.000	0.000	0.000								
6.	B-CA-D-PVAc-18	0.000	0.428	0.416	0.000	0.000							
7.	B-LA-D-PUR-6	0.000	0.000	0.000	0.179	0.000	0.000						
8.	B-LA-D-PUR-10	0.000	0.977	0.954	0.000	0.000	0.431	0.000					
9.	B-LA-D-PUR-18	0.000	0.524	0.521	0.000	0.000	0.178	0.000	0.514				
10.	B-LA-D-PVAc-6	0.863	0.000	0.000	0.001	0.382	0.000	0.000	0.000	0.000			
11.	B-LA-D-PVAc-10	0.291	0.000	0.000	0.007	0.087	0.000	0.000	0.000	0.000	0.340		
12.	B-LA-D-PVAc-18	0.473	0.000	0.000	0.000	0.935	0.000	0.000	0.000	0.000	0.405	0.094	

Table 26. Comparison of the effects of individual factors using Duncan's test on the coefficient of bendability (K_{bendB}) for beech and NWC on top.

No.	Type of Sample	(1) 0.016	(2) 0.017	(3) 0.006	(4) 0.024	(5) 0.021	(6) 0.009	(7) 0.030	(8) 0.016	(9) 0.005	(10) 0.022	(11) 0.022	(12) 0.008
1.	B-CA-U-PUR-6												
2.	B-CA-U-PUR-10	0.398											
3.	B-CA-U-PUR-18	0.000	0.000										
4.	B-CA-U-PVAc-6	0.000	0.000	0.000									
5.	B-CA-U-PVAc-10	0.000	0.002	0.000	0.003								
6.	B-CA-U-PVAc-18	0.000	0.000	0.014	0.000	0.000							
7.	B-LA-U-PUR-6	0.000	0.000	0.000	0.000	0.000	0.000						
8.	B-LA-U-PUR-10	0.682	0.621	0.000	0.000	0.000	0.000	0.000					
9.	B-LA-U-PUR-18	0.000	0.000	0.690	0.000	0.000	0.006	0.000	0.000				
10.	B-LA-U-PVAc-6	0.000	0.000	0.000	0.031	0.329	0.000	0.000	0.000	0.000			
11.	B-LA-U-PVAc-10	0.000	0.000	0.000	0.032	0.303	0.000	0.000	0.000	0.000	0.902		
12.	B-LA-U-PVAc-18	0.000	0.000	0.038	0.000	0.000	0.615	0.000	0.000	0.018	0.000	0.000	

As shown in Figure 4, the greatest K_{bendC} values in the aspen samples were found in the samples with thicknesses of 6 mm and 10 mm with a carbon fiber non-wood component placed on the bottom of the laminated material. These lamellas were bonded with PVAc adhesive. By contrast, the lowest K_{bendC} values were found in 18 mm thick lamellas, where the non-wood component was placed on the top of the laminated material. In the samples with a carbon fiber non-wood component, the effect of the adhesive used was also significant. The 6 mm thick and 10 mm thick samples with carbon fibers on the top of the material glued with PUR adhesive had significantly lower values (by more than 50%) than all the other samples.

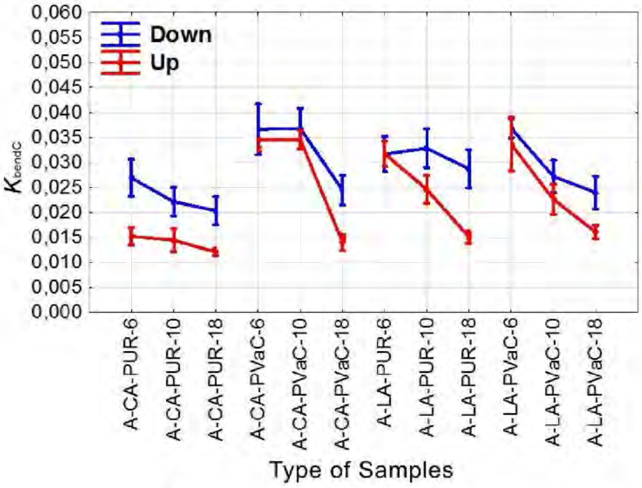

Figure 4. K_{bendC} in case of aspen.

The situation was similar with beech lamellas (Figure 5). The greatest K_{bendC} values were found in the beech samples with a 6 mm thickness, but unlike the aspen lamellas, no significant differences were found when different types of non-wood components were used. As with aspen lamellas, the lowest K_{bendC} values were measured in lamellas with a thickness of 18 mm. The lamella thickness affected the bending coefficient. In beech samples, there was one extreme in the case of lamellas with glass fibers bonded with PVAc adhesive. The values measured on these 6 mm thick and 18 mm thick samples were no different from those measured on the 10 mm thick samples.

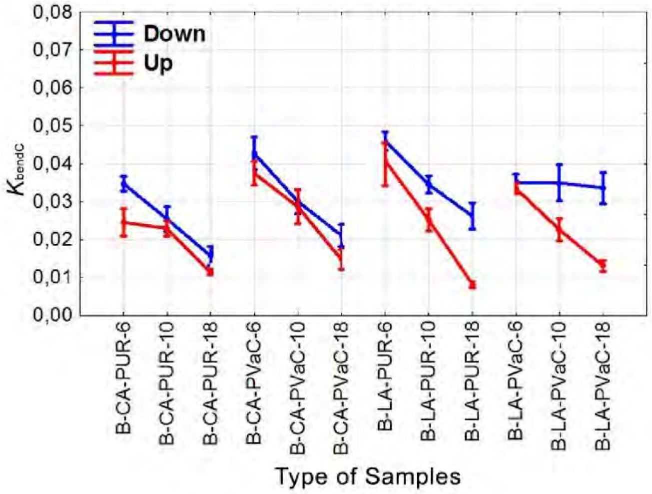

Figure 5. K_{bendC} in case of beech.

Figure 6 shows that the K_{bendB} values were affected most by the material thickness. Materials with lower thicknesses had greater K_{bendB} values. The greatest K_{bendB} values in the aspen lamellas were reached in samples with a non-wood component on the bottom of the laminated material. These lamellas were bonded with PVAc adhesive, and the non-wood component had no influence on these values. By contrast, the lowest values were measured in the aspen lamellas with carbon fibers on the top side of the material and bonded with PUR adhesive. The lowest K_{bendB} values were also found in the samples with a carbon fiber non-wood component placed on the top of the material. In the 6 mm thick and 10 mm thick samples bonded with PUR adhesive with a non-wood carbon fiber component, the values were more than 50% lower than in the samples bonded with PVAc adhesive.

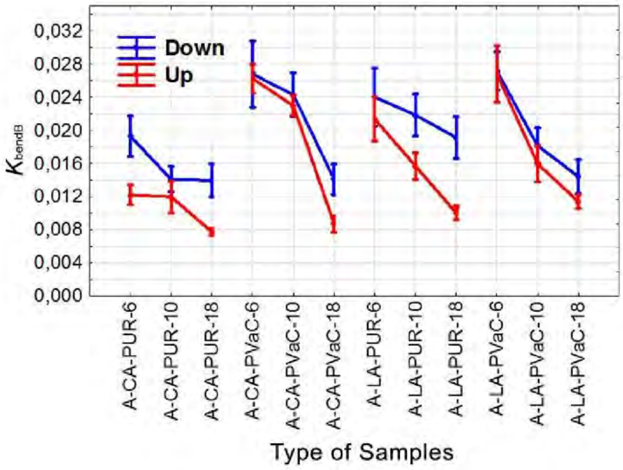

Figure 6. K_{bendB} in case of aspen.

The lowest K_{bendB} values in the beech samples were measured in the 18 mm thick samples bonded with PUR adhesive (Figure 7). In similar samples bonded with PVAc adhesive, the samples reached about 30% greater values. The highest K_{bendB} values were measured in the 6 mm thick beech samples, but unlike aspen lamellas, no significant differences were found with the use of different types of non-wood components and adhesives. As in aspen lamellas, the lowest K_{bendB} values were measured in the 18 mm thick lamellas. The lamella thickness affected the bending coefficient.

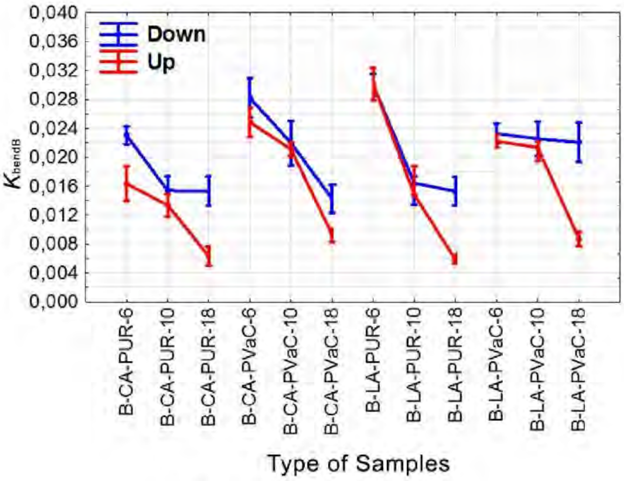

Figure 7. K_{bendB} in case of beech.

4. Conclusions

1. The type and position of the non-wood component used in the laminated materials had a significant effect on all the observed characteristics: K_{bendC}, K_{bendB}, R_{minC}, and R_{minB}.
2. Bending coefficient values based on the simple bending equation (K_{bendC}) tended to be greater than bending coefficient values based on bending geometry (K_{bendB}).
3. The greatest values of the bending coefficient based on the simple bending equation (K_{bendC}) and the bending coefficient based on bending geometry (K_{bendB}) were generally found in materials of lower thickness.
4. No rule was observed for the high or low measured values of the observed characteristics (K_{bendC}, K_{bendB}, R_{minC}, and R_{minB}) in relation to the wood species used.

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9.8 Manuskript číslo 1., Properties of Wood-Based Composited Manufactured of Densified Beech Wood in Viscoelastic and Plastic Region Force-Deflection Diagram (FDD)

Properties of wood-based composites manufactured of densified beech wood in viscoelastic and plastic region force - deflection diagram (FDD)

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ABSTRACT

There is still little or no knowledge about the properties of layered wood-based composites and non-wood components in the viscoelastic and plastic region of the force - deflection diagram (FDD). The properties of composites in this area are influenced by a number of factors such as the composition of the layered composite, the method of modification of the individual layers, the type of adhesive used, etc. This paper focuses on the analysis of the effect of the thickness of individual layers (5 mm, 9 mm) of beech wood (*Fagus sylvatica* L), modification of these layers with different degrees of densification (10%, 20%, 30%, 40%) and the type of non-wood component (carbon and high-strength glass fibers) used to reinforce the layered composite on the properties of materials in the plastic region of the force - deflection diagram (FDD). The paper describes the impact of selected factors and those interactions behavior of the tangent modulus in the whole force – deflection diagram.

Keywords: layered composite material, tangent modulus, chord modulus, wood bending, bending

INTRODUCTION

Wood is one of the most preferred building materials by architects and engineers due to its high specific strength, renewability, carbon locking ability and ease of processing with minimal energy. Besides, the properties of wood can also be engineered to meet specific requirement by various technological inventions such as densification, modification (chemical and thermal) as well as by composites. Creation of a wood-based composite with specific properties for a given purpose of use is currently one of the most progressive areas of research. As the name suggest, wood composite refers to a material composed of two or more components with wood as the major component. The individual components are connected by a binder. In order to develop a composite with improved material properties, it is essential to know the properties of each component [1]. With the

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information on the properties of each component and the ways to improve the properties, it is possible to control the properties of the composite for any given end application [2]. As wood is a biological material with anisotropic properties (different properties in orthogonal directions), it is necessary to minimize the anisotropy and improve its properties so that the composite can have desired properties for any given end application.

Knowledge of the properties of homogeneous as well as composite materials in the plastic region is of considerable practical importance [3]. Availability of relevant information on the material properties and the factors that affect them can help to model new composite structures with desirable properties [4]. Recently, there has been greater emphasis on the use of optimized materials [5]. Optimized material refers to materials having appropriate properties in ideal synergy with the end application. The properties of the optimized materials can be modified in various ways in the composite by using appropriate adhesive, appropriate alignment and placement of individual layers, suitable non-biological components and nanomaterials [6]. If such conditions are met, then a layer of a suitably selected wood with specific properties for the given purpose of use can also be considered as an optimized material. On the contrary, an unsuitable way of applying an expensive and sophisticated composite material results in its poor performance [7].

Layered wood-based composite materials can be categorized into five basic groups:

1. Parallel layers:
    - bonded layered wood
    - layered veneer
2. Cross-layers:
    - plywood materials
    - veneered boards with oriented strands
3. Reinforced wood
4. Sandwich panels
5. Mechanically bonded laminates [3]

The name of these groups indicates the type of wood components used, the orientation of fibers in individual layers and reinforcement. As these layered composites have different properties, it shows how the material type, orientation and reinforcement are important parameters in controlling the final properties of the composite [8; 9; 10]. The present study focuses on a composite material layered in parallel.

Layered composites are characterized by a wide range of uses. Wood in its natural form is characterized by the occurrence of structural deviations (defects), which increase its heterogeneity and reduce its load-bearing capacity when used as beams. [11; 12]. By cutting the beam into thin layers (lamellas) and then gluing them together with a random arrangement of defects, a beam with higher strength can be achieved, but not necessarily with increased stiffness. By arranging the lamellas so that lamellas with a higher number of defects are in the central part of the beam, its mechanical properties can be increased. A way to improve the properties of the laminated beam even more significantly is the elimination of all defects, or the densification of individual lamellas and subsequent layering of the bonded lamellas. The highest improvement can be achieved by combining laminated wood with an element with increased strength and stiffness [3; 13; 14]. Properties of wood-based composites are less heterogenous as compared to solid wood (Fig. 1). Strength distribution in glued laminated wood is therefore narrower and higher than its distribution in solid wood. The value of the fifth percentile, which is used to design wooden structures, is shifted to the right, as is the average strength value [15].

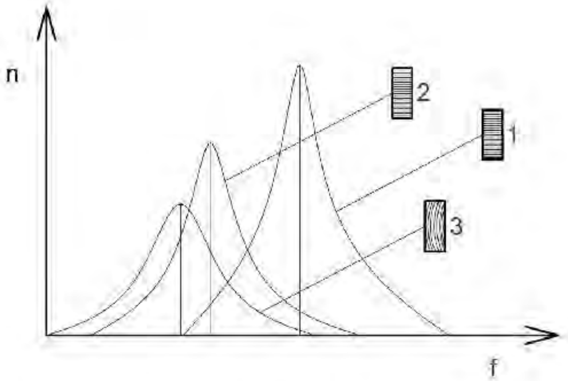


Fig. 1. Characteristics of laminated reinforced wood (1) compared with the strength distribution of laminated wood (2) and solid wood (3), n – Frequency, f – Material property value

The surface layers in layered wood composites play an important role as these layers experience the maximum stresses when the materials are loaded. There are currently a number of ways of strengthening or improving the quality of surface layers. The most common improvement method used in parallel layered wood composites is the densification of wood layers or its reinforcement with non-wood components based on high-strength carbon and glass fibers. A common disadvantage of these composite structures is delamination which, in the case of these materials, manifests itself in the form of multiple cracks. Local instability and crack growth in glued laminated timber can cause overall instability of large structural elements, which can even lead to failure of the entire structure in extreme cases [16; 17; 18; 19].

It is obvious that the type and quality of the adhesive used also plays an important role in the direction in which the strength properties of the layered material will move under stress. Selecting the type and form of adhesive depends on the nature of the adherents, the end-use requirements and the gluing processes [20]. A number of different adhesives are used for wood composites. Thermoset adhesives based on the use of formaldehyde resins obtained by polycondensation have dominated the woodworking industry for many years. Other products such as acrylate and polyvinyl acetate adhesives, which have long been proven in the woodworking industry, as well as newer products such as isocyanate and single-component polyurethane adhesives also finds application in wood-based industries [21].

Mostly the load and corresponding deflections within elastic region and breaking load are taken into account to calculate the modulus of elasticity (MOE) and strength of wood respectively. However, the shape of the force deflection diagram (FDD) in the plastic region is very crucial to ascertain the behavior of the material beyond the recoverable deformation. The purpose of this study was to improve the material property of layered composites through densification of wood lamellas as well as reinforcement with stiffer material (carbon and glass fibers) and assess the properties of the layered composites in the plastic zone. The material properties in the plastic zone were ascertained by calculating the tangent moduli. The tangent modulus at any stress refers to the slope of the tangent with respect to the horizontal axis. The tangent modulus within the limit of proportionality (elastic region) is constant and equivalent to Young's modulus of elasticity, while the values of tangent modulus beyond the elastic region are different and decreases until the sample fails [22]. As tangent modulus can be calculated at any specified stress or strain, and its value keeps changing in the plastic zone, it can serve as an ideal tool to compare the properties and behavior of different laminates in plastic zone.

Material and Method

Material

The experiment was carried out using radial beech wood (*Fagus silvatica* L.) lamellas. The lamellas were produced in two thickness of 5 and 9 mm, and the constant width of the lamellas was 35 mm. The length of the individual lamellas was determined so that it was possible to test the test specimens at 20 times the span of the lower supports of the test device (140, 220, 240 and 400 mm). Another material in the tested layered material was a reinforcing component in the form of high-strength fiber fabrics. Two types of fabrics were used, the first based on high-strength SikaWrap 150C/30 carbon fibers (SIKA CZ), and the second based on type E glass fibers (KITTFORT). All components in the composite were glued together using single-component PVAc adhesive (AG-COLL 8761/L D3). The adhesive was applied unilaterally manually with a spread in the range of 150-180 g/m^2.

Methods

Lamella densification

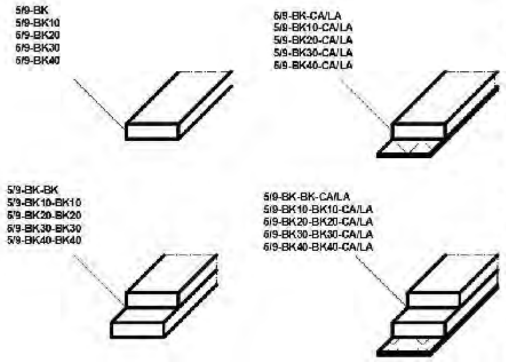
The individual input lamellas were densified by a standard thermo-mechanical method in double-sided heated press TOS Rakovník at a temperature of 140 °C (± 5 °C). The densification was performed in four stages (10, 20, 30 and 40%) with respect to the original thickness of the lamellas. An overview of the basic pressing parameters can be seen in Table 1. The densification resulted in a change in moisture content and density; these parameters were determined according to the relevant standards [23; 24].

Table. 1. Technical parameters of the pressing process

	Pressure (MPa)	Time (min.)
5 mm lamellas (10%)	30.2	5
9 mm lamellas (10%)	37.7	9
5 mm lamellas (20%)	31.5	6
9 mm lamellas (20%)	39.3	10
5 mm lamellas (30%)	34.2	7
9 mm lamellas (30%)	42.7	11
5 mm lamellas (40%)	36.3	8
9 mm lamellas (40%)	43.4	12

Creation of test sets

After the modification of the lamellas, layered materials were produced using other components listed in the materials section above. The tested sets can be classified as single-layer (default), two-layer without a non-wood component, two-layer with a non-wood component and three-layer with a non-wood component. A total of 60 test sets were created. Each test set consisted of 30 test specimens. A basic diagram of test sets with identification of individual materials in the composite can be seen in Figure 2.



5/9-BK	Single-layer: 5 or 9 mm material thickness, Beech wood
5/9-BK10	Single-layer: 5 or 9 mm material thickness, Beech wood
5/9-BK20	Single-layer: 5 or 9 mm material thickness, Beech wood
5/9-BK30	Single-layer: 5 or 9 mm material thickness, Beech wood
5/9-BK40	Single-layer: 5 or 9 mm material thickness, Beech wood
5/9-BK-BK	Two-layer without NWC: 5 or 9 mm material thickness, Beech wood
5/9-BK10-BK10	Two-layer without NWC: 5 or 9 mm material thickness, Beech wood densified on 10% of thickness + Beech wood densified on 10% of thickness
5/9-BK20-BK20	Two-layer without NWC: 5 or 9 mm material thickness, Beech wood densified on 10% of thickness + Beech wood densified on 10% of thickness
5/9-BK30-BK30	Two-layer without NWC: 5 or 9 mm material thickness, Beech wood densified on 10% of thickness + Beech wood densified on 10% of thickness
5/9-BK40-BK40	Two-layer without NWC: 5 or 9 mm material thickness, Beech wood densified on 10% of thickness + Beech wood densified on 10% of thickness
5/9-BK-CA/LA	Two-layer with NWC: 5 or 9 mm material thickness, Beech wood + CA - Cart or LA - glass fibers
5/9-BK10-CA/LA	Two-layer with NWC: 5 or 9 mm material thickness, Beech wood densified o 10% of thickness + CA - Carbon or LA - glass fibers
5/9-BK20-CA/LA	Two-layer with NWC: 5 or 9 mm material thickness, Beech wood densified o 20% of thickness + CA - Carbon or LA - glass fibers
5/9-BK30-CA/LA	Two-layer with NWC: 5 or 9 mm material thickness, Beech wood densified o 30% of thickness + CA - Carbon or LA - glass fibers
5/9-BK40-CA/LA	Two-layer with NWC: 5 or 9 mm material thickness, Beech wood densified o 40% of thickness + CA - Carbon or LA - glass fibers
5/9-BK-BK-CA/LA	Three-layer with non-wood component:5 or 9 mm material thickness, Beech wood + Beech wood + CA - Carbon or LA - glass fibers
5/9-BK10-BK10-CA/LA	Three-layer with non-wood component:5 or 9 mm material thickness, Beech wood densified on 10% of thickness + Beech wood densified on 10% of thickness + CA - Carbon or LA - glass fibers
5/9-BK20-BK20-CA/LA	Three-layer with non-wood component:5 or 9 mm material thickness, Beech wood densified on 20% of thickness + Beech wood densified on 20% of thickness + CA - Carbon or LA - glass fibers
5/9-BK30-BK30-CA/LA	Three-layer with non-wood component:5 or 9 mm material thickness, Beech wood densified on 30% of thickness + Beech wood densified on 30% of thickness + CA - Carbon or LA - glass fibers
5/9-BK40-BK40-CA/LA	Three-layer with non-wood component:5 or 9 mm material thickness, Beech wood densified on 40% of thickness + Beech wood densified on 40% of thickness + CA - Carbon or LA - glass fibers

Fig. 2. Types of test sets

In Figure 3 (a-f) can be seen representative photo of individual test group.

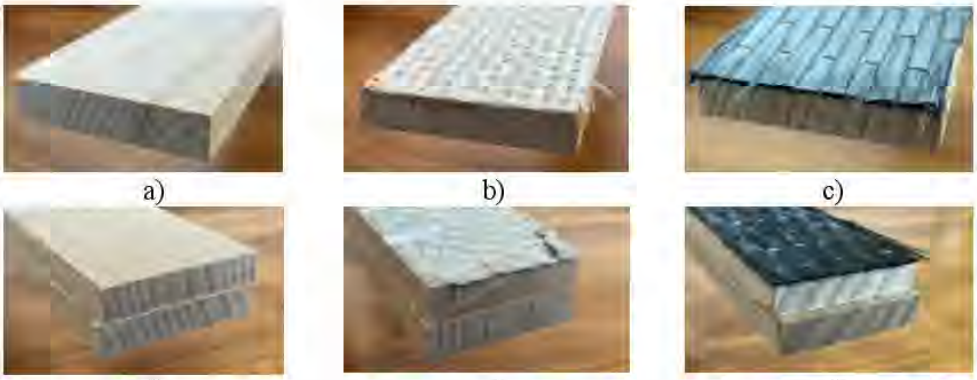

a) b) c)
d) e) f)

Fig. 3. Representative photo of individual test group a) single layer, b) two layered with glass fibers, c) two layered with carbon fibers, d) two layered without NWC, e) three layered with glass fibers, f) three layered with carbon fibers

In figure 4a and 4b is shown density profile for each types of test samples. The effect of density changed by the densification process is evident. However, it is also possible to observe inefficient densification at higher degrees of densification (30-40%), which is given by the chosen densification method. It is possible to observe slightly different trends of changes in tangent modulus at 5 mm and 9 mm densified lamellae. Changes in density profiles explaining the different changes in the tangent modulus of the different types of lamellae can be seen in figure 4a and 4b.

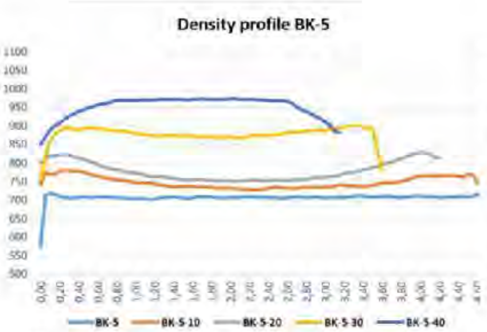


Fig. 4a. Density profile each types of test sets made from 5 mm lamellas

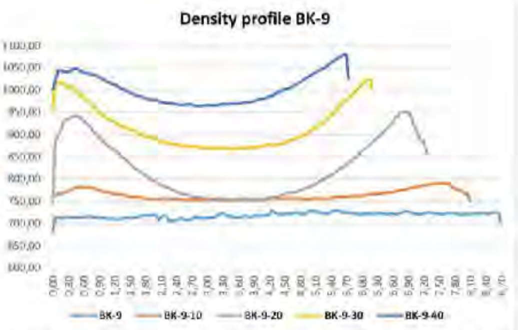


Fig. 4b. Density profile each types of test sets made from 9 mm lamellas

Mechanical testing

The monitored mechanical characteristics were obtained by three-point bending with a methodology corresponding to standard EN 310 [25]. The principle of three-point bending consists in loading an element with an insulated force in the middle of its length according to the diagram in Figure 4. Testing was performed on universal testing machine FPZ 100. Important parameters of the testing itself include the loading speed (3 mm/min), so that the testing itself is 30-90 s long, as well as the variable span of the lower support pins so that it corresponds to 20 times the thickness for all tested specimens.

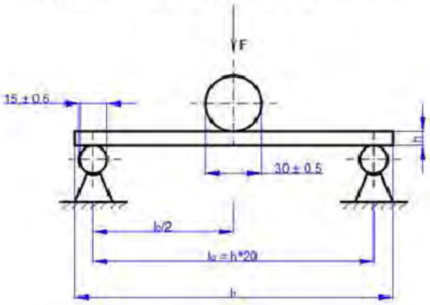


Fig. 4. Diagram of three-point bending test according to EN 310 1993

Evaluation and Calculation

Processing the force-displacement diagram (FDD)

Our measurements showed that the non-linear part of the FDD can be described by a second-degree parabola with the index of determination close to 0.999. The different stages of the FDD evaluation are shown in Fig. 5. The last part of this figure (Fig. 5d) shows the two derivations – one is the numerical derivation based on the data, the second is obtained from the derivation of the parabolic equation. The agreement of these two can be considered proof of the correct approach.

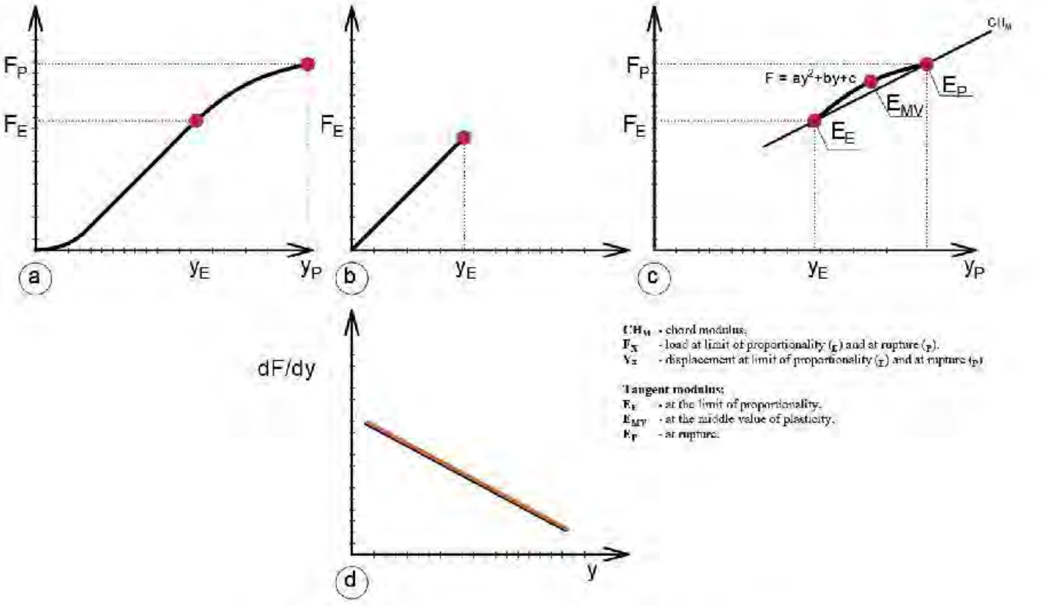


Fig. 5. Different stages of the FDD evaluation

Tangent and chord modulus

The tangent modulus is defined as the first derivative of either the force – deflection or the force-displacement diagram. In the elastic region it is a constant – modulus of elasticity, or the following value:

$$\frac{F_E}{y_E} = \frac{E_A.48.I}{l_0^3} \tag{1}$$

For description of non-elastic region of force deflection diagram can be used equation for second degree parabola (2).

$$F = a.y^2 + b.y + c \tag{2}$$

The tangent modulus of the force – displacement diagram becomes:

$$\frac{\partial F}{\partial y} = 2.a.y + b \tag{3}$$

For the tangent moduli and chord modulus for 3-point bending, the following equations applies:

$$E_E = \frac{F_E}{y_E} \cdot \frac{l_0^3}{48I} \tag{4}$$

$$E_{MV} = \frac{F_{MV}}{y_{MV}} \cdot \frac{l_0^3}{48I} \tag{5}$$

$$E_P = \frac{F_P}{y_P} \cdot \frac{l_0^3}{48I} \tag{6}$$

$$CH_M = \frac{F_P - F_E}{y_P - y_E} \cdot \frac{l_0^3}{4bh^3} \tag{7}$$

where F_P is the force at the elastic limit (N), F_E is the force at the proportionality limit (N), y_P is the deflection at the modulus of rupture (mm), and y_E is the proportionality limit (mm), y_{MV} is the deflection expressed as the average value between y_E and y_P (mm), l_0 is the span of the support during bending (mm), b (width) and h (thickness) are the cross-sectional dimensions of the test specimen (mm).

The standard for testing moduli of elasticity requires the fulfilment of the condition $l_0 = 20.h$. Then we can introduce the constant K:

$$\mathrm{K} = \frac{l_0^3}{4bh^3} \tag{8}$$

If the above-mentioned condition is not strictly fulfilled, it can be a source of substantial errors.

Statistical analysis

To evaluate the results, a four-factor analysis of variance of the effect of individual factors on the characteristics was used. Based on the P-level value, it was determined whether a factor affected the values of monitored characteristics. Diagrams were constructed for the 95% confidence interval, and the results were verified with Duncan's tests and also Spearman's rank-order correlation was carried out.

RESULTS AND DISCUSSION

Table 2 shows the average values of the chord modulus (CH_M) and tangent moduli at point of elasticity (E_E), at the middle point (E_{MV}) and at the point of modulus of rupture (E_P) as well as the corresponding coefficient of variation for all test groups. At the table are also evident changes in density caused by densification. In terms of the percentage change of the Chord modulus, we can see that the highest percentage change is recorded in modification by densification, and we can say that there was a higher increase in values in 5 mm lamellas. From the perspective of layering and densification, we can see that the largest increase in values is recorded in layered composites with lamellas densified by 20%. The trend observed when high-strength fibers are applied is not one-sided. In terms of percentage changes of E_E in single-layer and two-layer unreinforced materials, there is a similar trend as in the C_{HM}. An interesting trend of changes in values with respect to the thickness of the lamellas can be seen in reinforced two-layer materials; greater changes can be seen in the application of carbon fibers in 5 mm materials, with an opposite trend in 9 mm materials. Looking at the three-layer materials, this trend is ambiguous with densification; above 20%, the trend of changes reversed in the opposite direction. The percentage changes in the tangent modulus E_{MV} shown largely copy the trend of changes in the case of the Chord modulus. When the greatest changes were caused by densification of individual layers, in terms of layering using densified lamellas, in the application of lamellas densified by 30 and 40% a decline in the change was recorded again. Looking at the changes in tangent modulus at the modulus of rupture "E_P", it is possible to see a significant change in the monitored values caused by the densification of individual lamellas; as in previous cases, this change was affected by the input thickness of the lamellas. From the perspective of layering itself, we can observe an increase in values up to the application of lamellas densified by 20%, with a subsequent decrease in glued materials composed of lamellas with 30 and 40% densification. According coefficients of correlations made between density of the lamellas and monitored characteristics of plasticity, is clear that the correlation is mostly mean. Correlations made between degree of the lamellas and monitored characteristics of plasticity, is mostly small and between non-wood components of the lamellas and monitored characteristics of plasticity, is mostly small or trivial.

Table 2. Mean values of CH_M, E_E, E_{MV} and E_P and for the individual sets of test specimens and the coefficient of variation for Beech wood

	Code	**CH_M (MPa)**	**“r” “r_{II}” “r_{III}”**	**E_E (MPa)**	**“r” “r_{II}” “r_{III}”**	**E_{MV} (MPa)**	**“r” “r_{II}” “r_{III}”**	**E_P (MPa)**	**“r” “r_{II}” “r_{III}”**	**Density (kg/m^3)**	**No.**
Single-layer	**5-BK**	6314 (14.9)		10761 (10.6)		6193 (15.6)		5116 (2.5)		687.90 (5.3)	30
	5-BK10	10461 (12.7)		15651 (10.0)		10340 (12.9)		9960 (3.1)		789.59 (3.7)	30
	5-BK20	10209 (10.1)		14871 (8.9)		10103 (10.1)		9747 (5.3)		828.98 (3.7)	30
	5-BK30	9659 (13.4)		14000 (15.2)		9544 (13.6)		8262 (9.8)		914.20 (7.1)	30
	5-BK40	10198 (11.4)	***	15891 (11.2)	***	10042 (11.4)	***	9263 (6.6)	***	995.95 (5.8)	30
	9-BK	6747 (18.8)	***	10286 (14.6)	***	6656 (18.8)	***	5356 (10.1)	***	699.50 (6.7)	30
	9-BK10	8294 (16.3)		11325 (17.9)		8125 (20.5)		7801 (3.7)		730.84 (4.1)	30
	9-BK20	9038 (11.0)		12595 (9.6)		8986 (11.2)		7824 (7.2)		817.99 (3.7)	30
	9-BK30	8529 (17.9)		12068 (15.2)		8395 (18.7)		7340 (12.2)		902.29 (4.5)	30
	9-BK40	9124 (17.0)		13301 (15.5)		8962 (19.5)		7129 (5.7)		1007.63 (4.2)	30
Two-layer without NWC	**5-BK-BK**	6823 (22.5)		11067 (11.7)		6731 (22.8)		5171 (7.5)		698.77 (5.4)	30
	5-BK10-BK10	8394 (8.2)		13154 (9.1)		8274 (8.4)		7152 (7.5)		783.35 (2.6)	30
	5-BK20-BK20	9152 (18.3)		13675 (9.9)		8990 (19.0)		7181 (7.1)		842.05 (4.1)	30
	5-BK30-BK30	7451 (15.7)		12390 (10.8)		7347 (16.5)		6066 (4.6)		890.74 (5.2)	30
	5-BK40-BK40	6960 (18.5)	**	11719 (17.2)	***	6723 (20.9)	**	5382 (10.9)	*	912.65 (11.8)	30
	9-BK-BK	6909 (12.3)	*	10260 (16.1)	**	6808 (12.2)	*	6202 (7.0)	*	705.57 (3.6)	30
	9-BK10-BK10	7594 (18.6)		10123 (14.7)		7477 (19.7)		6535 (5.4)		741.68 (3.3)	30
	9-BK20-BK20	8632 (13.2)		11538 (14.4)		8473 (13.2)		7082 (5.9)		836.01 (4.0)	30
	9-BK30-BK30	7548 (16.4)		11075 (10.6)		7417 (17.4)		6482 (5.3)		870.08 (4.2)	30
	9-BK40-BK40	7829 (18.1)		11969 (10.8)		7697 (18.6)		6282 (13.1)		978.55 (3.7)	30
Two-layer with NWC	**5-BK-CA**	5517 (17.6)		11434 (18.2)		5283 (18.2)		4471 (18.4)		712.33 (4.7)	30
	5-BK-LA	5527 (18.7)		10424 (11.7)		5338 (19.4)		4372 (11.5)		757.52 (5.2)	30
	5-BK10-CA	6815 (18.3)		11349 (13.7)		6673 (19.0)		5110 (8.5)		763.99 (5.5)	30
	5-BK10-LA	6051 (11.3)		11096 (12.5)		5905 (12.1)		4399 (9.7)		786.06 (3.3)	30
	5-BK20-CA	7403 (17.8)		12402 (14.9)		7278 (18.1)		6373 (7.7)		863.56 (5.4)	30
	5-BK20-LA	6235 (16.8)		11471 (14.1)		6034 (18.3)		5626 (7.4)		833.06 (5.2)	30
	5-BK30-CA	6071 (10.3)	**	15986 (11.6)	***	5517 (13.2)	*	4596 (19.3)	**	901.36 (7.8)	30
	5-BK30-LA	6712 (16.3)	**	12208 (14.8)	***	6498 (16.9)	*	5153 (9.8)	**	989.08 (4.0)	30
	5-BK40-CA	6934 (14.2)	**	17671 (11.3)	***	6401 (17.4)	*	5586 (9.7)	**	1107.10 (4.9)	30
	5-BK40-LA	6383 (18.9)		12006 (19.1)		6208 (20.0)		5589 (9.2)		1102.85 (4.4)	30
	9-BK-CA	5900 (19.3)		10545 (17.8)		5806 (19.3)		4218 (18.4)		705.31 (5.0)	30
	9-BK-LA	6060 (19.5)		10693 (19.6)		5909 (20.0)		4713 (9.1)		745.78 (4.2)	30
	9-BK10-CA	6988 (17.6)		11176 (14.3)		6939 (17.2)		5516 (8.4)		734.97 (5.5)	30
	9-BK10-LA	6762 (14.3)		11839 (15.0)		6599 (14.3)		5717 (8.8)		800.38 (4.9)	30
	9-BK20-CA	6950 (12.3)		11616 (15.9)		6832 (12.3)		5878 (10.0)		816.33 (5.3)	30

	9-BK20-LA	7333 (16.5)		13461 (11.9)		7071 (17.6)		5847 (5.9)		884.08 (3.4)	30
	9-BK30-CA	6772 (14.2)		14675 (12.2)		6366 (16.1)		4917 (8.2)		931.14 (4.6)	30
	9-BK30-LA	5138 (16.7)		8771 (14.7)		4987 (17.9)		3122 (15.3)		935.67 (4.1)	30
	9-BK40-CA	6714 (12.2)		14812 (11.8)		6244 (14.0)		5088 (7.4)		1032.16 (2.4)	30
	9-BK40-LA	6001 (21.2)		9918 (16.8)		5827 (23.3)		4407 (7.5)		1060.78 (3.1)	30
Three-layer with non-wood component	**5-BK-BK-CA**	6294 (21.1)		10510 (13.0)		6198 (21.5)		5016 (7.5)		701.95 (5.3)	30
	5-BK-BK-LA	5746 (19.2)		9717 (14.9)		5654 (19.6)		4010 (10.7)		705.44 (5.8)	30
	9-BK-BK-CA	7001 (26.6)		10976 (18.2)		6921 (27.9)		5393 (6.5)		688.55 (5.6)	30
	9-BK-BK-LA	7101 (18.4)		11914 (10.9)		6980 (18.9)		5371 (21.1)		716.69 (5.9)	30
	5-BK10-BK10-CA	8274 (20.2)		12592 (16.2)		8172 (21.2)		7279 (4.9)		762.53 (5.9)	30
	5-BK10-BK10-LA	7351 (12.5)		13263 (9.7)		7202 (13.0)		7178 (5.8)		777.30 (4.4)	30
	9-BK10-BK10-CA	6625 (11.3)		15342 (9.8)		6246 (13.2)		5118 (8.1)		724.13 (6.1)	30
	9-BK10-BK10-LA	6886 (17.1)		12203 (20.8)		6721 (18.0)		5110 (7.8)		784.28 (4.0)	30
	5-BK20-BK20-CA	8734 (17.9)	***	18552 (12.8)	****	8259 (18.9)	***	7202 (5.7)	***	848.82 (5.2)	30
	5-BK20-BK20-LA	6178 (18.9)	**	11358 (22.3)	***	6047 (18.9)	**	5313 (6.5)	***	829.66 (9.7)	30
	9-BK20-BK20-CA	5821 (17.7)	*	10171 (14.7)	**	5704 (17.4)	*	4091 (10.0)	**	812.26 (5.0)	30
	9-BK20-BK20-LA	5900 (18.2)		9411 (20.9)		5800 (18.3)		4020 (8.1)		865.88 (3.1)	30
	5-BK30-BK30-CA	5475 (16.8)		11233 (14.7)		5298 (17.7)		4522 (6.4)		899.00 (4.8)	30
	5-BK30-BK30-LA	7047 (15.2)		10898 (10.8)		6921 (15.7)		5209 (6.7)		962.47 (3.8)	30
	9-BK30-BK30-CA	6626 (18.6)		10785 (22.1)		6496 (18.1)		5531 (9.6)		890.04 (2.5)	30
	9-BK30-BK30-LA	7438 (14.5)		13144 (12.2)		7237 (14.7)		6618 (3.8)		905.16 (3.2)	30
	5-BK40-BK40-CA	7482 (12.1)		13583 (9.6)		7246 (13.3)		6496 (4.6)		1100.39 (5.0)	30
	5-BK40-BK40-LA	7006 (12.4)		11431 (9.3)		6823 (12.1)		5499 (5.6)		1058.44 (3.6)	30
	9-BK40-BK40-CA	7061 (14.5)		12572 (16.3)		6794 (15.6)		5492 (4.7)		906.92 (2.4)	30
	9-BK40-BK40-LA	5946 (17.7)		9355 (13.5)		5773 (19.3)		4801 (23.5)		931.60 (3.2)	30

Values in parentheses are coefficients of variation (CV) in %, CH_M *- Chord modulus,* E_E *- Tangent modulus at the point of elasticity,* E_{MV} *- Tangent modulus at the middle point,* E_P *- Tangent modulus at MOR point, "r" Correlation between monitored characteristics and density of lamellas, "*r_{II}*" Correlation between monitored characteristics and degree of densification, "*r_{III}*" Correlation between monitored characteristics and non-wood components of the lamellas.*

Interpretation of the correlation coefficient:

*	*0,0-0,1 - trivial correlation*
**	*0,1-0,3 - small correlation*
***	*0,3-0,5 - mean correlation*
****	*0,5-0,7 - great correlation*
*****	*0,7-0,9 – very large correlation*
******	*0,9-1,0 – almost perfect correlation*

Effect of densification on tangent moduli

Figures 6a and 6b show the effect of densification of 5 mm beech lamellas on the values of the monitored characteristics describing the plastic properties of the material. Fig. 6a shows the average values of the monitored measured characteristics, and Fig. 6b shows the percentage change in the values of the monitored characteristics with respect to the untreated reference lamellas. The data provided in Fig. 6a show a positive effect of the densification of individual layers, which was manifested by an increase in all monitored characteristics (CH_M, E_E, E_{MV} and E_P). The data in Fig. 6b show that the highest increase was achieved by the effect of densification in the tangent moduli at the modulus of rupture E_P. In this case, 10% densification resulted in an increase of up to 95% in EP values. If we compare the monitored values of input materials with other wood-based composite materials, e.g., with OSB boards mentioned in article [26], we can see significantly lower tangent modulus values in OSB boards; however, the data in the article confirm the development trend of tangent modulus values.

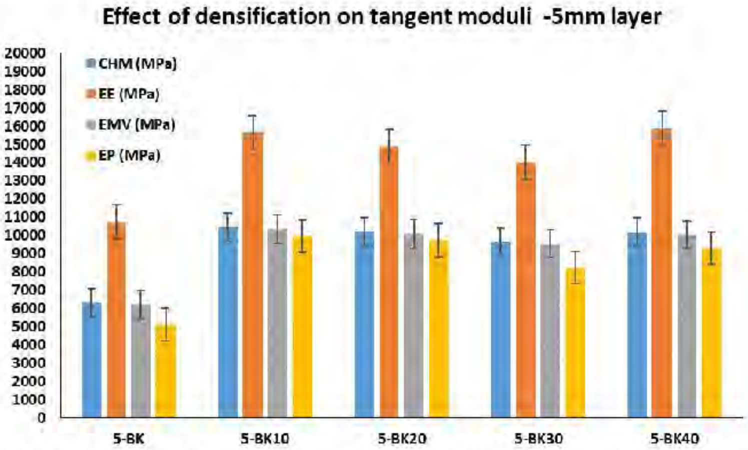


Fig. 6a. Effect of densification of 5 mm thick layer on tangent moduli.

The figures show that as the degree of densification increases, the percentage increase in all monitored characteristics decreases; this is probably due to the increasing destruction of the internal structure of the material. The material deforms after exceeding the 10% detection limit, but in the internal structure of the material there is an increase in micro-defects, which result in a decrease in the values of the percentage change. At 40% densification, we see a change in course and a slight increase in the percentage change from the values measured at 30% and 20% densification. It would therefore be interesting to determine the effect of higher degrees of densification. We also compared the results measured by us with the results published in the article [4], in which the effect of 10% and 20% densification was addressed. The waveforms of the values of all the monitored characteristics, as well as the variance of the values of the monitored characteristics, are very similar to the values measured by us at 10% and 20% densification. The results we found significantly expand knowledge in the use of densified wood in layered materials.

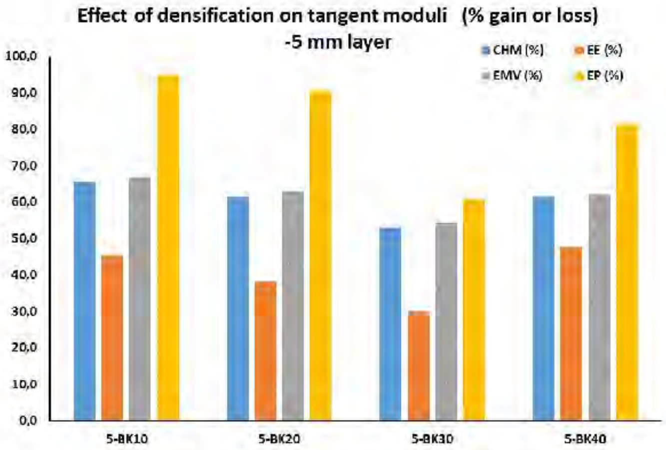


Fig. 6b. Effect of densification of 5 mm thick layer on tangent moduli expressed in percentage gain or loss with respect to non-densified wood

In 9 mm lamellas (Fig. 7a and 7b) the trend is clearer. We can basically say that as the degree of densification increases, so do the values of the monitored characteristics. A slight stagnation in the percentage change achieved by densification can be observed at 30% densification, where we see a nonsignificant slight decrease in the values of the monitored characteristics; however, at 40% densification they began to rise again.

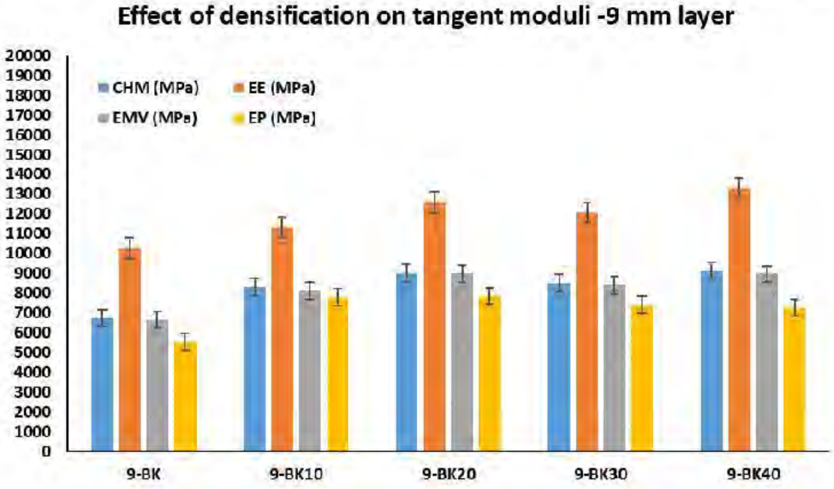


Fig. 7a. Effect of densification of 9 mm thick layer on tangent moduli

The difference in behavior between 5 mm laminated wood and 9 mm laminated wood can be mainly caused by the limit thickness, which affects the development of tangential stresses [9; 10; 12; 13]. In terms of absolute values, significantly higher values of the monitored characteristics are achieved by layering thinner materials (5 mm) [9; 10; 12; 13].

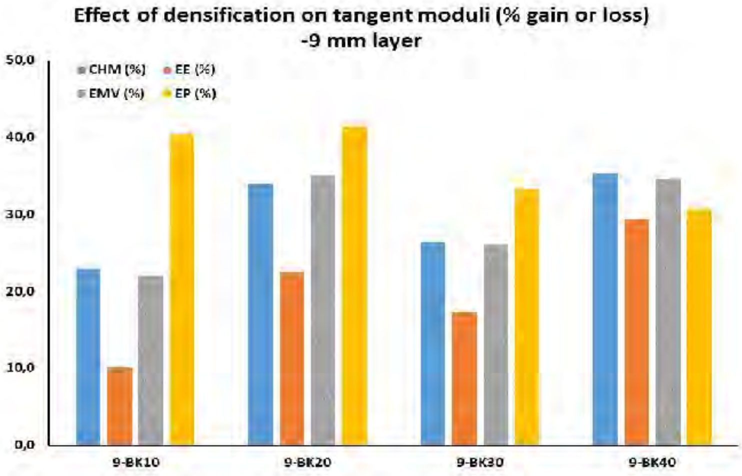


Fig. 7b. Effect of densification of 9 mm thick layer on tangent moduli expressed in percentage gain or loss with respect to non-densified wood

Effect of reinforcement on tangent moduli

Figures 8a and 8b show the effect of reinforcement on the values of the monitored characteristics in the plastic region (8a), and the effect of reinforcement on percentage changes in the values of the monitored characteristics in the plastic region (8b).

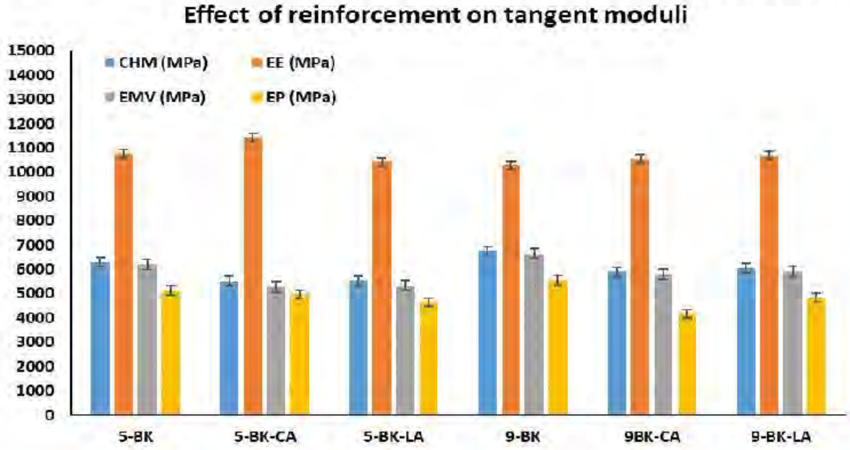


Fig. 8a. Effect of reinforcement of wood with high strength and high stiff synthetic fibers on tangent moduli.

The figures clearly show that at both thicknesses of wood, the effect of reinforcement caused the values of the monitored characteristics to decline. A slight increase (in the range of 2.5% to 6.2%) can be observed with the tangent modulus at the limit of proportionality "E_E", but this cannot be considered statistically significant based on the values of the significance level P. We assume that this increase was achieved due to the non-wood component and the effect of adhesion and cohesion of the wood with the non-wood component (Fig. 8b). After crossing the board on the limit of proportions, the destruction of the material increases, which results in a deepening decrease in the values of the observed characteristics in the plastic area.

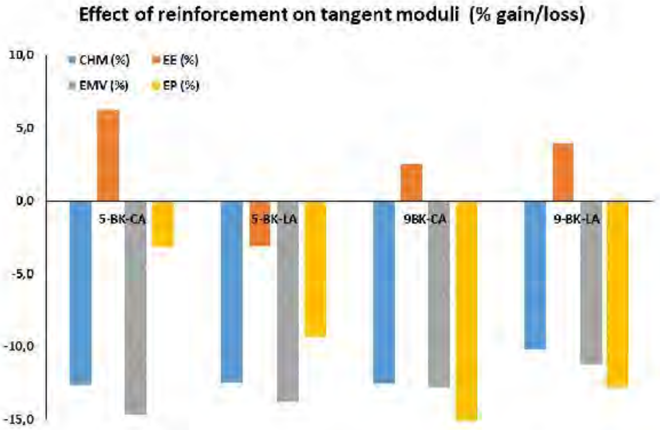


Fig. 8b. Effect of reinforcement on tangent moduli expressed in percentage gain or loss with respect to non-reinforced samples.

Combined effect of densification and reinforcement on tangent moduli

The effect of interaction between densification and reinforcement on the tangent modulus is shown in Figure 9a, and the percentage change caused by the interaction of these parameters is shown in Figure 9b.

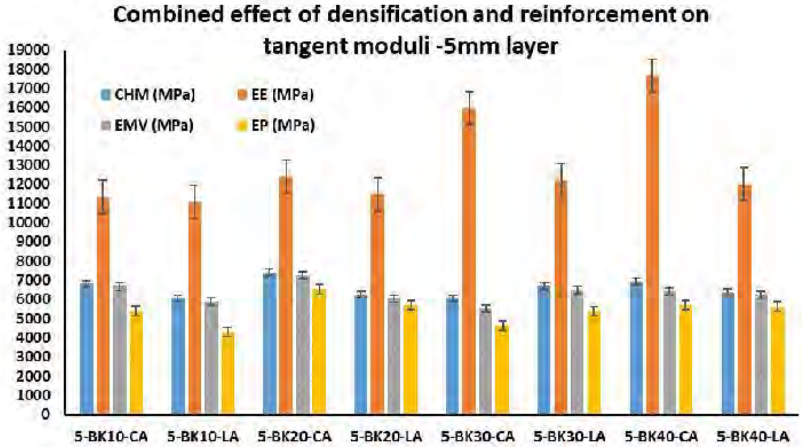


Fig. 9a. Combined effect of densification and reinforcement on tangent moduli in 5 mm thick lamellas.

The data in the figures show that the interaction of both monitored parameters, densification and reinforcement, does not bring the expected results to the values of characteristics describing the properties of the material beyond the limit of proportionality (Fig. 9a and Fig. 9b.) In all observed cases and for all monitored characteristics, we can see a decrease in values of the monitored characteristics in comparison with specimens without reinforcement. We can observe that with an increase in densification in the composition, we achieve a decrease of the observed characteristic. From this point of view, the densification of the lamellae in a layered composition proves to be a suitable tool for strengthening the layered material because it dampens the development of deformation.

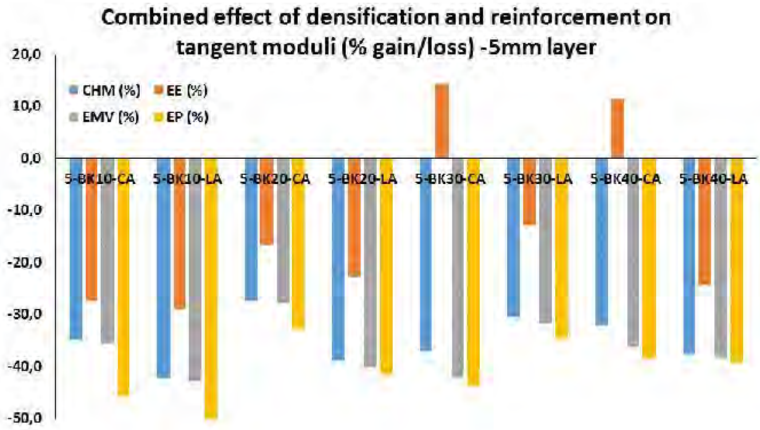


Fig. 9b. Combined effect of densification and reinforcement expressed in percentage gain or loss on tangent moduli in 5 mm thick lamellas.

Figures 10a and 10b show the effect of interaction between reinforcement and degree of densification in 9mm lamellas on the values of the monitored characteristics in the plastic region (10a), and on the percentage changes (10b).

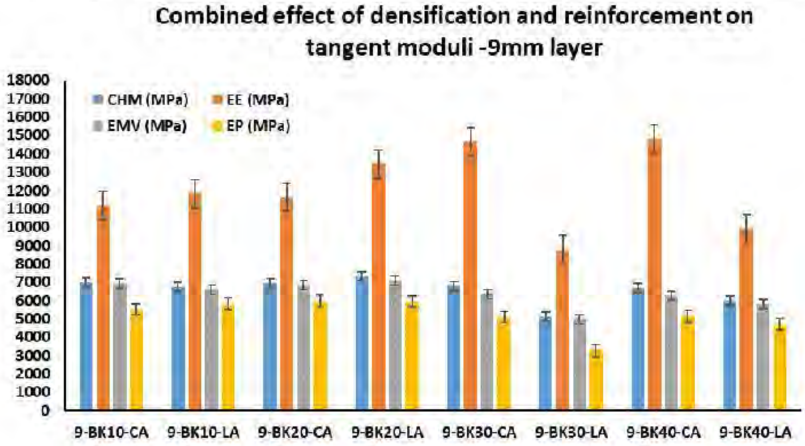


Fig. 10a. Combined effect of densification and reinforcement on tangent moduli in 9 mm thick lamellas.

In terms of the percentage change of the Chord modulus (Fig. 10b), we can see that the highest percentage change is recorded in modification by densification, and we can say that there was a higher increase in values in 5 mm lamellas. From the perspective of layering and densification, we can see that the largest increase in values is recorded in layered composites with lamellas densified by 20% (Table 2). The trend observed when high-strength fibers are applied is not one-sided. Results shows the trend of changes in the E_E. In single-layer and two-layer unreinforced materials, there is a similar trend as in the CH_M. An interesting trend of changes in values with respect to the thickness of the lamellas can be seen in reinforced two-layer materials; greater changes can be seen in the application of carbon fibers in 5 mm materials, with an opposite trend in 9 mm materials. Looking at the three-layer materials, this trend is ambiguous with densification; above 20%, the trend of changes reversed in the opposite direction. The percentage changes in the tangent modulus E_{MV} shown in Fig. 10a and 10b, largely copy the trend of changes in the case of the Chord modulus. When the greatest changes were caused by densification of individual layers, in terms of layering using densified lamellas, in the application of lamellas densified by 30 and 40% a decline in the change was recorded again. Looking at the changes in tangent modulus values at the modulus of rupture "E_P" (Fig. 10a, 10b), it is possible to see a significant change in the monitored values caused by the densification of individual lamellas; as in previous cases, this change was affected by the input thickness of the lamellas. From the perspective of layering itself, we can observe an increase in values up to the application of lamellas densified by 20%, with a subsequent decrease in glued materials composed of lamellas with 30 and 40% densification.

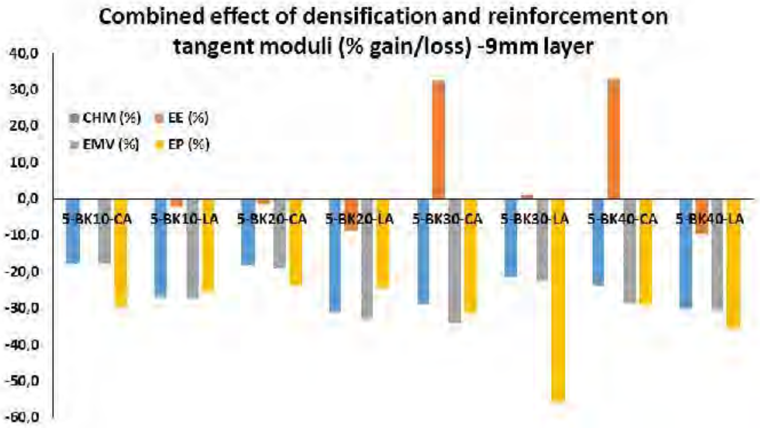


Fig. 14b. Combined effect of densification and reinforcement expressed in percentage gain or loss on tangent moduli in 9 mm thick lamellas.

Spearman's rank-order correlation

Tables 3 - 6 show the results of the Spearman's rank-order correlation analysis. The results of the correlation analysis of non-layered materials (Table 3) show a high dependence of all monitored characteristics, both with respect to the input thickness and the degree of densification.

Table 3. Spearman's rank correlation coefficient of bending characteristics for one-layer material

Variables	Thickness (mm)	Densification	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1,000	-	-	-	-	-
Densification	-	1,000	-	-	-	-
CH_M (MPa)	-0,314	0,442	1,000	-	-	-
E_{MV} (MPa)	-0,307	0,433	0,996	1,000	-	-
E_E (MPa)	-0,484	0,462	0,783	0,769	1,000	-
E_P (MPa)	-0,333	0,444	0,832	0,828	0,835	1,000

Table 4 shows the results of the correlation analysis of two layers of material without the application of high-strength fibers with respect to the input thickness of lamellas and the densification of individual layers. For these materials, a high dependence with respect to the input thickness of the lamellas was only demonstrated for the characteristics E_E and E_P. In the case of densification of individual layers, the dependence of both layers was only proven for the characteristics E_E and E_P. The dependence between all individual characteristics was also demonstrated.

Table 4. Spearman's rank correlation coefficient of bending characteristics for two-layer material without non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Densification of 2nd layer	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1,000	-	-	-	-	-	-

Densification of 1st layer	0,000	1,000	-	-	-	-	-
Densification of 2nd layer	0,000	1,000	1,000	-	-	-	-
CH_M (MPa)	-0,021	0,041	0,041	1,000	-	-	-
E_{MV} (MPa)	-0,019	0,030	0,030	0,995	1,000	-	-
E_E (MPa)	-0,391	0,191	0,191	0,604	0,582	1,000	-
E_P (MPa)	-0,150	0,193	0,193	0,843	0,826	0,682	1,000

Table 5 shows the results of the correlation analysis for two-layer materials reinforced with high-strength fibers where, as in the previous analysis, dependence on the thickness of materials was only shown for the characteristics E_E and E_P. For material densification, a significant dependence on the characteristics CH_M, E_E and E_P was demonstrated. In terms of high-strength fibers, dependence was proven for all monitored characteristics.

Table 5. Spearman's rank correlation coefficient of bending characteristics for two-layer material with non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Reinforcement	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1,000	-	-	-	-	-	-
Densification of 1st layer	-0,002	1,000	-	-	-	-	-
Reinforcement	-0,002	-0,002	1,000	-	-	-	-
CH_M (MPa)	0,037	0,132	-0,172	1,000	-	-	-
E_{MV} (MPa)	0,055	0,057	-0,126	0,981	1,000	-	-
E_E (MPa)	-0,124	0,344	-0,344	0,550	0,424	1,000	-
E_P (MPa)	0,094	0,183	-0,187	0,866	0,822	0,608	1,000

Table 6 shows the results of the correlation analysis for the three-layer materials tested. It is clear from these results that there is a high dependence between thickness and densification of all layers on all the characteristics CH_M, E_{MV}, E_E, E_P. In terms of reinforcing material, dependence was only shown between the characteristics E_E and E_P. As with other materials, the interdependence between all characteristics was demonstrated.

Table 6. Spearman's rank correlation coefficient of bending characteristics for three-layer material with non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Densification of 2nd layer	Reinforcement	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1,000	-	-	-	-	-	-	-
Densification of 1st layer	-0,002	1,000	-	-	-	-	-	-
Densification of 2nd layer	-0,002	1,000	1,000	-	-	-	-	-
Reinforcement	-0,002	-0,002	-0,002	1,000	-	-	-	-
CH_M (MPa)	-0,135	0,258	0,258	-0,066	1,000	-	-	-
E_{MV} (MPa)	-0,136	0,220	0,220	-0,043	0,993	1,000	-	-
E_E (MPa)	-0,221	0,398	0,398	-0,211	0,641	0,591	1,000	-
E_P (MPa)	-0,095	0,309	0,309	-0,181	0,894	0,868	0,696	1,000

CONCLUSIONS

1. Densification of lamellas results in an increase in tangent moduli values. Among the densification level, lamellas densified by 10% of their thickness showed the best results. With increasing degrees of densification, especially with densification by 30 and 40%, there was a slight decline in tangent moduli values in comparison

with lamellas densified by 10%, despite the fact that densification led to an almost linear increase in density. With the increase in lamella thickness, there is a marginal increase in the tangent moduli values.

2. In terms of the interaction of densification and layering in two-layer materials, highest values of tangent moduli were recorded for materials prepared with lamellas densified by 20% in both 5 mm and 9 mm input lamellas. A higher degree of densification (30 and 40%) in interaction with the layering caused a decrease in the values of the tangent moduli.
3. With respect to the input thickness of individual lamellas, the obtained results showed that with increasing input thickness of densified lamellas in the composition of the laminated material, was recorded a smaller increase in values of monitored characteristics, but we also recorded a smaller decrease in values in layered densified lamellas by 30 and 40%.
4. The results of two-layer and three-layer materials composed of densified lamellas reinforced with high-strength non-wood components did not show such a clear trend in the development of the values of the observed characteristics as in the previous cases. However, it can be stated that there is a strong dependence on the change in values of the monitored characteristics when applying high-strength non-wood components, and based on the results it can be said that a non-wood component based on high-strength carbon fibers generally proves to be a more suitable reinforcement material, while components based on glass fibers have better results in a price/performance comparison.
5. The result of the work shows that despite the fact that significantly higher density was achieved due to densification of lamellas by 30 and 40%, this fact did not signify an increase in tangent moduli values with respect to lamellas with a smaller degree of densification.

ACKNOWLEDGMENTS

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9.9 Manuskript číslo 2., Bending Work of Laminated Materials Based on Densified Wood and Reinforcing Components

Bending Work of Laminated Materials Based on Densified Wood and Reinforcing Components

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ABSTRACT

This work deals with the analysis of the influence of the composition of laminated materials based on solid and densified beech wood and the application of reinforcing elements in the form of high-strength fibers. The paper analyzes the behavior on the elastic, plastic and total bending work and their ratios. These characteristics are important in determining the appropriate use of these materials in structural systems with respect to the deformation energy in the elastic and plastic stress regions. From the material point of view, factors such as the input thickness of beech lamellas (5 and 9 mm), the degree of densification of lamellas (references, 10%, 20%, 30% and 40%) and the application of high-strength fibers (carbon and glass) were observed and distinguished. Two approaches can be used to determine plastic work in bending, namely by quantifying more accurate total plastic work and approximated plastic work. However, the approximated plastic work is reliable with an approximation error. One of the outputs of this work will be to determine the error of approximation for different material composition of layered materials, which will result in a modification of the calculations of the approximated work for materials with a specific composition.

Keywords: bending work; bending energy; plastic work; elastic work; total work; degree of densification; high-strength fibers; composition of material

INTRODUCTION

Wood has been used as a construction material for thousands of years. Due to the unrivalled potential of wood, understanding its structure as a building material are of great help to exploit more efficiently. Besides, the structural development of wood in the industrial framework depends on in-depth knowledge of the mechanical properties of this extraordinary natural material. Nonetheless, some of wood properties are not satisfactory. Wood with unfavorable mechanical and structural properties can be modified by diverse treatments included thermal, chemical and compressive (Kamke 2006).

There is a correlation between wood mechanical properties e.g. bending characteristics and its density (Kamke 2006). Given the fact that increasing the density of wood strengthens its mechanical properties, many endeavors have been carried out to expand an appropriate technique for increasing wood density (Blomberg Person 2004). Densification is one of the prevalent treatment methods through which makes it possible for modifying wood into products of high quality with enhanced mechanical and physical

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properties (Kutnar and Sernek 2007). Principally, wood densification is a modification method in which wood density, and subsequently its properties, are enhanced through compression in transverse direction, saturation of lumens with a liquid, or a combination of above methods (Kollmann *et al.*1975). Originally, densification was proposed to enhance the mechanical resistance of wood through removing wood porosity (Požgaj *et al.* 1997). Two primary methods have been defined for densification in the transverse direction: densification of the whole bulk of wood and surface densification (Sandberg *et al.* 2013). Alongside the beneficial impacts of densification, one disadvantage of total bulk densification is the loss in volume. An efficacious solution is to laminate densified wood with non-densified wood or other materials utilizing an adhesive (Kutnar *et al.* 2008, Nilsson *et al.* 2011).

The development of wood-based laminate materials is considered as the most immense scope in wood processing (Bal 2016). Laminated veneer lumber (LVL) is an engineered wood-based composite material manufactured of veneer lamella with configuration in the longitudinal direction (Wang and Dai 2005). Basically, the composition of LVL pertains on the end-use of the produced material and, nevertheless, the individual layers can be modified, unmodified and non-wooden components (Blomberg and Persson 2007, Gaff *et al.* 2015). The properties of LVL are affected by wood densification, the applied wood species and the thickness of layers (Glos and Denzler 2004). The benefits of non-wood components in the wood-based laminated veneer lumber are mostly reinforcement of the composite material, enhance its resistance, and improve the bending characteristics (Gaff *et al.* 2017, Babiak *et al.* 2018). Non-wood reinforcement materials include carbon fiber, aramid fiber, and fiberglass, polyvinyl alcohol (PVA) (Sviták and Ruman 2017). In the manufacture of wood-based composites, the use of non-wood components as well as the use of adhesive bonds increases the strength and stiffness of the product wood (Bloomberg and Persson 2007; Corigliano *et al.* 2017).

Bendability, as an important feature in end-use wood composite products, has received a lot of attention recently (Gaff *et al.* 2017a, Svoboda *et al.* 2019). The influence of applying a non-wood component and interaction of different components of such a material has not yet been extensively assessed (Svoboda *et al.* 2019). The densification of individual layers results in enhancing the value of the stress-strain diagram, due to increased mechanical properties of each densified layer (Gaff et al 2017). So, the bending specifications can be characterized from the stress-strain diagram. In the force-deflection diagram, the elastic deformation has been formed by force at the proportionality limit (Gaff *et al.* 2016; Gaff *et al.* 2017a; Babiak *et al.* 2018). Over the proportionality limit, no elastic deformation is present and plastic deformation occurs (Gaff *et al.* 2017b; Gaff and Babiak 2018a, b; Sikora *et al.* 2018). Within the scope of proportionality limit, the energy that induces the material deformation is potentially accumulated. In order for the object to return to its original form, the energy released during this time is converted to work in proportionality limit (Igaz 2015, Igaz 2016) which is called elastic work. The slope of the stress-strain diagram at any defined stress or strain is considered as the tangent modulus in which under the limit of proportionality is assumed as Young's modulus and upper the limit of proportionality there is different the tangent modulus (Schneider *et al.* 2005). However, the bending work has been described as the area under the curve by taking a linear gradient. Such the definition and calculation have an approximation error that can be removed by applying an integral calculation. In the current study, by using a mathematical equation created and developed by authors, the total bending work has been calculated including approximation error. Previously, some studies have been performed to evaluate the bendability in the plastic region (Gaff *et al.* 2017a) and elastic region (Gaff *et al.* 2017b).

In the current study, the bending work of reinforced laminated composites has been studied. The aim of this present study was to ascertain the effect of wood density (artificial densification), reinforcement of wood with high strength and high stiff material (carbon and glass fiber) and the combine effect of both measures on the bending work done. The work done was segregated into elastic as well as plastic work and finally combined to derive the total work.

Materials and Methods

Materials

The basic material in the test sets were European beech (*Fagus sylvatica* L.) milled lamellas with a nominal width of 35 mm, thicknesses of 5 and 9 mm and lengths of 140, 220, 240 and 400 mm. The length of the lamellas was based on the final thickness of the layered composite so that the distance of the lower supports during bending was 20 times of thickness. Beech lamella were conditioned to a moisture content of 8 % (± 1%) in climate chamber with condition of relative humidity of 40% and temperature 20°C according ISO 13061-1. In addition to the reference lamellas, was used densified lamellas in four basic degree of densification (10, 20 30 and 40%). Density of wood and its changes after densification was determined according ISO 13061-2. The standard thermo-mechanical method of densification in a heated hydraulic press at a temperature of 140 ° C (± 5 ° C) was used to densification of lamellae. The densification time was adequately adapted to the thickness and degree of densification. Two types of components were used as reinforcing high-strength fibers, the first based on high-strength carbon (CA) fibers (SikaWrap 150C/30, SIKA CZ) and the second based on type E glass (LA) fibers (KITTFORT). PVAc adhesive AG-COLL 8761/L D3 was used as an adhesive for lamination of individual components into built-up compositions (Fig. 1). The adhesive was applied on one side manually with a coating in the range from 150-180 g/m^2.

The tested sets can in principle be divided into single-layer (default), two-layer without reinforcement component, two-layer with reinforcement component and three-layer with reinforcement component. A total of 60 test sets were produced, each consisting of 30 test specimens.

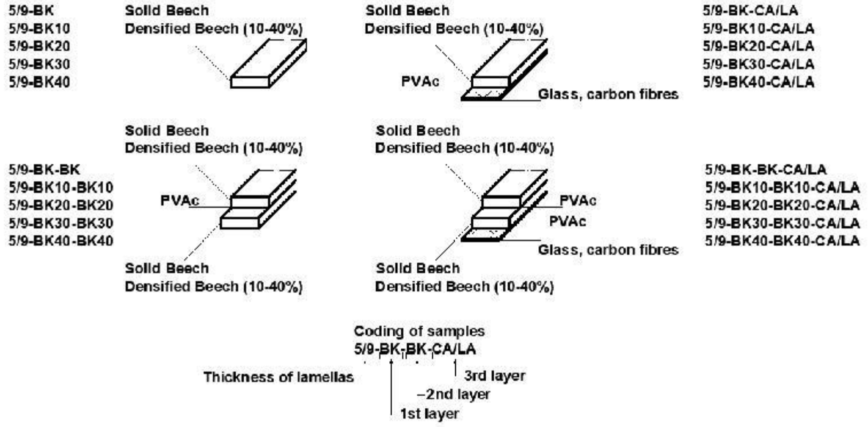

Fig. 1. Categorization of test samples

Methods

Mechanical testing

For experimental mechanical testing in bending, the method of three-point bending according to EN 310 was used in accordance of ISO 13061-3 and ISO 13061-4. The principle of this test consists in loading the element with an insulated force in middle of the length according to the diagram in Fig. 2. The testing itself took place on a universal test device (FPZ 100, TIRA, Schalkau, Germany). The testing took place in the tangential direction according to the course of the beech lamella fibers. Force and deflection data were recorded using an ALMENO 2690-8 data logger (AhlbornGmbH, Braunschweig, Germany).

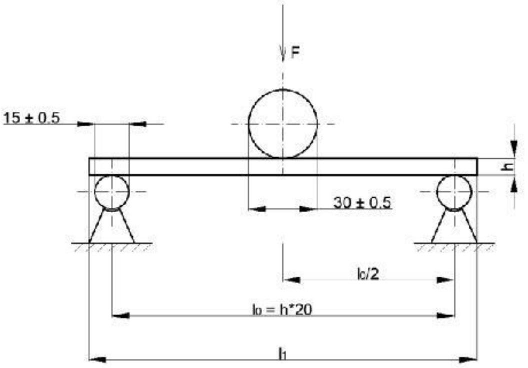

Fig. 2. Principle of three-point bending test

Calculations

Plastic work for deflection can be calculated by the integration of the regression equation of the plastic area trend of the force-deflection work diagram. Graphical display of this approach can be seen in the picture 3a. This approach was first use in work (Gaff and Babiak 2018b)

$$F(y) = a.y^2 + b.y + c \tag{1}$$

When using the integration limits between deflection at the limit of proportionality (y_E) and deflection at the plastic limit (y_P), the resulting equation will be in the form Eq. 2.

$$W_{TP} = \frac{a}{3}(y_P^3 - y_E^3) + \frac{b}{2}(y_P^2 - y_E^2) + c(y_P - y_E) \tag{2}$$

When using this method of determining the total plastic work, it is first necessary to determine the coefficients a, b and c.

An easier determination of the plastic work can be done by using a linear approximation according to (Gaff and Babiak 2018b), where the force and deflection at the limit of proportionality and the force and deflection at plastic limit are intersected by a straight line (Fig. 3b) and can be calculated by equation 3.

$$W_{AP} = \frac{F_P - F_E}{2}(y_P - y_E) \tag{3}$$

where F_P is the force at the plastic limit (N), F_E is the force at the proportionality limit (N), y_p is the deflection at the plasticity limit (mm), and y_E is the deflection at the proportionality limit (mm).

Difference between accurate total plastic work and approximated plastic work, can be determined by approximation error by equation 4 (Fig. 3c).

$$E_{AP} = \frac{W_{TP} - W_{AP}}{W_{TP}} 100 \qquad (4)$$

where E_{AP} is the approximation error (%), W_{TP} is the total plastic work (mJ), W_{AP} is the approximation elastic work (mJ).

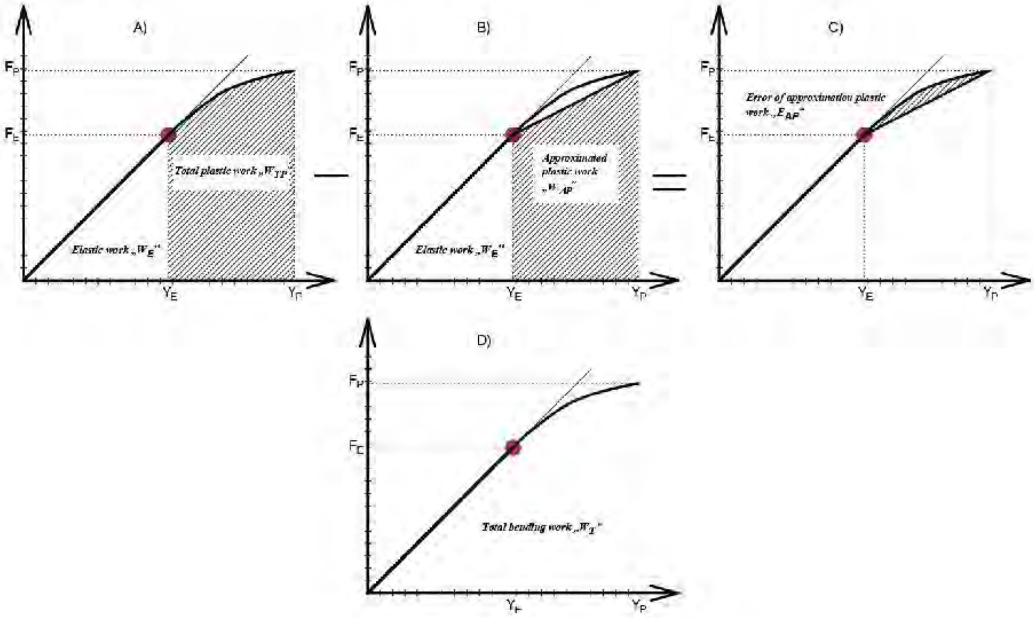

Fig. 3. Force – deflection diagram of wood in bending: A) Total plastic work, B) Approximated plastic work, C) Approximated error, D) Total bending work (mJ).

Elastic work can be expressed by equation 5 from work of (Gaff *et al.* 2017a)

$$W_E = P_E . V = \frac{3}{2}\frac{F y_{max}}{b h l_0} . V \qquad (5)$$

If the force F is expressed in newtons and dimensions (b, h, l_0) and the deflection y_{max} is expressed in mm, 'V' volume of material is expected in mm^3, then the resulting unit of P_E is MPa, i.e. MJ/m^3 and W_E is elastic bending work in mJ.

Total bending work will be express simply by sum of total plastic work and elastic work.

Statistical analysis

For evaluating the results, a four-factor variance analysis was used. Based on the P-level value, it was determined whether a factor affected the values of the monitored characteristics. Diagrams were constructed for the 95% confidence interval which reflects the significance level of 0.05 ($P < 0.05$), and the results were verified with Duncan's tests.

RESULTS AND DISCUSSION

The work done during static bending of wood is a measure of the mechanical energy absorbed by the wood. When a material is subjected to a force, the material deforms and stores potential energy, known as strain energy. The strain energy is equivalent to the work consumed in deforming the material and corresponds to the area under the load deflection curve. Hence, strain energy is quantified by the work done on the sample due to the influence of loading. Since work is the product of force times the deflection, work to any given point during static bending involves both load and deflection (Markwardt and Wilson, 1935).

The area under the load deflection curve up to any given value of deflection (strain) is the total mechanical energy per unit volume consumed by the material in deforming it to that value. When the stresses are within the elastic range (proportional limit), the strain energy is just the triangular area as the load-deflection curve is linear in this range. Energy is reversible in this range. But if the material is loaded beyond the elastic range, plastic deformation starts. Energy absorbed during plastic deformation always exceeds the energy released, when the stresses are removed, as a part of the energy is dissipated as heat. Work to proportional limit is termed as elastic work while work to failure is termed as total work. Elastic work (area under curve up to proportional limit) indicates the modulus of resilience while the total work (area up to fracture) is termed the modulus of toughness. Total work in static bending is a measure of the toughness under bending stresses that cause complete failure. Work to maximum load represents the capacity of the timber to absorb shocks that causes stress beyond the proportional limit and are great enough to cause some permanent deformation. Work to maximum load is closely related to height of drop in impact bending as a measure of shock resistance. It is a measure of combined strength and toughness of a material under bending stresses. The modulus of resilience is the quantity of energy absorbed by a material without suffering damage, while, the modulus of toughness is the energy needed to completely fracture the material. Although, the values of work do not find direct application in design, nevertheless, these values are very much useful for comparison of material's ability to withstand a combination of high load and high deflection (Markwardt and Wilson, 1935). While structures are designed to keep stresses within the elastic limit, a material with higher modulus of toughness is suited more to applications in which accidental overloading may occur (Pelleg 2012).

The results pertaining to the study has been presented in Table 1. It is apparent that the work done increases as the material thickness also increases. Material density has a significant effect on both elastic as well as plastic work, however, the relation was not linear for the entire range of densifications tested. Reinforcement with synthetic fiber also influenced both elastic and plastic work. In order to better understand the effect of each treatment, the data were segregated and plotted separately.

Table 1. Mean values of elastic, plastic work and total work and its ratio as well as density of individual sets of test specimens.

	Code	„W_E” Elastic work (mJ)	„W_{TP}” Total plastic work (mJ)	„W_T” Total bending work (mJ)	„R_P” Ratio of plastic and total bending work	Density (kg/m^3)
Single layer	**5-BK**	950 (31.5)	2224 (29.8)	3174 (15.3)	0.69 (16.4)	687.90 (5.3)
	5-BK10	1366 (15.2)	2095 (22.1)	3461 (17.1)	0.60 (8.7)	789.59 (3.7)
	5-BK20	1422 (16.8)	1889 (24.0)	3311 (15.4)	0.57 (13.1)	828.98 (3.7)
	5-BK30	862 (16.9)	1635 (23.5)	2520 (15.8)	0.62 (15.3)	914.20 (7.1)
	5-BK40	833 (23.4)	1943 (26.7)	2776 (16.9)	0.69 (10.5)	995.95 (5.8)
	9-BK	2858 (33.4)	5027 (37.9)	7885 (30.1)	0.62 (17.4)	699.50 (6.7)
	9-BK10	4167 (27.8)	4860 (28.7)	9027 (22.6)	0.53 (18.3)	730.84 (4.1)
	9-BK20	4000 (29.5)	4833 (28.7)	8833 (24.8)	0.54 (13.0)	817.99 (3.7)
	9-BK30	3003 (34.7)	3572 (38.5)	6574 (25.6)	0.54 (22.1)	902.29 (4.5)
	9-BK40	2561 (33.6)	3524 (44.7)	8280 (26.7)	0.56 (24.1)	1007.63 (4.2)
Two-layer without	**5-BK-BK**	2358 (30.0)	6679 (33.8)	9037 (23.8)	0.72 (14.7)	698.77 (5.4)
	5-BK10-BK10	5137 (13.1)	8550 (23.8)	13687 (17.1)	0.57 (16.8)	783.35 (2.6)
	5-BK20-BK20	5089 (18.9)	7341 (34.3)	12431 (21.6)	0.49 (19.8)	842.05 (4.1)
	5-BK30-BK30	3717 (22.7)	7245 (26.6)	10962 (16.5)	0.65 (14.7)	890.74 (5.2)
	5-BK40-BK40	3665 (26.4)	6605 (32.9)	10270 (20.9)	0.63 (18.4)	912.65 (11.8)
	9-BK-BK	7076 (43.4)	15219 (32.3)	22295 (31.1)	0.68 (9.8)	705.57 (3.6)
	9-BK10-BK10	14777 (29.5)	15505 (39.8)	30282 (31.4)	0.50 (15.7)	741.68 (3.3)
	9-BK20-BK20	13646 (22.3)	14811 (32.3)	28457 (20.8)	0.51 (19.2)	836.01 (4.0)
	9-BK30-BK30	9247 (20.0)	13965 (34.6)	23213 (19.7)	0.59 (18.4)	870.08 (4.2)
	9-BK40-BK40	8248 (22.2)	14114 (36.4)	22362 (23.7)	0.61 (16.8)	978.55 (3.7)
One layer with reinforcement	**5-BK-CA**	1222 (17.8)	3037 (27.9)	4117 (26.8)	0.70 (12.1)	712.33 (4.7)
	5-BK-LA	1185 (30.2)	2812 (32.0)	3997 (17.1)	0.69 (16.4)	757.52 (5.2)
	5-BK10-CA	1684 (16.9)	2881 (22.3)	4564 (16.5)	0.63 (10.3)	763.99 (5.5)
	5-BK10-LA	1534 (25.3)	3355 (22.1)	4889 (13.7)	0.68 (12.6)	786.06 (3.3)
	5-BK20-CA	1790 (17.7)	2881 (20.2)	4671 (14.0)	0.61 (10.3)	863.56 (5.4)
	5-BK20-LA	1877 (23.4)	3843 (27.1)	5720 (17.7)	0.66 (13.4)	833.06 (5.2)
	5-BK30-CA	1083 (32.1)	4844 (0.8)	5927 (22.9)	0.80 (11.5)	901.36 (7.8)
	5-BK30-LA	1248 (22.6)	2702 (22.3)	3950 (17.4)	0.68 (9.8)	989.08 (4.0)
	5-BK40-CA	1079 (26.7)	5293 (25.4)	6362 (20.9)	0.82 (7.2)	1107.10 (4.9)
	5-BK40-LA	1023 (24.2)	2962 (33.0)	3985 (22.6)	0.73 (11.6)	1102.85 (4.4)
	9-BK-CA	3256 (22.3)	6441 (27.1)	9697 (20.7)	0.65 (13.6)	705.31 (5.0)
	9-BK-LA	3822 (22.6)	7052 (33.5)	9874 (23.8)	0.70 (14.5)	745.78 (4.2)
	9-BK10-CA	4357 (23.2)	6861 (26.7)	11217 (22.4)	0.61 (11.4)	734.97 (5.5)
	9-BK10-LA	4917 (16.1)	8538 (25.9)	13455 (17.0)	0.63 (10.8)	800.38 (4.9)
	9-BK20-CA	40006 (25.6)	6092 (28.1)	10098 (21.7)	0.60 (13.4)	816.33 (5.3)
	9-BK20-LA	4280 (16.1)	7672 (22.1)	11951 (15.2)	0.64 (9.9)	884.08 (3.4)
	9-BK30-CA	3192 (18.4)	8708 (24.2)	11900 (15.8)	0.72 (9.7)	931.14 (4.6)
	9-BK30-LA	4365 (18.6)	6889 (30.6)	11254 (16.8)	0.60 (15.2)	935.67 (4.1)
	9-BK40-CA	3213 (25.4)	8751 (24.3)	11964 (17.9)	0.73 (10.2)	1032.16 (2.4)
	9-BK40-LA	3788 (20.3)	5538 (37.4)	9327 (21.5)	0.58 (17.6)	1060.78 (3.1)
Two -layer with reinforcement	**5-BK-BK-CA**	4114 (21.1)	8561 (28.4)	12676 (18.7)	0.66 (13.4)	701.95 (5.3)
	5-BK-BK-LA	3717 (29.4)	9037 (33.6)	12754 (22.6)	0.69 (15.2)	705.44 (5.8)
	5-BK10-BK10-CA	5374 (28.9)	9046 (32.0)	14702 (24.7)	0.63 (21.5)	762.53 (5.9)
	5-BK10-BK10-LA	4606 (23.6)	10223 (28.9)	14890 (22.4)	0.68 (11.9)	777.30 (4.4)
	5-BK20-BK20-CA	4750 (23.2)	8307 (24.6)	12770 (19.8)	0.63 (13.7)	848.82 (5.2)
	5-BK20-BK20-LA	3229 (19.0)	11584 (22.1)	14533 (16.1)	0.78 (5.5)	829.66 (9.7)
	5-BK30-BK30-CA	3631 (18.4)	14886 (25.3)	18037 (19.1)	0.79 (6.7)	899.00 (4.8)
	5-BK30-BK30-LA	3843 (20.3)	10589 (15.2)	13951 (17.3)	0.74 (7.2)	962.47 (3.8)
	5-BK40-BK40-CA	3683 (18.3)	12930 (19.7)	16589 (17.2)	0.78 (6.2)	1100.39 (5.0)
	5-BK40-BK40-LA	3589 (20.8)	9242 (28.2)	12444 (25.7)	0.72 (7.7)	1058.44 (3.6)
	9-BK-BK-CA	12034 (23.9)	22656 (21.6)	34689 (15.8)	0.65 (12.0)	688.55 (5.6)
	9-BK-BK-LA	9167 (25.4)	20624 (34.1)	29791 (26.5)	0.68 (13.5)	716.69 (5.9)
	9-BK10-BK10-CA	13157 (19.8)	35721 (28.4	48879 (19.5)	0.72 (10.7)	724.13 (6.1)
	9-BK10-BK10-LA	15051 (17.0)	25565 (25.2)	38292 (25.6)	0.62 (10.7)	784.28 (4.0)
	9-BK20-BK20-CA	11856 (15.1)	21431 (18.6)	32476 (21.8)	0.64 (5.9)	812.26 (5.0)
	9-BK20-BK20-LA	11245 (14.9)	29640 (20.7)	40567 (14.0)	0.72 (7.9)	865.88 (3.1)
	9-BK30-BK30-CA	11491 (16.0)	28027 (19.6)	40005 (14.6)	0.71 (6.7)	890.04 (2.5)
	9-BK30-BK30-LA	11001 (20.9)	18952 (23.4)	29624 (13.8)	0.63 (12.5)	905.16 (3.2)
	9-BK40-BK40-CA	12516 (16.1)	26481 (26.5)	39947 (14.6)	0.69 (7.1)	906.92 (2.4)

9-BK40-BK40-LA	12187 (17.5)	20833 (17.5)	33420 (11.8)	0.63 (9.5)	931.60 (3.2)

Values in parentheses are coefficients of variation (CV) in %,

Effect of densification on bending work

Fig 4a and 4b shows the effect of densification of 5 mm thick layer on the elastic, plastic and total work. Fig 4a shows the average values of work for each level of densification while Fig. 4b shows the percentage change in the values of work with respect to the non-densified control samples. Average elastic work (950 mJ for non-densified control) improved with the increase in densification up to 20% level (1422 mJ) and the values decreased as the densification increased beyond 20%. While the values at 10% and 20% are significantly higher as compared to the value of non-densified control samples ($p<0.001$), the values of 10% and 20% densified samples were comparable without any significant difference ($p=0.335$). The elastic work values obtained for 30% and 40% densified samples were lower than that of non-densified samples, though the differences were not statistically significant. The results were completely different for plastic work. Densification caused a reduction in the plastic work for 5 mm thick samples. There was a gradual reduction in the plastic work as the samples were densified up to 30% densification level, however, beyond 10 % densification the reduction in the plastic work was significant ($p \leq 0.026$) as compared to non-densified control samples. The plastic work value improved when the densification was increased to 40% level, even though the average value was lower than the non-densified control. The total work follows almost similar trend to that of elastic work. Total bending work increased as the densification level increased up to 20% densification level and beyond that the values decreased. Significant improvement in the total bending work with respect to non-densified control was obtained only at 10% densification level. From Fig. 4b, it is noted that 10% densification level was optimum in terms of combined improvement in elastic, plastic and total work in samples of 5 mm thick. It is worth mentioning that, the increase in total work due to densification is mainly due to the increase in the work in the elastic region.

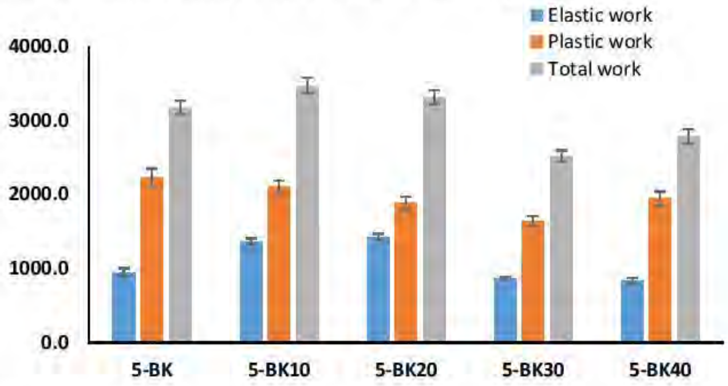

Fig. 4a. Effect of densification of 5 mm thick layer on the elastic, plastic and total bending work

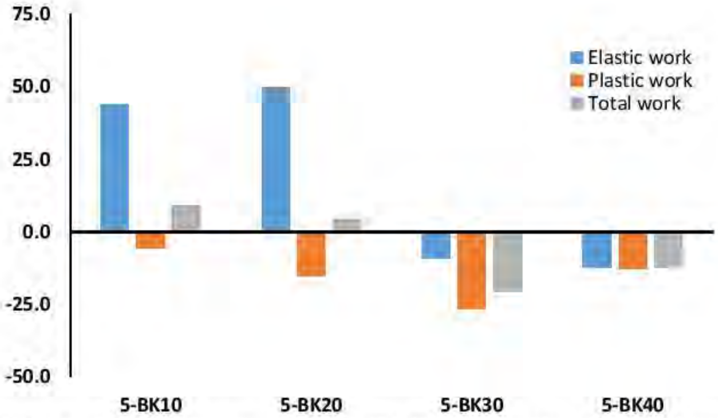

Fig. 4b. Effect of densification of 5 mm thick layer on the elastic, plastic and total bending work expressed in percentage gain or loss with respect to non-densified wood

Fig 5a and 5b shows the effect of densification of 9 mm thick layer on the elastic, plastic and total work. Fig 5a shows the average values of work for each level of densification while Fig. 5b shows the percentage change in the values of work with respect to the non-densified control samples. The trend in the result with 9 mm thick samples is almost similar to that of 5 mm thick samples except that the values for 9mm thick samples are significantly higher than that of 5 mm thick samples. Average elastic work improved significantly ($p<0.001$) with the increase in densification up to 20% level, however, the maximum improvement was obtained at 10% densification level (4167 mJ). Elastic work values of 10% and 20% densified samples were comparable without any significant difference ($p=0.583$). Densification at 30% caused a marginal increase in the elastic work while further densification up to 40 cased reduction in the elastic values as compared to the non-densified control sample, though the differences were not statistically significant ($p\geq0.211$). The trend in the results is different for plastic work. Like 5 mm thick samples, densification also caused a reduction in the plastic work in 9 mm thick samples. There was a gradual reduction in the plastic work as the samples were densified up to 30% densification level, however, beyond 20 % densification the reduction in the plastic work was significant ($p \leq 0.002$) as compared to non-densified control samples. The total work follows almost similar trend to that of elastic work. Maximum total work was obtained at 10% densification level which was significantly higher ($p=0.05$) as compared to that of non-densified control samples. The value of total work at 20% densification was marginally higher, though not significant ($p=0.11$), while the values at 30 and 40% densification were significantly lower ($p \leq 0.002$) as compared to non-densified control samples. From Fig. 5b, it is apparent that 10% densification level was optimum in terms of combined improvement in elastic, plastic and total work in 9 mm thick samples. Similar to the result of 5 mm thick samples, the increase in total work due to densification in 9 mm thick sample is mainly due to the increase in the work in the elastic region.

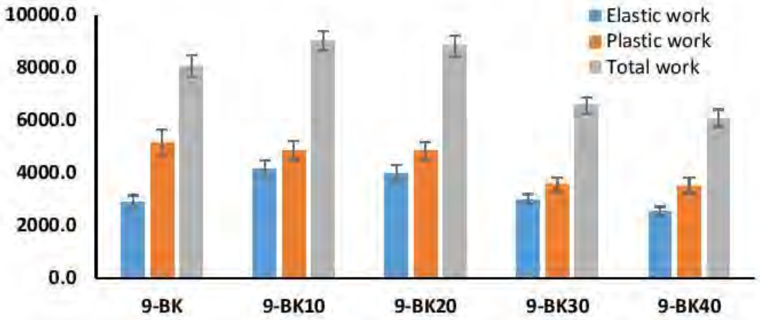

Fig. 5a. Effect of densification of 9 mm thick layer on the elastic, plastic and total bending work

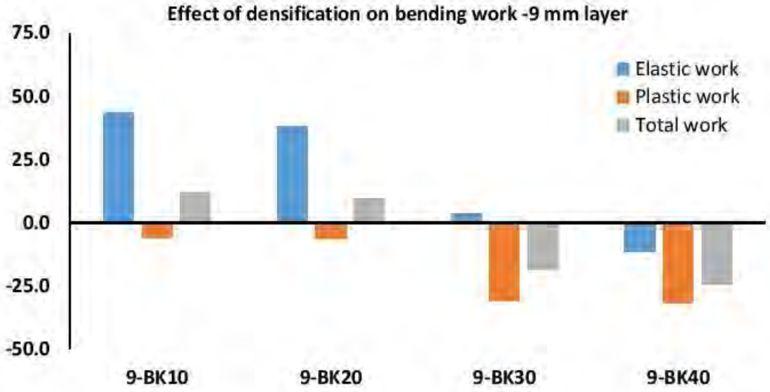

Fig. 5b. Effect of densification of 5 mm thick layer on the elastic, plastic and total bending work expressed in percentage gain or loss with respect to non-densified wood

Most of the mechanical properties of wood are linearly related to wood density. Higher the density, higher is the strength of wood and the reason being the greater number of wood elements and cell wall materials per unit volume to bear the load in denser wood. Densification though does not increase the number of wood elements or cell wall material per unit volume in true sense, it increases the wood density by reducing the volume through removal of voids present in the wood. As a result, cell to cell contact increases in wood which in turn facilitates uniform distribution of loads. However, the degree of densification can only have a positive influence on the mechanical properties of wood until there is no damage to the integrity of the wood elements. At lower level of densification, compression happens to minimize the voids present in the wood without much effect on the cellular integrity of the wood. As densification increases, compression and shear failure increase which in turn reduces the mechanical properties of wood. This may be the possible reason why lower level of densification (10%) gave better result as compared to higher level of densification.

The density profiles of 5 mm and 9 mm thick samples, as obtained by X-ray densitometry, have been shown in Fig. 6a and 6b respectively. In both the graphs, it is apparent that densification is not uniform across the sample thickness. Density of surface is higher as compared to that in the core of the sample. The only variation was in 5mm thick samples densified to 40 % level, where the density at the core was higher than density at the surface. The density gradient across the sample thickness in 9 mm thick samples is steeper as compared to 5mm thick samples particularly beyond 10 % densification level. For instance, the difference in the surface and core density at 10% densification is 6.8% for 5 mm thick and 6.4% for 9 mm samples. As the densification increased to 20%, the difference became 9.3% for 5mm thick sample and 15 % for 9 mm thick sample. Presence of higher density gradient suggests localized over-densification which in turn may cause cell damage resulting in poor performance under loading. In case of 5 mm, samples, densification up to 20% level caused more or less uniform gradient and as a result the corresponding samples exhibited higher total work. In 9 mm thick samples, the density gradient was more or less uniform only up to 10% densification level and the highest total work corresponds to that level of densification. Though, uniformity in densification is important for better performance under loading, it is secondary to level of densification. As shown in Fig. 6a, 5 mm thick samples densified to 30% level, showed very uniform densification across sample thickness (3.6% variation between surface and core), however, the elastic, plastic and total work values obtained for these samples were significantly lower as compare to samples densified to lower level.

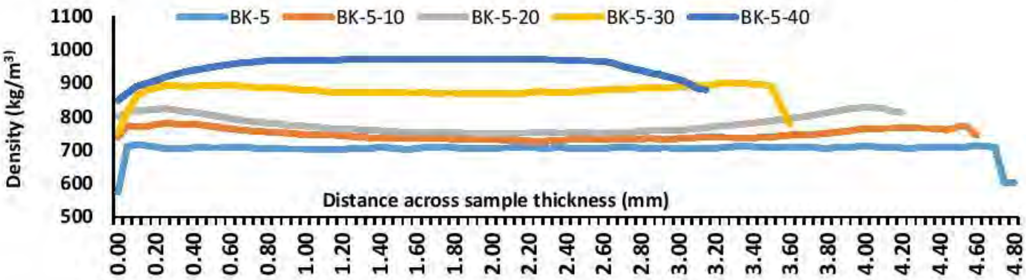

Fig. 6a. Density profile of 5 mm thick samples across the thickness after densification to different levels

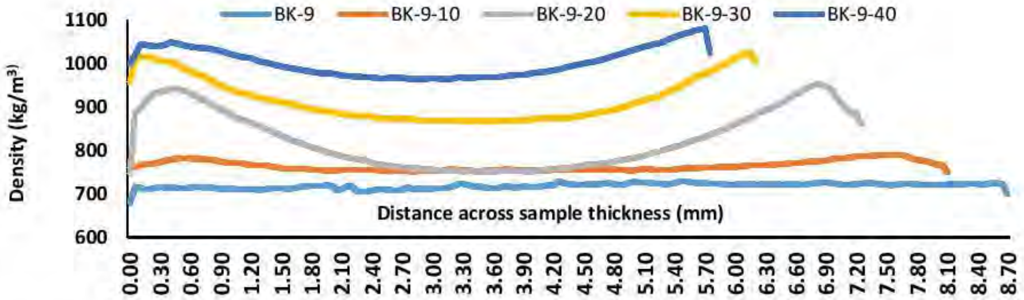

Fig. 6b. Density profile of 9 mm thick samples across the thickness after densification to different levels

Effect of reinforcement on bending work

The results pertaining to the effect of reinforcement of wood with high strength and high stiff synthetic fibers (carbon fiber and glass fiber) are shown in Fig 7a and 7b. Fig 7a shows the average values of elastic, plastic and total work while Fig. 7b shows the percentage change in the work values with respect to the non-reinforced control samples. In 5 mm thick samples, reinforcement with synthetic fiber caused significant improvement in the elastic, plastic and total bending work ($p \leq 0.008$). The extent of improvement depends on the fire type. Elastic work improved by 24.8 and 28.7 %, while the plastic work increased by 26.5 and 36.5% for glass and carbon fibers respectively. As a result, the increase in the total work was 26% for glass fiber reinforcement and 34% for carbon fiber reinforcement. Carbon fiber showed comparatively better result than glass fibers, though the values were statistically not significant.

The results of reinforcement in 9 mm thick samples are slightly different than that of 5 mm thick samples. Most of the improvements in the bending work values due to synthetic fiber reinforcement was achieved in the plastic region ($p \leq 0.004$). The improvement in the elastic work due to synthetic fiber reinforcement (CA and LA) was not significant ($p \geq 0.07$), though carbon fibers showed about 12% increase in the elastic work compared non-reinforced samples. The effect of carbon fiber was significantly ($p = 0.02$) better than glass fiber in the elastic work. Carbon fiber reinforcement caused about 25% increase in the plastic work while glass fiber reinforcement resulted 36% increase. Though, glass fiber reinforcement showed comparatively better result in plastic work than carbon fibers, the performance of both the fibers were comparable ($p = 0.258$). Consequently, the total work improved significantly ($p = 0.002$) due to reinforcement by synthetic fibers (20-22%) and the performances of both the synthetic fibers with relation to total work were comparable without any significant variation ($p=0.755$)

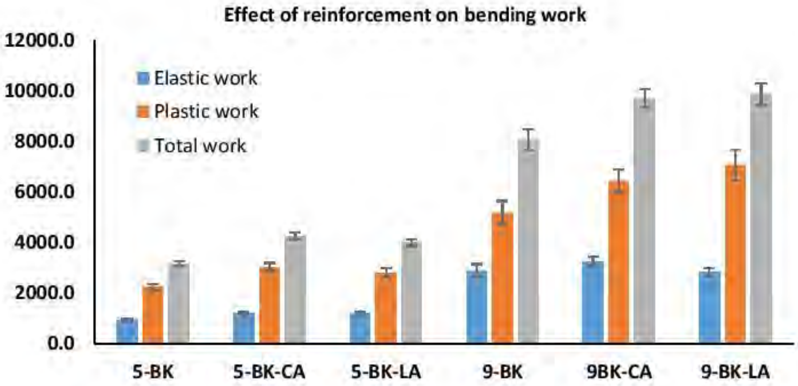

Fig. 7a. Effect of reinforcement of wood with high strength and high stiff synthetic fibres on elastic, plastic and total bending work.

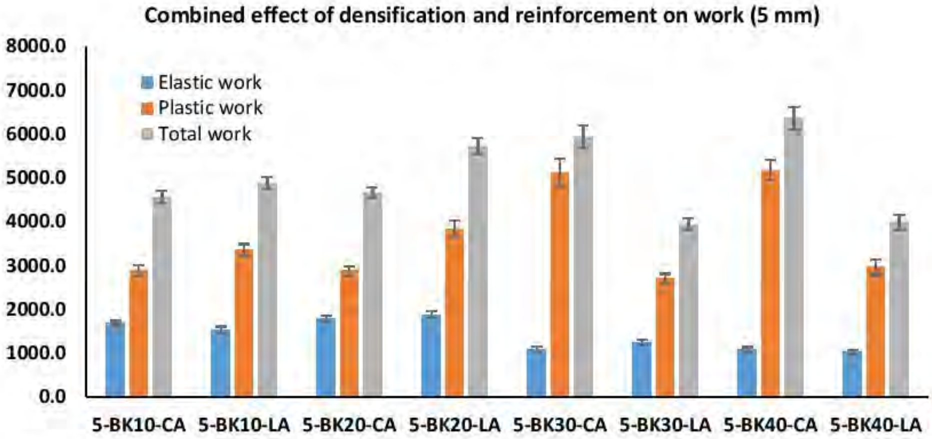

Fig. 8a. Combined effect of densification and reinforcement on the elastic, plastic and total work in 5 mm thick lamellas.

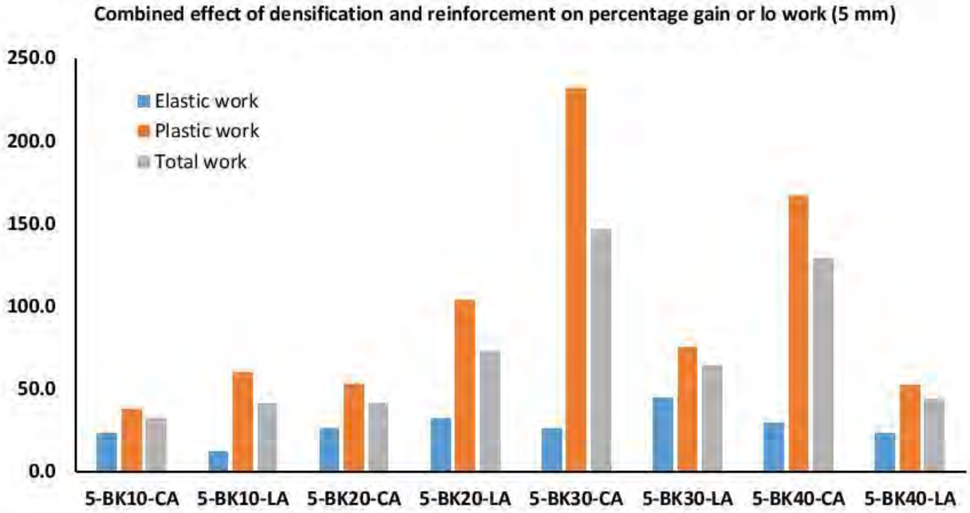

Fig. 8b. Combined effect of densification and reinforcement on the elastic, plastic and total bending work in 5 mm thick lamellas expressed in percentage gain or loss with respect to respective densified samples

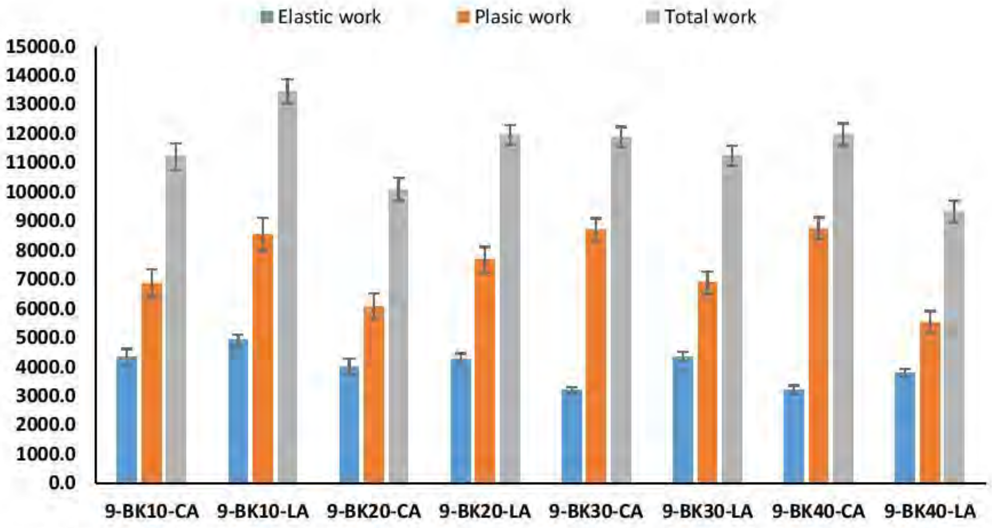

Fig. 9a. Combined effect of densification and reinforcement on the elastic, plastic and total work in 9 mm thick lamellas.

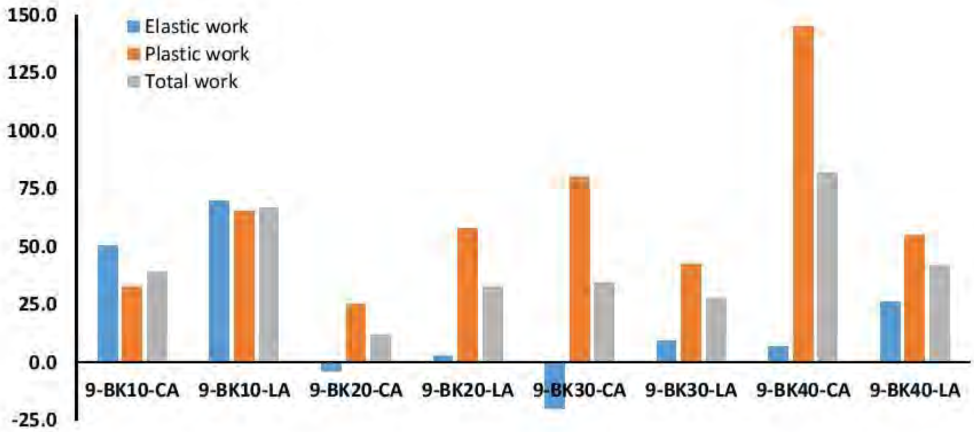

Fig. 9b. Combined effect of densification and reinforcement on the elastic, plastic and total bending work in 9 mm thick lamellas expressed in percentage gain or loss with respect to respective densified samples

Fig. 9a and 9b shows the result of both densification and reinforcement in 9 mm thick lamellas on elastic, plastic and total work. Optimum elastic, plastic and total work values were obtained with 10% densified samples reinforced synthetic fibers (Fig. 9a). WA reinforcement showed better result than CA reinforcement. Reinforcement of samples densified to higher level (beyond 10%) did not cause any significant improvement. Similar to the results obtained with 5 mm thick samples, reinforcement of samples densified beyond 10% level caused substantial improvement in the bending work in plastic region while, the bending works in elastic zone were significantly compromised. The higher percentage improvement in the plastic bending work values in samples densified beyond 20% level (Fig. 9b) and reinforced is due to the very poor plastic bending work values of the respective densified samples.

Comparison of results of all the treatments attempted (densification, reinforcement and combination) and both the thicknesses studied, indicate that, each treatment affects the bending work performance differently. Densification contributes towards improvement in the elastic work, while the plastic work was negatively affected. Reinforcement of wood with high stiff and high strength material, as expected, improved both elastic as well as plastic work, however, the improvement was more in the plastic region as compared to the elastic region. The improvement in the elastic work due to reinforcement was significantly lower as compared to that obtained by densification. Combination of densification and reinforcement provided synergistic effect on the bending work. Both elastic as well as plastic work improved significantly due to combination of densification and reinforcement. The improvement in the plastic bending work was higher as compared to the improvement obtained in elastic bending work. Although, reinforcement of control (non-densified) as well as densified wood improved the bending work, the improvement was not proportionate to the inherent properties of the reinforcing material (carbon and glass fiber). The plausible reason for this disproportionate result can be attributed to the relatively poor properties of the adhesive (PVAc) used to bind the reinforcing material with wood. Further, it was also observed that, the degree of improvement was marginally lower in thicker samples as compared to thinner sample.

CONCLUSIONS

This paper studies the effect of wood densification and reinforcement with strong and stiff synthetic fiber on the elastic, plastic and total bending work. Beech wood samples of two different thicknesses (5 mm and 9mm) were densified to four different levels (10-40%) by thermo-mechanical method (at 140 °C ± 5 °C) and reinforced using glass and carbon fibers. Three-point bending test was carried our using universal testing machine and the area under the stress strain curve was analyzed to ascertain elastic, plastic and total bending work. The salient findings of this study are as follows:

- Material density has a significant effect on both elastic as well as plastic work, however, the relation was not linear for the entire range of densifications tested.
- A densification level of 10% was found optimum in terms of improvement in the elastic, plastic and total bending work in both tested thicknesses (5 and 9 mm). The increase in total work due to densification is mainly due to the increase in the bending work in the elastic region as densification caused a marginal reduction in the plastic bending work.
- Reinforcement of non-densified with synthetic fiber influenced both elastic, plastic and total bending work. Improvement in plastic bending work was significant in both tested

material thicknesses, whereas the improvement in elastic bending work was only significant in samples of lower thickness only (5 mm).

- Reinforcement of densified lamellas caused significant improvement in the total work in relation to total work of the respective densified lamellas. Reinforcement improved the total work by making significant contribution in the plastic region (37-213%) as compared to the elastic region.
- When both densification and reinforcement are combined, the performance of reinforced samples densified by 10% was found optimum from the point of both elastic and plastic work.
- Bending work increased as the material thickness increases. However, when densified and reinforced, the degree of improvement was marginally lower in thicker samples as compared to thinner sample.

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9.10 Manuskript číslo 3., Densification and Reinforcement of Layered Wood and its Influence on Bending Potential

Densification and reinforcement of layered wood and its influence on bending potential

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ABSTRACT

Until recently, elastic and plastic potential approach in wood bending has not received much attention for the mechanical characterization of these composite natural materials. This article addresses the identification and quantification of wood potential characteristics on 5 mm and 9 mm thick wood and laminated materials. This work deals with the analysis of the influence of the composition of laminated materials based on solid and densified beech lamellae (5 and 9 mm) and the application of reinforcing elements in the form of high-strength carbon and glass fibers. Densified lamellae was subjected to different degrees of densification (from 0 to 40%). The individual layers were bonded with polyvinyl acetate adhesive (PVAc). The paper analyzes the behavior on the elastic, plastic and total bending potential and their ratios. The results of this study considerably expand existing knowledge necessary for the creation of layered materials with specific properties for a given purpose of use and be considered as a reference for further investigations in the present subject.

Keywords: bending potential; elastic potential; plastic potential; degree of densification; material thickness

INTRODUCTION

Different characteristics are used to identify mechanical performance of a material. Depending on their required predicative value, they can be classified as extensive, intensive and protensive characteristics. Intensive characteristics have a wide range of applications, but their predicative value is not reliable due to the fact that they are influenced by a number of other factors. Protensive characteristics are constantly changing and cannot be reproduced retrospectively. From a practical and scientific point of view, extensive characteristics are the most important for us, i.e. values characterizing the state of the system whose value depends directly on the size of the system. Bending potential can be divided into two regions on the stress-strain diagram, namely the elastic region and the plastic region (Fig. 1), the sum of which is the total potential. The elastic and plastic potential in wood bending has only been correctly mathematically defined recently [1; 2], and due to its mathematical formulation it can be classified as an extensive characteristic. Knowledge of these characteristics can help us obtain a large amount of useful information [3; 4; 5].

Nowadays, there is a trend of use materials that promote sustainable construction. Among these materials timber stands out because it has positive environmental attributes, including low embodied energy and low carbon impact, however, wood also has certain negative properties [6; 7]. By modifying the wood, significant changes in mechanical properties can be achieved. The positive effect of wood densification on the mechanical properties of wood is well known and has been presented in many articles [8; 9; 10; 11; 12; 13; 14]. Given that correct interpretation describing the potential of materials subjected to bending stress has only been described recently [1; 2], there is so far no knowledge on the effect of wood densification on characteristics describing the bending potential of wood. To increase the homogeneity of wood, it is possible to talk about the layering of wood, where the individual layers of wood are connected using adhesives [15]. Several authors have dealt with the application of densified layers of wood in composite layered material [16; 17; 18; 19; 20]; however, no one has examined the effects of densification of individual layers in interaction with their position in the layered material. This is the main aim of the present study, which describes the effect of these factors as well as their interactions. Similarly, the present approach can be applied on non-wood component (NWC) in a layered material, these materials have gained increased importance by the construction industry since they are considered higher performance structural materials [21]. There are many ways to use these materials, either from the point of view of the composition of the layered materials or from the point of view of the type and volume fraction used [15].The effect of these materials on the mechanical properties has been described in several papers [22; 23; 24; 25; 26; 27], but research was never focused on identifying and quantifying the influence of this type of material on the characteristics describing the potential of wood under bending stress in interaction with other monitored parameters.

In the current study, the bending potential of reinforced laminated composites has been studied. The aim of this present study was to ascertain the effect of wood density (artificial densification), reinforcement of wood with high strength and high stiff material (carbon and glass fiber) and the combined effect of both measures on the bending potential. The work invested was separated into elastic and plastic potential, subsequently, combined to derive the total potential.

ELASTIC AND PLASTIC POTENTIAL

The region under the stress-strain curve diagram during bending can be divided into an elastic (A) and plastic (B) region. The sum of these regions is the so-called total potential "$\mathbf{P_C}$" [1; 2]. Each of these characteristics has its own predicative value with scientific and practical use. The elastic potential "$\mathbf{P_E}$" expresses the amount of energy needed to bend the material to the limit of proportionality; it is also the amount of energy that this material absorbs and consumes after the applied mechanical forces are released to return to its original state [28]. The plastic potential characterizes the amount of energy required for the permanent transformation of the material [28]. By multiplying this value by the volume of the material, we get the amount of work needed to bend the material to the modulus of rupture, so it is of great practical importance. Based on the ratio of elastic potential "$\mathbf{P_E}$" or plastic potential "$\mathbf{P_P}$" to the total potential, it is possible to specify material properties for a given purpose of use. This approach is a basic approach of the theory of smart materials, according to which a balance should be maintained between the properties of the material, appropriately selected in synergy with the processes of their creation and their purpose of use, which aims to maximize the durability of materials and products created on their basis [29; 30; 31; 32; 33; 34; 35; 36; 37].

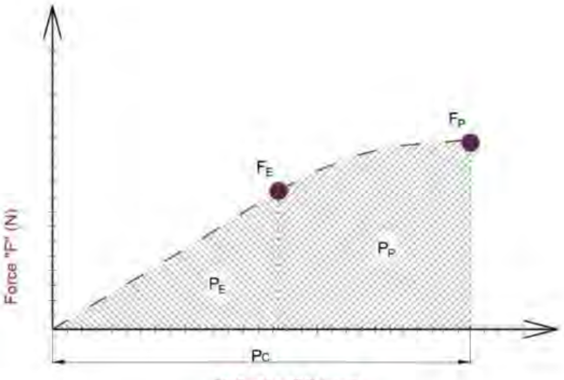

Fig. 1: Stress-strain diagram

MATERIALS AND CONFIGURATIONS

The experiments were performed on 5 mm and 9 mm beech (*Fagus Silvatica* L.) lamellas with a constant width of 35 mm (reference samples). The average density of wood was: 690 kg/m^3 at moisture content of 12%, the wood density was investigated according to ISO 13061-2 [38] and the moisture content of specimens was determined according to ISO 13061-1 [39]. The length of the test specimens was chosen so that it was possible to meet the requirement for the distance of supports, i.e. 20 times the thickness of the tested material. The lamellae were cut out so that the position of the annual rings was at an angle of 90-45 degrees to the perpendicular to the surface. The first tested method of modification was lamella densification. Lamellas were densified by 10, 20, 30 and 40% of their original thickness in heated press with temperature of 140 °C. Based on the relatively small thicknesses of the lamellae we assumed that the densification occurred in a homogeneous manner across the thickness. We created three sets of layered test specimens composed of two layers of wood without a non-wood component, two layers with a non-wood component and three layers with a non-wood component as shown in Fig. 2. The two- and three-layer composite materials were bonded with PVAc (AG-COLL 8761/L D3) adhesive. The adhesive was applied on one side with a coating ranging from 150-180 g/m^2.

Fig. 2: Categorization of test specimens.

5/9 means initial thickness of lamellae before densification, BK is code for beech lamella with degree of densification (10-40), CA is code for carbon fibers, and LA is code for glass fibers.

The real representative display of individual test specimens can be seen in Figure 3. Where Figure 3a) shows a single layer, 3b) two layers with glass fibers, 3c) two layers with carbon fibers, 3d) two layers without NWC, 3e) three layers with glass fibers, and 3f) three layers with carbon fibers.

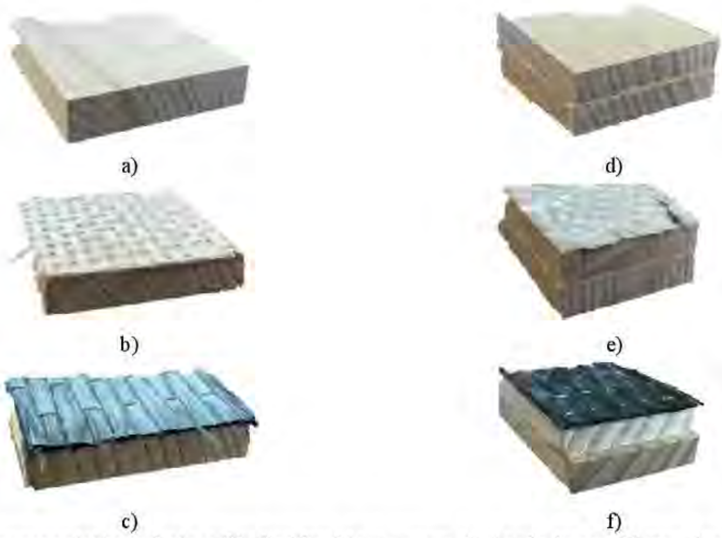

Fig. 3: Representative photo of individual test group a) single layer, b) two layers with glass fibers, c) two layers with carbon fibers, d) two layers without NWC, e) three layers with glass fibers, f) three layers with carbon fibers.

MECHANICAL TESTING

The monitored mechanical characteristics were obtained by three-point bending test by following the relevant standard [40] EN 310 (1993), with distance of lower supports corresponding to 20 times of the thickness for tested material. The principle of three-point bending consists in loading the element with an insulated force in the middle of its length as depicted in Figure 4. The testing was performed on universal testing machine FPZ 100. The stress and strain diagrams were recorded. Important parameters of the testing itself include the loading speed (3 mm / min), so that the testing itself is in the range of 30-90 seconds.

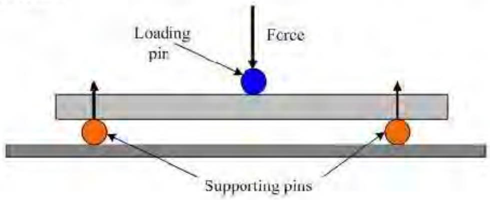

Fig. 4: Three-point bending test according to EN 310.

Evaluation and calculation

The elastic potential was calculated and the effect of individual factors was analyzed based on Equation 1 [1].

$$P_E = \frac{3Fy_{max}}{2bhl_0} \tag{1}$$

If the force F is expressed in N and dimensions b is the width of the specimen (mm), h is the thickness of the specimen (mm) and l_0 is the support span (mm) and the deflection y_{max} is expressed in mm, then the resulting unit of P_E is MPa, i.e. MJ/m^3.

The potential of visco-plastic region can be obtained according Eq. 2 [2].

$$P_P = \frac{A}{bhl_0} \tag{2}$$

When A is work in visco-plastic region calculated according equation Eq.3:

$$A = \frac{a}{3}(y_d^3 - y_b^3) + \frac{b}{2}(y_d^2 - y_b^2) + c(y_d - y_b) \tag{3}$$

where P_P is the plasticity potential (MPa), A is the work of deformation in the visco-plastic region (mJ), y_d is the deflection at the yield point (mm), and y_b is the deflection at the limit of proportionality (mm). It is necessary to emphasize that by integrating the given equation elastic deformations over time is neglected, which occurs in the limit region above the force at the limit of proportionality.

Statistical analysis

For evaluating the results, a gaussian distribution and multiple variance analysis was used. Based on the P-level value, it was determined whether a factor affected the values of the monitored characteristics. Diagrams were constructed for the 95% confidence interval which reflects the significance level of 0.05 ($P < 0.05$), and the results were verified with **Duncan's** tests.

RESULTS AND DISCUSSION

Table 1 shows the average values of the monitored potentials characteristics P_E, P_P and P_C and their mutual ratios as well as the corresponding coefficient of variation. From these results it is possible to observe the influence of individual modifications / structures on the monitored characteristics. To better understand the effects of individual modifications, the data were divided and plotted separately.

Table 1. Mean values of measured potential P_E, P_P, P_C and their ratios P_E/P_C, P_P/P_C for the individual sets of test specimens and the coefficient of variations

	Code	P_E (MPa)	P_P (MPa)	P_C (MPa)	P_E/P_C	P_P/P_C	Density (kg/m^3)
Single-layer	**5-BK**	56 (21.2)	91 (29.2)	148 (11.6)	0.39 (22.9)	0.61 (20.8)	687.90 (5.3)
	5-BK10	98 (15.2)	96 (22.1)	194 (16.2)	0.51 (10.5)	0.49 (10.9)	789.59 (3.7)
	5-BK20	114 (16.4)	91 (23.9)	205 (13.7)	0.56 (13.3)	0.44 (16.7)	828.98 (3.7)
	5-BK30	85 (17.0)	82 (21.9)	166 (20.4)	0.52 (17.9)	0.48 (19.7)	914.20 (7.1)
	5-BK40	96 (21.4)	110 (24.7)	206 (13.9)	0.47 (18.6)	0.53 (16.5)	995.95 (5.8)
	9-BK	49 (22.8)	71 (27.9)	120 (29.2)	0.43 (26.2)	0.57 (19.4)	699.50 (6.7)
	9-BK10	84 (28.1)	74 (29.0)	158 (23.1)	0.53 (17.4)	0.47 (19.8)	730.84 (4.1)
	9-BK20	102 (29.4)	83 (28.7)	180 (24.7)	0.55 (12.8)	0.45 (15.9)	817.99 (3.7)
	9-BK30	97 (26.0)	69 (27.1)	167 (25.2)	0.58 (18.9)	0.42 (26.4)	902.29 (4.5)
	9-BK40	104 (24.0)	77 (24.7)	181 (26.8)	0.58 (21.9)	0.42 (20.7)	1007.63 (4.2)
Two-layer without NWC	**5-BK-BK**	34 (20.1)	80 (23.6)	113 (22.7)	0.32 (25.9)	0.68 (16.6)	698.77 (5.4)
	5-BK10-BK10	87 (13.2)	111 (24.2)	198 (16.6)	0.44 (13.5)	0.56 (10.8)	783.35 (2.6)
	5-BK20-BK20	100 (18.2)	102 (24.6)	203 (21.4)	0.51 (19.0)	0.49 (19.8)	842.05 (4.1)
	5-BK30-BK30	81 (24.3)	103 (26.1)	184 (14.5)	0.44 (22.9)	0.56 (18.1)	890.74 (5.2)
	5-BK40-BK40	84 (20.3)	95 (23.8)	180 (21.6)	0.48 (25.6)	0.52 (23.2)	912.65 (11.8)
	9-BK-BK	30 (22.5)	57 (27.1)	87 (25.5)	0.36 (21.4)	0.64 (23.7)	705.57 (3.6)
	9-BK10-BK10	74 (29.2)	65 (29.5)	139 (21.1)	0.54 (14.3)	0.46 (17.1)	741.68 (3.3)
	9-BK20-BK20	88 (23.2)	70 (22.0)	158 (20.0)	0.56 (16.9)	0.44 (21.6)	836.01 (4.0)
	9-BK30-BK30	69 (20.4)	71 (23.8)	141 (16.6)	0.50 (22.0)	0.50 (22.3)	870.08 (4.2)
	9-BK40-BK40	77 (21.9)	80 (25.6)	157 (19.9)	0.50 (21.8)	0.50 (21.9)	978.55 (3.7)
Two-layer with NWC	**5-BK-CA**	65 (18.3)	118 (27.2)	183 (16.3)	0.36 (25.6)	0.64 (14.6)	712.33 (4.7)
	5-BK-LA	64 (20.0)	111 (22.0)	175 (14.2)	0.38 (23.5)	0.62 (20.2)	757.52 (5.2)
	5-BK10-CA	100 (17.2)	121 (22.7)	221 (16.2)	0.46 (14.6)	0.54 (12.3)	763.99 (5.5)
	5-BK10-LA	83 (24.0)	134 (23.5)	217 (13.3)	0.39 (24.3)	0.61 (15.4)	786.06 (3.3)
	5-BK20-CA	131 (17.4)	134 (20.4)	265 (13.3)	0.50 (13.4)	0.50 (13.3)	863.56 (5.4)
	5-BK20-LA	116 (23.4)	160 (26.9)	277 (15.9)	0.43 (22.5)	0.57 (14.7)	833.06 (5.2)
	5-BK30-CA	83 (29.5)	246 (21.4)	329 (18.2)	0.27 (27.8)	0.73 (17.4)	901.36 (7.8)
	5-BK30-LA	111 (21.9)	137 (22.6)	248 (16.3)	0.45 (17.0)	0.55 (13.9)	989.08 (4.0)
	5-BK40-CA	107 (27.4)	318 (23.8)	425 (20.1)	0.27 (21.8)	0.73 (15.1)	1107.10 (4.9)
	5-BK40-LA	107 (23.3)	160 (22.4)	267 (16.7)	0.41 (25.5)	0.59 (17.8)	1102.85 (4.4)
	9-BK-CA	59 (22.4)	95 (27.3)	154 (20.2)	0.39 (23.4)	0.61 (15.2)	705.31 (5.0)
	9-BK-LA	51 (22.6)	102 (23.3)	153 (22.4)	0.35 (20.6)	0.65 (16.4)	745.78 (4.2)
	9-BK10-CA	86 (23.5)	105 (27.0)	191 (22.4)	0.45 (15.5)	0.55 (12.9)	734.97 (5.5)
	9-BK10-LA	98 (16.9)	130 (25.4)	228 (15.6)	0.44 (16.6)	0.56 (12.8)	800.38 (4.9)
	9-BK20-CA	100 (25.8)	104 (28.3)	204 (21.3)	0.49 (16.8)	0.51 (16.3)	816.33 (5.3)
	9-BK20-LA	108 (16.7)	132 (21.7)	240 (13.9)	0.45 (14.7)	0.55 (12.3)	884.08 (3.4)
	9-BK30-CA	95 (17.6)	160 (23.7)	254 (12.4)	0.38 (21.9)	0.62 (13.3)	931.14 (4.6)
	9-BK30-LA	120 (17.4)	124 (20.1)	244 (13.2)	0.50 (19.5)	0.50 (19.4)	935.67 (4.1)
	9-BK40-CA	116 (23.9)	175 (23.8)	291 (14.7)	0.40 (22.4)	0.60 (15.1)	1032.16 (2.4)
	9-BK40-LA	137 (21.8)	110 (25.6)	247 (16.8	0.56 (18.7)	0.44 (23.9)	1060.78 (3.1)
Three-layer	**5-BK-BK-CA**	55 (21.2)	97 (28.2)	151 (18.5)	0.37 (25.1)	0.63 (14.8)	701.95 (5.3)
	5-BK-BK-LA	49 (29.0)	102 (24.8)	151 (22.7)	0.34 (22.8)	0.66 (17.0)	705.44 (5.8)
	5-BK10-BK10-CA	82 (28.9)	107 (24.7)	189 (26.9)	0.43 (22.4)	0.57 (24.5)	688.55 (5.6)
	5-BK10-BK10-LA	68 (22.8)	113 (26.7)	181 (26.5)	0.39 (24.4)	0.61 (15.8)	716.69 (5.9)
	5-BK20-BK20-CA	90 (23.6)	108 (23.8)	198 (21.3)	0.47 (27.1)	0.53 (23.9)	762.53 (5.9)
	5-BK20-BK20-LA	55 (19.0)	144 (24.0)	199 (18.8)	0.28 (19.5)	0.72 (7.7)	777.30 (4.4)
	5-BK30-BK30-CA	75 (22.2)	204 (27.3)	279 (18.1)	0.28 (29.8)	0.72 (11.5)	724.13 (6.1)
	5-BK30-BK30-LA	87 (23.9)	138 (27.4)	225 (13.5)	0.39 (20.5)	0.61 (19.8)	784.28 (4.0)
	5-BK40-BK40-CA	116 (16.8)	209 (27.2)	324 (18.0)	0.37 (22.5)	0.63 (13.0)	848.82 (5.2)
	5-BK40-BK40-LA	95 (21.3)	140 (22.2)	235 (18.6)	0.42 (25.8)	0.58 (18.4)	829.66 (9.7)
	9-BK-BK-CA	54 (24.3)	90 (21.7)	143 (15.9)	0.38 (21.3)	0.62 (13.0)	812.26 (5.0)
	9-BK-BK-LA	41 (25.9)	81 (23.9)	121 (26.0)	0.35 (26.9)	0.65 (14.5)	865.88 (3.1)
	9-BK10-BK10-CA	65 (18.2)	150 (28.1)	214 (19.1)	0.31 (26.2)	0.69 (11.9)	899.00 (4.8)
	9-BK10-BK10-LA	77 (17.2)	103 (20.1)	179 (19.9)	0.44 (19.1)	0.56 (14.8)	962.47 (3.8)
	9-BK20-BK20-CA	72 (19.8)	96 (27.0)	168 (21.3)	0.43 (14.3)	0.57 (11.0)	890.04 (2.5)
	9-BK20-BK20-LA	73 (15.0)	136 (27.4)	208 (16.8)	0.36 (24.7)	0.64 (13.9)	905.16 (3.2)
	9-BK30-BK30-CA	78 (18.6)	128 (27.4)	206 (19.9)	0.39 (26.4)	0.61 (16.8)	1100.39 (5.0)
	9-BK30-BK30-LA	87 (20.5)	101 (29.9)	188 (13.7)	0.47 (23.1)	0.53 (20.3)	1058.44 (3.6)
	9-BK40-BK40-CA	90 (24.3)	122 (20.1)	212 (14.4)	0.43 (29.0)	0.57 (22.1)	906.92 (2.4)
	9-BK40-BK40-LA	91 (21.9)	98 (24.4)	189 (15.8)	0.48 (16.6)	0.52 (15.6)	931.60 (3.2)

Values in parentheses are coefficients of variation (CV) in %, P_E – Elastic potential, P_P – Plastic potential, P_C – Total potential

Effect of densification on bending potential

Fig. 5a and 5b show the effect of densification of a 5 mm beech lamellas on the elastic, plastic and total bending potential. Fig. 5a shows the average potential values for each level of densification, while Fig. 5b shows the percentage change in potential values with respect to untreated control lamellas. The average elastic potential (56 MPa for the untreated reference) increased maximally at 20% densification (114 MPa), at higher densification rates than 20% densification, lower values were achieved than at this densification degree. Whereas the values of the elastic potential at 10% and 20% degree of densification are significantly higher compared to the value of the untreated control lamellas. The values of the elastic potential obtained in 30% and 40% of densified lamellas were higher than in the case of non-densified lamellas, but the degree of densification at these stages proves to be less effective than in the case of 10% and 20% densification. Another trend can be observed for a change in plastic potential. The highest plastic potential can be observed in lamellas densified by 40%, however, in terms of statistical significance, this change was also statistically insignificant. The total potential follows an almost similar trend as the elastic potential. The total bending potential increased as the level of compaction increased to a degree of densification of up to 20% and then the values decreased. A significant improvement in the overall bending potential with respect to the untreated reference was achieved at only 10% and 20% degree of densification. From Fig. 5b, which shows the percentage changes in the observed potentials, it can be seen that the 10% and 20% degree of densification were optimal for the combined improvement of elastic, plastic and total bending potential in beech lamellas with an input thickness of 5 mm. It is worth noting that the increase in total bending potential due to densification is mainly due to the increase in the elastic stress range.

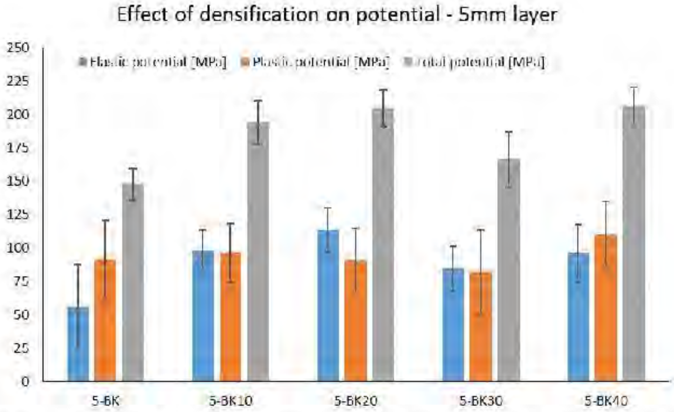

Fig. 5a: Effect of densification of 5 mm thick layer on the elastic, plastic and total bending potential

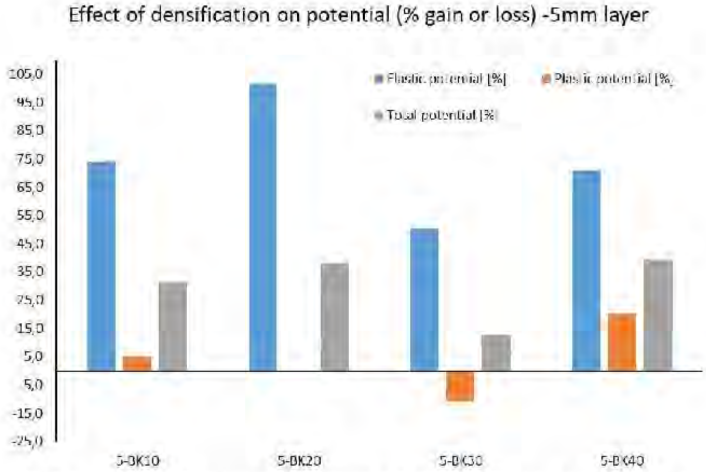

Fig. 5b: Effect of densification of 5 mm thick layer on the elastic, plastic and total bending potential expressed in percentage gain or loss with respect to non-densified wood

Fig. 6a and 6b show the effect of densification of a 9 mm beech lamellas on the elastic, plastic and total bending potential. Fig. 6a shows the average potential values for each degree of densification, while Fig. 6b shows the percentage change in potential values with respect to the untreated reference beech lamellae. The trend in the result for 9 mm thick lamellas is very similar to the trend for 5 mm thick lamellas. The average elastic potential improved significantly during densification by 20% (102 MPa), with regard to the reference, it was an increase in the elastic potential by 108.8%. In the case of 10% degree of densification (84 MPa) it was an increase by 70.7%. Densification by 30% and 40%, caused a significant increase in elastic potential values relative to the reference, but less effective with respect to degree of densification by 10% and 20%. The plastic potential, as well as the elastic potential, had the highest increase in beech lamellas densified by 20% (83MPa), i.e. there was an increase compared to the reference by 17.2%. In the case of other degree of densification, there was no significant change in plastic potentials. The total potential shows an almost similar trend as the elastic potential. The maximum total bending potential was obtained at a 20% degree of densification (185 MPa), which was significantly higher compared to the untreated reference lamellas. The values of the total bending potential at 30% (166 MPa) and 40% (180 MPa) degree of densification were lower than values at 20% degree of densification, i.e. without statistical significance. It can be seen from Fig. 6b that the 20% degree of densification was optimal in terms of the combined improvement of elastic, plastic and total bending potential of the lamellas with an input thickness of 9 mm. The increase in the total bending potential in densified lamellas (both 5 and 9 mm) is mainly due increase in the bending potential in the elastic region. In the case of comparing the obtained values, we can compare the data with [1] and [2], who dealt with changes in elastic and plastic potential in densified wood, their results show that thickness is a significant factor in changing bending potentials. On the contrary, our results show that the thickness itself does not affect the resulting values of the bending potential too much, i.e. that it is significantly affected mainly by the degree of used densification. Densification is a mechanical modification process in which the pore ratio decreases and the cross-sectional ratio of load-bearing cell walls increases. Densification above 20% already involves material failure in the microstructure of such a magnitude (cell wall dents, fractures) that, despite the increasing density, the potential does not further increase.

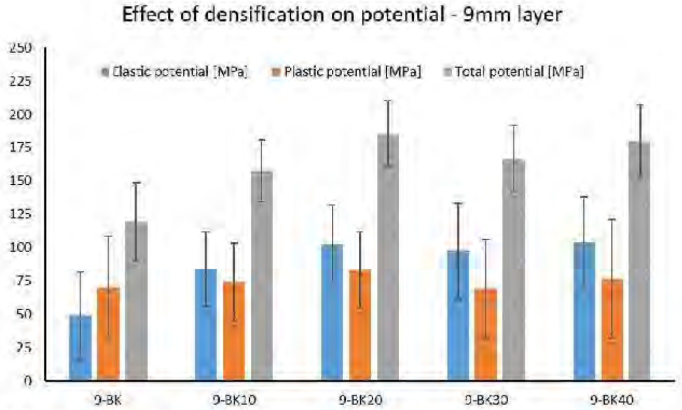

Fig. 6a: Effect of densification of 9 mm thick layer on the elastic, plastic and total bending potential

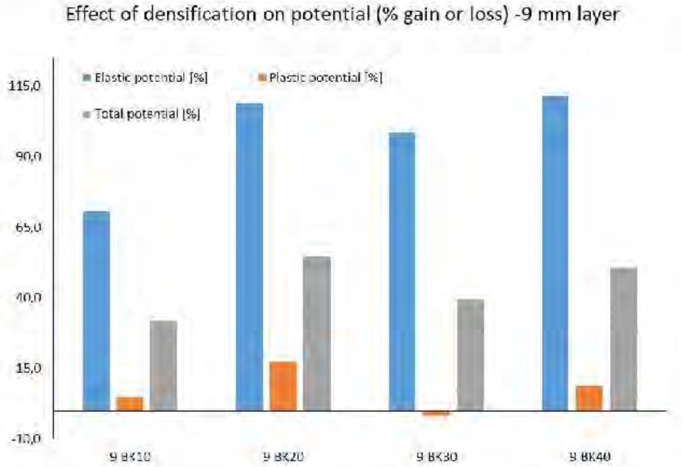

Fig. 6b: Effect of densification of 9 mm thick layer on the elastic, plastic and total bending potential expressed in percentage gain or loss with respect to non-densified wood

Effect of reinforcement on bending potential

The results regarding the reinforcement effect of the high-strength component and the highly rigid synthetic fibers (carbon and glass fibers) are shown in Figs. 7a and 7b. Fig. 7a shows the average values of elastic, plastic and total bending potential, whereas Fig. 7b shows the percentage change of these values with respect to the unreinforced reference lamellas. For test specimens with thickness of 5 mm, the synthetic fiber reinforcement caused a significant improvement in the elastic, plastic and total bending potential. The extent of improvement of the given properties depends on the type of fibers used [41; 42]. The elastic potential improved by 14.7% in the application of carbon fibers and by 13.3% in the application of glass fibers, while the plastic potential increased in the application of carbon fibers by 29.5% and in the application of glass fibers by 21.2%. As a result, the increase in total potential for glass fiber reinforcement was 18.2% and for carbon fiber reinforcement 23.8%. The application of carbon fibers showed a comparatively better result than the application of glass fibers, although the values were not statistically significant. The reinforcement results for lamellas with thickness of 9 mm differ slightly from the results for lamellas with thickness of 5 mm. The improvement in elastic potential due to synthetic fiber reinforcement (CA and LA) was not significant with the application of glass fibers, carbon fibers showed an approximately 20% increase in elastic potential compared to unreinforced lamellas. The effect of carbon fibers was significantly better with elastic potential than with glass fibers. Carbon fiber reinforcement caused an increase in plastic potential of approximately 34%, whereas glass fiber reinforcement led to an increase of up to 44.6%. Although the glass fiber reinforcement showed a comparatively better result in plastic potential than the carbon fibers, the performance of both fibers was comparable. As a result, the total bending potential improved significantly due to the synthetic fiber reinforcement in the range of 27-28%, and the performance of both synthetic fibers in relation to the total bending potential was comparable without significant deviation.

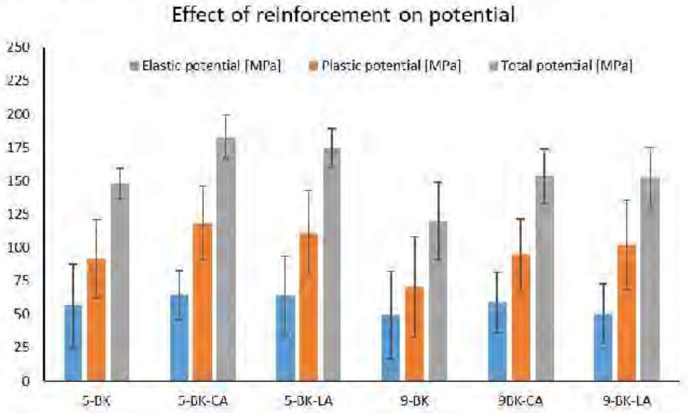

Fig. 7a: Effect of reinforcement of wood with high strength and high stiff synthetic fibers on elastic, plastic and total bending potential.

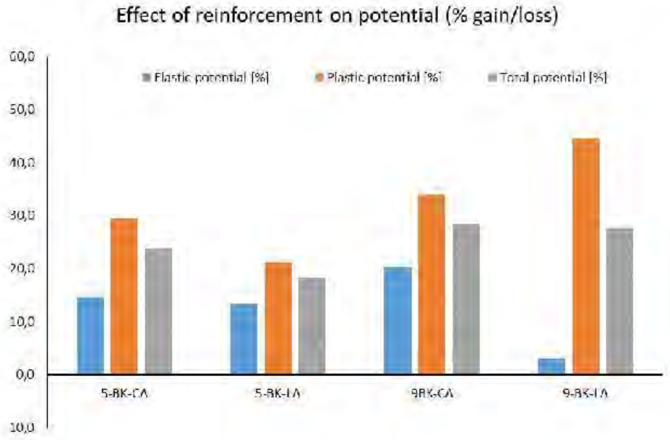

Fig. 7b: Effect of reinforcement of wood elastic, plastic and total potential expressed in percentage gain or loss with respect to non-reinforced samples.

Combined effect of densification and reinforcement on bending potential

The results regarding the combined densification and reinforcement effect (with CA and LA fibers) are shown in Figures 8-9. Fig. 8a and 8b show the results of lamellas with a thickness of 5 mm. It can be seen from Fig. 8b that the reinforcement of the densified lamellas caused a significant improvement mainly of the plastic and total bending potential in relation to the plastic and total bending potential of the respective densified lamellas. It is interesting to note that the reinforcement improved the total bending potential by making a significant contribution in the plastic area compared to the elastic area. The extent of changes in the elastic region due to synthetic fiber reinforcement ranged between -15 to 31%, whereas changes in the potential in the plastic region ranged between 26%-200% depending on the reinforcing materials. The highest improvement in elastic potential was achieved with a combination of 30% degree of densification and glass fibers. The effect of reinforcement of densified lamellas in the plastic potential region is different. LA reinforcement gave better results for lamellas densified to lower degrees (≤ 20%), while CA fibers gave significantly better results for lamellas densified to higher degrees (≥ 30%). Regarding the total bending potential, the maximum values were obtained for CA reinforced lamellas with 30% and 40% degree of densification, the plastic area contributed mainly to these values (Fig. 8b). The influence of the interaction of the modification and the type of material in the composite material on the elastic and plastic potential is obvious and can also be observed in the results in [43; 44], in which the type of alternative lignocellulosic composite material and traditional chip composite materials for bending potential characteristics were studied.

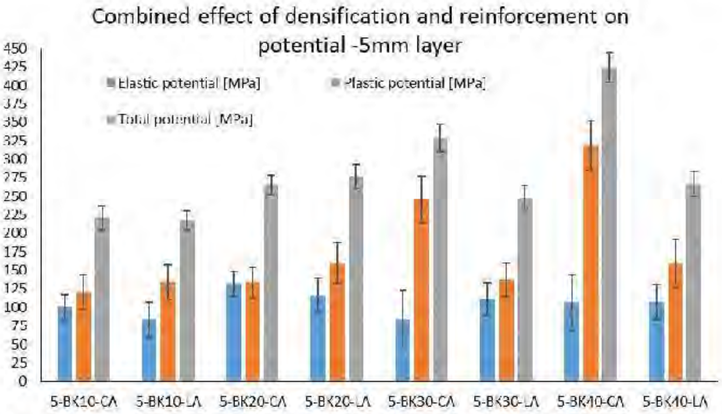

Fig. 8a: Combined effect of densification and reinforcement on the elastic, plastic and total potential in 5 mm thick lamellas.

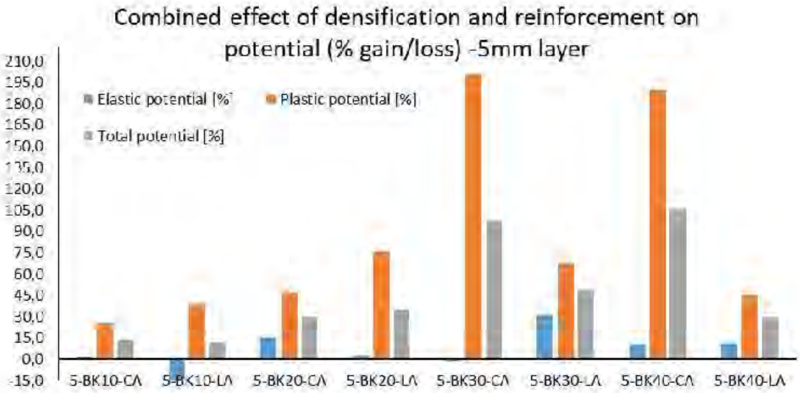

Fig. 8b: Combined effect of densification and reinforcement on the elastic, plastic and total bending potential in 5 mm thick lamellas expressed in percentage gain or loss with respect to respective densified samples

Fig. 9a and 9b show the results of a combination of densification and reinforcement in lamellas with a thickness of 9 mm for elastic, plastic and total bending potential. In terms of elastic potential, LA reinforcement showed better results than CA reinforcement. The higher percentage improvement in the plastic potential values of the densified lamellas above 20% (Fig. 9b) when applying the reinforcing component is due to the lower values of the plastic potential of the densified lamellas with a higher degree of densification. By comparing the results of all experiments and modifications (densification, reinforcement and their combination) and both investigated thicknesses, it suggests that each modification affects the bending potential differently. Density contributes to the improvement of the elastic potential, while the plastic potential was negatively affected. Reinforcement of wood with a highly rigid and high-strength fibers was expected to improve both the elastic and plastic potential, but the improvement was more in the plastic region compared to the elastic region, where in some cases it decreased compared to the reference. The improvement in elastic potential due to reinforcing was significantly lower compared to the improvement achieved by densification. The combination of densification and reinforcement provided a synergistic effect on the bending potential. Although the reinforcement of both non-densified and densified wood improved the bending potential, the improvement was not proportional to the inherent properties of the reinforcement material (carbon and glass fibers). The probable reason for this disproportionate result can be attributed to the properties of the adhesive (PVAc) used to bond the reinforcing material to the wood and to the different morphological changes in surface quality after densification.

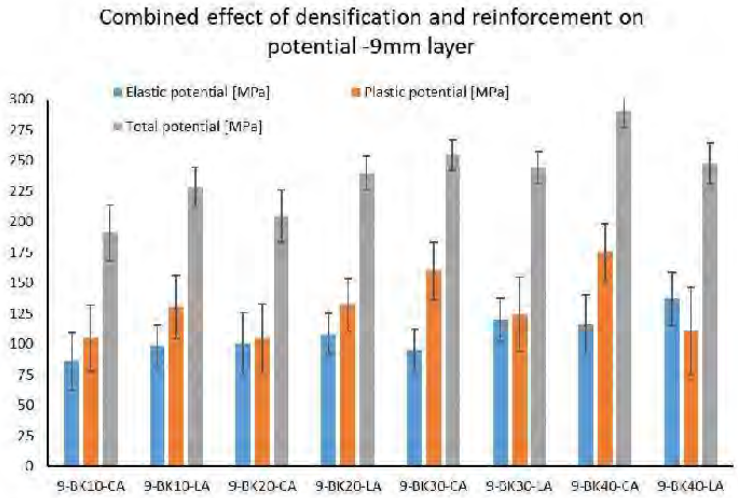

Fig. 9a: Combined effect of densification and reinforcement on the elastic, plastic and total potential in 9 mm thick lamellas.

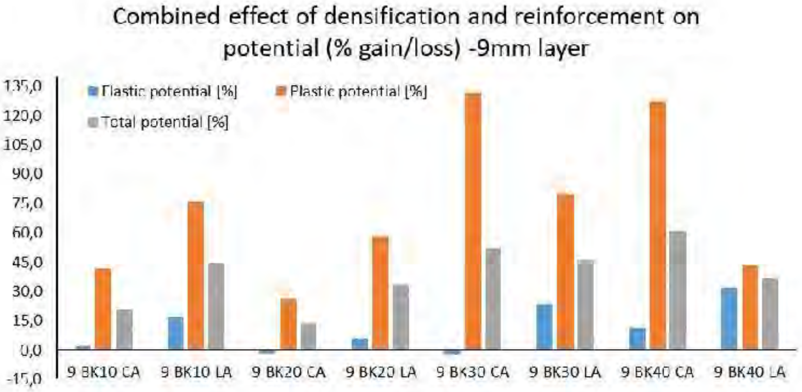

Fig. 9b: Combined effect of densification and reinforcement on the elastic, plastic and total bending potential in 9 mm thick lamellas expressed in percentage gain or loss with respect to respective densified samples

Spearman Rank Order Correlation

Tables 2-5 show the results of a Spearman Rank Order Correlation analysis [45]. The results of the correlation analysis of non-layered materials (Table 2) show a high dependence of all observed potentials (P_E, P_P, P_C) with respect to the input thickness of lamellas. The total potential was not proven to be dependent on the degree of densification. Characteristics P_E/P_C and P_P/P_C exhibit a dependence on the elastic and plastic potential, but not the total potential. High dependence is highlighted by red color.

Table 2: Spearman's rank correlation coefficient of bending characteristics for one-layer material

Variables	Thickness (mm)	Densification	P_E (MPa)	P_P (MPa)	P_C (MPa)	Pe/Pc	Pp/Pc
Thickness (mm)	1,000	-	-	-	-	-	-
Densification	0,000	1,000	-	-	-	-	-
P_E (MPa)	-0,109	0,426	1,000	-	-	-	-
P_P (MPa)	-0,339	0,076	0,194	1,000	-	-	-
P_C (MPa)	-0,248	0,380	0,789	0,710	1,000	-	-
Pe/Pc	0,189	0.299	0,533	-0,646	-0,006	1,000	-
Pp/Pc	-0,189	-0,299	-0,533	0,646	0,006	-1,000	1,000

Table 3 shows the results of the Spearman Rank Order correlation analysis for two-layer materials without a non-wood component, where the dependence of all observed potentials was demonstrated in terms of the thickness and densification of individual layers of materials (P_E, P_P, P_C). Characteristics P_E/P_C and P_P/P_C exhibit a dependence on the elastic and plastic potential, but not the total potential.

Table 3: Spearman's rank correlation coefficient of bending characteristics for two-layer material without non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Densification of 2nd layer	P_E (MPa)	P_P (MPa)	P_C (MPa)	Pe/Pc	Pp/Pc
Thickness (mm)	1,00	-	-	-	-	-	-	-
Densification of 1st layer	0,00	1,00	-	-	-	-	-	-
Densification of 2nd layer	0,00	1,00	1,00	-	-	-	-	-
P_E (MPa)	-0,18	0,42	0,42	1,00	-	-	-	-
P_P (MPa)	-0,47	0,17	0,17	0,30	1,00	-	-	-
P_C (MPa)	-0,40	0,37	0,37	0,77	0,81	1,00	-	-
Pe/Pc	0,22	0,31	0,31	0,56	-0,53	-0,01	1,00	-
Pp/Pc	-0,22	-0,31	-0,31	-0,56	0,53	0,01	-1,00	1,00

The results of the Spearman Rank Order correlation analysis for two-layer materials with a non-wood component are shown in Table 4. A high dependence of all monitored characteristics was proven, with the exception of the dependence of the elastic potential on the thickness of individual layers. Wood densification in this type of material shows a dependence on the elastic, plastic and total potential, but not on the ratios of the potentials. The application of a non-wood component only shows dependence on the plastic potential and the potential ratios.

Table 4: Spearman's rank correlation coefficient of bending characteristics for two-layer material with non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Reinforcement	P_E (MPa)	P_P (MPa)	P_C (MPa)	Pe/Pc	Pp/Pc
Thickness (mm)	1,00	-	-	-	-	-	-	-
Densification of 1st layer	-0,00	1,00	-	-	-	-	-	-
Reinforcement	-0,00	-0,00	1,00	-	-	-	-	-
P_E (MPa)	-0,00	0,55	0,08	1,00	-	-	-	-
P_P (MPa)	-0,27	0,44	-0,12	0,08	1,00	-	-	-
P_C (MPa)	-0,22	0,69	-0,08	0,55	0,82	1,00	-	-
Pe/Pc	0,18	0,07	0,14	0,61	-0,67	-0,21	1,00	-1,00
Pp/Pc	-0,18	-0,07	-0,14	-0,61	0,67	0,21	-1,00	1,00

Table 5 shows the results of the Spearman Rank Order correlation analysis for three-layer materials with a non-wood component. These results clearly show a high dependence between the thickness of the individual layers and all the monitored characteristics except the elastic potential. The densification of individual layers has a high dependence on all monitored characteristics. The application of a non-wood component showed a strong dependence on all monitored potentials but not on their ratios.

Table 5: Spearman's rank correlation coefficient of bending characteristics for three-layer material with non-wood components

Variables	Thickness (mm)	Densification of 1st layer	Densification of 2nd layer	Reinforcement	P_E (MPa)	P_P (MPa)	P_C (MPa)	Pe/Pc	Pp/Pc
Thickness (mm)	1,00	-	-	-	-	-	-	-	-
Densification of 1st layer	-0,00	1,00	-	-	-	-	-	-	-
Densification of 2nd layer	-0,00	1,00	1,00	-	-	-	-	-	-
Reinforcement	-0,00	-0,00	-0,00	1,00	-	-	-	-	-
P_E (MPa)	-0,06	0,63	0,63	-0,10	1,00	-	-	-	-
P_P (MPa)	-0,24	0,35	0,35	-0,11	0,19	1,00	-	-	-
P_C (MPa)	-0,22	0,56	0,56	-0,12	0,56	0,89	1,00	-	-
Pe/Pc	0,14	0,13	0,13	0,03	0,50	-0,68	-0,33	1,00	-1,00
Pp/Pc	-0,14	-0,13	-0,13	-0,03	-0,50	0,68	0,33	-1,00	1,00

CONCLUSIONS

This paper studies the effect of densification and reinforcement of wood with synthetic fibers on the elastic, plastic and total bending potential. The main findings of this study are as follows:

- The density of the material has a significant effect on the elastic and plastic potential, but the relationship was not linear for the whole tested area of densification.
- The degree of 20% densification was found to be optimal in terms of improving the elastic, plastic and total bending potential in both tested lamellas thicknesses (5 and 9 mm). The increase in the total bending potential due to densification is mainly due to the increase in the bending potential in the elastic region.
- Reinforcement of non-densified wood with synthetic fibers affect the elastic, plastic and total bending potential. The improvement in plastic potential was significant for both tested beech lamella thicknesses, whereas the improvement in elastic potential was more evident mainly for test specimens with a smaller thickness (5 mm).
- The reinforcement of the densified lamellas caused a significant improvement of the total bending potential in relation to the total potential of the respective densified lamellas. The reinforcement in combination with the densified lamellas improved the total bending potential with a significant contribution in the plastic field.
- When combining both densification and reinforcement, the performance of 10% densified reinforced lamellas was found to be optimal in terms of both elastic and

plastic potential, although the reinforcing components appeared more effective at higher degrees of densification.

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