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FACULTY OF MECHANICAL ENGINEERING
INSTITUTE OF AEROSPACE ENGINEERING

EXPERIMENTAL COMPARISON OF SHEAR PROPERTIES OF FRP MEASURED BY ASTM METHODS

EXPERIMENTÁLNÍ POROVNÁNÍ SMYKOVÝCH VLASTNOSTÍ KOMPOZITŮ MĚŘENÝCH METODAMI ASTM

BAKALÁŘSKÁ PRÁCE
BACHELOR´S THESIS

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ZADÁNÍ BAKALÁŘSKÉ PRÁCE

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který/která studuje v **bakalářském studijním programu**

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma bakalářské práce:

Experimentální porovnání smykových vlastností kompozitů měřených metodami ASTM

v anglickém jazyce:

Experimental comparison of shear properties of FRP measured by ASTM methods

Stručná charakteristika problematiky úkolu:

Znalost mechanických vlastností uhlíkem vyztužených plastů je nezbytnou součástí projektování letadel. K ověření stejných smykových vlastností existuje několik standardizovaných metod, které se liší tvarem zkušebního tělesa, způsobem zavedení síly při zatěžování a náročností provedení, potažmo cenou zkoušky.

Cíle bakalářské práce:

Cílem práce je vypracovat rešerši relevantních postupů a výsledků a na jejich základě navrhnout experiment, provést měření a porovnat jak se liší smykové vlastnosti kompozitních vzorků naměřené metodami ASTMD2344 a ASTMD5379.

Seznam odborné literatury:

[1] AMC 20-29 Annex II to ED Decision2010/003/R of 19/07/2010
[2] ASTM D3518 Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a645° Laminate
[3] ASTM D2344 Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates
[4] ASTM D5379 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method
[5] ASTM D5229 Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials

Vedoucí bakalářské práce: Ing. Tomáš Urík

Termín odevzdání bakalářské práce je stanoven časovým plánem akademického roku 2014/2015.

V Brně, dne 10.11.2014

L.S.

doc. Ing. Jaroslav Juračka, Ph.D. Ředitel ústavu	doc. Ing. Jaroslav Katolický, Ph.D. Děkan fakulty

ABSTRACT

Accurate shear stress-strain constitutive properties assessment of composite materials is essential for understanding the anisotropic material behaviour. Many test methods for assessment of the shear properties were developed. Because obtaining pure shear state in composites is difficult, it is provided only by few test methods. Use of digital image correlation as instrument for full field strain assessment to obtain constitutive shear properties from simple short beam shear test method is verified in this thesis. Results of this method are further compared to V-notched beam (Iosipescu) shear test.

ABSTRAKT

Přesné určení konstitutivních smykových závislostí napětí na deformacích je základem pro pochopení chování anizotropního kompozitního materiálu. Bylo vyvinuto mnoho zkoušek smykových vlastností kompozitních materiálu. Jelikož vyvolání čisté smykové napjatosti je složité, tento stav je vyvolán pouze některými z nich. V této práci je ověřeno použití systému Aramis k vyhodnocení průběhu smykového přetvoření a následnému výpočtu konstitutivních smykových vlastností při provedení jednoduché zkoušky ohybem krátkého nosníku. Tyto výsledky jsou dále porovnány se zkouškou podle Nicolae Iosipesca.

KEYWORDS

Composite materials; in-plane shear; interlaminar shear; shear modulus; shear properties; shear strength; shear testing; digital image correlation; Aramis

KLÍČOVÁ SLOVA

Kompozitní materiály; smyk ve vrstvě; smyk mezi vrstvami; smykový modul pružnosti; smykové vlastnosti; smyková pevnost; digitální měření 3D deformací; Aramis

BIBLIOGRAPHIC CITATION

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DECLARATION OF AUTHENTICITY

I, Tomáš Ponížil, declare that I prepared this bachelor’s thesis independently and disclosed all sources and literature.

29. 5. 2015

……………………………………….

Tomáš Ponížil

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CONTENT

INTRODUCTION

Since different properties at each material direction can be present in composite materials, these properties must be tested. Properties of composite materials can be sorted into two main groups: interlaminar (binding properties between layers) and in-plane properties. In-plane properties of laminated composites can be obtained in 1-2 and 2-1 planes. Interlaminar material properties are measured in 1-3 and 2-3 planes. Basic composite material directions are shown in Figure 0.1.

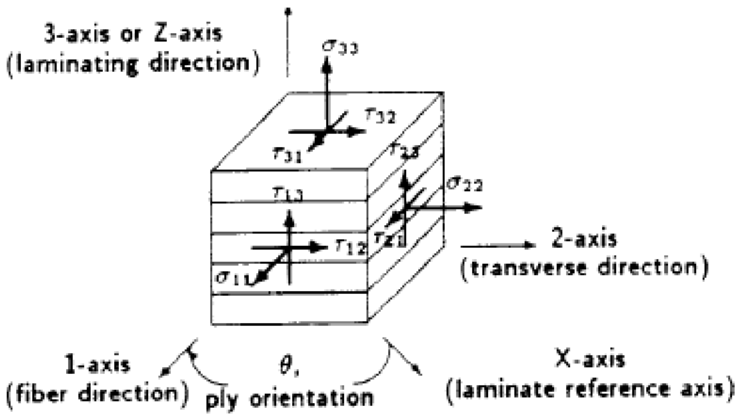


Figure 0.1 Basic composite materials coordinate system. Property of ASTM International

There have been developed more test methods for testing shear properties in past forty years, than tests for any other properties. Reasons for so many methods are difficulty in obtaining pure shear state in composite materials, and high costs of tests.

This thesis is focused on comparison of modified Short Beam Shear (further SBS) test method to V-notched beam (Iosipescu) test method to verify approach in work presented by Andrew Makeev and collective published to Elsevier Ltd, that uses Digital Image Correlation (further DIC) to evaluate stress-strain curves and shear modulus of elasticity.

1 CRITICAL REVIEW

In this part, most of test methods used will be described. Performance of those methods will be evaluated using comparative table from article written by Dr. Donald Adams to High-Performance Composites magazine [1].

Test Method (with ASTM Std. No., if applicable)	Uniform Shear Stress State	All Three Stress States Practical	Shear Strength Obtained	Shear Stiffness Obtained
Short Beam Shear (D 2344)			■	
Iosipescu Shear (D 5379)	■	■	■	■
±45° Tensile Shear (D 3518)			■	■
Two-Rail Shear (D 4255)			■	■
Three-Rail Shear (D 4255)			■	■
Double-Notched Shear (D 3846)			■	■
Torsion of a Thin Tube (D 5448)	■		■	■
Cross-Beam Sandwich			■	■
Torsion of a Solid Rod			■	■
Four-Point Shear			■	
Picture Frame Shear			■	■
Plate Twist				■
10° Off-Axis (Tensile)			■	■
V-Notched Rail Shear (D 7078)	■	■	■	■

Table 1 A comparison of the features and performance potential of available shear test methods. Reprinted from [1] by permission of the publisher Dr. Donald F. Adams

1.1 ±45° Tensile Shear

In this test method, shear strength is measured by performing a tensile test on a ±45° laminate. ±45° Tensile Shear test setup is shown in **Figure 1.1**, and specified in ASTM standard D 3518 [2]. In-plane shear stress is generated because of the shear coupling mismatch between the adjacent +45° and -45° lamina [3]. Simplicity of uniaxial tensile test makes it a popular shear test method. Dr. Don Adams in his comparative article shows, that ±45° Tensile Shear test provides Shear Strength and Shear Modulus calculation. On the other side, non-uniform stress state is present and only in-plane properties can be measured [1].

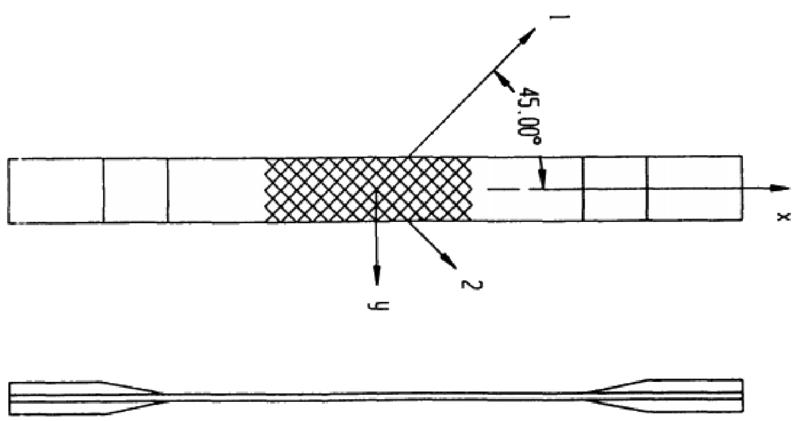


Figure 1.1 ±45° Tensile Shear test specimen loaded along x axis. Property of FAA

1.2 Two-Rail Shear

In Two-Rail Shear test method, specimen is attached between two rails by six bolts as shown in **Figure 1.2**. Loading is tensile and diagonal to specimen. Strain is measured in 45° angle to the rails. Method is designed for measuring in-plane shear properties and specified in ASTM standard D 4255 [4*]*. According Adams [1] this test provides Shear Strength and Shear Stiffness, but uniform shear stress state not.

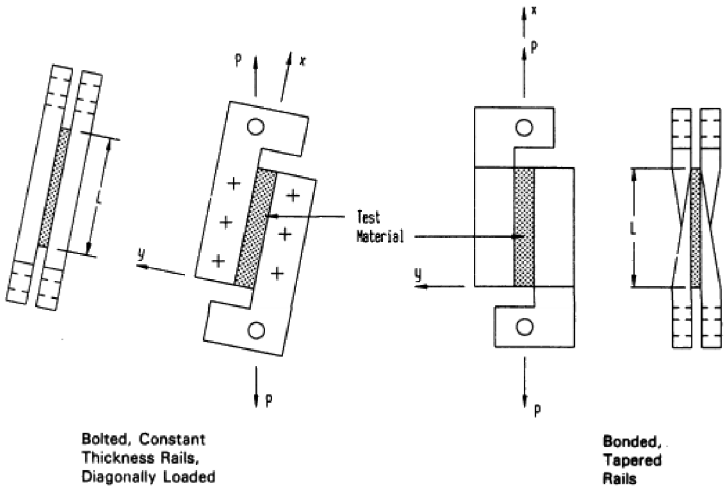


Figure 1.2 Two-Rail Shear test setup. Property of FAA.

1.3 Three-Rail Shear

Three-Rail Shear test method is specified in the same ASTM standard as Two-Rail test [4]. This modification is designed to produce a closer approximation to pure shear. The fixture consists of 3 pairs of rails clamped to the test specimen as shown in **Figure 1.3**. The outside pairs are holding the specimen. Middle pair of rails is loaded in. The shear force in laminate is generated via friction between rail and specimen. The strain gages are bonded to the specimen at 45° to the specimen's longitudinal axis.

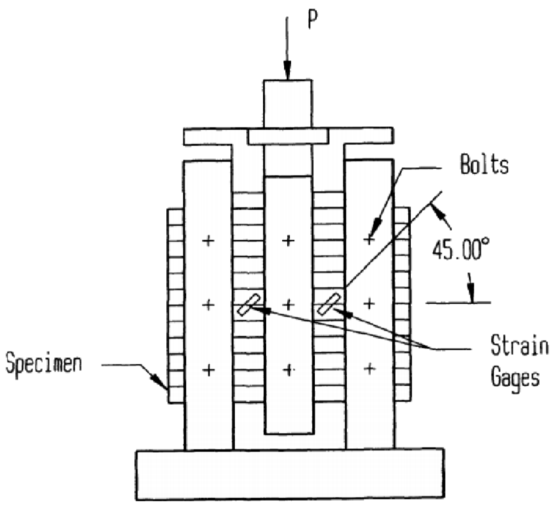


Figure 1.3 Three-Rail Shear test setup. Property of FAA.

1.4 Double-Notched Shear

This method is specified in ASTM standard D 3846. The straight-sided specimen, shown in **Figure 1.4**, contains half-depth, flat-bottomed notches on opposing surfaces [1]. When an axial compressive end loading is applied, a shearing action is induced along the specimen centreline between the notch roots, presumably leading to a failure on shear plane between notches. The specimen is relatively thin and tends to buckling under compressive end loading, lateral supports must be used. Fundamental problem with Double-Notch test is that significant stress concentrations occur at the roots of the notches. [5]

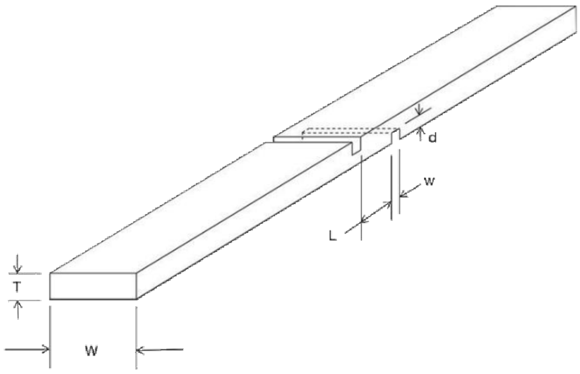


Figure 1.4 Double-Notched Shear test specimen. Property of Composites world

1.5 Torsion of a Thin Tube

Torsion of a Thin Tube is specified in ASTM STANDARD D 5448. Standard specimen for this test method is thin hoop wound tube with thickness to diameter (t/D) ratio less than 0.02 The specimen is bonded with a potting compound to end fixtures and devices to which torsional loading is applied. Setup of the specimen is shown in Figure 1.5. Uniform shear stress state is provided by this test and variation across the thin tube wall is small [6]. If torsion axis and specimen axis are not coaxial, induced bending moment can cause premature failure and thus inaccurate result. As secondary considerations, thin-walled tubes are not always representative of the usage form of the material being evaluated, and gripping them requires special procedures [1].

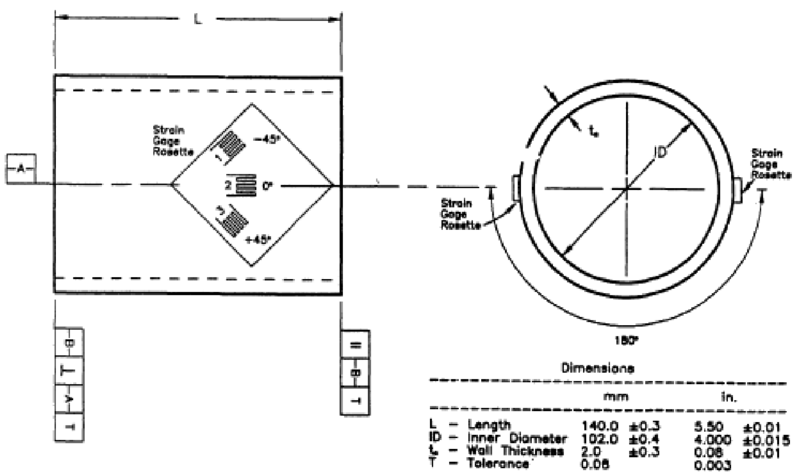


Figure 1.5 Thin tube specimen. Property of FAA.

1.6 Cross-Beam Sandwich

Cross-Beam specimen is shown in picture 1.6. The specimen prepared by bonding composite laminates to a honeycomb core. A biaxial loading device is required to apply equal and opposite loads on the two cross arms. The face sheets in the test section is subjected to tensile and compressive stresses in two perpendicular directions (longitudinal axes of the two beam arms) and a state of shear stress is created at 45° to these directions [6]. Shear stiffness and strength is obtained, but Non-uniform shear stress state is provided by this test method and a large and expensive sandwich panel specimen is required.

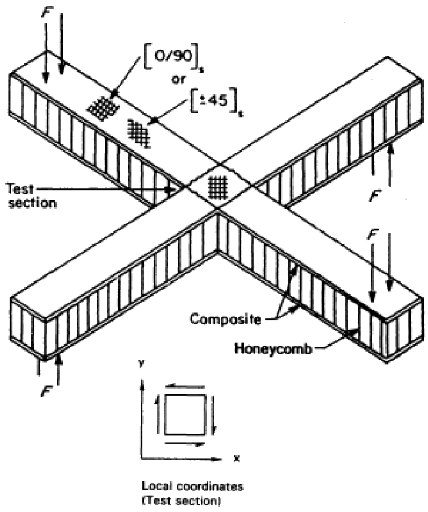


Figure 1.6 Cross-Beam Sandwich test specimen. Property of FAA.

1.7 Torsion of a Solid Rod

This test method is not standardized by ASTM. The specimen is circular bar, with flats ground for larger diameters to prevent slipping as shown in Figure 1.7. For the strain measurements rosette are recommended. A minimum gage section length-to-diameter ratio (L/D) of 16 is necessary because of complex stress state near the grips, yet damage is initiated near the grips. As can be seen in **Table 1** shear strength and stiffness can be obtained.

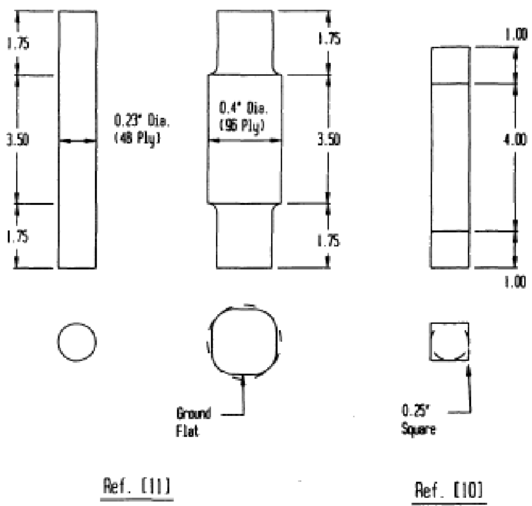


Figure 1.7 Solid Rod specimen. Property of FAA.

1.8 Picture Frame Shear

The picture frame test is mainly used for the shear testing of woven composites. The frame fixture is sketched in Figure 1.8. Specimen is cut parallel to fibres. A tensile force is applied at the crosshead mounting. The rig is jointed at each corner such that its sides can rotate and the interior angle between adjacent sides can change. The initially square frame thus becomes of diamond shape. The force required to deform the material is recorded at the crosshead mounting as a function of crosshead displacement. From this information the shear stress can be determined as a function of shear strain and shear strain rate [7]. According Adams, this method provides same performance as rail shear test, but requires complex test fixture [1].

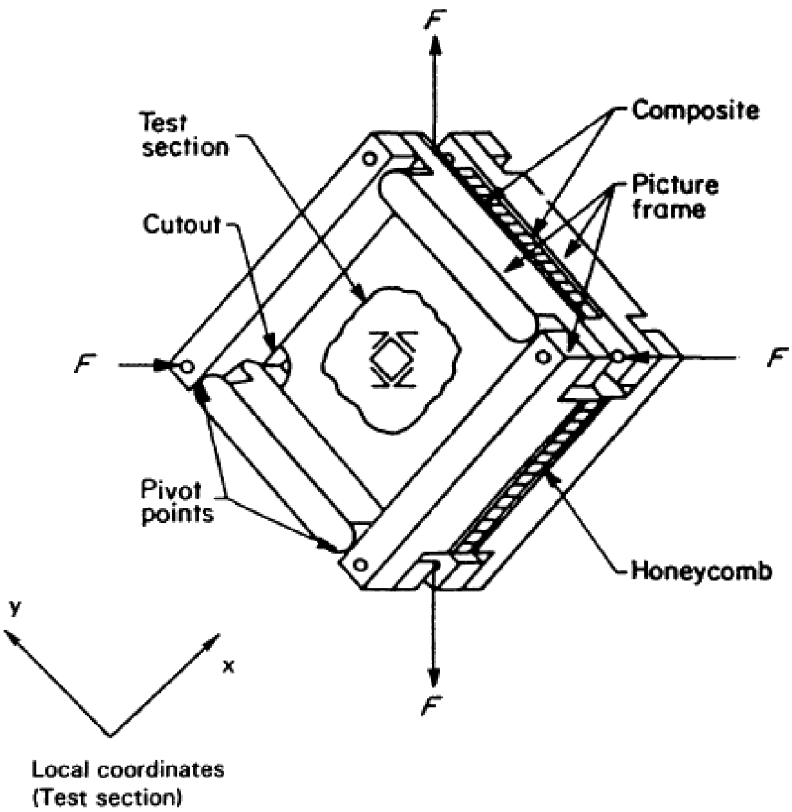


Figure 1.8 Picture Frame Shear test setup. Property of FAA.

1.9 10° Off-axis (Tensile)

10° Off-axis (Tensile) test method is designed for intralaminar (in-plane) shear characterization of unidirectional fibre composites. This test method was presented and investigated by Chamis and Sinclair [8].In **Figure 1.9** can be seen that the specimen has fibres oriented 10° from loading axis. Gripping system prevents displacements and rotations caused by the normal/shear coupling effect, but then a non-uniform stress field is produced [3]. Another disadvantage is sensitivity of shear stress result to small errors in the load orientation angle [8].

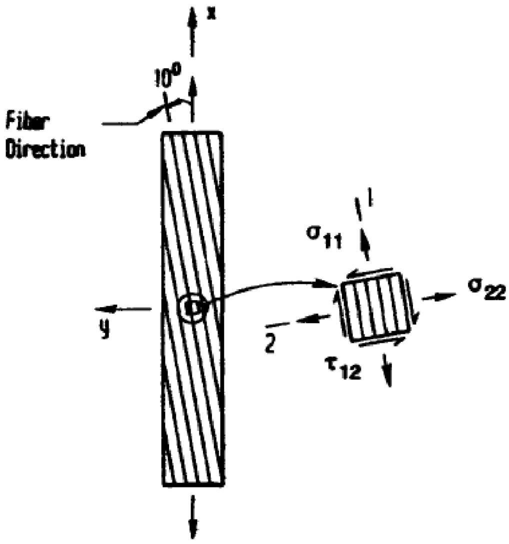


Figure 1.9 10° Off-axis test specimen. Property of FAA.

1.10 Plate Twist

In this test method square flat plates are used to determine the shear modulus, but shear strength not. Two upward forces are applied at the corners whereas two downward forces are applied at the other two, as shown in **Figure 1.10**. Deflection measurements are used to compute the modulus. Extreme care is needed in preparation of the sample and in load-deflection measurements. There are, however, problems, since large deformations have significant influence on the response and the corners are susceptible to damage. In addition, warpage during curing can influence the deflection [6].

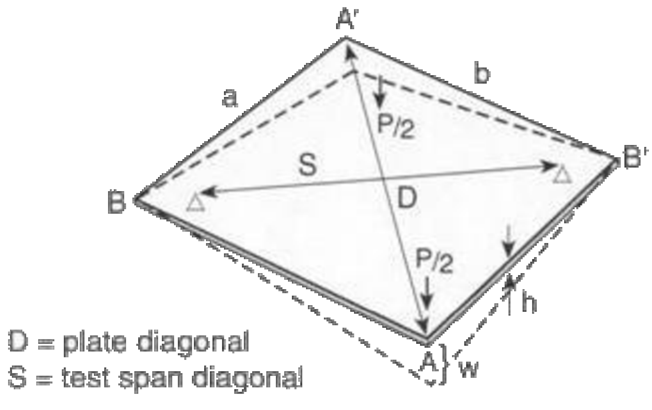


Figure 1.10 Plate Twist test specimen. Property of AdhesivesToolkit

1.11 V-Notched Rail Shear

V-Notched Rail Shear test is relatively new test method. It is standardized in ASTM D 7078. In basics it is combination of V-Notched Beam test (Iosipescu, described later) and Rail Shear test. Specimen, similar to Iosipescu, but wider, is attached between two rails. Rails are loaded in tension and pure shear state is obtained. According **Table 1** V-Notched Rail test provides also all three stress states, shear strength and stiffness [1]. Advantage of this method is that specimen is loaded thru faces, so higher forces are transferred to specimen than with edge loading in Iosipescu [9].

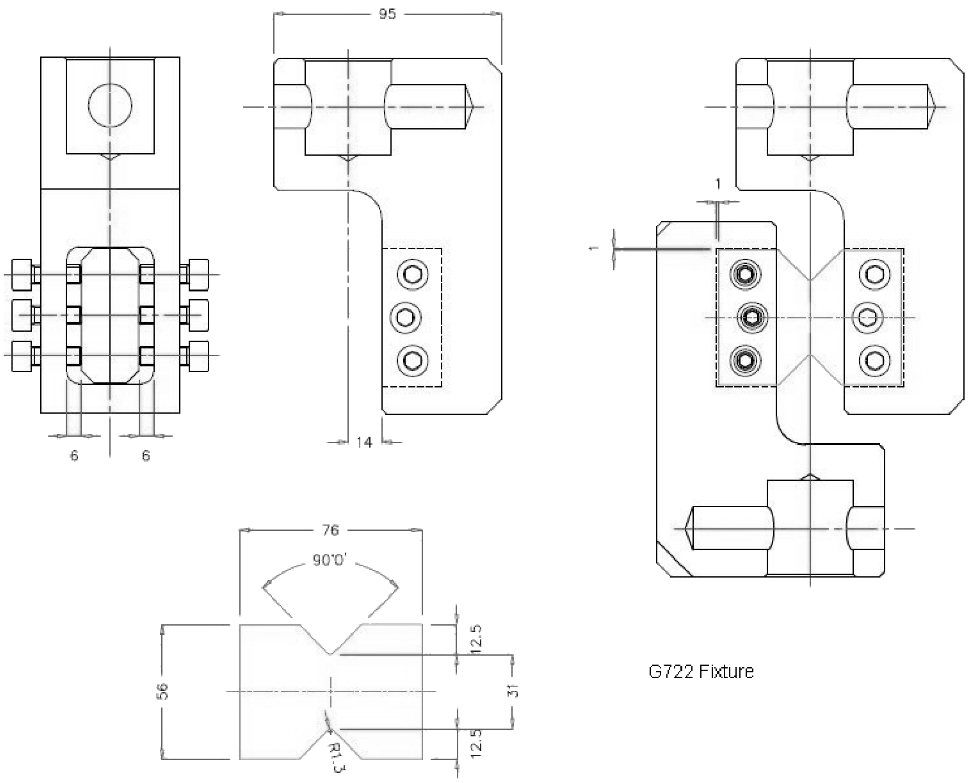


Figure 1.11 V-Notched Rail Shear test fixture and specimen. Property of Testresources, Inc

1.12 Four-Point Shear

Four-Point Shear test is modification, shown in **Figure 1.12**, of Three-Point Short Beam Shear test designed to reduce bending moment and pressure under the loading nose [6]. However, test data do not indicate any significant improvement in shear strength [1].

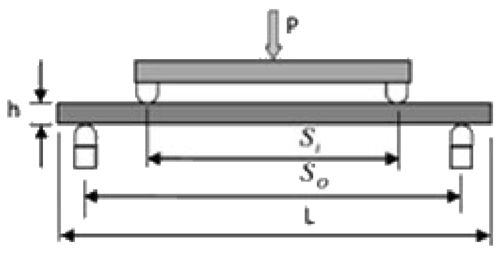


Figure 1.12 Four-Point Shear test setup. Property of IIT Bombay

1.13 V-Notched Beam (Iosipescu) Shear Test Method

1.13.1 History

Iosipescu Shear test is standardized by ASTM D 5379 as V-Notched Beam Method [10]. This test was developed by Nicolae Iosipescu in 1967 to characterise the in-plane shear properties of metallic materials [11]. Walarth and Adams first published the application of the test method on composite materials in 1983 [12].

1.13.2 Method setup

Specimen in the form of a rectangular flat strip with symmetrical centrally located v-notches, shown schematically in Figure 1.13, is loaded in a mechanical testing machine by a special fixture, shown in Figure 1.14. The specimen is inserted into the fixture with the notch located along the line of action of loading. One half of the fixture is compressed by a testing machine while load is monitored. The specimen is loaded by the relative displacement between the two halves of the fixture.

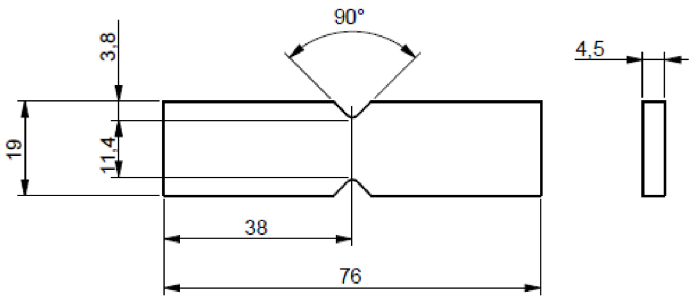


Figure 1.13 V-Notched Beam Test Specimen schematic

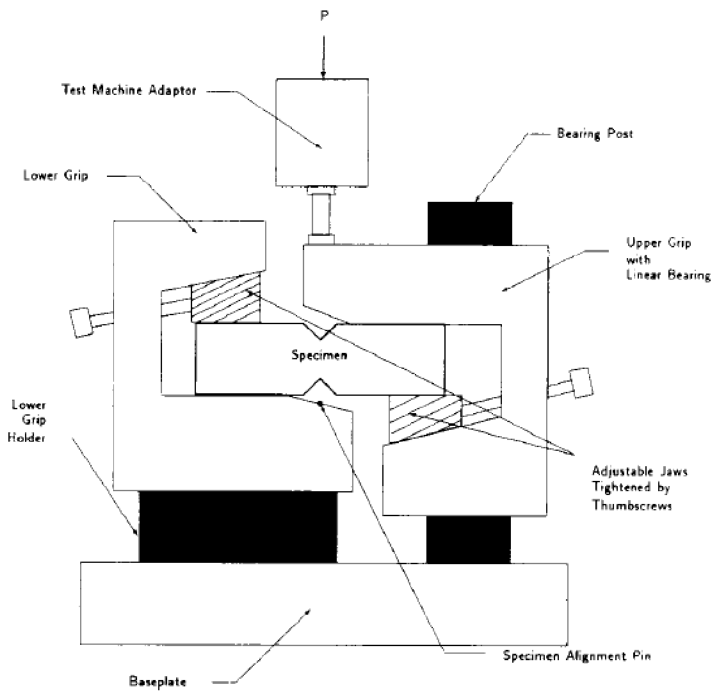
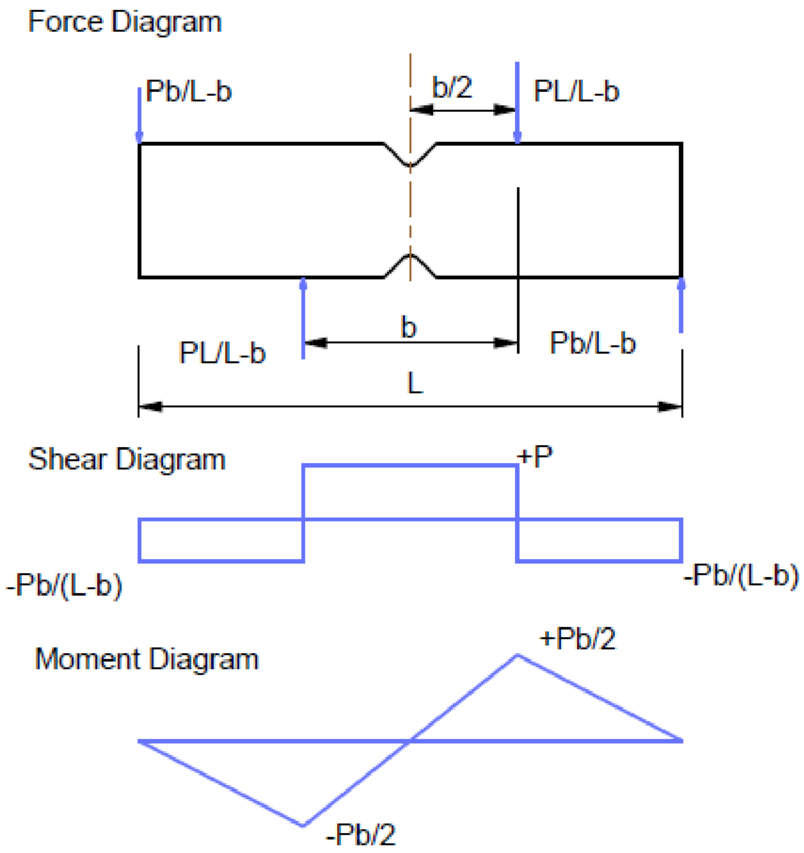


Figure 1.14 Iosipescu test fixture schematic. Property of ASTM

1.13.3 Loading

The loading can be idealized as asymmetric flexure as shown by the shear and bending moment diagrams of **Figure 1.15**. Because of notches, the shear distribution is more uniform along the loading direction. Strains can be measured with two gages in ±45° angle from loading direction.



P–force carried by specimen

L–specimen length

b–supports distance

Figure 1.15 Idealized Force, shear, and Moment Diagrams

1.13.4 Significance and Use

This test method is designed to produce shear property data for material specifications, research and development, quality assurance, and structural design and analysis. Either in-plane or interlaminar shear properties may be evaluated, depending upon the orientation of desired material plane to the testing plane, Figure 1.16. In-plane shear properties for laminated composites can be obtained in 1-2 and 2-1 planes. In 1-3 and 2-3 planes are measured interlaminar properties. Figure 1.17 shows Iosipescu test specimen configuration.

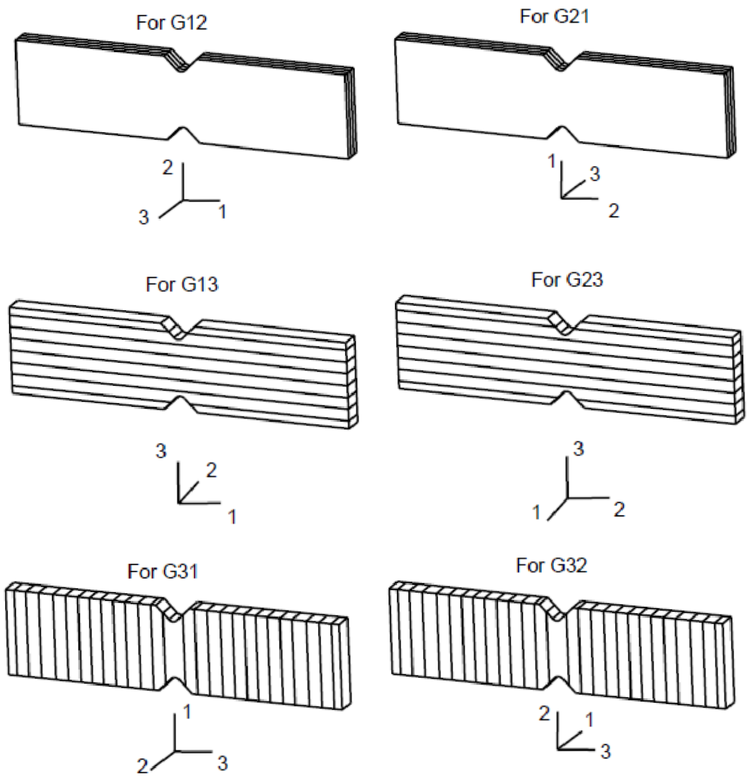


Figure 1.16 Orientation of Material Planes

1.13.5 Evaluation

According Adams [9] it has been the most accurate test method for more than 25 years, such performance is provided only by V-Notched Rail test since 2005. Imperfections can play a major role. Flat loading surfaces are required to avoid out of pane bending. Back-to-back gages should be employed to check for irregularities in loading. This leads to high costs of the specimen and test fixture.

1.14 Short Beam Shear Test Method

1.14.1 Description

Short Beam Shear (SBS) test method is due to its simplicity the most widely used screening method for measuring interlaminar shear strength (ILSS). This method is specified by ASTM standard D2344 [13].

1.14.2 Summary of Test Method

The specimens for this test method are centre-loaded flat or curved beams, as shown in Figure 1.17. The specimen ends rest on two supports that allow lateral motion, the load is applied by the loading nose directly on the midpoint of the test specimen. Specimen is only limited by loading span length to specimen thickness ratio of 4 and minimum thickness of 2 mm. Other dimensions are driven by recommendations. Specimen length should be thickness times 6 and specimen width should be thickness times 2.

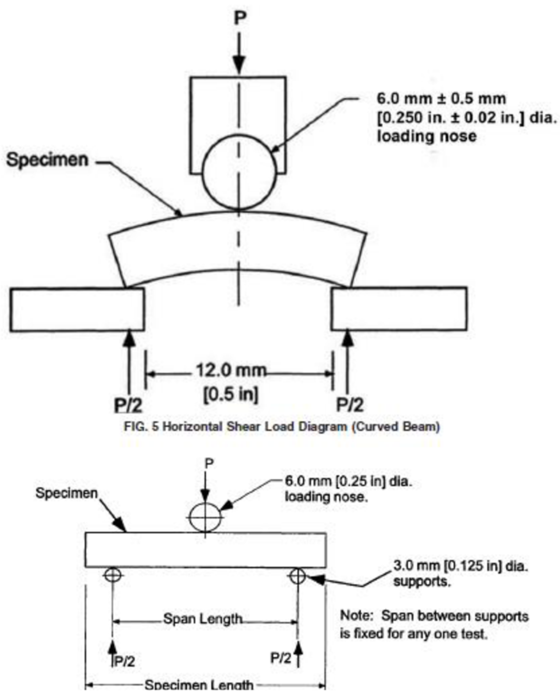


Figure 1.17 SBS test setup. Property of ASTM.

1.14.3 Significance and Use

The stress state in the specimens is highly complex. The shear stress distribution varies thru the length, as shown in Figure 1.18. The shear stress distribution deviates from classic Timoshenko beam theory [14] due to stress concentrations under loading and support noses. Another stress in the specimen is normal stress caused by bending moments. However, failures are normally dominated by resin and interlaminar properties, and the test results have been found to be repeatable for a given specimen geometry, material system, and stacking sequence [6].

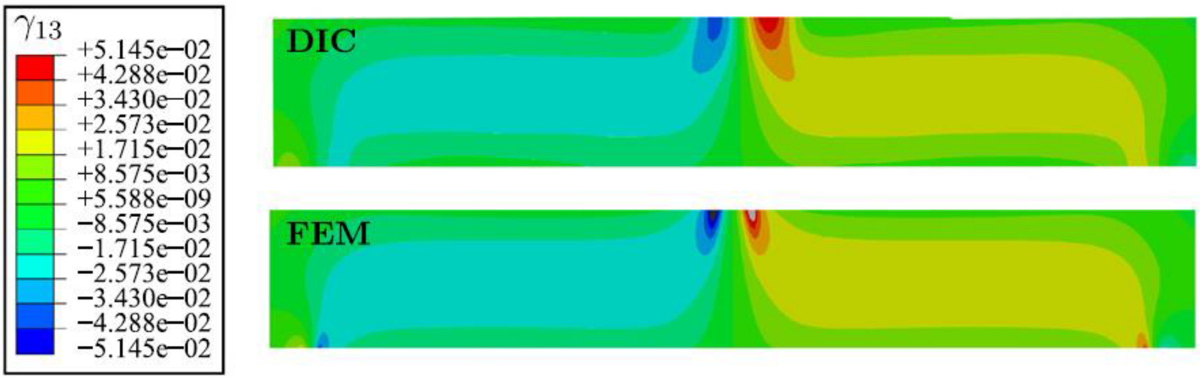


Figure 1.18 Shear strain distribution plot. Property of Elsevier Ltd.

1.14.4 Evaluation

This test method is cheap and easy to perform, but only shear strength is provided [1]. Short beam strength determined by this test method can be used for quality control or materials screening.

2 METHODOLOGY

2.1 Short Beam Shear

Various modifications of Short Beam Shear test method have been suggested in literature, that include use of larger diameter loading cylinder and different span-to-thickness ratio [15], tabbing top and bottom faces of the specimen [16], [17] and indirect loading through rubber pad and an aluminium seat [18]. Only stress concentration is improved by these modifications. Makeev [19] brought new approach to the test method evaluation, using Digital Image Correlation (DIC) [20]. Using DIC, stress-strain curves measuring is possible. Experiment will be performed to verify use of this modification. In Figure 2.1 are shown results presented in Makeev's work [21].

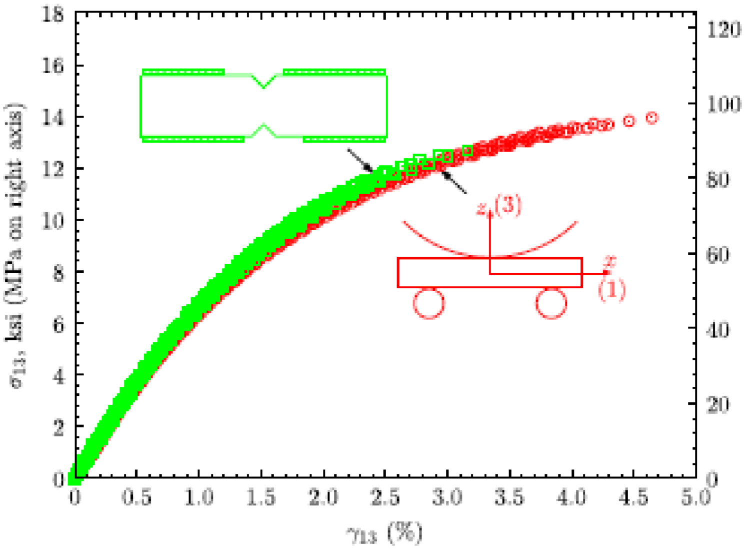


Figure 2.1 Comparison of shear Stress-strain responses for SBS specimens with V-notched beam specimens, Property of Composites Journal

2.1.1 Test Specimen

The test specimens will be manufactured according ASTM. Before testing will be measured and recorded every specimen's width and thickness at the specimen midsection with an instrument with an accuracy of ±0.002 mm and the specimen length with accuracy of ±0.1 mm.

$[0]_{ns}$ Test specimens will be cut from 4.5 mm thick unidirectional carbon composite panels 300×520 mm with fibre volume V_f = 51.5% and density of 200 g/m^2 with fibre orientation corresponding longitudinal direction.

Specimen's square cross-section thickness h will be cca. 4.5 mm. The width reduction, based on 3D finite element analysis presented in [19], is suggested for more uniform strain distribution through the specimen width. Other specimen dimensions will be manufactured according ASTM standard:

Specimen length $l = 6 \times h$

Support span length $L = 4 \times h$

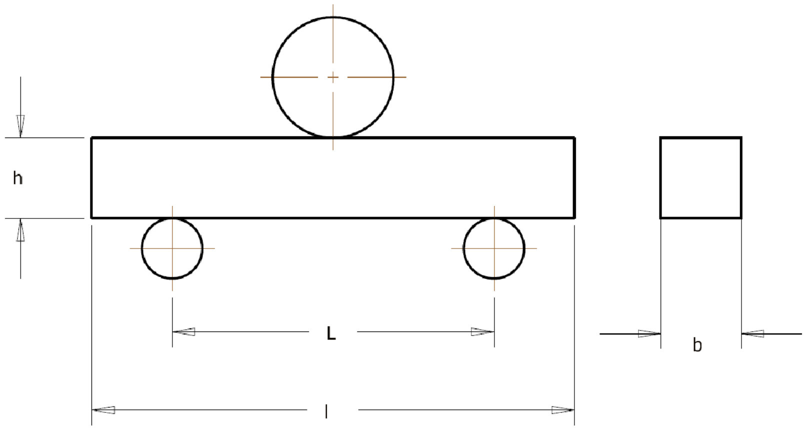


Figure 2.2 Basic Specimen Dimensions

2.1.2 Procedure

Testing will be conducted according ASTM Standard D2344M [13] with greater diameter of loading nose (10 mm) and use of Digital Image Correlation for strain assessment. The greater loading nose reduces compressive damage under the loading nose [15].

Shear stress will be calculated by Equation (1) from force, which will be measured by testing machine. Measuring of strain will be described in next chapter.

2.1.3 Measuring of strain

The DIC full-field surface strain assessment is based on the analysis of stereo images of the specimen surface with a random texture. **Figure 2.3** shows a random texture created on the SBS specimen surface using black and white spray paints. While the specimen is subjected to load, a sequence of images is acquired using a 12-megapixel stereo camera system. DIC system ARAMIS [22], shown in **Figure 2.4**, will be used in this work for assessment of Green–Lagrange strain tensor components on the specimen surface, especially in-plane shear strainε_{12}. The ARAMIS software determines complete three-dimensional positions before and after deformation by tracking the grey value pattern in small subsets throughout the acquired stereo image sequence. The shear strain data will be acquired from five points created on mid-plane between loading nose and support on each side.

Figure 2.3 Random texture on the SBS specimen [21]

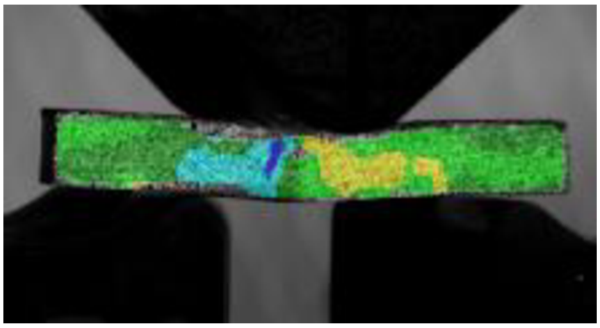


Figure 2.5 DIC data for surface strain components output from ARAMIS software

Figure 2.4 Aramis 12M. Property of GOM.

2.1.4 Calculation

According to beam theory [14], pure shear state with its maximum occurs in mid-plane. **Figure 2.6** shows shear and normal stress distributions along specimen thickness.

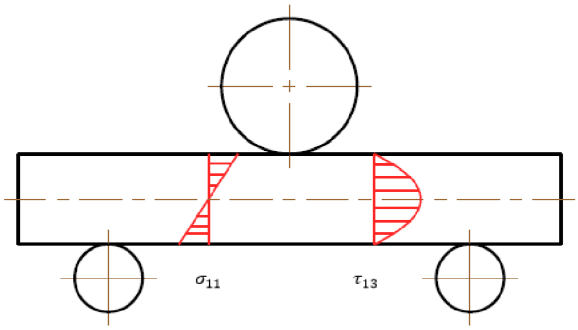


Figure 2.6 Normal and shear stress distribution thru the thickness of the specimen.

σ_{11} is normal stress and τ_{13} is shear stress

As pure shear state occurs, use simple closed-form approximation from Zurovsky's shear formula (1) is allowed to calculate shear stress in mid-plane [14]:

$$\tau_{xz} = \frac{T * U_y(z)}{b(z) * J_y} \qquad (1)$$

Where:

T = shear force;

$U_y(z)$ = first moment of area about y axis;

$b(z)$ = cross section width (depending on z);

J_y =second moment of area about y axis.

For rectangular cross section shear stress in mid plane is calculated from equation (2):

$$\tau_{12} = \frac{3}{4} \times \frac{P}{b \times h} \qquad (2)$$

Where:

P = load observed during the test, N;

b = measured specimen width, mm;

h = measured specimen thickness, mm;

τ_{12} = maximum in-plane shear stress.

Shear strain will be calculated as element of plane strain tensor (2), which is explained in **Figure 2.7.**

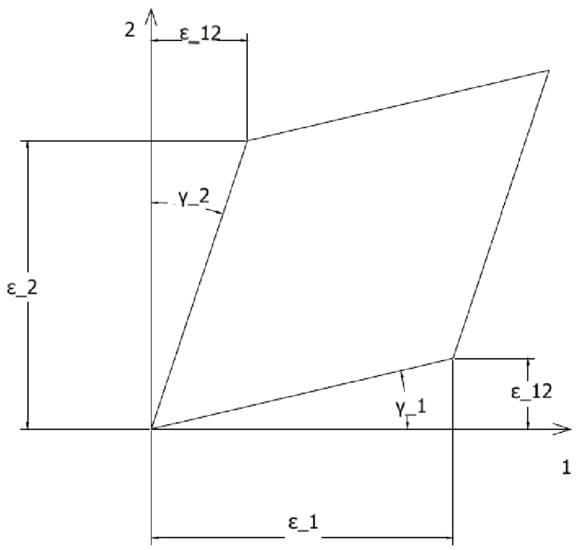


Figure 2.7 Description of plane Strain Tensor elements, γ_1 = γ_2

If small deformations are counted($\varepsilon \leq 0.05;\ tg\gamma \cong \varepsilon_{12};\ \gamma \cong \varepsilon_{12}$) , following equations are valid:

$$T_\varepsilon = \begin{pmatrix} \varepsilon_1 & \varepsilon_{12} \\ \varepsilon_{12} & \varepsilon_2 \end{pmatrix} = \begin{pmatrix} \varepsilon_1 & \frac{\gamma_{12}}{2} \\ \frac{\gamma_{12}}{2} & \varepsilon_2 \end{pmatrix} \qquad (3)$$

$$\gamma_{12} = \gamma_1 + \gamma_2 = 2\varepsilon_{12} \qquad (4)$$

Where:

γ_{12} = shear strain angle;

ε_{12} = shear strain.

ε_1 = longitudinal strain

ε_2 = transverse strain

T_ε = strain tensor

Chord Shear Modulus will be calculated according ASTM [10]:

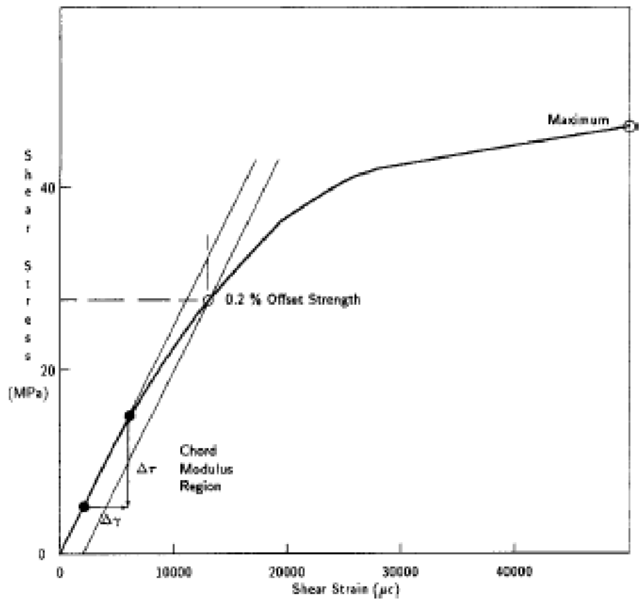


Figure 2.8 Illustration of Modulus Determination. Property of ASTM

$$G^{chord} = \frac{\Delta\tau}{\Delta\gamma} \quad (5)$$

Where:

G^{chord} = shear chord modulus of elasticity, GPa;

$\Delta\tau$ = difference in applied shear stress between the two strain points;

$\Delta\gamma$ = difference between the two strain points (nominally 0.004).

2.2 Iosipescu

2.2.1 Test Specimen

Test specimens will be cut from 4.5 mm thick unidirectional carbon composite panels 300×520mm with fibre volume V_f = 51.5% and density of 200 g/m^2. The specimens will be manufactured according to ASTM. Dimensions and geometric tolerances are shown in **Figure 2.9.**

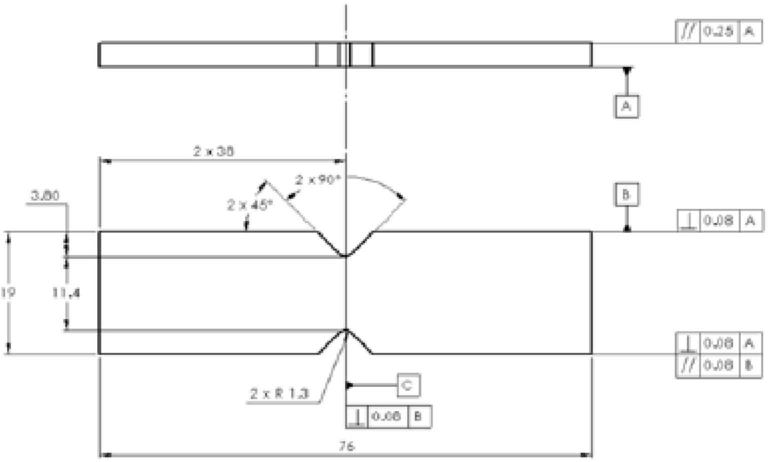


Figure 2.9 Drawing of the Iosipescu test specimen. Property of ASTM

Figure 2.10 Iosipescu test fixture

2.2.2 Procedure

V-Notched Beam test will be conducted following ASTM standard D5379M using test fixture, shown in **Figure 2.10**. Strain will be measured by two virtual strain gages centred between notch roots at ±45° angle, shown in **Figure 2.11**. Shear strain γ_{13}will be calculated from ε_{+45} and ε_{-45}, measured by optic method included in test machine:

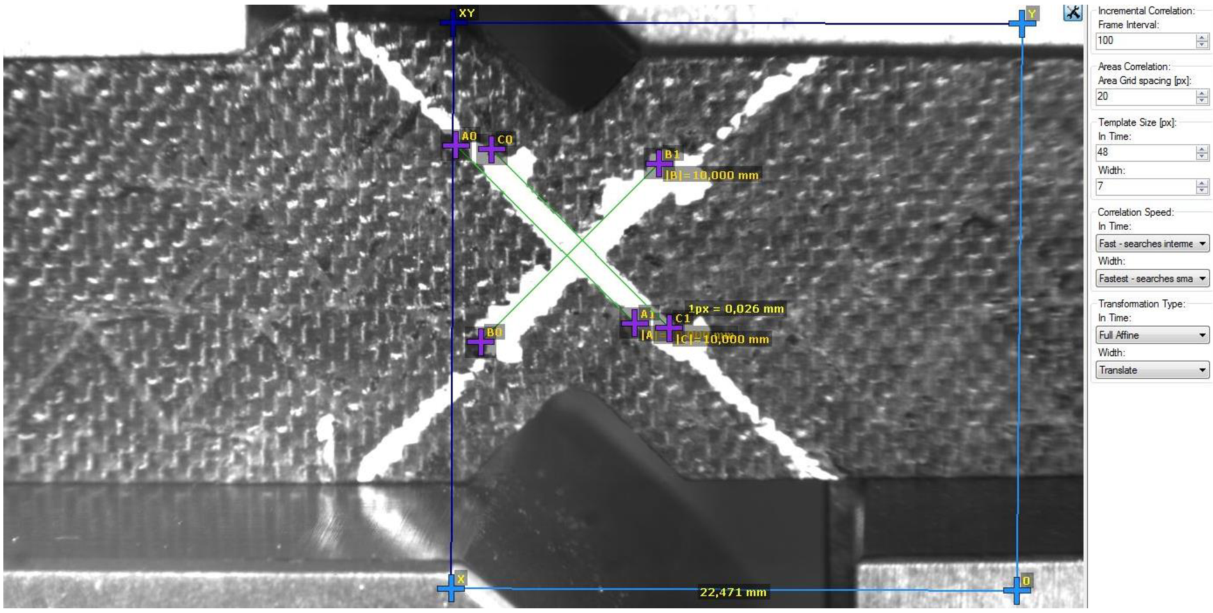


Figure 2.11 Virtual Strain Gages orientation

$$\gamma_{12} = |\varepsilon_{+45}| + |\varepsilon_{-45}| \quad (6)$$

Shear stress will be calculated by equation (7) from loading force measured by testing machine:

$$\tau = \frac{P}{w \times h} \qquad (7)$$

And ultimate shear strength at 5% strain will be calculated from equation (8):

$$F^u = \frac{P^u}{w \times h} \qquad (8)$$

F_u = ultimate strength, MPa

P_u = the ultimate force at 5 % engineering shear strain, N;

τ_i = shear stress at ith data point, MPa;

P_i = force at each data point, N

w = specimen width between notches

h = specimen thickness at notched area

Calculation of shear strain and chord shear modulus is described in chapter 2.1.4.

3 EXPERIMENT

Tests were conducted 12.5. 2015 at Institute of aerospace engineering at BUT on calibrated test machine Labortech LabTest 6.500. Load speed was set on 1 mm/min.

3.1 V-Notched Beam Shear Test (Iosipescu)

3.1.1 Sampling and evaluation method

The test specimens were manufactured from $[0°]_{ns}$ laminate on water jet cutter to meet tolerances given by the ASTM standard [10]. Before testing, each specimen was labelled and two contrast lines at ±45° angle were drawn between notches, **Figure 3.1**. Better surface points distinction is allowed by these two lines. Thickness and width between notches were measured and put into **Table 2**.

Figure 3.1 Contrast markings on the specimen 1.

Specimen		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
width	*w [mm]*	11.2	11.15	11.2	11.15	11.2	11.2	11.15	11.15	11.15	11.2
thickness	*h [mm]*	4.397	4.18	4.128	4.509	4.421	4.121	4.387	4.591	4.57	4.342

Table 2 Iosipescu specimen width and thickness between notches

Seven specimens were chosen and tested. Labortech LabTest 6.500 electromechanical test machine with maximum force 500 kN was equipped with optic contactless extensometer and load cell. For each test were written measured data files by Labortech Test&Motion® software. Sampling frequency was 100 Hz and large amount of data points was created [23]. Data files were evaluated using equations (5–8) and put into graphs.

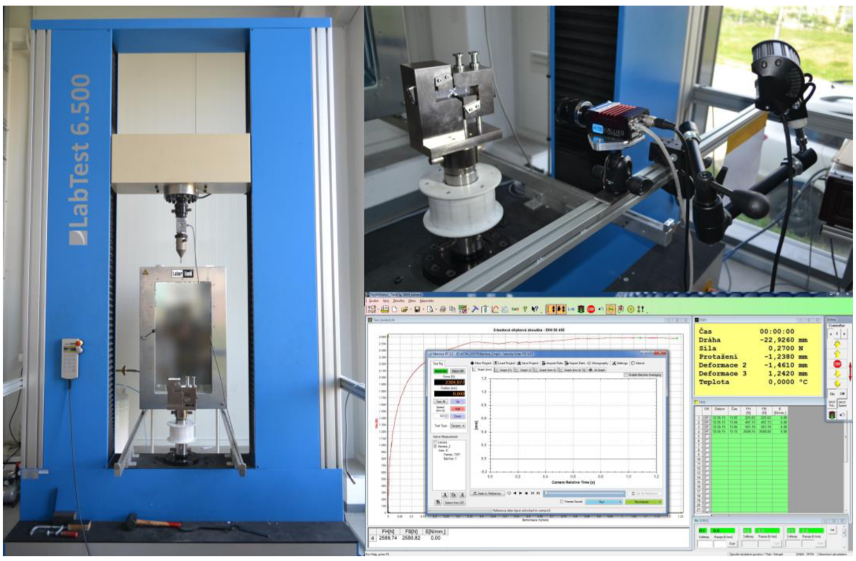
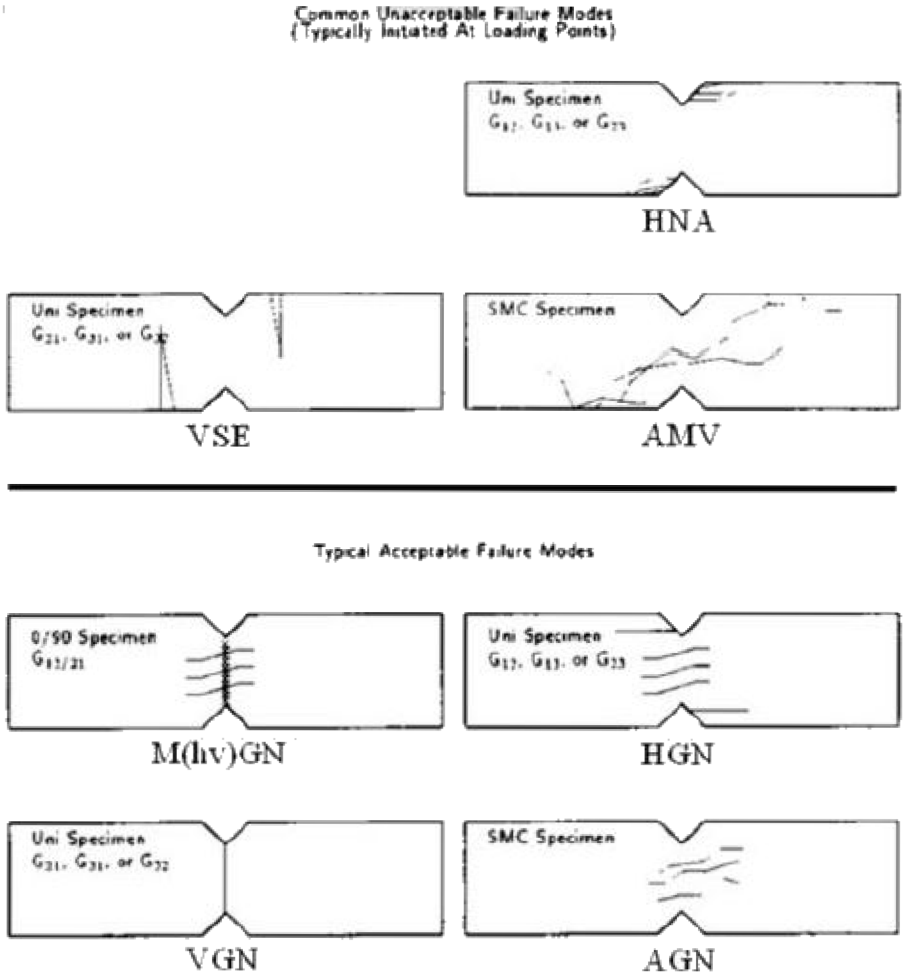


Figure 3.2 Test machine with equipment

3.1.2 Failure assessment

Every specimen's failure was compared to **Figure 3.3**, which shows acceptable and unacceptable failure modes.



First Character

Failure Type	Code
Horizontal cracking	H
Vertical cracking	V
Angled cracking	A
Edge crushing	E
Multi-mode	M(xyz)
Other	O

Second Character

Failure Area	Code
Gage section	G
Notch region	N
Side region	S
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
between Notches	N
Adjacent to notches	A
top and/or bottom Edge	E
Various	V
Unknown	U

Figure 3.3 V-Notched beam test failure types and codes. Property of ASTM.

As shown in **Figure 3.4**, every specimen’s failure mode was accepted. Specimen 4 did not show any obvious failure, but this was also acceptable.

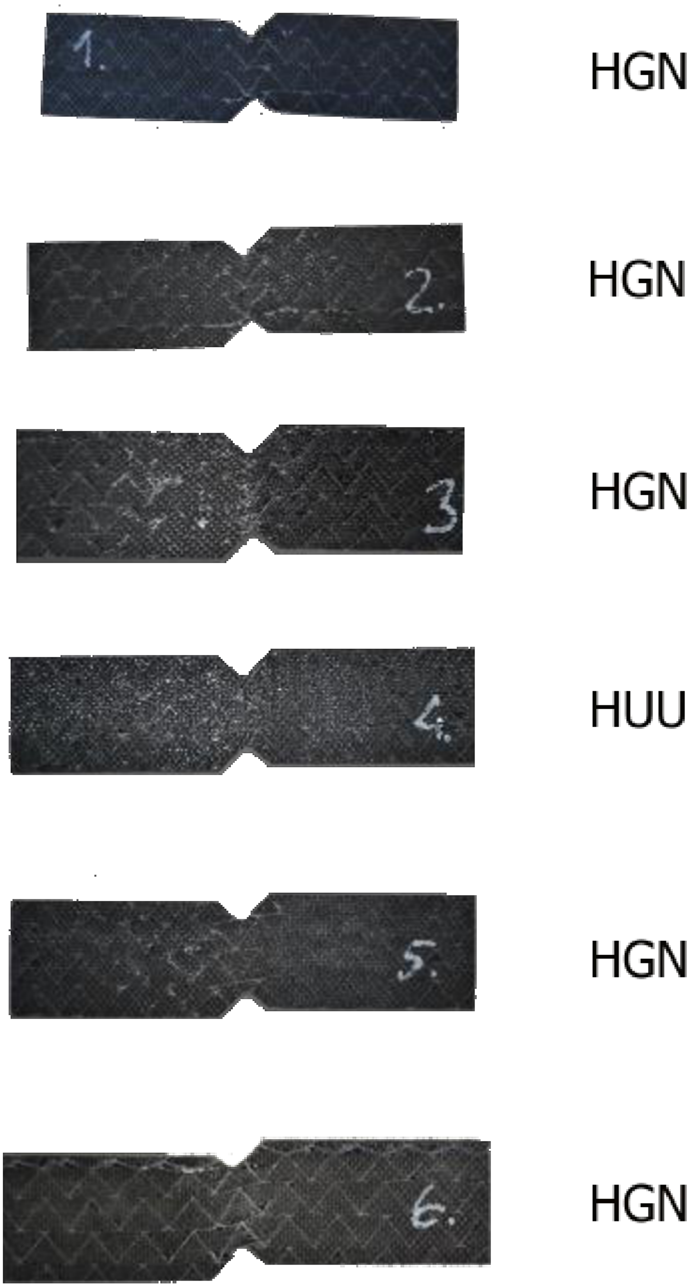


Figure 3.4 Specimen's failure mode characterization

3.1.3 Results

Specimens were tested in 1-2 plane to obtain in-plane material properties. In **Figure 3.5** are drawn load-displacement and stress-strain curves. Specimen 1 data of displacement were not recorded and this curve was leaved out. Differences between curves are caused by distance of loading head from test fixture.

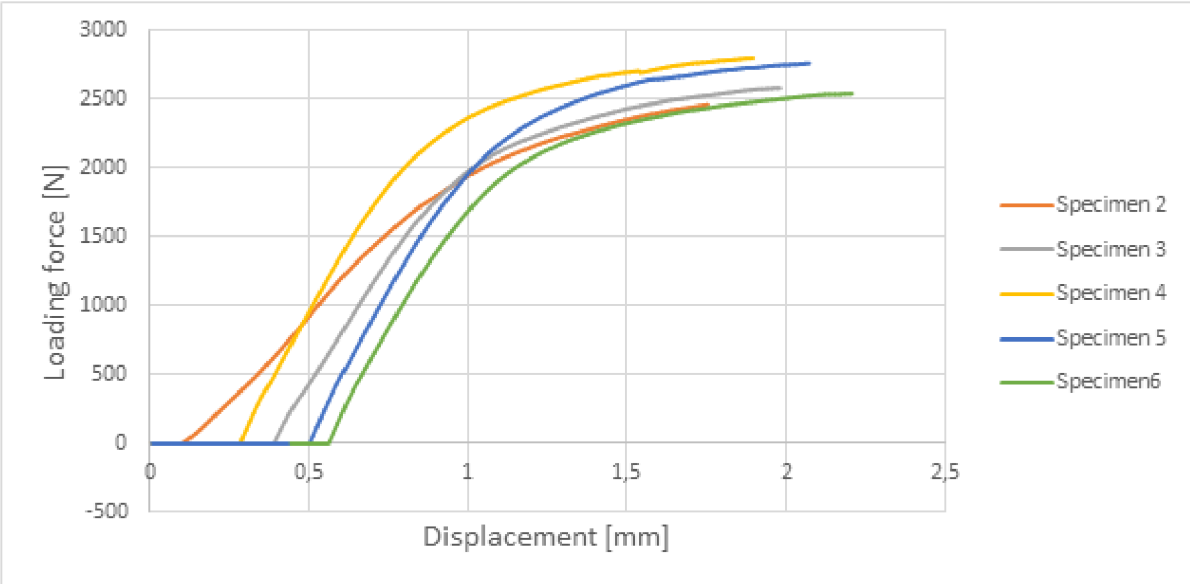


Figure 3.5 Load-displacement curves

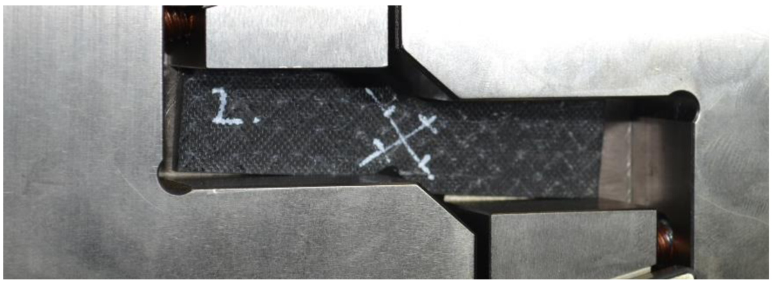


Figure 3.6 Detail of untightened specimen 2

Failure at tightening of fixture jaws was revealed by load-displacement curve of specimen 2 and visually in **Figure 3.6**, but any significant influence on stress-strain curve in **Figure 3.7** wasn't discovered.

In **Figure 3.7** are shown stress-strain curves derived from measured data. Curves show small scatter between specimens.

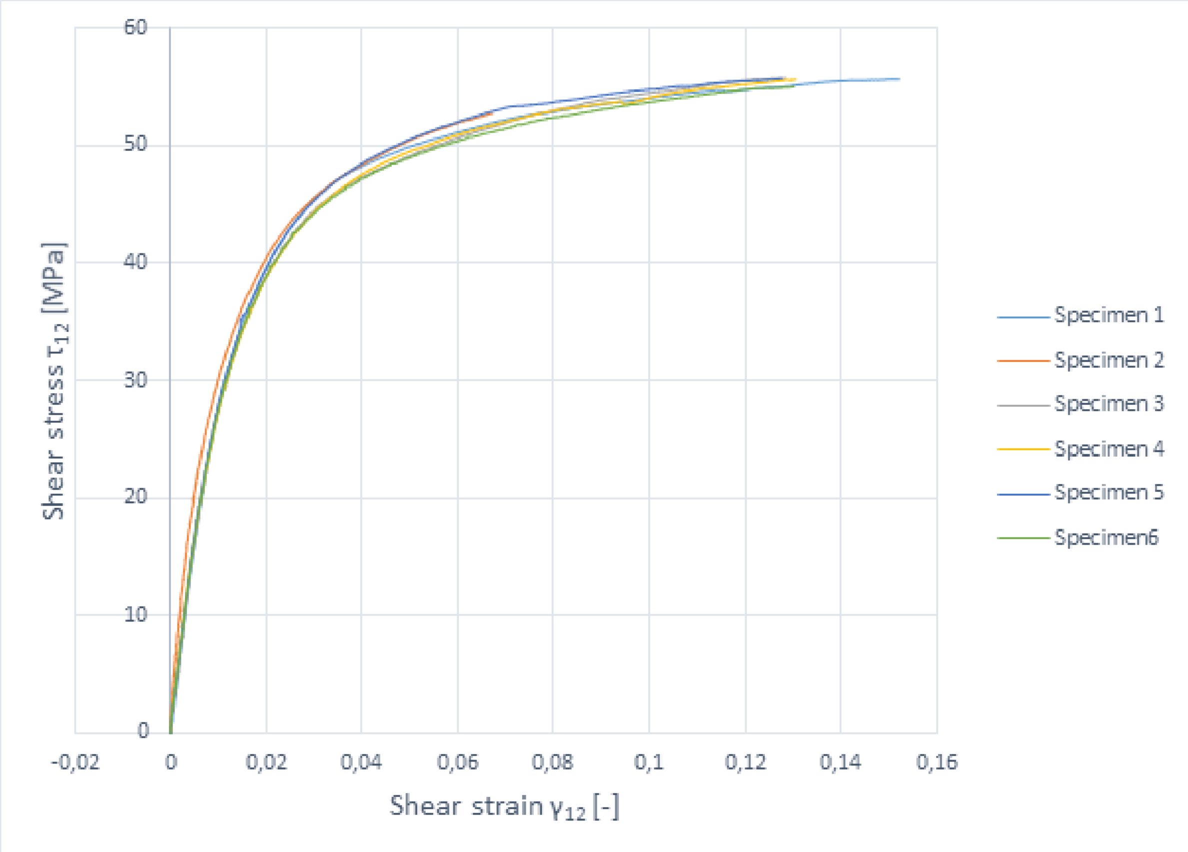


Figure 3.7 Stress-strain curves

From measured data were calculated material properties listed in Table 3. Chord modulus was calculated from strain range 0.2% - 0.7%.

Specimen number	Chord modulus G_{12} [Mpa]	Shear strength (5% strain) τ_{12} [Mpa]
1	2904.962	50.09
2	2901.946	50.614
3	2741.27	49.319
4	2900.39	49.678
5	2878.53	50.71
6	2735.36	49.153
average	2872.031	49.927
standard deviation	63.829	0.655
coefficient of variation [%]	2.2%	1.3%

Table 3 Results of Chord modulus and Shear strength

3.2 SBS Test

Testing was conducted on the same calibrated test machine Labortech LabTest 6.500 as the Iosipescu test. Fixture and the Aramis DIC measurement system is shown in **Figure 3.8**.

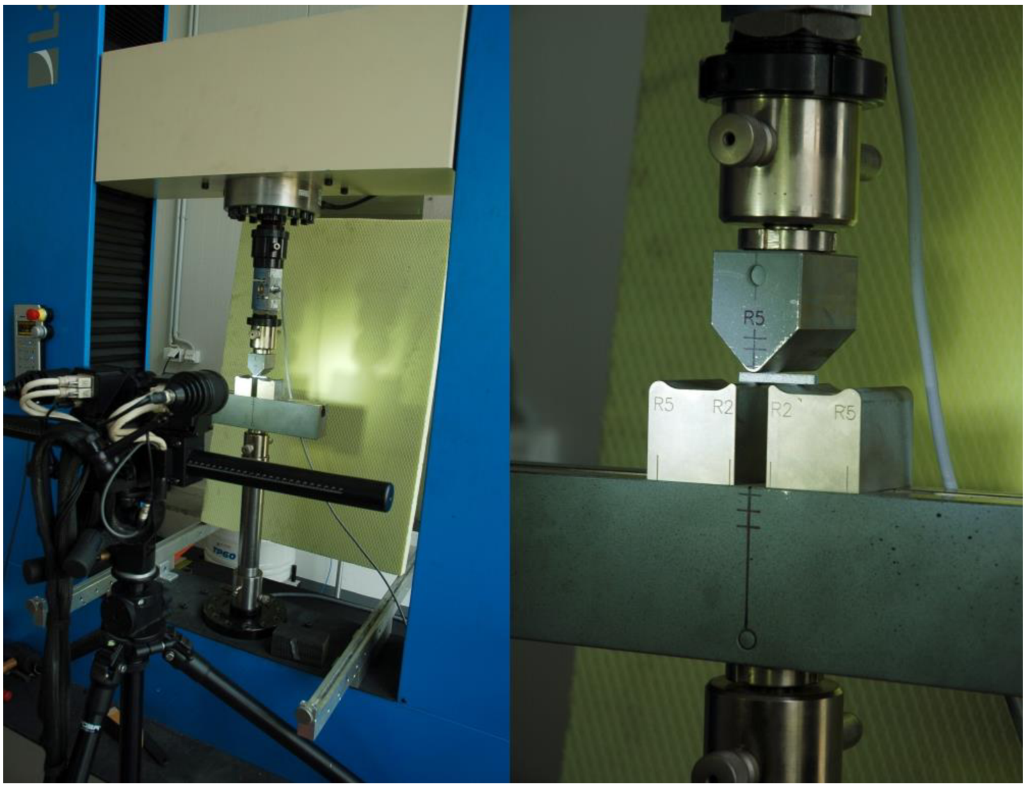


Figure 3.8 SBS test fixture and Aramis system

3.2.1 Sampling

Specimens were cut from non-affected parts of bending test specimens by hand on table saw and grinded with emery paper. The ASTM standard geometry tolerances were not fulfilled, this was test of precision requirements. To prove versatility of this test method and possibility of comparison with Iosipescu test, coupons were tested at 1-2 plane providing in-plane properties.

For every marked specimen were measured and noted width and thickness at both sides and centre, listed in **Table 4**. Average values were calculated for further use in calculations.

thickness [mm]				width [mm]			
Left	Centre	Right	average	Left	Centre	Right	average
4.355	4.378	4.363	**4.37**	4.355	4.376	4.359	**4.36**
4.657	4.691	4.577	**4.64**	4.304	4.31	4.384	**4.33**
4.311	4.3	4.23	**4.28**	4.309	4.298	4.233	**4.28**
4.061	4.015	3.988	**4.02**	4.495	4.48	4.509	**4.49**
4.544	4.679	4.722	**4.65**	4.3	4.344	4.386	**4.34**
4.812	4.86	4.91	**4.86**	4.214	4.278	4.233	**4.24**
4.616	4.487	4.449	**4.52**	4.499	4.528	4.474	**4.50**
4.2	4.3	4.33	**4.28**	4.724	4.728	4.678	**4.71**
4.352	4.346	4.297	**4.33**	4.164	4.034	4.081	**4.09**
4.138	4.21	4.306	**4.22**	4.248	4.253	4.273	**4.26**

Table 4 Width and thickness of the SBS specimens

Ten specimens were manufactured and marked with numbers, but for testing were chosen seven with the best geometry, shown in **Figure 3.9**. One side of the specimen was labelled with number and the other was sprayed with white and black spray to create texture for DIC measurement, already shown in **Figure 2.3**.

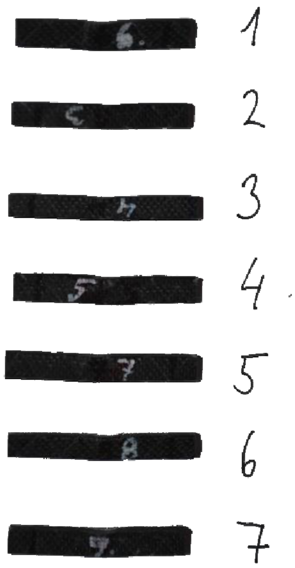


Figure 3.9 Tested specimens with markings

3.2.2 Data evaluation method

Force on loading head was measured by testing machine and transmitted as analogue signal into Aramis control unit, where it was converted into digital signal. From force and specimen's dimensions was calculated shear stress at each data-point using equation (2).

Shear strain angle ε_{xy} was evaluated by Aramis software and write down from 10 points, shown in **Figure 3.10**. Points were chosen away from loading nose and supports and close to mid-plane. For further calculations were used average values of middle three points and maximum of all five points on side to smoothen deviation from mid-plane, where maximum shear strain should occur. Shear strain γ_{12} was calculated using equation (4).

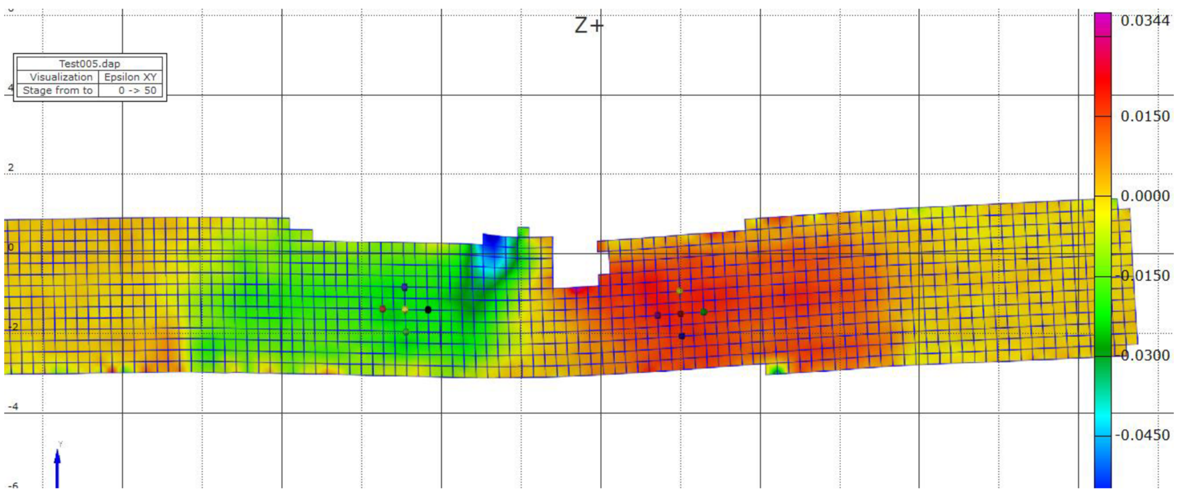


Figure 3.10 Results of ε_{xy} evaluated by Aramis software

3.2.3 Failure assessment

Unacceptable failure occurred only in specimen 2, shown in **Figure 3.11**. This premature failure is also noticeable on stress-strain curve of specimen 2 in **Figure 3.12**. Data from the specimen 2 were not included in further calculations.

Figure 3.11 Interlaminar failure of specimen 2

3.2.4 Results

In **Figure 3.12** are drawn stress-strain curves of each tested specimen. Note, that higher scatter of data is present.

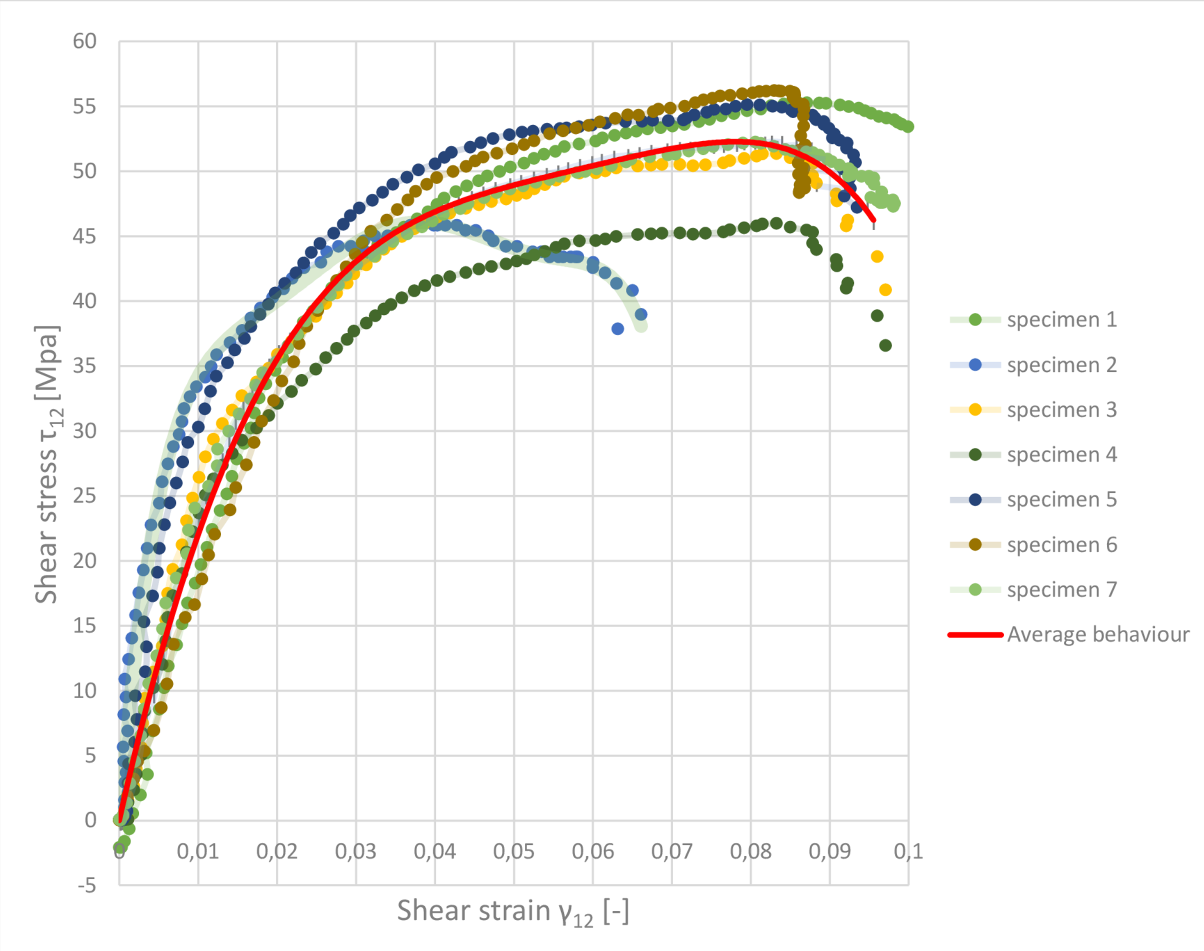


Figure 3.12 Stress-strain curves of SBS test specimens

From measured data were calculated chord shear modulus and shear strength. Chord modulus was calculated from strain range 0.2% - 0.7% using equation (5). Because no significant failure occurred, maximum shear strength was calculated at 5% strain. Calculated data are listed in **Table 5**.

Specimen number	Chord modulus G_{12} [Mpa]	Shear strength (5% strain) τ_{12} [Mpa]
1	2539.49	50.32
3	2871.51	48.13
4	2813.15	43.09
5	2757.14	52.81
6	1993.22	51.74
7	2682.54	48.65
average	**2609.51**	**49.12**
standard deviation	323.10	3.45
coefficient of varitation	12%	7%

Table 5 Chord modulus and Shear strength from SBS test

High chord modulus deviation of the specimen 6 makes this result invalid. Further evaluation will be performed without it in **Table 6**.

Specimen number	Chord modulus G_{12} [Mpa]	Shear strength (5% strain) τ_{12} [Mpa]
1	2539.49	50.32
3	2871.51	48.13
4	2813.15	43.09
5	2757.14	52.81
7	2682.54	48.65
average	**2732.76**	**48.60**
standard deviation	115.05	3.20
coefficient of varitation	4%	7%

Table 6 Chord modulus and Shear strength calculated without specimen 6

3.3 Evaluation

In **Figure 3.13** are compared stress-strain curves obtained from Iosipescu and SBS tests. According chapter 1.13 results from Iosipescu test can be taken as reference. It can be seen, that curves are close with difference under 10%. Vertical line segments represent 90% confidence interval (±5%) of SBS shear stress data.

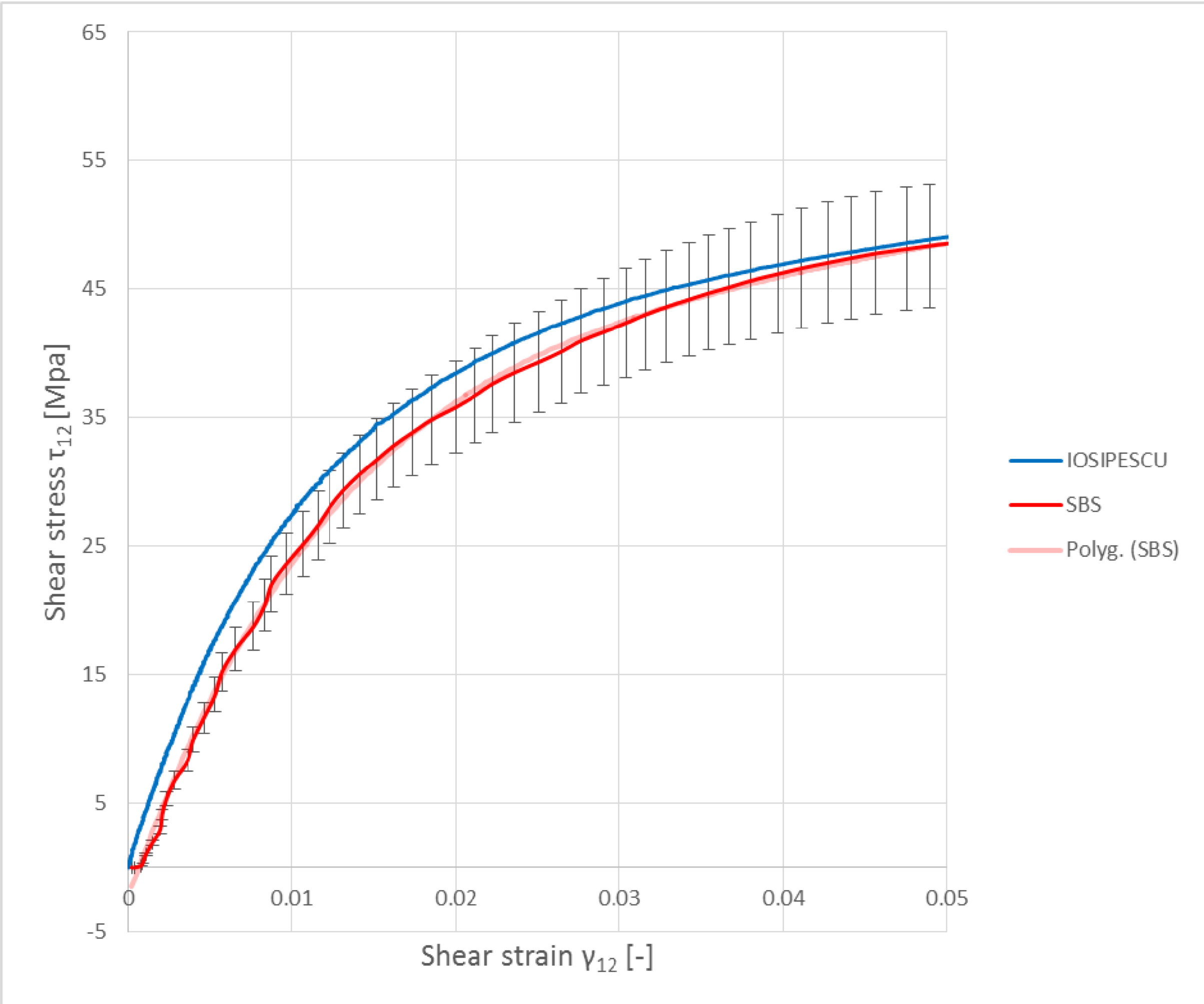


Figure 3.13 Comparison of Iosipescu and SBS stress-strain curves

Difference between curves and higher scatter of SBS data can be caused by coupons geometry, points where data were gathered and presence of virtual stress concentrations caused by lost elements in Aramis software.

In **Table 7** are written results of chord modulus and shear strength. Chord modulus varies by 5% between methods and shear strength only by 3%. Valid results of five out of seven tests are given, this fulfil ASTM standard criterion of minimum 5 tested specimens.

	Chord modulus G_{12} [Mpa]		Shear strength (5% strain) τ_{12} [Mpa]	
	Iosipescu	SBS	Iosipescu	SBS
	2872.031	2732.76	49.927	48.60
difference	139.27		1.33	
variation	5%		3%	

Table 7 Comparison of Iosipescu and SBS test results

In **Figure 3.14** is shown difference between results of surface shear strain calculated by Aramis software and results presented in Makeev's paper [24]. It can be seen that Makeev's results are more precise. It can be caused by higher resolution of Makeev's device (16 Megapixel) or software post-processing.

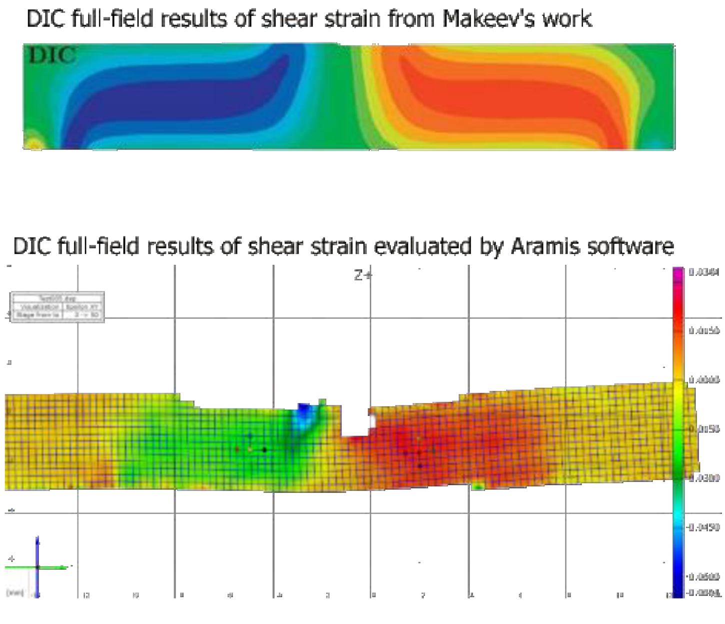


Figure 3.14 Comparison of DIC results provided by Aramis and presented in Makeev's work, property of Elsevier.

CONCLUSIONS

Most test methods for measuring shear properties of composite materials were listed in this thesis with focus on the most widely used Short beam and V-notched beam shear tests. Testing fixtures for those methods are available at Institute of Aerospace Engineering at Brno University of Technology. These two test methods were performed to evaluate modification of SBS test method.

SBS test method was modified by use of digital image correlation system for full field strain assessment and testing specimens in different orientation (1-2 instead of 1-3 specified by ASTM standard). Creation of stress-strain curves and computation of chord shear modulus of elasticity was allowed by this modification.

Results of modified SBS test are satisfactory and promising, but the Iosipescu test method shows still more precise results with lower data scatter. Main benefits of SBS test method are in lower material consumption and lower manufacturing costs. Imperfections of SBS test method are presence of small region with pure shear state and time consumption for data evaluation from Aramis software. Further research with emphasis on determination of this region using larger specimen or, if possible, softer mesh in DIC software is recommended.

Even though further research to get more precise results from modified SBS test method is recommended in this work, it can be used for better material screening than classical SBS test. Presented results are on the safer side of Iosipescu test results.

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LIST OF ACRONYMS AND SYMBOLS

symbol / acronym	Unit	Description
SBS		Short Beam Shear
DIC		Digital Image Correlation
P	[N]	Force applied on specimen
L	[mm]	Support span length
l	[mm]	Specimen length
σ_{11}	[MPa]	Normal stress
τ_{xz}	[MPa]	Shear stress
T	[N]	shear force
$U_y(z)$	[mm^3]	first moment of area about y axis
$b(z)$	[mm]	cross section width (depending on z)
J_y	[mm^4]	second moment of area about y axis
b	[mm]	specimen width
h	[mm]	specimen thickness
τ_{12}	[MPa]	Shear stress in 1-2 plane
γ_{12}	[-]	shear strain angle
ε_{12}	[-]	shear strain
ε_1	[-]	longitudinal strain
ε_2	[-]	transverse strain
T_ε	[-]	strain tensor
G^{chord}	[GPa]	shear chord modulus of elasticity
$\Delta\tau$	[MPa]	difference in shear stress between two strain points
$\Delta\gamma$	[-]	difference between the two strain points
$\varepsilon_{\pm 45}$	[-]	strain in strain gages oriented in ±45° from direction 1
Fu	[MPa]	ultimate strength
Pu	[N]	ultimate force or force at 5% strain
w	[mm]	width of Iosipescu specimen between notches

LIST OF FIGURES

LIST OF TABLES