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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING

FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AEROSPACE ENGINEERING

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MULTI-OBJECTIVE OPTIMIZATION OF COMPLEX COMPOSITE STRUCTURES WITH VARIABLE STIFFNESS

VÍCECÍLOVÁ OPTIMALIZACE SLOŽÍTÝCH KOMPOZITNÍCH KONSTRUKCÍ S PROMĚNNOU TUHOSTÍ

SHORT VERSION OF DOCTORAL THESIS

ZKRÁCENÁ VERZE DIZERTAČNÍ PRÁCE

AUTHOR Volodymyr Symonov, M.Sc.

AUTOR PRÁCE

SUPERVISOR assoc. prof. Ing. Jaroslav Juračka, Ph.D.

ŠKOLITEL

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Vysoké učení technické v Brně Fakulta strojního inženýrství, Technická 2896/2, 616 69 Brno

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INTRODUCTION

Everything is possible. The impossible just takes longer.
— Dan Brown, ***Digital Fortress***

Every leaving creature or process in nature is the result of millions of years' long extremely complex multidisciplinary, multi-objective and multi-parameter optimization. Such an approach gives the leaving creatures and processes the abilities to be extremely tightly incorporated into their natural life environment. Since the human is the part of nature the creatures made by him also always pass the multistep optimization. New scientific discoveries, technologies and materials make the optimization process to do the next step on the way to the ideal artificial structures and systems.

Thus, the composite materials as the relatively new ones give the humankind the outstanding capabilities in improvement of structures in many technical fields.

Among many other advantages the laminates are extremely flexible in strength and stiffness tailoring, therefore, they are very good materials in sense of structural optimization.

The aerospace industry is the frontier of implementation of progressive advanced composite structures and their manufacturing technologies. Moreover, weight of aerospace structures is one of the most critical parameters for aerospace products, which directly influences their performances such as range, payload capacity, service coast, etc. Application of composite materials for space structures is already normal practice for a long time, which does not require to be introduced and explained. Fully composite airframes for small one- to four-seater airplanes and sailplanes are also not new in the market for almost four decades. It can be seen very well from the AERO Fiedrichshafen Global Show for General Aviation, where within the recent several years the most part of participants presented composite airplanes. The new trend emerged within the last decade is entering the world market by wide-body airliners, which have a very high rate of composite materials in their airframe structures. For example, the use of composites in Boeing 787 Dreamliner is 50% by weight, the Airbus A350 XWB airframe structure is 53% made of composites and the new Russian airliner MS-21 has whole composite wing. Therefore, minimization of weight of composite aerospace structures' is very important and timely problem nowadays.

The modern approach to the design, stress analysis and optimization of aerospace structures is hardly thinkable without applying CAD and FEA software. Nowadays, an ordinary aerospace engineer is experienced in several types of such software and has skills for proceeding through design process using it. Of course, almost each software has its own build-in optimization abilities, however very often they are limited especially in case of composites. Considering this situation, it is very timely to think of a flexible approach, which will allow to widen optimization possibilities for aerospace engineers, who design composite structures. Within these optimization approach CAD and FEA software can be used for design, static and dynamic analyses of any type of thin-walled structure. It is very important to make possible incorporating any type of CAD and/or FEA commercial or domestic software, which is traditionally used by a company, into the optimization procedure.

1 The state-of-the-art review

Optimization of a complex aerospace structure is a complex mathematical and engineering problem, which comprises many parameters (for large structures can be several thousands). Evidently, such problems cannot be solved effectively using simple and well-known direct methods, which include all the variables describing a complex structure. Nowadays, such problems are decomposed into several levels and/or sub problems [1] - [4]. This approach is called multi-level optimization. It is capable of breaking down the optimization problem into several optimization problems that can be solved separately in an iterative process. A hierarchical decomposition divides the problem into a system level problem and a set of uncoupled component level problems. There are also non-hierarchical decompositions that divide the problem into several parallel problems. For example, the most common form of this decomposition applied to composite materials consists of decoupling the optimization of the thicknesses from that of the fiber orientations. At one level, only the thickness is optimized, leaving the search for the best fiber orientation for each ply to the second level.

The reviewed research [1] - [24] propose different approaches to the composite structures optimization problem. The main disadvantages are connected with:

- limiting the application of the algorithm to a certain type of structures, e.g., wing,
- using a special FE method, which is not available in a common FEA software,
- narrowing the optimization domain by fixing thickness or stacking sequence (or limiting it to a small number of angles, e.g., 0°, ±45°, and 90°) of the optimized sub-structures,
- not using (or using in an ineffective way) the coordination between the upper and lower levels of problem decomposition,
- lacking universalism.

The most advanced and promising algorithms use a GA as the only or one of the optimization methods. This choice can be supported by the reviews [10], [24] - [26]. According to them GAs obtain the highest rankings in comparison to the other algorithms applied to composite structures optimization.

Based on the above made review an image of a modern optimization methodology for composite structures can be created. The basic aspects of the methodology could be the next:

1) it should be universal enough to be applicable to a wide class of composite structures,
2) it should be able to use (integrate) the modern CAD and FEA software for building and analyzing FE models of the optimized structures,
3) it should decompose the optimization problems into several levels,
4) several different optimization methods should be used at different levels,
5) because the nature of the optimization problems supposes a large number of variables and several local optima a stochastic optimization method (e.g., GA) should be applied at one of the levels,
6) means to minimize the number of variables should be taken,
7) to accelerate the algorithm a parallelization of calculations should be provided.

2 Formulation of the optimization problem

The state-of-art review allows defining the optimization problem in detail, taking into account specifics of the airframe composite structures.

When we think of composite airframe components, first what is emerged in our mind are the monocoque or semi-monocoque structures. That means, in general, they consist of almost the same structural elements and their design approach is very similar. Thus, it is possible to create an optimization methodology, which will be in general applicable for optimization of almost any airframe component (wing, fuselage, etc.).

The airframe structures are complex assemblies, and each assembly unit consists of many structural elements. Moreover, every laminate itself may be a complex assembly of plies, which may be in general made of different materials and have different fibers' orientation. These circumstances are the reason that the number of design variables necessary for optimization of a large-scale composite structure counts a few thousands [9].

As it was discussed above, in such a case, it is not effective to do direct optimization. Therefore, the optimization procedure of a large-scale composite structure is decomposed onto levels (usually upper and lower ones [1], [2]).

At the upper level, the global parameters, which significantly influence the behavior of the entire structure, should be chosen and optimized. In the most of cases the internal load distribution and the structural layout are optimized here. Optimization objectives can be, for example minimum weight, maximum flatter speed, minimum deflection and twist angle. The deflection or twist angle also can serve as constrains. The constraints can be technological and design ones also. The continuity of the structure should be provided also.

At the lower level, the optimization process is broken into several local sub-problems. They are characterized with local parameters and constraints, which have small influence on the entire structure. These parameters and constraints could be unique for each sub-problem. Usually, this level deals with the thickness and stacking sequence of the laminate, plies' orientation, and structural dimensions. The optimization objective at this level is mainly the structural weight minimization limited at least by strength and stability constrains. The loading is kept constant. In general, the local optimization problem may be written as follows:

$$\begin{gathered} W(\bar{X}) \rightarrow min, \\ F_i(\bar{X}) \rightarrow min(max), \\ \min_j RF_j(\bar{X}) \geq 1, \end{gathered} \tag{2.1}$$

where W - weight of the local substructure; $\bar{X}$ – vector of variables; F_i – other objective functions; RF_j – reserve factors of different failure modes, including buckling ones.

The upper and lower levels are coupled with help of coordination algorithm [1], [2].

Thus, the above noted discussion makes evident that the optimization of a large-scale composite structure is a complex multi-stage, multi-disciplinary, multi-objective, and multi-parametric task.

3 Objectives of the thesis

Within the present study it is planned to **develop an optimization methodology for thin-walled composite structures** which, in general, is divided in several sub-structures with different stiffness. Each sub-structure may, in general, consist of several skin panels of different thicknesses, spars and stringers and separated from the neighboring sub-structures with ribs or frames. The structure may be loaded with aerodynamic, weight, inertial forces and in some cases with internal pressure. Several load cases should be considered. The cross section of the structure may be single-cell, multi-cell, open or combined.

Each structural element (skin, stringer, spar web, spar cap, etc.) may have different thickness and stacking sequence. Concerning materials, the symmetrical orthotropic laminates are considered only. In the most general case, the orthotropic laminate of each structural element may have such a stacking sequence $[0°, 90°, \pm\theta_1, \pm\theta_2, \dots, \pm\theta_k]_{ns}$.

In general, the optimization parameters will be the following:

- thickness and stacking sequence of each structural element being optimized,
- angles $\pm\theta_1$, $\pm\theta_2$,…, $\pm\theta_n$ for each structural element, in which they are used.

The input data for the optimization will be:

- baseline geometrical concept of the structure (means outer shape, position of spars, stringers and ribs, dimensions of the skin panels),
- materials and their properties,
- load cases.

The optimization objectives should be, in general, the following:

- weight minimization of the empty structure,
- deflection and twist angle minimization (these parameters could be used as constrains), etc.

The optimization constrains should be the next:

- static strength, local and global stability of the structure,
- maximum deflection and twist angle of the whole structure,
- maximum deflection of the skin panels,
- maximum thickness of the structural elements,
- blending rules.

At least **one application of the methodology should be shown** within the present work. The effectiveness and robustness of the methodology in comparison to the existing ones should be shown also.

4 Optimization methodology

The optimization methodology comprises the problem decomposition approach, optimization methods used at different levels, the coordination procedure required to interconnect the different levels and the analysis methods used at these levels.

The optimization method used at the upper level depends on the defined objectives, however in general it is an aeroelastic problem, which can be solved by joint aerostructural methods as in [4], [18], [27].

Since the present work is mostly focused on the structural problems, it is not planned to develop any aerostructural method within this thesis. Only structural optimization is developed here. Anyone can adopt and connect an appropriate aeroelasticity optimization method, which uses the upper-level structural parameters discussed below.

The upper and lower levels are usually connected to each other via stiffness of the structure. The structure is usually divided onto sub-structures, which have constant stiffness within their limits. Thus, the structural cross-sectional stiffness (axial, bending, torsional, etc.) of each sub-structure may be taken as an optimization variable at the upper level.

It was proved that the classical numerical optimization methods are not effective in solving such problems [24], [26]. The disadvantages of these methods are not inherent to the stochastic methods like GA [28] and swarm based methods [29] - [31]. They are able to solve problems with large number of variables and find the global optimum. The GAs have one more advantage in case of composite materials – they are very convenient for coding stacking sequences and dealing with discrete fenomena. According to [25] and [32] GAs obtain the highest rankings in comparison to the other algorithms applied to composite structures optimization. From the other hand, these methods are quite expensive because of many calculations of objective functions. This disadvantage may be eliminated by parallelization.

Hybrid methods, e.g. [33] - [36], can be even more effective.

In general, the multilevel optimization algorithm may consist of blocks shown in Fig. 4.1. It starts with the upper-level analysis of the initial global design of the structure, which provides the algorithm with the initial global responses and parameters including the distribution of internal forces.

This information is passed to the GA level. At this level a set of guiding stacking sequences (guides) is generated (in detail see Subsection 4.2). A guide represents a laminate of maximum allowed thickness. The ply angles of the guide are supposed to be fixed. The guides' stacking sequence is supposed to be the same through the structure or its part (the designer decides). Only thickness can be varied through the structure. The GA deals with the guides. Its goal is to find the best guide, which will provide the best correlation between the upper and the lower levels.

The guides and the upper-level parameters and the internal forces calculated at the upper level are sent to the lower-level sub-problems. Then the optimization of each lower-level sub-problem is performed. During this step the thickness of each local sub-structure should be optimized in such a way, that the in-plane stiffness of the sub-structure corresponds as much as possible to that found during the previous upper-level analysis. At the same time the local constraints should not be violated (e.g. the strength and buckling of the local sub-structures). The information from the lower-level optimization is passed to the GA level. Then the best guides found at the GA level are passed to the coordination procedure. In the last step the upper-level optimization follows. Here the weight of the structure and the internal load distribution are optimized. The local parameters of the sub-structures and their parts (laminate thicknesses and stacking sequences) are not considered.The convergence of entire optimization algorithm will occur, when the upper-level objective function is optimized, while the upper and lower-level constraints are satisfied.

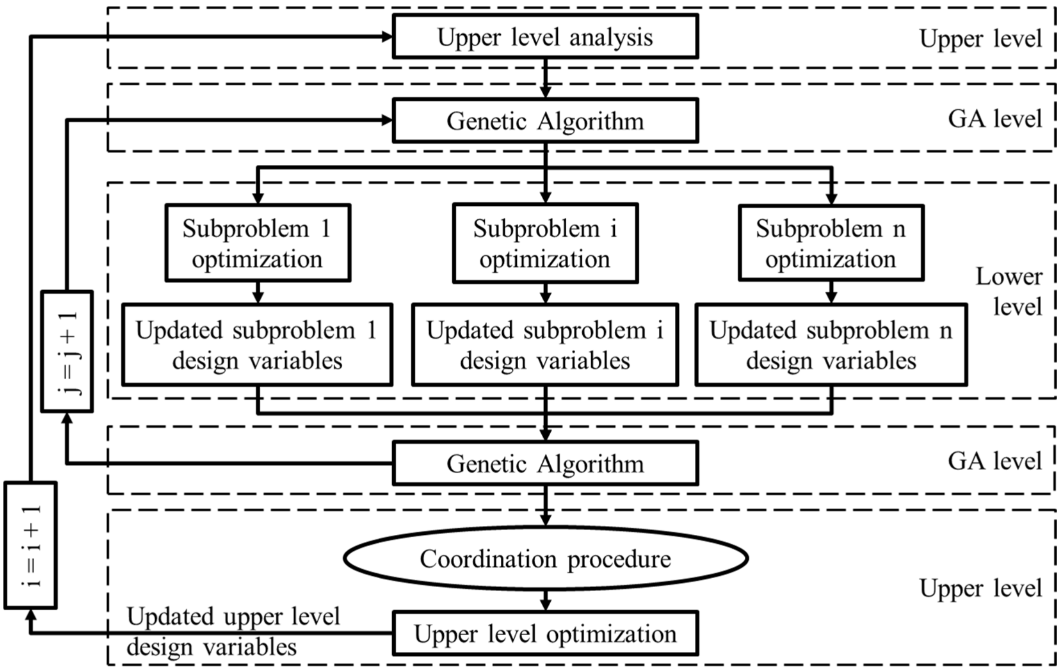

Fig. 4.1 Optimization flowchart

In further subsections a particular realization of the upper-, GA- and lower-level algorithms is proposed and described in detail.

4.1 Upper level

At the upper level the entire structure characteristics and responses are in focus, such as weight, deflections, twisting angle, global buckling, etc. All of them depend on the material and stiffness distribution along the structure. Thus, the most important global parameters of the structure correspond to its cross-sectional stiffnesses (axial, bending and torsional). Since they are not independent from each other and depend on the geometry and materials of a cross-section, it will not be correct to vary them directly and independently. There should be found independent parameters, which influence these stiffnesses. Since at the upper level it is not important what kind of geometry and materials will be applied at the lower level, the structure at the upper level can be modeled simplistically. If the structure is simple a conventional mathematical model from the structural mechanics or a surrogate model can be used, e.g. [4]. FE model is more appropriate for modern engineering and complex structures, where the design process starts from the global FE model and protrudes to the local ones.

To decrease the number of upper-level parameters as much as possible it is proposed to use lamination parameters for varying bending and membrane stiffness sub-matrices of laminated panels (see [4] and [37]). Also a smeared stiffness approach (see [37]) is used for defining composites at the upper level. With such an approach the membrane and bending stiffness sub-matrices are related to each other as follows:

$$D = A\frac{h^2}{12}, \tag{4.1}$$

where h - total thickness of a laminate.

In case of orthotropic composites only 2 lamination parameters are needed to define these two sub-matrices. Of course, in a complex structure, where several structural elements with different stiffnesses are in the cross-section, each element has its own A and D sub-matrices. Thus, the total number of upper-level parameters will be equal to number of structural elements (only those having unequal laminate stiffness matrices) multiplied by 2.

However, the lamination parameters are not independent quantities, and their physical meaning is questionable. It is more convenient and sensible to use some parameters, which are independent and has definite physical meaning. As it was deiscussed above, the parameters, which can be used for the coordination between the upper and lower levels are the bending and torsional stiffnesses of the cross-section (see [2]). The authors propose the next lower-level objective function:

$$f = \left[\frac{EJ_z - EJ_z^*}{EJ_z^*}\right]^2 + \left[\frac{EJ_y - EJ_y^*}{EJ_y^*}\right]^2 + \left[\frac{GJ - GJ^*}{GJ^*}\right]^2, \tag{4.2}$$

where EJ_z , EJ_y – bending cross-sectional stiffnesses, GJ – torsional cross-sectional stiffness. The star symbol (*) denotes the stiffness calculated at the upper level.

The stiffnesses depend on the material and geometry of the cross-section. In turns, for the thin-walled structures the geometry is defined by the thickness and the shape of the cross-section. For example, the bending stiffness of a simple cross-section, which consists of N composite panels with different thickness and stacking sequences [38] can be written as follows:

$$EJ_z = \sum_{i=1}^{N} (hE_x)_i \bar{J}_{zi}. \tag{4.3}$$

where i – index of a panel, $(hE_x)_i$ – product of thickness and longitudinal elastic modulus of $i - th$ panel, $\bar{J}_{zi} = \int_{s_i} y^2 ds$, s – curvilinear coordinate along the cross-sectional contour.

The stiffness EJ_y can be expressed in a similar way.

When the geometry is fixed, the quantities $\bar{J}_{zi}$ are constant. In that case the bending stiffnesses EJ_z and EJ_y depend on $(hE_x)_i$ products only. Also, it can be shown, the torsional stiffness GJ depends on $(hG_{xy})_i$ products only (G_{xy} – in-plane shear modulus of the panel).

4.1.1 *Definition of laminate stiffness matrix*

The membrane stiffness sub-matrix A of each laminated panel can be defined with help of lamination parameters in the same way as it was done in [37]. For orthotropic laminate the membrane stiffness sub-matrix can be formulated as:

$$A = \begin{bmatrix} A_{11} & A_{12} & 0 \\ \vdots & A_{22} & 0 \\ sym & \dots & A_{66} \end{bmatrix}. \tag{4.4}$$

The nonzero members of the matrix can be written through the lamination parameters as follows:

$$\begin{Bmatrix} A_{11} \\ A_{12} \\ A_{22} \\ A_{66} \end{Bmatrix} = h \begin{bmatrix} 1 & \bar{\xi}_3 & \bar{\xi}_1 & 0 \\ 0 & 0 & -\bar{\xi}_1 & 1 \\ 1 & -\bar{\xi}_3 & \bar{\xi}_1 & 0 \\ 0.5 & 0 & -\bar{\xi}_1 & 0.5 \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{Bmatrix}, \tag{4.5}$$

where $\bar{\xi}_1 = \frac{\xi_1}{h}$ and $\bar{\xi}_3 = \frac{\xi_3}{h}$ – lamination parameters, the constants U_i depend on the lamina stiffness matrix Q:

$$\begin{aligned} U_1 &= \frac{3Q_{11} + 3Q_{22} + 2Q_{12} + 4Q_{66}}{8}, \\ U_2 &= \frac{Q_{11} - Q_{22}}{2}, \\ U_3 &= \frac{Q_{11} + Q_{22} - 2Q_{12} - 4Q_{66}}{8}, \\ U_4 &= \frac{Q_{11} + Q_{22} + 6Q_{12} - 4Q_{66}}{8}. \end{aligned} \tag{4.6}$$

Let's introduce a term:

$$k = \frac{E_x}{E_y} = \frac{A_{11}}{A_{22}}. \tag{4.7}$$

Using the term k it is possible to rewrite the last three equations from (4.5):

$$\begin{aligned} \frac{A_{12}}{h} &= -\frac{A_{11}}{h}\frac{k+1}{2k} + U_1 + U_4, \\ \frac{A_{22}}{h} &= \frac{A_{11}}{h}\frac{1}{k}, \\ \frac{A_{66}}{h} &= -\frac{1}{2}\left(\frac{A_{11}}{h}\frac{k+1}{k} - 3U_1 + U_4\right). \end{aligned} \tag{4.8}$$

Thus, it can be seen, the entire membrane sub-matrix normalized with the thickness of the panel can be defined by $\frac{A_{11}}{h}$ and k terms only. From the other hand the $\frac{A_{11}}{h}$ term can be expressed via engineering constants:

$$\frac{A_{11}}{h} = \frac{E_x}{1 - \mu_{xy}\mu_{yx}}, \tag{4.9}$$

where E_x – longitudinal elastic modulus of the panel, $\mu_{xy} = \frac{A_{12}}{A_{22}}$ and $\mu_{yx} = \frac{A_{12}}{A_{11}}$ – Poisson's coefficients of the panel.

Using (4.8) the expression (4.9) can be transformed to the next quadratic equation:

$$\bar{A}_{11}{}^{2}\frac{(k-1)^2}{4k} - \bar{A}_{11}[(k+1)(U_1+U_4) - E_x] + k(U_1+U_4)^2 = 0. \quad (4.10)$$

The roots of the equation express the term $\frac{A_{11}}{h}$ as a function of E_x and k. Taking E_x and k as parameters, we can calculate $\bar{A}_{11}$ and further with help of (4.8) the entire normalized membrane stiffness sub-matrix $\bar{A}$. When it is known, the in-plane engineering constants of the panel (μ_{xy}, μ_{yx} and G_{xy}) can be calculated easily.

In order to calculate the stiffnesses of the panel for the equation (4.2) at the upper level we need to define its total thickness h. Also knowing the thickness, it is possible to calculate the membrane and bending stiffness sub-matrices according to (4.8) and (4.1).

Finally, at the upper level only 3 parameters (E_x, k and h) are required to fully define the stiffness of a laminate, which has constant thickness and stacking sequence. It is very clear and convenient from the engineering point of view. These parameters are independent opposed to the lamination parameters in [4] which are not independent. Moreover, the stacking sequence of the laminate is not important at this level.

Applying this approach to the global FE model only the lamina properties and the total thickness of the laminate are required to define each composite sub-structure.

In order to fully define a complex structure, which has variable stiffness, $3 \times N_{sub}$ parameters are required, where N_{sub} is the number of sub-structures or structural elements with different stiffness matrices.

The thickness h of each sub-structure is a discreet parameter, but E_x and k are the continuous ones. In general this is the reason that the upper-level optimization method should be able to deal with mixed integer-continuous parameters, however, as it was shown above (see (4.3)) the laminate total thickness is not so important at the upper level since the product hE_x is a continuous quantity. Therefore, h can be set as continuous at the upper level and well-known classical multi-parametric optimization methods can be used here.

4.2 GA level

At the lower level the structure is divided into several sub-structures, where they are optimized in detail. However, the optimization in different sub-structures can be done in parallel, the integrity of the entire structure should be kept. From the manufacturing point of view, in general, this means at least the neighboring sub-structures should have conforming stacking sequences what is called blending.

According to Section 1 the stochastic optimization methods including GAs have very high ranking in application to composite structures. They have vital advantages such as the ability to manage large number of design variables and to find the global optimum, they do not require gradient information, have low cost in parallel optimization and are very simple for realization. That why a GA was chosen for the optimization of the laminates stacking sequances in this work.

There exist two basic approaches to obtain blended designs in the neighboring sub-structures using GAs [39]. The general idea of the first one is in generating of multiple populations, which correspond to stacking sequences of different sub-structures (e.g., panels) and are optimized in parallel. The blended designs are obtained with help of evolutionary pressures acting on each population from neighboring ones. The pressure is realized by different methods, e.g., by random migration of individuals between the neighboring populations [40] or addition of continuity constraints [41]. However, the main disadvantage of this approach is in that it does not guarantee fully blended designs corresponding to the global optimum.

The second approach is based on so called “guides”. The guides are represented by stacking sequences in form of one-dimensional arrays with fixed length where each element is the orientation angle of a corresponding ply. Since only orthotropic laminates are considered in this paper the guides represent only a half of a stacking sequence. The angles can be chosen by a user depending on the manufacturing requirements. Each guide is accompanied with a fitness value which helps the guides from the same generation to compete. Within this approach each guide corresponds to a stacking sequence, which has the maximum possible thickness for entire structure. The stacking sequence for each sub-structure is obtained from the guide by deleting the redundant layers until the strength/stiffness/etc. criteria are violated. At the beginning the GA generates a population of guides, which are exposed to genetic operations then. At the end the global optimum design is represented by the best guide combined with an array, which contains the integer numbers corresponding to number of plies within laminates (or to number of plies subtracted from the guide) of each sub-structure. The main advantage of this approach is in that all designs considered are always blended right from the beginning of the optimization algorithm. In such a way the dimensionality of the problem becomes much less, and the continuity constraints are not required anymore. This fact simplifies the problem solution. However, this simplification is obtained at the expanse of flexibility loss when trading the degree of blending against weight. The reliability and resolution of this approach for sure in some extent covers above noted loss, since the slightly unblended designs should not be much lighter than the perfectly blended ones.

Because of the spoken advantages the guide-based approach was chosen for optimization of stacking sequences of laminates at the GA level in the present study.

The first generation of guides is created randomly taking into account manufacturing and design constraints such as for balance, orthotropy, etc. [36].

The key operators for any GA are the selection, crossover, mutation, and the replacement ones [38]. Also, it is very important how the fitness value is calculated. At the lower level it is calculated using the lower-level objective function (4.2). This function corresponds to a particular cross-section only but not to the entire structure. The integral function at the GA level for the entire structure is the following:

$$F = \sqrt{\sum_{k=1}^{N_S} f_k}, \tag{4.11}$$

where f_k – value of the function (4.2) calculated for a $k-th$ cross section, N_s – total number of defined cross sections of the structure.

Function (4.11) shows the difference in stiffness between upper and lower levels. However, it does not consider the weight of the structure. Therefore, the objective function at the upper level can be as follows:

$$F_{obj} = (1+F)W, \tag{4.12}$$

The selection operator is based on the modified elitist strategy. The first of the parent individuals is chosen from the population randomly. The second one is chosen from a group of the best individuals of the population (the number of individuals in the group is chosen during the customization of the algorithm) in such a way that the Euclidian distance (4.13) between it and the first parent is the smallest within this group. Such a strategy prevents premature convergence.

$$d = \sqrt{\sum_{j=1}^{n} (\theta_{1j} - \theta_{2j})^2}, \tag{4.13}$$

where n – total number of plies in a guide, θ_{1j} and θ_{2j} – orientation angles of corresponding $j-th$ plies of the first and the second parents.

The crossover operator happens with a high probability $P_c \geq 0.95$, which can be defined by a user. In this work two-point crossover is used (see Fig. 4.2). The positions "pos 1" and "pos 2" are defined randomly, while always "pos 1" ≠ "pos 2". Such an operator is used to have a higher probability to influence the thinnest sub-structures.

The mutation operator is applied to each of the children right after the crossover. This operator replaces the orientation angle of a randomly chosen ply with a new angle, which is randomly chosen from the group of angles allowed by the user. For sure the balanced stacking sequence is kept. It happens with a small probability $P_m \leq 0.1$ which can be adjusted by a user.

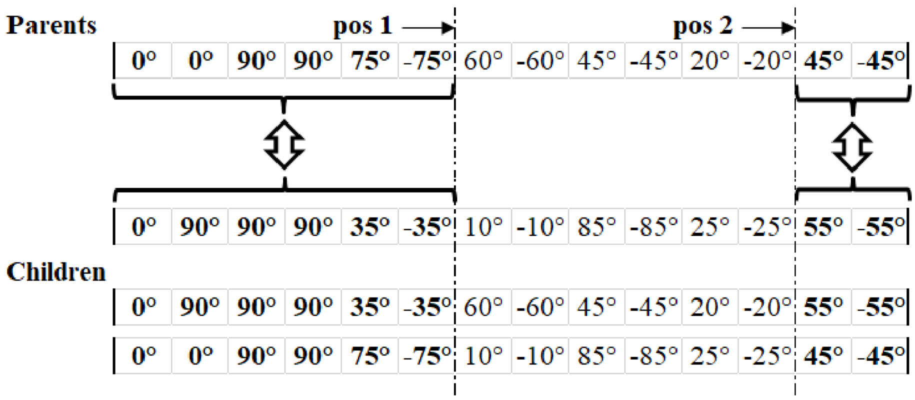

Fig. 4.2 Crossover operation

After mutation has been done, the children individuals are sent to one-dimensional optimization of the thickness of each sub-structure. As the result of this optimization the fitness values (4.12) of the new guides are calculated.

The replacement operator does the next actions:

- randomly choose C_f groups (each group has S individuals) of individuals from the population as candidates to be replaced by the new ones (children),
- within each group a candidate to be replaced is chosen, which has the smallest Euclidian distance (4.13) to the new individual, thus C_f candidates are found,
- the new individual replaces one of the found C_f candidates, which has the worst fitness value.

The above-described operators are repeated until a stop criterion is reached. Three stop criteria are used in this thesis. The simplest one is met when GA has reached a predefined number of generations. It, however, requires experiments and gaining experience in defining such a number, which can guarantee the global optimum to be found.

The second stop criterion is met when the predefined number of best guides (N_{best}) within the actual population have difference between their fitness and the average fitness not more than the predefined value ν, see (4.14). The ν value is defined by the user.

The third stop criterion is met when the best guide has its fitness less than the predefined value $F_{obj\,max}$. The value of $F_{obj\,max}$ is defined by the user.

$$\frac{F_{obj\,i} - \bar{F}_{obj}}{\bar{F}_{obj}} \cdot 100\% \leq \nu,$$
$$i = 1 \ldots N_{best}\,, N_{best} < N_{tot}, \tag{4.14}$$
$$\bar{F}_{obj} = \frac{1}{N_{best}} \sum_{i=1}^{N_{best}} F_{obj\,i},$$

where $F_{obj\,i}$ – fitness value (4.12) of the i-*th* best guide, N_{tot} – the total number of guides in population.

The described criteria can be applied apart or as a combination. However, the first criterion is always applied to limit the maximum number of iterations.

4.3 Lower-level one-dimensional parallel optimization

At the lower level within each sub-structure, which has constant thickness, the stacking sequence is already predefined by the guide. The only parameter, which can be varied, is the number of plies or thickness of the sub-structure. While the number of plies is being changed, the elastic characteristics of the sub-structure is being changed also. As it was shown in Subsection 4.1 when the geometry of the sub-structure is fixed its stiffnesses is defined by the (hE_x) and (hG_{xy}) parameters only. Therefore, it is not necessary calculating the stiffnesses as in (4.2). It is simpler to use (hE_x) and (hG_{xy}) values in the calculation of lower-level objective function when each sub-structure is optimized independently. Thus, the objective function (4.2) can be modified as follows:

$$f_d = \left[\frac{(hE_x) - (hE_x)^*}{(hE_x)^*}\right]^2 + \left[\frac{(hG_{xy}) - (hG_{xy})^*}{(hG_{xy})^*}\right]^2, \tag{4.15}$$

where the star symbol (*) still denotes the parameter’s value at the upper level.

The one-dimensional minimization of the function f_d, which is done in parallel for each sub-structure, is the objective of the lower-level optimization. The optimized parameter is the thickness/number of plies of the sub-structure. The constraints, which usually applied at this level, are the strength and the buckling of the sub-structure. The Gold Section method adopted to an integer variable (number of plies) is used here.

The calculations of structural responses (stress, buckling factors, etc.) are done by FE analysis of the local models in parallel.

4.4 Coordination between upper and lower levels

Since the distribution of loads depends on the stiffnesses distribution, the difference in stiffness (4.2) means the internal forces distributions at the upper and lower levels are not correlated and the entire optimization lacks convergence.

The authors in [2] propose a coordination procedure, which applies the next upper-level coordination constraints (one for each lower-level optimization):

$$g_k = f_k^U - (1-\varepsilon) f_{ok}^L \leq 0, \qquad (4.16)$$

where f_{ok}^L - the most recent value of the lower-level objective function (i.e., the optimum value of eq. (4.2) for the $k-th$ cross-section, f_k^U - estimate of the change in f_{ok}^L that would be caused by a change in the upper-level design variable values, and ε - specified tolerance defined as the coordination parameter.

Calculation of f^U requires quite expensive sensitivity analysis, which in case of complex composite structures becomes very difficult also.

In the present work the coordination is achieved through the minimization of the objective functions at the lower (4.15) and the GA levels (4.12). This minimization means that the difference in stiffness at the upper and lower levels aims to a minimum.

Of course, in some cases/iterations it is not possible to achieve good correlation between the upper and lower levels. However, it does not always mean a lower-level design violates the upper-level constrains. To check if a lower-level design does not violate the upper-level constrains another global model is introduced into the algorithm. This model is not the same as for defining stiffness distribution which was described above. It takes into account the optimal desings of all sub-structures found at the lower level within for the particular upper-level optimization step. The FEA of this model is performed only for the best guides and thickness distribution found at the GA level. If the upper-level constrains are not violated these designs could be considered as the potential optima.

5 Application of the developed optimization methodology

To parallelize the lower-level calculations and simplify the interconnection between the coded optimization algorithm and FEA software a commercial software Noesis Optimus by Noesis Solutions was used. This software allows to integrate many different engineering software and domestic codes into one powerful optimization algorithm. It is also possible to integrate an own newly developed domestic optimization algorithm into Optimus. Optimus allows building a flexible multilevel optimization algorithm, which can be adopted for optimization of different complex structures.

Since the Noesis Optimus software is used in this work, its terminology will be used further. Each optimization step where a new structural design is calculated is called experiment.

To calculate responses of a structure MSC Nastran is used. The optimization methods for GA and lower level are programmed using Python 2.7 language. The optimization method at the upper level is chosen from those proposed by Noesis Optimus software, which are built-in in it.

To validate the developed optimization methodology, it was applied to a simple optimization problem, which was proposed in [23]. Thus, the optimization results can be compared to those presented in this publication.

A simple wing-box structure is used for optimization in this problem. The wing-box is unswept, untapered and rectangular (see Fig. 5.1).

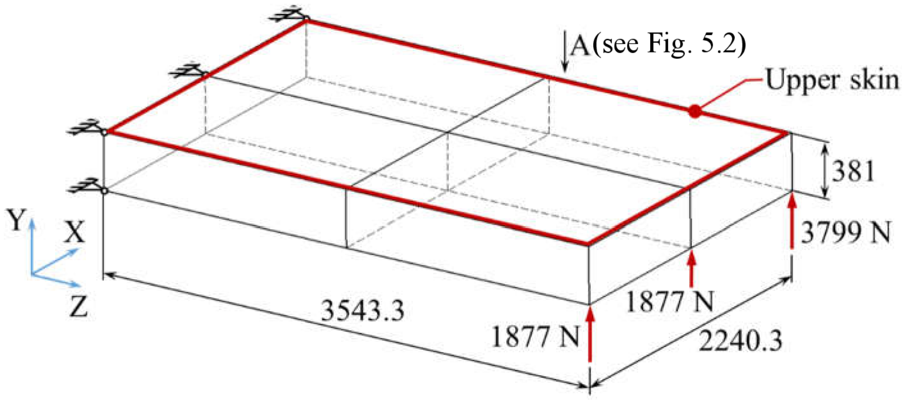

Fig. 5.1 Simple wing-box structure model

The spars and the ribs divide the top and bottom skins of the wing box into four panels of equal size. Only the top skin panels are being optimized, all other parts are fixed to the design $[\pm45_5/45]_s$. The upper panels' arrangement is shown in Fig. 5.2. The wing root is simply supported. The upward lift force is modeled by three concentrated loads at the free wing tip. The lamina material is the graphite/epoxy T300/5208 (see Tab. 5.1). The upper skin design only is subjected to strength and buckling constraints.

In general, the complexity of FE models at both levels is chosen by a designer according to the traditions and regulations/standards of a particular company. The descriptions of the upper-level and lower-level FE models in detail are provided below in the subsequent subsections.

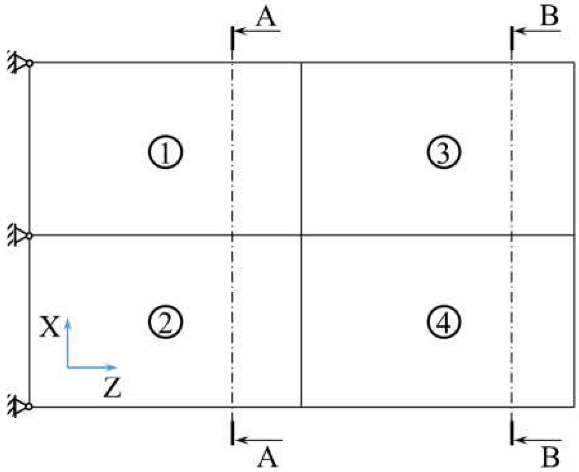

Fig. 5.2 Panels' layout for the upper skin (view A, see Fig. 5.1)

Tab. 5.1 Lamina material properties of graphite/epoxy T300/5208

Property	**Unit**	**Value**
Longitudinal elastic modulus, E_1	Pa	128×10^9
Transversal elastic modulus, E_2		13×10^9
In-plane shear modulus, G_{12}		6.4×10^9
Poisson ratio, μ_{12}	-	0.3
Longitudinal allowable strain, ε_{1a}		0.008
Transversal allowable strain, ε_{2a}		0.029
In-plane shear allowable strain, γ_{12a}		0.015
Lamina thickness, h_0	m	0.127×10^{-3}
Density, ρ	kg/m^3	1402.48

5.1 Upper-level construction

5.1.1 Optimization method

The upper-level optimization method is chosen from those available in the Optimus software. It is Efficient Global Optimization method (EGO) [42]. EGO "is a hybrid optimization algorithm in which an interpolating response surface model is built in every iteration and new simulation points are added based on the result of an optimization that is performed on the response surface model.

The response surface model that is chosen for the EGO algorithm is the Kriging model. The advantages of this type of model are the fact that the model will interpolate through all experiments, and the fact that an estimate can be made of the prediction error of the model.

5.1.2 Cross-section geometry of the wing box

To calculate the fitness values of guides (4.12) the stiffnesses of the structure in the important cross-sections should be calculated. The wing box structure (Fig. 5.1) has two such cross-sections. The first one is A-A, through the panels 1 and 2 and the second one is B-B, through the panels 3 and 4 (see Fig. 5.2). The geometry of the cross-sections is shown in *Fig. 5.3*. The thickness of the spars and lower skin (*t* = 2.794 mm) is constant and corresponds to $[\pm45_5/45]_s$ stacking sequence. The thickness $t_{1(3)}$ corresponds to the panel 1 in the A-A cross-section and to the panel 3 in the B-B cross-section. Similarly, the thickness $t_{2(4)}$ corresponds to the panels 2 and 4. The longitudinal elastic and in-plane shear moduli of these structural elements have similar indices: $E_z, G_{zx}(or\ G_{yz})$ – for spars and lower skin, $E_{z1(3)}, G_{zx1(3)}$ - for panels 1 and 3, $E_{z2(4)}, G_{zx2(4)}$ - for panels 2 and 4.

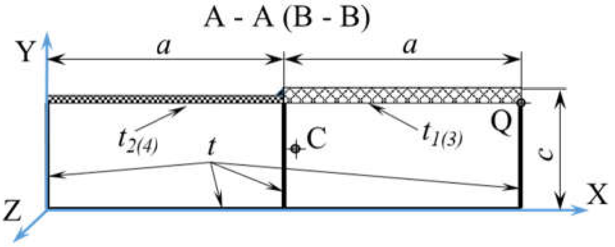

Fig. 5.3 Cross-section of the wing box structure

The extensional (longitudinal) stiffness of the cross-sections can be calculated as the following:

$$AE_{z1(2)} = \oint tE_z ds = tE_z(3c + 2a) + a\left(t_{2(4)}E_{z2(4)} + t_{1(3)}E_{z1(3)}\right). \tag{5.1}$$

The first moments of area are the following:

$$EI_{x1(2)} = \oint tE_z y ds = \frac{3}{2}tE_z c^2 + ca\left(t_{2(4)}E_{z2(4)} + t_{1(3)}E_{z1(3)}\right),$$

$$EI_{y1(2)} = \oint tE_z x ds = 3tE_z ac + 2tE_z a^2 + \frac{a^2}{2}t_{2(4)}E_{z2(4)} + \frac{3}{2}a^2 t_{1(3)}E_{z1(3)}. \tag{5.2}$$

Then the centroid C coordinates can be simply calculated:

$$x_{c1(2)} = \frac{EI_{y1(2)}}{AE_{z1(2)}}, y_{c1(2)} = \frac{EI_{x1(2)}}{AE_{z1(2)}}. \tag{5.3}$$

The bending stiffnesses can be calculated as follows, starting from the point Q:

$$EJ_{x1(2)} = \oint tE_z y^2 ds = tE_z c^3 + c^2 a\left(t_{2(4)}E_{z2(4)} + t_{1(3)}E_{z1(3)}\right),$$

$$EJ_{y1(2)} = \oint tE_z x^2 ds = tE_z\left(5a^2 c + \frac{8}{3}a^3\right) + \frac{a^3}{3}\left(t_{2(4)}E_{z2(4)} + 7t_{1(3)}E_{z1(3)}\right). \tag{5.4}$$

The bending stiffnesses in relation to the centroid C are the next:

$$EJ_{x01(2)} = EJ_{x1(2)} - y_{c1(2)}{}^2 AE_{z1(2)},$$
$$EJ_{y01(2)} = EJ_{y1(2)} - x_{c1(2)}{}^2 AE_{z1(2)}. \tag{5.5}$$

The method of redundant reactions allows deducing the formula for torsional stiffness:

$$GJ_{z1(2)} = \frac{4a^2c^2\left(\frac{6c+2a}{tG_{zx(yz)}} + \frac{a}{t_{1(3)}G_{zx1(3)}} + \frac{a}{t_{2(4)}G_{zx2(4)}}\right)}{\left(\frac{2c+a}{tG_{zx(yz)}} + \frac{a}{t_{1(3)}G_{zx1(3)}}\right)\left(\frac{2c+a}{tG_{zx(yz)}} + \frac{a}{t_{2(4)}G_{zx2(4)}}\right) - \left(\frac{c}{tG_{zx(yz)}}\right)^2}. \tag{5.6}$$

5.1.3 Description of the global FE model

Before building the upper-level optimization workflow the initial global FE model should be created. It could be a rough simplified model (Fig. 5.4).

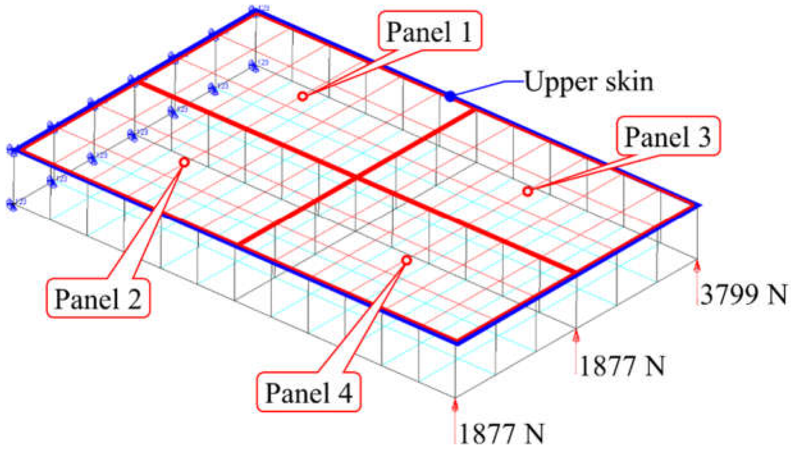

Fig. 5.4 Global FE model

In case of the example problem described above the wing structure was modeled using MSC Patran pre-processor. The laminates for the entire structure except the upper skin (to be optimized) are modeled traditionally using PCOMP and MAT8 cards. To realize the smeared stiffness approach (see Subsection 4.1 and expression (4.1)) for the upper skin panels they are modeled using shell elements with an equivalent section's property PSHELL [43]. The equivalent section's property is defined using MAT2 material cards and thickness. The MAT2 card allows defining a composite material through its extensional stiffness sub-matrix A [43]. It is used for defining the composite materials of each upper skin panel. All nodes of the wing root have all their translational DOFs fixed. Three concentrated loads are applied at the free wing tip. The average mesh size is 350 mm.

5.1.4 Description of the upper-level analysis

The workflow of the upper-level analysis if shown in Fig. 5.5.

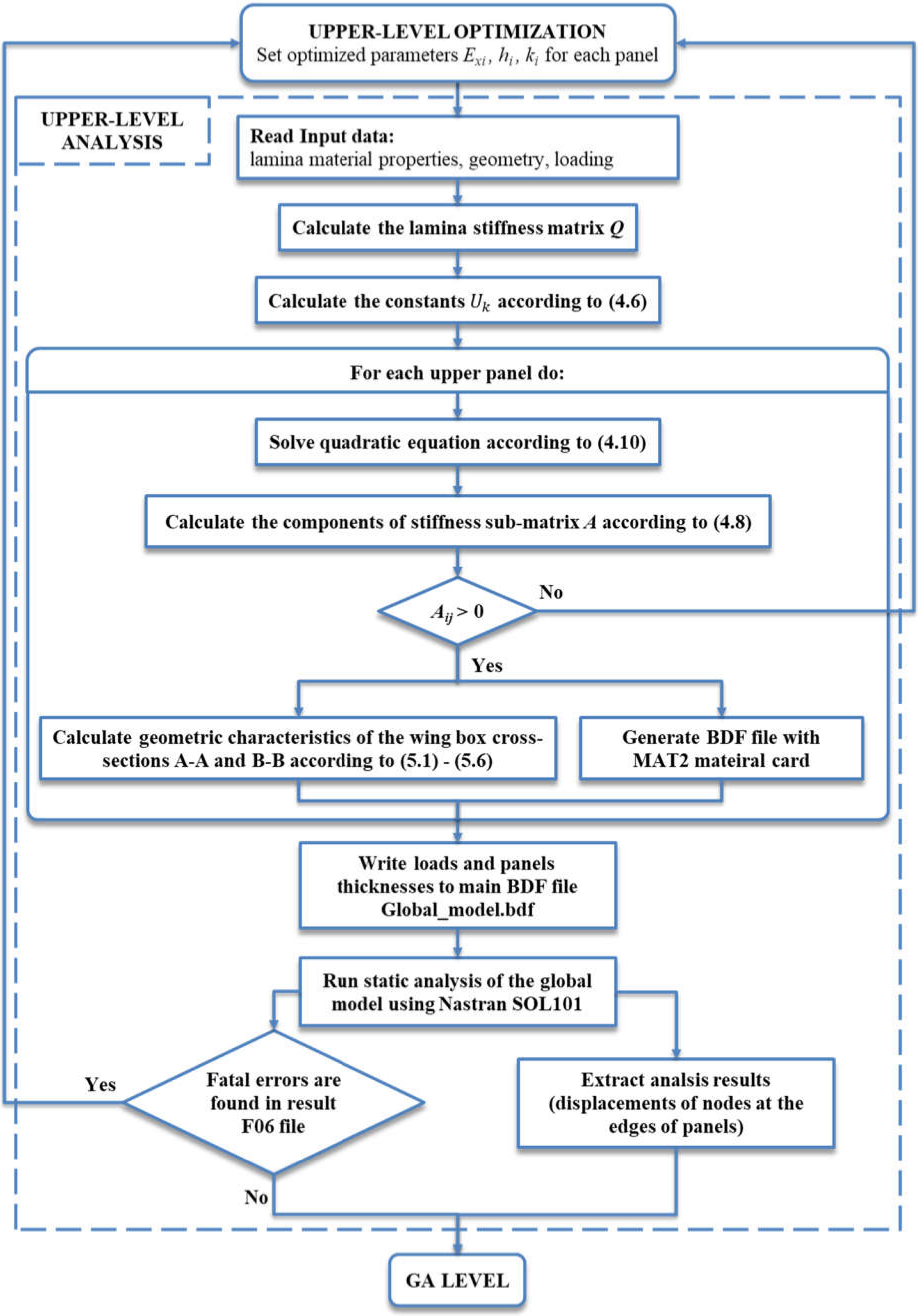

Fig. 5.5 Flow chart of the upper-level analysis

5.1.5 Description of the upper-level optimization workflow

The workflow for the upper-level optimization is shown in Fig. 5.6.

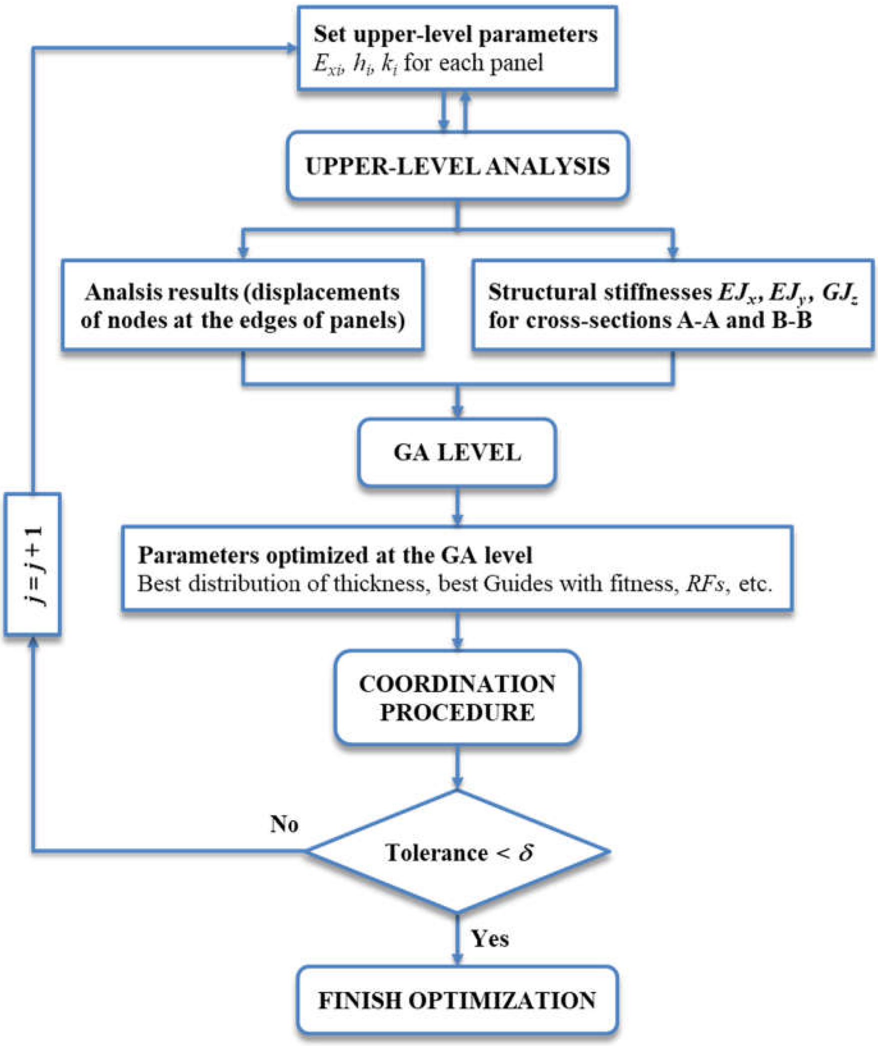

Fig. 5.6 Flow chart of the upper-level optimization

5.2 GA-level optimization

The GA level deals with generation of guides (see formatting of a file with guides in Fig. 5.7) and the GA, which performs genetic operations with the generated guides to improve them with help of simplified genetic evolution. No FE analysis is performed here, therefore there is no need in a FE model at this level. The fitness values (4.12) of the guides are calculated at this level. The algorithm developed for this level was programmed using Python language.

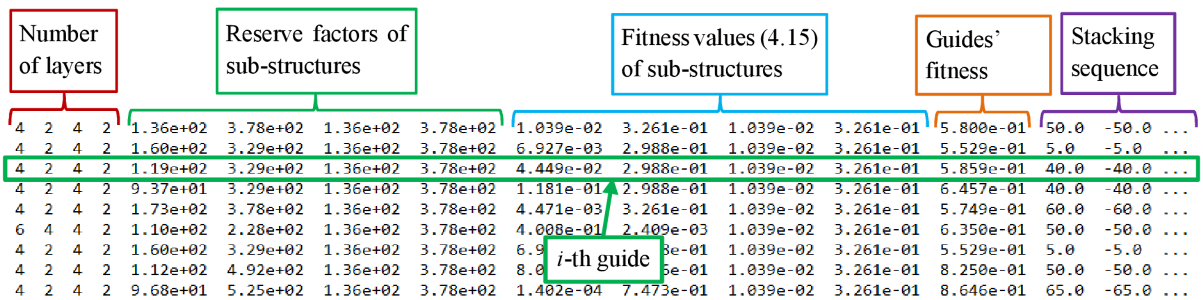

Fig. 5.7 Formatting of a "List_of_Guides.txt" file

The flow chart of the GA level optimization is shown in Fig. 5.8.

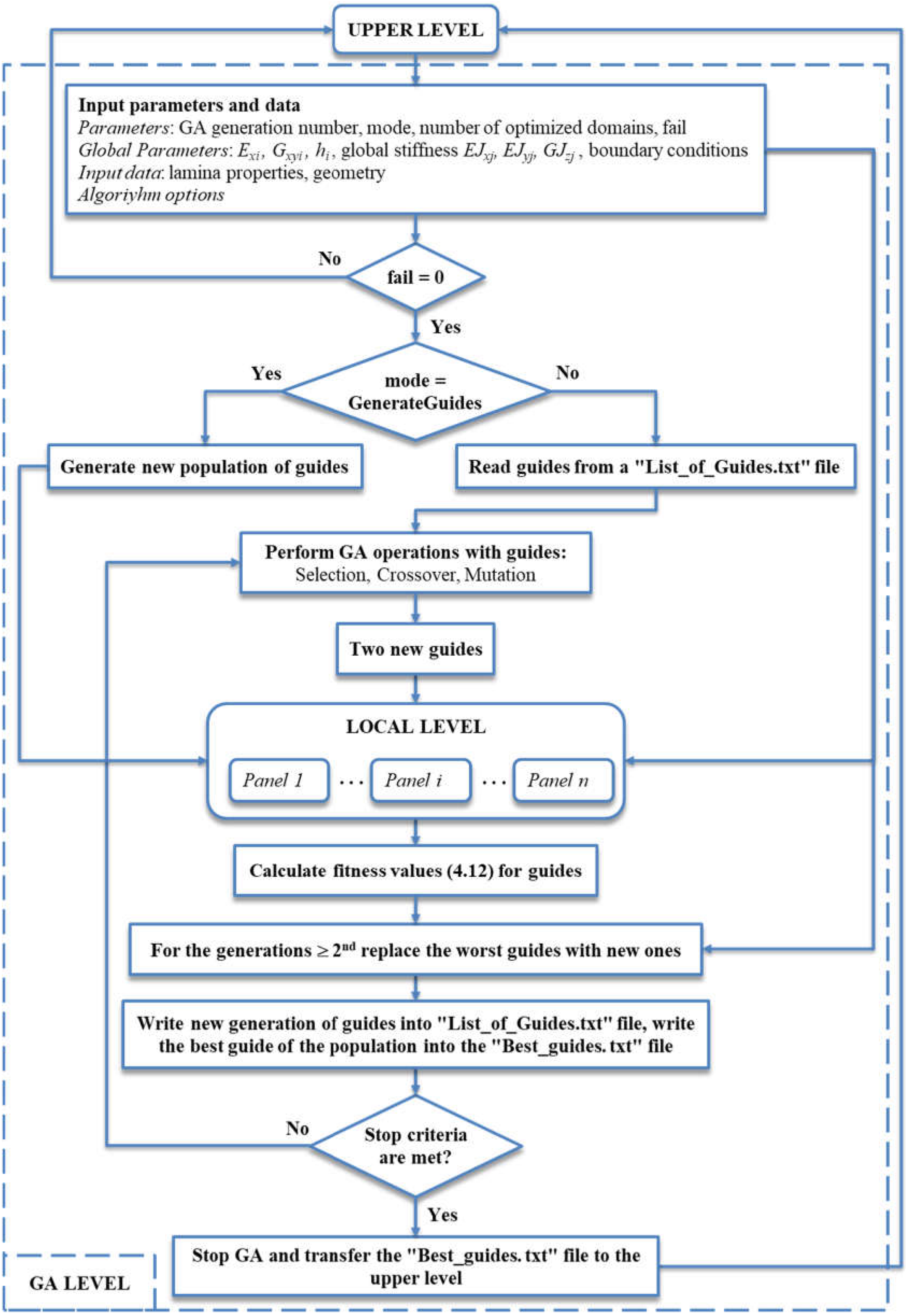

Fig. 5.8 Flow chart of the GA-level optimization

5.3 Lower-level optimization

The lower level deals with optimization of the guides generated at the GA level. For each guide sent to the lower level the optimal distribution of thickness is found. It is done by successive optimization of each panel (see Fig. 5.2). For each panel the optimum thickness is calculated, which corresponds to the best value of the objective function (4.15). The minimum reserve factor (RF_{min}) is calculated for each panel based on the element strains and buckling load factor extracted from the FE local model buckling analysis:

$$RF_{min} = min\left(\frac{\varepsilon_{1a}}{\varepsilon_1}; \frac{\varepsilon_{2a}}{\varepsilon_2}; \frac{\gamma_{12a}}{\gamma_{12}}; buckling\ load\ factor\right), \tag{5.7}$$

where first three members in brackets correspond to reserve factors calculated according to maximum strain criterion ($\varepsilon_1, \varepsilon_2$ and γ_{12} are extracted from the FEA result file, $\varepsilon_{1a}, \varepsilon_{2a}$ and γ_{12a} are taken from Tab. 5.1), buckling load factor – first positive eigenvalue extracted from the FEA result file.

Before starting the lower-level optimization workflow, the initial local FE model should be built. It should be a detailed model. In general, when the geometry of the structure is complex, there should be as many local models as the global model was divided into. Therefore, for each of them a lower-level optimization workflow should be build. In case of the example problem the panels being optimized have the same geometry. Thus, the only one initial local FE model (see Fig. 5.9) and corresponding to it lower-level optimization workflow were built (see Fig. 5.10).

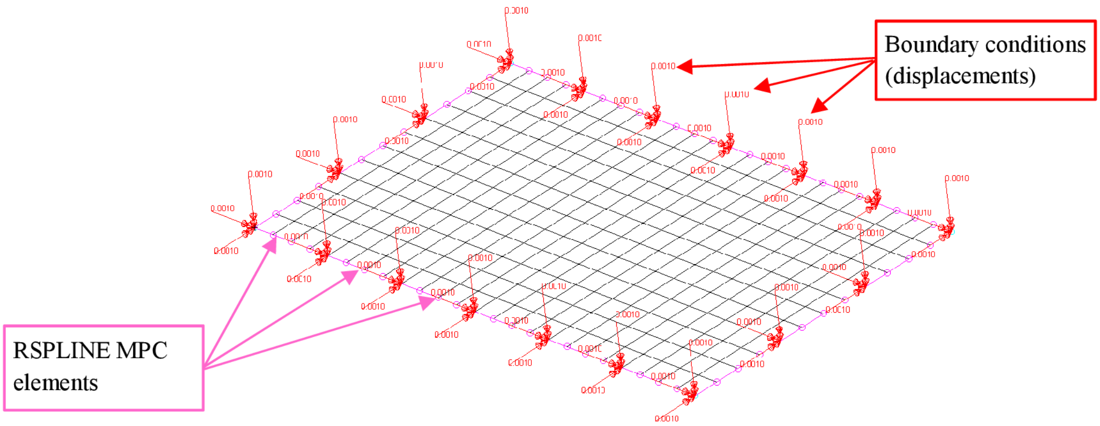

Fig. 5.9 Local FE model

The local model geometry corresponds to the geometry of optimized panels (see Fig. 5.1 and Fig. 5.2). The thickness of the panel is constant. The mesh is 16 times finer than in the global model. The boundary conditions are defined by the translational and rotational displacements taken from the global model nodes lying on the edges of the optimized panels (red arrows in the figure). The local model has 4 times more nodes on their edges than the global model. The displacements from the nodes of the global model can be applied only to the corresponding nodes of the local model. Therefore, the boundary conditions for the other nodes on the edges of the local model were interpolated using RSPLINE MPCs (multi-point constraints – see [43]) – pink elements on the edges of the panel (Fig. 5.9).

The laminate material is defined using PCOMP and MAT8 cards. The PCOMP card is generated into an external BDF file by a Python script and included into the main file of the model using the INCLUDE statement. The initial stacking sequence defined in the initial FE model can be whatever because it will be replaced by the Python script during optimization. The same is concerned to the displacements applied to the panel. The buckling FE analyses of the model are performed by MSC Nastran (SOL105) during the optimization at the lower level.

The lower-level optimization workflow is shown in Fig. 5.10. The workflow is performed for each panel one by one.

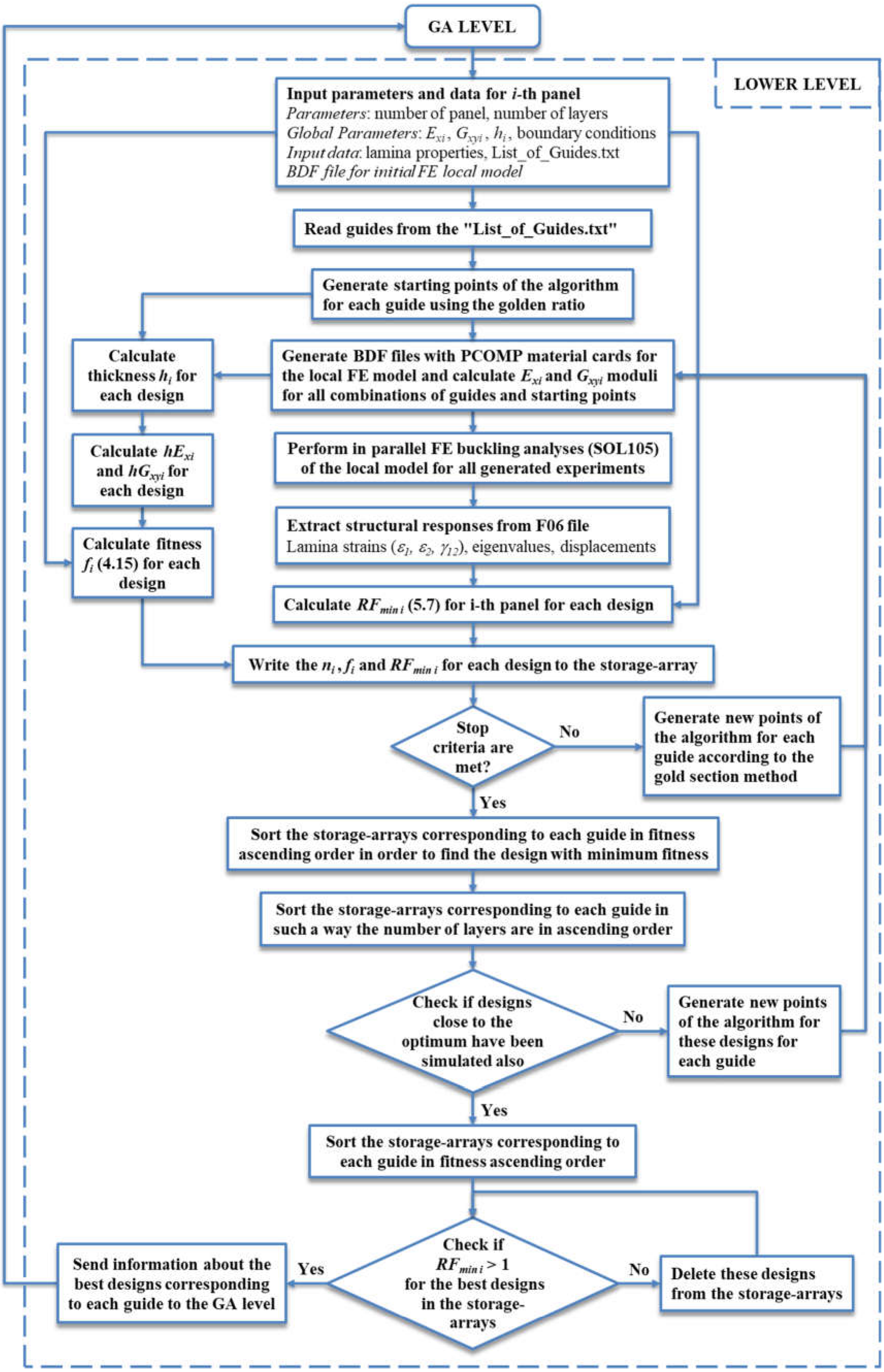

Fig. 5.10 Flow chart of the lower-level optimization

5.4 Coordination procedure

Before building the coordination procedure workflow the initial "detailed" global FE model should be build. This model should take into account the stacking sequences of the best guides and their best thickness distribution found at the GA level. These stacking sequences are modeled using PCOMP cards. There are four PCOMP cards in the "detailed" global model. Each of them corresponds to one of the four optimized panels of the upper skin. Thus, the laminates of the panels are not modeled using MAT2 cards like in Subsection 5.1.3 above.

The workflow for the coordination procedure is shown in Fig. 5.11.

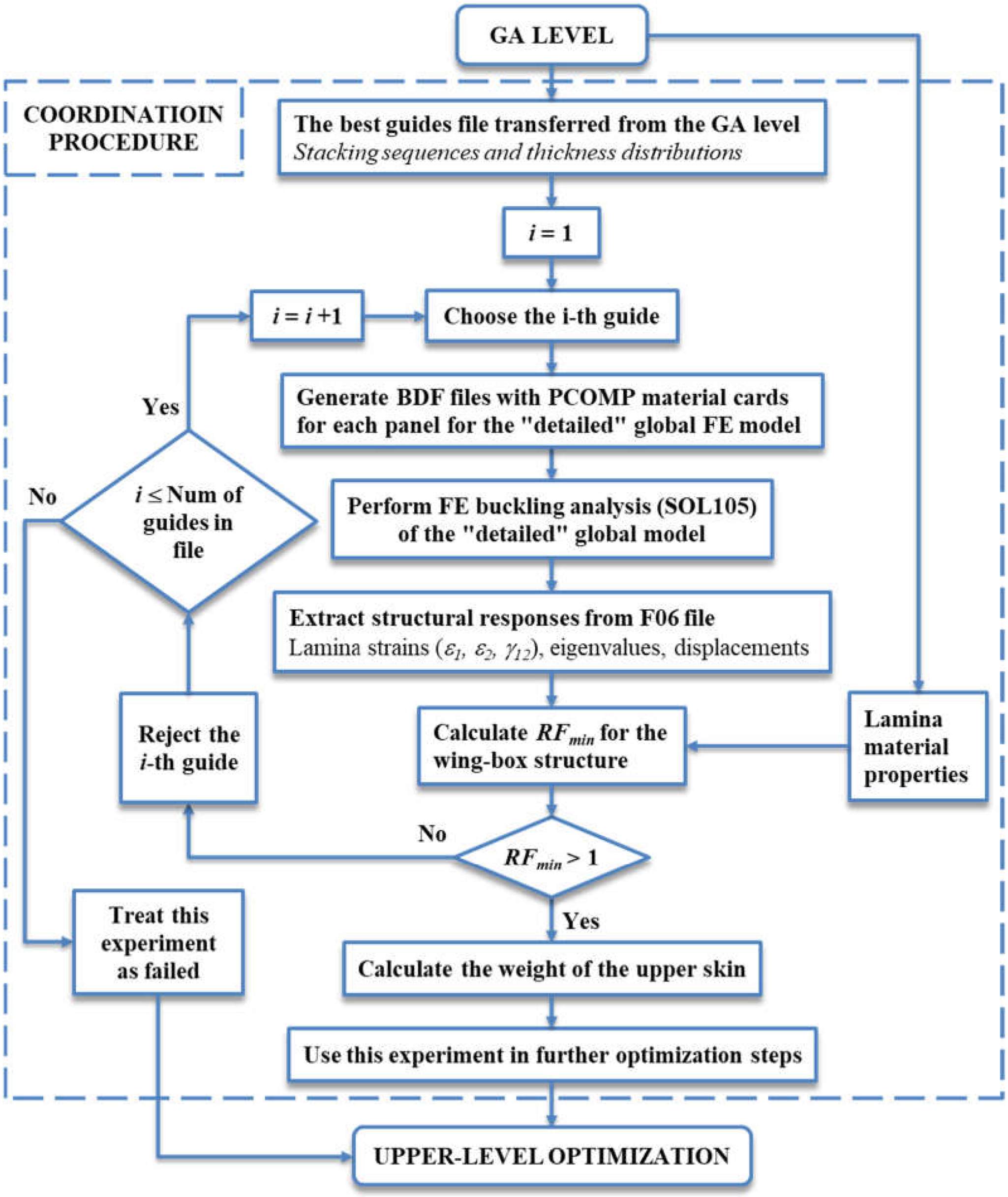

Fig. 5.11 Flow chart of the coordination procedure

5.5 Optimization results for the example problem

The example problem was solved on two computers with Intel Xenon CPU E5-2620 2.00 GHz (6 physical cores and 12 threats) connected in a network (16 processes are allowed by the

Optimus license to be run in parallel). The average run time was about 25 hours. For comparison, the authors in [23] used 200 node (400 processor) 1.4 GHz dual Opteron cluster. For solving the same problem they used 51 processor. They reported the average run time of 12 hours.

The orientation angles allowed for generation of guides were the following 0°, 15°, 30°, 45°, 60°, 75°, and 90°.

In the present work the maximum number of full iterations of the entire algorithm required to find the best solution was 14. The only one found optimal solution is slightly heavier than that found in [23]. Moreover, 3 found solutions are even lighter than that found in [23]. The information about the best designs is shown in Tab. 5.2. The layers of each desing for each panel should be taken from the end of the guide.

Tab. 5.2 The parameters of the best solusions

#	**Weight, kg**	**# of layers for panels 1 - 4**				**Stacking sequence**
1	10.604	10	8	6	6	[±45°/±75°/90°/0°/90°/0°/±45°/±15°/90°/0°/±60°/$\pm15°_2$]
2		8	8	10	4	[90°/0°/±45°/$0°_2$/±45°/±15°/±75°/$\pm30°_2$/±60°/0°/90°]

The algorithm proposed in [23] found another best stacking sequence with the weight of 12.018 kg (10 layers for panel 1, 11 layers for panel 2, 6 layers for panel 3 and 7 layers for panel 4).

6 Conclusions

An optimization methodology for thin-walled composite structures was developed during the present work. The methodology was realized based on commercial optimization software Noesis Optimus, originally programmed optimization code and commercial FEA software MSC Nastran. It fulfils all the objectives of the thesis (see Section 3). Specifically the developed methodology can be applied for optimization of a complex composite structure with variable stiffness, meaning the structure can be divided into several sub-structures with different stiffness. Each sub-structure may, in general, consist of several skin panels of different thicknesses, spars and stringers and separated from the neighboring sub-structures with ribs or frames. Several load cases are also possible.

The optimization parameters are thicknesses and stacking sequences of the optimized structural elements as it was planned. The optimization objectives are weight minimization of the empty structure, deflection and twist angle minimization. The optimization constrains were strength and buckling of the structure and blending of the neighboring sub-structures.

The developed methodology conforms to the basic aspects of a modern optimization methodology recited in the state-of-the-art review (see Section 1).

The methodology was applied to solve an example problem where the weight of a simple wing box was minimized. The results has shown the methodology is very effective. It allows finding the lighter designs in less time or using less computational resources in comparison to the previously developed methodologies [23].

The novelties of the present thesis are enclosed in the next aspects:

- the general approach to the problem decomposition,
- the flexibility of the algorithm interface,
- the approach to the definition of a laminate through E_x, k and h parameters (see Subsection 4.1), which allows to simply distribute composite material through the structure without insight into its details (stacking sequence, orientation angles, etc.),
- the newly developed genetic algorithm (see Subsections 4.2 and 5.2),
- the newly developed parallel one-dimensional algorithm based on Golden section method (see Subsections 4.3 and 5.3).

Besides the mentioned, the methodology has the next advantages.

Flexibility. It can be applied for optimization of a very wide class of composite structures. Within this thesis a FEA software was used for performing structural analyses. However, the flexibility of the developed interface allows using any other analysis methods, e.g., analytical calculations, surrogate models, etc., which can be simply integrated instead of FEA. A combination of FEA and other analysis methods can be used also. In case if FEA software is used for performing structural analyses the shape, complexity and loading of the structure can be whatever. The methodology allows to set many types of objectives and apply many types of constraints.

Simplicity. The developed interface is very intuitive and can be used by an engineer on-the-fly without a special time and coast consuming training.

Parallel processing. The analyses of models are run in parallel.

Of course, the methodology and the interface are not ideal and have disadvantages. They are mentioned below.

Commercial software Optimus. To integrate all levels, algorithm, and software a commercial optimization software Noesis Optimus is used which requires a license. However, a domestic interface can be developed easily, since the main and auxiliary optimization code is programmed by the author using Python language.

Computational expensiveness. Since a GA is used at the GA level, the methodology requires extensive computational resources. When FE software is used for structural analyses, it is even more computationally expensive.

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CURRICULUM VITAE

Date and place of birth: April 24, 1981, Zvolen, Slovakia

Contacts: symonov@fme.vutbr.cz, tel. 702-373-268

Education

National aerospace university by N.Y. Zhukovskiy – "KHAI", Faculty of Rokets and Space
M.Sc. in Mechanical Engineering, engineer-researcher, specialization field "Design and production of composite material products".

Employment history

11/2012 – present	Brno University of Technology, Faculty of Mechanical Engineering, Institute of Aerospace Engineering, Brno, Czech Republic	Researcher, aerospace structures design, stress analysis and optimization
7/2011 – 10/2012	Ukr-Progresstech, Ltd., Kiev, Ukraine	Stress-analysis engineer, aircraft sturctures stress and fatigue analysis
5/2008 - 6/2011	National aerospace university by N.Y. Zhukovskiy – "KHAI", Laboratory of Composite Materials, Kharkov, Ukraine	Head of the laboratory, research fellow, project manager
10/2007 - 5/2008	"TMM-Avia" Ltd, Kharkov, Ukraine	Aircraft design and stress analysis Engineer
5/2007 - 11/2007	"SKAETON" Ltd, Kiev, Ukraine	Aircraft stress analysis engineer
10/2003 - 04/2006	"Flight Design Ukraine", Kherson, Ukraine	Technical Project Manager, developement of a shock demping device for airplane's parachute rescue systém
9/2003 - 03/2005	"Engineering-Ukraine" Ltd, Kherson, Ukraine	Aircraft design and stress analysis engineer

Publications

Author or co-author of 7 journal papers and 10 conference papers, presenter on 8 international conferences, ORCID ID: 0000-0002-5172-6691

ABSTRACT

The thesis is dedicated to development of a multi-objective optimization methodology for complex composite structures with variable stiffness. A multi-level hybrid optimization algorithm is developed based on a hybrid optimization method with interpolating response surface, a Genetic Algorithm and a one-dimensional optimization. Finite element analysis software MSC Nastran is used for structural analyses. A new Genetic Algorithm and a parallel one-dimensional optimization algorithm based on "Golden section" method are developed for the methodology. The finite element analysis software and the developed optimization algorithms are integrated with help of a commercial optimization software Noesis Optimus by Noesis Solutions. The developed methodology is verified on an example optimization problem. The results of the problem optimization are compared to those obtained using previously developed methodologies.

ABSTRAKT

Disertační práce se věnuje vývoji metodologií pro vice-cílovou optimalizací složitých kompozitních konstrukcí s proměnnou tuhosti. Vice úrovňový hybridní optimalizační algoritmus je založený na bázi hybridní optimalizační metody s využitím interpolační plochy odezvy, genetického algoritmu a jednoparametrické optimalizace. Pro strukturální analýzy je využit MKP software MSC Nastran. Nový genetický algoritmus a paralelní jednoparametrický optimalizační algoritmus na základě metody Zlatého řezu jsou vyvinuty pro metodologii. MKP software a vyvinuté optimalizační algoritmy jsou integrované pomoci komerčního optimalizačního softwaru Noesis Optimus od Noesis Solutions. Vyvinutá metodologie je ověřena pomoci testovací optimalizační úlohy.