Chapter 3

Optimization of Lay-Up Stacking for a Loaded-Carrying Slender Composite Beam

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Additional information is available at the end of the chapter

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Abstract

Many aircraft composite structures experiencing the high operational loads must have the specified mechanical stiffness to prevent some structural failure due to the inadmissible deformations. Usually, such parts are manufactured using composites with orthotropic symmetry, which provides the best combination of structural rigidity, strength, and weight. In this chapter, we consider a cantilevered long tube-like composite structure with varied cross-section that is manufactured by winding of glass fiber unidirectional tape. The operational loads include the bending forces and the distributed torques. To reduce the total strain energy and peak von Mises stress, the search of the best lay-up scheme and its angles is performed. The wall thickness, lay-up scheme, and the total number of layers for each modeled design are assumed as unchanged along the tube, whereas its mechanical properties are considered as homogenized and dependent on the lamina properties and lay-up scheme only. The search of the pseudo-optimal design includes the analysis of all moduli angular distributions for each lay-up stacking. The better solutions are then studied by using the finite element model of the structure for three most critical load scenarios. The choice of the most preferred design is made by discarding the solutions with sharply degraded structural rigidity at least at one load scenario.

Keywords: structural optimization, aircraft composite structures, lay-up design

1. Introduction

The glass/carbon fiber composites are widely used in the design of various aircraft and rotorcraft components such as stringers, the spars of the rotor blades, the stiffened panels of the wings and stabilizers, which have predominantly a thin-walled geometry and are made of composite laminates that most often are adopted as orthotropic. The main requirements for these parts are the specified dynamic and endurance properties to provide the aerodynamic quality and reliability of the aircraft assembly at the different flight conditions with limited part weight [1]. Most of these parts are manufactured by laying-up or winding of the unidirectional lamina and curing in closed molds or autoclaves where the parts are exposed to the controlled pressure and temperature according to the predetermined process.

The rapid growth of composite applications in aircraft and rotorcraft industries, the very complex mechanical behavior of anisotropic composite materials require new structural strength, rigidity, modeling, optimization and failure prediction methods using virtual testing analysis method, which is a concept with several attributes and is to be understood as the simulation of aircraft structure [2, 3]. In the survey paper [4] the main milestones of development of the optimization and its applications in aircraft systems design, especially in the context of the composite structures, are considered. According to the concept, which is present in the considered paper, a full workflow process of the composite structure optimization consists of the following three phases:

- Free size or topology optimization
- Detailed design: ply-bundle sizing with ply-based FE (finite element) modeling
- Detailed design: ply stacking sequence optimization

During the second and third phases the composite plies with the different orientation are chosen and shuffled to determine the optimal stacking sequence for the given design optimization problem while satisfying some additional manufacturing constraints. As outlined in the article [5], such a composite structure optimization involved a large number of both the design variables and the objectives. As a result, designers must consider only a restricted set of parameters among the most influential. In the paper [5], the author uses the following parameters of optimized laminates: mass per unit area of an elementary plate, the compliance of elementary plate and the stiffness of a composite plate experienced by the uniform pressure. The stacking sequence, total number of plies and prepreg materials are accepted as the design variables, whereas the mass and the total number of layers are constrained. It was established that the ply orientation seems to have a significant influence on the most common mechanical criteria (mass, rigidity, etc.). Use of a more refined orientation set can improve the mechanical performance when accounting for inter-laminar stresses, or for laminates made of a few anisotropic plies. In most engineering applications, when there is a large number of plies, it is entirely warranted to restrict the layers' orientations to a limited number of predefined values. Similar technologies and appropriate soft tools are being developed and improved by leaders of aircraft industry such as Altair Engineering GMBH [6].

Because the dynamic behavior of the aircraft structures at the operating conditions being within the structure strength limits is very important, many investigations are limited by the study of composites at the elastic conditions. Such elastic phenomena were the main assumptions used at the modeling and were formulated in the early fundamental work [7]. These assumptions include: (1) The results obtained assume that the composite material may be modeled as a single-phase anisotropic homogeneous continuum. This assumption is adequate for the elastic constants, provided the main consideration is the interface, but is unlikely to apply to the strength properties. (2) There is a representative volume element whose mechanical properties are equal to the average properties of the particular composite. (3) The constituent materials are linearly elastic and homogeneous, but in general anisotropic. (4) Linearity of the stress-strain relations is assumed to hold for the composite materials.

Most investigations that have been implemented in this area use the finite element modeling for solve the forward structural mechanics problem combined with some optimization algorithms based on the soft computing concepts, for example, genetic algorithm [8–10], shuffled Frog-Leaping (SFL) algorithm [11] for lay-up sequence optimization of laminate composite structures. However, there are no theorems to prove that a soft algorithm ensures the achievement of a unique global optimum. Therefore, some researchers use analytical approaches to optimize the simplest composite systems [12] or empirical methods for more complex ones [13, 14].

Some works are devoted to the optimization of composite structures subjected to aeroelastic or hydraulic dynamic loading. The common part of such works is the subtask of simulating aeroelastic actions on a composite structure. In particular, the paper [15] examined phenomenon of bending-torsional coupling rigidity for achieving an optimal design of a composite wing with a maximum flutter speed. In order to ensure an effective way to achieve an optimal lay-up, two optimization approaches have been investigated. In the first approach, the flutter speed was set in the objective function directly. In the second approach, optimization was carried out to minimize an objective function containing the torsional and coupling rigidities rather than flutter speed. Kalavalapally and co-workers [16] solving a multidisciplinary optimization problem for a lightweight torpedo model subjected to underwater explosions observed that the composite torpedo model is stronger and lighter than the metallic design when subjected to an underwater explosions at a given standoff distance. The paper [17] presented the numerical method and results of the structural optimization of the mounting zones of wind turbine blades to diminish and flatten the stress distribution at the action of the extremely stressed wind load on the blade, which had the stiff carbon/epoxy composite skin and less stiff lightweight core body.

When composite structure with complex shape is studied, its CAD model needs to be used for the virtual aerodynamic testing by the means of FE tools. The main objective of the paper [18] is the optimization of wall thickness and lay-up sequence of shell-like cowling made of the transversely isotropic multilayered composite. The used approach assumed: (1) conversion of the CAD model of the cowling surface to the FE representation, then (2) wind tunnel testing simulation at the different orientation of airflow to find the most stressed mode of flight that uses at the formulation of the loading pressure conditions for the forward problem of structural mechanics. The optimization problem used the global strain energy calculated within the optimized shell as the objective, whereas the total weight of the optimized part was considered as the design constraints.

The important conclusion that can be made taking into account the surveyed works is the multiobjective nature of most composite optimization problems. Such a conclusion can be made on the basis of the present chapter, which is broken into several parts. First, we present a brief description of the optimized composite structure, which is the tube-like cantilever slender beam experiencing distributed bending and torsion forces. Then we determine the elastic properties of laminates used in the modeled tube. We start from the mechanical properties of reinforcing fibers and epoxy resin, and then we determine the properties of the unidirectional lamina and, finally, the laminate properties. Our optimization approach contains three sequential stages. The preliminary stage is based on the consideration of the angular distribution of all engineering constants of laminates. This analysis allows us to choose the small enough set of "candidate" lay-ups, which should be used at the modeling of the mechanical response of the studied structure at three different load scenarios. The next "candidates"—higher level "candidates"—are appointed for the final dynamic test, which includes applying full load to the preferred structures and gives us the possibility to make the expert decision about final choice of quasi-optimal structure. Last, we discuss some considerations influencing the final choice of the best lay-up parameters that are the design variables.

2. Modeled structure: geometry and operating conditions

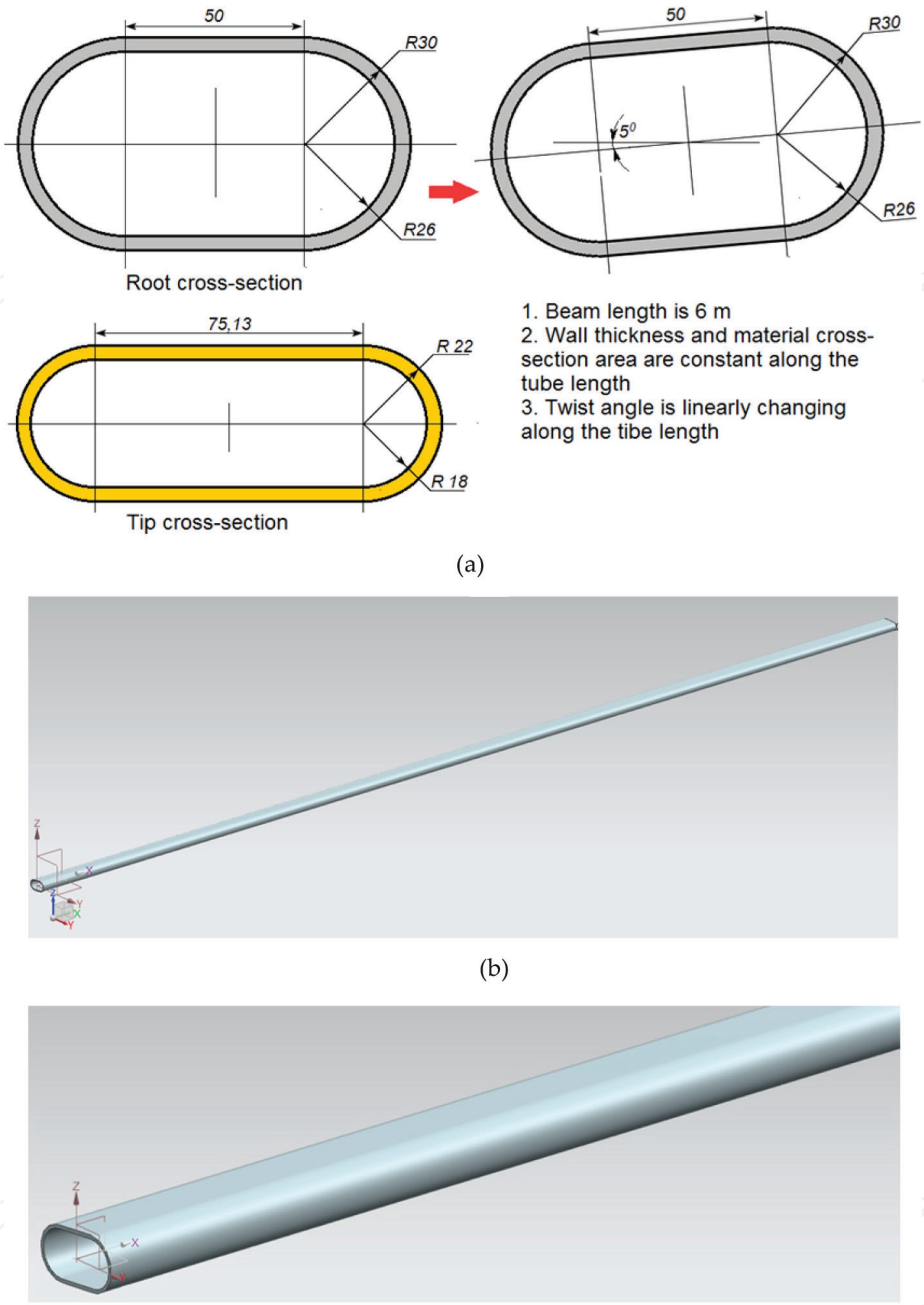
The composite beam studied in this research is a slender tubular structure with optimizing prepreg lay-up sequence. Its cross-section is comprised of two straight stripes and two half-circles, each of them is made of eight laminating layers (see **Figure 1**), that is similar to those studied in [19]. The simulated structure is a greatly simplified design of D-like spar of the helicopter main rotor blade. Such spars are typically characterized by thickening of the cross section near the root, decreasing thickness of the airfoil and its twist as it approaches the end of the blade, without tapering of airfoil. The CAD model of the structure was built by using NX CAD (Siemens®) capabilities and converted into the Structural Mechanics Comsol Multiphysics environment.

In order to define the structural anisotropy of the laminate and the distributed external loads, the curvilinear coordinate systems $(\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3)$ have been intended on the external surface of the tube. To do this, we used a diffusion method which solves Laplace's equation $\Delta U = 0$ and computes the vector field as $-\nabla U$. The boundary conditions were assigned as follows: on the internal surface $U_{\text{int}} = 1$, $U_{out} = 0$ on the outer surface, and $-\mathbf{n} \cdot \nabla U = 0$ on the end faces. The normal to the surface is assigned as $\mathbf{e}_1 = -\nabla U / |-\nabla U|$. The second component is the unit vector parallel to the beam longitudinal axis and third one $\mathbf{e}_3$ is normal to the plane $(\mathbf{e}_1, \mathbf{e}_2)$. The curvilinear coordinates are presented in **Figure 2**.

The root end face is fixed $(u, v, w) = 0$, where u, v, w are the displacements along the global axes (x, y, z), respectively. Three different external loads can be applied alternately or together:

$$F_{tors} = \begin{cases} 0 \cdot \mathbf{e}_1 \\ 0 \cdot \mathbf{e}_2 \\ 10^4 \cdot H(x-3, 1) \cdot \mathbf{e}_3 \end{cases} \tag{1}$$

$$F_{bend} = \begin{cases} 0 \cdot \boldsymbol{\xi} \\ 70 \cdot yload \cdot \boldsymbol{\eta} \\ 45 \cdot zload \cdot \boldsymbol{\zeta} \end{cases} \tag{2}$$



(a)

(b)

(c)

Figure 1. Sketch of the beam cross-sections (a), 3D view of the CAD model and magnifying view on the cross-section of optimizing structure.

In Eq. (1) the twisting load $H(x, \delta x)$ is the smoothed step-function with the coordinate of step x and smoothing width δx. The bending force F_{bend} is defined by the components in the global coordinate system whose unit vectors are $(\boldsymbol{\xi}, \boldsymbol{\eta}, \boldsymbol{\zeta})$ and by the parameters $yload, zload$, which can take alternatively or together, have the values of 0 and (or) one.

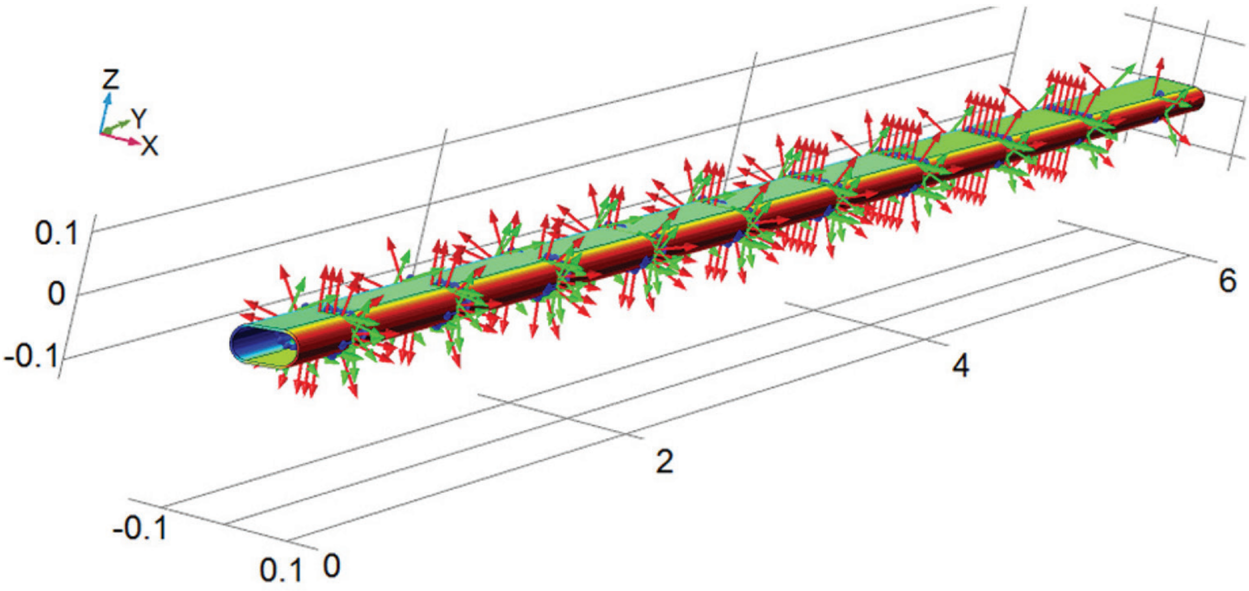


Figure 2. Curvilinear local coordinate systems on the beam surface.

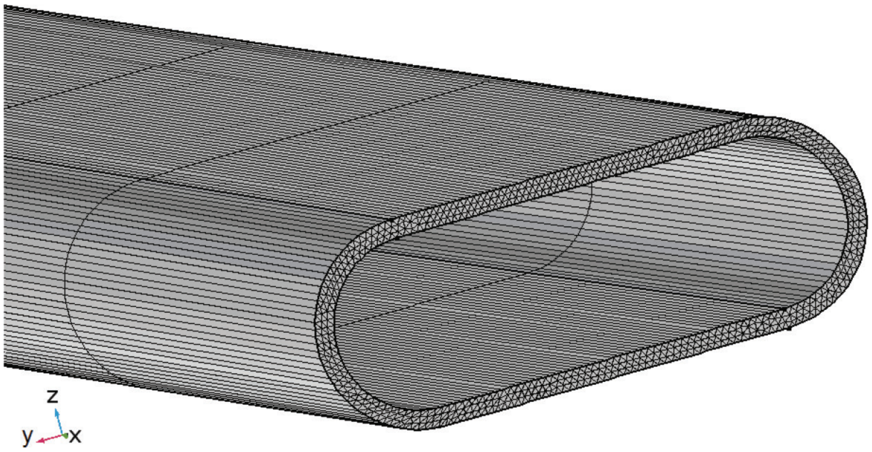


Figure 3. FE mesh used at the mechanics problem.

The FE mesh has been constructed for the given geometry as swept mesh (see **Figure 3**) consisting of 128,893 domain elements, 37,959 boundary elements and 1350 edge elements. The number of degrees of freedom solved for is 625,409.

3. Determination of lamina properties

All numerical and experimental studies have been implemented for glass fiber reinforced epoxy based prepreg VPS-7. Initially, the properties of the fibers and resin, which was accepted as isotropic, have been studied experimentally using testing machines Galdabini. The samples of resin and bundles of the fibers were experienced by tensile forces with strains

Components	Young module, GPa	Poisson ratio	Shear module, GPa
Glass fibers	87.5 (longitudinal)	$\nu_{12} = \nu_{13} = 0.255$	$G_{12} = G_{13} = 2.594$
Epoxy resin	2.55	0.364	0.94 (calculated)

Table 1. Mechanical properties of the composite constituents.

Elastic module	Determination method		
	Experiment	Mixing rule	FE modeling
E_1, MPa	**49,500 ± 2500**	**49,000**	**48,090**
E_2, MPa	6000 ± 500	5500	**8042**
ν_{12}	**0.315 ± 0.015**	**0.31**	**0.299**
ν_{23}	NA	NA	**0.459**
G_{23}, MPa	2600 ± 200	2000	**2758**
G_{12}, MPa	NA	NA	**2847**

Remark: Index 1 corresponds to the longitudinal ply orientation (along the fibers), whereas index 2 to the transversal ply orientation.

Table 2. Mechanical properties of lamina.

monitored by extensometers. During these experiments, the following elastic moduli have been obtained (see **Table 1**).

The properties of unidirectional lamina, which has transversely isotropic symmetry, were determined both numerically and experimentally for the samples with volume fraction $V_f = 0.534$. In order to determine the parameters inaccessible through the experimental tests, we used the mixing rule and FE modeling in Abaqus environment according to the recommendation of [20, 21]. The values all found properties are shown in **Table 2**, where bold numbers denote the most reliable values, which have been used in the follow-up investigation. These values have been used for determination of elastic moduli of laminates of chosen structures.

4. Determination of elastic moduli for laminates

In order to diminish the formation of the residual stress and strains, which can arise during cure we use only 8-layers symmetric balanced laminates in our investigation. All used schemes of lamina stacking are shown in **Figure 4** with their designations.

For each lay-up scheme the elastic moduli were determined independently by two methods: by the finite element method and on the base of the classical laminates theory. The last one proposes the following relationships for the elastic moduli of laminate.

$$\bar{E}_x = \frac{A_{11}A_{22} - A_{12}^2}{A_{22}H}\ ;\quad \bar{E}_y = \frac{A_{11}A_{22} - A_{12}^2}{A_{11}H}\ ;$$
$$\bar{G}_{xy} = \frac{A_{66}}{H}\ ;\qquad \bar{\nu}_{xy} = \frac{A_{12}}{A_{22}}. \tag{3}$$

where indices x, y correspond to the longitudinal and transversal directions of laminate, respectively, and the elements of $\{A\}$ matrix are calculated by the formula [22, 23].

$$A_{ij} = \sum_{k=1}^{N} \bar{Q}_{ijk}(z_k - z_{k-1}) \tag{4}$$

Where, $\bar{Q}_{ijk}$ are the i, j-th elements of the reduced stiffness matrix $\bar{Q}$ for the k-th layer, z_{k-1}, z_k are the bounds of the k-th layer and H is the laminate thickness.

The FE model for determining of elastic moduli simulated the experimental tests according to the standards ASTM D 3039–95 and ASTM D 5379–93 with the numerical methods for the

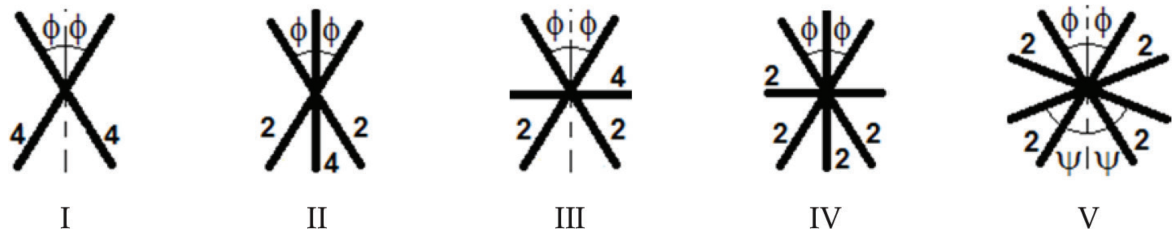


Figure 4. Used schemes of lamina stacking.

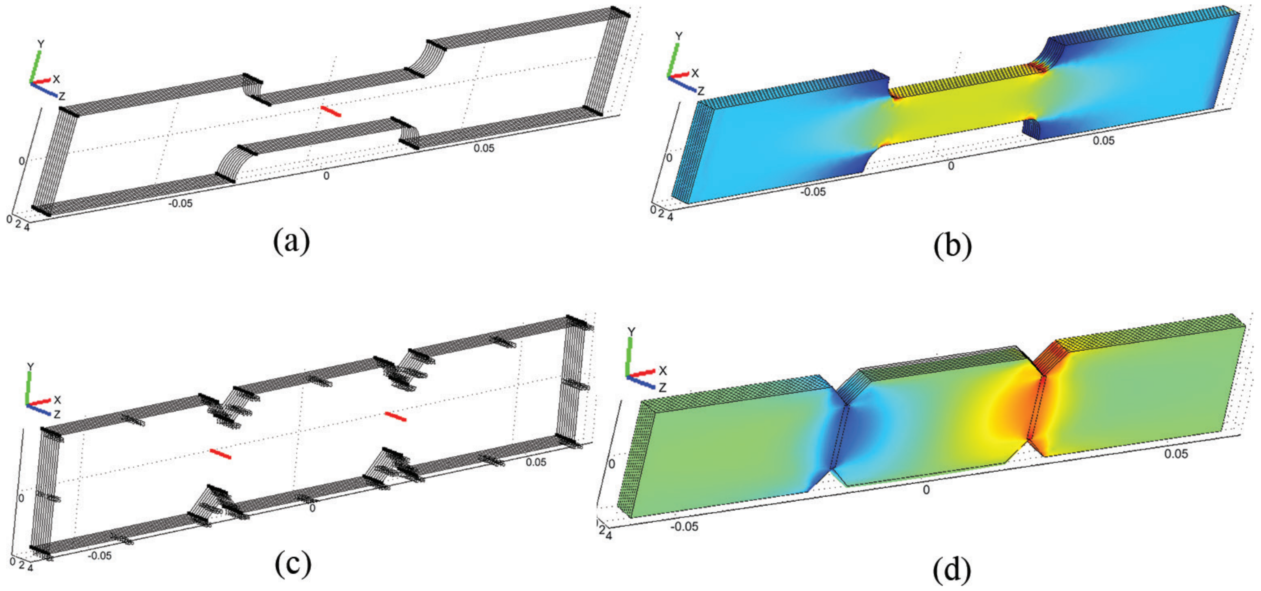


Figure 5. Geometry (a, c) and postprocessing results (b, d) of models simulating the mechanical tests ASTM D 3039–95 "Test Method for Tensile Properties of Polymer Matrix Composite Materials" (a, b) and ASTM D 5379–93 "Test Method for Shear Properties of Composite Materials by V-Notched Beam Method" (c, d).

accurate identification of the modules described in [24]. All modules to be determined in the numerical experiments are averaged by integration along the lines where the pure tensile or shear occurs (see **Figure 5**).

Geometry of the FE models consists of eight separated layers, each of which is characterized by its orientation of lamina. Numerical calculation of elastic modules has been implemented for all lay-ups (see **Figure 4**) with the step $\Delta\phi = 10^0$ of lamina orientation.

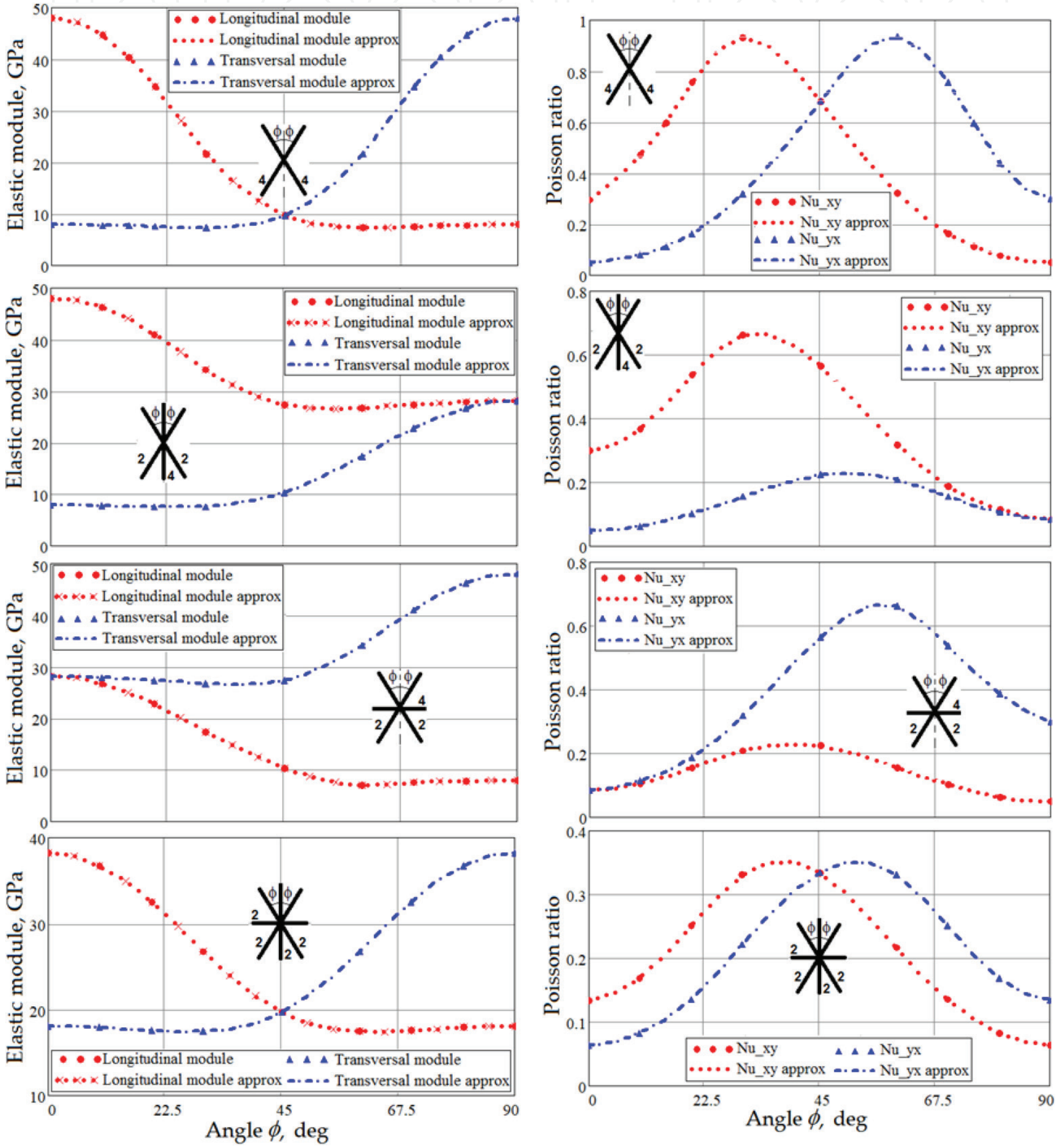


Figure 6. Some examples of longitudinal, transverse elastic moduli and Poisson ratios dependencies on the lay-up angles for the laminate stacking I, II, III, IV (see **Figure 4**).

Both moduli calculation methods have demonstrated a good correspondence, but FE method provides higher accuracy at the calculation of the Poisson ratios and in-plane shear module G_{xy}. Some examples of obtained results are shown in **Figures 6** and **7**. Each point on these plots at the chosen angle ϕ (or ϕ and ψ for the scheme V) represents the

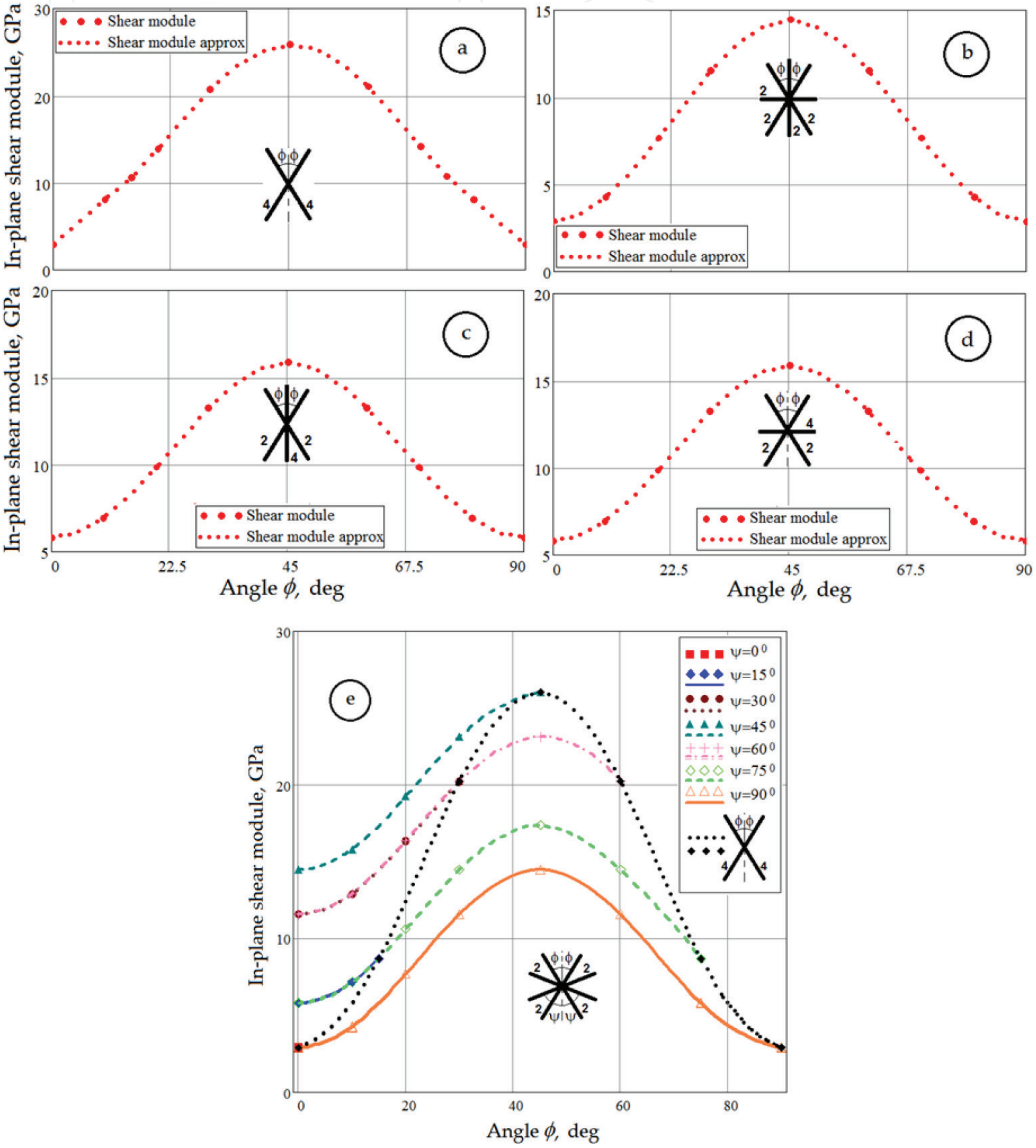


Figure 7. The in-plane shear module dependencies on the lay-up angles for the laminate stacking I, II, III, IV and V (see **Figure 4**).

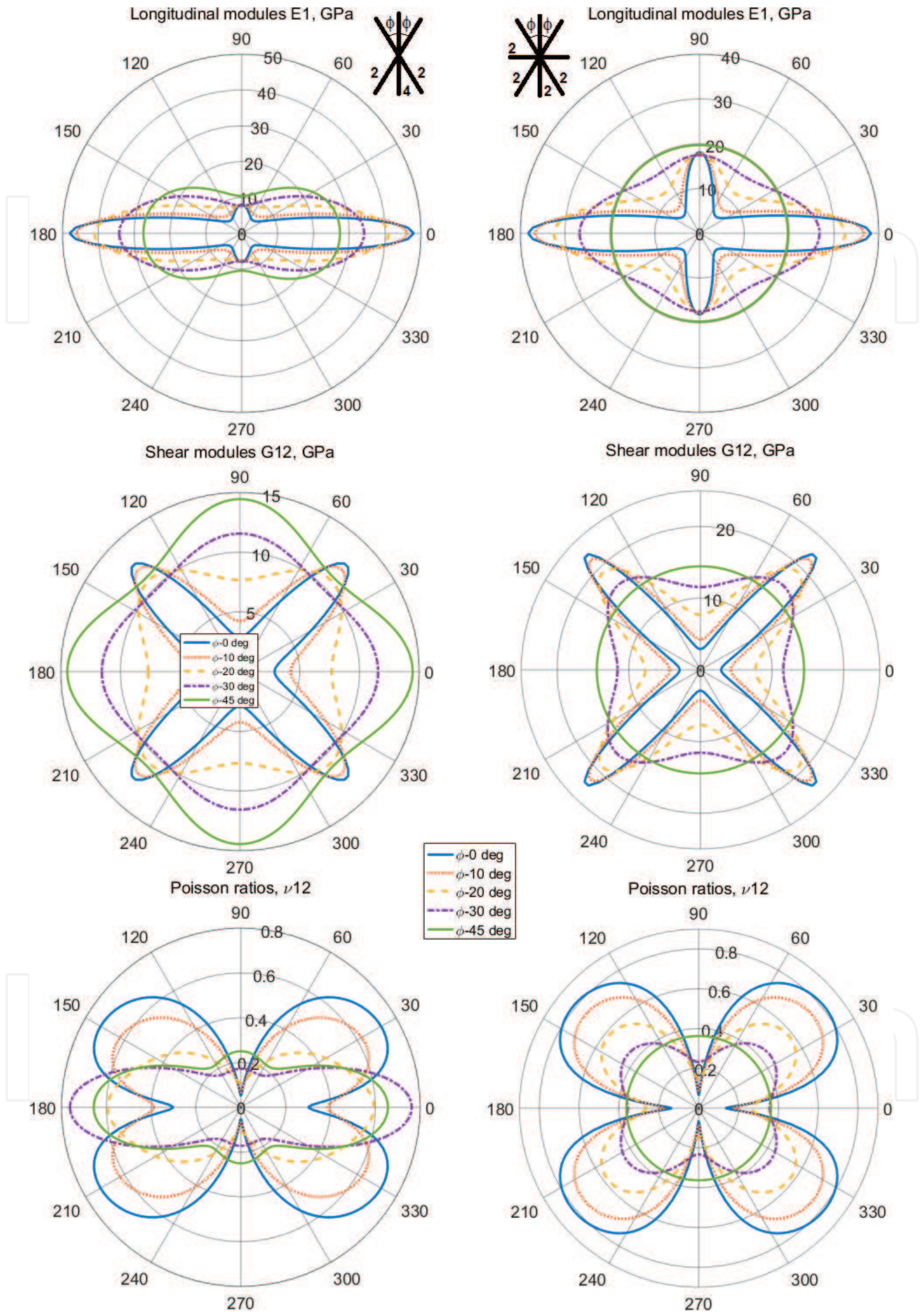


Figure 8. Angular dependencies of the longitudinal, shear modules and in-plane Poisson ratio for the lay-ups II (left) and IV (right) (see **Figure 4**).

values of effective elastic moduli for the laminate with given lay-up. Note that according to the homogenization hypothesis this laminate is considered as the solid body with uniform structure.

In the next stage of investigation, the angular dependencies of the effective moduli were investigated. In order to avoid the significant reduction of the structural rigidity in some directions, these dependencies should not have sharp drops, corresponding to these directions. Some examples of such angular dependencies are shown in **Figure 8**. These dependencies have been used for the preliminary selections of the "candidates" lay-ups, which have been further used to test them in mechanical testing of the optimized slender structure.

5. Mechanical testing of structure with different laminate lay-ups

The mechanical testing of the structure with different lay-ups and ply stacking angles has been implemented using FE model (see **Figures 1–3**) by using three abovementioned types of static bending and torsion loading. These loads were applied separately; for each load scenario the total strain energy E_{el}^{tot}, the maximum and averaged von Mises stress, two end deflections $\max(v_b)$, $\max(w_b)$ and torsion angles θ on the free face of the beam tip were calculated. At the solving of these subtasks a linear parametric solver was used. Results of these testing were used for the refinement of the "candidates," that is, select lay-ups that provide the minimum strain energy, bending and torsion deformations. Our study demonstrated a strong coupling of total strain energy of deformed structure with the values of maximum beam deflection (bending load cases) and maximum torsion angles (twisting load case). Moreover, two very interesting and important facts were established. First, we found that sensitivity of both maximum and averaged von Mises stress to the structural symmetry of orthotropic material is noticeably less comparing to the total elastic strain energy. Thereby we do not give here any von Mises dependencies. Second result is the practically independent response of the structure on the twisting load of the lay-ups II, III and IV. The reason for this is the practical identity of the shear modulus of these lay-up schemes at the same lamina angular orientation (see **Figure 7b–d**).

The calculated dependencies of maximum deflections and torsion angles of the loaded beams on the lay-up parameters are present in **Figure 9**. These results together with the angular dependencies of elastic moduli that are partially presented in **Figure 8** allowed to select eight "candidates" for further optimization. These candidates had to have acceptable values for the total strain energy and rigidity under all loading scenarios.

6. Pseudo-optimal choice of the preferred lay-ups

In the final stage of investigation, the optimizing structure made of the preferred lay-ups "candidates" has been loaded simultaneously by the systems of three forces: bending by the

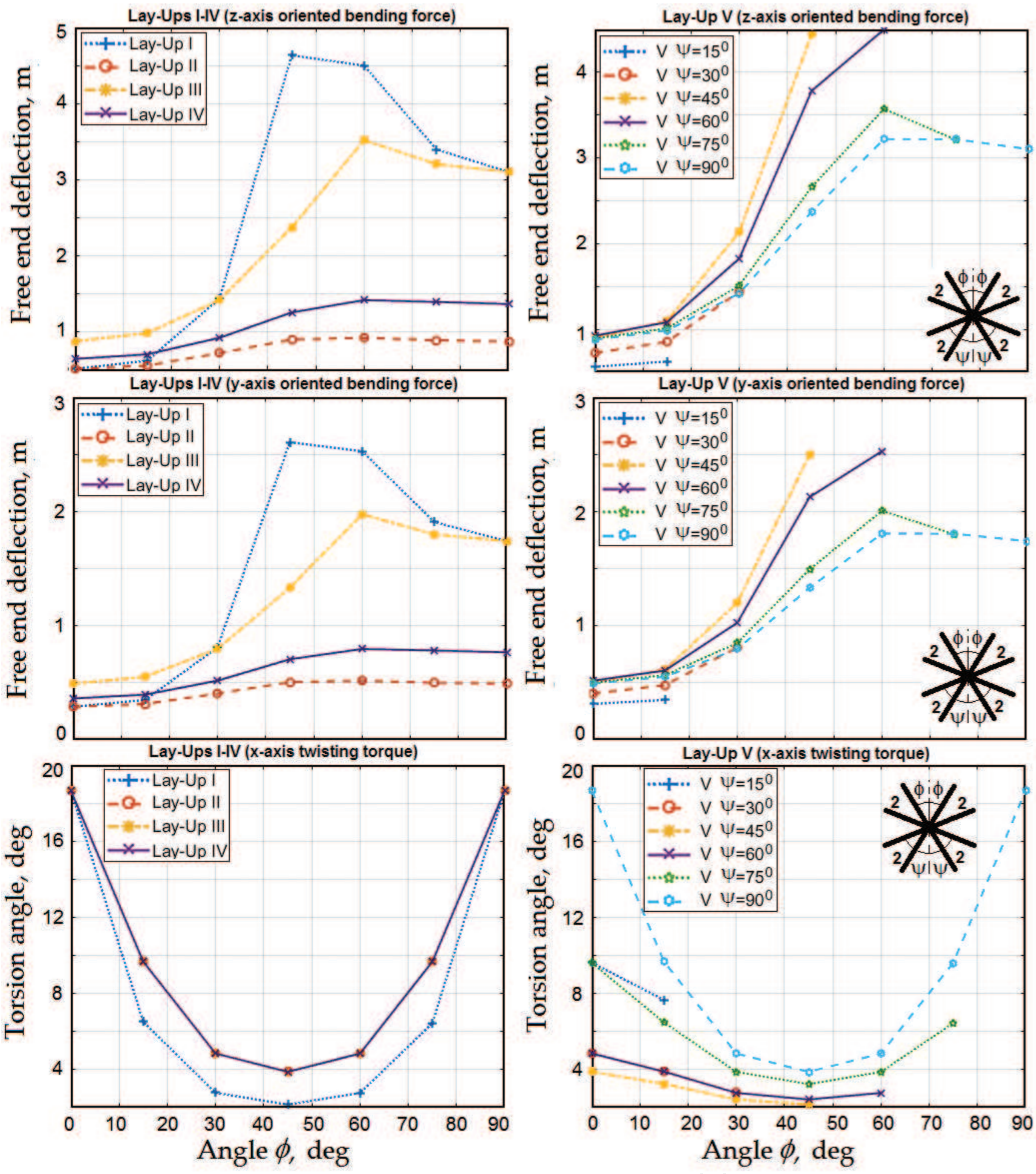


Figure 9. Dependencies of maximum deflections and torsion angles of the loaded beams.

distributed forces oriented along y and z axis and twisting torque applied to the external surface and given by Eqs. (1) and (2). The studied responses included total strain energy, the maximum bending deflections and objective, which was accepted in the normalized dimensionless form.

$$Obj = \theta/6 + \max(v_b) + \max(w_b)/1.5 \tag{5}$$

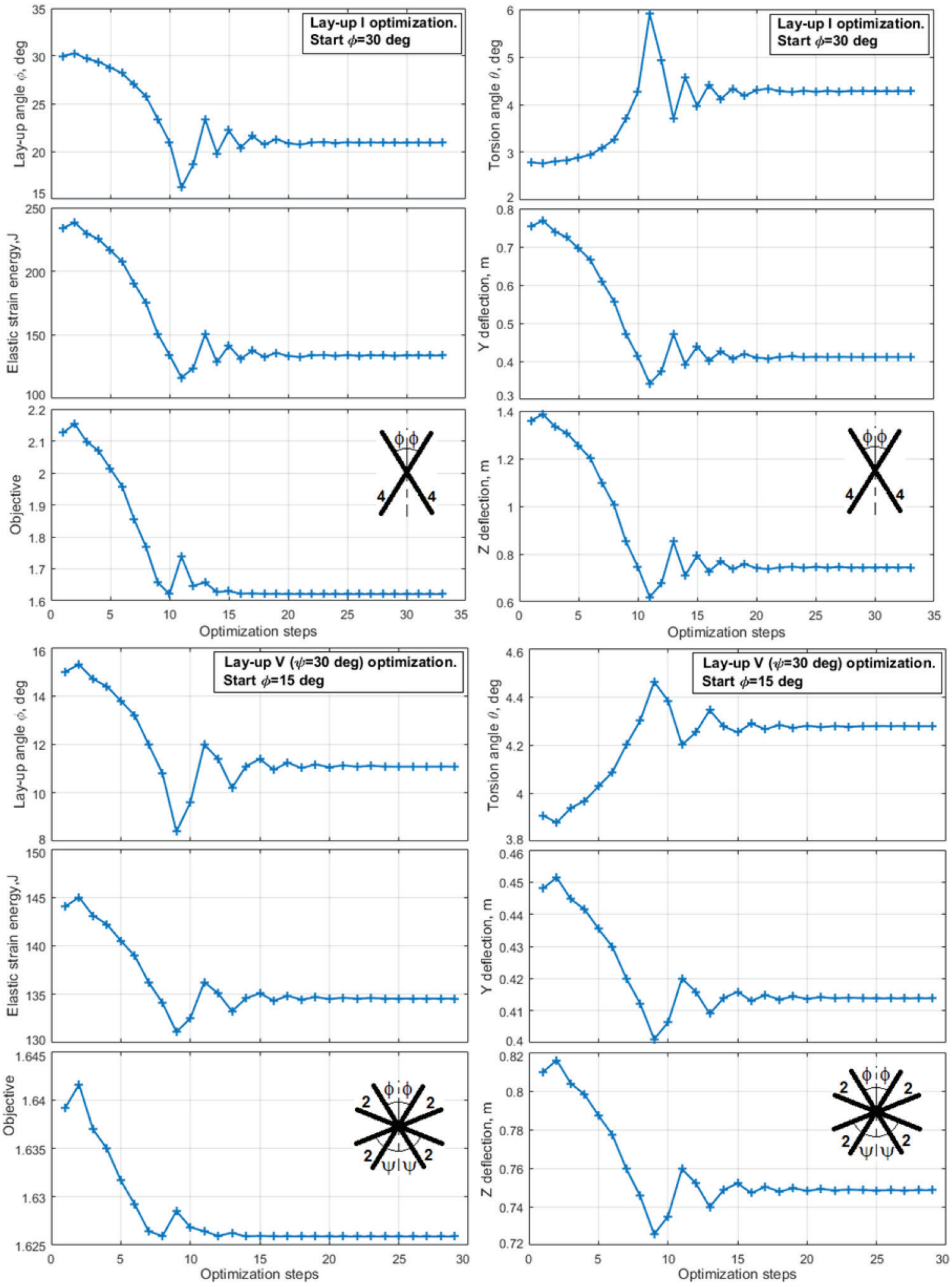


Figure 10. Evolution of lay-up angle, objective and mechanical properties of structure during optimization for two "candidate" lay-ups: (I $\phi\ in\ =\ 30\ 0$) and (V $\psi\ in\ =\ 30\ 0;\phi\ in\ =\ 15\ 0$).

Where, θ is the torsion angle and v_b, w_b are the beam tip deflections along the y and z, respectively. Naturally, definition of such objective function and weights for its components has a significant element of arbitrariness. Therefore, the total strain energy, the beam deflections and torsion angle were also monitored during optimization process along with the objective function determined by Eq. (5).

For the definiteness of the optimization problem statement the following constraints were imposed.

$$\begin{array}{ll} E_{ei}^{tot} \le 160J \; ; & \theta \le 4.5^0 \; ; \\ \max(v_b) \le 0.46m \; ; & \max(w_b) \le 0.86m \end{array} \tag{6}$$

At the optimization workflow, the forward structural mechanics problem has been called by the built-in gradient-free Nelder-Mead optimizer. In order to start the iterative optimization procedures, we used such “candidates”: (I $\phi_{in} = 30^0$); (II $\phi_{in} = 30^0$); (III $\phi_{in} = 30^0$); (IV $\phi_{in} = 30^0$); (V $\psi = 30^0; \phi_{in} = 15^0$); (V $\psi = 45^0; \phi_{in} = 15^0$); (V $\psi = 60^0; \phi_{in} = 15^0$) and (V $\psi = 75^0; \phi_{in} = 30^0$), which had

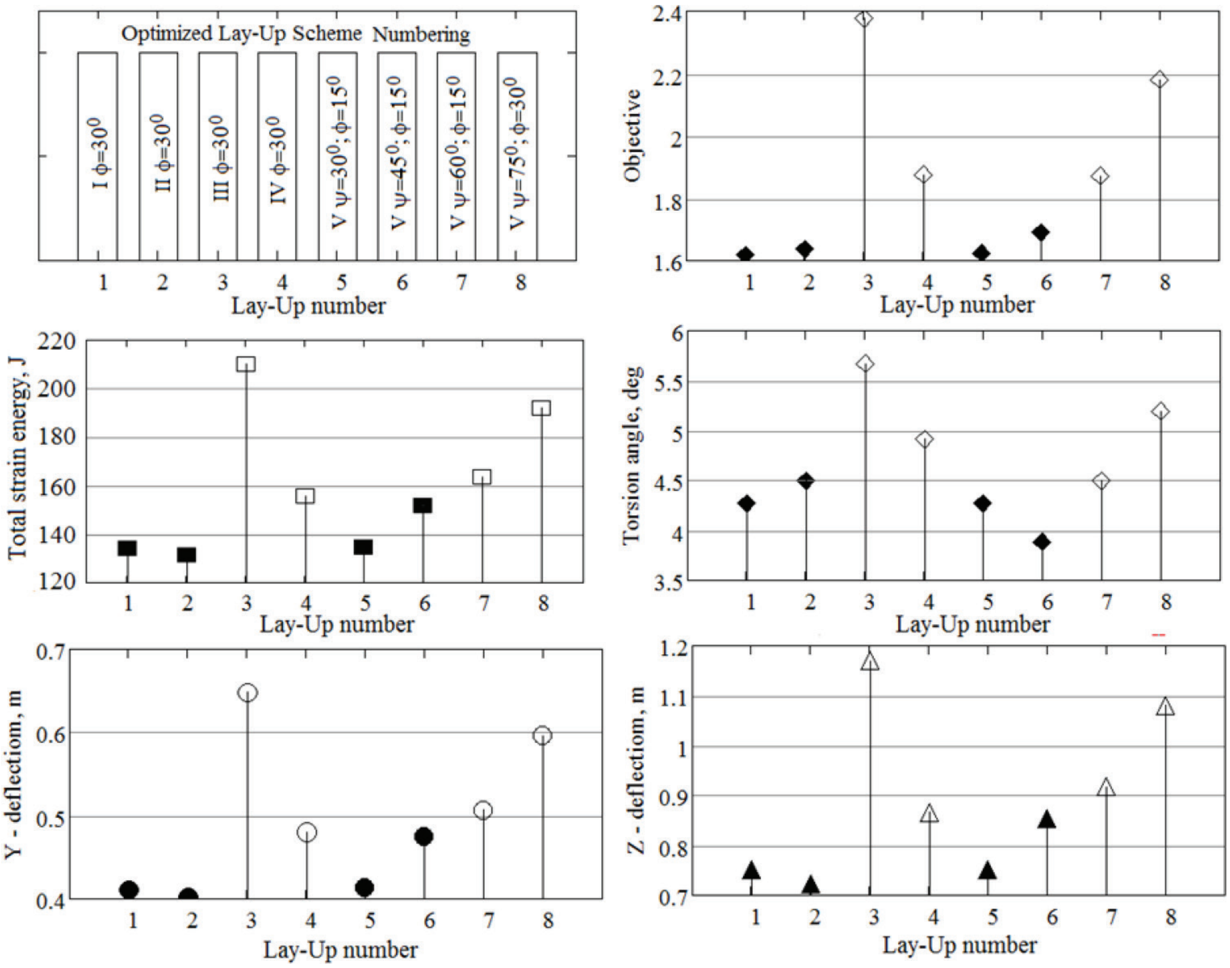


Figure 11. Comparison among the best lay-ups of the optimized structure (stems with the filled symbols correspond to the preferred lay-ups).

better results at the previous stage of the study (see **Figure 9**), where Roman numeral indicates the type of lay-up (see **Figure 4**) and the value of angle is its start value.

Figure 10 illustrates two examples of objective and other responses evolution during optimization process. These plots demonstrate very fast convergence to the quasi-optimal solutions for both optimized lay-up stacking. These solutions are not global optimum because they characterized by the different values of all responses.

The final features of all optimized "candidate" structures are present in **Figure 11**. All optimized lay-ups were ranked according to calculated responses. The optimized lay-ups (I $\phi_{in} = 30^0$) and (V $\psi = 30^0; \phi_{in} = 15^0$) provide minimal values of objective, but (II $\phi_{in} = 30^0$) provides the minimal total strain energy. Lay-up (V $\psi = 45^0; \phi_{in} = 15^0$) provides the greatest torsional stiffness, but its flexural rigidities are downscale. These considerations substantiate obligatoriness of multiobjective optimization at the design of load-carrying multilayered composite structures with orthotropic symmetry of the materials. The final decision can be made taking into account some constraints and requirements, for example, complexity of manufacturing, weight of ready structure, the natural vibration modes and eigenfrequencies and importance of a particular rigidity for the operability of the structure. An additional study of the strength of the composite layers according to the Tsai-Wu criterion [25] should be carried out at critical loads. Meanwhile, the used approach requires many tedious calculations, but allows us to obtain the visual substantial representations about chosen composite lay-ups for optimizing structures, and can be expanded to the composite structures with arbitrary number of arbitrarily oriented unidirectional layers.

7. Conclusion

This chapter studies a problem of lay-up optimization for a cantilevered long tube-like composite structure with varied cross-section that is manufactured by winding of glass fiber unidirectional tape. The optimized composite structure is the tube-like cantilever slender beam experiencing distributed bending and torsion forces. The multilayered composite material assumed and modeled as a single phase anisotropic elastic homogeneous continuum. We determine the elastic properties of laminates, which used in the modeled tube, taking as input data the mechanical properties of reinforcing fibers and epoxy resin to determine initially the elastic properties of the unidirectional lamina. For each accepted lay-up scheme and unidirectional prepreg orientation of the symmetric balanced laminate formation, the elastic moduli were determined independently by two methods: by the finite element method and on the base of the classical laminates theory.

The first stage of used optimization approach is based on the analysis of the angular distribution of all engineering constants of laminates. This analysis allows us to choose the small enough set of "candidate" lay-ups, which should be used at the modeling of the mechanical response of the studied structure at three different load scenarios. The higher level "candidates" were appointed for the final dynamic test, which includes applying full load to the selected structures and gives us the possibility to make the expert decision about final choice of quasi-optimal structure. The short discussion of the obtained results confirms necessity of multiobjective approach to the studied optimization problem, taking into account many requirements and constraints that allows to make the final choice of the best lay-up parameters.

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