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Konstrukcijska in geometrijska optimizacija spojev, narejenih iz laminiranih kompozitnih materialov

The Constructive and Geometrical Optimization of the Junctions in Structures Made from Laminated Composite Materials

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Porušni mehanizmi so za kompozitne materiale, še posebej za laminirane kompozitne materiale, dosti težji in zahtevnejši od porušnih mehanizmov pri homogenih in izotropnih materialih. Zaradi tega se trudimo, da bi imeli pri modeliranju in analizi le-teh krajevna napetostna stanja v conah, kjer nastajajo veliki napetostni gradienti. Predvsem v podpornih točkah, geometričnih prekinitvah, spojih itn. V primeru spojev je treba izboljšati konstrukcijsko in tehnološko rešitev, ki zagotavlja največjo mehansko trdnost, upoštevajoč interpretacijo med plastmi. Naslednji korak je v optimizaciji geometrijskih in konstrukcijskih konfiguracij samih spojev. Avtorji predlagamo metodologijo za geometrijsko in konstrukcijsko optimizacijo spojev in struktur narejenih iz laminiranih kompozitnih materialov. V tem prispevku je prikazanih nekaj primerov modeliranja z metodo končnih elementov za spoje v industrijskih primerih.

(Ključne besede: kompoziti laminarni, optimiranje, spoji, metode končnih elementov)

Failure mechanisms for composite materials and especially for laminated composites are different and more complex than for homogeneous and isotropic materials. This is why the modeling and analysis of such structures are done with the main aim being to determine the local stress states in the zones where high stress gradients occur, e.g., supports, points where loads are applied, geometric discontinuities, and junctions. In the case of junctions, one should elaborate constructive and technological solutions that ensure the maximum mechanical strength, taking into account the interpenetration between the layers. The next step is the optimization of the geometric and constructive configurations for the junctions. Here we propose a methodology for the geometrical and constructive optimization of the junctions in structures made from laminated composite materials. Some examples of modeling for junctions in industrial structures, using the finite-element method, are presented.

(Keywords: laminated composites, optimization, junctions, finite-element methods)

0 INTRODUCTION

Failure mechanisms for composite materials and especially for laminated composites are different and more complex than the ones for homogeneous and isotropic materials. That is why the modeling and analysis of these materials should be made with the main aim being to determine the local stress states in the areas with high stress concentrations, for example, supports, points where loads are applied, geometrical discontinuities, and junctions.

In the case of junctions, one should produce constructive and technological solutions about the interpenetration of the layers so as to ensure a better mechanical strength for the given loads. The next step is the optimization of the geometrical and constructive configurations of the considered junctions. Here we propose a methodology for constructive and geometrical optimization for junctions made from laminated composite materials. Some examples of finite-element modeling and analysis are presented for junctions belonging to process equipment.

1 EXAMPLES OF JUNCTIONS FOR STRUCTURES MADE FROM LAMINATED COMPOSITES

Some simple and frequently encountered junctions are presented in different constructive variants. For each one, depending on the functional, technological and economic factors, the optimum variant is chosen. In Fig. 1, four variants of a simple junction (variation of the external diameter from $2R_1$ to $2R_2$, with the internal diameter r) are presented for a tube manufactured from a composite material with six laminae (layers).

The following observations should be noted:

- the continuity of the laminae is not ensured for variant *a*;
- partial continuity exists for variant *b*;
- all laminae have continuity in variant *c*;
- the junction of the composite material with a homogeneous one is shown in variant *d*.

Different variants of a junction between a tube and a flange are depicted in Fig. 2. The tube has an external diameter $2R_1$, an internal diameter 2r, and the flange has a thickness h and an external diameter 2R. The composite material is made of three laminae for the tube and seven for the flange. One can see that in variant a where there is no interpenetration between the layers of the composite belonging to the flange and the tube (the flange is outside the tube and is glued with an adhesive), the mechanical strength of the structure is small. Delamination can occur for the external layer of the tube.

In Fig. 2, e and f, variants of the junction with one of the components made from a homogeneous material are shown.

For each of the above-mentioned variants, homogeneous elements for reinforcement may be introduced. For example, for an aluminum–resin composite material, a steel reinforcement is shown in black in Fig. 2, b–f.

For a more complicated junction, like the one between the cylindrical shell of a tank (with diameters $2R_1$ and $2R_2$) and a lateral nozzle (with diameters $2r_1$ and $2r_2$), five variants are presented in Fig. 3. Similar observations to those in the previous cases can be made. It is important to note variant c, in which a ring is used.

2 MODELING AND ANALYSIS OF JUNCTIONS

In the case of junctions, modeling and analysis have as the main goal a determination of the stresses in the layers and at the interface between the layers. If one uses the finite-element method,

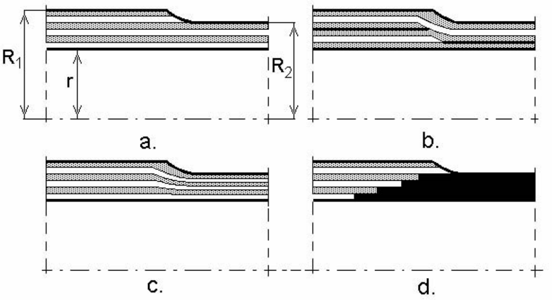

Fig. 1. *Variation of the external diameter of a tube*

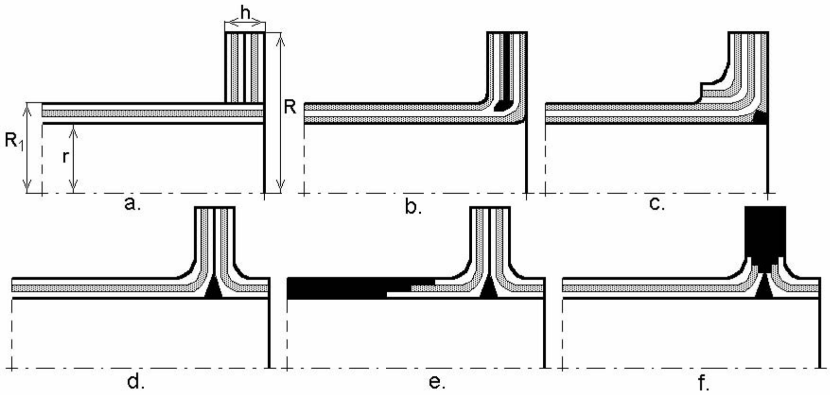

Fig. 2. *Junction between a tube and a flange*

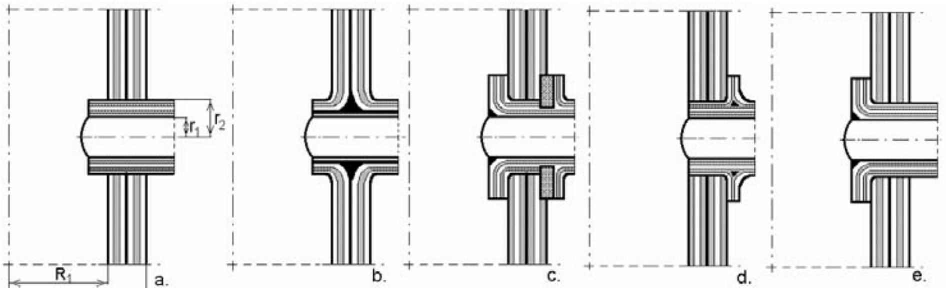

Fig. 3. *Junctions between a tank and a nozzle*

special elements for different types of composites are used.

A specific modeling, like for local problems, is necessary. This means that one should use a refined mesh in order to take into account the geometry and properties of each layer. In this way, information regarding the values of the interface stresses can be obtained, in order to assess any possible failure or delamination.

An example of finite-element modeling and analysis for the structure in Fig. 2,c is further presented in order to illustrate the previous assessments. The following dimensions were considered: $R_1 = 65$ mm, $r = 50$ mm, $R = 120$ mm, $h = 30$ mm, for an aluminum–epoxy-resin composite material. All the layers have a thickness of 5 mm. A steel ring was inserted (drawn in black in Fig. 4) in order to increase the strength and stiffness of the flange. The elastic constants are:

- $E = 70000$ N/mm^2, $G = 25000$ N/mm^2, $\upsilon = 0.35$ for aluminum
- $E = 2440$ N/mm^2, $G = 1200$ N/mm^2, $\upsilon = 0.46$ for resin
- $E = 2.1\cdot10^5$ N/mm^2, $G = 8.1\cdot10^4$ N/mm^2, $\upsilon = 0.3$ for steel.

An internal, uniform pressure of 5 N/mm^2 was applied to the tube. Constraints were applied on the frontal surface of the flange.

An axially symmetrical model was considered, using triangular elements. Each layer was separately modeled in order to introduce different elastic constants. The model has 243 nodes and 388 elements, and is shown in Fig. 5.

Some results of practical interest are shown in Fig. 6. The values of the von Mises equivalent stress σ_{eq}, the normal stress σ_y and the shear stress τ_{xy} were calculated in the nodes lying on the interface between two layers (drawn with a thick line).

The stresses were defined with respect to the global system of axes (Fig. 4). Using the values of these stresses, it is possible to assess whether the junction resists, or not, the applied loads, based on the specific criteria for composite materials [1].

3 METHODOLOGY FOR THE OPTIMIZATION OF THE JUNCTIONS IN STRUCTURES MADE OF LAMINATED COMPOSITES

In order to successfully optimize a junction in a structure made of a laminated composite material, some aspects should be taken into account:

1. The local character of the analysis is the fundamental problem in the case of junctions. That is why a sub-model or a sub-structure of the junc-

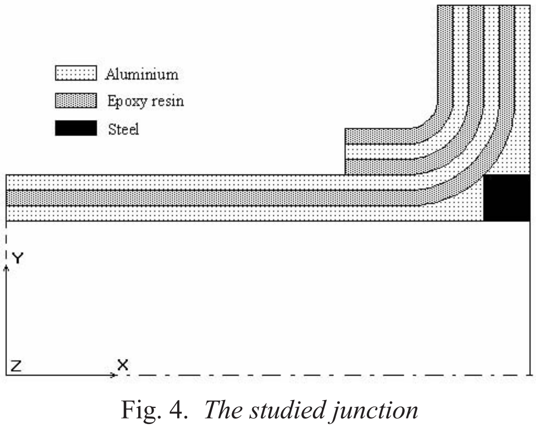

Fig. 4. *The studied junction*

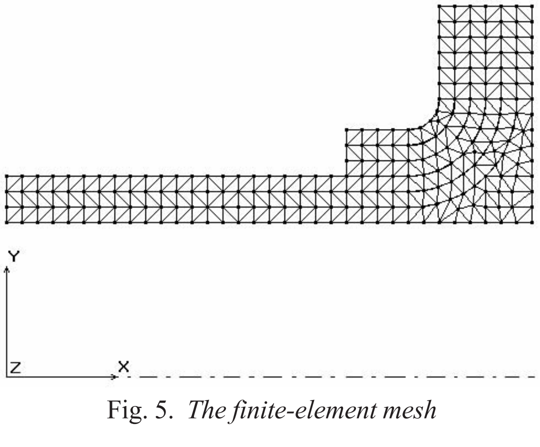

Fig. 5. *The finite-element mesh*

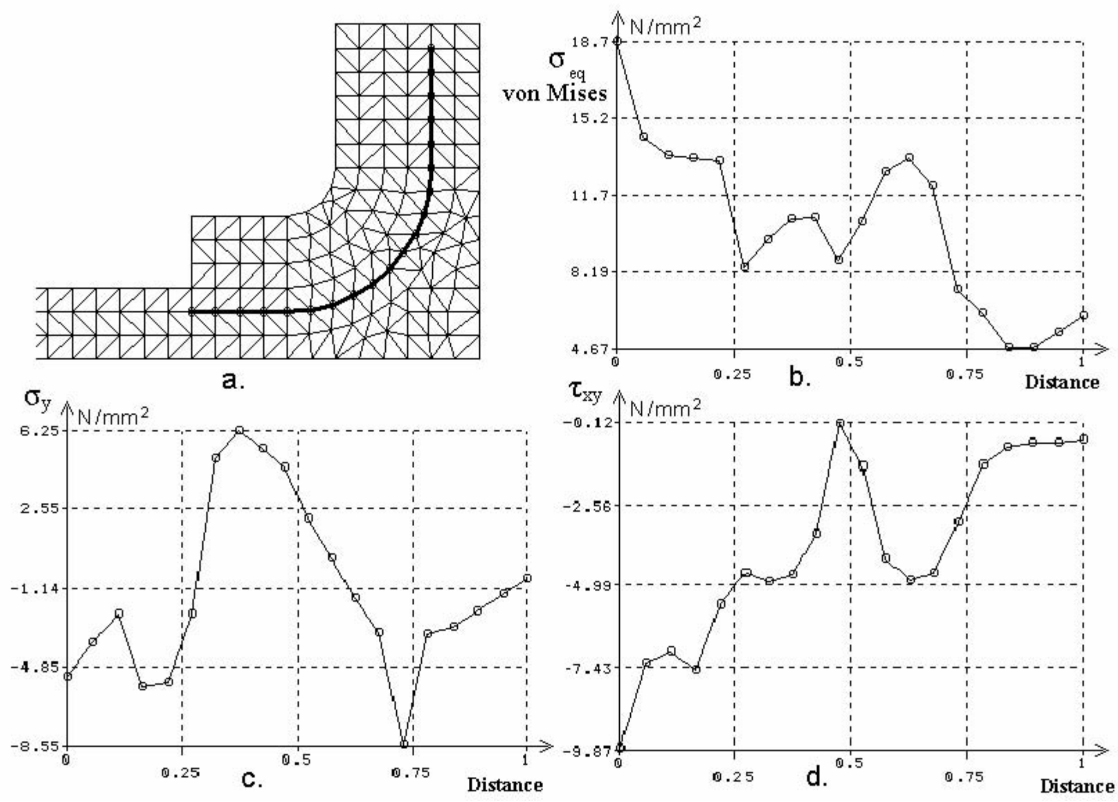

Fig. 6. *Results for the junction in Fig. 4*

tion is to be analyzed. This approach ensures the efficiency of the process;

2. A parametric mode is used, i.e., all dimensions will be denoted with letters. Some parameters will have constant values, others will be declared as *design variables*;
3. The constant values of the parameters must be established with discrimination in order to avoid a geometrical configuration with superposition, voids, distortions, etc;
4. The definition of the geometry (points, lines, surfaces, volumes) must be done so as to emphasize the different layers, because these layers are made from different materials. The results obtained following a finite-element analysis must give information regarding the *interface* stresses and strains;
5. The mesh must be obtained by generating the nodes and elements along each layer as distinctive groups of elements with different physical, mechanical and elastic properties.

All other aspects of the modeling, analysis and optimization are the usual ones for a finite-element analysis.

4 EXAMPLE OF THE OPTIMIZATION OF A JUNCTION

The variant of a junction between a tube and a cylindrical flange (Fig. 2, c and Fig. 4) was chosen in order to illustrate the above-mentioned optimization methodology. This junction is presented in Fig. 7, were three design variables were considered: H1, H2 and R1.

The composite material is aluminum–epoxy-resin, having the same elastic constants as in the previous example. The thickness of the layers were denoted as H1 and H2.

A constant internal pressure $p = 0.1$ N/mm^2 was applied to the tube.

An axially symmetrical model was considered, using triangular elements. Each layer was separately modeled in order to introduce different mechanical characteristics. The model has 1202 nodes and 2140 elements (Fig. 8).

The optimization function was the weight of the junction and the restriction was an imposed value for the equivalent von Mises nodal stress. Also, constant values were chosen

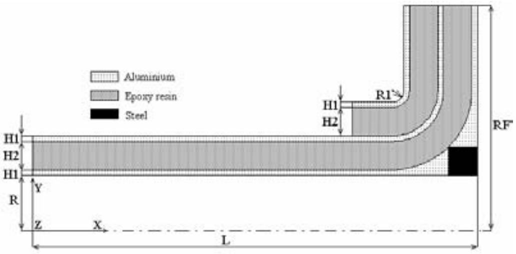

Fig. 7. *Constructive scheme of a tube-flange junction*

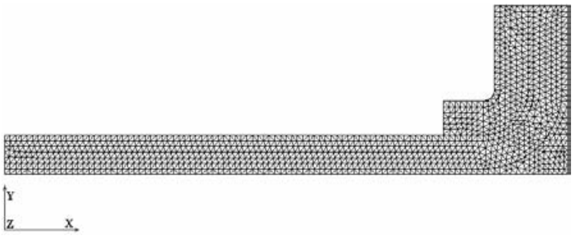

Fig. 8. *The finite-element mesh for the model in Fig. 7*

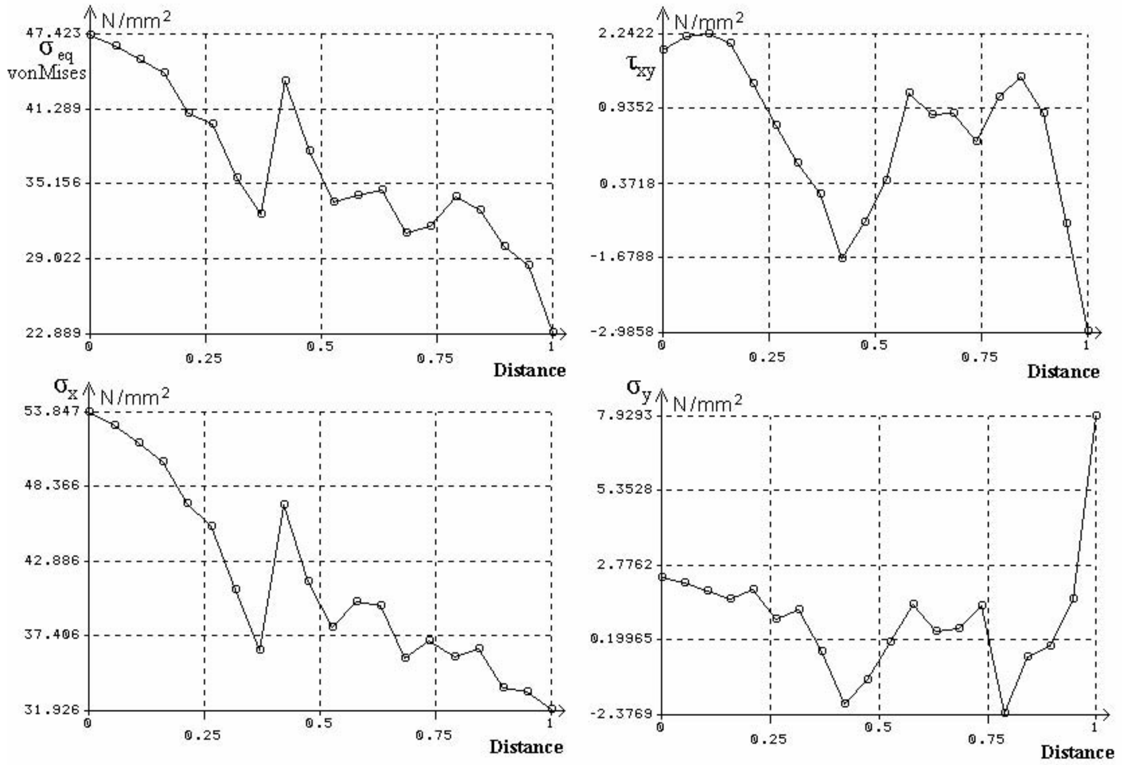

Fig. 9. *Results obtained for the junction from Figure 7*

for some parameters, i.e., R =50 mm, L = 4R, RF = 10R.

The following values for the design variables were obtained: H1 = 4.5 mm, H2 = 26.6 mm and R1 = 8.4 mm. The maximum value of the equivalent stress was 47.4 N/mm^2 and the weight of the junction was 156 N.

Some of the results are graphically presented in Fig. 9. In this figure the results were plotted for a part of a longitudinal line on the internal surface of the tube (starting from the middle to the flange surface).

The variations of the equivalent von Mises stress σ_{eq}, the normal stresses σ_x and σ_y and the shear stress τ_{xy} are plotted with respect to the global system of axes from Fig. 7.

5 CONCLUSIONS

A methodology for the optimization of junctions in structures made from a layered composite material is presented. Different types of junctions are presented, and the methodology is illustrated for one of these examples. Using this methodology one can obtain design variables with values that minimize an optimization function, for example, the weight of the structure, by imposing restrictions on the values of parameters such as the maximum equivalent stress.

The procedure can be successfully used in the design process, where all the aspects (constructive, technological, economic, etc.) must be taken into account.

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