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Numerical modelling of bolted composite joints. Bolts rigidity effect on normal stresses in the composite layers

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Abstract. Modern finite element programs have the opportunity to create finite element models (FEM) by "gluing" mismatched finite element meshes. This allows, in particular, to obtain relatively small 3D models of polymeric composite materials (PCM) in bolted connections for PC calculations, where the PCM in the hole zones is modeled layer by layer, and at some distance from them - approximately, according to the theory of the "effective module".

In previous model calculations of single-shear two-row bolted connection with PCM (contact task) with the detailed layer-by-layer modeling of the PCM structure in the hole zones, regularities were revealed for the distribution of contact forces in the bolt-hole surface contact, bolt stresses and near-contacting in the holes with the lateral surfaces of the bolts.

In the article, based on numerical calculations, the regularities of changes in normal stresses on the contact surfaces of holes in PCM, in layers with fibers oriented at 0 and 90 degrees, were found, depending on the rigidity of the bolts.

Keywords: numerical 3D modeling; PCM; Bolted connection; 3D model of PCM; FEM; PCM layers.

Introduction

The results of numerical modeling of the sample of bolted-type connection with PCM (Figure 1) are provided in [1-3]. Such samples are used to test the bolted connection with PCM for fatigue.

To simplify our terminology we further will use "sample" to denote a "sample of bolted-type connection with polymeric composite materials".

The sample consists of two PCM plates and a U-shaped beam made of aluminum alloy connected by four titanic bolts. The plates consist of 24 layers of carbon ribbon and carbon textile with the coupling agent.

We analyze the model of such sample imposing various initial bolt-hole gaps δ : 0, 10, 20 and 70 microns in diameter 5 mm. Any of these gaps was created by reducing the diameter of the bolt (Figure 2a [1]). In order to reduce the finite elements model, another head of the bolt was modeled instead of a nut threaded. This replacement could not prevent the achievement of the goal of the work. The force of screwing the bolted joint was modeled by reduction of the distance between bolt heads by a value of $\Delta = 0.08$ mm (Figure 2b [1]), which caused a force of about 4.5 kN in each bolt. Six structures of composite material named as PCM-0, ..., PCM-V (Table 4 [1]) were modeled.



Figure 1. Full geometric model of the test sample for fatigue characteristics of the bolted connection with PCM

Table 1

Structures of composite materials

Variant	Structure	Variant	Structure
PCM -0	[-45/0/45/90/-45/0/45/90/-45/0/45/90]s	PCM -III	[-45/45/90/-45/45/90/45/0/-45/0/90/0]s
PCM -I	[-45/90/45/0/-45/90/45/0/-45/90/45/0]s	PCM -IV	[-45/90/45/90/-45/90/45/0/-45/0/45/0]s
PCM -II	[-45/90/45/90/-45/0/45/90/-45/0/45/0]s	PCM -V	[-45/90/45/90/-45/90/45/0/-45/45/0/0]s

The sample is loaded with $N_x = 10$ kN tensile force.

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Detailed information on the created 3D models of the sample is given in [1].

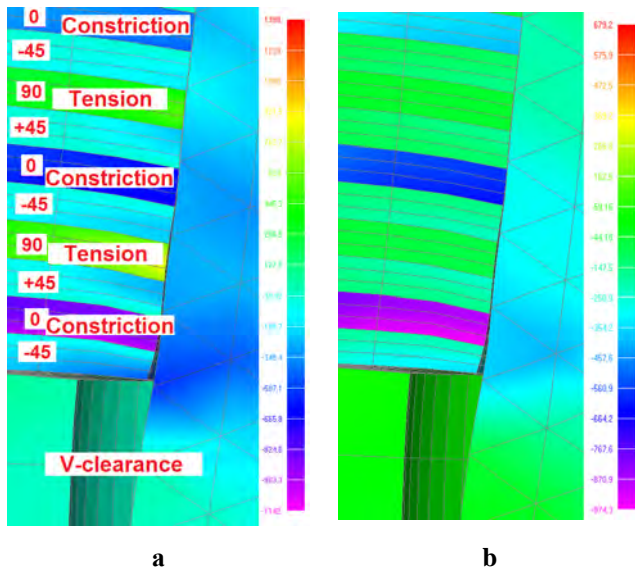


Figure 2. Stresses, MPa, in the contact areas of the holes of the PCM (plane dissection $Y=0$, the clearance bolt/hole $\delta=0 \mu\text{m}$, "animation", PCM-0):
a – σ_{11} [3], Fig.14-a; b – σ_x after recalculation to global coordinates

recalculation, the stress values in plies oriented at ± 45 and 90 degrees changed. In this connection, in comparison with [3], only the stress σ_x plots in Fig. 13-a changed. The graphs of these stresses, obtained after recalculation on the global X-axis, are shown in Fig.3.

It is obvious that the stresses in the layers arise under the tightening of the bolted joint and the main load N_x , as well as from adhesion to adjacent layers due to significant differences in the fibers orientation of the layers and the elasticity modules of the layers materials with three-dimensional orthotropy (see Table 3 in [1]).

However, as will be shown in this article, these factors have varying degrees of influence, and the rigidity of bolts also effect on stresses in layers.

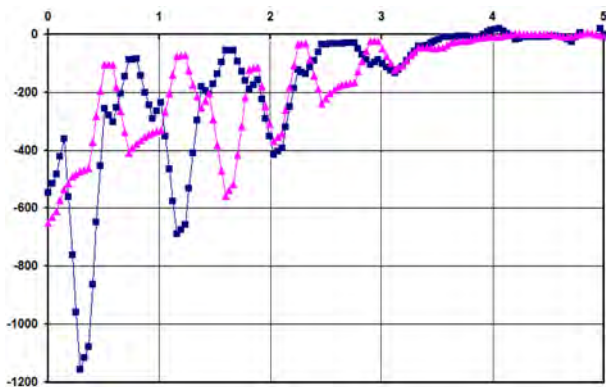


Figure 3. Stress σ_x graphs, MPa, along the line 1 (Fig.3-a from [3]) for the first hole in the PCM,
Clearance bolt / hole $\delta = 20 \mu\text{m}$, $N_x = 10 \text{ KN}$
(■ - PCM-0; ▲ - PCM-III)

calculations on the monitor or on the graphics, these stresses are recalculated into the nodes of the CE, also according to a linear law, i.e. possible nonlinearities are cut off. Therefore, instead of the zero value of the stresses on the free surface, one can see a nonzero value.

The aim of this analysis is to reveal the trends in the parameters affecting the stress-strain state (SSS) of the bolts and of the bolt-holes in the polymeric composite plates to find structures of the PCM with reduced values of the characteristics of SSS which determine the strength of the connection.

It was revealed that the most promising structure is the structure of PCM-III.

Next, for shortening, let's call "animation" the viewing of the calculation object in the deformed state with greatly enlarged deformations superimposed on the initial state.

For PCM in [3], it was pointed out that there were significant stress discontinuities between the layers. Fig. 2-a (Fig. 14-a in [3]) with significant "animation" shows images of stress σ_{11} distribution in PCM in contact areas (dissection plane $Y=0$, bolt / hole clearance $\delta=0 \mu\text{m}$) for PCM-0 structure. These stresses are derived by the Femap program in the directions of the main axes of the anisotropy of the material. It is these stresses that should be used in the strength criteria of PCM. And Fig. 2-b shows the results of the same calculation, but after recalculating the stresses in all layers of the PCM to the geometric axes of the sample (the X axis is directed along the sample, and the Z axis is vertical). During the

Recall that in a case of a contact of structures made of isotropic materials the compression zones are always formed under the contact surface. In these zones all the normal stresses are negative [4].

We note that a so-called edge effect in composite materials is observed [5], when the edges of the plates have locally perturbed state of stress due the load.

The emergence of this effect can be varied because it depends on the nature of the load and PCM structure.

The presence of stress discontinuities in the composites at the boundaries of the layers is a well-known fact [5]. In the holes this is of particular importance [6-10]. However, when using the average characteristics of the composite, discontinuities, which are natural, are not observed [11, 12].

In addition, we note that even in finite elements (CE) with quadratic approximation of displacements, the stresses are modeled by linear functions, and are calculated at the Gauss-Legendre integration points located inside the finite elements. To display the results of

Until now, the development of criteria for the strength of mechanical joints of composite materials, including bolts, has been very relevant [13]. However, for this it is still necessary to understand the degree of influence of various factors on the characteristics of the stress-strain state of composites in the zone of holes.

The purpose of this study is to identify the effect of bolt rigidity on the stress σ_x , σ_y and σ_z values in the PCM under the surface of the bolt-hole contact

To achieve the goal, in comparison with [1-3], additional numerical calculations were made.

Refinement of the finite element mesh in the bolts

To reduce the mesh-associated factors the refined FE mesh was generated in the bolts. The new mesh consists of higher density of hexagonal FE Parasolid CHEXA elements than one in the articles [1-3]. New mesh in the bolts was aligned with the FE mesh in the bolt-hole. In the initial state, each node of the bolt-hole surface corresponds to the appropriate node of the bolt surface.

Therefore, the accuracy of the solutions in the contact zone of the bolt – bolt-hole should be the best possible.

The results of calculations have not changed in comparison with those obtained on a coarser mesh of FE type Parasolid CTETRA in [1-3].

Normal stresses in the zone of the PCM holes from the screwing forces in the bolted joint

The calculation of $N_X = 0$ has shown (see. Figure 4) that the stresses in the top and lower parts of the PCM plates in the vicinity of the holes are different. We will analyze only the lower part, where the influence of the bolt head is not so large.

It was obtained (see Fig. 4-a, b) that there are tensile stresses directed along the fibers in the PCM layers oriented at 0 and 90 degrees only are caused by the tightening of the bolts ($N_X = 0$) at the exit of the layers into the hole, when the ribbon fibers are tangent to the hole surface. This is zone 1 (and others not marked in this way), where the fibers of the tape oriented at 90 degrees (here $\sigma_x \approx 0$, and $\sigma_y \approx (30 \div 50)$ MPa) are tangents to the surface of the hole, And this is zone 2, where the fibers of the tape oriented at 0 degrees ($\sigma_x \approx (30 \div 40)$ MPa, $\sigma_y \approx 0$) are tangent to the hole surface.

The slight differences of stresses value are apparently due to the different length of the PCM plate in these two directions. In zone 3, a part of the fibers of the fabric oriented at +45 degrees are tangent to the surface of the hole. The stresses $\sigma_x \approx \sigma_y \approx (5 \div 15)$ MPa are observed in this zone. Positive values indicate an increase in the diameter of the hole.

Figures 4-b,d shows images of stress σ_z distributions (directed vertically). Here the stress distributions are almost axisymmetric (relative to the axis of the hole), but there are also noticeable zones with local small excitations of compressive stresses (see Fig. 4a, c), and stress $\sigma_z \approx -(40 \div 45)$ MPa is in the lower part of the hole.

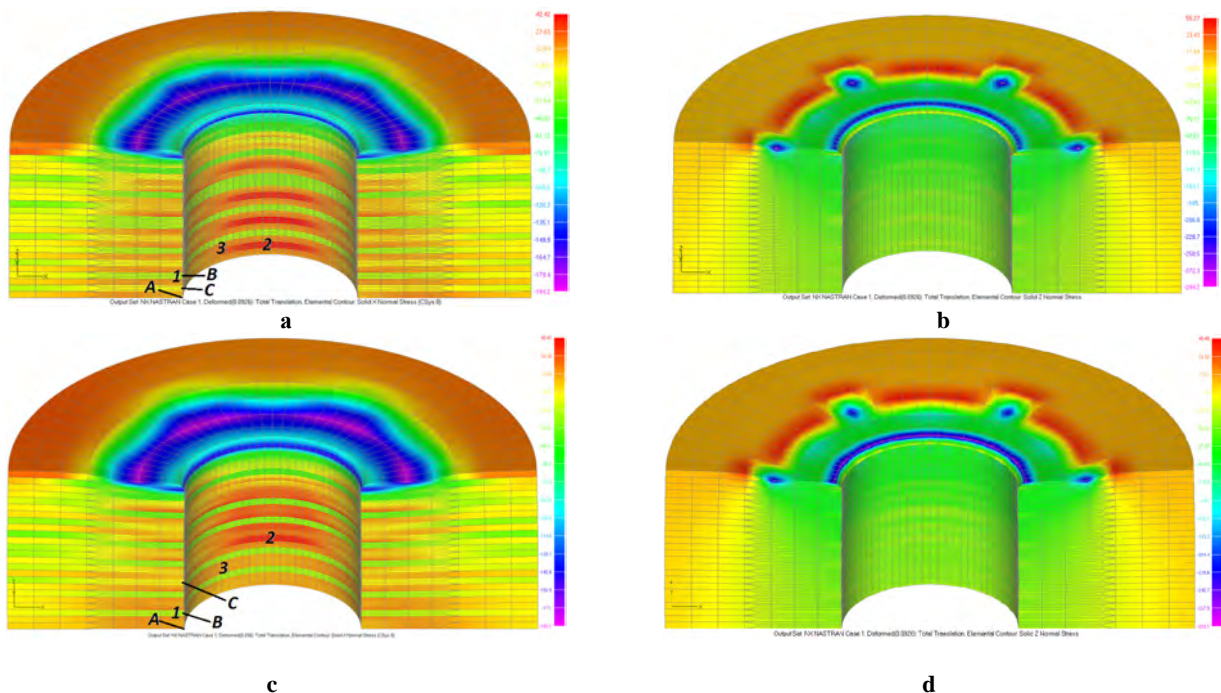


Figure 4. Stresses σ_x (a, c) and σ_z (b, d), MPa, in the contact areas of the PCM hole (plane dissection $Y=0$, $N_X = 0$, the clearance bolt /hole $\delta=0$ μm , PCM-0 (a, b), PCM-III (c, d), "animation")

Normal stresses after the addition of the tensile force of the specimen, with a change in the rigidity of the bolts

In the paper [14], it was proved by calculations that the bolt of a single-shear bolted joint always "works" not only on the shear but also on the bend.

Furthermore, it was found that when the sample is stretched by the force N_x V-shaped gap appears between the PCM bolt-hole surface and a bolt even in the absence of the initial bolt-hole gap ($\delta=0 \mu\text{m}$).

Fig. 2 shows this effect. In this figure, we can see that the surface of the hole does not remain cylindrical and contact surfaces of the bolt hole have a "wavy" appearance. This is because, in contact, the PCM plies oriented at 0 degree have a more rigid contact effect on bolts than plies with other angles.

Obviously, such geometric changes should depend on the bending rigidity of bolts.

The rigidity of bolts was artificially increased in numerical experiments to determine the dependence of the stress σ_x in these layers on the values of the bending of bolts.

The schematic sketches (Fig. 5) represent various models of connections that were studied. The U-shaped bar was removed and its action on the PCM plate was simulated by applying pressure on the lower surface of the PCM plate on the entire contact surface (the pressure field was "transferred" from the previous calculation using program tools of Femap).

First, bolts were rigidly fixed in the direction of the X axis in their lower parts, (on the lower heads (Fig. 5-a)), then their length was reduced twice from below, and also similarly fixed (Fig. 5-b, c).

Then the bolts were additionally rigidly fixed in the direction of the X axis in their upper parts, (on the upper heads (Fig. 5d)).

Finally, Young's modulus of the bolt material was increased by a factor of 10 (Fig. 5-e).

The obtained values of stress σ_x in the vicinity of the point B and C (Fig. 4-a,c) are presented in table 2 (structure PCM-0) and in table 3 (structure PCM-III). We used values in this table to plot the graph of the dependence of stress σ_x on value $s = u_B - u_A$. Value s is the relative horizontal displacement between points A and B shown on Figure 4a.

These relative displacements actually uniquely control the stiffness of the "bolt" model in bending. Measurements were made only for the first bolt, in which all the effects are most notable.

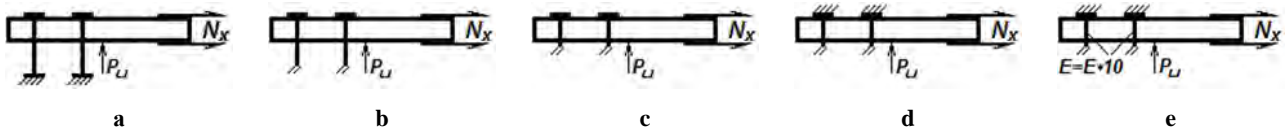


Figure 5. Schemes for changing the stiffness of sample bolts: a – the complete geometry of the bolts; b – bolts without lower heads; c – maximum shortened bolts; d – as (c) but with additionally fixed upper heads; e – as (d), but with an addition of 10 times Young's modulus of the bolt material

Table 2
Normal stresses in the vicinity of the point B and C (Fig. 4-a) of PCM plate at $N_x = 10 \text{ KN}$ and $\delta = 0$, structure PCM-0

Variant of the calculation scheme	s – relative horizontal displacement of points B and A, mm	Stresses at point B, MPa			Stresses at point C, MPa		
		$\sigma_x = \sigma_{22}$	$\sigma_y = \sigma_{11}$	σ_z	$\sigma_x = \sigma_{11}$	$\sigma_y = \sigma_{22}$	σ_z
a	0.0214	-113	570	-80	-1735	-25	-104
b	0.0189	-101	534	-66	-1578	-22	-91
c	0.0084	-51	401	-3	-894	5	-33
d	0.0053	-43	362	-16	-654	4	-41
e	0.0012	-41	328	-29	-539	-1	-45
e, but without P_U	0.0005	-28	261	-3	-516	7	-6

Table 3

Normal stresses in the vicinity of the point B and C (Fig. 4-a) of PCM plate at $N_X = 10$ KN and $\delta = 0$, structure PCM-III

Variant of the calculation scheme	s – relative horizontal displacement of points B and A, mm	Stresses at point B, MPa			Stresses at point C, MPa		
		$\sigma_x = \sigma_{22}$	$\sigma_y = \sigma_{11}$	σ_z	$\sigma_x = \sigma_{11}$	$\sigma_y = \sigma_{22}$	σ_z
a	0.0448	-157	772	-116	-698	-17	-93
b	0.0295	-141	716	-95	-672	-12	-79
c	0.0165	-77	522	-24	-566	3	-4
d	0.0098	-58	441	-1	-406	-1	4
e	0.0014	-53	379	-27	-484	-3	-23
e, but without P_C	0.0011	-37	303	-6	-483	4	-9

Figure 6 shows the graphs of the stress changes as a function of $s = u_B - u_A$ (bolt rigidity) illustrating the most important data of Table 2 and Table 3.

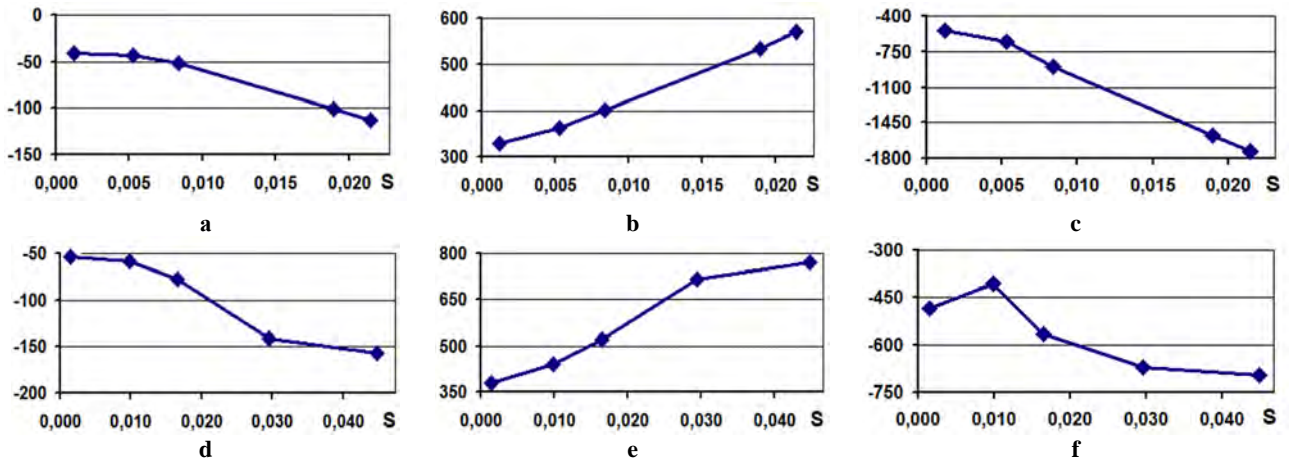


Figure 6. Normal stress σ_x (a, c, d, f), and σ_y (b, e), MPa, mm in the vicinity of the point B (a, c, d, f) and point C (b, e) Fig. 4a (PCM-0) and Fig. 4b (PCM-III) of the PCM plate, depending on $s = u_B - u_A$, mm, $N_X = 10$ KN, $\delta = 0$

These calculated data showed a significant but only partial dependence of the normal stresses on the rigidity of the bolt: with increasing stiffness, the stresses changed by two or more times, but the values obtained only from the screwing forces did not reach (the left part of the graphs in Fig. 6). Stresses are negative and insignificant.

There was only one possibility: the dependence of the normal stresses on the value of the load. You can even not make calculations, because it is clear that as the value N_X decreases, these stresses smoothly change from the corresponding value of Table 2 to the previously obtained values at $N_X = 0$.

Normal stresses only from the tensile force N_X

Another calculation of the sample was carried out in the absence of a pre-tightening force for the circuit (e). For scheme (e), it was assumed that the pressure from the channel is absent: $P_C = 0$. The obtained normal stresses are placed in the last lines of the tables 2 and 3.

Since for schemes (e) with P_C and without P_C the difference of the obtained stresses value $\Delta\sigma_x = -41 - (-28) = -13 \neq 0$ MPa, and $\Delta\sigma_y = 328 - 261 = 67 \neq 50$ MPa (PCM-0 structure), it can be concluded that three power factor: two forces of contraction of the packet (from two bolts) and force N_X influenced on the values of normal stresses at point

B of Fig. 4-a is nonlinear, although weakly. This is natural, because nonlinearity is an ordinary situation for contact problems, even with bodies of linearly elastic materials.

Conclusions

Based on the results of numerical modeling, the following main conclusions can be formulated:

- the lines of force are formed so that in the zone of the vicinity of the point B (Fig. 4a,c) (and in similar zones) for all considered loading cases and any real rigidity of the bolt, the stress $\sigma_y > 0$ will always be realized, and the point B is in contact with the lateral surface of the bolt slightly with insignificant force (see Fig. 2 and stress values $\sigma_x < 0$ in Table 2 and Table 3);
- the value of the stress in the vicinity of point B (and in similar zones) (Fig. 4a) depends weakly nonlinearly on all the force factors acting on the sample, and to a large extent are determined by the PCM plate structure;
- changes of σ_z with changes in the rigidity of the bolt (Table 2, 3) are manifestations of the classical edge effect in the composite, but all values of σ_z under the action of the screwing force are negative and it is not danger for composite material (in terms of the composite strength), if the screwing force is not excessive.

This line of research needs to be continued since the number of parameters of influence and subtle effects are much larger than that considered in this and other articles in which finite-element models of bolted connections with PCM were realized, as close to real ones.

Численное моделирование болтовых соединений из ПКМ. О влиянии жесткости болтов на нормальные напряжения в слоях композита

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Аннотация. В современных конечно-элементных программах есть возможность создавать, конечно-элементные, модели тел "склеиванием" несогласованных конечно-элементных сеток. Это позволяет, в частности, получать для расчетов на ПЭВМ относительно небольшие 3D-модели полимерных композиционных материалов (ПКМ) в болтовых соединениях, в которых ПКМ в зонах отверстий моделируется послойно, а за ними – приближенно, согласно теории "эффективного модуля".

В проведенных ранее модельных расчетах 3D-моделей образцов односрезного двухрядного болтового соединения с ПКМ (контактная задача) с подробным послойным моделированием структуры ПКМ в зонах отверстий были выявлены закономерности распределения контактных усилий в контакте болт – поверхность отверстия, напряжений в болтах и в приповерхностных зонах ПКМ, контактирующих в отверстиях с боковыми поверхностями болтов.

В статье на основе численных расчетов выявлены закономерности изменений нормальных напряжений на контактных поверхностях отверстий в ПКМ, в слоях укладки под 0 и 90 градусов, в зависимости от жесткости болтов.

Ключевые слова: численное 3D моделирование; ПКМ; болтовое соединение; 3D-модель ПКМ; МКЭ.

Чисельне моделювання болтових з'єднань з ПКМ. Про вплив жорсткості болтів на нормальні напруження в шарах композиту

Ю.М. Дифучин, К.М. Рудаков

Анотація. В сучасних скінчено-елементних програмах є можливість створювати скінчено-елементні моделі тіл "склеюванням" неузгоджених скінчено-елементних сіток. Це дозволяє, зокрема, отримувати для розрахунків на ПЕОМ відносно невеликі 3D-моделі полімерних композиційних матеріалів (ПКМ) в болтових з'єднаннях, в яких ПКМ в зонах отворів моделюється пошарово, а за ними - приблизно, відповідно до теорії "ефективного модуля".

У проведених раніше модельних розрахунках 3D-моделей зразків односрізного дворядного болтового з'єднання з ПКМ (контактна задача) з докладним пошаровим моделюванням структури ПКМ в зонах отворів були виявлені закономірності розподілу контактних зусиль в контакті болт - поверхня отвору, напружень в болтах і в приповерхневих зонах ПКМ, які контактують в отворах з бічними поверхнями болтів.

У статті на основі чисельних розрахунків виявлені закономірності змін нормальних напружень на контактних поверхнях отворів в ПКМ, в шарах укладання під 0 і 90 градусів, в залежності від жорсткості болтів.

Ключові слова: чисельне 3D моделювання; ПКМ; болтове з'єднання; 3D-модель ПКМ; МСЕ

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