COMPUTATIONAL AND EXPERIMENTAL RESEARCH OF BOLT JOINTS OF METAL AND COMPOSITE IN AIRFRAMES

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Abstract

The results of experimental research of double-shear bolted joints of composite and metal plates are presented in this paper. The test results of single-row, two-row and three-row joints are given. Computational study of the stress-strain state of the specimens was carried out on the basis of the finite element method. The results of experiments with the specimens and the results of modeling of the stress-strain state in the area of the hole during contact interaction with the bolt were used to select a failure criterion that adequately describes the failure of the joint of metal and composite. The results of computational research of the influence of design parameters on the strength of bolted joints of metal and composite are also presented in the paper.

1 Introduction

One of the main tasks of the composite material airframes development involves ensuring of the strength of the composite-to-metal joints. Such joints are used in areas with high local loads. They are usually carried out mechanically - by means of bolts, for reliability reasons. A feature of composite deformation materials is that they do not have a yield line and do not have the ability of load transfer, as observed in metal joints [1]. Fast response of composite materials to stress concentrators requires investigation of stress distribution directly in the vicinity of the concentrator and development of design criteria that take into account this feature of the material.

To analyze the strength of composite materials a large number of failure criteria was suggested [2], [3]. The criteria that take into account the stress concentration occurring in a zone of structural irregularity or defect are of interest for the purpose of our research. One approach to the computation of composites with concentrators in the form of cutouts or holes is to introduce a fictitious crack and apply the linear fracture mechanics approaches for strength assessment [3]. The introduced crack takes into account the actual area of cracking in a high-stress zone. Other approaches use the correlation between the strength of plain specimens and specimens with notches. The stress distribution analysis in the hole area shows that at the time of failure the tensile stresses σ are higher than the ultimate strength of the plain material σ_f in the interval (a; $a + r$), where a is the radius of the hole. The distance r to the point where at the time of failure the stresses reach the limit value for plain material σ_f weakly depends on the size of the hole. Therefore the value of r may serve as a constant for the material, which can be determined by the experiment-calculated approach. This criterion was first proposed by Whitney and Nuismer and proved to be the most appropriate and convenient for calculation of plates with holes [4]. There is also a modification of this criterion according to which the failure occurs when average tensile stresses in the interval (a; $a + r$) reach the ultimate strength of the plain material

σ_f. A more sophisticated version of the Nuismer criterion is to represent the characteristic dimension r as the hole radius function:

$$r = k\sqrt{a} \qquad (1)$$

where k is the coefficient to be selected on the basis of several experiments with different radiuses of the hole [3].

The Nuismer criterion is in good agreement with the experimental data in the case of unloaded hole and is easy to use. In the work presented here this criterion workability for the design analysis of the composite joints specimens test results was investigated [5].

2 Experimental Analysis Data of Bolted Metal-Composite Joints Specimens Strength

For the investigation we collected and analyzed the strength test data of bolted joints specimens of carbon fibre reinforced plastic plates with metal plates.

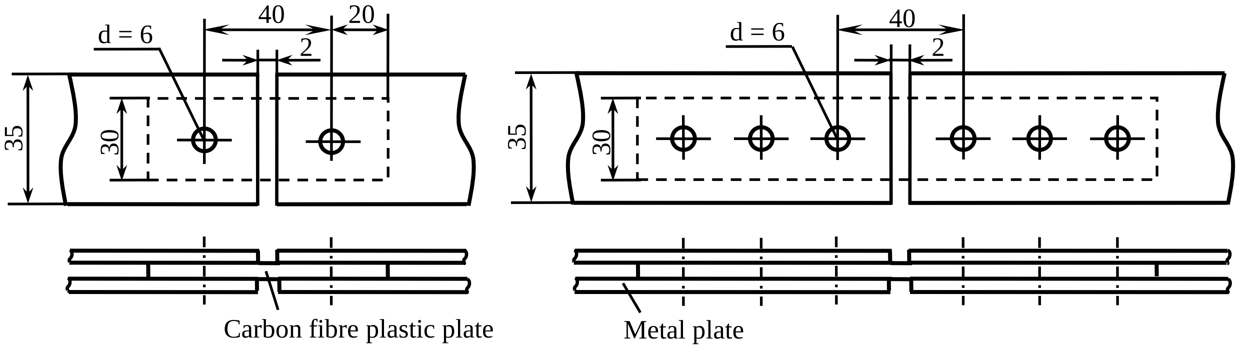
The specimens of double-shear bolted joints of carbon fibre plastic plates KMKU 3 mm thick with plates from D16ATV 3 mm thick were tested in SibNIA. The specimens simulated two types of joints – single-row and three-row with bolts diameters of 6 mm (Fig.1). The bolts made of steel 30XGSA were installed with the tightening torque M ≈ 4,9 N·m. Ply lay-up in the composite plate was as follows: [0°/±45°/0°/90°/0°/±45°/90°/0°/0°/±45°/0°/90°/0° /±45°/0°/90°/0°/±45°/0°]. The first and the last layers of the composite are of glass fiber plastic KMKS-2M.120.T10.37, the rest are of carbon fibre plastic KMKU-2M120.E01.45. Properties of laminas are shown in the Table 1.

Table 1 Properties of Laminas

	KMKU - 2M120.E01	KMKS - 2M120.T10	CYCOM 977-2
δ, mm	0,12±0,01	0,25±0,01	0,197
σ^t_{1f}, MPa	883	549	2629
E^t_1, GPa	113	23,5	164
σ^t_{2f}, MPa	42	382	86,4
E^t_2, GPa	8,09	21,6	8,05
ν_{12}	0,29	0,229	0,322
σ^c_{1f}, MPa	883	549	1534
E^c_1, GPa	108	24,5	134
σ^c_{2f}, MPa	115	422	213
E^c_2, GPa	8,83	21,6	8,54
τ_{12f}, MPa	118	108	112
G_{12}, GPa	2,94	2,94	4,37

The failure of all specimens was the same – by the tension failure of the carbon fibre plastic plate in the loaded hole (Fig. 2.a), while the residual elongation of the unfractured holes was not observed. The failure load of specimens was determined in tests and a record of dependence of metal plates free end faces mutual displacement was carried out. Stiffness of the unit bolted-type connection was determined from experimental data on the single-row joint specimen sheets displacement, it was equal to C = 24 810 kN/m.

The single-row, two-row and three-row bolt joints specimens of the composite plates



a) b)

Fig.1 The Specimens of Double-Shear Bolted Joints of a Composite Plate with Metal Plates: a) Single-Row Joint; б) Three-Row Joint made of carbon fibre plastic CYCOM 977-2 were tested in TsAGI. Ply lay-up was as follows: $[+45/0/-45/0_2/90/0_2/-45/0/+45]_3$. The thickness of the lamina $\delta = 0{,}197$mm, the nominal thickness of the specimen from 33 laminas $t = 6{,}5$ mm. Properties of the lamina CYCOM 977-2 are shown in the Table 1.

The composite plates in the single-row joint specimens were cut along the direction $\alpha = 0^{\circ}$. Here α is the angle between the specimen longitudinal axis and the composite plate maximum stiffness direction. The specimens of the composite plate with different width – 12mm, 15 mm, 18 mm, 24 mm, 30 mm – were tested. The failure mode of composite is the elongation of the hole with the carbon fibre plastic surface layer separation (Fig. 2b), sometimes with the bending of bolts. The failure load of specimen on bearing failure was determined in the tests.

The specimen of two-row joint of composite plates made of carbon fibre CYCOM 977-2 and steel plates is shown in Fig. 3. Two-row and three-row joint specimens were tested with loose bolts and different distances of the bolt setting (18 mm, 24 mm, 30 mm). The composite plates in the joint specimens were cut along the direction $\alpha = 0^{\circ}$ and $\alpha = 90^{\circ}$.

The failure mode of specimens was various. For the specimens with α = 90° the failure by the tension occurred in the most loaded hole, like in the specimens from KMKU (Fig. 2.a). In the specimens with α = 0° the bearing failure occurred (Fig. 2c), as well as the bearing failure with a shear and a tension failure of a specimen half (рис. 2d), plastic bending of bolts and in some cases bolt shearing in two planes. For the specimens with α = 0°, at the near to failure loads a considerable increase of the joint compliance occurs, which can be attributed to a sharp increase of the mounting holes elongation associated with the bearing failure. Dependences for the single-row joint specimens have a similar nature. Bearing failure of the holes proved to be critical for these

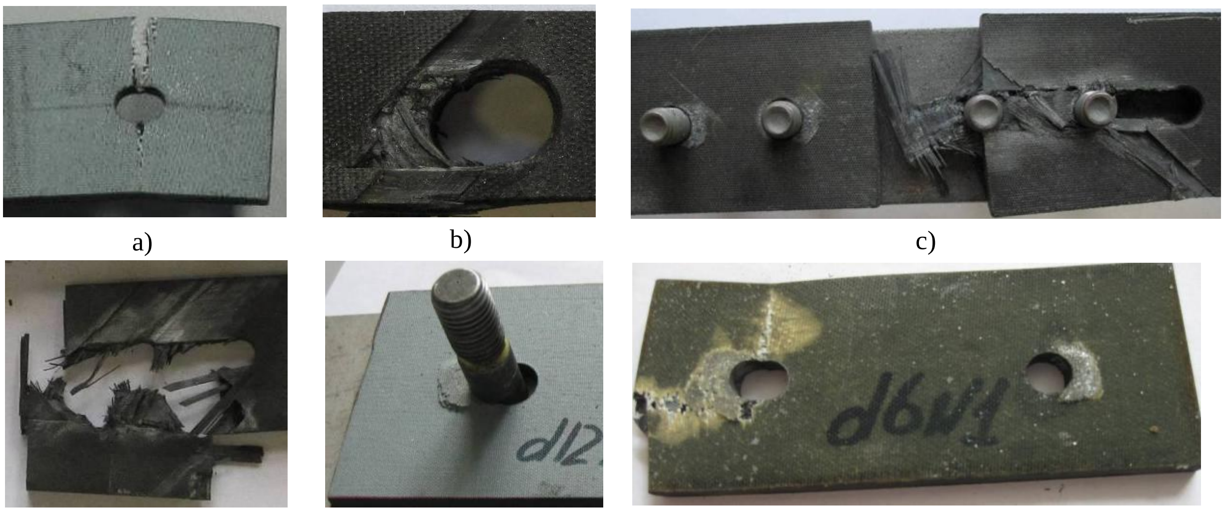

a) b) c)
d) e) f)

Fig. 2 Failure Modes of Specimens

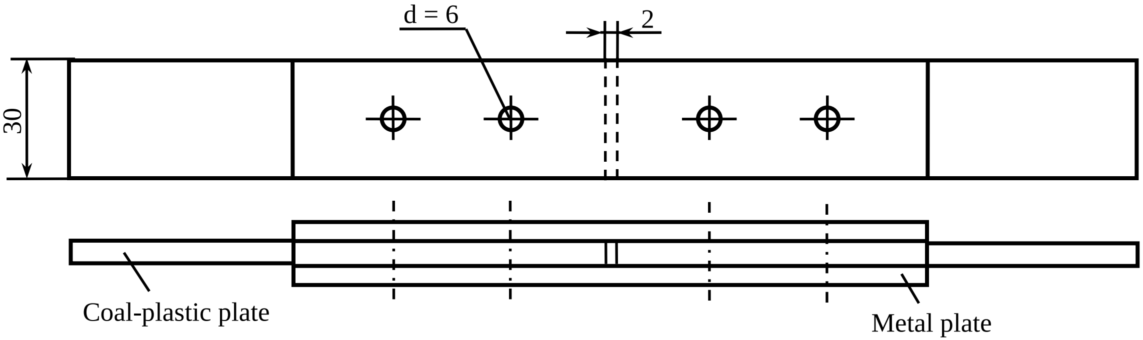


Fig. 3 The Specimens of Two-Row Joint

specimens. It should be noted that the failure load turned out to be almost independent of the bolt spacing.

Within the frame of this work the test of the specimens of bolted joint of composite plates KMKU with the plates from the alloy D16T was carried out. The composite plate consisted of 32 laminas with the following ply lay-up: [0º/±45º/0º/90º/0º/±45º/90º/0º/±45º/90º/0º/±45º/0º/90º/0º/±45º/0º/90º/0º/±45º/0º/90º/0º/±45º/0]. The first and the last laminas were made of the glass fibre plastic KMKS, the rest 30 were made of the carbon fibre plastic KMKU. The properties of laminas are shown in the Table 1. Two groups of specimens were tested: with the bolt diameters of 6 mm and 12 mm (Fig. 4). The specimens were cut and tested in the direction α = 0º. One specimen from each of two groups was tested without bolt tightening. The specimen with the bolt $d = 12$ mm was fractured by bearing failure of the holes, in the area of the holes a lamination and a shear of the material in the area of the contact with the bolt occurred (Fig. 2e). For the specimen with the bolt $d = 6$ mm in one of the holes there was a fracture of the mixed type: a cleavage tension failure (Fig. 2f). There is a residual elongation in the second hole. The material in the area of the contact with the bolts also has zones of lamination and shear. Two specimens of each size were tested with bolt tightening. The specimens fracture occurred by the tension failure in the hole.

3 Experimental Data Analysis

The summarized results of tests are presented in table 2. The following notations are used in the table: n – a number of fastener rows in a specimen, t_c – a composite plate thickness, d – a bolt diameter, Δ — elongation of the hole ($\Delta = d_{\max}/d$), σ^t_f – estimated tensile strength, $\sigma_{br\,f}$ – ultimate bearing strength for the loose bolt, $\sigma_{net} = P_{\max}/F_{\text{net}}$; $\sigma_{br} = P_{\max}/F_{\text{br}}$, where $P_{\max}$ – is a failure load (average for the group of specimens).

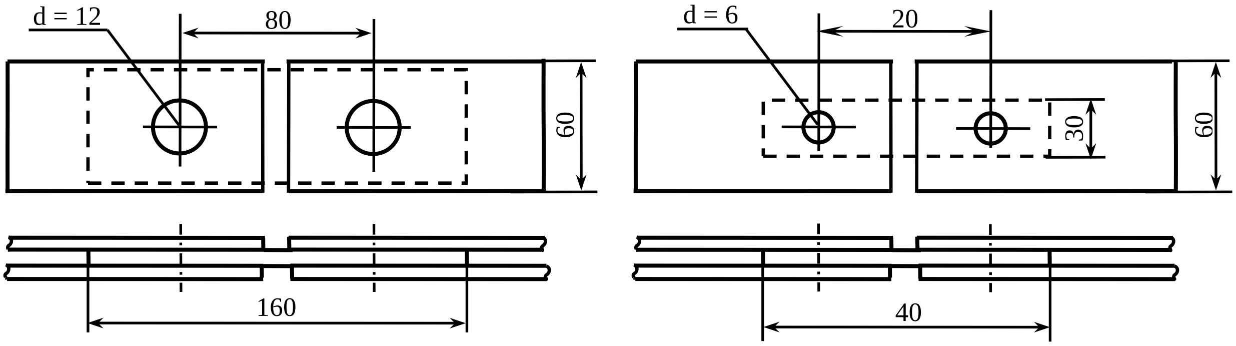


Fig. 4 The Specimens of Single-Row Joint

Table 2 Test Results of Double-Shear Bolted Joints of Coal-Plastic and Metal

Laminate	σ^t_f, MPa	$\sigma_{br\,f}$, MPa	n	d, mm	t_l, mm	M, N·m	σ_{net}, MPa	σ_{br}, MPa	Δ, %	Failure mode	α, º
CYCOM	1554	549	1	6	6,5	0	–	549	19…30	Bearing	0
CYCOM	1554	549	2	6	6,5	0	424	848	–	Mixed	0
CYCOM	1554	549	3	6	6,5	0	584	778	–	Mixed	0
CYCOM	444	–	2	6	6,5	0	293	585	–	Tension	90
CYCOM	444	–	3	6	6,5	0	316	421	–	Tension	90
KMKU	372	–	1	6	3,14	4,9	202	809	0	Tension	0
KMKU	372	–	3	6	3,14	4,9	305	407	0	Tension	0
KMKU	360	523	1	6	4,9	0	178	594	8	Mixed	0
KMKU	360	523	1	12	4,9	0	138	523	30	Bearing	0
KMKU	360	523	1	6	4,9	9,81	195	843	0	Tension	0
KMKU	360	523	1	12	4,9	58,8	183	745	0	Tension	0

In general, the results presented in the Table 2 give a varied presentation. However some qualitative conclusions can be done which are of interest to develop the design analysis criteria:

- When the composite plate fracture by the tension failure occurs in the loaded hole there is no distinct yield point area on the diagrams of dependence of the connectable plates relative displacement from the load. There is no residual elongation and lamination/shear of the material in the area of the contact with the bolt. A failure occurs when $\sigma_{net}/\sigma_f > 0{,}5$.
- The bearing stress at which a lamination/shear of the material in the composite plate takes place is highly dependent on the bolt tightening. It is minimal in the presence of the clearance between connectable plates, increases with the clearance adjustment and increases with the bolt tightening.
- On the mixed fracture modes the composite failure load is preceded by the residual elongation which is accompanied by the lamination/shear of the material.
- Not only ply lay-up and the load direction influence the laminate failure mode but the bolt tightening as well.
- During the test of specimens made of KMKU the scale effect influence upon the joint strength was insignificant: with the doubling of the hole diameter (from 6 mm to 12 mm) the failure stresses in the net section decreased as much as 6…7%, which is comparable to the experimental data accuracy.

4 Stiffness and Strength Calculation of the Composite Material Specimens

Elastic properties for the computaional analysis of the specimens’ stress state and strength were determined by calculation basing on the passport data of laminas. The calculation was carried out under the assumption of two-dimensional stress state implementation in the layer.

The calculated elastic properties of the laminates are presented in the Table 3. To calculate the strength properties of the laminate the Norris (2), Azzi-Tsai (3), Yamada-Sun (3) criteria were used:

$$\frac{\sigma_1^2}{\sigma_{1f}^2}+\frac{\sigma_2^2}{\sigma_{2f}^2}-\frac{\sigma_1\sigma_2}{\sigma_{1f}\sigma_{2f}}+\frac{\tau_{12}^2}{\tau_{12f}^2}=1, \qquad (2)$$

$$\frac{\sigma_1^2}{\sigma_{1f}^2}+\frac{\sigma_2^2}{\sigma_{2f}^2}-\frac{\sigma_1\sigma_2}{\sigma_{1f}^2}+\frac{\tau_{12}^2}{\tau_{12f}^2}=1, \qquad (3)$$

$$\frac{\sigma_1^2}{\sigma_{1f}^2}+\frac{\tau_{12}^2}{\tau_{12f}^2}=1, \qquad (4)$$

The values of ultimate stresses for the laminates in the test specimens are shown in Table 4. For the estimated strength at failure of the composite plates the least values obtained from the Azzi-Tsai criterion were taken.

Table 3 Elastic Properties of Laminates

	KMKU 24 laminas	CYCOM 977-2	KMKU 32 laminas
E_x, GPa	48,6	101	47,2
E_y, GPa	33,5	34,8	35,7
G_{xy}, GPa	13,0	18,0	13,7
ν_{xy}	0,351	0,437	0,344
ν_{yx}	0,242	0,150	0,260

Table 4 Strength Properties of Laminates

	KMKU 24 laminas	CYCOM 977-2	KMKU 32 laminas
Norris			
σ_{xf}, MPa	378	1631	365
σ_{yf}, MPa	256	494	271
τ_{xyf}, MPa	203	391	214
Azzi-Tsai			
σ_{xf}, MPa	372	1554	360
σ_{yf}, MPa	245	444	264
τ_{xyf}, MPa	196	338	207
Yamada-Sun			
σ_{xf}, MPa	380	1628	370
σ_{yf}, MPa	262	555	279
τ_{xyf}, MPa	206	341	218

The calculation of elastic and strength properties was checked by comparison of the calculated characteristics with the experimental data. The test was carried out for the carbon fibre plastic of KMKU. The composite plate contained 32 laminas.

The following data were obtained in the test: tensile strength $\sigma^{t}_{f} = 355$ MPa, compressive strength $\sigma^{c}_{f} = 406$ MPa, tensile modulus $E = 44{,}4$ GPa.

Corresponding calculated values and the ratio of the calculated value to experimental one in brackets are presented below: $\sigma^{t}_{f} = 360$ MPa (1,013); $\sigma^{c}_{f} = 367$ MPa; $E_x = 47{,}2$ GPa (1,063).

Calculated and experimental values are in good agreement; the error does not exceed 10%.

5 Computational Investigation of the Local Stress State of the Specimens

The stress distribution in the area of the hole of the composite plate under the contact interaction with the bolt is computationally determined in the work. The computational investigation results were used to check the Nuismer criterion workability for loaded holes. It should be reminded that according to this criterion the failure of the composite specimen occurs when stresses reach the limit value at a certain distance from the hole edge characteristic for the given material. According to [3] for the holes with the diameter of 6 mm the value r_0 was assumed to be 1 mm, for the holes with other diameters the relation (1) was used.

The computational investigations were carried out on the basis of the finite element method. The task of the stress state in the bolt joint of composite and metal definition was solved in two stages. At the first stage the load distribution between bolts were calculated using two-dimensional models (Fig. 5). At the second stage the stress distributions calculation in the vicinity of the loaded hole was carried out. For this purpose three-dimensional models of the contact interaction of the orthotropic plate with the bolt were used (Fig. 6). The elastic properties included into the model were equal to the characteristics of the laminate (Table 4). Stiffness of the springs simulating bolts was adopted according to the test data of specimens of the single double-shear bolting.

According to this scheme the specimens from the carbon fibre plastic of KMKU and CYCOM 977-2 were calculated. With the purpose of checking the calculation error by the two-stage scheme for the specimens from the carbon fibre plastic of CYCOM 977-2 the stress calculation on complete three-dimensional models was carried out. Values of the error on the execution of calculation by the two-stage scheme are presented in Table 5. The results of comparison show a validity of the stress calculation and an operability of the simpler two-stage scheme of calculation.

For the stress calculation of the single double-shear bolting of the composite plate

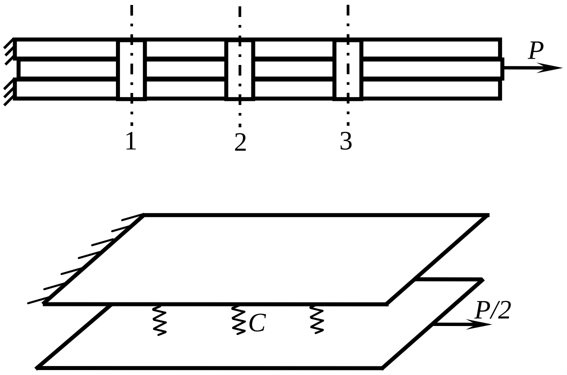


Fig. 5 Model for Determination of the Load Distribution between Bolts

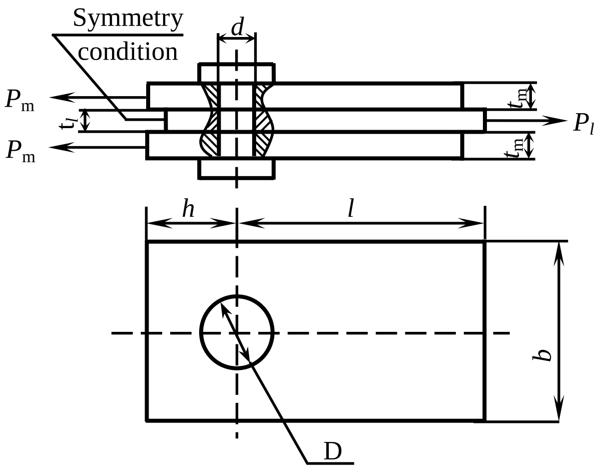


Fig. 6 Model for Determination of the Stress Distribution in the Vicinity of the Loaded Hole

from the carbon fibre plastic CYCOM 977-2 and steel plates a complete model of the specimen was used. Calculations were carried out for the specimens with the various widths of the composite. Calculation results were summarized in Table 6, where the values of σ_1 were taken at the characteristic distance r_0 =1mm from the hole contour.

Table 5 Calculation Error of the Two-Stage Scheme

α,°	Two-row joints	Three-row joints
0	-3,2%	-3,9%
90	-3,7%	-5,9%

The stress calculation of specimens of the single-row bolt joint of the composite plate from the carbon fibre plastic KMKU with 32 laminas was carried out for two cases considered in the experiment: with and without the bolt tightening.

The results of all calculations are presented in Table 7, where the following notations are used: M – tightening torque; σ_1 – first principal stresses at the characteristic distance; ε — estimation error of the failure load according to Nuismer criterion.

The calculation results show that the selected criterion gives results acceptable for practice in the case of the composite failure by tension and may be recommended for use. In the case of bearing failure, cut or shear it gives unacceptably overestimated strength assessment. For the specimens of these failure modes an attempt was made to find dependence between compression stresses in the area of the contact during the failure load and strength characteristics of the laminar, but it was not successful. This phenomenon is probably related to strength properties of the binder between laminas. Stress state simulation showed that in the area of the contact with the bolt through the thickness of the plate tensile stresses occur, comparable with the ultimate tensile strength of the binder. These stresses are most dependent on the tightening torque of the bolt, which according to experimental data strongly influences the ultimate bearing failure strength of the composite plate. For the research in this direction the experimental data on the composite plate thickness strength are necessary. Such data obtaining requires special specimens and devices, which is not included in the frame of this work and is the subject of our further research.

Table 6 Calculated Stress for the Single Double-Shear Joint

Width of the laminate, mm	12	15	18	24	30
Failure load, kN	20,7	21,1	21,4	20,7	22,9
σ_0, MPa	547	442	391	318	325

Table 7 Computational Results of Research of Double-Shear Bolted Joints of Coal-Plastic and Metal

Laminate	n	d, mm	t_l, mm	r_0, mm	M, N·m	σ_1, MPa	$\sigma_{\text{в}}^{+}$, MPa	ε, %	Failure mode	α, °
CYCOM	1	6	6,5	1,0	0	547	1554	- 64,8	Bearing	0
CYCOM	2	6	6,5	1,0	0	654	1554	- 58,0	Mixed	0
CYCOM	3	6	6,5	1,0	0	842	1554	- 45,8	Mixed	0
CYCOM	2	6	6,5	1,0	0	468	444	+ 5,41	Tension	90
CYCOM	3	6	6,5	1,0	0	484	444	+ 9,01	Tension	90
KMKU	1	6	3,14	1,0	4,9	370	372	- 0,5	Tension	0
KMKU	3	6	3,14	1,0	4,9	436	372	+17,2	Tension	0
KMKU	1	6	4,9	1,0	0	289	360	- 19,7	Mixed	0
KMKU	1	12	4,9	1,4	0	314	360	- 12,7	Bearing	0
KMKU	1	6	4,9	1,0	9,81	385	360	+ 6,9	Tension	0
KMKU	1	12	4,9	1,4	58,8	354	360	- 1,7	Tension	0

6 The Influence of Design Parameters on the Strength of Bolt Joints of Metal and Composite

When designing the construction of composite and metal joints it is important to know the influence of design parameters (hole diameter, thickness of the joined parts, location of the holes, bolts tightening, etc.). The results of computational research of the influence of design parameters and loading parameters on the stress state of the composite plate are presented in the work.

The influence of the bolted joint parameters on the stress state in the vicinity of the loaded hole of the composite plate was investigated on the base of the finite element method on the model problem. The problem design model is shown in Fig. 6. The material of the composite plate is the carbon fibre plastic Cykom 977-2. The properties of the lamina are presented in Table 1. The bolt diameter d was varied in the tasks, which was connected with the other model's dimensions in the ratios: $t_{\text{к}}/d = D/d = h/d = l/h = 2$. The load ratio influence on the metal plate – P_{m} and the composite plate – P_l was also investigated. Various ratios $2P_{\text{m}}/P_l$ were specified, changing the load on the metal plate P_{m}. The summarized data of computing of stress concentrations on the loaded hole edge are presented in Fig. 7.

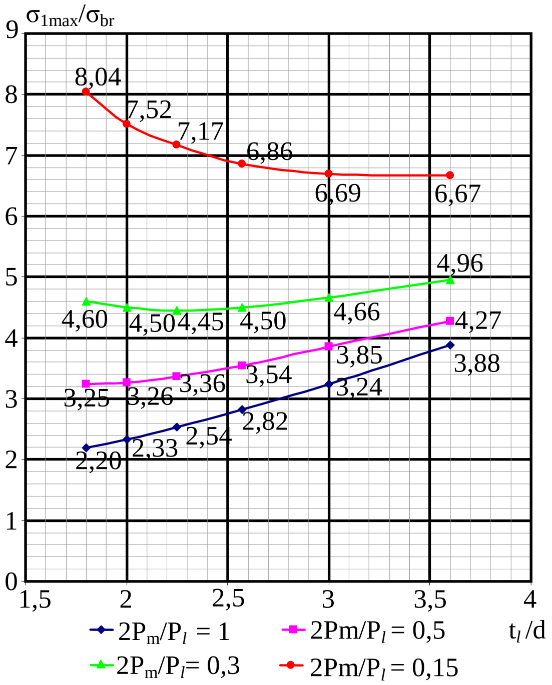


Fig. 7 Dependence of the Stress State on the Hole Edge on Design Parameters and Load

In some cases connectable parts are made with the bevel for the joint bolts loads balancing. The design scheme of the model problem for the study of the plates' bevel influence on the stress concentration is presented in Fig. 8. The elastic behaviour of the materials was the same as in the previous task. The stressed state at the hole in the plate with the bevel was compared with the stressed state of the hole in the flat plate. The parametric calculation was performed for the case $t_{\text{m}} = 8$ mm, $t_l = 36$ mm for the three diameters of the bolts: d = 12 mm; 16 mm; 20 mm for different values of the parameter $2P_{\text{m}}/P_l$. The calculation showed that in the joint with the bevel the stress concentration is higher. The bevel effects the stress concentration the stronger the higher is the bearing force of the bolt (the ratio $2P_{\text{m}}/P_l$) and the greater is the ratio t_l/d. Thus three-row bevel joints are more effective than two-row ones, as they have smaller ratio $2P_{\text{m}}/P_l$ in the design section.

The joint strength is essentially dependent on the bolts tightening. The design model shown in Fig. 6 was used to investigate the influence of tightening on the stress concentration on the loaded holes edges. The

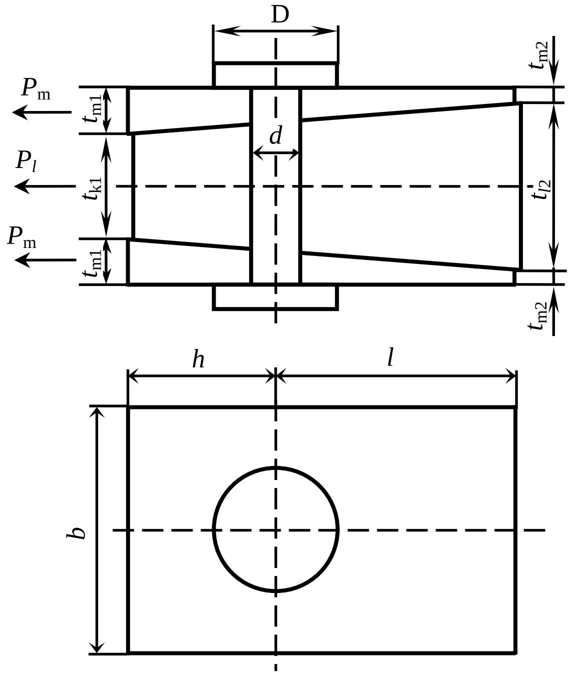


Fig. 8 Model for Determination of the Stress State of the Joints with Variable Thickness

dependence of maximum tensile stresses at the hole edge $\sigma_{t\ max}$ from the value of the bolt load and the bolt tightening force – P_t is shown in Fig. 9, a. Here P_f is the failure tensile load for the bolt. It is seen that with the increase of tightening the dependence $\sigma_{t\ max}$ from the joint load decreases. At the same time we can assign a threshold value of the bolt load up to which $\sigma_{t\ max}$ is independent of the bolt load. The stronger the bolt is tightened, the higher the threshold value.

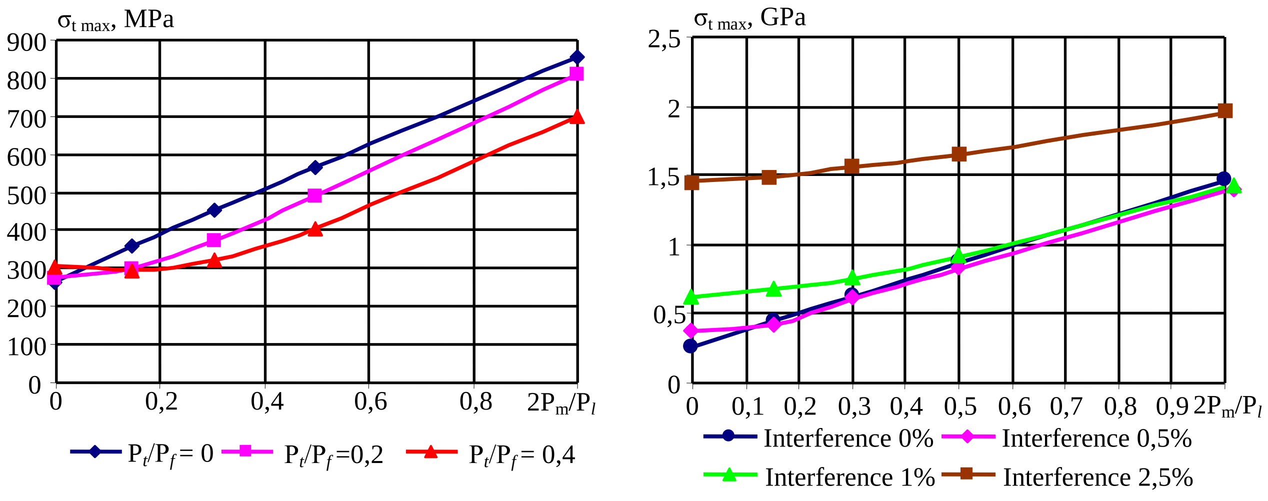
Radial interference is an effective means to reduce the dependence of the stress concentration on the holes edges in bolted joints from the external load. To investigate the influence of interference the same design model is used that in the investigation of the influence of tightening. The calculations are performed for the bolts d = 12 mm. The dependence of maximum tensile stresses from the ratio $2P_m/P_l$ is presented in Fig. 9, b. You can select the interference value, above which it is not possible to reduce $\sigma_{t\ max}$. It depends on the bolt load.

On the basis of the fulfilled computational research of the influence of different geometrical parameters and loading parameters on the stress state of the composite plate the guidelines for choosing the joint of composite and metal parameters were developed.

Choice of bolt diameters. In this case we should be guided by the next dependence: the greater the bolt diameter the higher the working stress and respectively smaller the panel thickness and weight in the area of joint. However the diameter increase leads to the increase in the pitch of hole and the size of joint along the line of action of a force, which increases its weight. For ratios $2P_m/P_l = 0{,}3\ldots0{,}45$ implemented in two-row and three-row joints the gain in weight owing to the bolt diameter increase is almost compensated by the increase in weight due to the increase in the pitch of hole. Thus the choice of diameter will be determined by bearing and shearing strength limitations and technological considerations.

Choice of arrangement of different diameter holes. Hole diameters alternation in ascending order (12 mm, 16 mm, 18 mm) measured from the plane of symmetry of the joint brings to less stresses on the hole edged in the composite plate compared to the decreasing order (18 mm, 16 mm, 12 mm). The most advantageous proved to be the variant with equal bolt diameters.

Effect of the bevel of mating surfaces of joint. The bevel of mating surfaces leads to the increase of stress concentration at the holes, but allows more uniform load distribution on he bolts. Another disadvantage of the bevel is a torque retention loss of the panel under a tension of the joint. This makes the application of beveled parts unreasonable, especially in two-row joints. It is preferable to adjust the load of bolts by the step change of thickness.



a) b)

Fig. 9 Dependence of Maximum Tensile Stress on the Hole Edge: a) on Tightening Force; b) on Radial Interference

Choice of the bolts radial tightness. The radial interference reduces the dependence of tensile stresses at the hole contour on the external load, which increases the joint fatigue characteristics. However under the great radial interference the risk of matrix cracking increases. With consideration of this finding it is rational to limit the recommended interference to the value of 1%.

Choice of the bolts tightening. The bolts tightening as well as the radial interference reduces the dependence of stresses at the hole contour on the external load. The tightening up to the axial force in the bolt equal to 40% of the failure tensile load of the bolt ensures practically constant stresses at the hole edge up to load $2P_{\mathrm{m}}/P_{l} \approx 0{,}3$. Maximum bolt tightening may be recommended up to the limit, determined by the bolts strength and cracking of the composite.

7 Conclusion

Three main types of the composite failure were obtained in the experiments on the double-shear joints of composite and metal plates: the tension failure, the bearing failure and the shear. In some cases the failure occurred by the mixed type – cleavage tension failure. The test results analysis shows that the fracture process begins with the bearing failure of the hole. It appears in the form of lamination and shears of the material in the area of the contact with the bolt. Therefore in terms of the strength design procedure the bearing failure design is the major to estimate the strength according to three forms of failure – the bearing failure, the shear and the cleavage tension failure.

The results of the investigation showed that the approach on the base of the Nuismer criterion is applicable to calculate the failure load under the tension failure in the most loaded hole.

In the case of bearing failure, cleavage tension failure or shear the Nuismer criterion gives unacceptably overestimated strength assessment. The failure according to these types is associated with the lamination and shear of the material in the area of contact. Bearing stresses at which the lamination $\sigma_{\mathrm{br}} = P / (d \cdot t) = \sigma_{\mathrm{br}\ f}$ begins depend on the structural and technological features of the joint (the bolt tightening torque, the direction of a force action, etc.) and can be determined only experimentally on the structurally similar specimens. To develop a more universal criterion than $\sigma_{\mathrm{br}\ f}$, more research is needed.

Recommendations for choosing the structural and technological parameters of the double-shear joint of the composite plate with metal structural elements are based on the results of the study on the stress concentration around the hole dependence on the parameters of geometry and loading.

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