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Strength determination of metal composite multiple-row joints

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Abstracts. The results obtained using standard and improved (modified) calculation methods for load distribution on fasteners and joints strength are analyzed on the examples of four types of multiple-row metal-composite joints with cover plates of various thickness and various diameters of fasteners. A modified technique based on the Nuismer criterion is used to determine the load-bearing capacity. It was determined that for all joints the difference between the calculation results and the experiment is 14 - 26% using this criterion. It's desirable to use a modified scheme of the Nuismer criterion to improve a calculation convergence of the load-bearing capacity with experimental data. In this case, the maximum difference between the calculation results and the experimental data for the considered joints was 12.9%.

1 Introduction

The design of mechanical joints in composite structures is a rather difficult problem as previously it is necessary to know the types of possible fractures in composites under the action of an applied load and their dependence on geometric parameters and material properties.

Tests of composite specimens with holes loaded through a steel pin shows that, regardless of the specific failure type, all curves in dependence of force versus displacement have some common features - they are practically linear up to 80 - 90% of the maximum load P_{max}, after that followed a slight deviation from linearity, and further followed a sudden decrease in force associated with primary failure (Figure 1). An experimental research of fiberglass specimens' failure given in [1] has shown that, as a rule, in case of specimen failure by tension along the net-section of the specimen or shearing after the specimen reaches its maximum load, the last one decreases to zero level rapidly (Figure 1).

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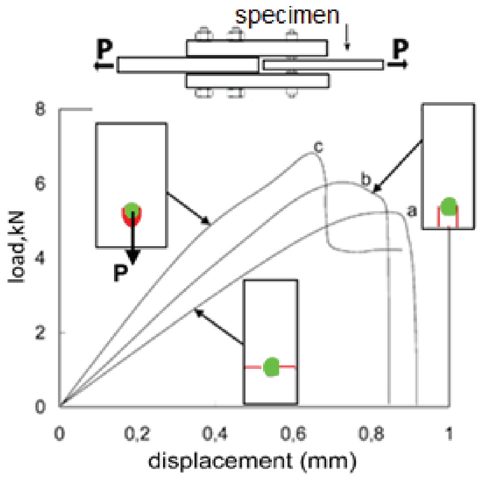

Fig. 1. Dependence of collapse load P for different types of failure for fiberglass specimens: (a) breaking, (b) shearing and (c) bearing.

If during the failure the bearing of composite material under the a steel pin or bolt takes place after achievement the maximum load, at first the last one decreases till the value ~ 0.7Pmax and then in the absence of strain can stay at this level for a long time until final failure. Such behavior of composites that has been pointed out by many researchers [2] gives preference bearing which is more desirable than other types of failure at bolt joints design.

As the most dangerous for a structure is the failure type by breaking, it is necessary to work up the most exact calculation method for its prediction.

To assess tensile strength of composite unit joints the different force and strain criteria are proposed based on calculation, respectively, of critical stresses and strains [3,4]. One of such criterion is Nuismer point criterion [5]. It was proposed by Nuismer and Whitney in 1974 and was experimentally tested in the USA at elements structure failure made of fiberglass with stress concentrators as holes and cracks. Results of its application for composite calculations made using carbon fiber are less known, and it is necessary to be verified its by experimental methods.

2 Specimens' Structures

Different types of multi-row metal-composite specimens consisting of composite and metal plates are considered. Their layouts are shown on Figure 2, characteristics are shown in Table 1. Laying types of composite are:

$$P_1= [45/-45/0/-45/0/45/0/45/-45/90/-45/45/45/0/-45/90]_s$$

$$P_2= [45/-45/0/-45/45/0/45/0/-45/0/-45/45/0/45/-45/0/-45/90/45/0/45/-45/90/45/-45/0/-45/0/45/0/-45/0/45/-45/90/45/-45/45/0/90]_s$$

The mechanical characteristics of monolayer are shown in Table 2. Estimated evaluation of integrated mechanical properties of carbon-fiber plastic plates material was carried out according to the method described in [6] (see Table 3).

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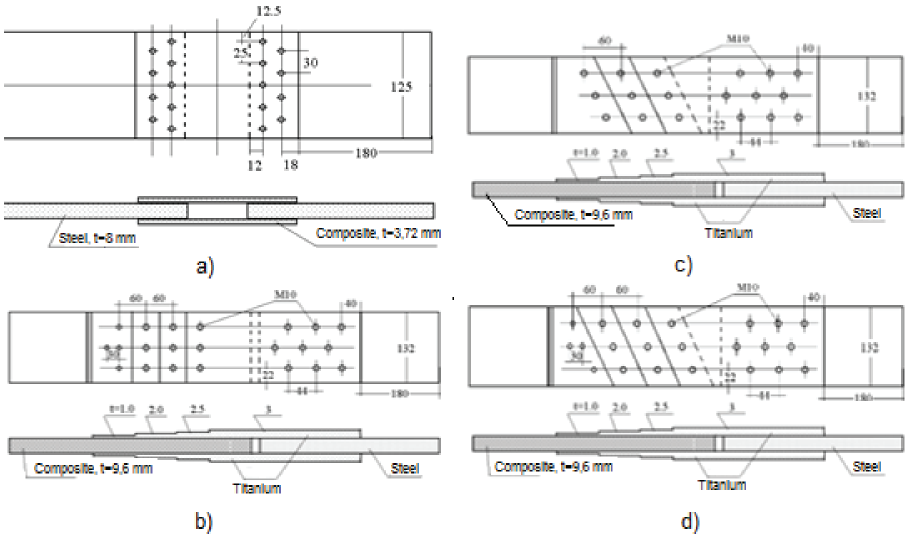

Fig. 2. Specimens layout: a) O1, b) O2, c) O3, d) O4.

Table 1. Characteristics of specimens

№ of specimen	Laying	Diameter of bolt	Bolts' quantity	Rows' quantity	Columns' quantity	Thickness of laminate. mm
O1	P2	6	9	5/4	2	9.6
O2	P1	10/6	9/4	3	5	3.72
O3	P2	10	9/3	3	3	9.6
O4	P2	10/6	9/4	3	5	9.6

Table 2. - Laying types of composite

Properties	MPa	Properties	MPa	Properties	MPa
E_{11}	135000	E_{12}	4470	σ_{b22}	38.7
E_{-11}	126000	ν_{12}	0.33	σ_{-b22}	-189
E_{22}	8800	σ_{b11}	1239	σ_{b12}	81.2
E_{-22}	10700	σ_{-b11}	-1081		

Table 3. Mechanical properties of specimens

Properties* at 20^{0}C (dry)	Specimens				Properties* at 20^{0}C (dry)	Specimens			
	O1	O2	O3	O4		O1	O2	O3	O4
t. mm	3.72	9.6			ν_{+xy}	0.527	0.508		
E_{+x}. MPa	51300	56250			σ_{+bx}. MPa	582	639		
E_{-x}. MPa	48700	53270			σ_{-bx}. MPa	-445	-492		
E_{+y}. MPa	34700	34900			σ_{+by}. MPa	385	384		
E_{-y}. MPa	33500	33800			σ_{-by}. MPa	-320	-323		
G_{xy}. MPa	23400	22000			σ_{bxy}. MPa	280	266		

* - the x-axis is directed along. and the y-axis is across the specimen.

Internal steel plates of joints are produced from 30CrMnSiA steel with elastic modulus of 210000 MPa. ultimate tensile strength σ_b =1080 MPa and yield strength $\sigma_{0.2}$=750 MPa. Cover plates and bolts are produced from titanium alloy with elastic modulus E = 110000 MPa. shear strength - τ_{av}=700 MPa and Poisson ratio – ν=0.3.

3 Strength criterion for calculating the load-bearing capacity of joints

Let use Nuismer strength criterion to strength estimation of joints. According to this criterion specimen failure occurs not at the moment when the maximum stresses on the hole outline reach the ultimate strength of the material σ_b. but when the stress in the specimen reaches the limit σ_b at some distance d_0 from the point of the hole outline. Nuismer explains this situation by the fact that in the area of stress concentration there is a preliminary area of cracking material the size of which is characterized by the value of d_0.

According to the theory of the maximum normal stresses. the failure of brittle materials at complex stress state take place when the main tensile stress reaches the ultimate tensile strength value σ_b or when the main compressive stress reaches the ultimate compressive strength value $\sigma_{\beta\chi}$. Based on this criterion we assume that the failure of plate will occur at the moment when the stress σ_x reaches the ultimate strength of the material at some distance d_0 from the hole.

In this case. the breaking stress value $\sigma_{\square}$. acting far from the hole. is defined by

$$\sigma_p=\sigma_\beta/K_\delta. \tag{1}$$

Where $Kd=\sigma_\xi/\sigma$ – is stress concentrate factor at the boundary of the composite cracking area. σ – is the stress in the gross-section far from the hole. If the value σ_p and the value of the cross-sectional area of the specimen F is known. it is possible to define breaking load of specimen P_p:

$$P_p=\sigma_p\cdot F. \tag{2}$$

Nuismer criterion. used to determine tensile specimens failure with single circular hole 6 mm in diameter produced from quasi-isotropic layered fiberglass [5] has allowed to define the value of $d_0 \sim 1$ mm experimentally.

Either the value of characteristic distance to calculate the joints strength is determined experimentally on specimens with a filled hole or various analytical approximations are proposed to determine it. Earlier in [7] to calculate characteristic value d_0 when calculating composite plates with circular filled holes of various diameters the following formula is proposed:

$$d_1 = 1\text{mm} \cdot \sqrt{\frac{D}{6\text{mm}}} = \sqrt{\frac{D}{6}}\,(\text{mm}) \quad . \tag{3}$$

Where D - is the hole diameter.

The value of this size made it possible to predict strength of joints produced from a low-strength composite (σ_b <400 MPa) to within ~ 17%.

In [8]. a computational and experimental justification of application Nuismer criterion with the characteristic value d_0 estimation (3) to calculate strength of metal-composite joints produced from high strength composite (σ_b>50 MPa) on series of two-. three- . and four bolted joints is carried out. Comparison of computation with experiment has shown that results that are more accurate are obtained when the characteristic size is approximated by the following formula [8]:

$$d_2 = \sqrt{\frac{d}{6}\cdot\frac{E_{+x}}{E_{+y}}}. \tag{4}$$

which we will use to estimate strength of given joints.

Computation was carried out using the ABAQUS program [9]. Models were created using volumetric octagonal orthotropic finite elements with linear approximation of displacements. All the models of joints had the same boundary conditions: at the left end. they were fixed. and at the right one equal efforts were applied to them with an equivalent force of 100 N. Using equations (3) and (4). the characteristic sizes d_{01} and d_{02} were calculated for the holes located in the most stressed zones.

By computation results in maximum stresses zones diagrams of relative stresses σ_x/σ_0 (σ_0 – tensile stress far from joint bolts) were drawn (Figure 3) according to which. at a distance d_{0i} from the hole outline. the stress concentration factors K_{d0i} were determined. the values of which are given in Table 7.

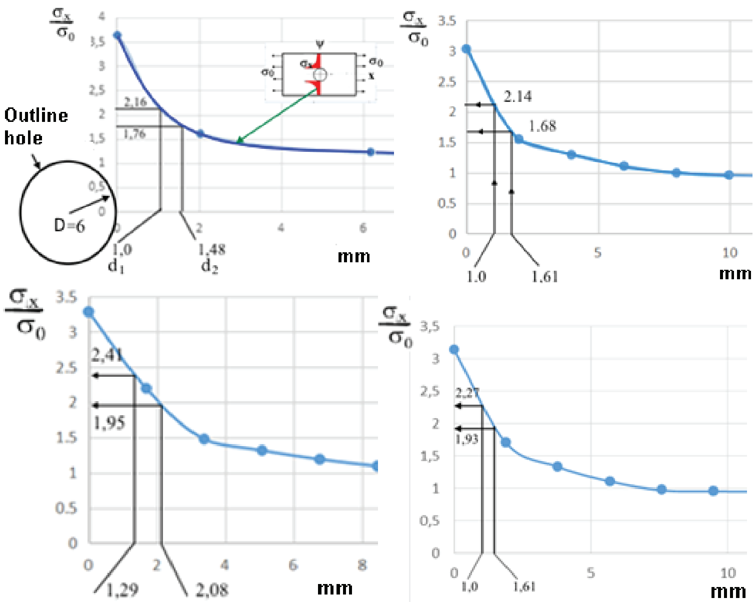

Fig. 3. Determination of stress concentration factors in the areas of the most loaded holes: a) O1. b) – O2. c) – O3. d) – O4.

The load-bearing capacity of the joint P_{pi}. was determined by $P_{pi} = b \cdot t \cdot \sigma_{+bx}/K_{d0i}$. The values of breaking loads are shown in table 4 also in this table is shown the experimental value of them.

Table 4. Values of the breaking force P_p.

Specimen	Width of cover plate b. mm	σ_{+bx}. MPa	P_p. kN Experiment	K_{d0i}	P_p. kN Calculation	γ. %	K_{d0i}	P_p. kN Calculation	γ. %
				Nuismer criterion			Modified Nuismer criterion		
O1	125	582	291.5	2.16	250.58	-14	1.76	307.53	5.5
O2	132	639	484.5	2.16	378.38	-21.9	1.68	481.98	-0.5
O3	132	639	409.9	2.41	335.99	-18	1.95	415.25	1.3
O4	132	639	481.8	2.27	356.71	-25.9	1.93	419.55	-12.9

As follows from Table 4 using Nuismer criterion difference calculation results the difference between calculating results of the breaking force and the experiment is 14-26%

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for all joints. At the same time. there is a clear tendency that the calculation results included into the margin of safety. If the modified Nuismer criterion is used in the calculations. there is a quiet good compliance of calculation results with experimental results – 1-6% for the most joints. The maximum difference between the calculation results and the experiment for the fourth joint was 12.9%.

4 Conclusion

It was found that using the Nuismer criterion the difference computation results of failure joint force from the experiment is 14-26% for all joints. At the same time. there is a clear tendency that the calculation results included in the margin of safety. To improve the calculation convergence of joints load-bearing capacity with experimental data. it is desirable to use a modified scheme of Nuismer criterion. in which the calculation of the characteristic distance d_2 is calculated according to (4). In this case. for the most of the considered joints. there is a very good agreement between the calculation results and the experimental results with an accuracy of 1-6%. and the maximum difference between the calculation results and the experiment for the fourth joint was 12.9%.

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