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Load capacity of bolted joints of carbon fibre reinforced plastics

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Abstract. Experimental and numerical investigations of the load capacity for the bolted joints were the aims of this work. Influence of a stacking configuration was investigated. Influence of the geometric parameters of bolted joints on its load capacity was analyzed. Digital image correlation method was used for the measurement of displacements. Numerical model of bolted joints was created in finite element system *Abaqus*.

Introduction

Currently, amount of products that utilize composite materials is rapidly increasing. Usually, a whole structure is not replaced with composite materials, but only a certain part of it is replaced. Joints are often the critical parts of constructions. A bolted joint is one possibility of joining of composites with composite or metal parts [1, 2]. The bolted joint is an example of removable joints.

Load capacity of bolted joints depends on many parameters, especially on the types of fibres and resin, and geometric properties of the joint [4]. The type of the failure depends on the geometry of the composite part and on the type of composite (material of constituent, layup, etc.) [1].

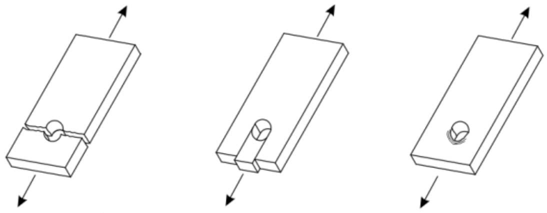

Fig. 1 Typical failure mechanisms of composite bolted joint

The experimental analysis and numerical prediction of load capacity of bolted joints is the aim of this work.

Specimens

The experimental specimens (Fig. 2) were cut using water jet from composite plate. The holes were milled. The composite plate was made from 8 prepreg layers (*HexPly 913C-HTS(12k)*). The composite material consisted of *Tenax HTS 5361* high-strength carbon fibres and epoxy resin. The specimens were cut in two mutually perpendicular directions, two types of stacking configurations were tested in this work ([0/–45/+45/90]s and [90/+45/–45/0]s).

Two types of bolts (M6 and M8) were used. The clamp load was done using a torque wrench *Atlas Copso-tensor ETV ST61-50-10*. Width of specimen was W = 24, 32 or 40 mm, distance from the centre of the hole to the free end was E = 18, 24 or 30 mm, thickness was H = 2.4 mm and length was L = 50 mm. Angle φ is orientation of the outside layer of plate relative to the longitudinal direction. Geometric parameters of specimens and tightening torque are presented in Table 1 and Table 2.

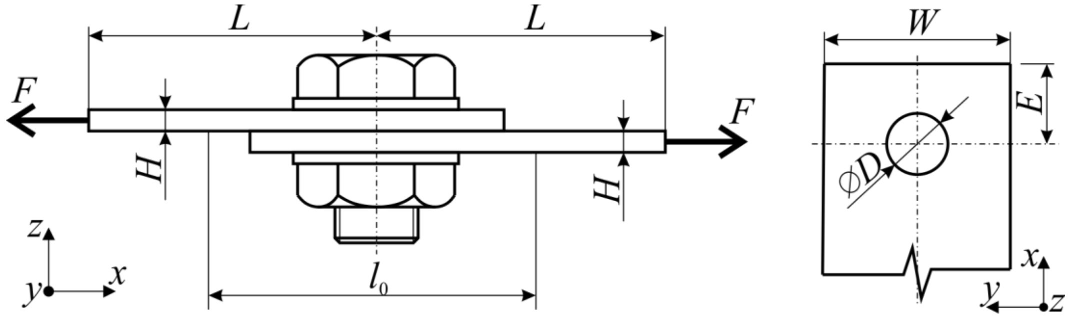

Fig. 2 Geometric parameters of bolted joint

Tab. 1 Geometric parameters of specimens, tightening torque M_t
and load capacity for bolt M6

Specimen name	2E [mm]	W [mm]	φ_1 [°]	φ_2 [°]	M_t [Nm]	F_{max} [N]
D6_E18_W24_0_0_1	36.7	23.9	0	0	10.6	8113
D6_E18_W24_0_0_2	36.6	23.8	0	0	10.5	8362
D6_E18_W24_0_0_3	36.4	23.9	0	0	10.6	7876
D6_E18_W24_90_90_1	36.9	23.8	90	90	10.5	7620
D6_E18_W24_90_90_2	36.3	23.9	90	90	10.6	7375
D6_E18_W24_90_90_3	36.0	23.8	90	90	10.6	7016
D6_E18_W32_0_0_1	35.8	32.8	0	0	10.6	8388
D6_E18_W32_0_0_2	36.1	32.0	0	0	10.6	8390
D6_E18_W32_0_0_3	35.9	31.8	0	0	10.7	8405
D6_E18_W32_90_90_1	36.0	31.9	90	90	10.5	8121
D6_E18_W32_90_90_2	35.9	31.9	90	90	10.6	7839

Tab. 2 Geometric parameters of specimens, tightening torque M_t
and load capacity for bolt M8

Specimen name	2E [mm]	W [mm]	φ_1 [°]	φ_2 [°]	M_t [Nm]	F_{max} [N]
D8_E24_W24_0_0_1*	48.9	23.8	0	0	20.6	-
D8_E24_W24_0_0_2	48.3	23.9	0	0	20.6	9744
D8_E24_W24_0_0_3	47.8	23.8	0	0	20.7	9552
D8_E24_W24_90_90_1	48.4	23.8	90	90	20.7	9168
D8_E24_W24_90_90_2*	48.2	23.8	90	90	20.6	-
D8_E24_W24_90_90_3	48.7	23.8	90	90	20.7	9631
D8_E30_W24_0_0_1	60.2	23.8	0	0	20.7	9322
D8_E30_W24_0_0_2	59.9	23.9	0	0	20.7	9723
D8_E30_W24_0_0_3	60.2	23.8	0	0	20.7	9422
D8_E30_W24_90_90_1	60.4	23.8	90	90	20.6	9654
D8_E30_W24_90_90_2	60.0	23.8	90	90	20.7	9961
D8_E30_W24_90_90_3	60.0	23.8	90	90	20.7	9084
D8_E30_W40_90_90_1	59.8	39.9	90	90	20.4	8851
D8_E30_W40_90_90_2	60.7	39.8	90	90	20.6	9011
D8_E30_W40_90_90_3	59.8	39.8	90	90	20.7	8728

* specimen slipped in the jaws

Experiments

Specimens were tested in tension in the longitudinal direction. *Zwick/Roell Z050* testing machine was used. The loading speed was v = 3 mm/min.

The Digital Image Correlation (DIC) method was used to analyze the plate displacements (x and y directions). A random high-contrast color pattern was applied on the side surface of the specimen. *Dantec Dynamics Q-400* system made a picture during the test. An extensometer was used for measuring the displacement (Fig. 4). The gage length was l_0 = 80 mm (Fig. 2)

The specimen during the test is shown in Fig. 3. Typical force-displacement dependencies are presented in Fig. 4. The dependencies were similar for all specimens. The first significant decrease of the force means a slippage in bolted joint. Slippage occurred about F = 1500÷2000 N in case of M6 bolt, and about F = 2000÷2500 N in case of M8 bolt. The next decrease of the force means failure of composite parts. Failure of the specimen (bearing mode) is shown in Fig. 5. This type of failure occurred for all specimens.

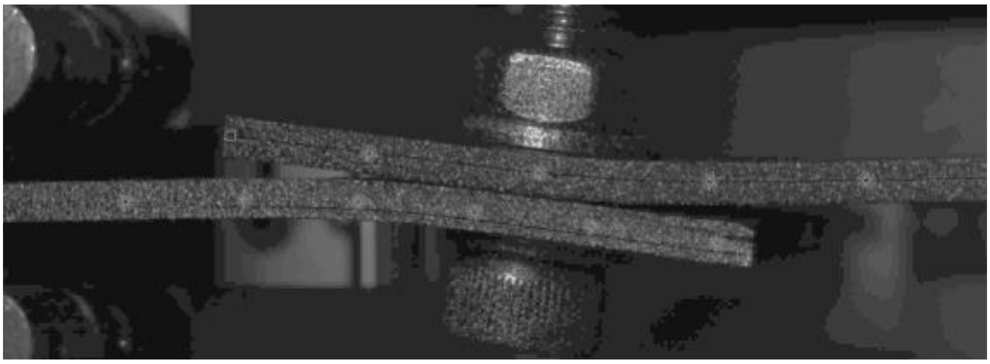

Fig. 3 Specimen during the test

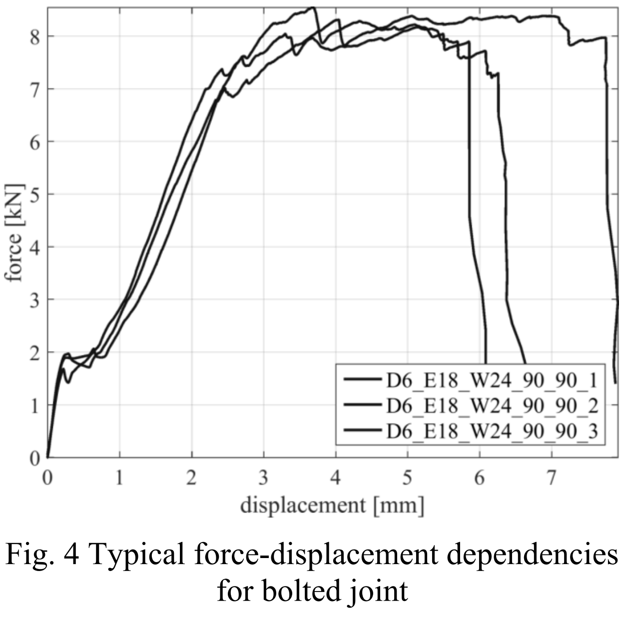

Fig. 4 Typical force-displacement dependencies for bolted joint

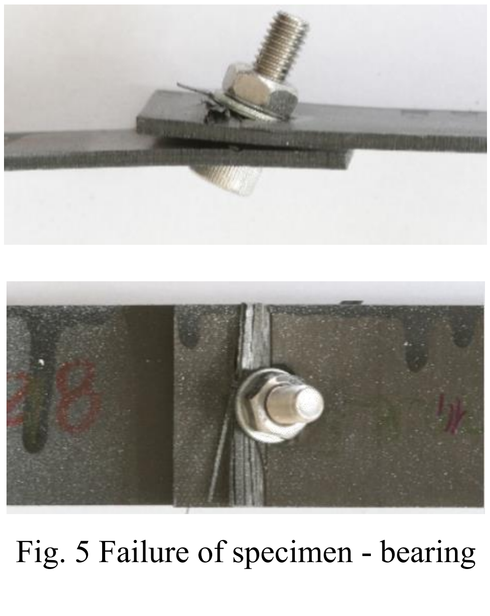

Fig. 5 Failure of specimen - bearing

Maximum forces (load capacities) are presented in Table 1 and Table 2. In case of M6 bolt, influence of the stacking configuration on load capacity if the bolted joint was discover. In case of geometrical parameters E = 18 mm and W = 24 mm, the load capacity for specimens with $\varphi = 0°$ was higher by 10% than for specimens with $\varphi = 90°$. In case of geometrical parameters $E = 18$ mm and $W = 32$ mm, the difference was only 5%. In case of M8 bolt, influence of stacking configuration on load capacity of bolted joints was not determined. Increasing the width increased the load capacity by 9% in case of M6 bolt and $\varphi = 90°$. In case of M8 bolt, the larger width caused a decrease of load capacity by 8% for $\varphi = 90°$.

Numerical simulation

Numerical model was created in the finite element system *Abaqus*. The composite layup solid elements were used for model of the plates. The solid elements with 8 nodes were used for model of bolt, nut and washer. Isotropic material (E_s = 210 GPa, ν_s = 0.3) was applied in the steel parts. Transverse isotropic material (Table 3) was set in each composite layer. A friction between components was considered (composite/composite f_{cc} = 0,12, composite/metal composite/metal f_{cm} = 0,12, metal/metal f_{mm} = 0,10).

Tab. 3. Material properties of composite [3]

E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	ν_{12} [-]	ν_{13} [-]	ν_{23} [-]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]
120.0	8.0	8.0	0.337	0.337	0.33	4.6	4.6	3.0

The numerical simulation was carried out in two steps. First, the clamp load was applied in the bolt. In the second step, the specimen was loaded by means of displacement. The maximum stress criterion was used for prediction of the load capacity of the bolted joints. The strength parameters of the composite are presented in the Table 4. The maximum stress criterion predicted first failure in the composite. But this first failure is not obvious from the force-displacement dependencies. This failure occurred at about 40% of the experimental load capacity.

Tab. 4. Strength parameters of composite [3]

X_T [MPa]	X_C [MPa]	Y_T [MPa]	Y_C [MPa]	Z_T [MPa]	Z_C [MPa]	S_{12} [MPa]	S_{23} [MPa]	S_{13} [MPa]
1800	850	55	213	55	213	82	82	82

A comparison of the displacements from the experiment and numerical simulation is presented in the Fig. 6. Displacement in experiment was measured by means of DIC method.

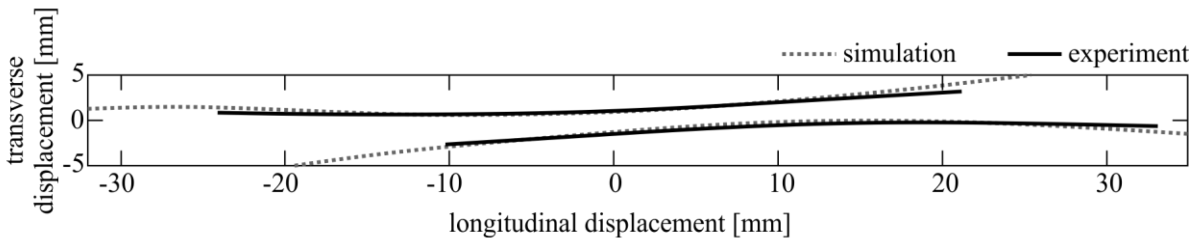

Fig. 6 Comparison of the displacements

Conclusions

Two plates were connected by bolted joint. The load clamp was applied in the bolt. Experimental analysis of the load capacity of the bolted joints was done. Displacements in x and y directions were measured by means of DIC method. The numerical model of this bolted joints was created in finite element system *Abaqus*. The maximum stress criterion was used for load capacity prediction.

Influence of stacking configuration on load capacity was determined in case of M6 bolt. This influence was not determined in case of M8 bolt. Increasing the width increased the load capacity in case of M6 bolt with outer layer having fibre orientation 90°.

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