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Original Research

INFLUENCE OF TEMPERATURE CHANGES ON STRESSES IN CARBON COMPOSITE FASTENING BOLTS

WPŁYW ZMIAN TEMPERATURY NA NAPRĘŻENIA W ŚRUBACH ŁĄCZĄCYCH KOMPOZYTY WĘGLOWE

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Abstract

High joint strength of composite structures can be achieved by using mechanical fasteners. The materials used for rivets and bolts have lower coefficients of thermal expansion than composites in the direction perpendicular to the reinforcement fibers. It is suspected, therefore, that temperature changes can cause stress changes in mechanical fasteners. The purpose of this study was to experimentally determine and analytically substantiate the values of stress changes resulting from a change in temperature in the range from -20 to 60°C in M8 steel bolts fastening carbon composite. The value of stress changes was estimated to be around 100 MPa, which can consequently lead to joint unsealing or plastic deformation of the mechanical fastener.

Keywords: carbon composites, mechanical fasteners, thermophysical properties, thermal interactions

Streszczenie

Wysoka wytrzymałość połączeń struktur kompozytowych może zostać osiągnięta dzięki zastosowaniu łączników mechanicznych. Materiały wykorzystywane do produkcji nitów oraz śrub cechują mniejsze wartości współczynników rozszerzalności cieplnej niż kompozytów w kierunku prostopadłym do włókien zbrojenia. Podejrzewa się więc, że zmiany temperatury mogą powodować zmiany naprężeń w łącznikach mechanicznych. Celem przeprowadzonych badań było eksperymentalne określenie i analityczne uzasadnienie wartości zmian naprężeń wynikających ze zmiany temperatury w zakresie od -20 do 60°C w stalowych śrubach M8 łączących kompozyt węglowy. Wartość zmian naprężeń oszacowano na około 100 MPa, co w konsekwencji może prowadzić do rozszczelnienia połączenia lub plastycznych odkształceń łącznika mechanicznego.

Słowa kluczowe: kompozyty węglowe, łączniki mechaniczne, właściwości termofizyczne, oddziaływania termiczne

1. Introduction

Carbon Fiber Reinforced Polymers (CFRP) are structural materials that are increasingly replacing metal alloys in the construction of modern aircraft airframes (Kaufmann et al. 2009). This state of affairs is a consequence of the mechanical properties of CFRP composites, especially their high specific strength (strength related to density) and high specific stiffness (Young's modulus related to density). In addition, these materials are characterized by high fatigue strength and technological susceptibility, which allows the simple manufacture of parts with complex shapes, such as airframe covers with two curvatures (Dipen et al. 2019; Emanoil et al. 2019; Vol'mir et al. 1972; Kamali et al. 2017; Mandalgiri 1999).

Fiber-reinforced composites can have monotropic, orthotropic or quasi-isotropic properties. In each type of these composites there is a direction that is not reinforced with fibers arranged along that direction. In the case of fabric-reinforced composites (orthotropic and quasi-isotropic), this direction is perpendicular to the fabric surface (Donglin et al. 2023; Ochelski 2004; Hull and Clyne 1996; Ochelski and Gotowicki 2007; Carlsson et al. 2013). In this direction, carbon composites are characterized by a low value of Young's modulus about 6-7 GPa (Ochelski and Gotowicki 2008; Arkuszyńska et al. 2023) and low tensile strength due to the strength of the polymer matrix. Studies show that in this direction the coefficient of linear expansion of the composites at ambient temperature has a value of about 70×10^{-6} 1/K. In addition, in this direction the composites exhibit distinct rheological characteristics, including susceptibility to creep (Goertzen and Kessler 2006; Ornaghi et al. 2021).

Composite parts are joined to other composite or metal parts. If the composite parts have low tensile strength and stiffness (thin-walled parts), structural bonding may be a reasonable way of joining (Higgins 2000; Cavalcanti el al. 2021). For higher strength parts, mechanical fasteners such as rivets or bolts should be used. In aeronautical structures, the connections of primary parts (which are decisive for the safety of flying) cannot be only adhesive joints (Gamdani et al. 2022). Studies show the great suitability of adhesive-mechanical hybrid joints for joining composite parts (Nabil et al. 2016). The use of such joints complicates the assembly process due to the need to ensure proper adhesion properties of the surfaces to be joined and proper joint design.

The use of mechanical fasteners requires the drilling of holes in the composite parts to be joined, which creates additional problems, since classical drilling can lead to delamination of the composite and its significant weakening (DeFu et al. 2012; Gaugel et al. 2016; Fernández-Pérez et al. 2017). To avoid these phenomena, special drills or pressure during drilling are used to prevent delamination.

When joining composites using the riveting method, avoid forming the rivet point directly on the composite material, as it may crush. When the rivet is upset, its shank increases in diameter and cancels the clearance between the hole and the rivet. In a riveted lap joint, the composite is loaded mainly on pressure.

Bolted joints used in aircraft construction include special bolts called Hi-Lok. Their distinctive feature is a nut that breaks at a certain torque value, which prevents the allowable pressures from being exceeded during the assembly of the joint (Tomkinson 1991, Yanishevsky et al. 2013). Connections using Hi-Lok fasteners must have a specific length related to the thickness of the package to be joined, which requires having a large assortment of these fasteners. In bolted connections, the load is carried by frictional forces and, once they are exceeded, by the bolt shanks, which press against the walls of the holes.

Considering that metal fasteners have different thermophysical properties than composite materials, it seems that the preload of bolt fasteners should change as the temperature changes. The purpose of the tests carried out was to see to what extent the stresses in a steel bolt connecting composite elements can change if the temperature varies by +40°C and -40°C from the assembly temperature, 20°C. Such temperature changes can occur during aircraft operations.

2. Materials and test methods

An orthotropic composite with a thickness of 7.3 mm autoclaved manufactured at the Silesian Science and Technology Center of Aerospace Industry Sp. z o.o. based on GG 204T g/m^2 IMP 503 ZHT carbon prepreg with a thickness of 7.3 mm, consisting of 25 layers arranged according to the $[0°]_{25}$ scheme, was tested. The conditions for manufacturing the plate are a pressure of 400 kPa and a curing temperature of 120°C.

To test the modulus and compressive strength in the x_3 axis direction (the axis perpendicular to the arrangement of the layers of composite material, 7 cubes measuring 27 x 27 x 7.3 mm with 10.1 mm diameter holes were bonded together (Figure 1).

Fig. 1. A cube cut from the tested composite

A specimen with a height of 52 mm and a cross-sectional area of 633 mm^2 was obtained, which was loaded with a force of up to 250,000 N, and the dependence of the displacement of the crosshead of the machine (Instron 8802) as a function of force was recorded (Figure 2). In addition, the stiffness characteristics of the testing machine were determined by compressing its platens without the specimen (Figure 3).

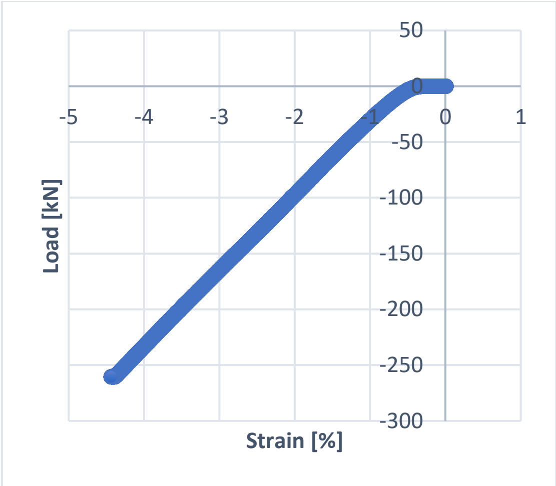

Fig. 2. Compression curve of the composite specimen

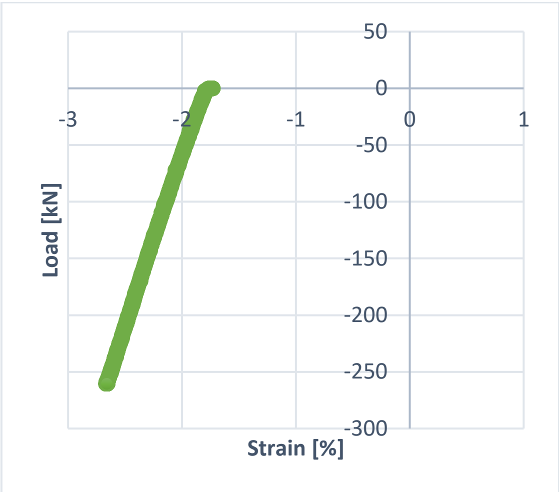

Fig. 3. Stiffness characteristics of the Instron 8802 testing machine

Based on the two compression curves obtained, the value of Young's modulus of the tested orthotropic composite in the x_3 direction, that is, in the direction of compression of the material by the bolt, was calculated. The modulus was estimated at 6240 MPa.

A CL20M8 force sensor with a measuring range of 10 kN (ZEPWN J. Czerwinski & Associates) was used to test the tensile force of the bolt. First, it was examined to what extent a temperature change of ±40°C affects the force measurement. The M8 bolt itself was tightened in the sensor to such a torque that a gauge reading of 6000 N was obtained (stresses in the bolt 183 MPa).

The effect of elevated temperature was studied by holding the force sensor specimen in a laboratory dryer by heating its chamber to 60°C, and the effect of reduced temperature – by holding the specimen in a freezer for one hour. The measurements showed, that there was an increase of 120 N in the increased temperature, and a decrease of 230 N in the reduced temperature. Thus, the change in force did not exceed 4%. These values were considered by changing the force values recorded when testing the composite. Hence, for the purposes of this study, the notion of registered force and actual force was defined, the value of which was calculated by correcting the measured value by the deviation determined experimentally and generated by the sensor itself at variable temperature.

The effect of elevated temperature on the screw-sensor system was studied by holding the force-sensor sample in a laboratory dryer heated to 60°C, and the effect of reduced temperature was studied by holding the sample in a freezer for one hour. The measurements showed that there was an increase in force of 120 N at the increased temperature, and a decrease of 230 N at the reduced temperature. Thus, the change in force did not exceed 4%. These values were taken into account by subtracting them from the force values recorded when testing the composite, and the real forces were obtained.

To study the change of stress in the bolt loading the composite material, 4 cubes of 27 x 27 x 7.3 mm (Figure 4) and 1 cube of the same dimensions (Figure 5) were used, in which 8.1 mm diameter holes were drilled centrally. These cubes were applied to an M8 bolt and, in addition, a force measurement sensor was used. The nut was tightened to such a torque that a clamping force of 6000 N was obtained.

Fig. 4. Four composite cubes and a load cell bolted together with an M8 screw

Fig. 5. One composite cube and force sensor bolted together with an M8 screw

The changes in clamping force with time and at elevated and depressed temperatures were then checked.

3. Test results

First, the change in bolt force at ambient temperature of a specimen with a composite package thickness of 29.5 mm was checked (Table 1).

An approximate 9% decrease in strength due to composite creep was found.

Table 1. Variation of compression bolt tension of 29.5 mm thick composite package as a function of time at ambient temperature

Time [h]	Recorded force [N]
0	6000
0,5	5770
18	5470

The results of further testing of the specimen at different temperatures are given in Table 2.

Table 2. Variation of compression bolt tension of 29.5 mm thick composite package as a function of time and temperature

Temperature [°C]	Time [h]	Recorded force [N]	Real force [N]
60	1	6630	6510
20	0,5	4800	4800
60	0,5	6470	6350
	1	6220	6220
20	1	4150	4150
60	1	6080	5960
20	50	4160	4160
60	1	6060	5940
-20	1	2310	2540
60	1	5970	5850
-20	1	2240	2470
60	1	5900	5780
20	18	3960	3960
60	1	5890	5770

Subsequently, similar tests of the change in screw clamping force at ambient temperature (20°C) and at variable temperature (20°C, 60°C, -20°C) were carried out for a 7.3 mm thick composite. The results are shown in Tables 3 and 4, respectively.

In tests at ambient temperature (20°C), there was about a 3.7% decrease in strength due to composite creep.

Table 3. Variation of compression bolt tension of 7.3 mm thick composite as a function of time at ambient temperature

Time [h]	Recorded force [N]
0	6000
0,5	5930
18	5780

Table 4. Variation of compression screw tension of 7.3 mm thick composite as a function of time and temperature

Temperature [°C]	Time [h]	Recorded force [N]	Real force [N]
60	0,5	6480	6360
	1	6390	6270
20	0,5	5300	5300
60	1	6280	6160
20	1	5190	5190
60	1	6200	6080
20	1	5120	5120
-20	1	3970	4200
60	1	6150	6030
20	18	5190	5190
-20	1	4010	4240
60	1	6140	6020
-20	1	3970	4100

Table 4 (cont.). Variation of compression screw tension of 7.3 mm thick composite as a function of time and temperature

Temperature [°C]	Time [h]	Recorded force [N]	Real force [N]
60	1	6040	5920
20	0.5	5080	5080
20	18	5040	5040
20	70	5080	5080
20	24	5110	5110
20	24	5020	5020

4. Analysis of test results

The tests showed a significant effect of temperature change on the value of the force with which the bolt compressed the tested composite or its package. The tests also show that with the applied load (force of 6000 N, washer pressure on the composite of 41.6 MPa) there was creep of the composite already at ambient temperature, resulting in a decrease in force from 6000 N to 5470 N in 18 hours for a composite package of 29.5 mm thickness and from 6000 N to 5780 for a composite of 7.3 mm thickness (Figure 6).

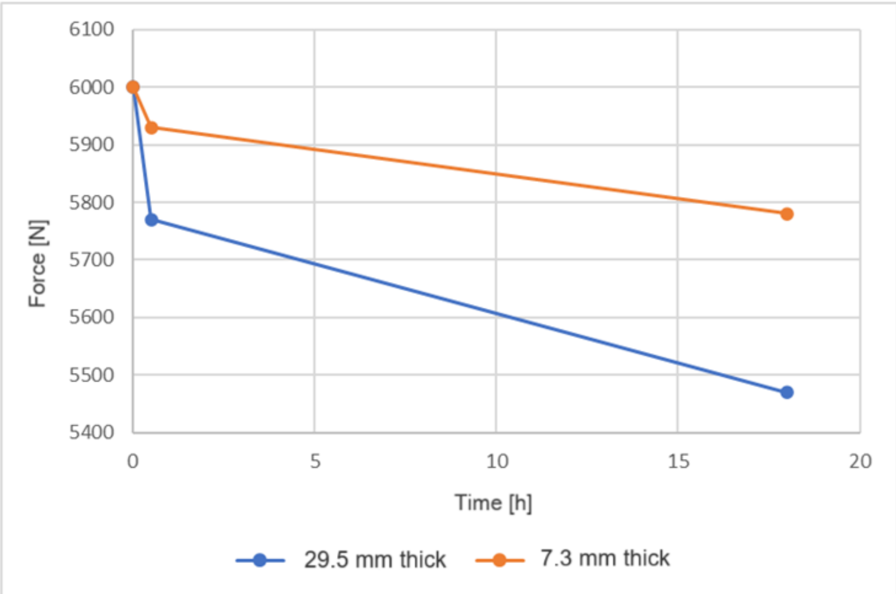

Fig. 6. Change intime of the forces with which the screw compressed the composite of different thicknesses at ambient temperature

Heating the tested composite package joint by 40°C increased the force from 5470 N to 6510 N. Taking into account the height of the composite package (29.5 mm) and the length of the bolt shaft (46 mm resulting from the height of the composite package and the height of the force sensor), the difference in thermal deformation of the composite and the bolt was calculated.

$$\Delta l = l \times \alpha \times \Delta T \quad (1)$$

where: l - height of the composite package/ length of the bolt shaft, α - thermal expansion coefficient, ΔT - temperature change.

$$\Delta l_c = 29.5 \times 70 \times 10^{-6} \times 40 = 0.0826\,mm \quad (2)$$

$$\Delta l_b = 46 \times 11 \times 10^{-6} \times 40 = 0.0203\,mm \quad (3)$$

$$\Delta l_{c-b} = 0.0826 - 0.0203 = 0.0623\,mm \quad (4)$$

The calculated strain is the sum of the deformations of the bolt and the composite. These deformations are inversely proportional to the tensile stiffness of the joint components. The actual strain of the composite (Δl_{cr}) can be calculated from the relationship:

$$\frac{\Delta l_{cr}}{\Delta l_{c-b} - \Delta l_{cr}} = \frac{A_b \times E_b}{A_w \times E_c} \quad (5)$$

where: E_b - Young's modulus of the bolt (steel), E_c - Young's modulus of the composite, A_b - cross-sectional area of the bolt M8, A_w - area of the bolt washer M8.

$$\frac{\Delta l_{cr}}{0.0623-\Delta l_{cr}} = \frac{32.8\times200}{144.2\times6.24} \tag{6}$$

$$\Delta l_{krz} = 0.0548\ mm \tag{7}$$

The real deformation of the bolt can be calculated from the relationship:

$$\Delta l_{br} = \Delta l_{c-b} - \Delta l_{cr} = \ 0.0075\ mm \tag{8}$$

The stress increment in the bolt due to its elongation can be calculated from Hooke's law:

$$\Delta\sigma = \frac{\Delta l_{br}}{l_b}\times E = \ \frac{0.0075}{46}\times 200000 = 32.6\ MPa \tag{9}$$

The force increment is the product of the stress increment and the bolt's cross-sectional area:

$$\Delta F = \Delta\sigma \times A_b \ = 32.6 \times 32.8 = 1070\ N \tag{10}$$

The calculated value of the force increment is close to the value derived from the experiment:

$$6510 - 5470 = 1040\ N \tag{11}$$

The study also showed that during the loading of the composite package with a thickness of 29.5 mm at different temperature there was a continuous slow decrease in the recorded forces which was caused by creep of the composite material. A decrease in force at ambient temperature was found from 5470 N to 3960 N, or about 28%. Such a large deformation of the composite associated with its creep was due, among other things, to the large thickness of the tested package.

The difference in the compressive force of the 29.5-mm-thick composite package at 60°C and -20°C was 3310 N, resulting in a change in the bolt stress of about 100 MPa from 176.2 to 75.3 MPa.

When the 7.3-mm-thick composite was loaded, there was also a decrease in recorded forces at ambient temperature, but in a smaller range from a force of 5780 N to 5190 N, and thus by about 10%. This is as expected, since the permanent deformation resulting from creep of the thinner composite has a lower value.

The difference in the compressive force of the 7.3-mm-thick composite package at 60°C and -20°C was 1,790 N, resulting in a change in the stress in the bolt of about 54.5 MPa from 183.8 to 129.3 MPa.

The differences in the changes in compression forces of the composites associated with changes in temperature from from +40 to -20°C determined for composites of different thicknesses are because for the two cases considered, the ratio of the active length of the bolt (thickness of the composite plus thickness of the sensor) to the thickness of the composite was different. For a composite of 7.3 mm thickness it was 3.26, and for a composite package of 29.5 mm thickness it was 1.56. In real joints, if we ignore the thickness of the washer, this ratio is 1. It follows that temperature changes in the considered range will cause more than 28% changes in the compressive forces of real joints of composite materials. Making simplifying assumptions that in the considered range of temperature changes the coefficient of linear expansion of the composite and the value of its Young's modulus do not change, and that the composite deforms uniformly under the washer, it is possible to estimate the range of changes in the forces acting on the M8 bolt under the influence of temperature changes.

$$\Delta l_c = l \times 70 \times 10^{-6} \times 80 = 0.0056 \times l\ mm \tag{12}$$

$$\Delta l_b = l \times 11 \times 10^{-6} \times 80 = 0.00088 \times l\ mm \tag{13}$$

$$\Delta l_{c-b} = (0.0056 - 0.00088)l = 0.00472 \times l\ mm \tag{14}$$

$$\frac{\Delta l_{cr}}{\Delta l_{c-b}-\Delta l_{cr}} = \frac{A_b\times E_b}{A_w\times E_c} \tag{15}$$

$$\frac{\Delta l_{krz}}{0.00472\times l-\Delta l_{krz}} = \frac{32.8\times200}{144.2\times6.24} = 7.29 \tag{16}$$

$$\Delta l_{cr} = 0.00415 l\ mm \tag{17}$$

$$\Delta l_{br} = \Delta l_{c-b} - \Delta l_{cr} = \ 0.00057 l\ mm \tag{18}$$

$$\Delta\sigma = \frac{\Delta l_{br}}{l_b}\times E = \frac{0.00075 l}{l}\times 200000 = 114\ MPa \tag{19}$$

$$\Delta F = \Delta\sigma \times A_b \ = 114 \times 32.8 = 3740\ N \tag{20}$$

In an M8 bolt, the range of force change due to temperature change by 80°C will be at 3740 N. The range of stress change in steel bolts (about 114 MPa) should depend little on the diameter of the bolt, and only to some extent on the dimensions of the washers.

To check the validity of the analysis, numerical calculations of the effect of temperature change on the value of stresses in the bolt connecting the composite material were carried out. The calculations were carried out in ANSYS 19.2. A numerical model of a 7.3-mm-thick composite specimen with a hole d = 8.1 mm was built, in which an M8 steel bolt was placed. In the built model, the bolt head and nut were modeled as cylinders with washer diameter (d = 16 mm) and thickness of 4 mm. The specimen model with a grid of elements is shown in Figure 7.

The mechanical and physical properties of the steel were taken from the ANSYS system library. The properties of the composite were declared based on tests performed and data from the system's library of composite materials (Table 5).

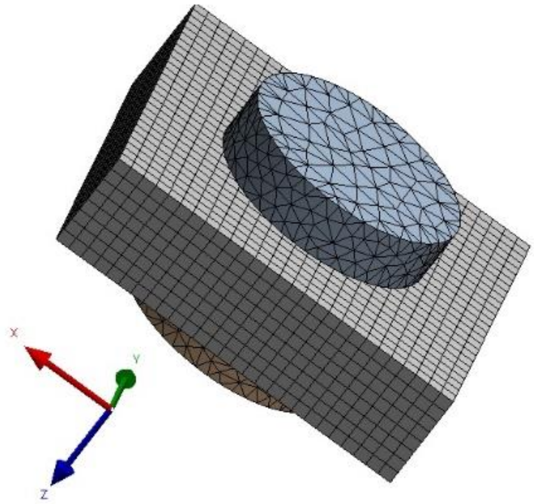

Fig. 7. Grid of elements of the analyzed specimen

Table 5. Material constants of the composite adopted for numerical calculations

E_x [GPa]	E_y [GPa]	E_z [GPa]	ν_{xy} [-]	ν_{yz} [-]	ν_{xz} [-]	G_{xy} [GPa]	G_{yz} [GPa]	G_{xz} [GPa]	α_z [1/K]
30,00	30,00	6,24	0,04	0,30	0,30	18,00	2,70	2,70	5×10^{-5}

There was a gap between the bolt shaft and the hole. A 'no separation' contact was declared between the surfaces of the cylinders mapping the head and nut with washers and the surfaces of the composite cube. The outer surface of one cylinder was deprived of the possibility of movement. All elements of the specimen were loaded with a temperature change by 80°C. The average normal stress in the bolt shaft after the temperature change was about 100 MPa (Figure 8), which was about 14% lower than that resulting from analytical calculations (114 MPa for the same temperature change by 80°C).

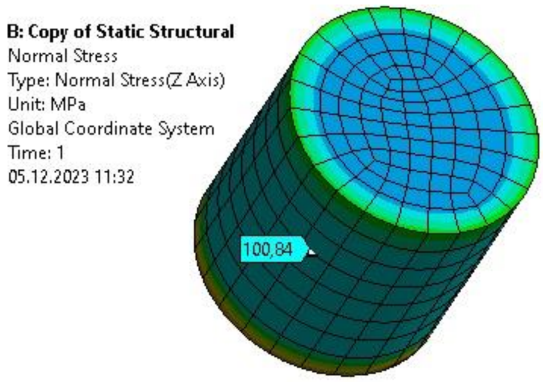

Fig. 8. Normal stresses in the bolt shank of the specimen loaded with a temperature increment of 40°C

The results of the numerical calculations should be considered more reliable due to the simplifying assumptions made in the analytical calculations, including the assumption that the composite deforms uniformly under the washer.

5. Conclusions

Mechanical fasteners (bolts and rivets) used to join composite parts are most often positioned perpendicular to the fiber laying plane. In this direction, composite materials are characterized by a low value of Young's modulus - a few GPa (Ochelski and Gotowicki 2008) and a relatively high value of the coefficient of linear expansion.

In stressed bolts connecting composite parts, there is a decrease in stress over time, resulting in a decrease in the value of the clamping force of the parts being joined. This is due to the rheological properties of the polymer matrix of the composites, which result in composite creep. With the passage of time, the intensity of creep, like that of other materials, such as steel alloys (Bolanowski 2013) - decreases. Increased temperature accelerates the creep process.

Approximately seven times the value of the coefficient of linear expansion of composites in the plane perpendicular to the stacked fibers (70×10^{-6} 1/K) than the coefficient of linear expansion of steel (1.1×10^{-6} 1/K) results in stress changes in the bolts as the temperature changes. An increase in temperature relative to the joint assembly temperature results in an increase in stress, while a decrease in temperature results in a decrease in stress.

Experimental studies and analyses show that in the case of a carbon-epoxy composite joined by steel bolts, changes in temperature in the range from +60 to -20°C cause stress changes in the range of 100 MPa. Such large stress changes can significantly affect the strength of the connections, cause them to unseal or load the bolt with a force that causes the material to exceed its yield strength.

To reduce the range of stress changes in bolts connecting composite materials resulting from changes in the temperature of the joint, bolts should be made from materials whose value of the coefficient of thermal expansion is more similar to the value of this feature of the composite, such as from aluminum alloys (25×10^{-6} 1/K).

Acknowledgments

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