LOAD TRANSFER BY FRICTION IN BOLTED COMPOSITE JOINTS UNDER CYCLIC LOADING

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Abstract

Pretensioned bolted joints are designed to transfer in-plane loads by friction. A cyclic in-plane loading can become critical due to preload losses in particular when using composite parts at increased temperatures. This is experimentally investigated with double-lap bolted joints using carbon epoxy laminates from a RTM manufacturing process. Different influences on the load transfer such as temperature (22, 45, 70 and 95 °C), load ratio regarding maximum static friction load (70, 80 and 90 %), friction surface condition (rough, wet, oily and impregnated) and assembly preload (10 and 14 kN) are studied. The results show, that all bolted joints – even tests at increased temperatures – are able to transfer at least 1.7E6 load cycles at a load ratio of 90 %. The bolt preload measurements and the results from static friction tests after cyclic loading reveal an increase of coefficient of static friction by up to 33 %, which compensates the preload loss during cyclic loading. This increase can be even so high that transferable loads after cyclic loading are higher than without cyclic loading. The results show a high load carrying capacity of pretensioned bolted composite joints under cyclic loading and thus contribute to a larger field of applications.

1. Introduction

Load introductions by friction can be used in different fields of applications, e.g. automotive, aerospace or mechanical construction, depending on the existing requirements. They offer the advantage of a potential tolerance compensation between the clamping components, which can be very helpful e.g. in assembly process of automotive structures where it is not allowed to drill fitting holes due to cleanness requirements. Furthermore they enable a simple disassembly and reparability. Considering the increase use of CFRP structures and cost-efficient productions, friction based load introductions can be a good choice compared to conventional composite joining technologies as bonding, riveting or bolting [16, 18]. The anisotropic and inhomogeneous properties of CFRP materials [18] have to be considered in the design process to enable a high performance lightweight load introduction. In particular, this includes the loss of bolt preload at elevated temperatures and the friction conditions of the joint components [12]. A failure of the joint can occur, if bolt preload falls below the minimum preload which is necessary to transfer the acting loads. Cyclic in-plane loads can cause a preload loss und thus a failure of the bolted joint. For this reason, their influence on the transferable loads is studied within this work.

2. Load transfer by friction

The load transfer by friction is investigated in principal on the basis of double-lap bolted joints, Figure 1. The necessary preload F_S is produced by tightening the bolt, thus the joint components are subjected to compression. Friction loads in the contact area of adjacent components enable the transfer of in-plane loads. The maximum transferable in-plane load $F_{ip,max}$ (= maximum static friction load) can be determined from a load balance at the joint using Coulomb's law of friction [5, 11, 17]:

$$F_{ip,max} = 2\,\mu_S\,F_S\ , \tag{1}$$

where μ_S is the coefficient of static friction (CSF). As long as F_{ip} is less or equal $F_{ip,max}$ the components stick together, if F_{ip} becomes greater than $F_{ip,max}$ sliding occurs and the joint fails. A further increase of F_{ip} is possible due to bearing [14], if the sliding process is continued until the contact of the bolt and the joint components.

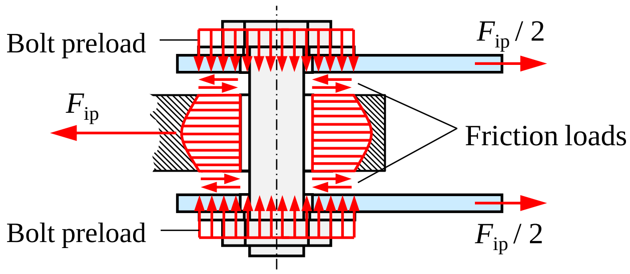

Figure 1. Transfer of in-plane load F_{ip} by friction in a double-lap bolted joint

A 3D finite element analysis [11] shows a local beginning of sliding in the contact area (see Figure 2 left). The related contact pressure shows basically a radial decreasing pressure distribution with increasing distance from the edge of the bolt hole (see Figure 2 middle). The related shear stress (see Figure 2 right) has reached the maximum in the areas of sliding, a further increase is not possible. It shows that most of the in-plane load is transferred at the edge of the bolt hole, where maximum contact pressure appear. The in-plane load can be increased until the remaining sticking areas begin to slide and the entire contact area slides.

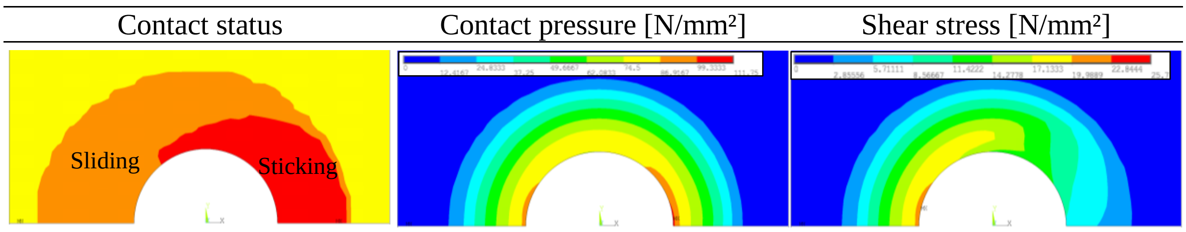

Figure 2. 3D finite element analysis of load transfer by friction at the transition from sticking to sliding with related contact pressure and shear stress [11]

The CSF is required to design pretensioned bolted joints. However the actual friction conditions of the joint's components can be very complex and depend on different parameters. That is why they are not always known in advance. Hence friction tests are advisable.
Primarily the CSF is a function of the material combination. An average value of 0.279 for carbon epoxy laminates with a smooth, untreated and cleaned surface is determined from static friction tests with double-lap joints [11]. As shown in this study, the surface condition and the presence of external mediums significantly influence the CSF. Furthermore, results indicate that the layup of laminates has no influence on the CSF. From tests with 2 to 14 kN bolt preload [11], friction tests using CFRP material combinations at low normal loads [7], frictions tests using CFRP epoxy specimens with metallic washers at normal loads up to 9 kN [10] as well as in general from the literature [17] can be concluded that for

most applications bolt preload has a negligible influence on the CSF. A dependence on temperature is expected, if properties of mating surfaces changes [17], e.g. in the region of glass transition of polymers. The CSF of CFRP materials can increase logarithmically with the contact time due to viscoelastic effects [4, 17]. A significant increase in CSF can be achieved by inserting an additional structured layer [8]. If sliding between the clamped parts occurs, signs of wear on the surfaces can arise [4], e.g. wear of matrix [15].

Bolted composite joints show a loss of preload due to different mechanism, which are important to consider in design process. The mechanisms can be divided in slackening (= preload relaxation), this includes embedding, creeping and plastifications, and self-loosening as a result of slackening [22]. The mechanisms themselves can appear sequentially or in parallel. Preload losses of bolted composite joints have been studied experimentally and numerically in several different scientific works [1-3, 6, 9, 11-13, 19, 20]. In particular the preload loss at increased temperatures due to matrix creeping has to be considered. Bolt preload measurements show a slight influence of specimens' layup at room temperature and enhanced influence at increased temperature (especially for unidirectional layups) [12]. Preload losses as a result of embedding can increase under cyclic loading (cf. [21]). All of these preload losses are important to know, but finally the maximum transferable load of the joint is decisive. This is the most relevant information for the designer of the load introduction.

3. Experimental investigations

The load transfer by friction under cyclic loading is studied using double-lap bolted joints. The aim is to transfer 90 % of the maximum static friction load over at least 1.7E6 load cycles without a failure.

3.1. Test setup

The specimens are preloaded by a standard ISO metric M 8 hexagonal head bolt (Figure 3 left). To ensure that the in-plane load is transferred solely by friction without bearing a through hole diameter of 10 mm is used. The bolt preload is measured by an embedded strain gauge inside the bolt's shank. In addition a commercial force washer from manufacturer Hottinger Baldwin Messtechnik with two load introduction washers is used to validate the preload measurement of the strain gauge. The double-lap joint is clamped into a servo-hydraulic testing machine (Figure 3 right). Temperature loads during the test can be produced by a surrounding environmental chamber.

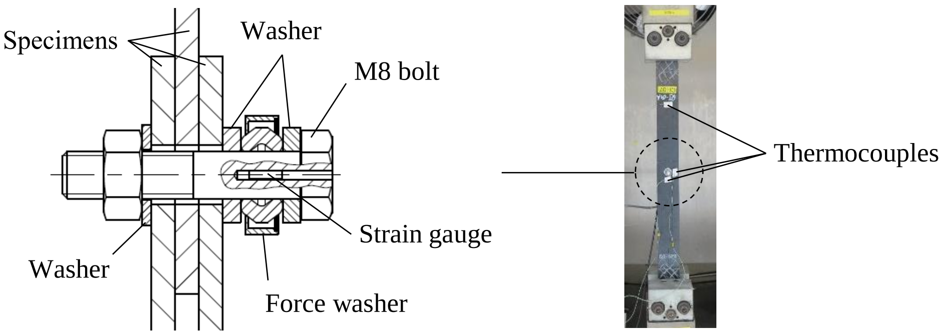

Figure 3. Section view of bolted joint (left) and test setup clamped into the testing machine (right)

3.2. Specimens

Carbon epoxy laminates (T700 fiber, 55 % fiber volume fraction) are available with three different layups: unidirectional (UD), biaxial fabric (0/90) and quasi-isotropic (QI) with a stacking sequence of $[0]_{4s}$, $[0/90]_{2s}$ and $[(0/90/\pm45)_2]_s$. Specimens are cut from a plate manufactured in an automotive RTM process, the dimensions are given in Figure 4. The 0°-direction is orientated in longitudinal direction of the specimen. Surfaces are very smooth and edges show a good quality.

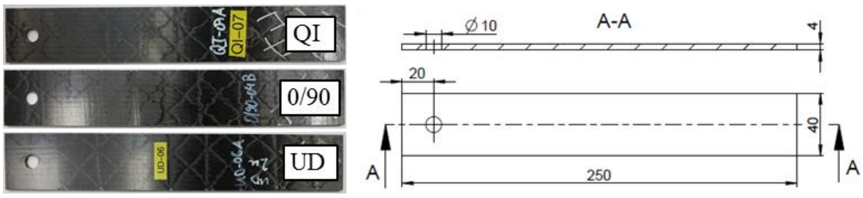

Figure 4. Test specimens (QI = quasi-isotropic, 0/90 = biaxial fabric and UD = unidirectional)

3.3. Test procedure

The influence of temperature T: 22, 45, 70 and 95 °C, load ratio n regarding static friction load: 70, 80 and 90 %, friction surface condition: rough, wet, oily and impregnated with an assembly paste and assembly preload F_M: 10 and 14 kN on the cyclic load transfer is investigated, Table 1. Parameters are varied based on a reference parameter set (CT01a-c). Each bolted joint consists of specimens from the same laminate and cyclic tests are conducted regardless of the layup (see chapter 2). Friction surfaces are cleaned using an alcoholic cleaner. Assembly preloads are set to desired value by observing the measured preload on measuring amplifier. Specimens are concentrically centered to their bolt holes and the bolt is centered to the bolt holes. The test frequency is 5 Hz at a load ratio of R = 0.1.

Table 1. Test plan for cyclic tests including assembly preload F_M, temperature T (RT = room temperature, ≈ 22 °C), load ratio n, upper cyclic load $F_{ip,cyc,u}$ and condition of frictions surfaces

Test	Spec.	F_M (kN)	T (°C)	n (%)	$F_{ip,cyc,u}$ (kN)	Friction surface	
CT01a	0-90	10	RT	90	4,680	Cleaned, untreated	
CT01b	QI	10	RT	90	5,382	Cleaned, untreated	Reference
CT01c	QI	10	RT	90	4,788	Cleaned, untreated	
CT02	UD	10	RT	80	3,856	Cleaned, untreated	
CT03	UD	10	RT	70	3,528	Cleaned, untreated	
CT04	0-90	14	RT	90	7,381	Cleaned, untreated	
CT05	0-90	10	RT	90	1,604	Oily (from Ballistol)	
CT06	QI	10	RT	90	3,168	Wet (Water)	
CT07	0-90	10	RT	90	6,390	Rough (abrasive paper, grade 400), Cleaned	
CT08	UD	10	RT	90	6,807	Assembly paste with micropearls	
CT09	QI	10	45	90	5,508	Cleaned, untreated	
CT10	QI	10	70	90	4,829	Cleaned, untreated	
CT11	QI	10	95	90	4,099	Cleaned, untreated	

A static friction test is conducted prior and after a successful cyclic test to determine the exact value of CSF for each bolted joint and the remaining transferable load after the cyclic test, Figure 5. Static tests are conducted at room temperature using a tensile testing machine.
The CSF $\mu_{s,stat,0}$ prior to cyclic test is calculated from the maximum transferable load $F_{ip,stat,0}$ and the bolt preload $F_{S,stat,0}$ before applying the in-plane load:

$$\mu_{s,stat,0} = F_{ip,stat,0} / (2\, F_{S,stat,0}) \;. \tag{2}$$

It is used to determine the upper cyclic load $F_{ip,cyc,u}$ from the load ratio n and the bolt preload $F_{S,cyc,0}$ prior to cyclic test according to equation (1):

$$F_{ip,cyc,u} = n\,(2\,\mu_{s,stat,0}\,F_{S,cyc,0})\ . \quad (3)$$

The bolted joint is completely disassembled after the friction test, cleaned and re-assembled inside the servo-hydraulic testing machine. The test setup is heated up to the desired temperature before applying the cyclic load. Preload measurement is only possible up to 80 °C, so the preload is not measured in cyclic test at 95 °C (CT11). The cyclic test is stopped earliest after 1.7E6 and latest after 2.0E6 load cycles.

After a successful cyclic test the bolted joint is dismounted from the clamping device of the servo-hydraulic testing machine without loosening the bolt and is subsequently clamped into the tensile testing machine. A CSF $\mu_{s,stat,0}$ can be determined also for this test:

$$\mu_{s,stat,1} = F_{ip,stat,1}\,/(2\,F_{S,stat,1})\ , \quad (4)$$

where $F_{ip,stat,1}$ is the maximum transferable load and $F_{S,stat,1}$ is the bolt preload before applying the in-plane load. The part of the specimens including the bolt hole is cut after this test and a new bolt hole is drilled for the next bolted joint to be tested.

The complete test procedure consisting of the cyclic test and the associated friction tests are depicted in Figure 5. The bolt preload and the in-plane load are schematically shown as a function of time and important values for test evaluation are marked. Since bolt preload depends on temperature, it is given at room temperature (solid line) and at increased temperature T > RT (dashed line).

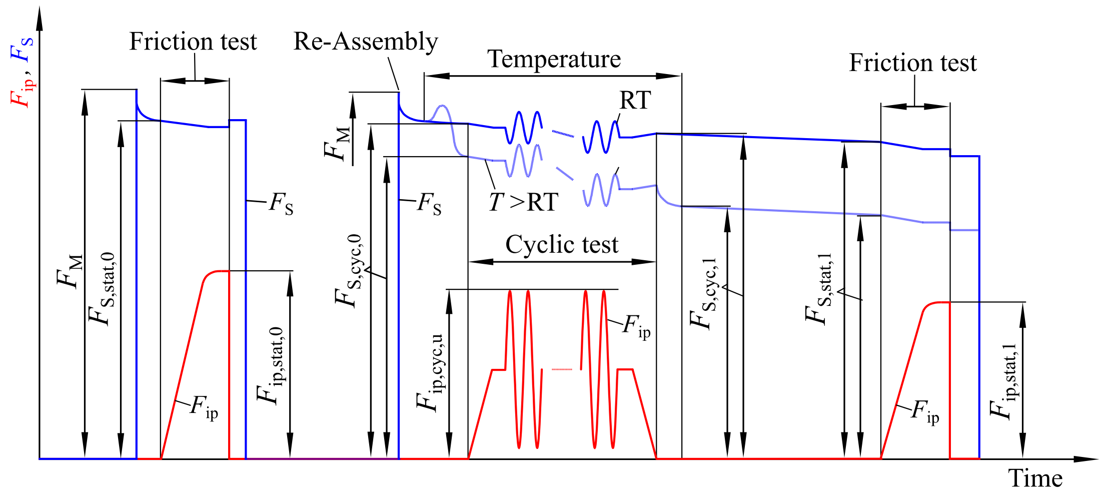

Figure 5. Test procedure with bolt preload F_S (blue) and in-plane load F_{ip} (red)

3.4. Results

Experimental results of cyclic and static friction tests are presented and discussed in the following paragraphs.

3.4.1 Coefficient of static friction prior to cyclic tests

The CSF $\mu_{S,stat,0}$ determined from friction tests prior to cyclic tests are summarized in Figure 6. The CSF of bolted joints with an untreated and cleaned friction surface are averaged (0.274) and compared to the other friction conditions. A rough surface and a use of an assembly paste increase the CSF to 0.355 and 0.382, whereas an oily or wet surface reduce it to 0.09 and 0.176. These values confirm the results from earlier static friction tests with double-lap joints [11]. The upper cyclic load $F_{ip,cyc,u}$ is individually calculated for each bolted joint from the associated CSF's (not from the averaged value above) according to equation (3).

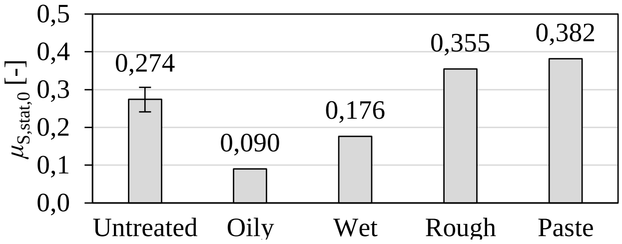

Figure 6. CSF $\mu_{S,stat,0}$ determined from static friction tests prior to cyclic loading depending on surface conditions (average for untreated and cleaned surfaces with min./max. deviation)

3.4.2 Cyclic loading

All tested double-lap joints reached the predefined minimum number of 1.7E6 load cycles without sliding or self-loosening. Measurements from a thermal imaging camera and the thermocouples reveal a temperature increase during cyclic loading of less than 1 °C, and thus a negligible self-heating of the specimens. The preload measurements show a reduction of bolt preload under cyclic loading. A relatively high preload loss of 36.8 % after cooling is observed for cyclic test at 70 °C (CT10), see bolt preload $F_{S,cyc}$ (blue line) in Figure 7 on the left. It can be seen that bolt preload falls below the theoretical minimum bolt preload $F_{S,cyc,min}$ which is necessary to transfer the upper cyclic load without sliding. Nevertheless the in-plane load is still transferred. A similar result is assumed for cyclic test at 95 °C (CT11), where preload loss should be greater than at 70 °C and also no sliding is observed.
Bolt preload losses are calculated from bolt preloads $F_{S,cyc,0}$ and $F_{S,cyc,1}$ prior and after cyclic loading (for tests with temperature load it is the bolt preload before heating and after cooling), Figure 7 right. A reference preload loss (Ref) is determined by averaging the preload losses of CT01a-c (with min./max. deviation). Preload losses of cyclic tests at 80 % (CT02), 70 % load ratio (CT03), 14 kN assembly preload (CT04) and a rough surface (CT07) are comparable to the reference preload loss. An increased preload loss is measured for an oily (CT05) and impregnated (CT08) surface. It is assumed that parts of these substances are partially pressed out of the contact region during cyclic loading and thus elastic deformations of the bolted joint are reduced. Considering a wet surface (CT06), probably most of the water is pressed out during assembly due to higher viscosity resulting in lower preload loss.

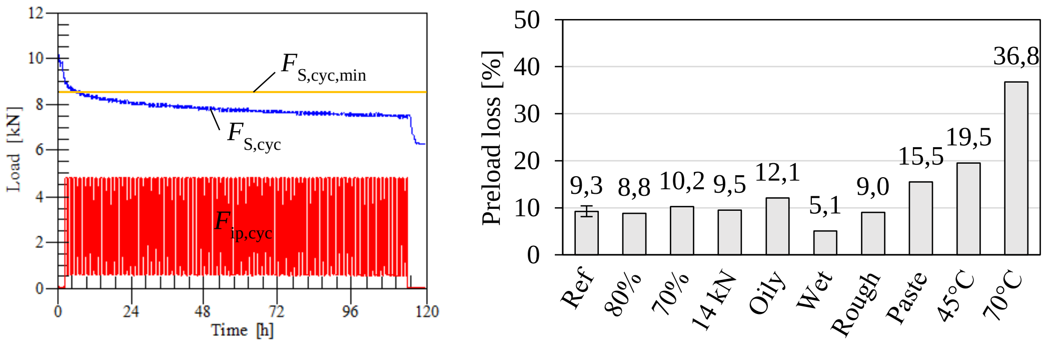

Figure 7. Bolt preload measurements during cyclic loading: cyclic test at 70 °C (left) and preload losses due to cyclic loading summarized for all cyclic test (right)

3.4.3 Transferable loads after cyclic loading

The maximum transferable loads after cyclic loading $F_{ip,stat,1}$ are compared to those from static friction tests before cyclic loading $F_{ip,stat,0}$ (see Figure 8 left). These depend on the bolt preload and the CSF (cf. equation (1)). An increase of transferable loads can be found – despite a reduction of bolt preload (see

Figure 7) – for cyclic tests with the reference configuration (Ref: CT01a-c), load ratio of 80 % and 70 % (CT02 & CT03), wet surface and assembly paste (CT06 & CT08). Cyclic tests with an oily and rough surface (CT05 & CT07), as well as tests at increased temperatures (CT09-CT11) show a decrease of the transferable loads. Latter results include the preload reduction due to cooling to room temperature (static friction tests are conducted at room temperature).
The CSF's $\mu_{S,stat,1}$ after cyclic loading are calculated using $F_{ip,stat,1}$ and $F_{S,stat,1}$ and the deviations to CSF's prior to cyclic tests $\mu_{S,stat,0}$ are given in Figure 8 on the right. From this figure it can be seen that CSF's increase with cyclic loading or remain nearly constant for cyclic tests with an oily and rough surface (CT05 & CT06). Contrary to the expectations, the CSF deviation of cyclic test with 14 kN (CT04) is with 11.9 % approximately only one third of those tests with 10 kN assembly preload and a cleaned, untreated surface at room temperature and thus it has to be validated in future tests. The increase of CSF for tests with a cleaned and untreated surface can be explained by the viscoelastic behavior of friction surfaces. The peaks of surface roughness are flattened under cyclic loading, so that the effective contact area increases resulting in an increased CSF. At the same time the bolt preload reduces due to the conversion of elastic in plastic deformations. Therefore the transferable load depends on the ratio of both mechanism: increase in CSF and decrease of bolt preload. The CSF deviations of tests with an external contact medium (water, oil, assembly paste) is more complex and needs deeper analysis in future.

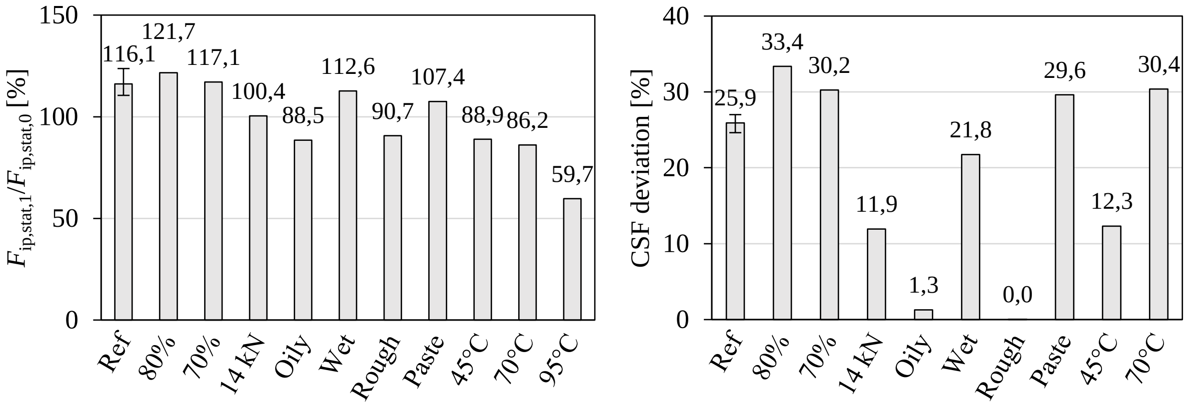

Figure 8. Left: ratio of maximum transferable in-plane load after and before cyclic loading, right: CSF deviation from after to prior cyclic loading

4. Conclusions

The experimental investigations with double-lap joints show that bolted composite joints are in principle well suited for cyclic in-plane loading independent of friction surfaces condition, load ratio and temperature. 90 % of maximum static friction load can be transferred for at least 1.7E6 load cycles for all tested joint configurations without any sliding failure. In particular, cyclic tests at 70 and 95 °C show that a possible increased preload loss causes no sliding failure, when the upper cyclic load is determined from the bolt preload after heating to the desired temperature. Preload measurements and the comparison of static friction tests before and after cyclic loading reveal an increase in CSF. It can be concluded that this increase, which is essentially due to viscoelastic properties of contact surfaces, compensates the preload loss during cyclic loading. Considering an untreated and cleaned surface an averaged CSF of 0.274 before cyclic loading is determined and it increases to 0.345 (+25.9 %) after cyclic loading. Also the transferable load has increased by 16.1 %. It is found that bolted composite joints under cyclic in-plane loading can be designed only by the CSF and the bolt preload prior to cyclic loading.
In future works the cyclic tests ought to be extended to bolted joints with CFRP and metallic components. The results of pretensioned bolted composite joints have to be compared to bonded and bolted joints to evaluate the lightweight performance especially for thin laminates.

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