Optimized threaded fastening of composite structures with dual flow of preload

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Introduction

More and more components made of long fiber reinforced plastics (composite laminates) are used for light components in vehicles, aircrafts and mechanical engineering like high speed machining centers, wind energy plants a.s.o. Always fastening of such components has to be focused in detail. In order to realize fast and reliable installation, maintenance or repairing also components made of composites have to be fastened mechanically. To meet these requirements often screw joints are suitable and fibers are oriented transverse to the screw axis. So the components are compressed perpendicular to the fibers when tightened. More information due to transverse force transmission see [1]. General information due to composite fastening with screws see [2].

Force-Elongation-Diagram

In this case the question has to be answered, what happens in the fastening system when theses structures are pre-tensioned. The well established Force-Elongation-Diagram (FED) has to be discussed and adapted, especially if a dual flow of preload is used. This paper deals with this situation and gives criteria for design of such threaded fastening systems. It is suitable to do so, because other literature sources do not deal with this constellation, but they provide many details of screw joints in general [3, 4, 5].

Fig. 1 shows the mechanical principle for a screw joint transverse to fiber orientation with a dual flow of preload through the clamped parts which is realized by using an additional sleeve. It also indicates the parallel arrangement regarding the closed flow of preload. So, different clamped parts are stressed at the same time when tightened (long fiber reinforced plastic and also sleeve). If the axial deformation is higher than Δf_0, then both stiffnesses c_{p1} and c_{p2} are arranged in parallel.

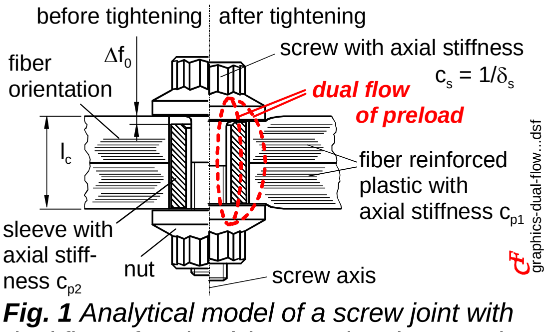

***Fig. 1** Analytical model of a screw joint with dual flow of preload (composite plates and sleeve); situations shown in figure: before and after tightening*

That means: $c_p = c_{p1} + c_{p2}$ (please note that the stiffness is the inverse value of the resilience which is normally used for calculation of bolted joints). Index 1 refers to the fiber reinforced plastic (laminate); index 2 refers to the sleeve. If the axial stiffness of sleeve c_{p2} is much larger than the axial stiffness of the long fiber reinforced plastic c_{p1}, then a large portion of the preload F_p and the axial operating load F_A of the screw joint is transmitted only by the sleeve and, therefore, protects the laminate from overloading.

Fig. 2 shows the corresponding FED with assumed linear behavior (that means no material in the closed flow of preload exceeds its yield point and no smoothening of surface roughness peaks takes place). The FED represents in axial direction the elongation/compression dependent on the axial force F_z. In the closed flow of preload after tightening the same force F_p (preload) elongates the screw and compresses the clamped parts (laminate and sleeve). At minimum it is used F_{pmin}.

It emphasizes that two gradient lines for the clamped parts exist (with gradients c_{p1} and $c_{p1} + c_{p2}$). The change in gradient is given by the undeformed length difference Δf_0 from Fig. 1. This means that the fastening system should be designed, so the operational load F_A and its separation into F_{SA} and F_{PA} is working completely in the region of steep gradient c_p (a steep gradient of clamped part reduces the load factor Φ).

The characteristic line for the clamped part can be expressed with the mathematical equations:

1. $0 < f_p < (f_{pmax} - \Delta f_0)$: $c_p = c_{p1} + c_{p2}$
2. $(f_{pmax} - \Delta f_0) < f_p <$ fpmax: $c_p = c_{p1}$

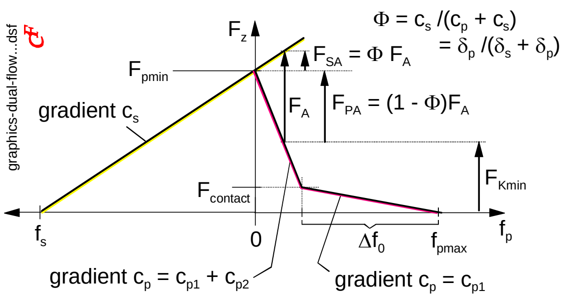

***Fig. 2** Corresponding Force-Elongation-Diagram FED of the threaded fastening system from Fig. 1 when tightened*

$F_{contact}$ is determined by the undeformed length difference Δf_0. The preload is separated within the clamped parts into two clamp loads F_{Kmin1}

and F_{Kmin2} for laminate and sleeve based on the ratio of c_{p1} and c_{p2}. F_{Kmin1} and F_{Kmin2} result in the same total clamp force $F_{Kmin} = F_{Kmin1} + F_{Kmin2}$ as for a flow of preload without sleeve. The clamp force plays a major role due to friction-based force transmission between components [1].

Criteria for determination of length difference Δf_0

Resulting from these considerations the design of the length difference Δf_0 is important, because it determines the behavior of the entire fastening system. So, it is necessary to have a guideline for finding the right value for Δf_0.

Three criteria should be considered:

1. provide sufficient compression force to guarantee working with a steep gradient for operating load. The safety margin from the change of stiffness is set to 1.5. This leads to
$F_{pmin} >= 1.5 \cdot \Delta f_0 c_{p1} + (1 - \Phi) \cdot F_A$
and transformed to Δf_0:
$\Delta f_0 <= (F_{pmin} - (1 - \Phi) \cdot F_A)/(1.5 c_{p1})$
2. limit the compression deformation in the laminate to 3% of clamp length l_c (think on allowed contact pressure and creeping behavior). This leads to
$\Delta f_0 <= 0.03\ l_c$
3. provide sufficient minimum clamp force $F_{contact}$ in the laminate (think on avoiding delamination at bore. It should be at least 20% of F_{Kmin}. This leads to
$F_{contact} >= 0.2 \cdot F_{Kmin}$
It follows from this
$c_{p1} \cdot \Delta f_0 >= 0.2 \cdot (F_{pmin} - (1 - \Phi) \cdot F_A)$
and transformed to Δf_0:
$\Delta f_0 >= (0.2(F_{pmin} - (1 - \Phi)F_A)/c_{p1}$

All criteria 1., 2., 3. have to be valid for a reliable design. This leads to the relations calculated above and needs a certain minimum clamp length l_c dependent on the axial operational load F_A because of Φ, Δf_0.

Calculation Example

The theoretical considerations above present a number of interdependencies between the geometric- and material data of the fastening system from Fig. 1. The following sample calculation presents important typical values for design in practice (input data in **Tab. 1**, results for single- and dual flow of preload in **Tab. 2**). The criteria for Δf_0 above are valid.

It has been calculated with [6]. Note that the load factor for single flow of preload is much higher than for dual flow (0.410 instead of 0.073) – this means app. 5.5x increase of screw loading for the same operation force F_A. Therefore, with dual flow of preload the danger of failure in fatigue can be reduced significantly or even be eliminated.

***Tab. 1** Input data for sample calculation*

screw type	M8, Titanium with UTS 1100 MPa, E_s = 110000 MPa, outer support diameter of head d_w 17.0 mm, corresponding nut
clamp length	l_c 16.0 mm
sleeve	made of Al_2O_3, inner diameter 8.5 mm, E_{p2} = 350000 MPa, outer diameter d_4 12.0 mm, length difference Δf_0 0.3 mm
clamped part	two carbon fiber plates, t 8.0 mm thickness each, Epoxy matrix, E_{p1} = 8000 MPa in transverse direction of fibers (in direction of screw axis)
tightening	Torque T_{tot} 28 Nm
loading	F_A 2500 N (axial; generates a stress amplitude in screw shank of 76 MPa for single flow of preload

***Tab. 2** Main results of sample calculation*

	single flow of preload (without sleeve)	dual flow of preload (with sleeve)
preload range $F_{pmin} \ldots F_{pmax}$ of screw directly after tightening*	18…27 kN*	18…27 kN*, portion laminate / sleeve 60% / 40%
load factor Φ; screw load F_{SA}	0.410; 1025 N	0.078; 195 N
contact pressure at laminate p_c	105 MPa	86 MPa
minimum clamp load at laminate	16.4 kN* (F_{kmin})	9.4 kN* (F_{Kmin1})

* consider also preload relaxation for operation

Conclusions

The investigation correlated significant advantages of dual flow of preload regarding effecttive fastening of laminates with quantitative criteria for improved design; main benefit is the variable compression level of the laminate and the reduction of load factor; this avoids overloading of the laminate and is recommended for pre-stressing transverse to fibers. Other aspects which are not covered in this paper are nonlinear numeric analysis with FEA, influences from tolerances as well as friction- and creeping behavior when designing threaded fastening systems with dual flow of preload; also the separation of clamp force between laminate and sleeve could not be presented in detail.

Literature

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