Fastener stiffness measurement methodology

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Abstract: The stiffness of fasteners is needed for calculation of crack growth and damage tolerance parameters for large aeronautical structures. Experiments were performed on single fastener specimens made of aluminium alloy joined by aluminium rivets. The joints were loaded in pairs to prevent secondary bending and the load was introduced by increasing steps to monitor the change in stiffness with the increasing load level. Various plate thicknesses from 1.2 mm up to 6 mm and different rivet diameter combinations were analysed based on the structure of L-410 NG airplane. The paper includes the results of quasi-static testing of the riveted joints and a comparison with analytical models. The modelled stiffness was on average 16% higher than measured values. Maximum analysed difference was 44% which means that the experiment is irreplaceable.

Keywords: Aluminium alloy; fastener; stiffness; experiment; aerospace.

1 Introduction

The structure of L-410 NG airplane developed by Aircraft Industries will be certified by damage tolerance philosophy. Therefore, finite element calculations are performed to analyze fatigue crack growth and residual strength of the structure in the vicinity of joints. The large and complex structure parts cannot be efficiently modeled with individual rivet meshing and various contact parameters. Consequently, a rivet is substituted by a virtual spring with a stiffness parameter. This simplification is making the modelling much more time efficient.

2 Material and Methods

Specimens for the experiment were made of aluminum alloy D16čATV for series 1, 2, and 4, and aluminum alloy 7475 T7351 for series 3 and 5. The rivets were made of an aluminum alloy with the diameters and eventual countersink according to Tab. 1. The specimens were tested in pairs to prevent secondary bending (Fig. 1). Doublers were used to compensate the thickness of the samples that were attached to each other during the test (Fig. 2a). Each series consisted of 3 pairs of samples and the results were averaged. Loading was controlled by force that was introduced in increasing steps according to Ref. [1] as shown in Fig. 2b.

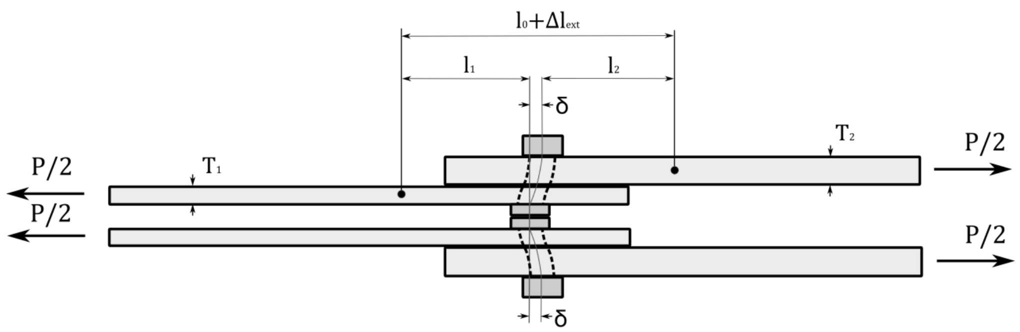
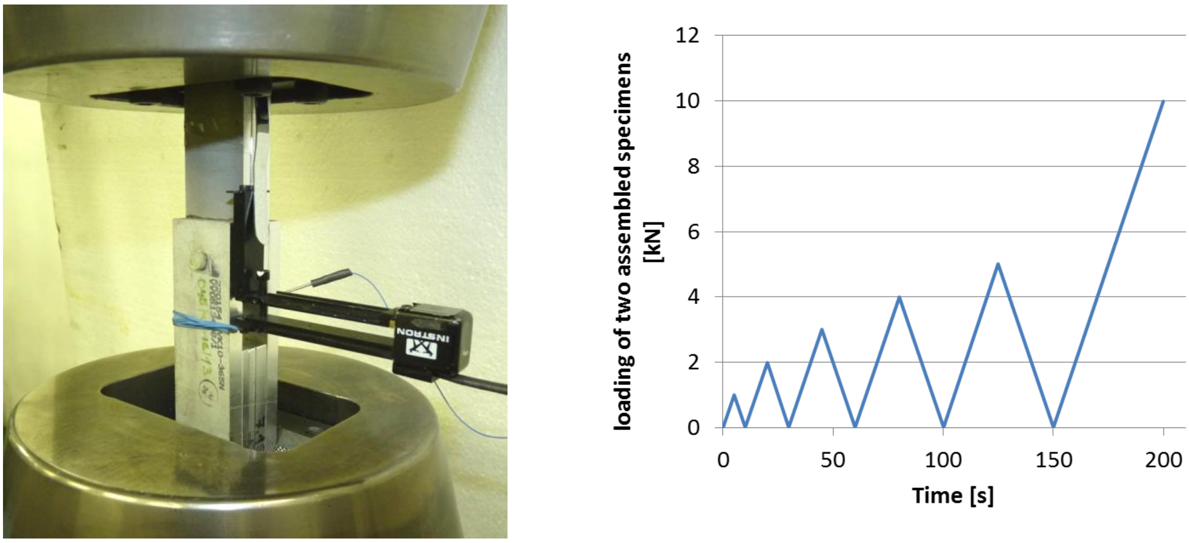


Fig. 1: Configuration of the stiffness measurement on two specimens tested simultaneously.

This type of loading can show the joint behavior even after certain rivet settling. The elastic deformation of joined parts over the 50 mm extensometer base was calculated and subtracted from the total deformation to evaluate only the local fastener flexibility. The fastener flexibility is a measure of the influence of fasteners on the flexibility of the whole joints. It plays an important role when considering the factors influencing the strength level and fatigue life of an aircraft joint. The flexibility f is reciprocal value of stiffness K:

$$flexibility\ (f) = \frac{1}{stiffness\ (K)} = \frac{\delta}{P} \quad (1)$$

in which P refers to the external force applied to a single fastener (P/2 in case of paired testing) and δ to the deflection of the joint due to the fastening.



a) Test set-up with attached extensometer.

b) Introduced loading.

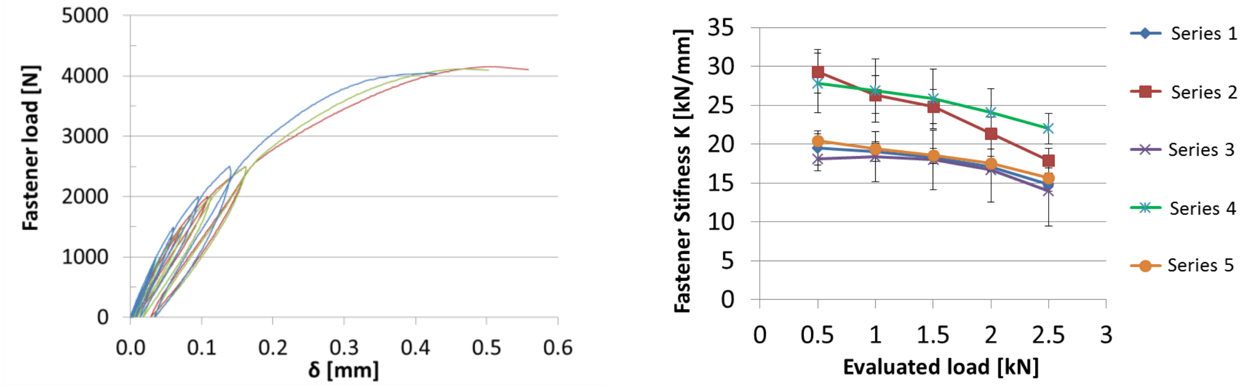
Fig. 1: Stiffness measurement test set-up and loading.

3 Results

In total 30 specimens were tested divided to 5 series. Typical loading curve with loops is visible in Fig. 2a. The parameters for each series of joints and the average stiffness measured for various loop load levels is included in Tab. 1. The stiffness K was evaluated for the increasing load of each loop. Generally, K was linearly decreasing with the increase of load level of loops (Fig. 2b). Series 2 had significantly higher stiffness than series 1 even for lower fastener diameter. It could be explained by the sealant effect that affect the gap between connected parts and thus cause the stiffness difference.

Tab. 1: Specimen parameters and measured average stiffness K for various load levels.

series no.	T_1 [mm]	T_2 [mm]	rivet diameter [mm]	countersink [yes/no]	average stiffness K [kN/mm]				
					0.5 kN	1 kN	1.5 kN	2 kN	2.5 kN
1	2	1.2	3.5	y	19.5	19.0	18.3	17.1	14.9
2	2	1.2	3	y	29.3	26.4	24.8	21.4	17.9
3	4	1.2	3	y	18.1	18.4	18.0	16.7	14.0
4	2	1.2	4	n	27.8	26.9	25.8	24.1	22.0
5	6	1.2	4	n	20.4	19.4	18.5	17.5	15.7



a) Typical loading curves.

b) Measured stiffness based on load level.

Fig. 2: Stiffness measurement test set-up parameters and a picture of a configuration.

Fig. 3 shows typical fracture of a joint with visible dark sealant area and a fastener failed surface. The bearing was approximately 0.5 mm and the failed surface of the fasteners was smooth and flat. The sealant covered both fracture faces.

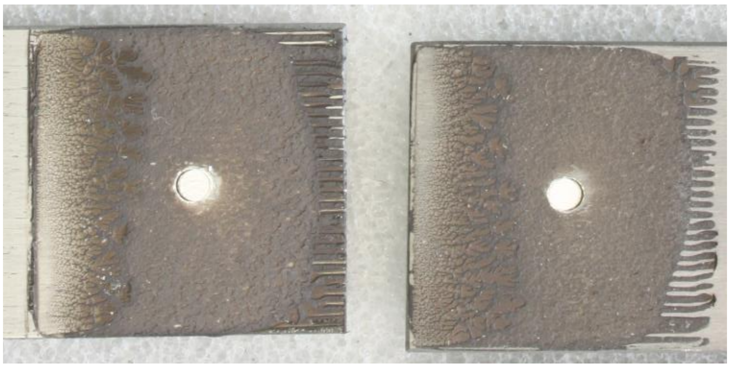


Fig. 3: Typical fracture of a joint with visible dark sealant area and a fastener failed surface.

4 Model comparison and discussion

Several models for stiffness were retrieved from Ref. [2, 3]. Five models are expressed below as equations for stiffness f where E and E_f are Young modulus of the sheet material and the fastener, respectively; D is rivet diameter and μ is Poisson number of the sheet material. The equations are not in general form but they were simplified for single shear riveted joints with same sheet material for both parts. Barrois model, that distinguishes free heads and clamped heads, was evaluated by reading values from graphs included in Ref. [4].

Boeing I:

$$f = \frac{1}{K} = \frac{1}{ED}\left[5 + 0.8\left(\frac{D}{T_1} + \frac{D}{T_2}\right)\right] \tag{2}$$

Douglas (Swift):

$$f = \frac{1}{K} = \frac{5}{DE_f} + 0.8\left(\frac{1}{T_1 E} + \frac{1}{T_2 E}\right) \tag{3}$$

Tate & Rosenfeld:

$$f = \frac{1}{K} = \frac{1}{T_1 E_f} + \frac{1}{T_2 E_f} + \frac{1}{T_1 E} + \frac{1}{T_2 E} + \frac{32(T_1+T_2)(1+\mu)}{9E_f \pi D^2} + \frac{8\left(T_1^3+5T_2^2 T_1+5T_2 T_1^2+T_1^3\right)}{5E_f \pi D^4} \tag{4}$$

Boeing II:

$$f = \frac{1}{K} = \frac{2\left(\frac{T_1}{D}\right)^{0.85}}{T_1}\left(\frac{1}{E} + \frac{3}{8E_f}\right) + \frac{2\left(\frac{T_2}{D}\right)^{0.85}}{T_2}\left(\frac{1}{E} + \frac{3}{8E_f}\right) \tag{5}$$

Huth:

$$f = \frac{1}{K} = \left(\frac{T_1+T_2}{2D}\right)^{2/5} 2.2\left(\frac{1}{T_1E} + \frac{1}{T_2E} + \frac{1}{2T_1E_f} + \frac{1}{2T_2E_f}\right) \quad (6)$$

The modelled stiffness was on average 16% higher than measured stiffness for 0.5 kN load as is shown in individual comparisons in Tab. 2. Maximum analyzed difference was 44%.

Tab. 2: Relative difference between a modelled stiffness and the measured stiffness K for 0.5 kN load.

Series	Boeing I (2)	Douglas (3)	Tate&Rosen. (4)	Boeing II (5)	Huth (6)	Barrois (clamped)	Barrois (free)
1	32%	32%	13%	36%	13%	48%	-37%
2	-11%	-11%	-43%	-1%	-39%	9%	-91%
3	36%	36%	-6%	45%	15%	44%	15%
4	10%	10%	-18%	11%	-18%	28%	-88%
5	42%	42%	-3%	46%	10%	48%	26%
Median	32%	32%	-6%	36%	10%	44%	-37%

These significant differences were also reported in Ref. [2] where the measured and modeled stiffness differed by factor of 2 up to 10. This can be explained by the fact that the equations were developed internally in commercial companies where various geometry, technology and materials were used. Also the test set-up and method of data evaluation is not known for the models. In terms of fatigue crack modelling, the modeled stiffness, that was generally higher than measured, is not on the safe side. This is because the crack faces would be hold open in the stiffer configuration and the modelled crack growth would be slower than in reality. Tate & Rosenfeld model seems to be the most suitable for this case.

5 Conclusion

To conclude, the results of quasi-static testing of riveted joints showed that the modelled stiffness was on average 16% higher than measured values that is not on the safe side considering fatigue crack growth modelling. Maximum analysed difference was 44% which means that the experiment is irreplaceable for precise stiffness related calculations needed for aerospace structures.

Acknowledgement

This work was funded by the Technology Agency of the Czech Republic, project no. TE02000032.

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