EXPERIMENTAL INVESTIGATION OF FATIGUE BEHAVIOUR IN COMPOSITE BOLTED JOINTS

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SUMMARY: This paper presents an experimental investigation of fatigue behaviour in composite joints. Composite plates were bolted by six fasteners made of titanium or composite material. The specimens were subjected to fatigue loading with stress ratio, R=–1. Several methods of measurement were used to investigate the fatigue behaviour. Strain-gauge measurements were done to analyse strain distribution and load transfer between bolt rows. An extensiometer was used to observe bolt-movement mechanisms. The fatigue behaviour of specimens with titanium fasteners has shown that they have excellent fatigue-resistance properties. Fatigue analysis determined that specimen failure was generally due to bolt failure. The bolt movement was found to increase measurably throughout the fatigue life. Strain-gauge measurements have shown that the different bolt rows transfer not the same amount of applied load due to fatigue degradation at the bolt rows.

KEYWORDS: bolted joints, fatigue, strain, load transfer, bolt movement.

INTRODUCTION

Mechanically fastened joints are often used to join composite materials in aircraft structures. They have an advantage over adhesive joints in regard to joining of thick structures which are difficult to bond. Furthermore, mechanical joints are the most preferable solution in cases where the need for component disassembly is required. They can be detached without damaging the structural members, making repair possible. However, mechanical joints also have disadvantages, the main one being that bolt holes cause stress concentrations which reduce the resistance of the joint construction to applied loads, and thus its efficiency. Loading conditions, such as type of loading and load configuration, are one of the most important factors in designing a joint in a structure. Most published papers deal with the influence of geometry parameters, material system, and joint configuration on the fatigue performance of composite joints [1-8]. However, fundamental understanding of fatigue behaviour in joints, and particularly, the influence of individual parameters on joint fatigue resistance is not complete. Therefore, it would seem that further investigations are needed in order to provide modern aircraft structures with efficient mechanical joints.

The objective of this study were to obtain experimental data on the fatigue behaviour of specimens with different fastener systems. This includes to study failure mechanisms during fatigue tests at different load levels. Load transfer between parts of the joint have been measured. Strain distribution between bolt rows have been analysed by strain measurements. Bolt-movement measurements have been done to analyse the fatigue process.

EXPERIMENTAL PROCEDURE

Specimen plates were manufactured from carbon fiber/epoxy material system (HTA7/6376) with the lay-up $[(\pm 45, 0, 90)_{12}]_S$. The composite plates were joined by six fasteners of three different types: composite (ACF), titanium Torque-set, and Huck-comp. The specimen geometry and fastener types are shown in Fig. 1.

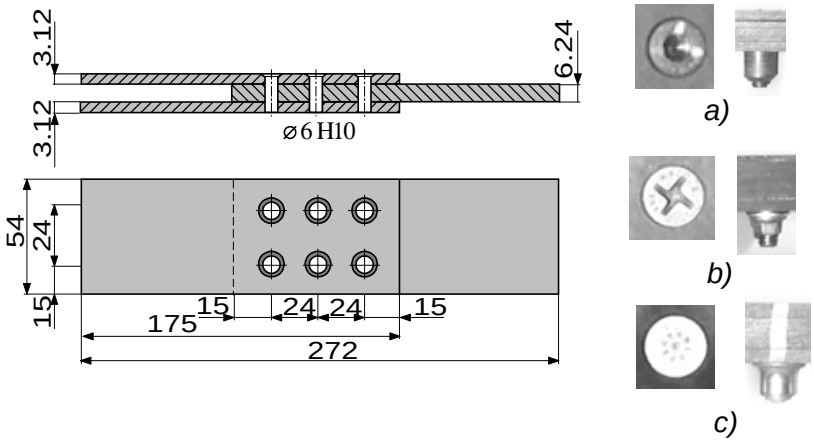


Fig. 1: Specimen configuration and fastener types:
a) composite; b) Torque-set; c) Huck-comp

Specimens with Torque-set bolts were fastened by 9 Nm torque. Huck-comp fasteners were installed using a special hydraulic machine. The composite fasteners were designed in such a way that the part, where the torque was applied, broke off when sufficient torque had been applied. The average amount of that torque was equal to 2.7 Nm.

An extensiometer was used to measure bolt movement during fatigue loading as shown in Fig. 2 a. Strain gauges were used for measuring strain distribution of the specimens during fatigue tests. Their locations on the top plate with countersunk cut-outs are shown in Fig. 2 b.

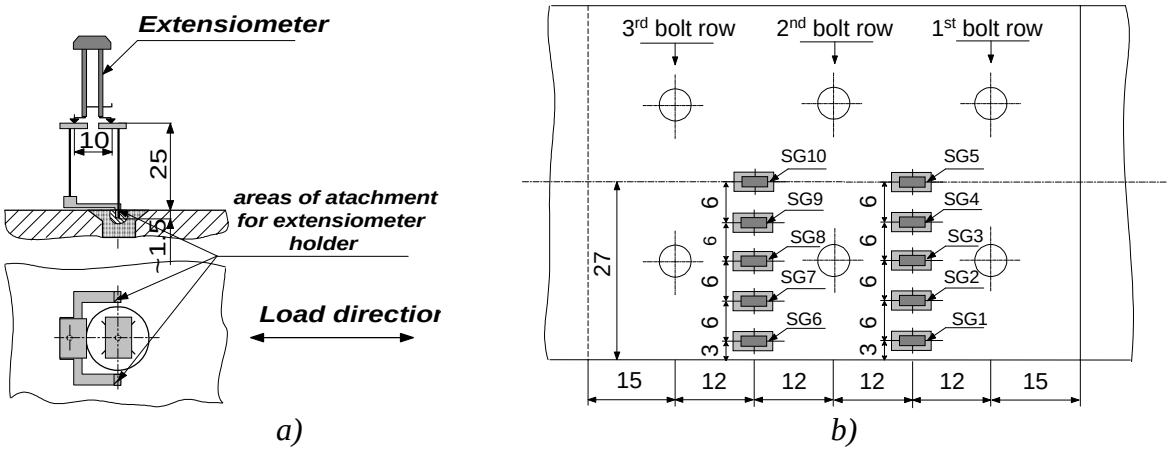
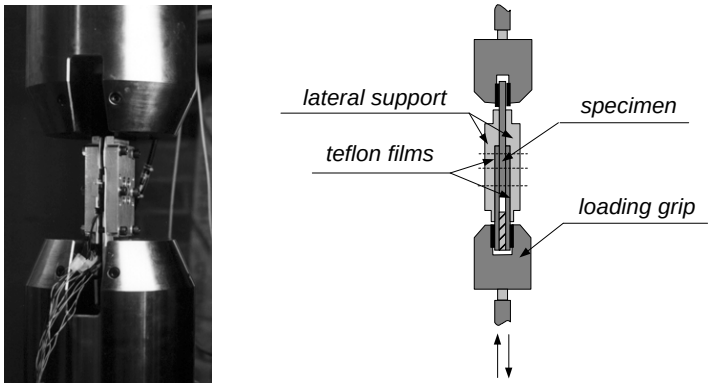


Fig. 2: Applications of extensiometer (a) for bolt-movement measurement and (b) strain gauges

The machine grips with the specimen are shown in Fig. 3.



a) *b)*

Fig. 3: The testing machine grips with the specimen and lateral support: a) picture illustration; b) schematic specimen loading configuration

To prevent specimen bending and out-of plane deflections, an aluminium lateral support was mounted on the specimen as shown in Fig. 3 b. The specimen plates and the support were interleaved with teflon sheets to decrease the friction force between them. Fatigue tests were done with stress ratio, $R=-1$, where $R=\sigma_{min}/\sigma_{max}$. The experiments were carried out at room temperature. The testing machine was set to stop fatigue loading when the grip-displacement limit was reached and failure was thus assumed to have occurred. This limit was determined by adding 0.4 mm to the initial deflection magnitudes of the specimen during compression and tensile parts of the load cycle. The frequency of fatigue tests was limited by a maximum bolt temperature of +33°C, in order to make sure heating did not occur in specimen.

RESULTS AND DISCUSSIONS

Fatigue test results

The load levels for fatigue loading were determined from the quasi-static tests. The joints were tested at different fatigue load levels of the corresponding quasi-static tensile strength. Basic fatigue results are summarised in Table 1.

Table 1: Fatigue test results

Specimen number	Fastener type	Load level (kN/%)	Number of cycles to failure	Failure mode
2.0-2	ACF	±46.5/50%	299	Bolt failure
2.0-3	ACF	±23.1/25%	2800488	Bolt failure
2.1-1	ACF	±37.2/40%	3275	Bolt failure
2.1-2	ACF	±30.3/33%	212178	Bolt failure
2.1-5	Torque-set	±59.0/50%	115132	Bolt failure
2.1-6	Torque-set	±88.4/75%	1579	Bolt failure
2.1-7	Torque-set	±88.4/75%	3277	Bolt failure
2.3-6	Torque-set	±59.0/50%	146909	Bolt failure
2.3-1	Huck-comp	±59.0/50%	2077033	Bolt failure
2.3-2	Huck-comp	±88.4/75%	24682	Net-section
2.3-3	Huck-comp	±88.4/75%	22349	Bolt+net-section
2.3-4	Huck-comp	±69.5/59%	955982	Net-section
2.3-5	Huck-comp	±103.0/87%	6089	Bolt+net-section

As can be noted in the table, in fatigue tests the dominating failure mode was bolt failure. In Fig. 4 the fatigue-life results are presented by applied stress versus number of cycles curves.

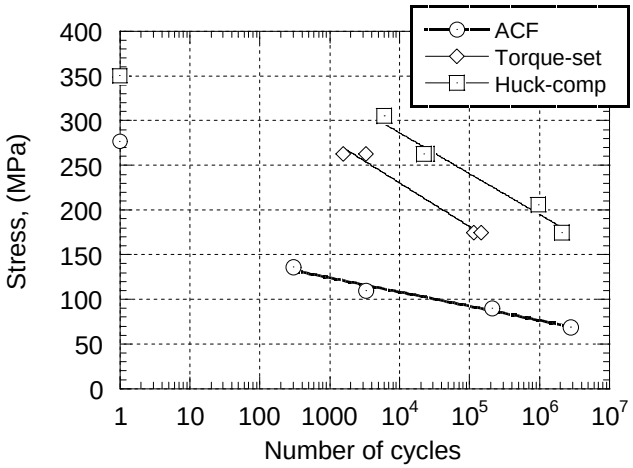


Fig. 4: Applied stress versus number of cycles curves for fatigue specimens

As can be seen, the specimens bolted by metal fasteners (Torque-set and Huck-comp) yielded the same static strength which is higher than that of the specimen jointed by composite (ACF) bolts. Both specimens with metal fasteners broke in the same failure mode, that is net section through the third bolt row; whereas the specimen with ACF bolts failed due to bolt failures during its quasi-static loading. The overall results indicate that the fatigue life of specimens with Huck-comp fasteners was generally longer than that for specimens with Torque-set and composite fasteners. Specimens with ACF fasteners exhibited the lowest fatigue resistance. A possible explanation for the low fatigue resistance might be found in low mechanical properties of composite bolts to support shear loading since all joints bolted by this type of fasteners failed due to bolt-failure mode at low fatigue load levels (see Table 1). An example of the tested specimen with composite bolts is presented in Fig. 5 a.

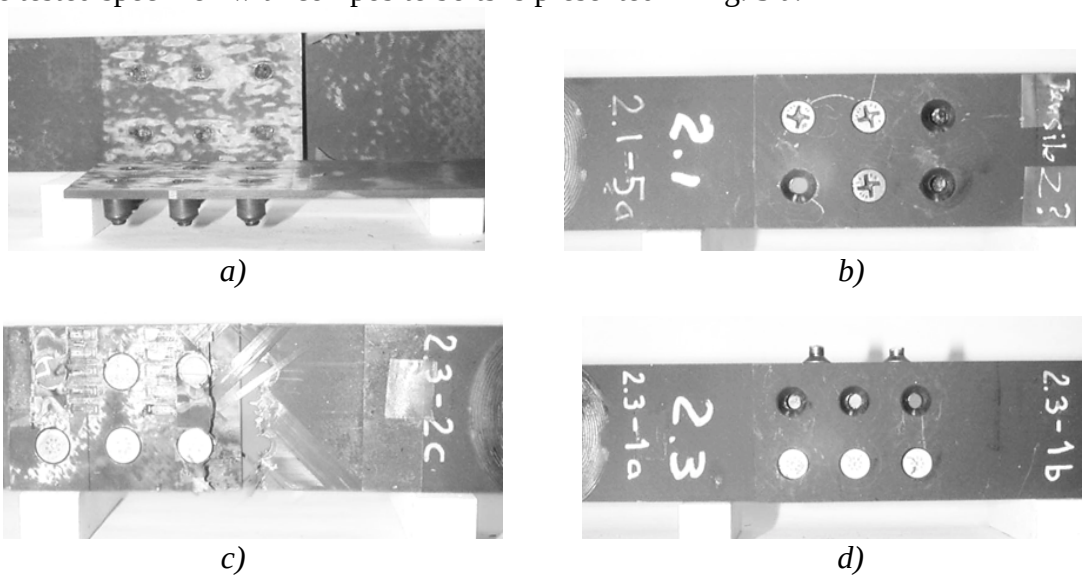


Fig. 5: Pictures of fatigue tested specimens:
a) ACF fasteners (50% load level);
b) Torque-set bolts (50% load level);
c) Huck-comp fasteners (75% load level);
d) Huck-comp fasteners (50% load level)

This specimen was tested at 50% load level and its bolts were sheared off in three pieces by the composite plates. Figure 5 b shows typical mode of failure for specimens fastened by Torque-set bolts. These specimens failed after at least two of the bolts had broken. As the fatigue tests showed, the specimens bolted by Huck-comp fasteners which were tested at load levels higher than 50% usually failed in two failure modes, bolt and net-section ones (see Fig. 5 c). However specimen 2.3-1 tested at 50% load level broke due to only bolt failures. The difference in failure mode of specimens with Huck-comp and Torque-set fasteners might be related to the prestress in the bolts. It is reasonable to assume that the Huck-comp fasteners have a higher prestress than the Torque-set bolts. This would result in more load being transferred between the specimen plates by friction for the specimens with Huck-comp fasteners than those with Torque-set. As a result the oscillating stress is lower in the Huck-comp fasteners and their fatigue life increases. Therefore, the specimens fail in net-section before the fasteners break and the fatigue life of the specimens increases.

Load transfer during fatigue life

Load transfer (LT) was calculated by integrating measured strain. The calculated results of LT-ratio for specimens with Torque-set bolts and Huck-comp fasteners are presented in Fig. 6 a and b, respectively.

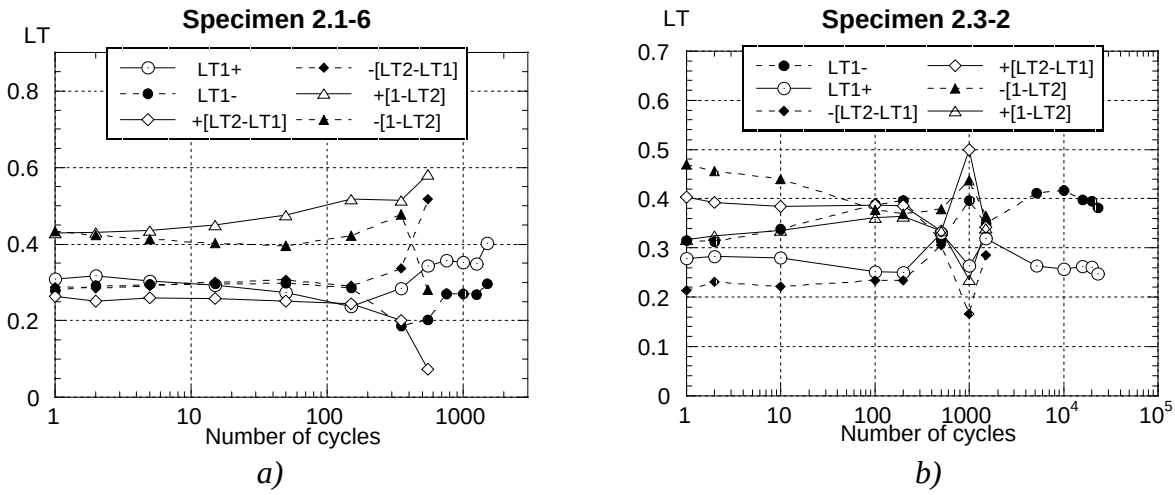


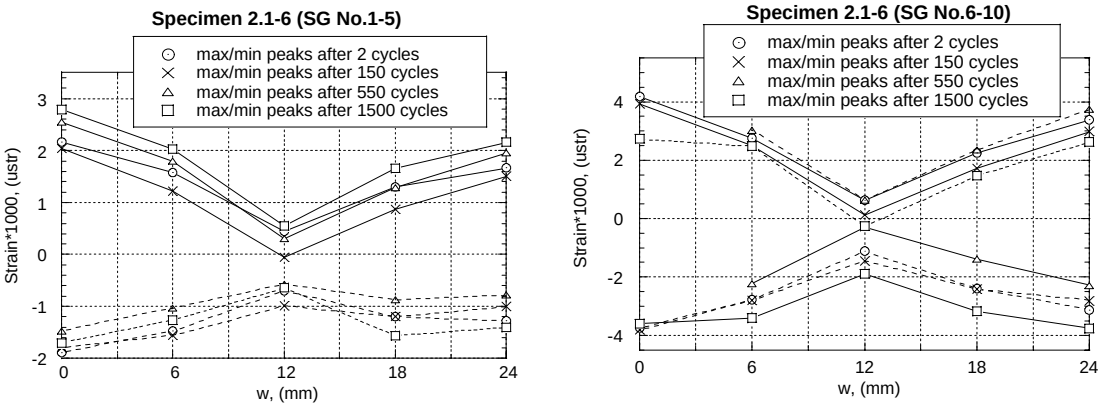
Fig. 6: Load-transfer ratio for specimens with (a) Torque-set and (b) Huck-comp fasteners

The [LT1+] and [LT1-] are the load-transfer values for the bolt row to the right in Fig. 1. The positive sign [LT1+] is for the peak tensile load and [LT1-] is for the peak compressive load. Load transfer for the middle bolt row is [(LT2)-(LT1)] for the peak tensile load and corresponding expression for the compressive load. Load transfer for the left bolt row in Fig. 1 is [1-(LT2)]. The LT-ratio plots show that the bolt rows did not transfer the same amount of applied load. As shown by the [1-(LT2)] curves for the specimen fastened by Torque-set bolts, the third bolt row transferred the highest part of the applied load during the specimens fatigue life (see Fig. 2 a). It is highly probable that fracture processes would occur in that bolt row which was much more loaded than the others. According to visual observation, both bolts from the third bolt row were often found as broken at the end of fatigue test. The LT-ratio curves for the specimen joined by Huck-comp fasteners show less variation of the load transfer between different bolt rows during the fatigue loading. However, as the curves for both specimen types show, the load transfer did not stay at the initial value which had been achieved at the beginning of the fatigue test. As fatigue loading proceeded, the LT-ratio

decreased or increased depending on which bolt row is considered. Fatigue damage at the bolt rows, such as hole wear, reduction in prestress in the bolts, fracture processes in some of the fasteners, developed rapidly during the cycle loading. This can be expected to affect the load transfer of the bolt rows. Additionaly, due to misalignment of the bolt holes the clearence between bolts and bolt hole varied for different bolts, and as a result this would probably affect the load transfer as well.

Strain distribution during fatigue life

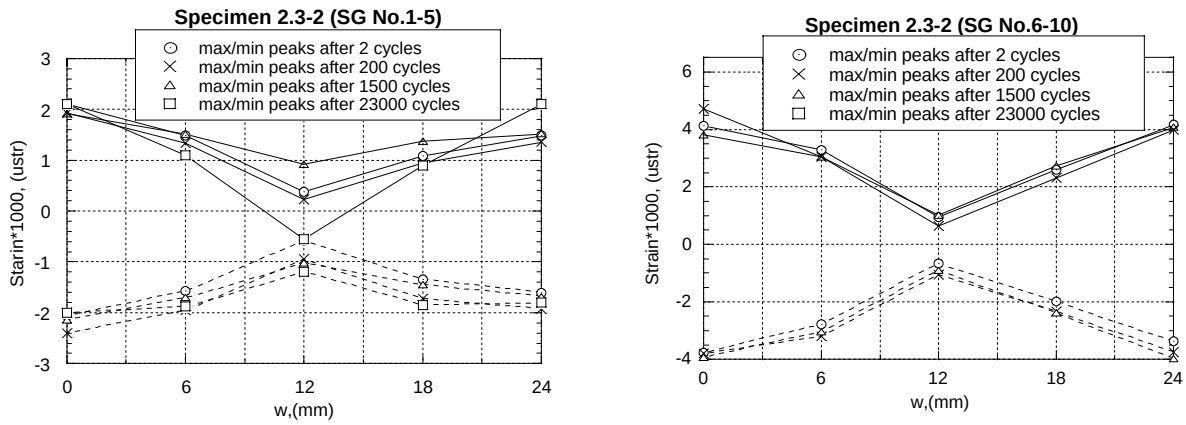
Figure 7 includes plots of strain distribution after different number of cycles for specimen 2.1-6 with Torque-set fasteners. Strain-gauge data are plotted as markers and as a function of position, where zero position is in the specimens center.



a) *b)*

Fig. 7: Strain distribution during fatigue life of specimen with Torque-set bolts: a) strain gauges No.1-5; b) strain gauges No.6-10

As can be seen, strain between the first and second bolt rows is lower than that between the second and third bolt rows. The minima of strain are for strain gauges No.3 and No.8 located between two bolts in the same bolt column (see Fig. 2 b). During the first cycles the highest strain occurs at the center line and edge of the specimens. However, as fatigue loading proceeded, the volume of fatigue damage at the bolt rows increased, which affected the load transfer of the bolt rows. As a result the strain distribution changed because different bolt rows, or even different fasteners, did not transfer the same amount of the applied load. The strain-distribution plots for specimen 2.3-2 with Huck-comp fasteners are plotted in Fig. 8.



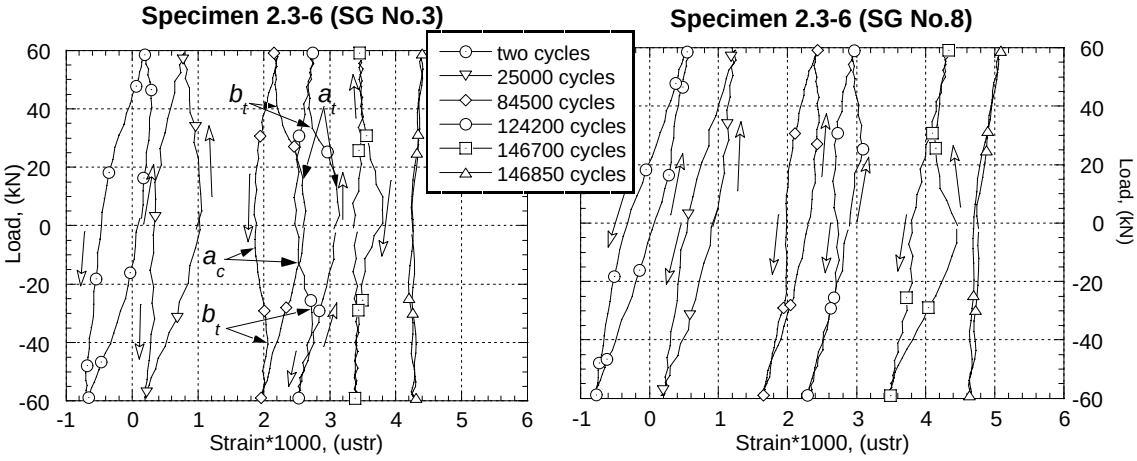
a) *b)*

Fig. 8: Strain distribution during fatigue life of specimen with Huck-comp fasteners: a) strain gauge No.1-5; b) strain gauge No.6-10

They show the same maxima and minima of strain comparing with the specimen bolted by Torque-set fasteners. However, if comparing the strain distribution at the beginning with that at the end of the fatigue test, it is possible to note that the strain variations do not differ as much at these stages of the fatigue test as was found for the specimen with Torque-set bolts mentioned above. It could be due to that different mode of failure occurred for the two types of specimens. The specimen fastened by Huck-comp fasteners failed in net section, whereas the specimen bolted by Torque-set bolts failed due to bolt-failure mode. Thus, the strain distribution between the bolt rows for the specimen with Huck-comp fasteners was less affected by fatigue damage propagation at the bolt rows since net-section mode is a material mode of failure. Thus, it can lead to that the strain distribution between the bolt rows is less affected by fatigue for specimens with Huck-comp fasteners than for specimens fastened by Torque-set bolts.

Strain-gauge loops

It has been found that strain gauges located between two bolt holes will behave differently compared with other strain gauges when loading is applied. Therefore, strain gauges No.3 and No.8 are plotted after different number of cycles in Fig. 9 for specimen 2.3-6 with Torque-set bolts. The different loops have been shifted with 1000 μstr to facilitate their observation. The arrows with blank heads indicate the direction of the loops.



a) *b)*

Fig. 9: Strain gauge No.3 (a) and No.8 (b) loops after different number of cycles

The plots show that there are several subtle changes in strain gauges No.3 and No.8 loops. After 25000 cycles, it is possible to define some accents of inflections in the SG No.3 loops, but they are much more visible in the following loops(see points (*a*) and (*b*) in Fig. 9 a). Subscript marks, *t* and *c*, correspond to tension and compression parts of the load cycle. It can be assumed that during loading from zero load until the first point (*a*) some load is transferred between the specimen plates by friction. Then, as loading proceeded, the plates began to apply more load on the bolts inducting their bending. The next point (*b*) corresponds to a moment when the bolt bending became restricted by the countersunk hole surface. In the beginning of the test some load is transferred by friction between the specimen plates. This would cause the inflection points to be softer. As the number of cycles increased, the prestress in the bolts is reduced due to the hole degradation, and as a result, more load is transferred by the bolts, inducting the inflection points to be sharper. However strain gauge No.8 loops do not show the same changes as SG No.3 (see Fig. 9 b). The loops do not show any more or less visible

inflection points, only the area under the loops and their contour show that small changes occur during the test. This could be due to the initial difference in the bolt clearance. But, the last two loops look different compared with previous ones, and they look very similar to SG No.3 loops plotted after the same number of cycles. It could be due to some of the bolts broke during this part of the test, and as a result, it would affect the strain-gauge loops.

Bolt-movement measurements

Figure 11 includes the results of bolt-movement measurements for specimens with all types of fasteners: specimen 2.1-2 with ACF bolts, specimen 2.3-6 with Torque-set bolts, and specimen 2.3-2 with Huck-comp fasteners. The open marks reflect bolt-movement data, whereas the filled marks represent grip-displacement data.

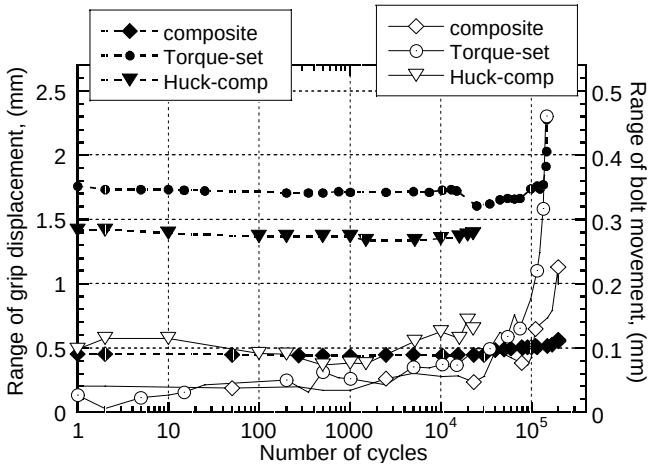


Fig. 10: Bolt movement versus number of cycles curves for specimens with different types of fasteners

The plots show almost the same behaviour of the bolt movement and the grip displacement throughout the fatigue tests for all specimens. The initial decrease in both curves for each specimen could be due to an increase of coefficient of friction between the composite plates. Following increase can be explained by reduction in prestress in the bolts and as a result the bolt could move with higher amplitude of movement. The increase in both curves could also be due to bolt-holes degradation. Because of the removal of fatigue debris, the clearance between the hole and bolt would increase, thus, producing more available space for movement of the bolt. These debris could also cause a decrease in bolt movement at the beginning of the test by filling up available space between the bolt and hole surface. Later, the debris would be transported out of the hole, thus, increasing the clearance in the hole. The plots show that at the end of the tests the bolt movement and grip-displacement curves follow each other. In other words, test behaviour of the bolts would reflect fatigue behaviour of the specimens under cyclic loading. In Fig. 11, the evolution of bolt movement is presented by displaying measured load versus bolt-movement loops after different number of cycles for specimen 2.3-6 with Torque-set bolts. The different loops have been shifted with -0.2 mm to facilitate their observation. The arrows with blank heads indicate the direction of the loops.

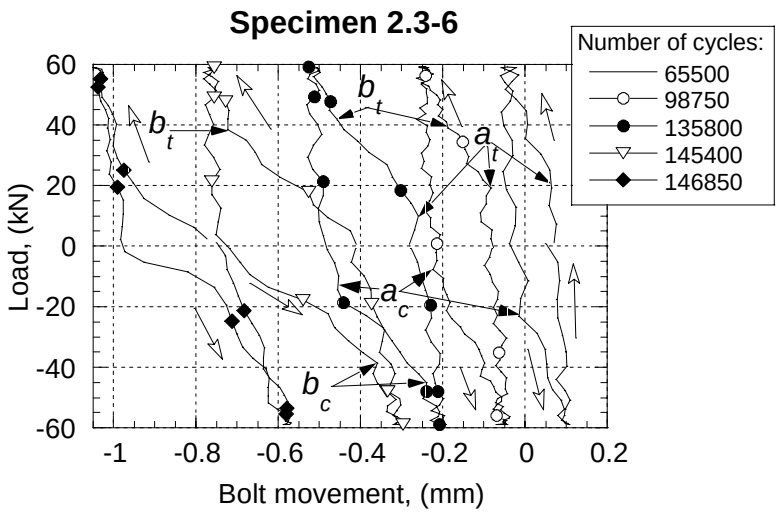


Fig. 11: Bolt-movement loops for specimen 2.3-6 after different number of cycles

As can be seen, the bolt-movement loops show that there are some subtle changes in their shape. After approximately 65500 cycles, the loop can be divided into several different stages which occur during one load cycle. Consider unloading from maximum or minimum load, until points (*a*), the load was mostly transferred by friction between the specimen plates; therefore the amount of bolt movement is not significant at this stage. Points (*a*) in the loops probably correspond to a moment when the bolt started to bend in the bolt hole. As can be noted, the load level, at which these points appear, decreases slightly with increasing number of cycles. Subscript marks, *t* and *c*, correspond to tension and compression parts of the load cycle. For example, point a_t appears at 20 kN after 98750 cycles, whereas this point appears at ~10 kN after 135800 cycles. As has been mentioned, since the initial prestress in the bolts decreased due to fatigue damage at the bolt rows, the friction force decreased as well. As a result, more load would be transferred by the bolts inducing the inflection points to be charper as fatigue loading proceeded. However, the last two loops do not show visible points of inflections, (*a*). This could be due to that the bolt had started to rotate which make the points to be softer. In the bolt-movement loops after 98750 cycles, additional points of inflection, b_t and b_c, appear. It could be explained by that the following bolt bending was restricted by the countersunk surface of the hole. This behaviour occur because due to hole wear and following change in hole shape, i.e. hole elongation, the amplitude of the fastener movement increases. It means that the angle of bolt bending has increased, and as a result the bolt head would get in contact with the countersunk surface which restricts the bolt movement. It is noteworthy to note that the load at which points (*a*) and (*b*) occur agrees with the load at which the inflection points appear in the SG No.3 loops (see Fig. 9 a). Therefore, the bolt-movement observation can fairly reflect fatigue damage evoluation in the joint system.

CONCLUSIONS

The fatigue behaviour of specimens bolted by metal fasteners have shown that these joints perform excellent fatigue resistance properties. However, specimens fastened by composite bolts exhibited the lowest resistance to fatigue. Fatigue failure analysis has determined that joint failure was generally due to bolt failure. The calculated ratio of load transferred at different bolt location to total specimen load show that the load transfer of the bolt rows is affected by damage accumulation, and as a result the load transfer changed during fatigue life. Observation of loops

for strain gauges which were located between two bolts, found how the strain gauges would be affected by bolt presence throughout fatigue loading. Bolt movement was found to increase measurably during the fatigue life. The obtained experimental results from detailed measurements show well agreement between each other and are consistent with the general fatigue behaviour of composite bolted joints.

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REFERENCES

1. Poon, C., "Literature review on the design of mechanically fastened composite joints", In *Behaviour and Analysis of Mechanically Fastened Joints in Composite Materials*, AGARD-CP-427, 1987.

2. Saunders, D.S., Galea, S.C. and Deirmendjian, G.K., "The development of fatigue damage around fastener holes in thick graphite/epoxy composite laminates", *Composites*, Vol. 24, No. 4, 1993, pp. 309-321.

3. Benchekchou, B., White, R. G., "Stress around fasteners in composite structures in flexure and effects on fatigue damage initiation part 1: cheese-head bolts", *Composite Structures* 33, 1995, pp. 95-108.

4. Benchekchou, B., White, R. G., "Stress around fasteners in composite structures in flexure and effects on fatigue damage initiation part 2: countersunk bolts", *Composite Structures* 33, 1995, pp. 109-119.

5. Lanciotti, A., Lazzeri, L. and Raggi, M., "Fatigue behaviour of mechanically fastened joints in composite materials", *Composite Structures* 33, 1995, pp. 87-94.

6. Whitworth, H.A., "Fatigue Evaluation of Composite Bolted and Bonded Joints", *Journal of Advanced Materials*, 1998, pp. 25-31.

7. Persson, E., Hammersberg, P. and Eriksson, I., "Propagation of Hole Machining Defects in Pin-Loaded Composite Laminates", *Journal of Composite Materials Part A*, Vol. 31, No. 4, 1997, pp. 384-408.

8. Persson, E., Eriksson, I., "Fatigue of Multiple-Row Bolted Joints in Carbon/Epoxy Laminates: Ranking of Factors Affecting Strength and Fatigue Life", accepted for publication in *International Journal of Fatigue*.