An experimental investigation on crack paths and fatigue behaviour of riveted lap joints in aircraft fuselage

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ABSTRACT. *Effects of variables related to design and production of riveted lap joints representative of longitudinal sheet connections for a pressurized transport aircraft fuselage were experimentally investigated. The specimens from an aircraft Al alloy D16 Alclad sheets of three different thicknesses (1.9, 1.2 and 0.8 mm) were assembled under load control using round head rivets and rivets with the compensator from a P24 Al alloy. For the joints from 1.9 mm thick sheets fatigue tests indicated a dependency of the crack initiation site and crack path on the squeeze force level and on the rivet type. At the same time, increasing the squeeze force led to improved fatigue properties of the joints, specimens assembled using the rivets with the compensator showing fatigue lives consistently longer than joints with the round head rivets. All observed trends have been explained based on hole expansion and load transfer measurements. For thin sheets connected using the round head rivets, local deformations and indentations under the driven rivet head promoted crack initiation and failure in the adjacent sheet. Fatigue test results indicated that the detrimental effect of this type imperfections could outweigh the benefits associated with a decrease in secondary bending due to thinning the sheets. The rivets with the compensator were observed to cause significant local imperfections beneath the manufactured head, which adversely affected the joint fatigue performance.*

INTRODUCTION

Riveting remains a preferred method for connecting elements of an aircraft structure, though adhesive-bonded and riveted-bonded joints are also applied. A typical design solution for joining sheets of a pressurized transport aircraft fuselage in the longitudinal direction is a riveted lap joint, usually comprising three rivet rows, as shown in Fig. 1. Due to eccentricities occurring in the overlap region for this type of a joint, the so-called secondary bending is induced under nominally axial loading on the sheets. The phenomenon of secondary bending can lead to considerably elevated stresses in the sheets and affects the mode of failure of the joint [1].

The fatigue crack nucleation location, crack path geometry and fatigue properties of a riveted lap joint depend on the integrated effect of a number of factors related to joint design and production as well as loading conditions. This paper focuses on the influence of the squeeze force, sheet thickness and rivet type.

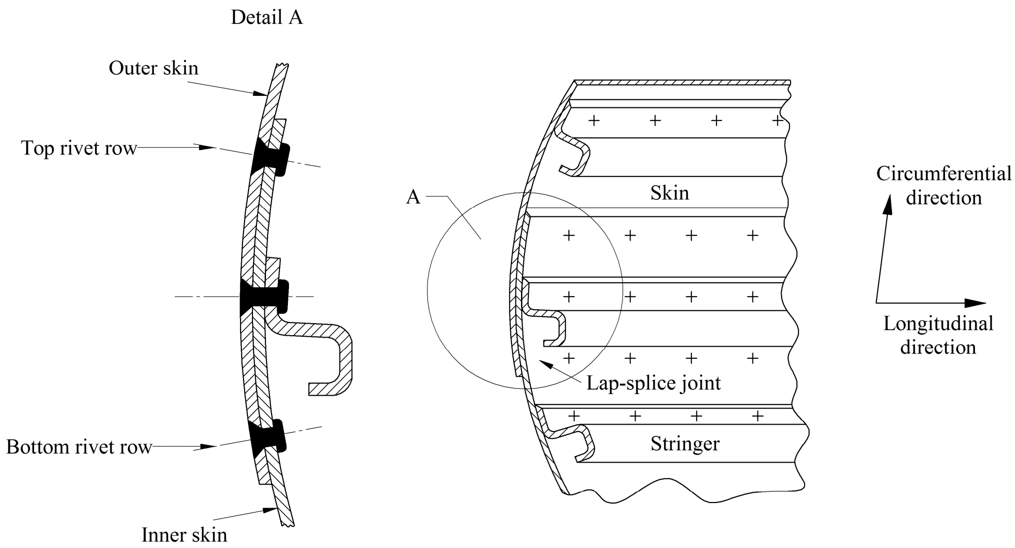

Figure 1. Typical fuselage longitudinal riveted lap splice joint.

SPECIMENS AND TESTING EQUIPMENT

Configuration of three-row riveted lap joint specimens used in the fatigue tests is shown in Fig. 2 and the specimens' dimensions are specified in Table 1. The rivet row spacing $s=5d$ (d – rivet diameter) and the rivet pitch in row $p=5d$ are typical for fuselage skin connections. The rivet holes were drilled according to the process specification of the Polish aircraft industry. The total length L of the specimens was chosen to eliminate the effect of specimen fixture in the fatigue machine on stress conditions in the overlap region [2]. The sheet material was a Russian Al alloy D16CzATWH in the Alclad condition. The mechanical properties (0.2% yield stress = 291 MPa, ultimate strength = 433 MPa, elongation = 13%) and the fatigue crack growth behaviour of this material are similar to those of the western Al 2024-T3 alloy [3]. Two types of protruding head rivets differing in the manufactured head geometry, namely with a round head and with the so-called compensator were used to assemble the sheets, Fig. 3. The compensator, which is a small protrusion on the mushroom rivet head, causes increased rivet hole expansion. The rivet material was the P24 Al alloy equivalent to the western 2117-T3 material used for the AD rivets. Force controlled riveting was applied using a squeezer mounted in the grips of a MTS 810 fatigue machine [4]. The same machine was utilized in the fatigue tests carried out under constant amplitude loading at a stress ratio of 0.1. This type of loading simulates variations of the hoop stress in the fuselage skin generated due to the cabin pressurization. Crack growth on the sheet surface was monitored using a travelling microscope.

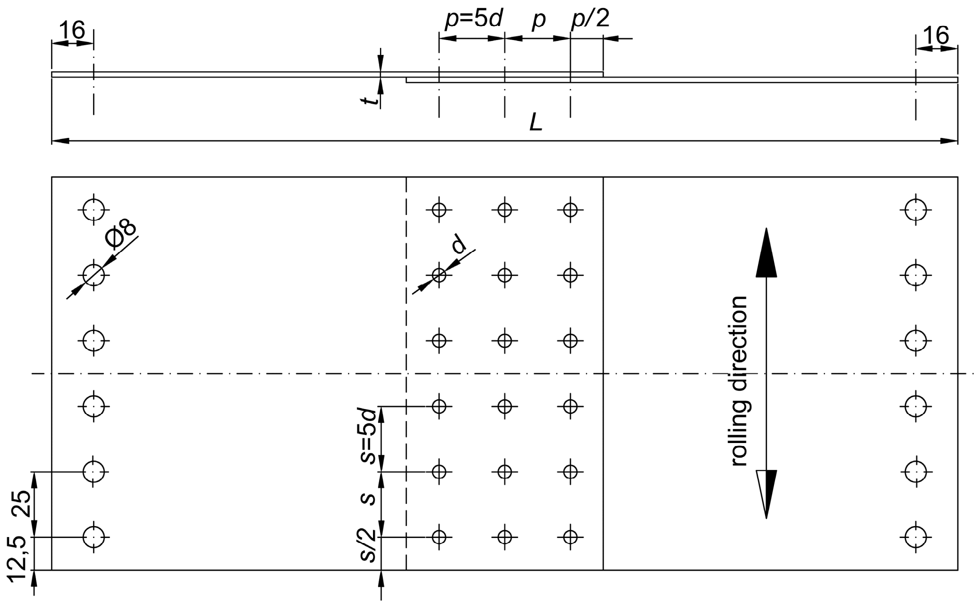

Figure 2. Specimen for fatigue tests.

Table 1. Characteristic dimensions of riveted specimens

Sheet thickness t, mm	Rivet diameter d, mm	Hole diameter d_o, mm	Specimen length L, mm
0.8	3.5	$(d+0.05)^{+0.12}_{0}$	208
1.2	4.0		260
1.9	5.0		345

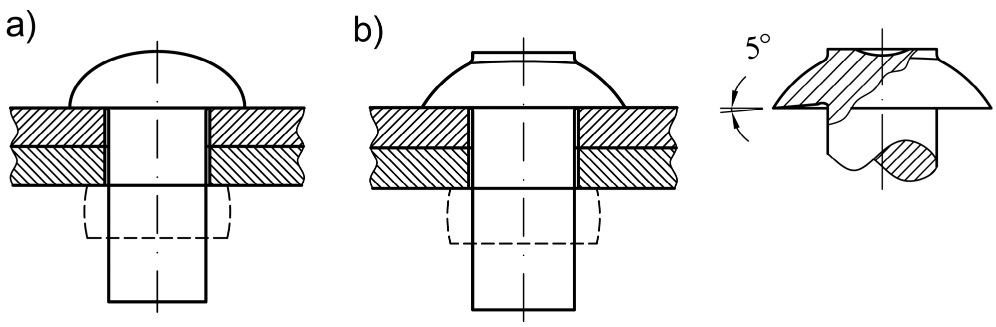

Figure 3. Rivet types used in experiments: (a) round head rivet; (b) rivet with the compensator.

EFFECT OF SQUEEZE FORCE

In production practice, the squeeze force is represented by a ratio of the rivet driven head diameter (*D*) to the rivet shank diameter (*d*) which increases with the squeeze force level. The *D/d*-value is, therefore, a first indicator of the riveting process quality. Typical *D/d* ratios range from 1.3 to 1.5, the latter value being considered as optimal [2]. The rivet installation causes rivet hole expansion, which generates compressive residual tangential stresses in the hole vicinity. The higher the squeeze force level, the larger the compressive tangential stress area, which affects the initiation location and path of fatigue cracks at rivet holes and the joint fatigue life. Increasing squeeze force yields also a higher residual clamping between the sheets beneath the rivet heads. This leads to transmitting a portion of the applied load by friction, which again can influence a mode of joint failure. As an example, Table 2 gives fatigue test results observed under an applied maximum cyclic stress S_{max}=120 MPa for specimens from 1.9 mm thick sheets with the round head rivets installed using four different squeeze force levels, resulting in four different *D/d*-values.

A trend of increasing the fatigue life with the squeeze force, demonstrated in Table 2, was also exhibited at S_{max} of 100 and 80 MPa. No impact of the stress level on the location of crack nuclei and crack path was found.

An illustration of the results from Table 2 are fractographic observation results shown in Fig. 4. It is seen that fatigue cracks always initiate on the faying surface in one of end rivet rows, which results from the influence of secondary bending [1]. For a limited squeeze force, the cracks initiate at the edge of the rivet hole and propagate in the net cross section, Fig. 4a. A more intense squeezing of the rivet leads to crack initiation outside the hole, but propagation through the hole, usually shifted above the net cross section, Fig. 4b. For a relatively high squeeze force fatigue cracks nucleation occurs above the hole, near the edge of the clamping area beneath the rivet head, and the crack propagates outside the hole, Fig. 4c. The latter behaviour is partly contributed by fretting [5].

Table 2. Fatigue lives and crack behaviour for specimens riveted with different squeeze forces. 1.9 mm thick sheets, round head rivets

<table>
<tr><th>D/d</th><th>Fatigue life* kcycles</th><th>Crack initiation site; Crack shape</th><th>Crack path</th></tr>
<tr><td>1.3</td><td>81.6</td><td>Under driven head; Quarter elliptical</td><td>Net cross section</td></tr>
<tr><td>1.4</td><td>160.0</td><td>Under driven head; Quarter elliptical</td><td rowspan="2">Above net section, through rivet hole</td></tr>
<tr><td>1.5</td><td>235.5</td><td>Under manufactured head; Quarter/semi-elliptical</td></tr>
<tr><td>1.6</td><td>298.2</td><td>Under manufactured head; Semi-elliptical</td><td>Outside rivet hole</td></tr>
</table>

*Average from three tests

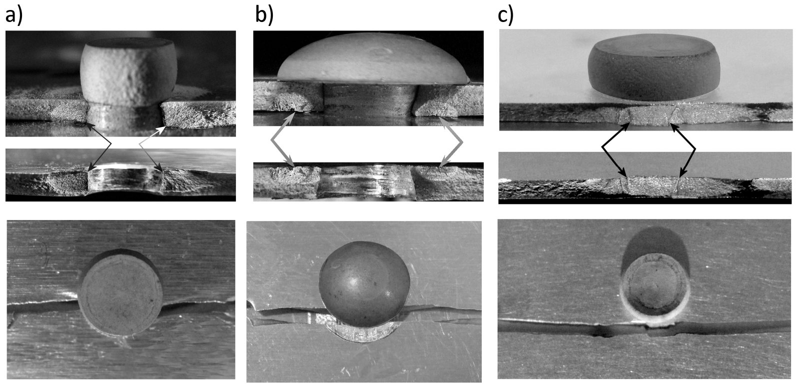

Figure 4. Effect of squeeze force on fatigue crack initiation and path. Explanation in text.

It is seen in Table 2 that the specimens with *D/d* of 1.5 and 1.6 always failed in the sheet adjacent to the rivet manufactured head, while in the case of *D/d*≤1.4 the crack nucleation and failure occurred in the sheet under the driven head. The above behaviour can be explained based on rivet hole expansion measurements shown in Fig. 5 and load transfer measurements shown in Fig. 6. In Fig. 5a, hole expansion is defined as $he=(d_e - d_o)/d_o$, where d_e is the expanded hole diameter. As shown in Fig. 5a, for *D/d* of 1.5 and, especially, 1.6, *he* in the sheet next to the rivet driven head considerably exceeds that in the sheet next to the manufactured head. At the same time, Fig. 6 demonstrates that loads transferred by the end rivet rows are almost equal. Consequently failure occurs in the sheet with smaller hole expansion, i.e. under the manufactured head. For *D/d*≤1.4 *he* in both sheets is relatively small and only slightly larger under the driven head (Fig. 5a). In that case, the negative influence of a much higher transfer load in the sheet adjacent to the driven head (Fig. 6) dominates and determines the failure location. A more uniform load transmission distribution for *D/d* of 1.5 compared to *D/d* of 1.3 shown in Fig. 6 stems from lower flexibility of rivets installed with a higher squeeze force [1].

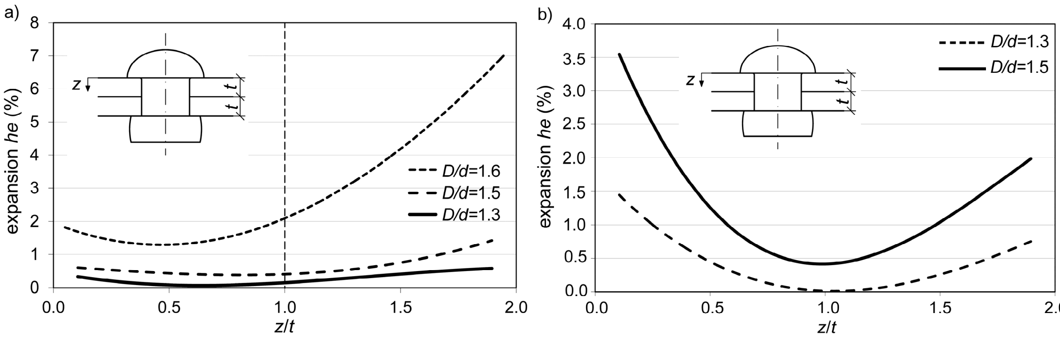

Figure 5. Hole expansion measurement results for sheet thickness t=1.9 mm: (a) round head rivet; (b) rivet with the compensator.

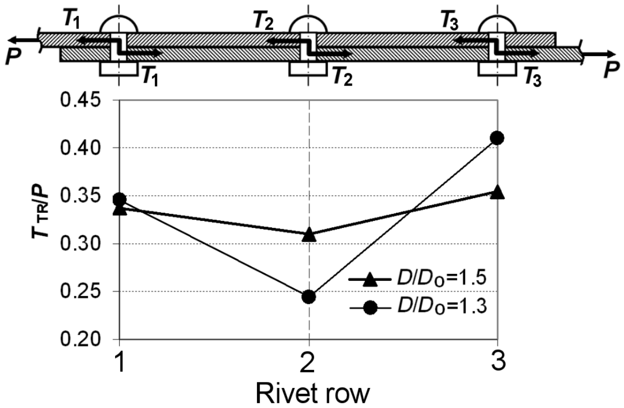

Figure 6. Load transfer distribution in riveted joint for two squeeze force values: round head rivet, sheet thickness t=1.9 mm.

Fig. 5b shows measurements results on *he* for the rivet with the compensator for two *D/d*-values. From a comparisons with Fig. 5a is seen that due to the compensator *he* in the sheet next to the manufactured head becomes considerably larger than for the standard, round head geometry. Fig. 5b indicates that *he* below the manufactured head of the rivet with the compensator is larger than below its driven head, which explains why in all fatigue tests on specimens assembled using this type rivets fatigue failure occurred in the sheet adjacent to the rivet driven head. Similarly as in the case of specimens with the round head rivets, a higher squeeze force yielded an increase in the fatigue life. For a given *D/d* ratio, fatigue lives of specimens assembled using the rivets with the compensator observed at S_{max}=120 and 100 MPa were by 40 to 90% higher than for specimens with the round head rivets.

EFFECT OF SHEET THICKNESS

In order to assess the effect of sheet thickness on the mode of failure and fatigue properties of the joint, specimens from 0.8 mm and 1.2 mm thick sheets were fatigue tested in addition to the specimens from 1.9 thick sheet considered in the previous section. The sheets were connected using the round head rivets applying two different squeeze force values leading to *D/d* of 1.3 and 1.5 for either specimen series. The fatigue tests were carried out at three S_{max} stress values, namely 120, 100 and 90 or 80 MPa. In the case of the *D/d*=1.3 specimens, the crack path for both sheet thicknesses and at all load levels was through the rivet holes, slightly above the net section, Fig. 7a. With the *D/d*=1.5 specimens, the cracks initiated and propagated above the rivet holes, Fig. 7b. In all cases failure took place in the sheet adjacent to the rivet driven head. It can be concluded from confronting the above observations with information in Table 2 that the mode of failure for joints from the thin sheets (0.8 and 1.2 mm) is different than in the case of joints from the thicker sheets (1.9 mm). The reason behind the above differences can be local deformations and indentations under the rivet driven head that occur during the rivet installation in thin sheets due to their low stiffness. Note that the driven head diameter is smaller than the manufactured head diameter (about 2*d*).

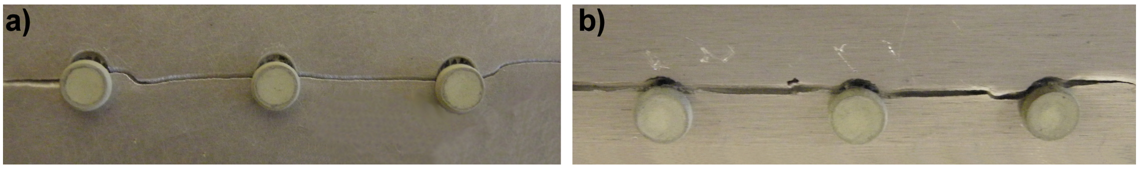

Figure 7. Failure mode for specimens from thin sheets with round head rivets: (a) t=1.2 mm, D/d =1.3, S_{max}=90 MPa; (b) t=0.8 mm, D/d =1.5, S_{max}=120 MPa.

Results presented in Table 3 indicate that sheet thickness has an impact on the joint fatigue life. Increasing sheet thickness should yield a lower fatigue life due to the effect of secondary bending. For example, at S_{max} of 120 MPa the bending factor $k_b=S_b/S_{max}$, where S_b is the nominal bending stress computed according to Schijve's model [6], equals 1.1 and 0.85 for t=1.9 and 0.8 mm respectively. For S_{max}=80 MPa, somewhat higher k_b factors of 1.25 and 0.9 are obtained for the above t-values [1]. However, as seen in Table 3, the observed effect of thickness on the fatigue life is not systematic, due to the addressed above imperfections inherent in the joints.

Applying the rivets with the compensator to connect thin sheets brings no benefits compared to the round head rivets because, due to a specific shape of the manufactured head bottom surface (cf. Fig. 3b), significant local imperfections of the sheet beneath that rivet head precipitate failure. For the above reason, fatigue cracks develop in the sheet under the manufactured head and can grow outside the rivet hole, Fig. 8.

Table 3. Fatigue lives (kcycles) for specimens of different thicknesses. Round head rivets

S_{max}, MPa	120		100		90	
D/d	1.3	1.5	1.3	1.5	1.3	1.5
t=0.8 mm	288.5	322.2	483.0	1666.1	743.6	1665.0
t=1.2 mm	177.0	396.4	347.7	768.5	586.8	1135.4
t=1.9 mm	81.6	235.5	257.2	355.0	507.3*	1174.5*

*Results for S_{max}=80 MPa

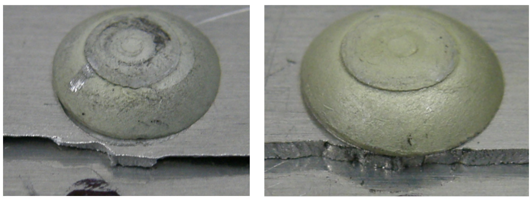

Figure 8. Typical failure mode for specimens from thin sheets and rivets with the compensator: t=0.8 mm, D/d =1.4, S_{max}=120 MPa.

CONCLUSIONS

Experimental observations presented in the paper lead to the following conclusions:

1. The initiation and growth of fatigue cracks in riveted lap joints and the joint fatigue performance depend on rivet hole expansion, and hence on the rivet type and rivet squeeze force, as well as on the sheet thickness. Fatigue cracks initiate always on the faying surface of the sheets in one of the outer rivet rows.
2. Essentially, joint from thicker sheets fail in a sheet with smaller hole expansion, but the distribution of load transfer through the joint can also play a role. For the round head rivet smaller hole expansion occurs in the sheet below the manufactured head, while for the rivet with the compensator smaller expansion is observed in the sheet adjacent to the driven head. For relatively low rivet squeeze forces the crack path is close to the net cross section along one of the outer rivet rows. At high squeeze forces cracks can start and grow outside the rivet hole. The fatigue life increases with the squeeze force value and is always longer for the rivets with the compensator than for the round head rivets.
3. The above observations are not valid for joints from thin sheets. For round head rivets the riveting process can locally introduce imperfections in the sheet adjacent to the rivet driven head, which promotes crack nucleation at this location. In this case, no systematic dependency of the joint fatigue life on the sheet thickness is exhibited. Rivets with the compensator are not suitable for connecting thin sheets because significant local imperfections beneath the manufactured head cause a premature failure at that location.

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