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SIGNIFICANCE OF RIVET FLEXIBILITY FOR LOAD TRANSFER IN LAP JOINTS

SUMMARY

Presented in this paper are results of an experimental investigation on the rivet flexibility and load transmission in a riveted lap joint representative for the aircraft fuselage. The test specimens consisted of two aluminium alloy Alclad sheets joined with three rows of rivets. Rivet flexibility measurements have been performed under constant amplitude fatigue loading using several methods including two novel optical techniques developed by the present authors. The axial forces in the sheets required to determine the rivet flexibility have been derived from strain gauge measurements. In order to eliminate the effect of sheet bending the strain gauges have been bonded at the same locations on the outside and faying surface of the sheet. Variations of the rivet flexibility during the fatigue loading as well as the dependence of the rivet flexibility and load transmission on the rivet squeeze force have been studied. The experiments enabled to evaluate the usefulness of various techniques to determine the rivet flexibility. It was observed that although the measured flexibility was identical for both outer rivet rows, the load transfer through either of these rows was different. Previous experimental results of the authors suggest that the non-symmetrical load transfer distribution through the joint is associated with large differences between the rivet hole expansion in the sheet adjacent to the driven rivet head and the sheet under the manufactured head. It has been concluded that commonly used computation procedures according to which the load transfer is only related to the rivet flexibility may lead to erroneous results.

***Keywords**: riveted lap joints, fatigue, squeeze force, load transfer, aluminium alloys*

ZNACZENIE PODATNOŚCI NITÓW W TRANSFERZE OBCIĄŻENIA W POŁĄCZENIACH ZAKŁADKOWYCH

Przedstawiono wyniki pomiarów podatności nitów oraz transferu obciążenia przez poszczególne rzędy nitów w zakładkowym połączeniu typowym dla konstrukcji lotniczych. Blachy ze stopu aluminium D16CzATW łączono trzema rzędami nitów zakuwanych z dwoma różnymi siłami. Prowadzone przy stałej amplitudzie obciążenia pomiary podatności nitów pozwoliły na porównanie i określenie użyteczności różnych technik pomiaru, w tym dwóch oryginalnych metod optycznych zaproponowanych przez Autorów. Konieczne do określenia podatności nitów osiowe siły działające w poszczególnych przekrojach poprzecznych łączonych blach wyznaczano przy użyciu tensometrów oporowych. Zbadano wpływ siły zakuwania na transfer obciążenia przez poszczególne rzędy nitów oraz na podatność nitów na różnych etapach trwałości zmęczeniowej połączenia. Stwierdzono nieco mniejszą podatność nitów w środkowym rzędzie połączenia w porównaniu z rzędami skrajnymi. Chociaż w obu skrajnych rzędach podatności nitów były takie same, to transfer obciążenia przez każdy z nich był inny. Wynika stąd, że zwykle stosowane procedury obliczeniowe uzależniające transfer obciążenia od samej tylko podatności nitów prowadzić mogą do zafałszowanych wyników.

***Słowa kluczowe**: nitowane połączenia zakładkowe, zmęczenie materiału, siła zakuwania, transfer obciążenia, stopy aluminium*

1. INTRODUCTION

The knowledge of the stress distribution within a riveted joint is a fundamental step in estimating its fatigue life and damage tolerance characteristics. In order to approach the problem of stress conditions at the rivet holes the distribution of loads acting in the joint must be known. The role of a rivet is to transfer the load from one sheet to the other sheet in the overlap region. For a configuration with more than one row of the rivets the applied force P is split at the first row into the bypass load (T_{BP}) which remains in the sheet and the transfer load (T_{TR}) transmitted to the other sheet, as schematically shown in Figure 1. The T_{TR}-load is comprised of the bearing force (T_{BR}) resulting from the bearing pressure exerted by the rivet shank on the hole surface and the friction force (T_{FR}) induced by friction between the mating sheets. Friction is localized mainly beneath the rivet heads where the maximum clamping occurs.

As shown in Figure 2 for an overlap of two sheets with three rivet rows, the internal axial forces in the sheets can be computed by considering the displacement compatibility between the sheets and rivets, Eq. (1), and the equilibrium condition for each transverse section of the overlap, Eq. (2). The elongations of the sheets (Δ) and the rivet deflections between the sheets (δ) can be expressed in terms of the internal axial forces in the sheets (T) through Eq. (3) and (4).

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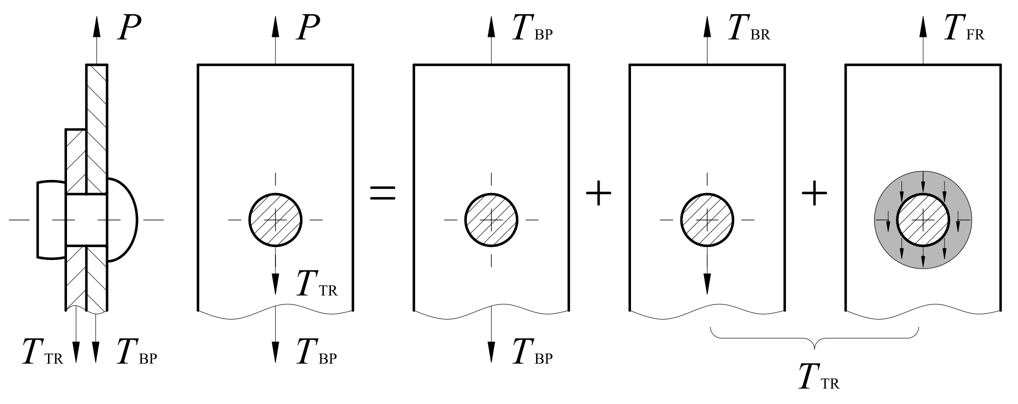

Fig. 1. Axial forces in sheets of a two-layer lap joint

In Eq. 3, $(EA)_j$ is the longitudinal rigidity of sheet j while f_i in Eq. (4) is the parameter representing the flexibility of rivets in row „i". The interest in fastener flexibility measurements has been caused by the desire to calculate the load transfer distribution in joints with multiple fastener rows using the above procedure. The literature evidence indicates that the rivet flexibility depends on the sheet and rivet material, the joint geometry and can be affected by the riveting process, e.g. (Morris 2004, Jarfall 1986).

$$l_i + \Delta_{1,i} + \delta_{i+1} = l_i + \Delta_{2,i} + \delta_i; \quad i = 1, 2, 3; \; j = 1, 2 \tag{1}$$

$$T_{1,i} + T_{2,i} = P \quad \text{with } T_{1,0} = T_{2,3} = P \text{ and } T_{2,0} = T_{1,3} = 0 \tag{2}$$

$$\Delta_{j,i} = \frac{T_{j,i}\, l_i}{(EA)_j} \tag{3}$$

$$\delta_i = \left(T_{1,i-1} - T_{1,i}\right) f_i \tag{4}$$

Presented in this paper are measurement results on the rivet flexibility and load transmission for a simple lap joint of two sheets of equal thickness representative for the aircraft fuselage. An attempt has been made to account for the effect of sheet bending on the measurement data. Variations of the rivet flexibility during the fatigue loading as well as the dependence of the rivet flexibility and load transmission on the rivet squeeze force have been investigated. Because literature data on the rivet flexibility show a very large spread, as evidenced by comparisons between empirical formulas on rivet flexibility produced in (Morris 2004, Jarfall 1986), several methods of rivet flexibility measurements have been applied and evaluated in the present investigation, including the novel optical techniques proposed in this paper. The axial forces in the sheets observed in the experiments have been compared with those computed according to the procedure given in Figure 2.

2. SPECIMENS

The rivet flexibility and load transfer were measured during constant amplitude fatigue loading ($S_{\min}$=12 MPa, $S_{\max}$=120 MPa) on riveted lap joint specimens assembled from two D16 Alclad 2 mm thick sheets using 5 mm dia round head AD rivets. For each of two specimens tested, the rivets were squeezed with a different force to obtain the D/D_o ratio of 1.3 and 1.5, where D and D_o is the diameter of the rivet driven head and rivet shank respectively. The overlap configuration and the location of the extensometer and the strain gauges are shown in Figures 3a and b.

Besides the riveted specimens a monolithic specimen of the same Al alloy and dimensions shown in Figure 3c was also used in some methods of the rivet flexibility measurements, as detailed in the next section.

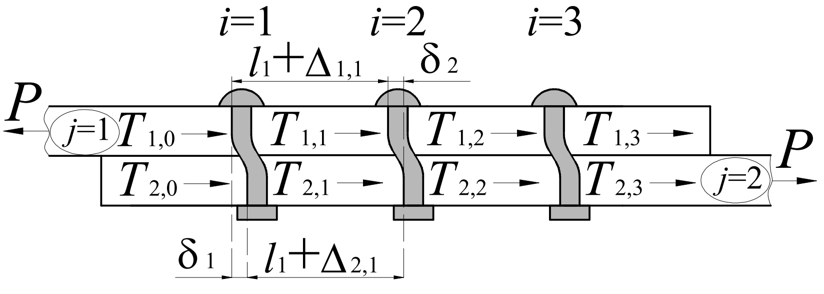

Fig. 2. Scheme of three rivet row lap joint for the computation of axial forces in the sheets

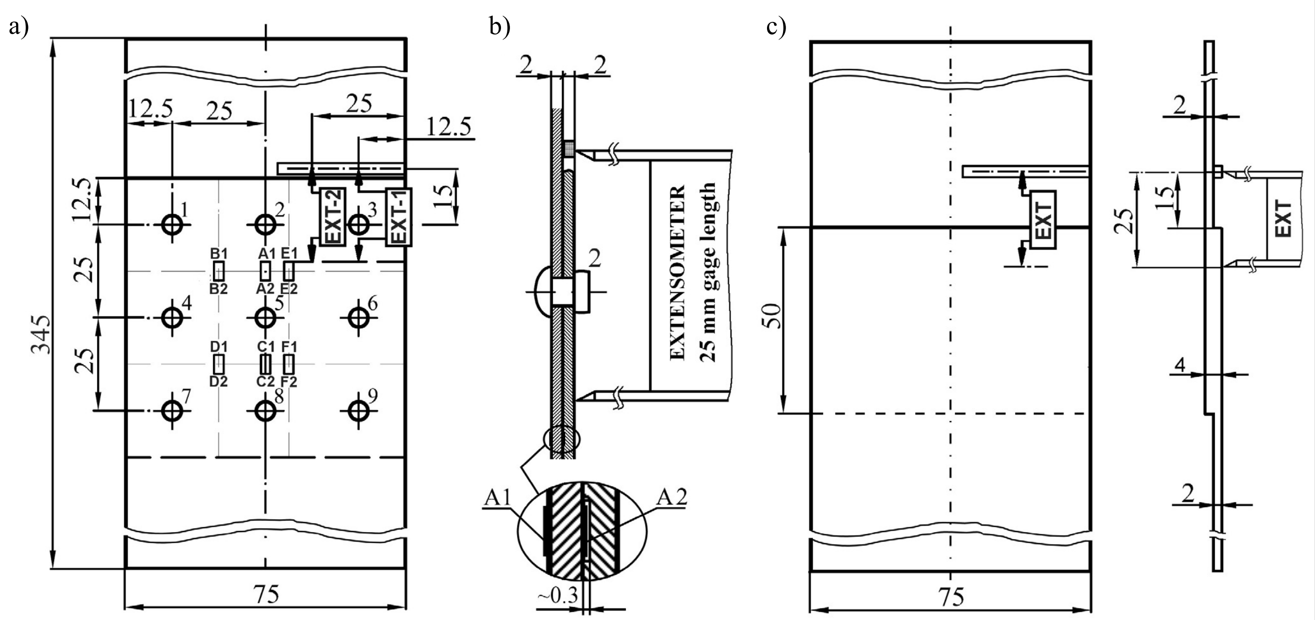

Fig. 3. Specimens for rivet flexibility and load transfer measurements: a) riveted specimen; b) extensometer and strain gauge locations; c) dummy specimen

3. RIVET FLEXIBILITY MEASUREMENTS

The rivet flexibility measurements should ensure as far as possible that the measured results are not influenced by the sheet bending because this effect is not accounted for in the computation of the rivet flexibility from the measurement data (cf. Fig. 2). The specimen extension between the clamping edges and then the average rivet flexibility value for the joint can be derived from records of the machine displacement gauge (LVDT transducer), Figure 4a, provided that the component resulting from the compliance of machine elements is subtracted from the measured displacement value (Δl). The middle rivet rows may show a different deflection response than the fatigue critical end rows because the middle rows undergo much more uniform bearing pressure than the end rows where the maximum moment due to sheet bending occurs. In order to measure the flexibility for the end rivet rows the extensometer can be positioned as shown in Figure 3b. At that short gauge length, however, the sheet curvature due to the bending should be accounted for because the difference between the displacements measured at the outer surface and those occurring at the faying surface can be of the same order of magnitude as the rivet deflection. Figs 4b and c show the principle of optical measurements of the rivet flexibility, not affected by secondary bending, proposed by the present authors. The technique further referred to as the edge method (Fig. 4b), enables to determine the deflection of a rivet in the end row from the measured relative displacement between the mating sheets at the overlap edge: $\Delta y = y_{\max} - y_{\min}$, where the distances $y_{\max}$ and $y_{\min}$ correspond to the $S_{\max}$ and $S_{\min}$ stress of the fatigue cycle. Because Δy is in the order of 10^{-2} mm, a high accuracy measurement system is required. The method presented in Figure 4c is applicable to rivets in both the outer and the inner rows. The effect of sheet bending is compensated by using a piece of wire bonded to the sheet surface near the rivet head. The rivet deflection is determined from the measurements of the rivet head displacement on both sides of the overlap, Δy_1 and Δy_2, and the displacement of the tip of the bonded piece of wire, Δy_3, as $\delta = 2\Delta y_2 - \Delta y_1 - \Delta y_3$, with $\Delta y_i = y_i(S_{\max}) - y_i(S_{\min})$.

All above mentioned techniques have been applied in the present experiments. As shown in Figure 3a, the extensometer was mounted at locations EXT-1 and EXT-2 in order to measure the end row rivet flexibility along the rivet column and midway between the columns. Both these locations were also considered when the optical edge method (Fig. 4b), was used.

As said above, with the technique utilizing the protruding wire element the rivet deflection can be directly derived. When other techniques were used two approaches were applied in an attempt to extract the rivet deflection from the measured data. One of these referred to as the analytical compensation involved subtracting from the measured extension appropriate sheet elongations computed from the Hook law (cf. Eq.(c), Fig. 2). In the case of the LVDT transducer records this analytical compensation can only eliminate the sheet extension between the specimen clamping edges but it is not capable of eliminating the deformation of the machine components included in the measured Δl data. With the other approach referred to as the experimental compensation and applicable only in the case of the extensometer measurements and the LVDT transducer records extensions measured for the monolithic dummy specimen shown in Figure 3c were subtracted from those acquired for the riveted specimens. It was believed that this concept

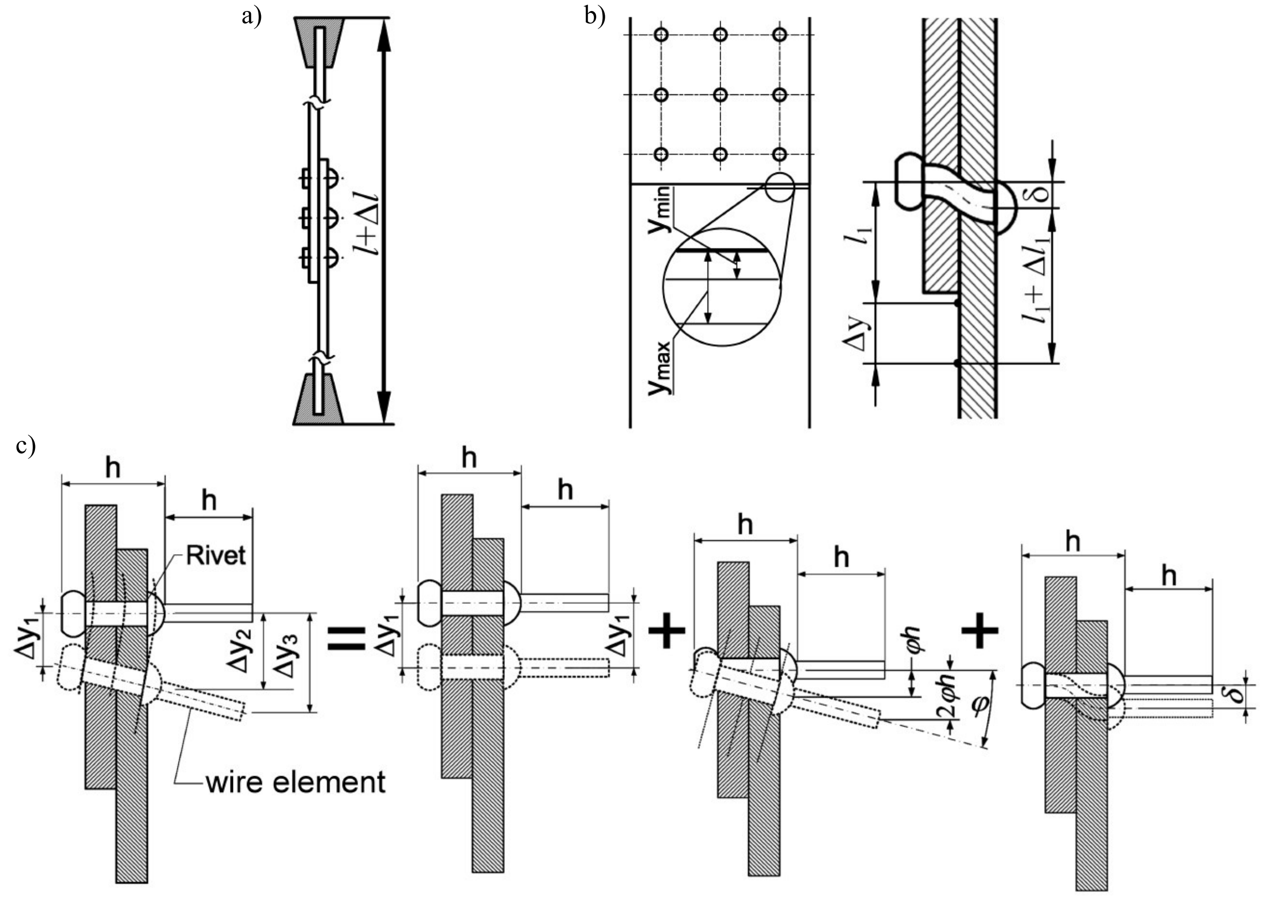

Fig. 4. Various methods for rivet flexibility measurements: a) LVDT transducer records; b) edge method; c) protruding wire method

should enable to eliminate also the contribution of the machine elements compliance included in the LVDT transducer records.

The axial forces in the sheets needed to compute the sheet elongations and the rivet flexibility using Eqs. (c) and (d) respectively (cf. Fig. 2) were determined from strain gauge measurements, as detailed in the next section.

The results on both the rivet flexibility (except for the optical techniques) and the axial loads were derived from averaged measurement data on strains, extensions or displacements recorded during three consecutive load cycles. The data acquisition was repeatedly performed at some cycle intervals throughout the fatigue tests.

Comparisons between some results on the rivet flexibility derived for the D/D_o = 1.3 specimen are presented in Figure 5. For clarity, only the data captured along a single rivet column are shown in the case of the extensometer measurements and the edge method. Slightly higher f-values midway between the columns compared to those along the columns were only detected using the edge method and solely for the D/D_o = 1.3 specimen. The measurements indicated a good repeatability of results obtained for various rivets in a given row and symmetry of the flexibility values for both end rows. It can be seen in Figure 5 that the optical methods and the extensometer measurements coupled with the analytical compensation yield similar results for the rivets in the end rows. Altogether, the measurement data for both the D/D_o = 1.3 and D/D_o = 1.5 specimen have indicated that the scatter of the f-values measured using the considered three methods for the rivets in the end rows is within ±10%. Behind the differences between the results from these three techniques can be simplifications involved in computing the sheet extension, like neglecting the stress concentration and, in the case of the extensometer measurements, ignoring the sheet curvature due to the bending. Note also that the accuracy of the optical measurement setup used in this investigation (±2 μm) equals several per cent of the measured deflection values. Especially in the case of the method employing the bonded wire element which involves measurements of three small quantities a somewhat higher resolution of the optical system would be desired. Only the latter method enables to measure f for the middle row. The corresponding data reveal a lower flexibility parameter of rivets in that row compared to the flexibility measured for the outer rows, as evidenced in Figure 5 by the results for rivet no. 4 consistently lower than those for rivets no. 1 and 7.

The effect of the fatigue loading on the flexibility behaviour was found to depend on the squeeze force level. In the case of the D/D_o = 1.3 specimen an insignificant decrease of

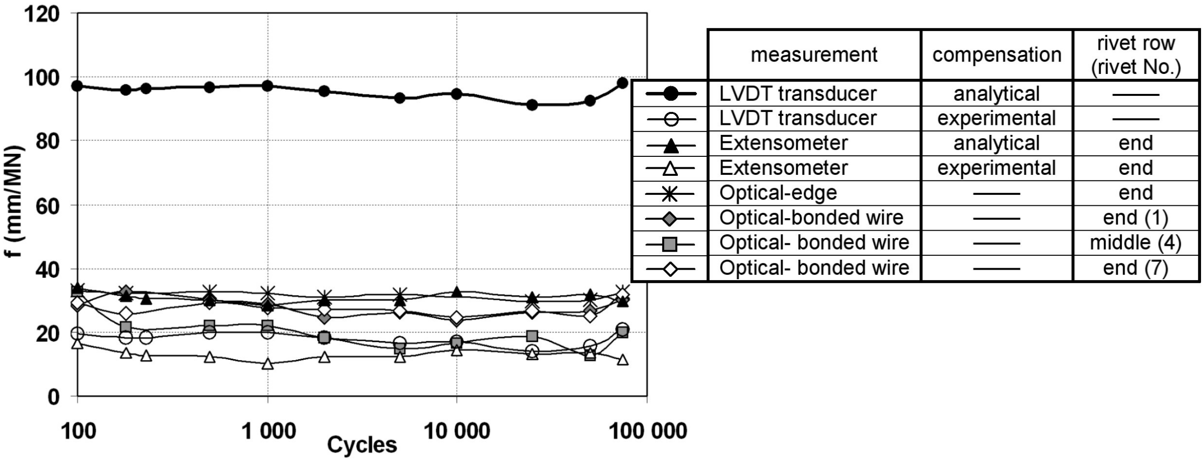

Fig. 5. Exemplary results on rivet flexibility from several measurement techniques

the flexibility during the fatigue loading was observed only for rivets in the middle row. For the D/D_o = 1.5 specimen a moderate decrease in f occurred also for the outer rows. After 100 kcycles the rivet flexibility for the latter specimen became reduced by 20%. A decrease in the joint flexibility during both constant amplitude and variable amplitude fatigue loading has also been reported by Jarfall (1986). This behaviour can be understood if it is recalled that the rivet deflection is controlled by the bearing force rather than by the total transfer force. Load transfer measurements demonstrate that whilst the load transfer ratio (T_{TR}/P) remains essentially invariable during the fatigue loading, the friction contribution (T_{FR}) can significantly increase with the number of cycles causing the bearing component to decrease (Jarfall 1986, Terada 1985).

Whilst the extensometer measurements and both optical methods provide the flexibility for a specific rivet, the results derived from the LVDT transducer records represent the average rivet flexibility of the joint. Figure 5 demonstrates that compared to other measurement techniques the latter method coupled with the analytical compensation which does not cover the deformation of the machine parts yields an over threefold overestimate of the rivet flexibility. Thus the present results offer the explanation for the overly high f-values according to the Morris (2004) formula based on the same measurement technique. On the other hand, the data in Figure 5 imply that the experimental compensation leads to an underestimate of the flexibility because the average results on f obtained from the LVDT transducer data and, especially, the extensometer measurement results for the outer rows are even below the flexibilities measured for the middle row. Evidently the deformation of the dummy specimen cannot properly represent the deformation of the sheets in the riveted specimen. Altogether the present work suggests that due to difficulties with allowing for the compliance of the machine parts reliable f-values cannot be derived from the LVDT transducer records.

In Table 1 the measured rivet flexibility parameters averaged over the initial 75 000 load cycles for either specimen and the corresponding load transfer ratios computed for the measured f-values according to the procedure from Figure 2 are given. It is seen that due to the lower difference between the flexibility for the outer and middle rivet row in the case of the D/D_o = 1.5 specimen the computed load transmission through the joint is for that specimen more levelled of than for the D/D_o = 1.3 specimen. The computed T_{TR}/P ratio higher for the middle row than for outer rows is reflective of the lower f-value for the middle row. These results cannot be, however, considered reliable because the sheet bending which contributes to the differences between the rivet flexibility for the outer and inner row is neglected in the load transfer computations.

4. MEASUREMENTS OF AXIAL FORCES IN THE SHEETS

In order to measure the axial loads in the sheets the riveted specimens were instrumented with twelve 2 mm base length strain gauges A1, A2 to F1, F2, Figures 3a and b. For joints with eccentricities, like the lap joints, the measured axial stresses indicate a combined effect of the axial loads and bending moments. The stresses contributed by the axial

Table 1

Measured rivet flexibilities and computed load transfer ratios for outer and middle rivet row

D/D_o	f_{outer} (mm/MN)	f_{middle} (mm/MN)	$T_{TR,out}/P$	$T_{TR,mid}/P$
1.3	26.7	16.4	0.293	0.414
1.5	18.1	12.8	0.314	0.327

forces were obtained as the average of the stresses measured by the gauges bonded at the same location at the outer and faying surface of the sheet adjacent to the manufactured rivet heads, as shown for gauges A1 and A2 in Figure 3b. It is seen that bonding the gauges at the faying surface required that a 0.3 mm deep recess for each gauge had to be machined in the mating sheet. Also, about 0.3 mm deep slots were milled in that sheet to lead out the gauge wiring. In either of the two transverse sections considered in the measurements the gauge located midway between the rivet columns indicated nearly the same stress as the gauge located at a distance of 6.25 mm from the column, i.e. the stress measured at location B equalled that measured at location E, and the stress at location D was the same as that at location F. Considering above, the axial loads in the sheets have been computed by integrating the stress distributions schematized as shown in Figure 6a, where the measured stresses are specified as a percentage of the tensile stress applied on the joint. It is seen in Figure 6a that compared to the D/D_o-ratio of 1.3 the stress distribution corresponding to $D/D_o = 1.5$ is more levelled off as in the latter case the differences between the stress value at the rivet column and between the columns are smaller in either of the two sections. This observation is consistent with the experimental results of Terada (1985) obtained using a thermo-elastic analyser.

Integrating the measured stress field presented in Figure 6a yields the distribution of the load transfer ratio through the joint shown in Figure 6b. Here, a most striking feature is the non-symmetrical load transmission by the end rivet rows. For both the $D/D_o = 1.3$ and $D/D = 1.5$ specimen load $T_{1–3}$ transferred from the sheet adjacent to the rivet manufactured head to the sheet adjacent to the driven head is lower than load $T_{7–9}$ transmitted at the other end row, i.e. from the sheet next to the driven head to the sheet under the manufactured head. The difference in the load transfer distribution by the outer rows is more pronounced for the $D/D_o = 1.3$ than for the $D/D_o = 1.5$ specimen for which the load transmission through all three rows is more homogeneous.

The non-symmetrical load transfer observed experimentally is not reflected by the rivet flexibility measurements which for either of the two specimens provide identical results on f for both outer rivet rows. The differences in the load transmission by these rows are, presumably, associated with large differences between the hole expansion in the sheet adjacent to the driven head and in the sheet next to the manufactured head revealed in experimental (Skorupa *et al.* 2009, Skorupa *et al.* 2010) and numerical (Rans 2007, Müller 1995) studies.

5. CONCLUSIONS

Rivet deflections in lap joints of Al-alloy sheets with three rivet rows have been observed using several methods including new techniques developed by the authors. Axial forces in the sheets needed to compute the rivet flexibility were determined from strain gauge measurements performed in the way to account for the effect of sheet bending. The major conclusions are the following:

1) The novel optical techniques for rivet flexibility measurements proposed in this work are superior to experimental methods reported in the literature in that they enable to handle the influence of sheet bending and to determine the flexibility for a specific rivet row. Erroneous results on the average rivet flexibility ensue when the fatigue machine displacement gauge (LVDT transducer) records are employed to derive the rivet deflections, as practised for longer overlaps with multiple rivet rows.
2) The higher squeeze force yields lower values of the rivet flexibility parameter and a more levelled off load transmission through the joint.
3) A decrease of the rivet flexibility parameter with the number of cycles is more significant at the higher squeeze force level.
4) The rivet flexibility parameter for the inner rivet row is lower than for the outer rows due to the different amounts of sheet bending at either of these locations.

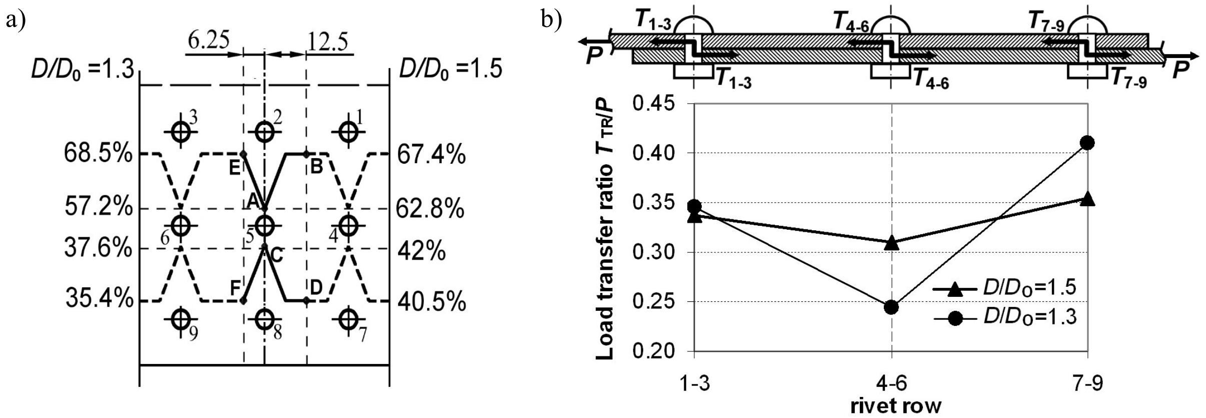

Fig. 6. Transfer load measurement results: a) schematization of the stress distributions in the transverse sections between the rivet rows; b) load transfer ratios for the lap joint

5) The non-symmetrical load transfer observed experimentally is not reflected by the rivet flexibility measurements which for a given specimen provide identical results for both outer rivet rows. A most probable reason for this behaviour are differences in the hole expansion under the manufactured and driven rivet head.
6) The present work reveals that the rivet flexibility is not the only factor which affects the load transmitted by the rivet. This implies that the procedure typically used to compute the load transfer through the joint and utilizing conditions of the displacement compatibility between sheets and rivets may provide quantitatively and even qualitatively incorrect results.

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