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Effect of load transfer by friction on the fatigue behaviour of riveted lap joints

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ABSTRACT

An experimental investigation of load transmission throughout a riveted lap joint is presented with a focus on the role of friction. The main objective was to generate results to be utilized in a semi-empirical model for predicting the fatigue life of riveted joints, which is being developed by the authors. The test variables accounted for in the experiments were the rivet squeeze force and the faying surface condition. Triple-row riveted lap joint coupons of aluminium alloy 2024-T3 Alclad sheets intended to be a simple representation of longitudinal connections in the aircraft fuselage skin structure were assembled with two different rivet squeeze forces. For either force half of the joints had a thin Teflon interfoil in the overlap area in order to minimize friction between the sheets. Friction measurements reveal that, contrary to the friction coefficient between the Alclad mating surfaces, the friction coefficient between the Teflon and Alclad contact surfaces is considerably lower and does not increase with the cycle number.

A convenient method of the determination of load transmission throughout a lap joint is proposed utilizing measurements by strain gauges mounted on only outer surfaces of the overlapping sheets supplemented by the secondary bending analysis according to a simple theoretical model. The results obtained indicate that the effect of the squeeze force and the faying surface condition on axial forces in the overlapping sheets is quantitatively insignificant. It is noted that an analytical procedure commonly used to compute axial forces in the sheets of joints with mechanical fasteners considerably underestimates load transfer by the critical, outer rivet rows.

Comparative fatigue tests on the riveted coupons with the Teflon interlayer and without such a layer reveal superior fatigue lives of the former. These results demonstrate, contrary to the prevailing opinion, an overall detrimental influence of frictional load transfer at applied stress values representative of those experienced in service by lap splices of the aircraft fuselage.

Post-failure examinations of the riveted joints provide evidence that the crack initiation locations and crack paths depend on the test variables and the stress level. For the uncoated joints, the effect of the squeeze force and applied load on the area of fretted regions around the rivet holes was noted, whilst the total roughness heights did not exhibit such a dependency.

It is shown that the present and reported in other works experimental results on the effect of coatings on the fatigue performance of riveted joints cannot be explained based on FE stress analyses available in the literature due to simplifications involved in modelling the faying surface condition. A major conclusion of the present work is that because of the extremely complex determinants of frictional load transfer, its effect on the fatigue behaviour of riveted joints can only be predicted using a semi-empirical approach.

1. Introduction

Reliable fatigue life predictions for fatigue critical members of an aircraft structure, as for example riveted joints, are essential to its in-service safe operation. Available fatigue life prediction concepts for riveted joints [1,2] only account for features related to the joint geometry and rely on the "similarity" between the actual joint, for which the predictions are made, and a reference joint for which the fatigue life is known. The precise formulation of a criterion for the similarity of the joints is not possible due to the interdependence of many design and production variables known to affect the fatigue behaviour of riveted joints. As elucidated elsewhere, rivet hole expansion and residual clamping between the sheets induced by the installation of a rivet have a profound impact on the fatigue response of a joint [3]. A fatigue life

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prediction model by the present authors, of which a preliminary version is presented in Ref. [4], attempts to allow explicitly for the influence of the riveting process by utilizing a dependency of the multiplier in the Basquin equation on rivet hole expansion. A significant improvement in the prediction accuracy of this concept compared to a model which disregards the effect of riveting was demonstrated [4]. Recently, the model has been modified to consider separately the impact of the interference between the rivet and the hole and the impact of frictional load transfer. This new formulation allows for extending the model transferability to the case when the faying surface condition for the reference joint and for the actual joint are different.

As in the case of the other prediction concepts referred to above, it is assumed in the present model that the fatigue life of a riveted joint is controlled by the stress amplitude at the rivet hole in fatigue critical, outer rivet rows. The stress at that location is determined by superposing contributions of the bypass load (portion of load remaining in the sheet), transfer load (portion of load transmitted by the rivet to the other sheet) and secondary bending moment (induced under nominally axial loading due to the joint eccentricity). Accordingly, the stress at the critical location is expressed as

$$\sigma = S \cdot \left(\alpha_{BP}(1 - R_{TR})K_{f,BP} + \alpha_{BR}\alpha_{FR}R_{TR} \cdot K_{f,BR} + \alpha_b k_b \cdot K_{f,b}\right) \quad (1)$$

where S is the applied stress level, $K_{f,BP}$, $K_{f,BR}$, and $K_{f,b}$ are the fatigue notch factors for a finite width plate with open hole under remote tension, pin loading, and pure in-plane bending respectively, $R_{TR} = T_{TR}/P$ is the transfer load ratio (T_{TR} – transfer load, P – applied load), $k_b = S_b/S$ is the bending factor (S_b – nominal stress due to secondary bending), α_{BP}, α_{BR} and α_b are the rivet hole expansion dependent coefficients, and the α_{FR} coefficient accounts for the contribution of frictional forces to load transmission possible due to residual clamping between the sheets. It can be expected that, in addition to the magnitude of clamping, the faying surface condition will have a profound impact on α_{FR}. Also the R_{TR}-ratio may show a dependency on the riveting process, primarily because of the effect of rivet hole expansion on rivet flexibility [5]. As demonstrated experimentally and analytically, both the residual clamping force and rivet hole expansion increase when the rivet is more severely squeezed [6,7].

To determine the riveting process dependent quantities incorporated in Eq. (1), an experimental program was designed. An investigation to obtain the α_{BP}, α_{BR} and α_b coefficients is produced elsewhere [8]. An objective of the present work is to obtain the R_{TR} ratio and to generate results leading to derive the α_{FR} coefficient. To this end, experiments were carried out on three-row riveted lap joint coupons of aluminium alloy 2024-T3 Alclad sheets and universal head AD rivets, intended to be a very simple representation of longitudinal connections in the aircraft fuselage skin structure. The coupons were assembled with two different rivet squeeze forces and for either force half of the joints had a thin Teflon interlayer in the overlap area to minimize friction between the sheets. In order to recognize a difference between the friction coefficients for the two faying surface conditions, friction measurements for the Alclad mating surfaces and for Alclad and Teflon contact surface are conducted. The dependency of the R_{TR} ratio on the rivet squeeze force and the faying surface condition is obtained from strain gauge measurements within the overlap region of the joints. Difficult gauge installations on the faying surface of the sheet, typically applied in this type measurements, e.g. [9], are avoided as the secondary bending stresses for either sheet are computed from the appropriately modified model by Schijve [10].

The explanation of the role of friction between the mating sheets of a riveted joint implies that the deleterious effect of friction, which is the development of fretting damage, enhances its favourable impact, namely carrying out a certain portion of the applied load. Investigations on how the load transmission by friction affects the fatigue properties of riveted joints are scarce and inconclusive as both a beneficial influence of enhanced friction on the faying surface [11] and an increase in the fatigue life due to a reduction in frictional forces have been reported [6]. In the present paper, the overall effect of frictional load transfer on the riveted joint fatigue life is recognized from comparative tests on the joints of the Teflon coated and uncoated sheets. This type results obtained for a range of sheet thicknesses and riveting process conditions will be a basis for deriving the α_{FR} coefficient in Eq. (1).

Post-failure examinations of the joints are conducted to investigate the dependency of crack initiation locations and crack paths on the rivet squeeze force and faying surface condition. Also, the effects of the squeeze force and applied load level on the fretted surface topography for the uncoated joints are studied in terms of the fretted regions area beneath the rivet head and roughness profiles.

The obtained results are confronted with those of available in the literature experimental and FE studies on the impact of coatings on the fatigue behaviour of riveted joints. Finally, justified by the present investigation conclusions on the inadequacy of FE modelling the friction condition on the faying surface, as well as arguments in support of applying a semi-empirical approach to fatigue life predictions for riveted joints are presented.

2. Riveted specimens

The load transfer measurements and the fatigue tests were conducted on single lap joint specimens consisting of 2024-T3Alclad sheets 1.6 mm thick connected using three rows of universal head MS20470-AD (2117-T4 Al alloy) rivets 3.8 mm in diameter. The coupon geometry is presented in Fig. 1. The CNC machining of the plates ensured a good repeatability of all features of the specimen geometry. The riveting was carried out under load control, as detailed elsewhere [12], to obtain ratios of the rivet driven head diameter (D) to the rivet shank diameter (d) of 1.3 and 1.5, both values falling into a range typical of the aircraft industry practice. In order to avoid a premature crack initiation from rivets located at the specimen edges (the so called edge effect), these rivets were installed with a squeeze force increased by 10% compared to the inner rivets.

With the purpose of studying the effect of friction between the sheets, half of the specimens were assembled with a 0.05 mm thick Teflon foil on the contact surface of either sheet in the overlap of the joint. Four coupon series differing in combinations of the D/d ratio and the faying surface condition resulted, namely: $D/d = 1.3$ & Alclad, $D/d = 1.3$ & Teflon, $D/d = 1.5$ & Alclad, and $D/d = 1.5$ & Teflon.

The post-fatigue failure examinations of the dismantled joints revealed that the Teflon foils remained stuck together and undamaged. This indicates that during the fatigue loading on the Teflon foil fitted joints relative movements on the faying surface are controlled by friction between the Alclad and Teflon mating surfaces rather than by friction between the Teflon foils.

3. Friction measurements

To determine the coefficients of friction relevant to the present riveted lap joint coupons in the as-manufactured condition, friction tests were carried out by using three partly overlapping 1.6 mm thick Alclad sheet strips clamped together with an instrumented clamp, which could be adjusted to set the normal force F_{cl}, as shown in the top of Fig. 2. The middle strip, uncoated or coated