International Journal of Fatigue 94 (2017) 41–57

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Fatigue life predictions for riveted lap joints

M. Skorupa, T. Machniewicz *, A. Skorupa, A. Korbel

AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, al. A. Mickiewicza 30, 30-059 Krakow, Poland

ARTICLE INFO

Article history:
Received 6 June 2016
Received in revised form 13 September 2016
Accepted 15 September 2016
Available online 15 September 2016

Keywords:
Aircraft riveted joints
Fatigue life prediction
Fatigue tests
Hole filling effect
Faying surface condition

ABSTRACT

A semi-empirical fatigue life prediction model for riveted lap joints representative of the aircraft fuselage skin connections is developed. The effect of the interference fit between the rivet and the hole is taken into account utilizing fatigue test results for 2024-T3 Alclad aluminium alloy coupons with an open and filled hole. The effect of contact surface friction is considered based on comparisons between the fatigue lives of lap joints from 2024-T3 Alclad sheets and universal rivets with the Alclad contact surface and the fatigue lives of similar joints with the Teflon interfoil which eliminates friction between the sheets. Dependencies between coefficients incorporated into the model to account for the above mentioned effects and several quantities related to the amount of rivet squeezing, and thus representative of the riveting process, are provided. The fatigue life is assumed to be controlled by the local stress amplitude at the critical location of a joint. Analyses of the fatigue test results for the 2024-T3 riveted joints prove that the local stress estimated using the superposition approach can adequately represent the combined effect of the applied loading, interference between the rivet and the hole and faying surface friction condition on the fatigue life. The adequacy of the proposed model is substantiated by a good agreement between the fatigue lives predicted and observed for lap joints from D16 aluminium alloy sheets and round head rivets.

1. Introduction

The fatigue behaviour of riveted joints is affected by many variables, often interrelated, associated with the design, production and the stress level. The installation of a rivet induces rivet hole expansion and residual clamping between the sheets. Experiments and analyses indicate a dependency of both hole expansion and residual clamping not only on the amount of rivet squeeze but also on the sheet thickness, rivet diameter and rivet type [1(pp. 73–87, 134–143),2]. Local residual membrane stresses generated due to hole expansion affect the crack initiation location [1(pp. 188–194),3], crack shape development [1(pp. 199–203)], and consequently the fatigue life of a joint [2–4]. Residual clamping caused by a difference in the elastic spring back of the rivet and the sheets gives rise to friction between the sheets under applied loading. Friction promotes fretting fracture, accounts for some of load transfer throughout the joint [4,5], and also modifies the membrane stress distribution in the rivet hole vicinity [6,7]. Though the isolated effect of friction on the fatigue properties of riveted joints is difficult to experimentally quantify, frictional load transfer is commonly thought to have a beneficial influence. A complicated aspect of the fatigue behaviour of riveted joints remains their response to various common coatings found in aircraft joints, like corrosion inhibitors and sealants. Available literature data, some of them being cited in Ref. [3], indicate that the influence of coating on the fatigue properties can be either detrimental or beneficial. The design and production of the joint (geometry, magnitude of clamping, clearance or interference fit between the fastener and hole), the type of loading (constant or variable amplitude), the load level, and – in the case of variable amplitude loading – also spectrum severity play a role.

Due to simplifications involved in FE modelling of riveted joints, such analyses are not always helpful in explaining various experimental trends, even qualitatively. For example, FE stress analyses in which fretting is simulated by merely assigning a high friction coefficient value to the contact surface assumed to be flat cannot be considered a useful tool to investigate frictional load transfer and draw conclusions about its implications for the fatigue performance of a joint [3].

Because of the outlined above, extremely complex determinants of the fatigue behaviour of riveted joints, both the fatigue life and crack growth predictions are very difficult. The prediction approaches are strongly empirical to account for phenomena that are either not well understood or too complicated to be covered analytically. As aircraft manufacturers place reliance on damage

* Corresponding author.
E-mail address: machniew@agh.edu.pl (T. Machniewicz).

http://dx.doi.org/10.1016/j.ijfatigue.2016.09.007

tolerance designs, available prediction models mainly concentrate on crack growth. The concept of equivalent initial flaw size (EIFS), which is the size of a hypothetical crack assumed to be present at the rivet hole prior to service, has been conceived to allow correlation of the entire crack growth using the stress intensity factor (SIF) [8]. The EIFS must be derived by the back extrapolation of the crack size versus number of cycles (N) data known from fractographic measurements to N of zero. Investigations indicate that EIFS values for riveted joints are affected by manufacturing, design solution, loading conditions and a crack growth prediction methodology used. An ample overview of approaches applicable to cracks in riveted lap joints [1(pp. 241–268)] leads to a conclusion that currently available crack growth prediction techniques are not capable of providing fully reliable results, especially in the case of multiple site damage (MSD).

Fatigue life predictions models for riveted joints employ concepts commonly applied to the crack initiation life analysis for notched structural members. This type predictions are methodologically easier than crack growth predictions in that the quantity assumed to control the fatigue life, usually a function of the stress and/or strain at a notch, is associated with the uncracked geometry and, in contrast to the SIF, it does not vary with crack growth. It should be emphasized that reliable predictions on the fatigue life can indirectly bring some information on the crack development stage as fatigue tests of fuselage panels with riveted splice connections indicate that cracks visible on the outer surface are detected after 50–75% of the panel total fatigue life [9,10].

In models presented in Refs. [11–13] it is assumed that the fatigue life is governed by the amplitude of the local stress at the critical location of a riveted joint. For a lap joint with multiple rivet rows considered in the present work, the critical location is the rivet hole edge in one of the outer rows. Like the SIF in crack growth predictions for riveted joints, this stress is obtained by superposition of solutions for the bypass load, transfer load and secondary bending obtained for a plate with a single hole. Because the local stress is determined taking only the geometry of the joint into account, the applicability of the models referred to above is limited to cases when the actual joint, for which the predictions are made, and the reference joint, for which the model has been tuned, differ solely in geometry. It is required that the riveting process should be similar for the actual and reference case, but the similarity criterion cannot be formulated in a precise way. In Ref. [2] the present authors proposed to explicitly account in the fatigue life prediction model for the influence of riveting. This was achieved utilizing a unique relationship between rivet hole expansion on the sheet interface and the multiplier in the Basquin equation fit to the local stress amplitude versus fatigue life data points. Produced in Ref. [2] comparisons between the fatigue lives computed and observed in over 80 fatigue tests on aluminium alloy lap joint specimens involving various combinations of the production variables indicated a significant improvement in the prediction accuracy compared to a model which disregards the effect of riveting.

The literature evidence, e.g. [4,7], as well as experiments by the present authors [3] indicate that riveted joints characterized by the same rivet hole expansion but different friction conditions on the faying surface may show very different fatigue properties. Such results imply that transferability of the model will increase if the effect of the interference between the rivet and the hole and the effect of frictional load transfer on the fatigue life will be considered individually.

In this paper, the implementation of the above conception in the fatigue life prediction model is presented. Accordingly, the stress at the critical location is expressed as

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

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.

The derivation of the R_{TR} ratio, the k_b factor, and the fatigue notch factors in Eq. (1) was addressed in previous works [3,14,15]. This paper starts with the presentation of experimental investigations required to determine the α_{BP}, α_{BR}, α_b and α_{FR} coefficients and to relate them to riveting process characteristics. The experiments included measurements of several quantities corresponding to the rivet squeeze and a study of the evolution of friction on the faying surface of a riveted joint during cyclic loading. Fatigue tests on riveted lap joints as well as on coupons with open and filled holes were also carried out. The three-row riveted lap joint specimens of 2024-T3 Alclad sheets were intended to be a simple representation of longitudinal connections of the skin in the pressurized aircraft fuselage. The generated experimental results are subsequently used to validate the superposition approach involved in Eq. (1). The predictive capability of the model is evaluated based on comparisons between the fatigue lives computed and observed in a large number of fatigue tests on various riveted lap joints of D16 aluminium alloy sheets carried out previously by the authors [2,14,16]. Finally, following from the present study suggestions for future work are offered.

2. Riveted specimen fabrication

The geometry of the riveted lap joints used in the fatigue tests is shown in Fig. 1a, whilst the dimensions are given in Table 1. The deviations from the nominal rivet hole diameter (d_o) ranged from 0 to 0.03 mm. The rivet pitch in row (s) was the same as the rivet row pitch (p) and approximately equal to 5d. The 2024-T3 Alclad

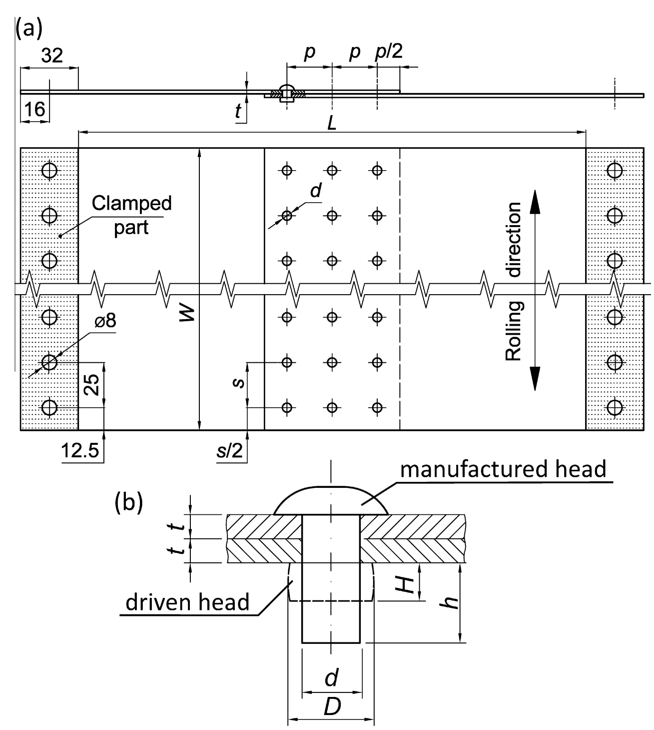

Fig. 1. Geometry of: (a) riveted specimen; (b) rivet.