Influence of technological imperfections on residual stress fields in riveted joints

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Abstract

The analysis of riveted structures requires a local-global approach in modelling. The local model is used to calculate the residual stress and strain fields around the rivet hole and analyse the influence of technological imperfections on the quality of the joint. The influence of the rivet with compensator on the stress distribution at the rivet hole is presented. Contact phenomena with Coulomb friction between collaborating parts of the joint and application of an elasto-plastic material model are taken into consideration.

Keywords: Riveted joint, imperfections, local analysis, FEM;

1. Introduction

Riveting is the oldest and the most popular method of joining metal parts in aircraft structures. Thin walled structures consist of a frame (stringers, ribs or spars) supporting other components. The frame is covered with thin metal or composite sheets of thickness varying from 0.6 mm to 4 mm.

Modelling of aircraft structures requires a local-global approach on several levels. The analysis of large parts of structures like fuselages, wings or multi-row riveted specimens can be performed using global models [1], whereas local and micro-local models are used to simulate the riveting process, to calculate residual stress state, to analyse the conditions causing crack initiation [2] and to study the influence of manufacturing factors on the quality of the riveted joint [3]. The strength of large structural components subjected to static load can be successfully determined from global analysis and classical methods according to aircraft standards like FAR (Federal Aviation Regulations) or JAR (Joint Aviation Requirements). However, the fatigue performance of riveted joints depends on local and micro-local phenomena in the contact interface between mating parts and its analysis requires a local approach.

Furthermore, riveted joints are critical areas of the aircraft structure due to severe stress concentrations, plastic strains and effects such as surface damage (fretting wear) and secondary bending. Therefore, the fatigue crack initiation starts at the rivet holes. The contact surface is subjected to mechanical, thermal and electrochemical interaction (i.e. corrosion). However, the paper is focused on mechanical aspects only.

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Residual stresses (locally exceeding yield stress level) and plastic strain states occur in the joint after the riveting process. The residual stress can be defined as the stress state that remains in a part of a structure after all applied forces have been removed. The total stress experienced by the material at a given location within a component depends on the residual and applied stress. The residual post-riveting stress fields are widely accepted to have a significant influence on the fatigue life of aircraft structures. An axisymmetric stress field appears around the rivet hole of a properly driven rivet. Non-axial rivet position or other manufacturing imperfections (like initial gaps) may cause an asymmetric stress field related to the non-uniform distribution of pressure during the riveting process, whereas some technological factors may have positive influence on the residual stress fields. A modification of the riveting process based on squeezing the rivet with restriction of the shop head dimension is proposed in paper [4]. The rivet head is upset while its diameter is restricted (limited) by the additional ring to the nominal head diameter. This modification causes a better rivet hole filling capacity. The paper deals with another solution associated with improving the ability to transfer load to the hole by upsetting rivet in a more uniform way. The influence of a geometry imperfection, namely the rivet with compensator, on the residual stress and strain fields is presented.

2. Numerical analysis

Numerical FEM calculations of global and local models are carried out with MSC.Nastran and Marc codes. Materials used in riveted joints are subjected to high plastic deformation. The aluminium alloy 2024T3 (equivalent to PA77T) as sheet and PA25 as rivet material are considered. Tensile and compressive tests are required to determine the mechanical property data, including Young’s modulus of elasticity (71 GPa for rivet and 68 GPa for sheet material), yield strength (318 MPa and 374 MPa, respectively) and nonlinear stress-strain curve above the yield stress level. A method of stress-strain curve determination for the rivet shank upsetting is proposed by de Rijck et al. [5]. It is based on the formula

\[
F_{sq} = \frac{\pi D^2}{4} K \left( \ln \left( \frac{H_0}{H} \right) \right)^n
\]

where \( F_{sq} \) is the squeezing force, \( D \) is the shank diameter, \( H \) and \( H_0 \) are its current and initial heights, \( K \) denotes a strength coefficient and \( n \) is the strain hardening exponent.

The force and rivet dimensions are known from experimental tests while \( K \) and \( n \) are estimated by data fitting. Formula (1) is obtained under the following assumptions: the elastic strain is ignored, the logarithmic average plastic strain \( \varepsilon_p \) is established and the squeezing stress \( \sigma_{sq} \) is equal to true stress \( \sigma_p \)

\[
\varepsilon_p = \ln \left( \frac{H_0}{H} \right) \quad \frac{4 F_{sq}}{\pi D^2} = \sigma_{sq} = \sigma_p = K \left( \varepsilon_p \right)^n
\]

Assuming that the friction coefficient \( \mu \) (between the tool and the rivet shank) is greater than zero and that the tangential stress is constant on the contact surface and equal to \( \mu \sigma_p \), the squeezing stress and force can be written as follows [6]

\[
\sigma_{sq} = \sigma_p \left( 1 + \frac{\mu D}{3 H_0} \right) \quad F_{sq} = \frac{\pi D^2}{4} K \left( \ln \left( \frac{H_0}{H} \right) \right)^n \left( 1 + \frac{\mu D}{3 H_0} \right)
\]

The stress-strain curve is obtained from a uniaxial test. The measurement of yielding for the multiaxial state is performed using the von Mises yield criterion. The classical updated Lagrange procedure for elastic–plastic materials and large strain plasticity option is used due to large geometrical and material non–lineairities. The Coulomb contact model with a friction coefficient \( \mu = 0.2 \) is defined between the mating parts of the joint, while the penalty method is applied to numerically implement the contact constraints.

2.1. Global approach

A global approach is the first step of analysis which allows an estimation of the tearing (ultimate) force and the mechanism of the global specimen failure. In the global model, the sheets are represented as shell elements and
simplified models of rivets are used. The correct stress state can be obtained by taking into consideration the hole in the sheet, the rivet axis (as a rigid or beam element) and contact elements between the rivet and the hole as well as between the sheets [7].

Calculations are carried out for the single lap riveted joint consisting of two thin sheets (1.2 mm thick) connected by six rivets (3.5 mm diameter). The sheets are 21 mm wide and 170 mm long. The riveted joint is subjected to a tensile load. The deformations and force distribution obtained in the global analysis determine the boundary conditions of the local model, where simulation of the riveting process is performed.

2.2. Local approach

The local model is used to determine the residual stress and strain fields at the solid mushroom rivet and around the hole after the riveting process. A square area of the sheets (10.5 mm wide) surrounding a single mushroom rivet (shank diameter \( r = 3.5 \) mm) is considered. The dimensions of the mushroom rivet are taken according to Russian standard [OST 1 34040-79] (head radius \( R = 4.2 \) mm, diameter \( D = 7 \) mm, height \( h = 1.88 \) mm). The radius \( R_p \) of the rounded tool surface is equal to 4.8 mm. The local model geometry consists of three solids: a rivet and two sheets, whereas FE mesh contains about 90 000 eight-node isoparametric three-dimensional brick elements (Hex8 type) with a tri-linear interpolation function. The cases of the rivet geometry with and without a compensator (c1 and c2 respectively) are analysed (Fig. 1).

The rounded and flat rivet tools are assumed to be rigid surfaces. The outside edges of the sheets are constrained in normal direction. This model describes a part of the multi-riveted joint.

The joining process is performed according to aircraft technology using a squeeze or pneumatic riveter. Dynamic process simulation is presented further in this paper. Two load steps are considered: step I – upsetting the rivet, step II – unloading (removing the riveter). In case c2 the lower (rounded) tool is fixed and initial kinetic energy 15 J is specified for the upper one (reverse riveting). The rivet with a compensator is driven according to standard (case c1s) and reverse (case c1r) riveting procedure.

The curves of the radial and hoop stresses as well as the plastic strains versus radial distance from the rivet hole are shown in Fig. 2 - 4. The average stress and strain values in every sheet are presented.

The radial stress values in the upper sheet (from the side of the shop rivet head) for both cases (c1 and c2) are similar while the maximum value of hoop stress is obtained for case c2. Application of the rivet with compensator causes an increase of radial and hoop stress values in the lower sheet (Fig. 3).

![Fig. 1. Rivet numerical model (a) geometry case c1; (b) case c2](image)

![Fig. 2. Stresses in the upper sheet vs radial distance a) radial b) hoop component](image)

Irreversible plastic deformations of the sheet material around the rivet hole (Fig. 4) remain after the riveting process as a result of the rivet shank swelling in the hole. The plastic deformation region in the middle surface of the lower
sheet is two times smaller than the corresponding region of the upper sheet (for case c2). The compensator (c1) has a significant influence on the plastic region of the lower sheet since it almost doubles in comparison to case c2.

![Stresses in the lower sheet vs radial distance](image)

**Fig. 3.** Stresses in the lower sheet vs radial distance a) radial b) hoop component

![Plastic strains around the rivet hole vs radial distance](image)

**Fig. 4.** Plastic strains around the rivet hole vs radial distance a) upper sheet b) lower sheet

3. **Conclusions**

A method for determining the stress-strain curve of rivet shank under compression is proposed that takes into account the friction between the rivet and the tool.

With regard to the manufacturing process, an application of a compensator aiming at reducing the non-uniform stress distribution in the rivet hole is proposed and analysed. Using the rivet with a compensator results in a better rivet hole filling capability (better load transfer to the lower sheet) and the same stress level in upper and lower sheets.

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**References**

1. Jachimowicz J, Wronicz W. The selected problems of modelling riveted thin-walled aircraft structures (in Polish), *Przegląd Mechaniczny* 2008, 67 (5): 25-34
2. de Rijck J. Stress Analysis of Fatigue Crack in Mechanically Fastened Joints, (Doc. Dissertation), Delft University of Technology 2005
3. Szymczyk E, Jachimowicz J, Sławiński G. Riveting process simulation – upsetting of the mushroom rivet, *Journal of KONES* 2008, 15(2): 493 – 502
4. Szymczyk E, Jachimowicz J, Sławiński G, Derewonko A. Numerical modelling and analysis of riveting process in aircraft structure (in Polish), *Górnictwo odkrywkowe* 2008, 4–5: 88 – 94
5. de Rijck J, Homan JJ, Schijve J, Benedictus R. The driven rivet head dimensions as an indication of the fatigue performance of aircraft lap joints, *International Journal of fatigue* 2007, 9: 2208-2218
6. Wasiunyk P. Theory of forging and pressing (in Polish). WNT, Warszawa 1982
7. Szymczyk E, Jachimowicz J, Sławiński G. Global approach in modelling of riveted joints, *Shell Structures Theory and Applications* October 14-16, 2009, Jurata (Poland)