NUMERICAL STUDY OF THE INFLUENCE OF SHAPE IMPERFECTIONS ON RESIDUAL STRESS FIELDS IN A RIVET HOLE

Grzegorz Sławiński, Tadeusz Niezgoda, Elżbieta Szymczyk, Jerzy Jachimowicz

Military University of Technology
Department of Mechanics and Applied Computer Science
2 Gen. Sylwestra Kaliskiego Street, 00-908 Warsaw, Poland
tel.+48 22 6837201, fax: +48 22 6839355
e-mail: gslawinski@wat.edu.pl

Abstract

The paper deals with the numerical analysis on residual stress and strain fields in a rivet hole. This stage of study concerns improving of the fatigue performance of riveted joints in an airframe. Riveting, particularly in aviation, is a traditional but still commonly used method of joining sheet metal components. Aircraft structures are thin-walled ones, with coverings made of thin sheets stiffened by stringers, frames or ribs. Sheets are typically assembled by a multiple rivet or bolt joints. Rivets and bolts are also used to joint sheets and stiffeners. Therefore, fatigue resistance of the aircraft structure depends on tens of thousands or even hundreds of thousands rivet joints, which are used to build it. The local numerical models of the joint are considered with regard to the aim introduced in the paper. Numerical FE simulations of an upsetting process are carried out using the LS-DYNA code. Three-dimensional numerical models are used to determine the resulting stress and strain fields at the mushroom rivet and around the hole. This type of problem requires the use of contact between the elements assembled and non-linear geometric and elasto-plastic multilinear material models to simulate the behaviour of the rivet and sheets. The influence of shape imperfection on strain and stress states is studied.

Keywords: *FEM, riveted joints, imperfections, residual stress*

1. Introduction

Riveting is a traditional but still popular method of joining thin-walled parts of aircraft structures. It is used in large airliners, freight aircraft and in light fighter-trainers planes as well as in helicopters where riveting is the basic method of joining metal and composite components [1]. The number of rivets is counted in millions and their weight may achieve a few tons. Therefore, fatigue resistance of the aircraft structure depends on thousands riveted joints, which are used to build it.

The 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 [1, 2]. The contact surface is subjected to mechanical, thermal and electrochemical interaction (i.e. corrosion). Though, the paper is focused on mechanical aspects only. However, residual stress fields are widely accepted to have a significant influence on fatigue life of riveted joints [3]. Compressive residual stress fields are beneficial due to their tendency to decrease the probability of stress corrosion and fatigue cracking.

An axisymmetric stress field appears around the rivet hole of a properly driven rivet (Fig. 1a). A nonaxial rivet position or other geometrical imperfections may cause an asymmetric stress field (related to the non-uniform distribution of pressure during the riveting process), observed in Fig. 1b [4-6]. The paper deals with another solution associated with improving the ability to transfer a load to the hole by upsetting the rivet in a more uniform way. The influence of geometry imperfection on the deformations and strain fields is presented.

The methods of driving solid shank rivets can be classified in two types: static and dynamic [6]. The static (squeeze) method is the most efficient one since it causes that all rivets are driven with

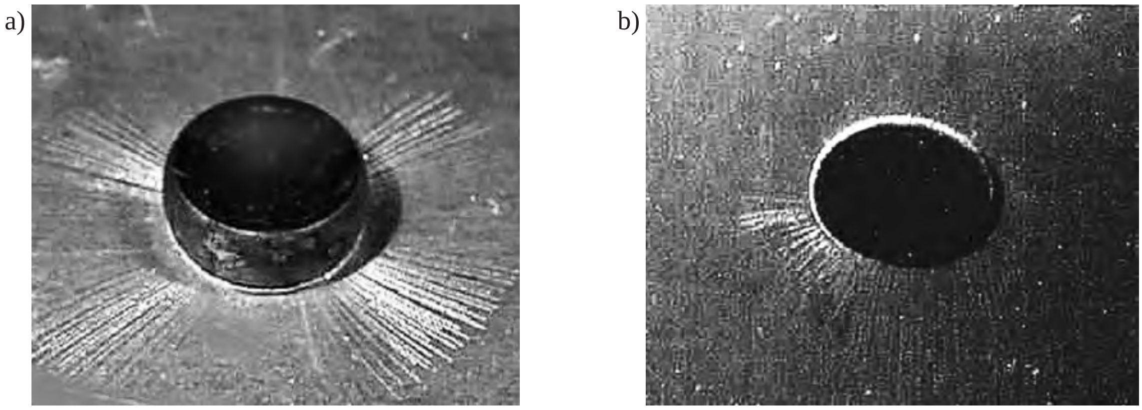

Fig. 1. Visual detection of cracks field around the rivet hole: a) properly driven rivet, b) effect of non-uniform pressure distribution [4]

uniform pressure and the rivet shank are sufficiently and regularly expanded to fill completely the rivet hole. Regrettably, the application of this method is limited.

The most common upsetting tool used in an aircraft is a pneumatic riveter. Two methods of dynamic riveting can be used depending on the location and accessibility of the part being jointed. In the former method, the manufactured head is driven with the set and a hammer while the shank's end is bucked with a suitable bucking bar, whereas in the latter one the shank's end is driven and the manufactured head is bucked. This method is called reverse.

2. Numerical Models

The analysis is carried out for a solid mushroom rivet (shank diameter d = 3.5 mm) joining two aluminium sheets (thickness 1.2 mm). A three-dimensional numerical model of the neighbourhood (10.5 mm wide) of a single rivet is considered (Fig. 2). Dimensions of the mushroom rivet are taken according to a Russian standard [7] (head radius R = 4.2 mm, diameter D = 7 mm, height h = 1.88 mm). The radius Rp of the rounded tool surface is equal to 4.8 mm.

The models of the rivet and sheets consist of eight-node, isoparametric, three-dimensional SOLID elements with tri-linear interpolation. Materials used in riveted joints are subjected to high-strain deformation (plastic deformation). Tensile and compressive testing is required to determine mechanical property data like: Young's modulus of elasticity, yield strength and nonlinear behaviour of stress - strain curve above the yield stress level. A sheet material (2024-T3) is tested for a standard flat specimen (in PN-91/H-04310 specification). Tensile and compressive tests are performed for the "rivet" sample.

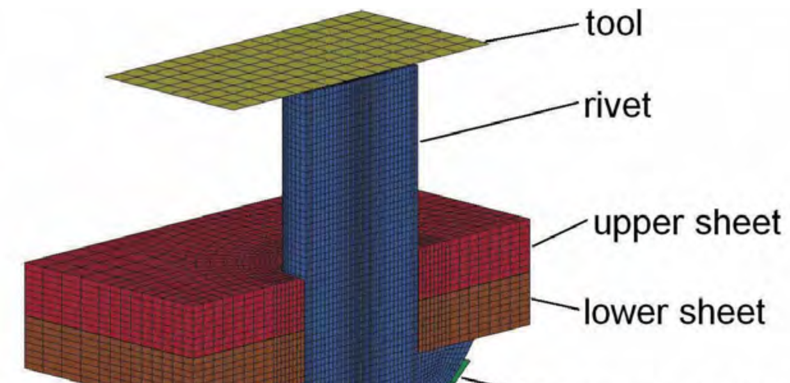

Fig. 2. The Model of a riveted specimen

Elasto-plastic material models are considered. Multilinear material true stress –logarithmic strain curves for a sheet and rivet alloy are shown in Fig. 3. Material property data are presented in Tab. 1. The magnitude of the yield stress and tensile strength are obtained from a uniaxial test. The yield stress for the multiaxial state is calculated using the von Misses yield criterion and it is based on the following formula:

$$\sigma_{equivalent} = \sqrt{\frac{3}{2}\sigma_{ij}^{d}\sigma_{ij}^{d}} = \sigma_y, \qquad (1)$$

where σ_y is the yield stress and $\sigma_{ij}^{d} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$ is the deviatoric Cauchy stress.

An explicit numerical procedure is used due to large geometrical and material nonlinearities.

Tab. 1. Mechanical properties of aluminium alloys PA25 and 2024-T3

Aluminium alloy	Young's modulus [MPa]	Poisson's ratio ν	Yield stress [MPa]	Strength [MPa]	Elongation [-]
PA25	71000	0,33	318	488	0,14
2024-T3	68000	0,3	374	460	0,16

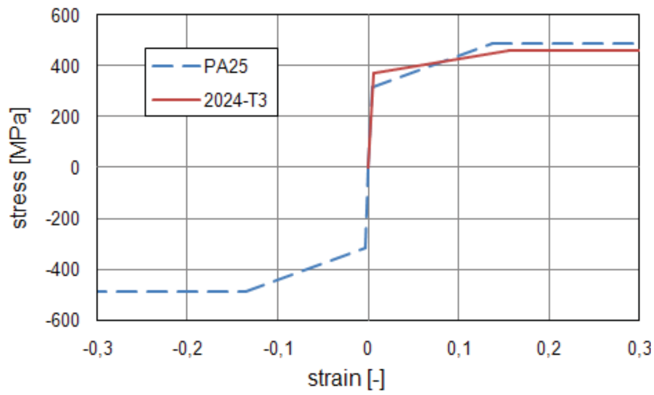

Fig. 3. Nonlinear stress–strain curves

The outside edge of the sheets is constrained in normal direction. This model describes a part of the multi - riveted joint. The rounded and the flat rivet tools are described as rigid surfaces. The contact with friction is defined between the mating parts of the joint. The Coulomb friction model with friction coefficient ν = 0.2 is used.

The joining process is performed according to aircraft technology using a pneumatic riveter. Dynamic process simulation is presented in this paper. In each cases, the lower (rounded) tool is fixed and initial kinetic energy 15 J is specified for the upper one (flat) (Fig. 4a). Five cases of the numerical simulation of the riveting process are shown in Fig. 4.

In this work selected results from numerical research of following cases of upsetting were presented: nominal variant (w0), maximal clearance holes (w1), ovalization of the holes (w2), misalignment holes (w3), skew formed rivet head (w4).

3. Numerical Calculations

The numerical calculations are performed for five cases of upsetting (w0, w1, w2, w3, w4) described by the shape and inside diameter of the rivet hole (Fig. 4).

Irreversible plastic deformations of a sheet material around the rivet hole remain after the riveting process as a result of the rivet shank swelling in the hole. The fields of the plastic strain in the upper and the lower sheet after a riveting process are presented in Fig. 5. Plastic strain fields around

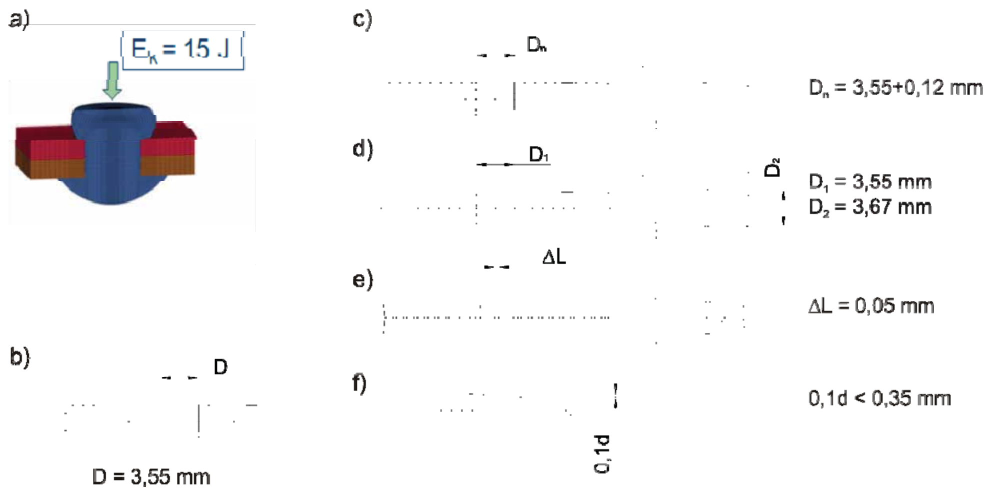

Fig. 4. Cases of numerical simulations: a) riveting process, b) w0; c) w1; d) w2; e) w3; f) w4

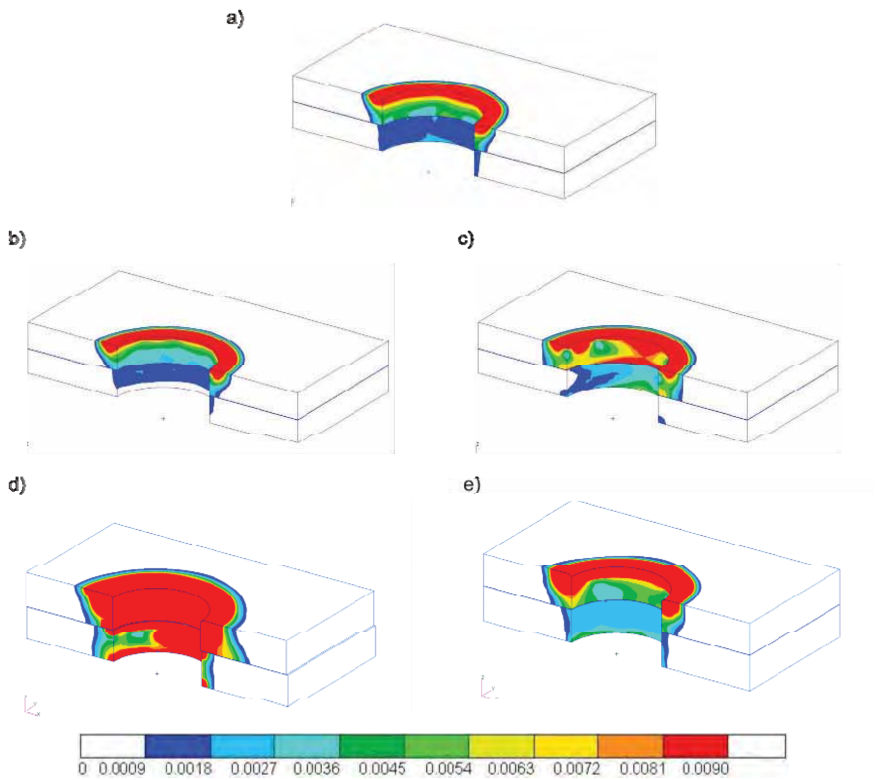

Fig 5. Plastic strain fields in the upper and lower sheet

the rivet hole for case w0 and w1 have axisymmetric distribution and asymmetric, for the others cases. Simultaneously, for case w0 the hole in the lower sheet (from the side of the manufactured rivet head) is better filled with the rivet material than in the others.

Distributions of radial stress in the upper and lower sheets after a riveting process for five cases are shown in Fig. 6-10. In each case, stresses around the rivet hole in the upper sheet are larger than in the lower sheet. Stresses occur at the rivet hole and tend to decrease with the increase of the radial distance from the hole. Stress fields around the rivet hole for case w0 and w1 have axisymmetric distribution and asymmetric, for the others cases. Stress concentrations occur under the driven rivet head. For upper sheet, maximum extreme values of the stress occur at the rivet hole is equal to -460 MPa (case w4) and minimum extreme is equal to -308 MPa in case w0. In the lower sheet, the maximum negative value of the stress occur at the rivet hole is equal to -408 MPa (case w2) and minimum negative value is equal to -226 MPa in case w0.

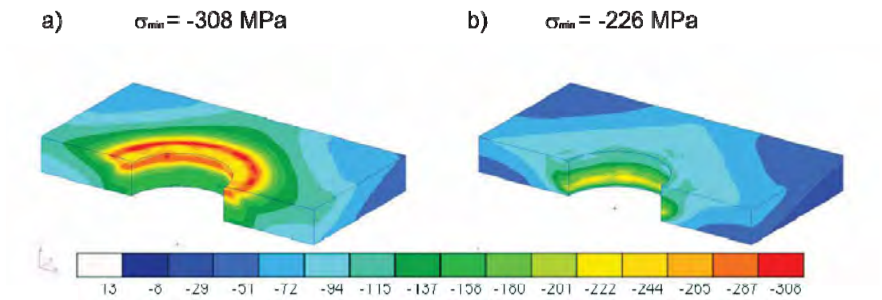

Fig. 6. Radial stress fields for case w0: a) in the upper sheet, b) in the lower sheet

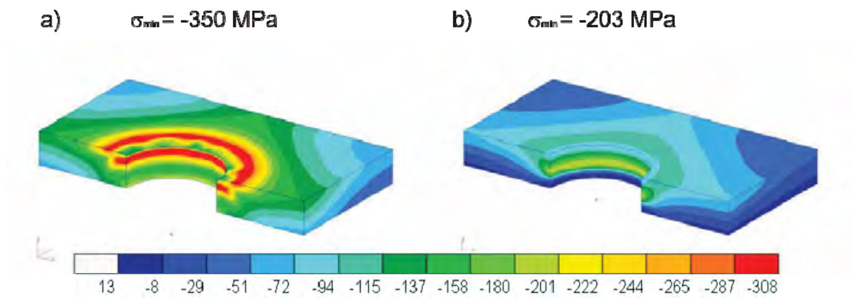

Fig. 7. Radial stress fields for case w1: a) in the upper sheet, b) in the lower sheet

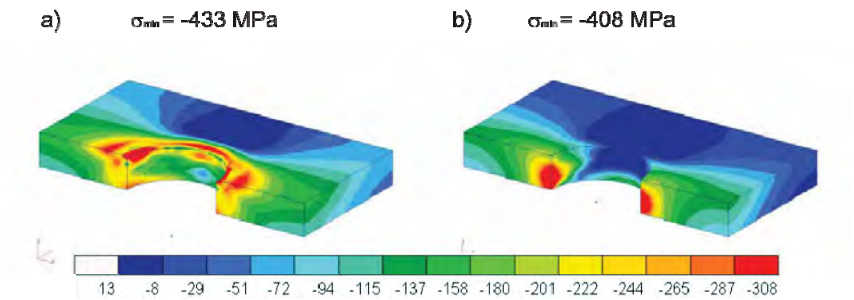

Fig. 8. Radial stress fields for case w2: a) in the upper sheet, b) in the lower sheet

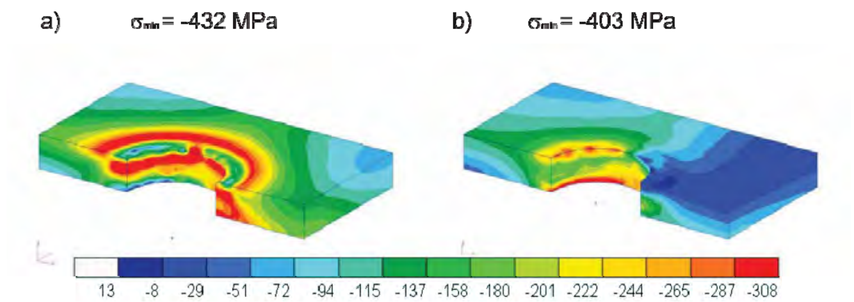

Fig. 9. Radial stress fields for case w3: a) in the upper sheet, b) in the lower sheet

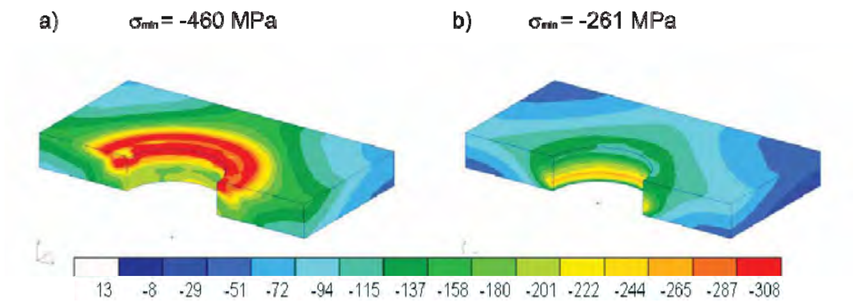

Fig. 10. Radial stress fields for case w4: a) in the upper sheet, b) in the lower sheet

Distributions of the hoop stress in the upper and lower sheet after the riveting process for five cases are shown in Fig. 11-15. They are identical in nature to the radial stress. For upper sheet, maximum extreme values of the stress occur at the rivet hole, on the top surface of the sheet under the driven rivet head, is equal to -520 MPa (case w3) and the minimum extreme is equal to -360 MPa in case w1. In the lower sheet, the maximum negative value of the stress occur at the rivet hole is equal to -420 MPa (case w3) and the minimum negative value is equal to -58 MPa in case w1.

A change of the stress value in the middle surface in the upper and lower sheet versus a change of the angle are presented in Fig. 17 and 18. Stress measurements are made at a distance of 1.8 mm from the edge of the hole in terms of changing the angle from 0 deg to 180 deg (Fig. 16).

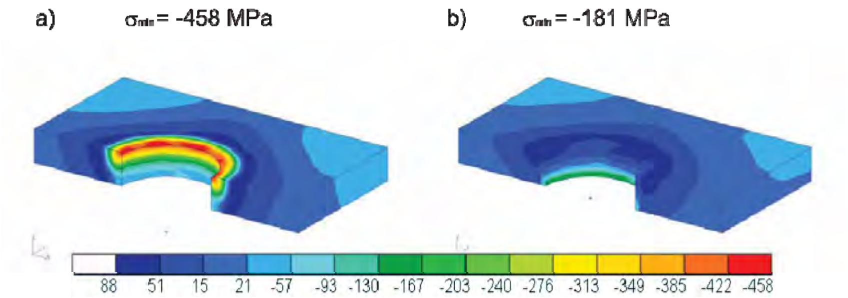

Fig. 11. Hoop stress fields for case w0: a) in the upper sheet, b) in the lower sheet

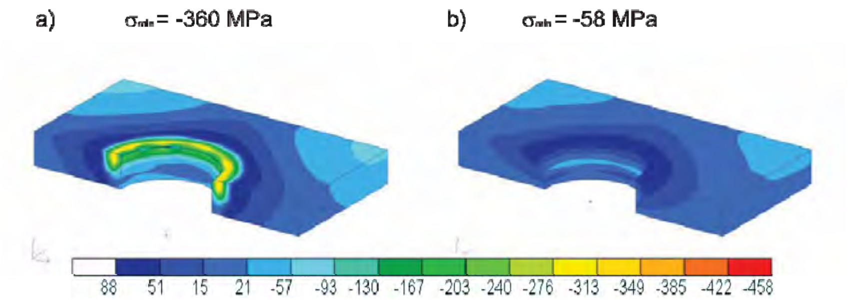

Fig. 12. Hoop stress fields for case w1: a) in the upper sheet, b) in the lower sheet

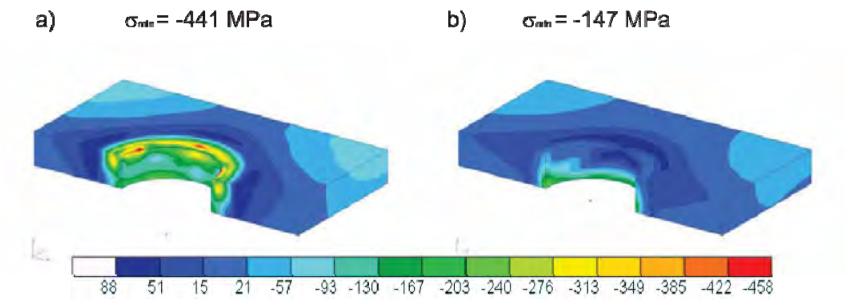

Fig. 13. Hoop stress fields for case w2: a) in the upper sheet, b) in the lower sheet

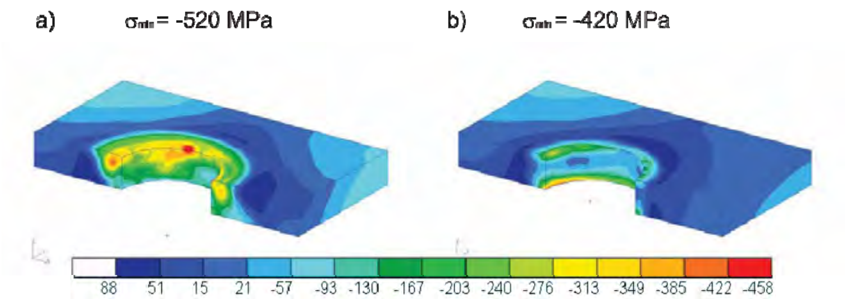

Fig. 14. Hoop stress fields for case w3: a) in the upper sheet, b) in the lower sheet

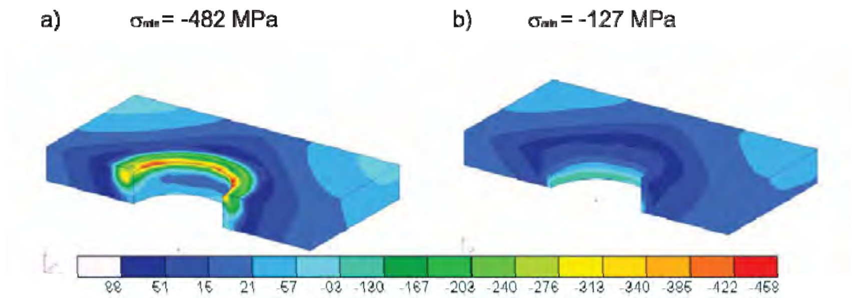

Fig. 15. Hoop stress fields for case w4: a) in the upper sheet, b) in the lower sheet

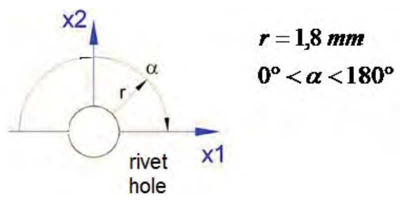

Fig. 16. Coordinates

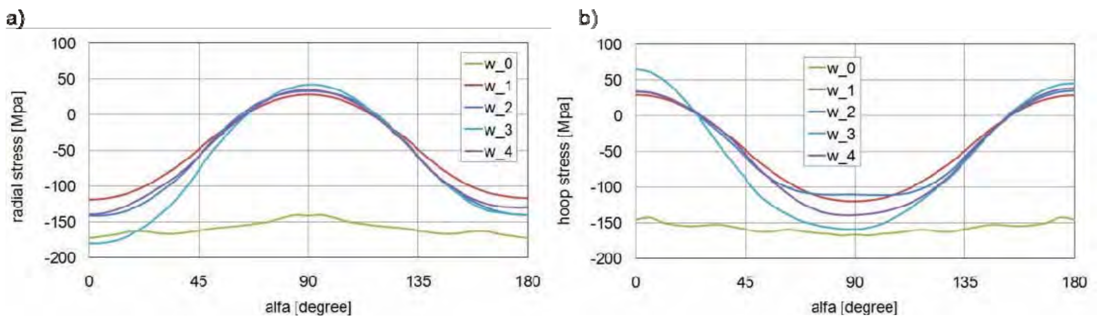

Fig. 17. Residual stress vs. change angle in the upper sheet: a) radial stress b) hoop stress

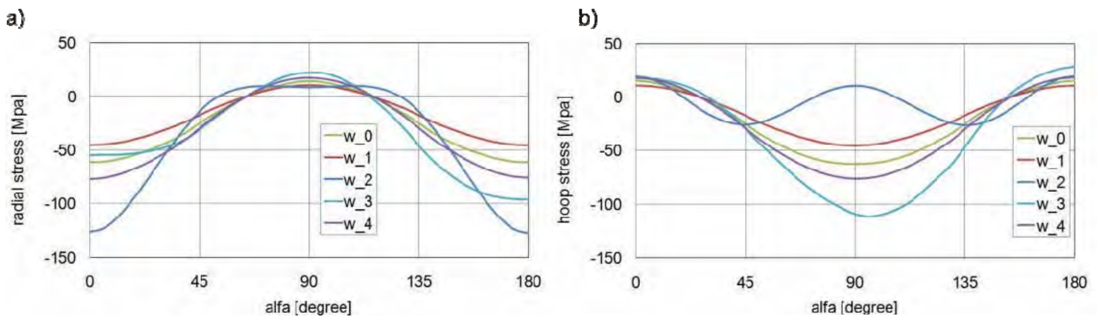

Fig. 18. Residual stress vs. change angle in the upper lower: a) radial stress b) hoop stress

Homogeneous distribution of the stress occurs in the upper sheet in case w0 and it is desirable as it improves the fatigue resistance of the aircraft structure. For cases w2, w3 and w4, the shape imperfection of a rivet hole causes the radial and hoop stress increasing in the upper sheet for 90 deg and decreasing for 0 deg. For 90 deg the shape imperfection causes increasing the stress value from negative to positive.

4. Conclusions

The obtained results of numerical calculations show us the influence of defects and the geometrical imperfections on fatigue resistance of the aircraft structure as well as indicate that the high-grade work of a rivet hole can have a significant influence on correct work of a riveted joint under load. Our further investigations will be directed towards an experimental verification of the obtained results.

Acknowledgements

This work was carried out under the financial support of Polish Ministry of Science and Higher Education within a research project in the framework of the Eureka Initiative.

References

[1] de Rijck, J., *Stress Analysis of Fatigue Crack in Mechanically Fastened Joints*, (Doctoral Dissertation), Delft University of Technology, 2005.
[2] Muller, R., *An experimental and numerical investigation on the fatigue behaviour of fuselage riveted lap joints*, Doctoral Dissertation, Delft University of Technology, 1995.
[3] de Rijck, J., Homan, J. J., Schijve, J., Benedictus, R., *The driven rivet head dimensions as an indication of the fatigue performance of aircraft lap joints*, International Journal of Fatigue, Vol. 9, pp. 2208-2218, 2007.
[4] Szymczyk, E., Jachimowicz, J., Derewońko, A., *Analysis of residual stress fields in riveted joint*, Journal of KONES, Vol. 14, pp. 465-474, Warsaw 2007.
[5] Jachimowicz, J., Kajka, R., Szachnowski, W., Szymczyk, E., *FEM and experimental analysis of strain and stress states around the rivet hole in the thin walled aircraft structure* (in polish), Analizy numeryczne wybranych zagadnień mechaniki, 21, pp. 399-424, Warsaw 2007.
[6] Szymczyk, E., Jachimowicz, J., Sławiński, G., *Riveting process simulation – upsetting of the mushroom rivet*, Journal of KONES, Vol. 15, pp. 493-502, Warsaw 2008.
[7] OST 1 34040-79.