ANALYSIS OF RESIDUAL STRESS FIELDS IN THE RIVETED JOINT

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Abstract

The riveted joints are critical areas of the aircraft structure. The residual stress and strain state appears at the rivet hole after the riveting process and improves fatigue behaviour of the joint. Numerical FE simulations of the upsetting process are carried out using the MARC code. Three-dimensional numerical models are used to determine the resulting stress and strain fields at the countersunk rivet and around the hole. The contact with friction is defined between the mating parts of the joint. Calculations are carried out in an elastic-plastic range. The influence of the rivet geometry, rivet stiffness and the sheet material model on strain and stress states is studied. Non-destructive testing methods like X-ray diffraction, liquid penetrant inspection and visual detection analysis with a UV lamp are used for validation of numerical results. Comparison between numerical and experimental results gives a satisfactory agreement. Numerical simulations allow investigating the influence of imperfections on the strength of the joint.

Keywords: *riveted joint, FEM local model, non-destructive testing methods*

1. Introduction

Riveting, particularly in aviation, is a traditional but still commonly used joining method for metal and composite elements. The riveted joints are critical areas of the aircraft structure due to severe stress concentrations and effects such as surface damage (fretting) and secondary bending. These phenomena cause initiation and propagation of fatigue crack and decrease fatigue resistance of the riveted joint [1, 5, 7].

The residual stress (locally exceeding yield stress level) and plastic strain states are generated in the joint after the riveting process. Residual stress can be defined as the stress state that remains in a part of structure after all applied forces have been removed. Thermal and mechanical processes like heat treatment, hot or cold rolling, riveting etc. have an influence on the level of residual stresses. The total stress experienced by the material at a given location within a component depends on the residual and applied stress. Residual-stress fields are widely accepted to have a significant influence on fatigue life of aircraft structures. Compressive residual stress can be beneficial because it tends to decrease probability of stress corrosion and fatigue cracking [1].

Various methods of determining the residual stress state generated in the joint during riveting process are compared. The paper presents a certain stage of study of the local physical phenomena in riveted joints in the aspect of fatigue behaviour [2-7].

2. Riveted specimen

The analysis is carried out for tensile loaded lap riveted joint (Fig. 1). The sample consists of two aluminium sheets (50 mm wide and 157 mm long) connected by six steel rivets. Many undesirable phenomena, like electro-chemical corrosion, occur in the riveted joint due to different material properties of steel and aluminium alloy. It tends to accelerate surface damage, makes fatigue tests shorter, and allows easily detecting fretting wear [6, 7].

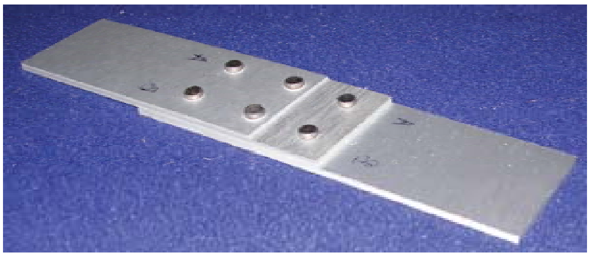


Fig. 1. Specimen geometry

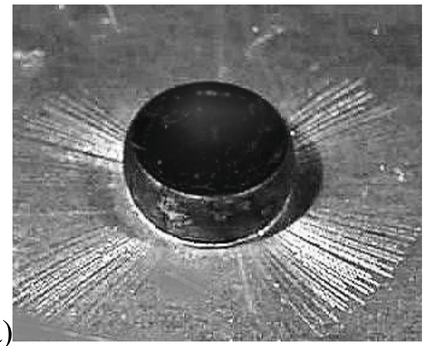
Materials used in riveted joints are subjected to high-strain deformation (plastic deformation). Mechanical tensile and compressive testing is required to determine mechanical property data like: Young's modulus of elasticity, yield strength and nonlinear behaviour of stress – strain curve above the yield stress level.

Sheet material (D16) is tested for standard flat specimen (in PN-91/H-04310 specification). Tensile and compressive tests are performed for the "rivet" sample [5]. Experimental results (engineering stress/strain values) are shown in table 1.

Tab. 1. Mechanical property data (tensile test) for sheet and rivet material

	Yield strength R_e [MPa]	**ultimate tensile strength R_m [MPa]**	**Young's Modulus E [MPa]**	**elongation ε [%]**
sheet (D16)	374	460	70 914	16,0
rivet (ST3n)	331	670	197 000	-

3. Experimental tests

a) 

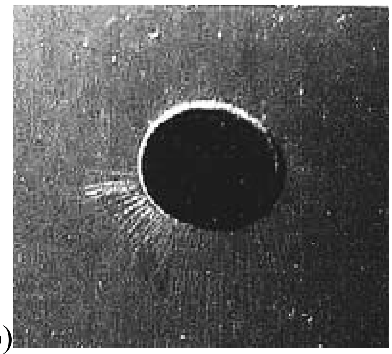
b) 

Fig. 2. Visual detection of cracks field around the rivet hole: a) properly driven rivet, b) effect of non-uniform pressure distribution

Joining process of the specimen is performed using riveting press according to aircraft technology. Non-destructive testing method [7] like X-ray diffraction, liquid penetrant inspection and visual detection analysis with a UV lamp are used for quantitative and qualitative tests of riveted specimens. Axisymmetric stress field appears around the rivet hole for properly driven rivet (Fig. 2a). Nonaxial rivet position and asymmetric stress field (related to the non-uniform distribution of pressure during the riveting process) are observed for a few samples (Fig. 2b).

The radial component of residual stress is measured using X-ray diffraction in selected points at the distance of 2 mm, 4 mm and 8.5 mm from driven rivet head (Fig. 3).

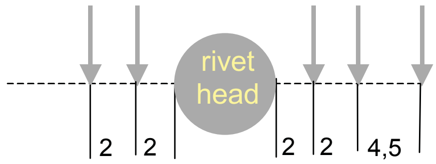


Fig. 3. Measurement points

The X-ray diffraction method is based on the phenomenon of the monochrome X-ray beam scattering. In a certain (only one) direction constructive interference (diffraction) of scattered radiation occurs dependent on the spacing d between the atom planes and the wavelength λ of the incident radiation (Fig. 4). The law that governs diffraction (1) is known as Bragg's law [9]

$$n \cdot \lambda = 2d\,sin\,\theta\,, \tag{1}$$

where:

- n – an integer number,
- λ – wavelength,
- d – spacing between atom planes,
- θ – Bragg's angle of reflection of X-ray beam.

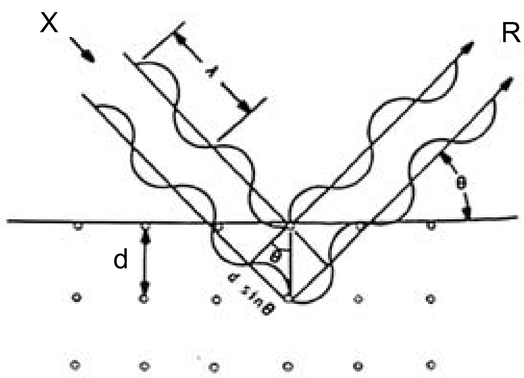


Fig. 4.Diffraction of X-rays and Bragg's law [9]: X – ray incident beam, R – reflected beam

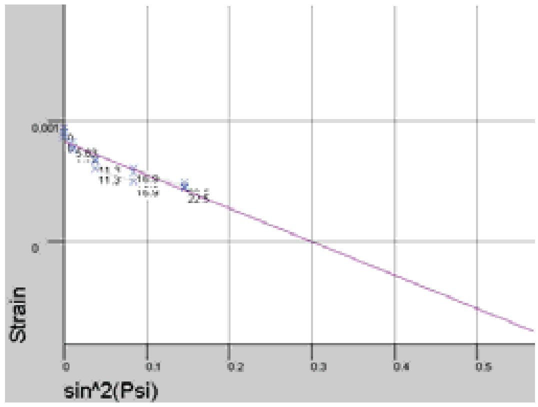


Fig. 5. A linear graph of strain vs. $sin^2\,\psi$

When the relation (1) is satisfied, two reflected rays will be in phase, which results in constructive interference. By using a monochromatic X-ray beam of known wavelength and measuring the diffraction angle 2θ, it is possible to determine interplanar spacing d. This technique is the basis of structure analysis and of residual stress measurement.

Stress is not measured directly by the X-ray diffraction; it is always strain that is measured. Then the stress is calculated using appropriate equations of elasticity and $sin^2\psi$ method [7, 9]. A result of X-ray diffraction measurement can be a linear behaviour of strain vs. $sin^2\psi$ (Fig. 5). The estimated value of stress component σ_r in radial direction is obtained from equation (2)

$$\sigma_r = m\frac{E}{1+\nu}, \tag{2}$$

where:

- m – slope of the linear plot (Fig. 5),
- E – Young's modulus of Elasticity,
- ν – Poisson's coefficient.

4. Numerical models

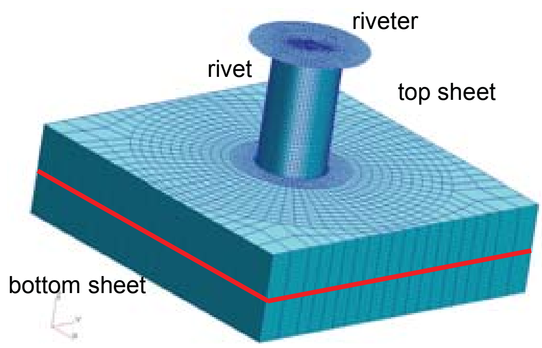


Fig. 6. Model of riveted specimen

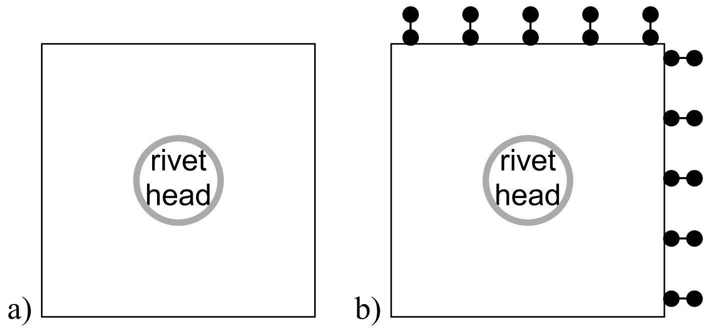


Fig. 7. Constrains a) single rivet b) part of multi rivet sample

Numerical simulation of the riveting process is carried out for the rivet (shank diameter r = 5mm) and its neighbourhood in the sheets (Fig. 6). The calculations are performed for a single rivet sample (sheet edges are free) and for a part of the multi riveted joint (symmetry of the joint and reactions of the remaining part of the specimen determine the boundary conditions in this model) (Fig. 7). The contact with friction is defined between the mating parts of the joint [6]. Two load steps are considered: step I – upsetting the rivet, step II – unloading (riveter removing).

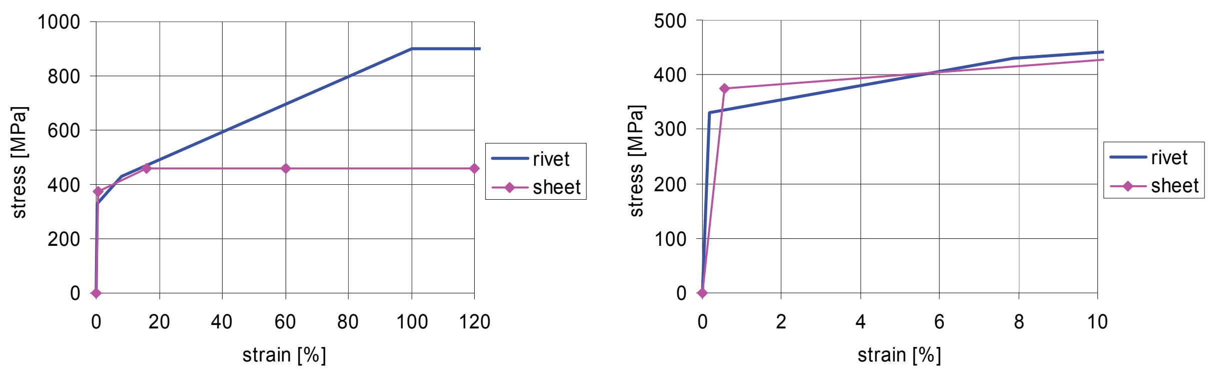


Fig. 8. Nonlinear stress–strain curves

Elasto–plastic material models are considered. Multilinear material real stress – real strain curves [8] for steel and aluminium alloy are presented in Figure 8. The magnitude of the yield stress is obtained from uniaxial test. The measurement of yielding for the multiaxial state is performed using the von Misses yield criterion.

$$\sigma_{\text{equivalent}} = R_e \,. \tag{3}$$

5. Numerical calculations

The numerical calculations are performed for a single rivet sample and a part of the multi riveted joint. The rivet and the hole deformation are presented in Figure 9 and 10. Comparison between numerical and experimental [5] results gives a satisfactory agreement.

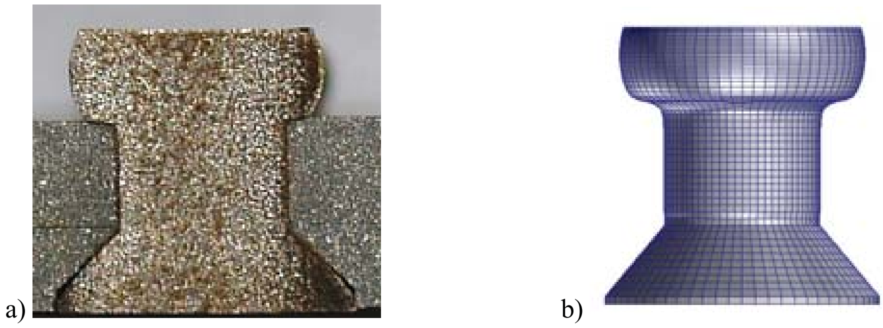


Fig. 9. Deformation of the driven rivet a) experiment b) calculations

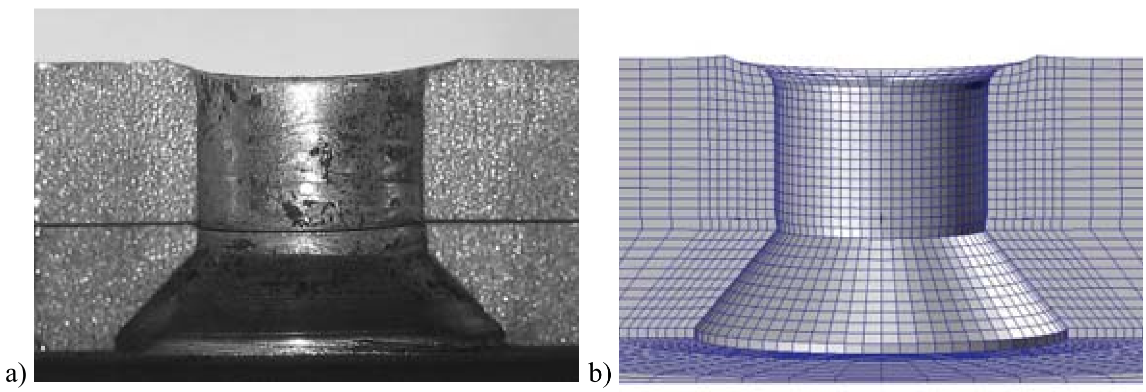


Fig. 10. Deformation of the rivet hole after riveting process a) experiment b) calculations

Axisymmetric radial and hoop stress fields appear in the neighbourhood of the rivet hole (Fig. 11 a ÷ 14 a). The neighbour rivets result in a non–symmetric stress state in the part of the riveted specimen (Fig. 11 b ÷ 14 b). The difference between stress values for the single rivet and the part of specimen is at the level of 40 MPa. It is five percent of the peak radial stress in the riveted hole.

After unloading (removing press equipment) the maximum value of radial stresses in the sheet decreases about two times (from 713 to 435 MPa) (Fig. 11 b and 12 b).

Radial and hoop stress graphs vs. distance (from the rivet axis) in the radial direction are presented in Figures 15 ÷ 18. Numerical and analytical results for a single rivet and a part of the multi riveted specimen are compared. Two load steps are taken into consideration.

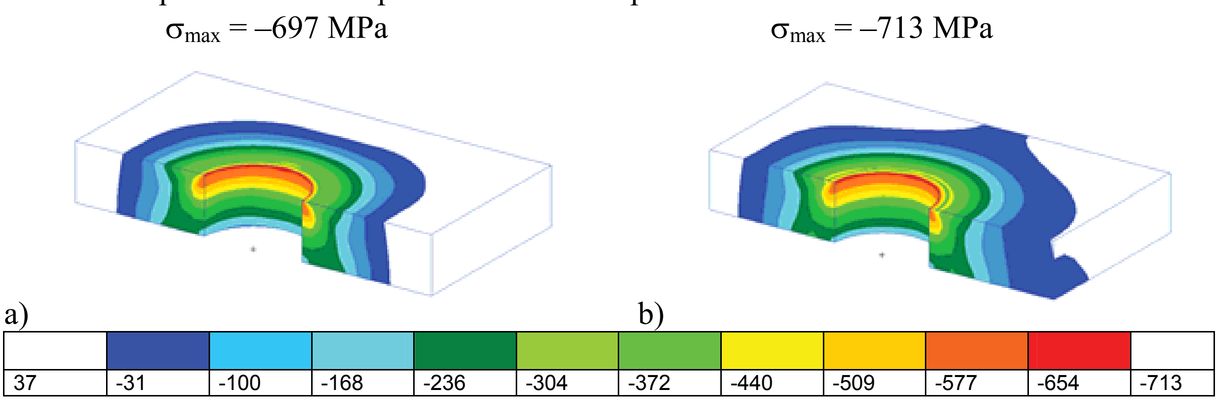
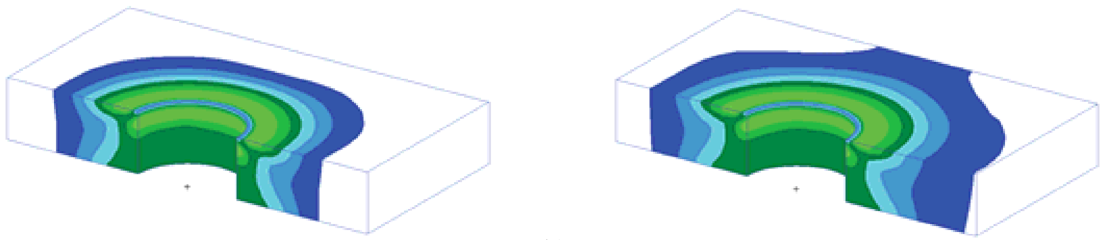


Fig. 11. Radial stresses – step I (pressure) a) a single rivet b) a part of the multi riveted specimen

σ_{max} = –441 MPa　　　　σ_{max} = –435 MPa



a)　　　　b)

Fig. 12. Radial stresses – step II (unloading) a) a single rivet b) a part of the multi riveted specimen

σ_{max} = 287 MPa > σ_{min} = –658 MPa　　　　σ_{max} = 304 MPa > σ_{min} = –670 MPa

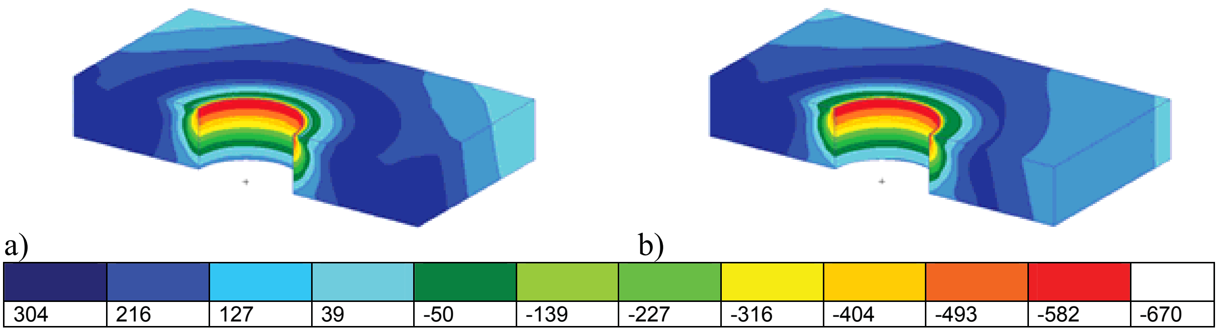
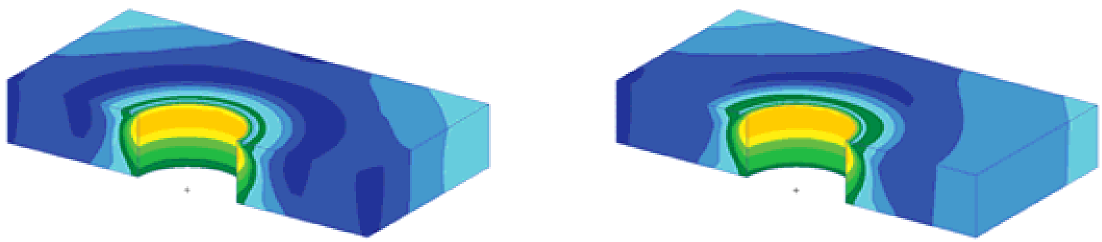


Fig. 13. Hoop stresses – step I (pressure) a) a single rivet b) a part of the multi riveted specimen

σ_{max} = 260 MPa > σ_{min} = 463 MPa　　　　σ_{max} = 253 MPa > σ_{min} = –485 MPa



a)　　　　b)

Fig. 14. Hoop stresses – step II (unloading) a) a single rivet b) a part of the multi riveted specimen

Radial and hoop stress analytical functions are calculated according to the Lame equations [10] assuming that the rivet hole is subjected to an internal pressure

$$p = \frac{uE}{r\left(\frac{r^2 + b^2}{b^2 - r^2} + \nu\right)}, \tag{4}$$

where:

- u – numerically calculated internal displacement of the rivet hole,
- r – rivet (hole) radius,
- b – external radius,
- E, ν – mechanical property data.

The results for a single rivet and a part of the multi riveted specimen are compared in Figure 18. The points represent stress values obtained by X–ray measurement. The numerical and experimental results are in good accordance. Radial and hoop graphs vs. distance in circumferential direction in the settled distance from the rivet are shown in Figure 19 and 20. The cyclic behaviour of the stress curve for a single rivet is the result of a square shape of analysed rivet neighbourhood. Maximum differences between stress values for a single rivet and a part of riveted specimen are observed in the range from 0° to 90°. This is the result of influence of other rivets (compare Fig. 7).

a) b)

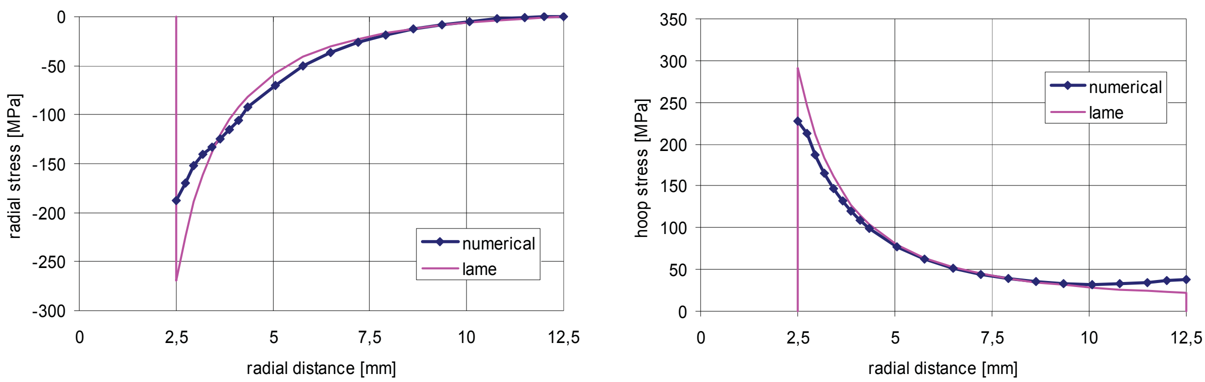


Fig. 15. Radial and hoop stress graph – elastic behaviour

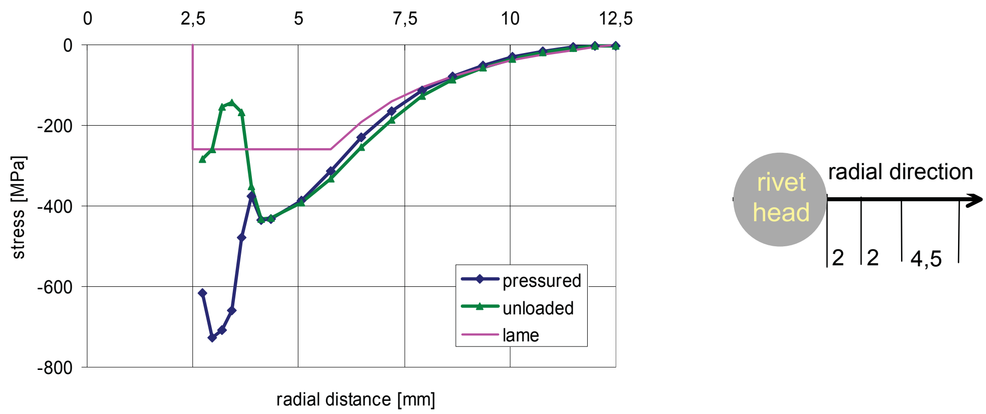


Fig. 16. Radial stress graph: step I – pressure, step II – unloading

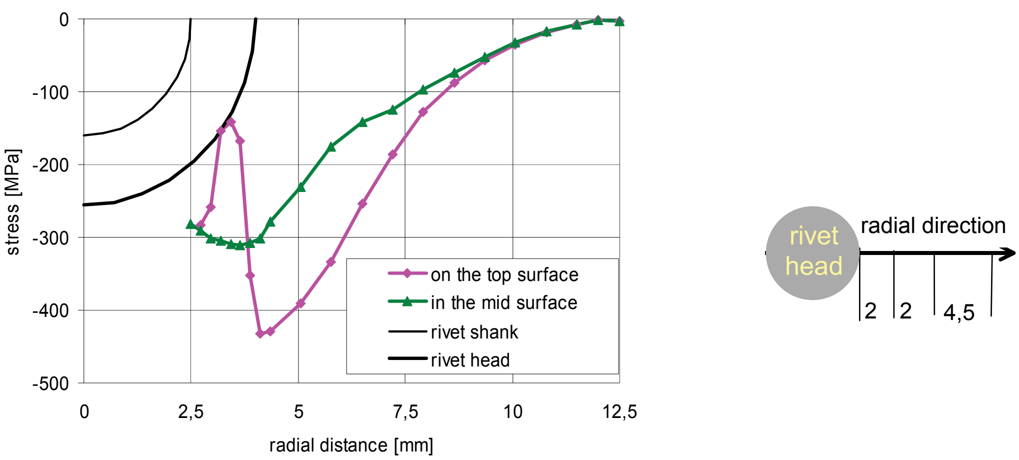


Fig. 17. Radial stress graph on the top surface and in the mid – surface of the sheet (step II - unloading)

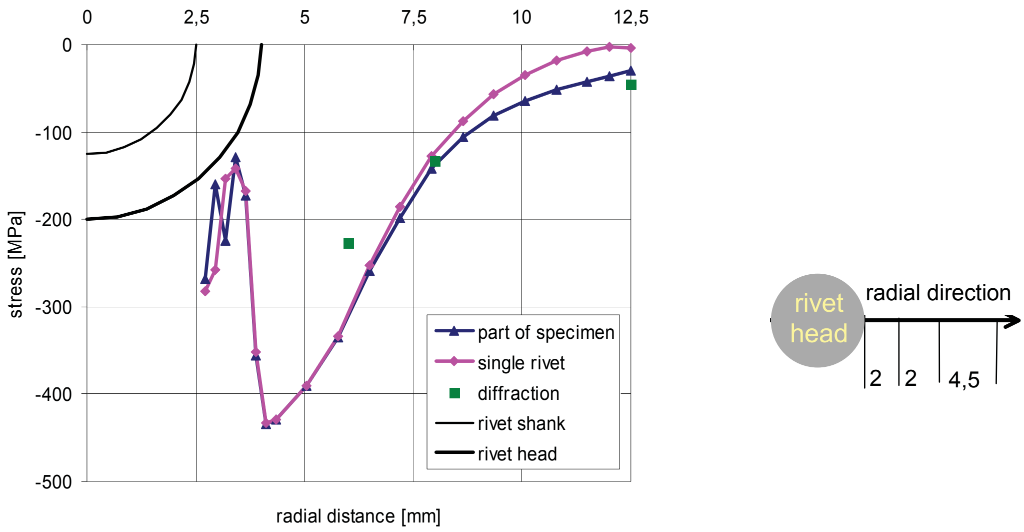


Fig. 18. Radial stress graph on the top surface of the sheet – step II (unloading)

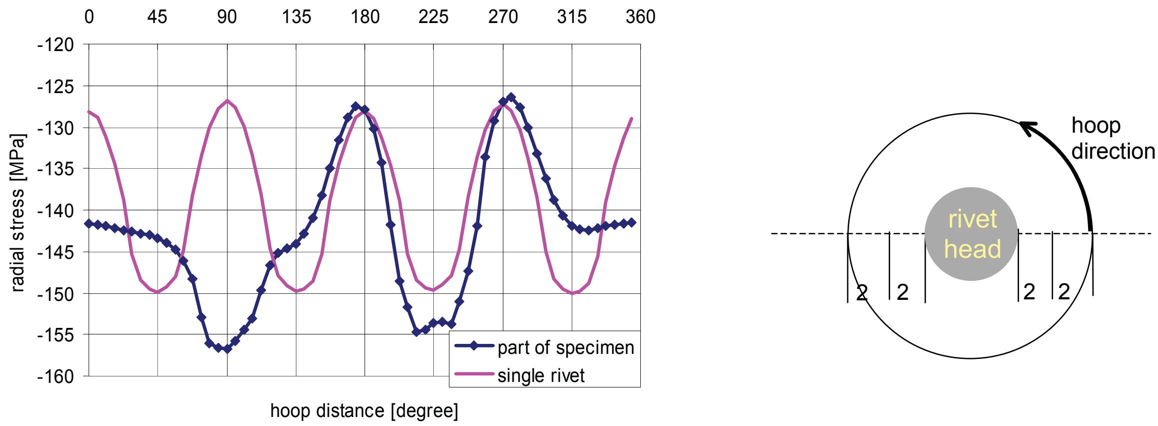


Fig. 19. Radial stress graph at the distance of 4mm from the rivet head – step II (unloading)

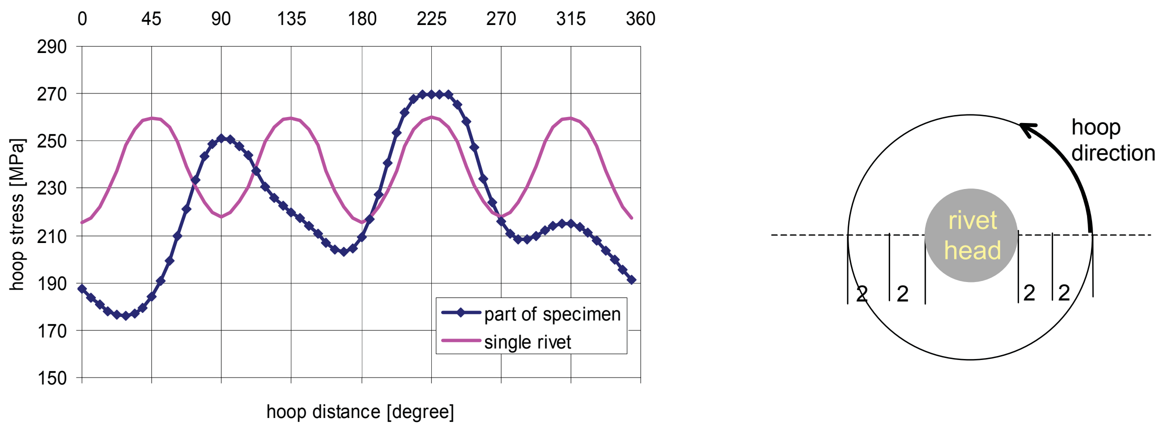


Fig. 20. Hoop stress graph at the distance of 4mm from the rivet head – step II (unloading)

6. Conclusions

Parallel consideration of non-destructive testing methods (like X-ray diffraction and visual detection) and numerical calculations (determining of stress and contact force fields) allow to make efficient qualitative and quantitative analysis of the residual stress state in a selected riveted joint.

Numerical calculations allow obtaining an accurate (for a selected model) stress and strain intensity factors for elastic, but especially for elasto – plastic material behaviour.

In the area of structure modelling, some solutions to the problem connected with analysis of riveting process are proposed. The influence of the numerical model parameters (like mesh density, shape of finite element in the contact area) on the correctness of numerical simulation results is investigated [2-7]. Friction and material models have significant influence on residual stress fields. Various stress – strain curves for tension and compression should be considered.

Numerical calculations and models are validated on the base of experimental tests. It allows using developed models and verified procedure of modelling in further analysis. Technological imperfections, like initial gaps between the rivet and the hole, nonaxial riveting etc., should be taken under consideration.

Acknowledgements

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