Stochastic Simulation of Aircraft Fuselage Assembly Considering Manufacturing Uncertainties

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1 Introduction

In aircraft production the use of rivets as permanent mechanical fastener to assemble lightweight sheet metal structures is very common. At assembly the rivet is placed in a through boring and the buck-tail is plastically deformed to create a second head. Thus rivets are positive locking and can carry axial tension loads. However, rivets are mainly used to transfer shear loads via the seating stress of their cylindrical shaft. The remaining pre-stress in the rivet and its local area after the riveting process is subject to immanent manufacturing scatter. When assembling the fuselage of commercial aircrafts additional inherent uncertainties are impacting the riveting process. The cylindrical barrels of a fuselage are typically manufactured from large thin walled shell structures underlying geometric tolerances and variations of the boundary conditions. Managing these uncertainties has a significant impact on the geometrical and structural product quality.

In this paper the resulting variations of the three-dimensional residual stress condition will be analysed by simulation. To simulate the fuselage assembly process the model must be able to predict the influence of manufacturing uncertainties appropriately. Therefore these uncertainties will be considered already during the modelling by stochastic parameters and random fields. While most application examples in the literature are quite simple [1], the present paper aims to apply random fields in an industrial application using LS-DYNA®. By utilizing non-invasive methods the approach can be adapted to different FE-Solvers without too much effort.

2 Modelling of the deterministic fuselage structure

The stochastic simulation is based upon a finite element model of two aircraft fuselage barrels during assembly process (Figure 1). The fuselage barrels consist mainly of three types of parts, the circular ribs, the stringers and the sheet metal skin. In the LS-DYNA model these are represented by shell elements. In addition the basic floor structure including Samer Rods and bilge structures are modelled. The floor is also represented by shell elements while the remaining structure is modelled from beam elements. Metallic parts are modelled with a linear-elastic material model of a typical aluminium-copper alloy. The floor made of carbon fibre sandwich material with orthotropic properties a suitable material model is chosen.

The two fuselage barrels are assembled by riveting their flanges on one shared rib. While in reality the barrels are joined by pushing them onto the shared rib from both sides the simulation is modelled to start in-situ directly after moving the barrels together. A Surface-to-Surface-Interference contact is defined to avoid initial penetrations and consider potential pre-stresses resulting from geometrical imperfections of the barrels. This penalty based contact includes the shared rib as well as the sheet metal skin of the barrels in the flange area.

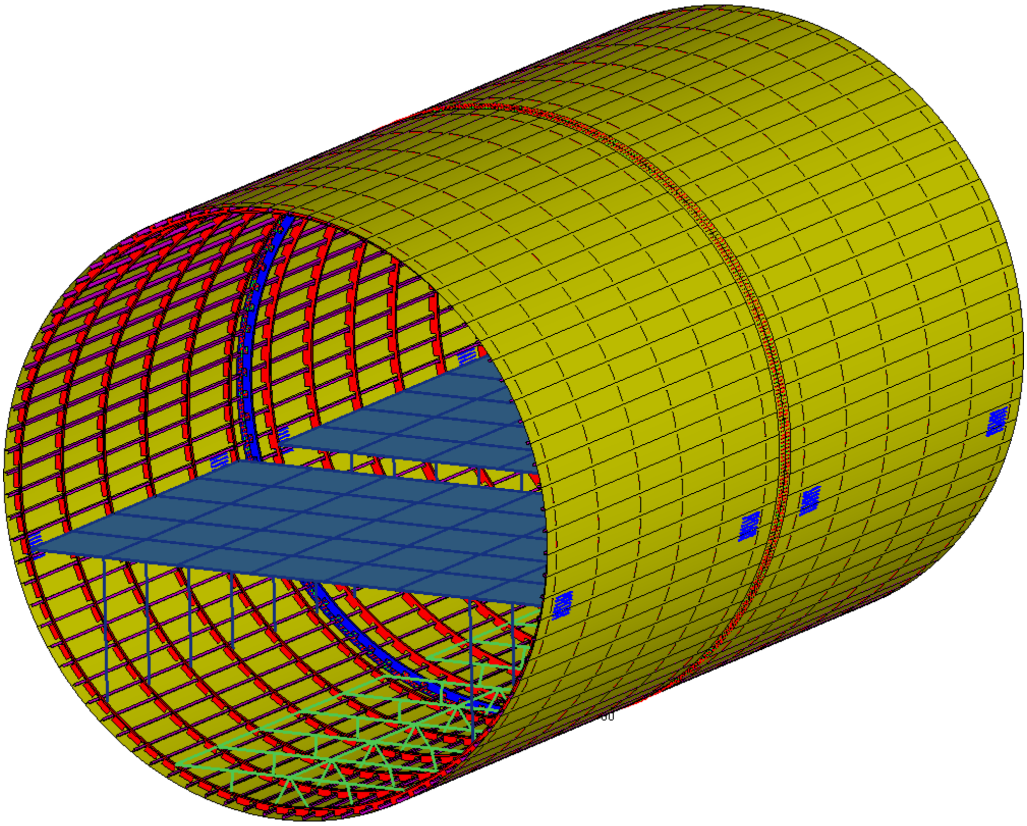

Fig. 1: Model of two aircraft fuselage barrels during assembly

The penalty based interference contact allows controlling the contact stiffness and damping individually. In modelling state the manufacturing uncertainties of both barrels are represented by geometric imperfections (Figure 2). Before simulation start the contact is initialised with high damping and progressively increasing contact stiffness up to material stiffness. Potential penetrations are transformed into pre-stresses. After the static equilibrium is reached the damping is reduced to normal values and the actual simulation starts.

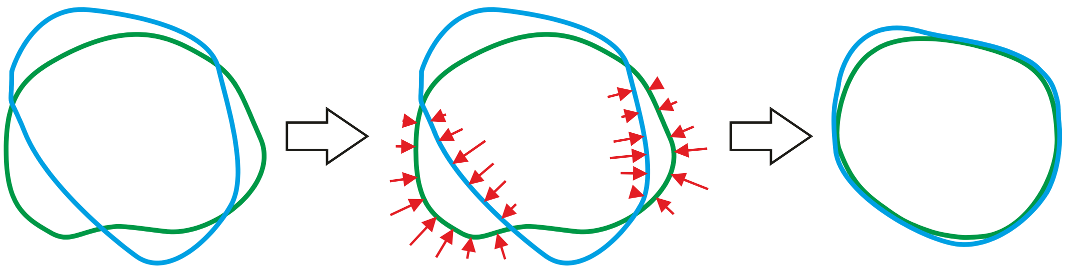

Fig. 2: Contact initialisation between fuselage cross-sections with imperfections

The rivets are modelled from beam elements that are mesh independently fixed with a tied contact to the shell elements of the fuselage sheet metal skin and the shared rib. By introducing initial local pressures on the regarding shell elements during initialisation of the tied contact the specific pre-stressing of the rivets is controlled. Figure 3 shows a close-up view of the model where the barrels and the shared rib (indicated in blue) are riveted together. The rivets are grouped by sectors whose borders are defined by the stringers for each fuselage skin area. The simulation model is setup to execute the riveting process sector by sector.

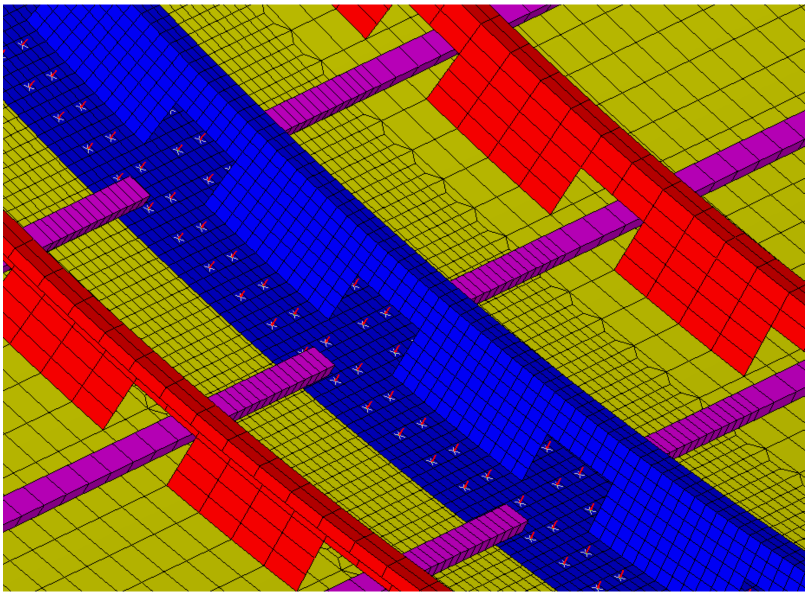

Fig. 3: Detailed model view of the shared rib and flange areas to be riveted

3 Modelling of the uncertainties

Two major manufacturing uncertainties will be considered. The remaining pre-stress in the rivets and the geometrical imperfections of the fuselage barrels deviating from an ideal cylinder. In separate studies the variation of the riveting pre-stress was analysed. It is assumed the riveting force follows a normal distribution function with a mean of 4450 N and a standard deviation of 360 N. To compare the influence of the riveting sequence the stochastic study is performed two times with different setups (Figure 4).

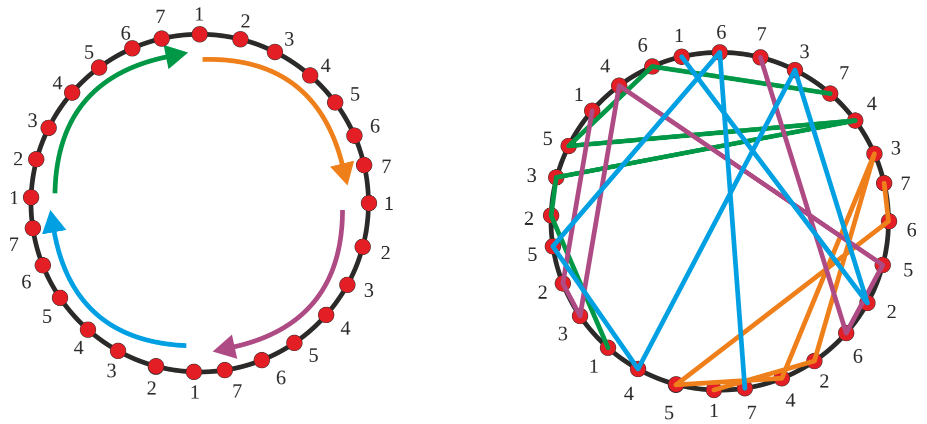

Fig. 4: Analysed riveting setups (4-quadrant sequence, left; random sequence, right)

In manufacturing it is very common to perform the riveting parallel in four quadrants with clockwise sequence (Figure 4, left). For comparison a random riveting sequence is chosen (Figure 4, right). Each rivet is assigned with an individual stochastic parameter controlling the variation of the riveting force.

Unlike the pre-stressing of rivets only little is known about the detailed geometrical imperfections of the fuselage barrels resulting from manufacturing. Detailed analysis and experimental measurements about spatial imperfections of thin walled cylindrical shell structures were performed in [2]. These measured sample database is available as a set of Fourier coefficients for a two-dimensional Fourier series from [3]. It is assumed the geometrical imperfections of the fuselage barrels have a similar order of magnitude in relation to the size of the cylindrical shell structure. To obtain suitable sample data the imperfections are scaled to the aircraft fuselage size and used to model the random fields.

A random field represents the variation of a property of a given parameter as a function of space or of time and space. Applying random fields to FEA the grain size of the field is only limited by the element discretization. Several approaches for the implementation of random fields into simple FEA problems are described in literature [4, 5, 6]. For implementing the random field a non-invasive approach is chosen, since the LS-DYNA solver will remain unmodified. In this paper the Karhunen-Loève transform is used to model the random field based on the sample database. Similar to a Fourier series the stochastic property is modelled by a series of orthogonal base functions. For a one-dimensional random field the Karhunen-Loève series around the mean value is defined as follows:

$$X(t) = \mu + \sum_{i=1}^{\infty} \sqrt{\lambda_i}\, \xi_i \psi_i(t) \quad (1)$$

The regarding scale factors $\sqrt{\lambda_i}$ and the orthogonal base functions ψ_i can be derived as eigenvalues and eigenvectors of the covariance function from the following integral equation:

$$\int_D Cov(t_1, t_2)\psi_i(t_1)dt_1 = \lambda_i \psi(t_2) \quad (2)$$

In this case the characteristics of the random field can be derived from the covariance matrix of the direct measurements of the geometric uncertainty (e.g. distortions). Metaphorically the Eigenvectors create the geometric basic shapes which assemble the stochastic field by random superposition (Figure 5).

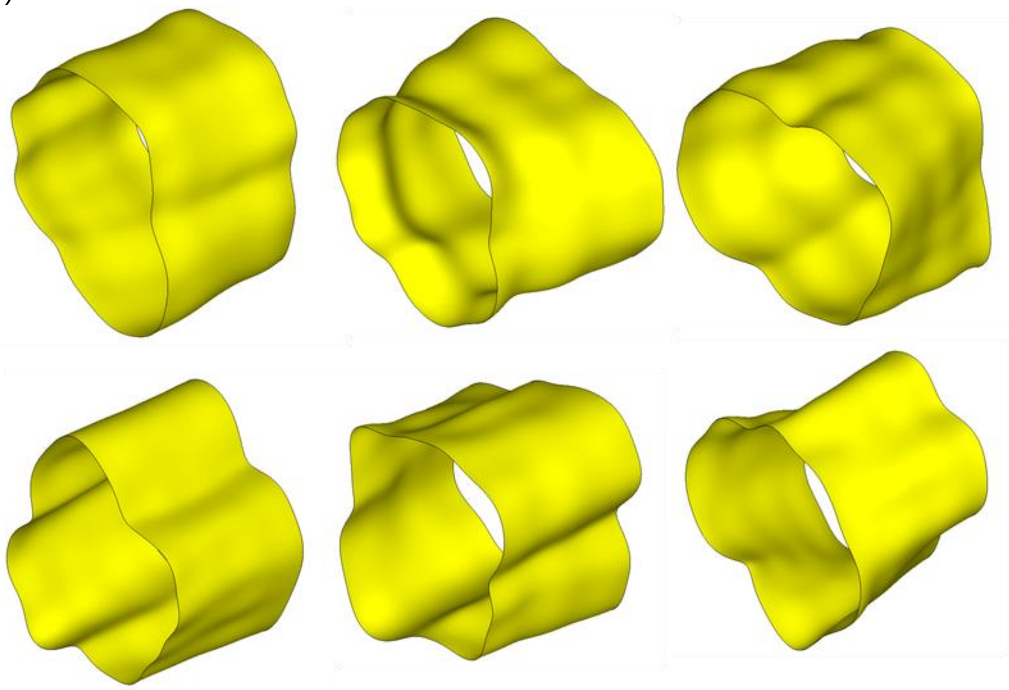

Fig. 5: Geometrical representation of 6 Eigenvectors from the covariance function

To match the spatial resolution of the fuselage barrels FE mesh with the random field resulting from the discrete Karhunen-Loève transform and interpolation based on radial basis functions is implemented. For the interpolation the thin plate spline base function described in [7] is used, for best approximation of the thin walled fuselage barrel. This interpolation method allows a very good continuity of the mesh and therefore high quality representation of the random field.

4 Simulation results

The stochastic simulation is executed by means of the Monte Carlo method using a Latin-Hypercube strategy with 100 samples each. To solve the simulations of both comparative studies a high performance compute cluster is used. The whole computational time takes about 8300 hours to solve all simulation samples.

Figure 6 shows a single simulation sample directly after the interference contact initialisation before the riveting process starts. Some areas exhibit internal stress due to geometric imperfections of the fuselage barrels while others remain nearly free of stress. A detailed analysis shows small gaps between the parts in these stress free regions. Of course the stress distribution and intensity is different for all stochastic simulation samples.

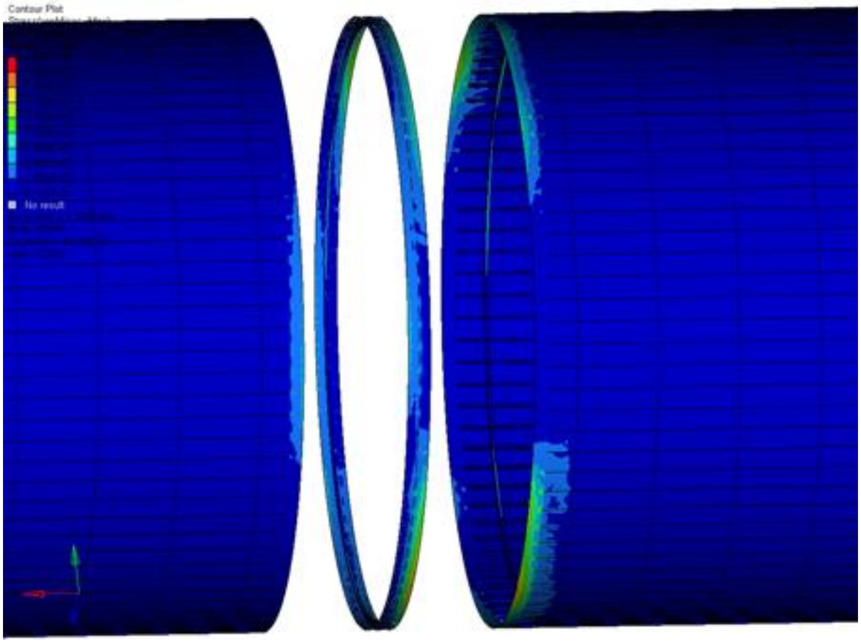

Fig. 6: Stress after contact initialisation caused by geometrical imperfections (exploded view)

Taking a look at the global stochastic simulation results gives further insight. Figure 7 shows the matrix of Spearman's rank correlation coefficients for the global parameters. The correlation matrix of both studies is nearly identical. Like supposed there is a noticeable dependency $r_{SP} = 0.34$ between the riveting force and the remaining pre-stress in the rivets while these parameters are independent from all others. A very high correlation of $r_{SP} = 0.9$ can be observed between the global distances before and after joining of both barrels that are caused by their geometrical imperfections. A negative correlation of $r_{SP} = -0.68$ indicates that larger distance between the barrels before joining will decrease the stress before the riveting process. The opposite counts for the distances between the barrels after joining them and the remaining stress after the riveting process, $r_{SP} = 0.73$.

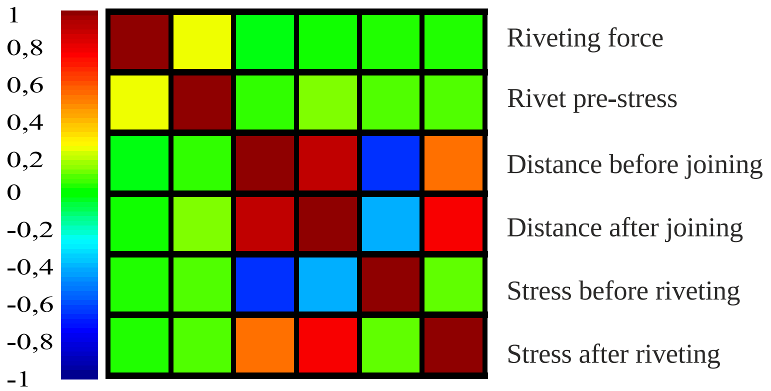

Fig. 7: Correlation matrix of global stochastic simulation results

Comparing the probability density functions of both stochastic simulation studies (Figure 8) exhibit some remarkable details. Both densities have a similar shape with one distinct accumulation point and a positive skew. But the variation of the 4-quadrant sequence is higher and thus the process is less robust. There is a visible higher amount of results with an average residual stress after riveting between 40 N/mm^2 and 50 N/mm^2.

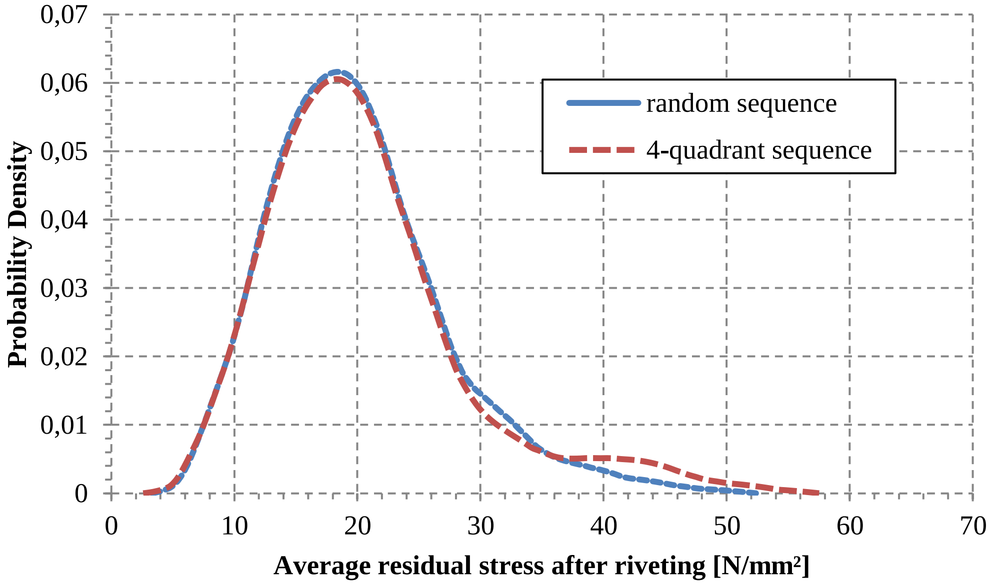

Fig. 8: Density estimate of average residual stress after riveting

These findings are supported by the arithmetic mean and standard deviation of the residual stress after riveting. While the random sequence has a mean of 19.9 N/mm^2 and a standard deviation of 4.4 N/mm^2 the 4-quadrant sequence has a mean of 20.6 N/mm^2 and a standard deviation of 7.3 N/mm^2. Hence the riveting process in four quadrants with clockwise sequence is less robust against manufacturing uncertainties.
A detailed look at the local stress distribution around the fuselage barrels after riveting shows why. Figure 9 shows the arithmetic mean of the residual stress after riveting plotted over sectors around the barrel. The 4-quadrant sequence started riveting at sectors 1, 23, 45 and 67. Precisely at the end of each quadrant the peak stresses occur. Following the riveting sequence over simulation time one can observe the accumulation of initial gaps in front of the current riveting sector. At the end of each quadrant the accumulated gap is closed with the last riveted sector which results in stress up to 4 times higher than the average. Contrary to the 4-quadrant sequence no particular accumulation of gaps can be observed. In general the variation of the residual stress after riveting correlates well with the distance of the barrels due to geometric imperfections, for each sector.

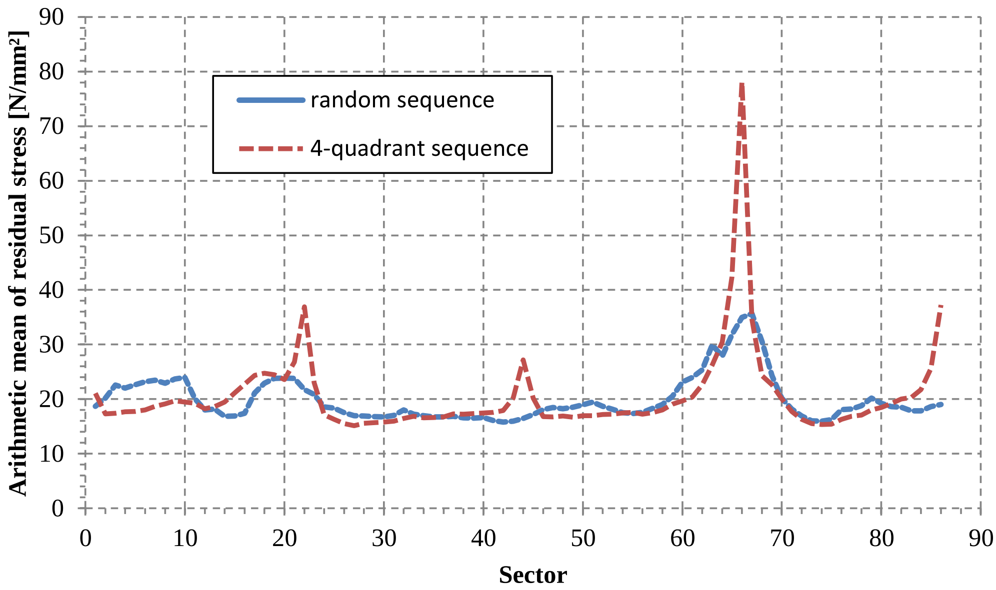

Fig. 9: Arithmetic mean of residual stress plotted over riveting sectors

5 Conclusion

In the present paper manufacturing uncertainties of an aircraft fuselage assembly process have been modelled by stochastic parameters and random fields. Two stochastic simulation studies with different riveting sequences were performed for comparison. A strong dependency between the geometric imperfections of the fuselage barrels and residual stresses in the structure was identified while the variation of the riveting force showed no significant impact. Surprisingly the common manufacturing practise of parallel riveting in four quadrants with clockwise sequence was very sensitive to these uncertainties and caused high local stress concentrations. In comparison the random riveting sequence exhibited a more robust behaviour against geometric imperfections of the fuselage barrels. The analysis shows the importance of considering manufacturing processes and regarding uncertainties in combination. Based on this study, future work aims to analyse the influence of additional uncertainties, material combinations and different riveting sequences. The final goal is to optimise the riveting strategy, to design a process with low residual stresses and robustness against inherent manufacturing uncertainties.

6 Literature

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