Simulation of the Manufacturing Process of Self-Piercing Rivets with LS-DYNA with Focus on Failure Prediction for Sheets and Rivet

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1 Introduction

There are many two-sheet and three-sheet material combinations in a body-in-white which can be joined via self-piercing rivets (SPR). A physical trial-and-error approach to ensure the feasibility of all combinations would be very time consuming and expensive. In addition the physical manufacturing test will not deliver the amount of accumulated damage in the sheets which is relevant for the strength of the SPR in a successive crashworthiness load case. An appropriate virtual simulation of the manufacturing process can be used to assess manufacturability and to evaluate the accumulated damage.

2 Innovation by Virtual Methods

In a single car with modern multi-material lightweight design more than 1k self-piercing rivets are used in combination with adhesive bonding. JLR has initiated an improved model for the failure prediction of self-piercing rivets in crashworthiness simulation [1], named `*Mat_SPR_JLR`. However 20k physical tests (for manufacturing feasibility & structural integrity) have to be performed to support a single vehicle programme. In this area there is a high potential for cost saving and development time reduction. The necessary steps are given in Figure 1.

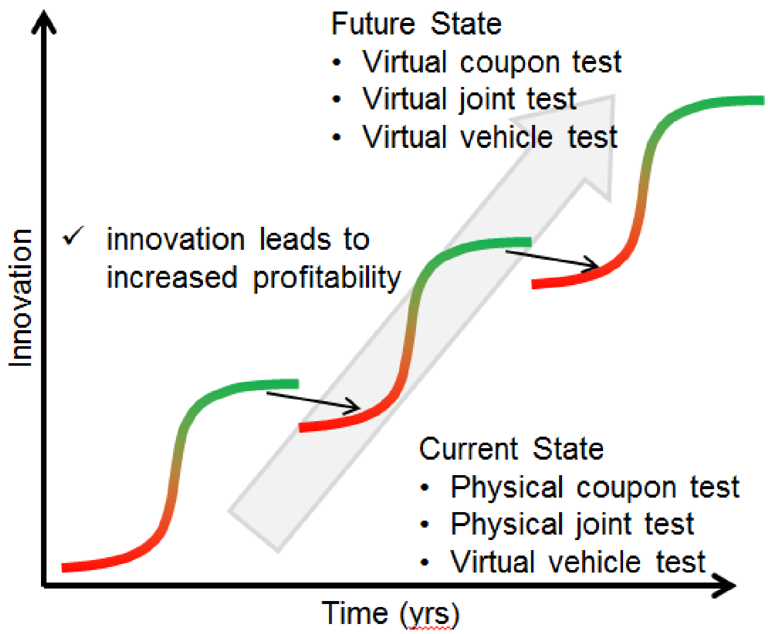

Fig.1: Innovation by introduction of virtual testing

A robust and predictive simulation method for the manufacturing process is a prerequisite for this virtual approach. The simulation of the manufacturing process must include a prediction of damage in the sheet materials and rivet. This accumulated damage can be used in a subsequent simulation of the mechanical test of the SPR joint (=> virtual testing). This paper highlights the simulation of the manufacturing process with damage and failure prediction.

3 Simulation Approach

The use of 2d-rotational symmetric elements with r-adaptivity is the most effective way to simulate the riveting process. R-adaptivity is supported in the SMP version of LS-DYNA. In a first step a study was performed on the numerical robustness and accuracy of the r-adaptivity algorithms (see Chapter 4).

The functionality of r-adaptivity in LS-DYNA includes a geometric criterion for the splitting of the upper sheet during the riveting process. The geometric criterion is defined by a residual thickness of the upper sheet controlling when elements are deleted for final sheet fracture. This approach might give acceptable results for very ductile sheet qualities (e.g. mild and high strength steels). However for aluminium sheets and AHSS grades the upper sheet may be split earlier due to limited ductility. Also there is a risk for fracture in the lower sheet which has to be estimated with an appropriate fracture model. In the case of riveting AHSS grades there is also a chance of a rivet fracture **[2**].

The focus of the development work in this paper was an improved prediction of material failure in this simulation environment. The user material MF GenYld+CrachFEM of MATFEM was used for this purpose. The available functionality of module CrachFEM for the prediction of material failure is summarized in [3]. The riveting of two aluminium sheets was used as an example (case 1 with alloy type ENAW6xxx-T4 and identical thickness, case 2 with alloy type ENAW5xxx and different thicknesses of upper and lower sheet). Simulation results with the simple geometrical splitting criterion are shown in Chapter 4 and can be compared with the predicted splitting of the upper sheet based on a physically based fracture criterion in Chapter 5.

4 Optimization of Numerical Parameters for R-adaptivity

In a first attempt the numerical parameters for r-adaptivity of 2d-rotational symmetric elements were optimized to ensure correct results (e.g. fulfill volume constancy of the sheets). For this study the basic material model **`*Mat_024`** without physically based failure criteria was used. First simulations with mesh size 0.1 mm in both sheets (sheet thickness 1.5 mm) and rivet and a small time step between adaptive meshing yielded unrealistic deformations in the sheets and rivet. Volume constancy of the sheet material was significantly violated. In some cases the simulations stopped due to high element distortion or due to remeshing problems. The parameter study yielded the following outcome:

- shorter remesh time intervals show a positive effect on numerical stability of simulation
- shorter remesh time intervals show a negative effect on the volume constancy
- remeshing of the rivet (in addition to remeshing of the blanks) shows a negative effect on numerical stability of simulation
- Finer mesh sizes (0.05 mm instead of 0.1 mm) improve volume constancy
- different mesh sizes seem to require different remeshing time intervals
- A limiting equivalent plastic strain for element elimination is needed (suggested value 3.0) to avoid severe element distortion after fracture of the upper sheet

With optimized numerical parameters the deformation of sheets and rivet and force-deflexion of the rivet are predicted in good accordance with reality for the joining of two aluminium sheets. Figure 2 shows an example for the joining of two sheets ENAW6xxx-T4 with similar thickness. However the prediction of relevant geometrical details – like undercut between rivet and lower sheet – are still not perfect. This can be explained both by the scatter of experiments (in reality the rivet can even show a non-symmetric deformation) and still existing deficits of the simulation model. Also the time and direction of splitting the upper sheet may influence the radial deformation of the rivet and as a consequence can change the predicted undercut. An improved splitting prediction can only be performed with a physically based fracture model.

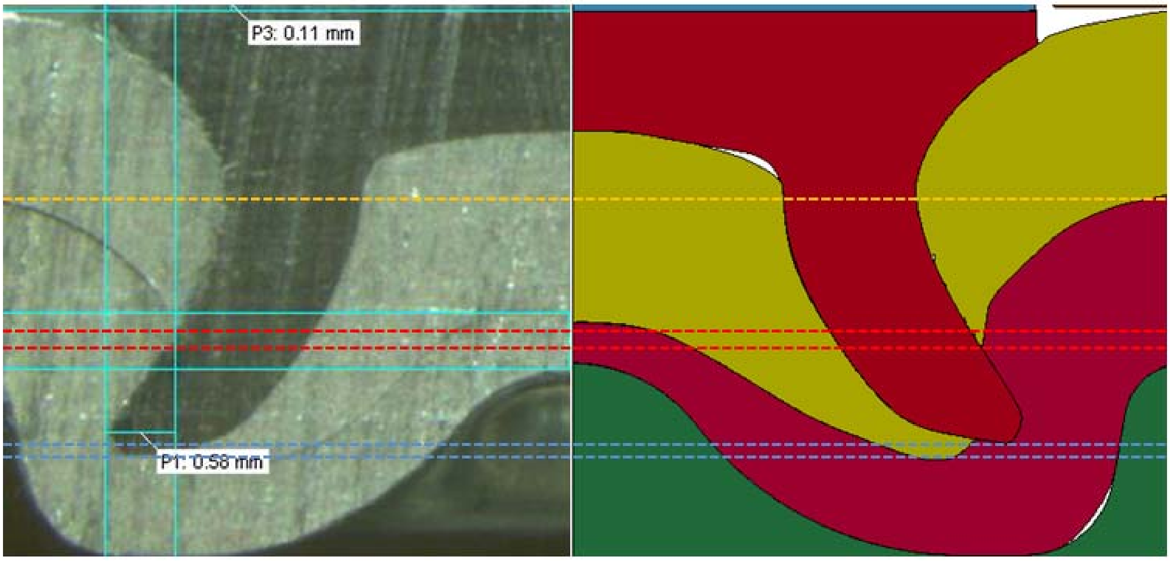

Fig.2: Correlation of predicted geometry of SPR joint (right) with cross section of a sample (left) for joining of two sheets of type ENAW6xxx-T4 in the same thickness

5 Application of Material Model MF GenYld+CrachFEM for Failure Prediction

5.1 Overview

In a second step the user material model MF GenYld+CrachFEM with failure criteria for ductile normal fracture (DNF) and ductile shear fracture (DSF) was introduced to allow for a damage accumulation in the sheet materials and the rivet material. Besides an improved prediction of the sheet failure of the upper sheet, the failure criteria also allow the user to estimate the margin of safety for a possible fracture of the rivet and of the lower sheet. The accumulated damage in sheets and rivet might be used later on for simulations of virtual mechanical tests on the riveted structure (e.g. to derive strength values for crashworthiness simulation).

The two fracture models in CrachFEM are based on stress state parameters which can be used as a unique measure also in 3D stress states [3]. The fracture curves for the two aluminum sheet alloys under consideration have been experimentally evaluated in an earlier project.

5.2 Ductile Normal Fracture

For the plane stress condition (as in a shell discretization) it can be assumed that the equivalent fracture strain ε_{eq}^{**} (definition of equivalent plastic strain according to Mises) is a function of the stress triaxiality η only, defined by the principal stress components:

$$\eta = \frac{3 \cdot \sigma_m}{\sigma_{eq}} = \frac{\sigma_1 + \sigma_2}{\sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2}} \tag{1}$$

For the general three-dimensional stress state (as in a solid discretization in FE analysis), the stress triaxiality η is no longer unique. Two stress state parameters are necessary to describe the stress state. For ductile fracture the stress triaxiality η and the ratio σ_1/σ_{eq} of first principal stress and von Mises equivalent stress have been used in CrachFEM. For an individual material, the two stress state parameters can be combined to a ductile fracture parameter β:

$$\beta = \beta\left(\frac{\sigma_1}{\sigma_{eq}}, \eta\right) = \frac{1 - s_d \cdot \eta}{\left(\sigma_1 / \sigma_{eq}\right)} \tag{2}$$

Here, s_d is a material dependent parameter. Ductile fracture can occur only if the first principal stress σ_1 is positive. The ductile fracture diagram is described by the analytical function

$$\varepsilon_{eq}^{**} = d \cdot e^{q \cdot \beta} \tag{3}$$

with two material coefficients d and q. An approximation of fracture data with equation (3) should include the boundary condition that the fracture strain tends towards zero for triaxial tension. This β-model can be used in CrachFEM for shell and solid discretizations throughout.

5.3 Ductile Shear Fracture

For ductile shear fracture, it is assumed that the equivalent strain at fracture, ε_{eq}^{**} is a function of the shear fracture parameter θ :

$$\theta = \frac{1 - k_S \cdot \eta}{\phi} \tag{4}$$

where k_s is a material parameter and ϕ is the ratio of the maximum shear stress and the equivalent stress according to von Mises:

$$\phi = \frac{\tau_{max}}{\sigma_{eq}} \quad \text{where} \quad \tau_{\max} = \frac{\sigma_1 - \sigma_3}{2} \tag{5}$$

Because θ depends on the stress triaxiality and the ratio τ_{max}/σ_{eq}, it can be used for both plane-stress and general three-dimensional stress conditions. The equivalent plastic strain for shear fracture with respect to θ is given in an analytical function:

$$\varepsilon_{eq}^{**} = \frac{\varepsilon_S^{+} \sinh\left(f\left(\theta - \theta^{-}\right)\right) + \varepsilon_S^{-} \sinh\left(f\left(\theta^{+} - \theta\right)\right)}{\sinh\left(f\left(\theta^{+} - \theta^{-}\right)\right)} \tag{6}$$

where θ^{+} and θ^{-} are the values of θ for equibiaxial tension und compression. Equation (6) has three material parameters, ε_s^{+}, ε_s^{-} and *f*, where ε_s^{+} and ε_s^{-} are the equivalent plastic strains at fracture for equibiaxial tension and equibiaxial compression. Equation (6) may be extrapolated to lower and higher values of θ.

5.4 Damage Accumulation for Fracture

Both fracture models are based on a fracture diagram that represents the equivalent plastic strain at fracture ε_{eq}^{**} as a function of the stress state, i.e. the stress state parameters β or θ. The function ε_{eq}^{**} (β or θ) can be used directly as a fracture criterion in the case of a linear strain path. For the more general case of a nonlinear strain path, an integral fracture criterion is necessary. Kolmogorov [4] has presented an integral criterion with scalar description of damage:

$$\int_0^{\varepsilon_{eq}^{**}} \frac{d\varepsilon_{eq}}{\varepsilon_{eq}^{**}(x)} = 1 \tag{7}$$

Here, x is the relevant stress state parameter (in CrachFEM: β or θ). An accumulated failure risk of 1 constitutes the onset of fracture. Values between 0 and 1 indicate a reduced ductility level, but are not necessarily a measure for real material damage.

Integral criteria can account for nonlinear strain paths. In more severe cases of load path changes (e.g. compression-tension reversal) even the integral criteria with scalar description of damage are no longer valid. CrachFEM accounts for such cases and offers a tensorial criterion with a nonlinear damage accumulation. The tensorial fracture criterion is discussed in the following section.

For CrachFEM a tensorial damage model has been implemented. The damage tensor is expressed as follows:

$$d\psi_{ij} = f\left(\Psi, \varepsilon_{eq}^{**}\right) d\varepsilon_{ij}^{p} \tag{8}$$

Ψ is a scalar measure of damage, which is derived by:

$$\Psi = \int_0^{\varepsilon_{eq}^{**}} \frac{d\varepsilon_{eq}}{\varepsilon_{eq}^{**}} \tag{9}$$

Here $d\varepsilon_{eq}$ is the increment of equivalent plastic strain according to Mises. The fracture criterion is:

$$\psi_{ij}\psi_{ij} = 1 \tag{10}$$

5.5 CrachFEM in combination with r-adaptivity in LS-DYNA

The tensorial description of damage provides more realistic fracture predictions in the case of nonlinear strain paths compared to a scalar description of damage. Pronounced nonlinear strain paths will happen in the sequence of SPR manufacturing and subsequent mechanical testing. However the damage tensor must be expressed in a material coordinate system. An orthotropic mapping would be needed, if this tensorial description is used throughout an adapative meshing process. This orthotropic mapping is supported in LS-DYNA for an adaptive meshing with shells (h-adaptivity) in deep drawing simulation, but is still not available for the r-adaptivity with 2d-rotational symmetric elements. Therefore the damage model in CrachFEM was reduced from a tensorial description to a simplified scalar description for the SPR application. Only for the process of riveting the assumption of linear strain paths might be still acceptable.

5.6 Simulation Results

Predictions of force-deflection and cross section geometry after riveting were already in good agreement to the experiments with the standard material model **`*Mat_024`** and optimized numerical parameters for r-adaptivity. By the use of material model MF GenYld+CrachFEM the fracture of the upper sheet is predicted based on the ductility of the sheet material and no longer due to a simplified geometrical criterion. As a consequence the time of splitting and direction of splitting can be different (see Figure 3). As a consequence the final geometry (e.g. undercut) can change.

In addition a failure risk is predicted for both sheets and rivet material. This can help to assess the margin of safety of the surrounding material for a subsequent mechanical load.

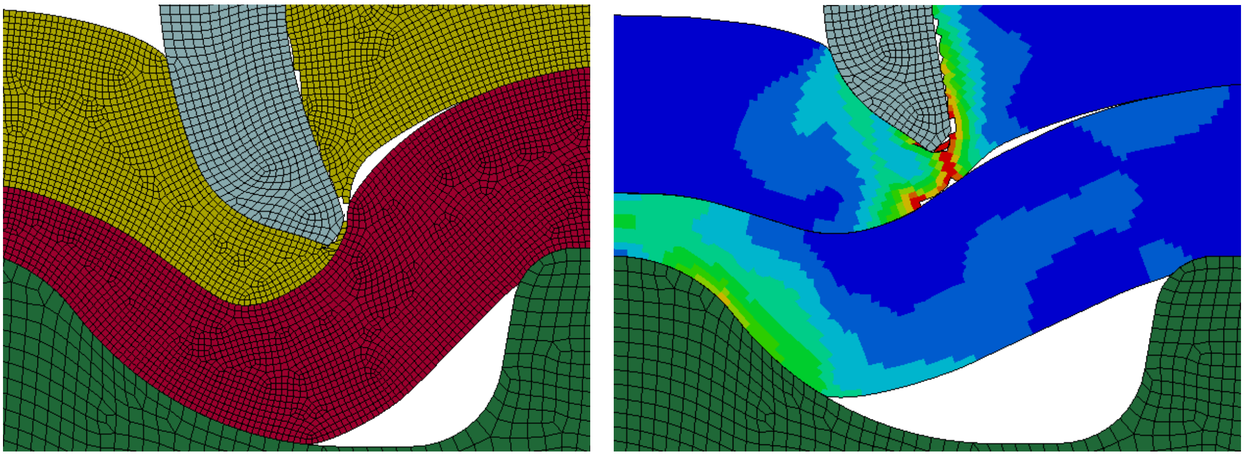

Fig.3: Predicted splitting of upper sheet with geometrical criterion based on minimum thickness of 0.05 mm (left) and last plot step before splitting in simulation with physically based fracture criterion (right, failure risk for ductile shear fracture is shown), example with riveting of sheet type ENAW6xxx-T4 in same thickness

As soon as element elimination is initiated in one of the sheets the crack propagation process is mesh size dependent (typically one element represents the crack tip zone). For the given mesh size of 0.05 mm the residual strength of the crack seems to be unrealistically low. The crack propagates too quickly. In metals a critical radius of the plastified zone around the crack tip is necessary for crack propagation according to [5]. MF GenYld+ CrachFEM offers the possibility to scale the fracture limit curves as a function of mesh size for crack propagation problems to achieve a correct crack resistance. However scaled curves will not give a correct value for the failure risk in regions of stable deformation. Figure 4 shows the situation for the predicted fracture in the lower sheet.

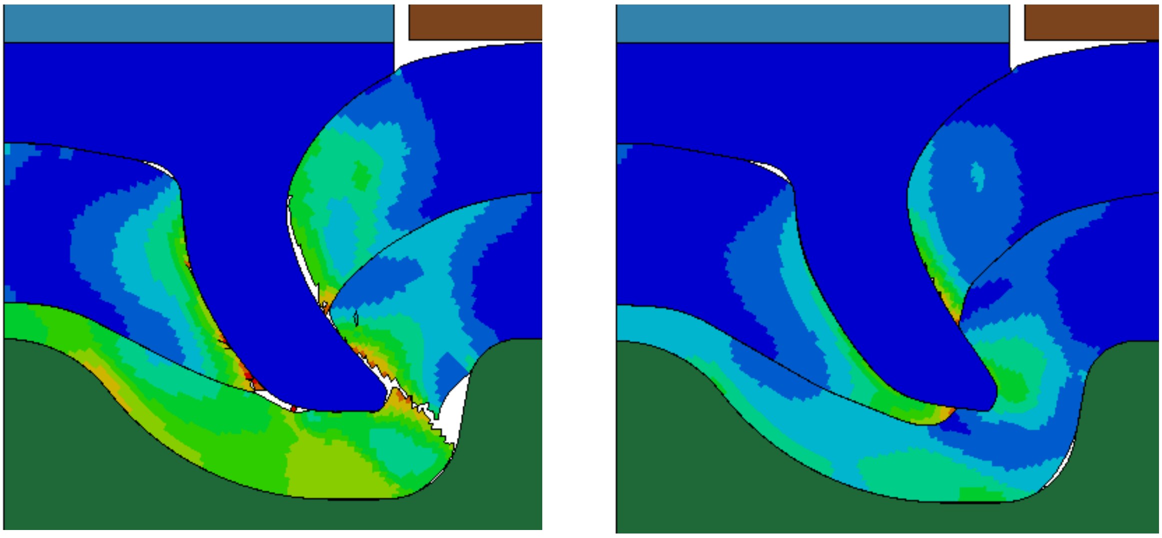

Fig.4: Predicted material failure in lower sheet in simulations with reference fracture limit curves (left) and scaled fracture limit curves (right; limit curves scaled by factor 2); example with riveting of sheet type ENAW6xxx-T4 in same thickness

As a consequence the fracture models should be combined with **`*Mat_nonlocal`** in the future to ensure a correct prediction both for failure risk and crack propagation.

6 Summary and Discussion

The assessment of the manufacturing process and the subsequent evaluation of the mechanical strength of self-piercing rivets by numerical simulation offers a significant potential for cost saving and development time reduction for a new vehicle programme. The use of 2D-rotational symmetric elements with r-adaptivity is an effective way to simulate riveting processes in LS-DYNA. However the user should optimize discretization and numerical parameters to ensure robust results (e.g. avoid violation of volume constancy). The use of physically based fracture criteria is a step forward in the numerical assessment of the manufacturing process of self-piercing rivets. However crack propagation still suffers from mesh size dependency. A combination of the fracture model with **`*Mat_nonlocal`** might solve the problem in future.

7 Literature

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