An experimental and numerical investigation on self-piercing riveting

R. Porcaro[1,2], M. Langseth[2], S. Weyer[2,3], H. Hooputra[2,3]

[1] *SINTEF Materials and Chemistry – N-7465 Trondheim, Norway*
URL: www.sintef.no *e-mail: raffaele.porcaro@sintef.no;*

[2] *Structural Impact Laboratory (SIMLab), Centre for Research-based Innovation, Department of Structural Engineering, Norwegian University of Science and Technology – N-7491 Trondheim, Norway*
URL: http://www.ntnu.no/simlab *e-mail: magnus.langseth@ntnu.no;*

[3] *BMW AG, Forschungs- und Innovationszentrum – Knorrstrasse 147, D 80788 Munich, Germany*

ABSTRACT: In this paper, the self-piercing riveting process is studied experimentally and numerically. A 2D axisymmetric numerical model of the riveting process was generated using the finite element code LS-DYNA. The model was validated against experimental results. The results from the riveting process simulation were used to generate a 3D numerical model of the riveted connection. This model was based on the post-process geometry and corresponding material properties obtained from the riveting process. The 3D model was used to simulate the structural behaviour of the riveted connection under combined tensile and shear loading conditions.

Key words: Testing, modelling, self-piercing riveting, aluminium, connector, process.

1 INTRODUCTION

A better understanding of the mechanical behaviour of the riveted connection is required in order to improve the existing shell-based numerical models [1] of self-piercing riveted connections used in large-scale crash analyses of car structures. In this paper, the self-piercing riveting process was studied in order to obtain information on the material properties of the sheets in the region around the rivet after the process. A simple test device was developed that was capable of reproducing the riveting process. This simple device permits to control all the riveting process parameters and records the force-displacement history during the process. A 2D axisymmetric model of the riveting process was generated including two sheets to be joined, the rivet and the tools. The rivet and tool geometries were based on the Böllhoff standards [2]. The model was validated against the experimental results. The final configuration was then used as initial configuration for a 3D model of the self-piercing rivet connection where the residual stresses and plastic strain fields were mapped to the deformed initial configuration. This 3D numerical model was used to study the effect of the process parameters on the mechanical behaviour of a riveted connection and to improve the understanding of the failure mechanisms of self-piercing riveted connections.

2 SELF-PIERCING RIVETING PROCESS

Self-piercing riveting is essentially a cold forming process, in which a semi-tubular rivet, pressed by a plunger, pierces through the thickness of the upper sheet and flares into the bottom sheet, forming a mechanical interlock between the two sheets. The self-piercing riveting process can be described by the following four steps, figure 1: a) Clamping; b) Piercing, c) Flaring and d) release of the punch.

2.1 Experimental procedure

A simple testing device [3] was developed at SIMLab in order to investigate the riveting process, figure 2. The device is composed of the following

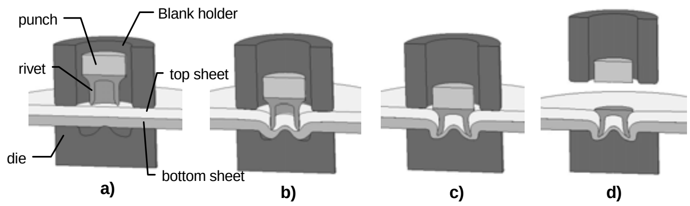

Fig. 1. Self-piercing riveting process.

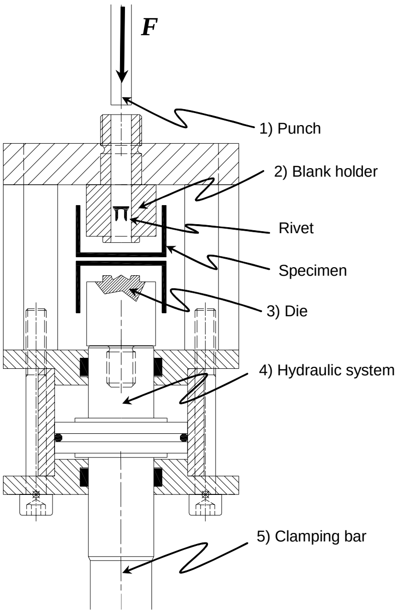

Fig. 2. Riveting process test device.

parts: 1) punch, 2) blank holder, 3) die, 4) hydraulic system, 5) clamping bar. The die is the top part of a cylinder block made of high-strength steel that is screwed on the hydraulic piston, which is connected to the clamping bar. In this way, the die can be easily changed by substituting the small cylinder. The blank holder is mounted on a steel frame connected to the clamping bar. The steel frame can be changed in order to use different specimen geometries. The tests were performed under displacement control. The cross section of a typical joint after riveting is shown in figure 3a, while the force-displacement curve measured during the riveting process is shown in figure 3b. The cross section enables a visual inspection of the joint and can be used together with the force-displacement curve to validate the numerical model.

2.2 Numerical model

Numerical simulations of the self-piercing riveting process were done using the finite element code LS-DYNA. A 2D axisymmetric model was generated including the two sheets to be joined, the rivet and the tool. The rivet and tool geometry were based on the Böllhoff standards. As the problem is axisymmetric, the 4-node 2D axisymmetric elements have been used, with four Gauss points and a stiffened-based hourglass control. The size of the smallest element in both the sheets and rivet was 0.1 x 0.1 mm2. The punch, blank holder and die were modelled as rigid bodies, while the material of the rivet and the sheets were modelled as elasto-plastic

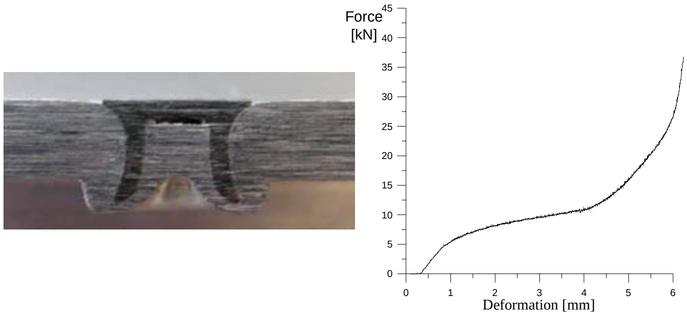

Fig. 3. Riveting process test results

materials, adopting the von Mises yield criterion, a piecewise linear isotropic strain-hardening rule (*MAT_PIECEWISE_LINEAR_PLASTICITY). An implicit solution technique with r-adaptivity and a geometrical failure criterion based on the change in thickness of the connected plates was used. Contact was modelled using an automatic 2D single-surface penalty formulation available in LS-DYNA. Figure 4 shows the initial configuration of the riveting process. Firstly, a displacement is prescribed for the blank holder. When the sheets are clamped between the blank holder and the die, a pressure is applied to the blank holder in order to keep the sheets tight. Secondly, a displacement is prescribed for the punch that pushes the rivet through the sheets until the joint is formed. Finally, a springback analysis is performed on the final configuration of the joint in order to simulate the release of the tooling force. A visual comparison between the final geometry of the joint obtained from the numerical simulation and the experimentally obtained cross-section of the joint together with a comparison between the numerical and experimental force-deformation curves from the riveting process was used to validate the model, figure 5.

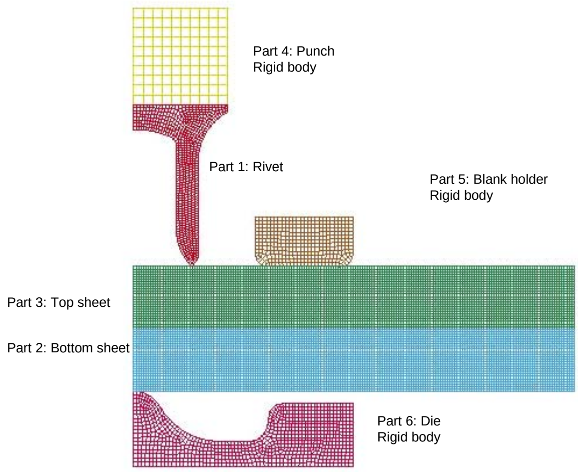

Fig. 4. Numerical model of the riveting process.

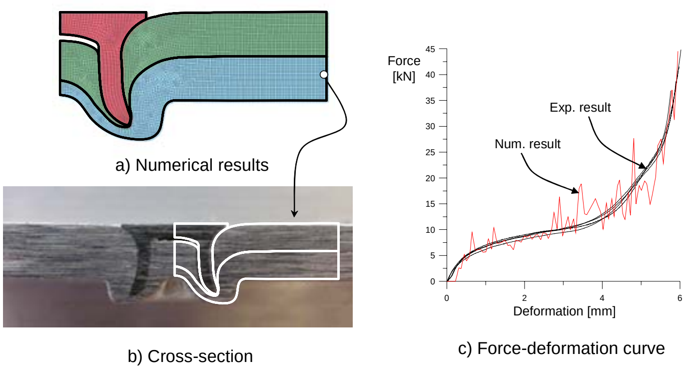

Fig. 5. Validation numerical model.

In the figure the borders of the numerical joint have been placed on the picture of the cross section of the specimen.

3 STRUCTURAL BEHAVIOUR

3.1 *Experiments*

The structural behaviour of a self-piercing riveted connection was studied experimentally using a "single-rivet" specimen, figure 6a. The specimen is composed of two U-shaped elements joined together in the central part with one rivet. The "single-rivet" specimens were tested under combined shear and pull-out quasi-static loading conditions using a testing device [4] shown in figure 6b. This test fixture enables to mix and control tensile and shear loads. Varying the angular position leads to several load combinations. The load-displacement histories were recorded during testing and the displacement measured from the machine is representative of the displacement of the test specimen. Figure 6c shows typical load-displacement curves for the single rivet specimen.

3.2 *Numerical model*

The results from the riveting process simulation were used to generate a 3D numerical model of the "single-rivet" specimen. This model was based on the post-process geometry, figure 7a, and corresponding material properties obtained from the riveting process [5]. The 3D model is divided into two sub-groups: the internal part and the external part. The first part is representative of the region that contains the rivet, figure 7b. It is composed of the top plate, the bottom plate and the rivet. The geometry and the history variables are obtained from the riveting process simulation. The region of interest, where the material properties have changed

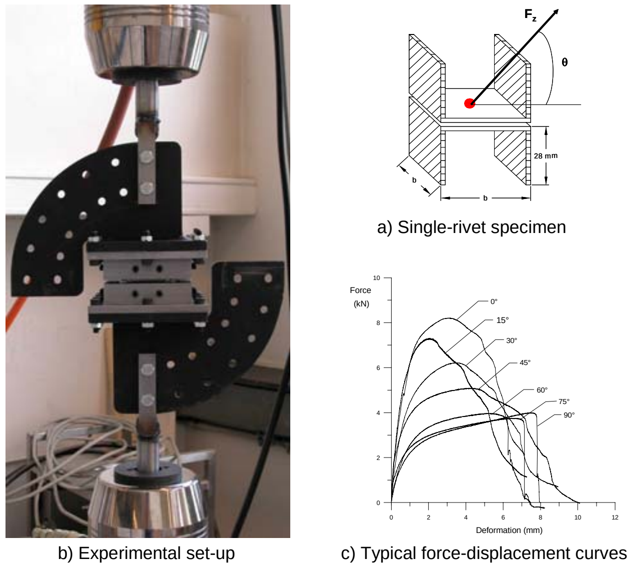

Fig. 6. Experimental test set-up.

due to the riveting process, is the region around the rivet inside the die and blank holder region. The diameter of this region is equal to 24 mm. Outside this region no changes in material properties have been observed in the riveting process simulation. The second part, figure 7c, is the rest of the geometry of the specimen with a hole in the middle where the internal part is then inserted. The material properties for the last part correspond to the "virgin" material obtained from tensile tests. The internal part was then merged with the external part, figure 7d. The external mesh was generated such that the number of nodes and elements along the interface were the same as in the internal part. The two parts were thus merged together by replacing the duplicate nodes on the interface surface with only one node. In order to simplify the model, only half of the specimen was modelled using symmetry conditions. The material of the rivet and the plates were modelled as an isotropic elasto-plastic material, type 24 in LS-DYNA. The mesh for the 3D model was generated using 8-node hexahedron solid elements with 1-point integration and constant stress was used together with a stiffened-based hourglass control. Furthermore, a pinball segment-based contact algorithm was used with the following values for the friction between the different parts: 0.2 between the rivet and the plates and 0.15 between the plates. The mesh in the thickness direction was 0.25x0.25 mm^2 in the central region of the internal part, the rivet and the region of the plates in contact with the rivet. As we move far from the central part, the mesh became coarser, i.e. 0.5x0.5 mm^2. The 3D model was validated against experimental results.

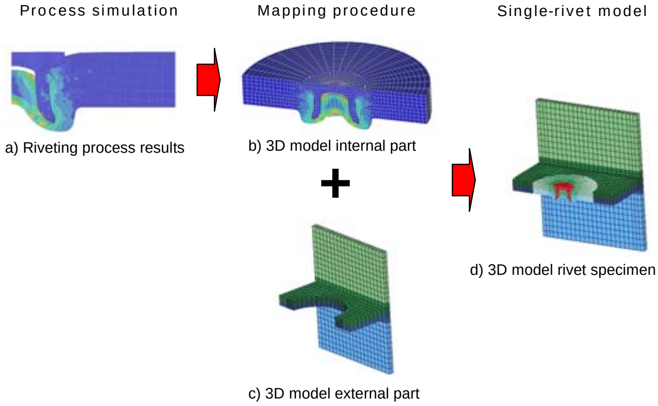

Fig. 7. 3D numerical model.

Figure 8 and figure 9 show a comparison between the numerical results and the experimental tests in terms of failure mode and force-displacement curve for pure shear and pure pull-out loading conditions respectively. As shown in the figures, the model is able to reproduce the measured curves as well as the failure mode with reasonable accuracy.

4 CONCLUSION

Numerical simulations of the self-piercing riveting process have been carried out using the commercial code LS-DYNA. A 2D axisymmetric model was generated including two sheets to be joined, rivet and tools. An implicit solution technique together with an r-adaptive method has been used. Good agreements between the riveting process simulations and the experiments have been found, both with respect to the force-deformation curves as well as the deformed shape of the rivet and plates. A 3D numerical representation of a self-piercing riveted connection was generated based on the results obtained from the simulation of the riveting process.

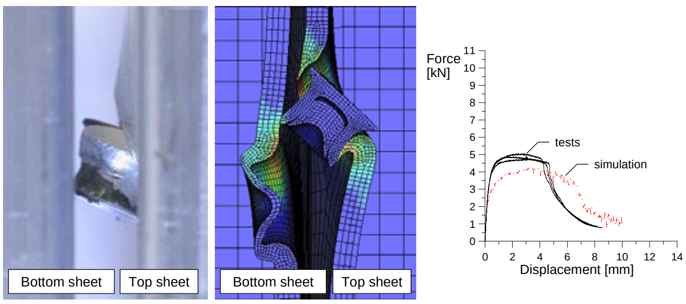

Fig. 8. Comparison between experimental and numerical results for pure shear condition.

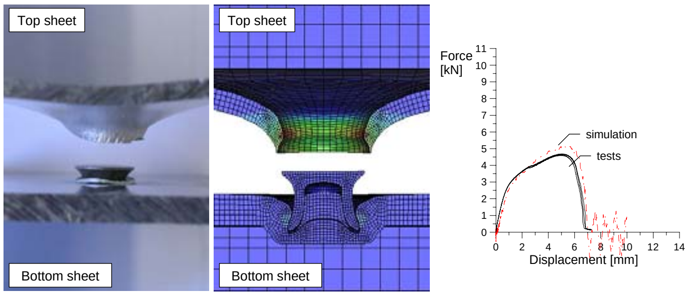

Fig. 9. Comparison between experimental and numerical results for pure pull-out condition.

In this way, the simulation of the mechanical strength of the riveted joints was initialized with the proper deformed shape and the current post-riveting stress-strain state. The correct initialization of the model was important in order to obtain the correct force level in the simulation. The 3D numerical model was able to reproduce the correct behaviour of the riveted connection with reasonable accuracy, both in terms of the force-displacement curve and the deformation mode. The 3D model can be used to fully understand the behaviour of the connection, i.e. opening of the plates, rotation of the rivet at failure and forces acting on the rivet. All these information can be used to create a new shell-based rivet model for large-scale crash analysis of car structure.

ACKNOWLEDGEMENTS

The present work has been carried out with financial support from the Norlight programme and SIMLab-Centre for Research-based Innovation.

REFERENCES

1. R. Porcaro, A.G. Hassen, A. Aalberg, M. Langseth, *Joining of aluminium using self-piercing riveting: Testing, modelling and analyses*, International Journal of Crashworthiness, 9 (2), 2004, 141-154.
2. Böllhoff Systemtechnik, www.boellhoff.de.
3. R. Porcaro, A.G. Hanssen, M. Langseth, A. Aalberg, *Self-piercing riveting process, an experimental and numerical investigation*, Journal of Materials Processing Technology, 171 (1), 2006, 10-20.
4. R. Porcaro, A.G. Hanssen, M. Langseth, A. Aalberg, *An experimental investigation on the behaviour of self-piercing riveted connections in aluminium alloy AA6060*, International Journal of Crashworthiness, 11 (5), 2006, 397-417.
5. R. Porcaro, A.G. Hanssen, M. Langseth, A. Aalberg, *The behaviour of a self-piercing riveted connection under quasi-static loading condition*, International Journal of Solid and Structures, 43 (17), 2006, 5110-5131.