Modeling of Self-Piercing Rivets Using Fasteners in Crash Analysis

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Abstract: Self-piercing rivets are represented as fasteners in an ABAQUS/Explicit crash analysis. The deformation behavior of a rivet is described using connector elasticity and plasticity models, while its failure is modeled using the “connector damage” card. In order to consider the dependence of the rivet failure on loading direction, the connector damage is defined as a function of the mode-mix ratio. The deformation and damage behavior of the connector is calibrated with test results carried out on single rivet specimens, as well as with peeling test results. The calibrated rivet model is then used in an axial crash test simulation. The simulation results were found to be in good agreement with the test results.

Keywords: rivet, self-piercing rivet, fastener, connector, connector plasticity, connector damage, crash.

1. Introduction

Self-piercing rivets are used in many automotive components to connect metal sheets. The deformation and failure behavior of the rivets has significant effects on the behavior of these components under crash loading. For a realistic crash analysis an appropriate description of the deformation and failure behavior of the rivets is required. Within a project at BMW a model should be developed to describe the behavior of self-piercing rivets in a crash analysis.

Figure 1 shows an example of self-piercing rivets. The piercing process results in very large local deformation of the sheet metal in the area and vicinity of the rivet. The behavior of sheet materials in this area is thus very different from that outside this influence area due to plastic deformations resulting from the piercing process. In order to determine the influence of the piercing process on the behavior of the rivet and the sheet materials in its vicinity, one could conceivably attempt to simulate the piercing process and use the simulation results in a crash analysis with detailed modeling of the rivets and their vicinities. This approach, however, is very costly because the crash analysis with detailed modeling of rivet areas requires very small stable time increments due to the refined mesh in the rivet areas.
With its fastener capability, ABAQUS provides a more practicable approach for modeling self-piercing rivets and their adjacent plasticity influence zones (ABAQUS, Inc., 2006). In this approach the rivet and the sheets in the vicinity are modeled using a generic “connector” element with structural distributing couplings defined at each end of the connector. The distributing couplings are used to attach the connector end points to the sheets being connected. The behavior of the rivet including its plasticity influence zone is then described using the connector behavior and the behavior of sheets in the influence area of the rivet. The sheet material behavior in the influence area is set equal to the behavior outside the influence area as if the piercing process had not taken place. The connector behavior is calibrated to match the behavior of specimens under various loadings. The specimen behavior can be measured from experimental tests, or determined through numerical simulations of the piercing process and the experimental tests with a detailed model.

In this project, the fastener capability in ABAQUS was used to model self-piercing rivets. Test results were used to calibrate the connector behavior. The calibration results were then used in a simulation of an axial specimen crash test. The simulation results were verified by comparison with the test results.

2. Experimental tests

The experimental tests were carried out on a newly developed test setup (Porcaro, 2005). Figure 2 shows the shapes of single rivet and peeling specimens used in these tests. The regions where the specimens are clamped in the test device are marked. All tests were performed using displacement control actuators. Single rivet specimens were pulled in directions $\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ,$ and $90^\circ$. For each loading direction three tests were carried out to ensure the reproducibility of the results. The $\alpha = 0^\circ$ loading direction corresponds to a pure shearing of the rivet. For the $\alpha = 90^\circ$ loading direction the rivet is loaded axially in tension. The test machine can be assumed to be rigid in the pull direction. For the direction perpendicular to the pull direction a nominal lateral stiffness was estimated for the test set-up.
Figure 3 shows test results for the sheet pair in Figure 1. The abscissa is the displacement measured in the pull direction, the ordinate is the force measured in the same direction. As an example only one curve is shown for each loading direction of single rivet specimens. These results will exemplarily be used to calibrate the connector behavior defined in the next section.

Figure 2. Shapes of the specimens

Figure 3. Measured load-displacement curves for the sheet pair in Figure 1

3. Fastener and connector definition

The following options were used to define the fastener and connector behavior for modeling the behavior of self-piercing rivets:
*PARAMETER
radius of rivet area
orn = K/r

*FASTENER, INTERACTION NAME=name, PROPERTY=name, ELSET=rivet_fast_conn,
REFERENCE NODE SET=name, COUPLING=structural

*FASTENER PROPERTY, NAME=name
<r>

*CONNECTOR SECTION, ELSET=rivet_fast_conn, BEHAVIOR=fast_conn_behav
Bushing
Ori_fast_conn
*ORIENTATION, NAME=Ori_fast_conn
1.0, 0.0, 0.0, 0.0, 1.0, 0.0
*CONNECTOR BEHAVIOR, NAME=fast_conn_behav
*CONNECTOR ELASTICITY, COMPONENT=1
E_S
*CONNECTOR ELASTICITY, COMPONENT=2
E_S
*CONNECTOR ELASTICITY, COMPONENT=3, RIGID
*CONNECTOR ELASTICITY, COMPONENT=4, RIGID
*CONNECTOR ELASTICITY, COMPONENT=5, RIGID
*CONNECTOR DERIVED COMPONENT, NAME=FN
3, 1.0
*CONNECTOR DERIVED COMPONENT, NAME=FS
4, 5
<orn>, <orn>

*CONNECTOR PLASTICITY

*CONNECTOR DAMAGE INITIATION, CRITERION=plastic motion
\( \tau_{Pl,i}^{D} = \Psi_{m,i} \)
...\( \tau_{Pl,n}^{D} = \Psi_{m,n} \)

*CONNECTOR DAMAGE EVOLUTION, TYPE=motion, SOFTENING=linear
\( \tau_{Pl,i}^{f} - \tau_{Pl,i}^{D} = \Psi_{m,i} \)
...\( \tau_{Pl,n}^{f} - \tau_{Pl,n}^{D} = \Psi_{m,n} \)
The parameter **COUPLING=structural** of the option *FASTENER* invokes the new structural distributing coupling (ABAQUS, Inc., 2006) to avoid unrealistic contact interaction between the sheets being connected, which would occur if conventional distributing coupling would be used. Connector type **BUSHING** is chosen to model the rivet because it provides six available components of relative motion (three translations and three rotations) and can describe a general deformation state. With *ORIENTATION* the connector is oriented in the normal direction of the sheets as required by the connector type (see Figure 4).

![Figure 4. Rivet connection: connector orientation and derived components](image)

Uncoupled elastic behavior is assumed for the connector. The same shear stiffness $E_S$ is used for the two shear directions (components 1 and 2) based on the assumption of isotropic sheets and isotropic cross section of the rivet. The elastic behavior is assumed to be rigid in the axial direction (component 3) and for the two flexural components (components 4 and 5). No elastic stiffness is defined for torsion about the rivet axis (component 6) in order to take into account that the rivet can be easily rotated about this axis.

To describe the plastic behavior of the connector, a connector potential is defined as

$$P = \left( \frac{F_N}{R_N} \right)^{\beta} + \left( \frac{F_S}{R_S} \right)^{\beta} \right)^{\frac{1}{\beta}},$$  \hspace{1cm} (1)

with

$$F_N = |f_3| + \frac{k_e}{r} \cdot \sqrt{m_1^2 + m_2^2} \quad \text{as the equivalent normal force},$$  \hspace{1cm} (2)

$$F_S = \sqrt{f_1^2 + f_2^2} \quad \text{as the equivalent shear force},$$  \hspace{1cm} (3)
where $f_1$, $f_2$, $f_3$, $m_1$, and $m_2$ are connector forces and moments as shown in Figure 4; $\beta$, $R_N$, $R_S$, and $K$ are constants to be determined by calibration; $r$ is the radius of the rivet. The connector potential, $P$, can be interpreted as an equivalent connector force. The contribution of the bending moments, $m_1$ and $m_2$, to $P$ is determined by the constant $K$. The yield function is defined as

$$\phi([f], \bar{\pi}^{pl}) = P([f]) - F^0(\bar{\pi}^{pl}) \leq 0,$$

where $\{f\} = (f_1, f_2, f_3, m_1, m_2)^T$ is the collection of connector forces and moments active in the yield function; $F^0$ is the equivalent yield force and defines the yield surface size as a function of the equivalent plastic relative motion, $\bar{\pi}^{pl}$, using a hardening law. The equivalent plastic relative motion, $\bar{\pi}^{pl}$, is defined below in Equation 7.

If yielding occurs, the associated plastic flow rule is used to calculate the plastic relative motion

$$\{\dot{\bar{\pi}}^{pl}\} = \bar{\pi}^{pl} \cdot \frac{\partial \phi}{\partial [f]},$$

where $\{\dot{\bar{\pi}}^{pl}\} = (\dot{u}_1^{pl}, \dot{u}_2^{pl}, \dot{u}_3^{pl}, \dot{\bar{\pi}}_1^{pl}, \dot{\bar{\pi}}_2^{pl})^T$ is the collection of plastic relative motion rate in the components active in the yield function; $\bar{\pi}^{pl}$ is the equivalent plastic relative motion rate, and is defined as

$$\bar{\pi}^{pl} = \sqrt{\frac{\partial \phi}{\partial [f]} \cdot \frac{\partial \phi}{\partial [f]} - \{\dot{\bar{\pi}}^{pl}\} \cdot \{\dot{\bar{\pi}}^{pl}\}^T}.$$

The equivalent plastic relative motion, $\bar{\pi}^{pl}$, is defined as

$$\bar{\pi}^{pl} = \int_0^t \bar{\pi}^{pl} dt.$$

For pure shear, for example in local direction 1, and for pure tension in axial direction following equations apply:

$$\bar{\pi}^{pl} = R_S \cdot u_1^{pl} \text{ for pure shear in direction 1,}$$

$$\bar{\pi}^{pl} = R_N \cdot u_3^{pl} \text{ for tension in axial direction.}$$

Isotropic hardening is assumed for the evolution of the yield surface. The size of the yield surface, $F^0$, is defined as a tabular function of the equivalent plastic relative motion, $\bar{\pi}^{pl}$, using *CONNECTOR HARDENING.
To describe the failure behavior of self-piercing rivets, connector damage initiation and connector damage evolution are defined based on the equivalent plastic relative motion, $\vec{u}^{pl}$. This makes it possible to define the equivalent plastic relative motion, $\vec{u}^{pl}_{DI}$, at which damage is initiated as a function of the mode-mix ratio $\Psi_m$ in order to consider the dependence of the failure upon loading direction (see Figure 3). For damage evolution the difference between the equivalent plastic relative motion at ultimate failure, $\vec{u}^{pl}_{fu}$, and the equivalent plastic relative motion at damage initiation, $\vec{u}^{pl}_{DI}$ ($\vec{u}^{pl}_{fu} - \vec{u}^{pl}_{DI}$), is also specified as a function of the mode-mix ratio $\Psi_m$. The mode-mix ratio is defined as

$$\Psi_m = \frac{2}{\pi} \tan^{-1} \left( \frac{F_N}{F_S} \right).$$

(10)

4. Calibration of the connector behavior

Figure 5 shows the FEM meshes used for calibrating the connector behavior of the rivet shown in Figure 1. Shell elements S4R with edge lengths of approximate 5mm are used. The end points of the connector have the same positions as mesh nodes. The clamped parts of the sheets are assumed to be rigid. The reference node of the upper rigid body is pulled in the desired direction. In the perpendicular direction a spring with a stiffness of 1500 N/mm is defined at each rigid body reference node in order to consider the lateral stiffness of the test machine. All other degrees of freedom are restrained.
In order to determine shear and axial stiffness of the connector, simulations are carried out for loading directions $\alpha = 0^\circ$ and $\alpha = 90^\circ$ based on the assumption that the connector remains rigid for all components. From a comparison of the simulation and the test results a shear stiffness of $E_S = 9000.0 \, N/mm$ is derived (Figure 6a). The first correlation of simulation and test results for the loading direction $\alpha = 90^\circ$ showed that the FEM model with rigid connector was too flexible in comparison with the real specimen (Figure 6b). This is attributed to the local deformation of the shells in the area of the rivet resulting from the structural distributing coupling. Therefore, the elastic behavior in the axial direction (component 3) was subsequently assumed to be rigid. For the same reason the elastic behavior for the two bending components 4 and 5 is assumed to be rigid too.

![Figure 6. Calibration of the elastic behavior of the connector](image)

The calibration of the plastic behavior and the damage behavior of the connector requires some trial and error. From a preliminary examination it was observed that the bending moments $m_1$ and $m_2$ are negligible in comparison to the connector force components $f_1$, $f_2$ and/or $f_3$ in tests with single rivet specimens, while in peeling tests the bending moments are of the same order of magnitude as the connector forces. Therefore, the calibration is carried out initially using only the single rivet specimen test results, where the value of the constant $K$, which controls the contribution of the bending moments to the equivalent normal force (see Equation 2), is set to zero. The actual value of $K$ is determined from the peeling test results.

The procedure for calibrating the connector plastic behavior can be summarized as follows:

1. For tests with $\alpha = 0^\circ$ Equations 1 to 4 result in:
\[ F^0 = \frac{F_S}{R_S} \]  

A peak value of \( F_{S,max} = 3390 \) N is estimated for the equivalent shear force, \( F_S \), from the test results. The maximum for \( F^0 \) is chosen to be equal to 100.0, so that \( R_S \) is equal to 33.9.

2. From a comparison of the elastic simulation results and the test results with \( \alpha = 0^\circ \) the plastic displacement is estimated for several force levels. Using Equations 8 and 11 a table can be created with the equivalent yield force, \( F^0 \), as a function of the equivalent plastic relative motion, \( \pi^{pl} \), for \texttt{CONNECTOR HARDENING}.

3. For tests with \( \alpha = 90^\circ \) Equations 1 to 4 result in:

\[ F^0 = \frac{F_N}{R_N} \]

A peak value of \( F_{N,max} = 2230 \) N is estimated for the equivalent normal force, \( F_N \), from the test results. With \( F^0_{max} = 100.0 \) we get \( R_N = 22.3 \).

4. With the plastic behavior calibrated in steps 1 to 3 tests with other loading directions are simulated using various values of \( \beta \). By comparison of the simulation and the test results a value is estimated for \( \beta \).

5. To obtain a good description for all tests with single rivet specimens it may be necessary to repeat the steps 1 to 4 with new adjusted values for \( R_S \) and \( R_N \). This way \( R_S = 33.9 \), \( R_N = 22.7 \), and \( \beta = 1.6 \) were determined for the sheet pair in Figure 1. Figure 7a shows the calibrated hardening data.

After calibration of the plastic behavior of the connector the damage initiation can be easily calibrated using the following procedure:

1. Choose a displacement from the simulation results for each loading direction at which the damage should be initiated;

2. Determine the corresponding equivalent plastic relative motion for each loading direction using the displacements chosen in step 1;

3. Calculate the mode-mix ratio from connector forces at the displacement at which the damage should be initiated for each loading direction.

The equivalent plastic relative motion at damage initiation can then be defined as a tabular function of the mode-mix ratio (see Figure 7b).

The calibration of the damage evolution is not as straightforward as the calibration of the damage initiation because the mode-mix ratio does not remain constant during the damage evolution for loading directions other than \( 0^\circ \) or \( 90^\circ \). Through trial and error a function shown in Figure 7c is
defined for the dependence of the difference between the equivalent plastic relative motion at ultimate failure, \( \overline{\mu}_{pl}^{f} \), and at damage initiation, \( \overline{\mu}_{pl}^{DI} \), on the mode-mix ratio \( \Psi_m \).

Using the calibrated connector behavior shown above, simulations of the peeling test are performed using different values of the constant \( K \). From the comparison of the simulation and the test results a value of \( K = 0.56 \) is determined. In Figure 8 results of simulations carried out with the final constant set are compared with results from all tests. The test results can be accurately described with the set of determined constants.

**Figure 7.**

a) Equivalent yield force as a function of equivalent plastic relative motion

b) Equivalent plastic relative motion at damage initiation as a function of mode-mix ratio

c) Difference between equivalent plastic relative motion at ultimate failure and at damage initiation as a function of mode-mix ratio
a) Single rivet specimens, loading direction 0°, 45°, 90°

b) Single rivet specimens, loading direction 15°, 60°

c) Single rivet specimens, loading direction 30°, 75°

d) Peeling test

Figure 8. Comparison of simulation and test results for tests with single rivet specimens and peeling tests
5. **Mesh-independence of the calibration results**

In order to examine if the calibration results are mesh-dependent, the tests with single rivet specimens and the peeling test were simulated using four different meshes (Figure 9) and using the constant set determined in section 4. In mesh 1 in Figure 9 the elements have a size of approximately 2.5x2.5mm so that the element edges are half as long as in the mesh used to calibrate the connector behavior (Figure 5). As in the mesh in Figure 5 the connector end points have the same positions as mesh nodes. In Figure 10 the simulation results from these two meshes are compared. From this comparison it can be concluded that a refinement of the mesh has no significant influence on the calibration results.

In meshes 2, 3, and 4 in Figure 9 the elements have approximately the same size as in the mesh used to calibrate the connector behavior (Figure 5), while the connector end points here are not positioned at mesh nodes, but at element centers or at the middle of element edges. In Figures 11 the results from mesh 2, 3, and 4 of Figure 9 are compared with the results from the mesh used for the calibration (Figure 5). It can be concluded that the positions of the connector end points do not have significant effect on the simulation results.

![Figure 9. Meshes to examine the mesh-independence of the calibration results](image)
Figure 10. Comparison of the results from the mesh for calibration and from mesh 1 in Figure 9. Left: single rivet specimens; Right: peeling test

Figure 11. Comparison of the results from the mesh for calibration and from meshes 2, 3, 4 in Figure 9. Left: single rivet specimens; Right: peeling test
6. Simulation of an axial crash test

Figure 12 shows the finite element model for the axial crash test considered here. The test part is a tube consisting of two M-profiles which are connected with 20 self-piercing rivets. The lower end of the tube is partly fixed onto a base plate. An impactor with a mass of 500 kg falls on the upper end of the tube with an initial velocity of 10 m/s. During the test the displacement of the impactor and the reaction force at the base plate were measured.

In order to simulate this test, the connector behavior used in the fastener definition to model the self-piercing rivets has been calibrated using data from tests carried out with single rivet specimens, as described in section 4. Because no data from peeling tests is available, the constant $K$ in Equation 2 was determined from the crash test results by comparing of the simulation results with the measurements.

In Figure 13 the simulation results are compared with the measured results from two tests. The simulation results show a good agreement with the physical test results. Figure 14 shows the final, deformed shape of the tube from the analysis.
Figure 13. Comparison of simulation and test results for the axial crash test

Figure 14. Deformed shape of the tube at the end of the measurement from the simulation
7. Conclusions

In this paper it has been shown that the fastener capability in ABAQUS is suitable for modeling self-piercing rivets, and the deformation and failure behavior of self-piercing rivets can be described accurately using connector behavior descriptions for elasticity, plasticity and damage. Connector elasticity, plasticity and damage behavior was formulated for self-piercing rivets. Procedures to calibrate the connector behavior were described and demonstrated with an example. Data from tests with single rivet specimens and from peeling tests were used for calibrating the connector behavior. It was shown that the calibration results are mesh-independent. An axial crash test was simulated. The simulation results show a good agreement with the measured results.

8. References