

SPOT WELD MODELING WITH IMPLEMENTED RUPTURE CRITERIA

Jan Morawski¹, Beate Lauterbach¹, Ilka Schwarzer¹, Laia Ramon-Villalonga¹,
Michael Tryfonidis²

Adam OPEL AG¹
Beta CAE²

KEYWORDS –

Spot weld, rupture, heat affected zone (HAZ), automated spot weld realization

ABSTRACT –

In today's automotive CAE models the prediction of spot weld rupture is of high importance for vehicle performance assessments. Coming from single coupon tests, ANSA is utilized to apply all necessary information about the spot welds definition (e.g. weld partners, nugget diameter, sheet and nugget material properties and heat affected zones) to the full vehicle CAE model.

The advantage of this very detailed modeling is shown exemplarily with a seat console weld performance within an ECE R14 kind of test setup. Different approaches of modeling techniques were investigated.

This process is implemented efficiently in an automated way by means of ANSA scripting functionality.

1 INTRODUCTION

The entire body of a modern vehicle typically contains a few thousand spot welds joining different materials and gage combinations. The consideration of their mechanical properties and fracture behavior is a key to accurately predict the response of vehicle structures in the virtual development process. In case a spot weld detaches, the load which is transferred from part to part will change and may result in different deformation results of full vehicle crashes.

In order to be able to reproduce the behavior of all different spot weld joint combinations a large number of experiments is required. Based on experimental results a comprehensive database for FE analysis containing detailed spot weld information such as nugget and heat affected zone (HAZ) material properties, diameter as well as rupture characteristics needs to be established.

The pre-processor ANSA with its new spot weld scripting functionality is applied to implement all necessary information about the spot weld in the full vehicle FE model in an efficient and automatic manner.

The necessity and importance of the ANSA automated spot weld realization is shown exemplary in this paper by means of a component test: a seat console within the ECE R14 test regulation.

2 METALLURGICAL TESTS AND COUPON TENSILE TESTS

Because of the large number of different material and gage combinations in the entire vehicle body, the spot weld characterization for FE analyses requires a vast number of experimental tests. In addition to that, the presence of mainly three sheet joints rather than just two sheet joints increases the number of combinations that need to be considered even more.

In a first step physical tests of symmetrical two sheet joints (same gage and material) are performed in order to understand the spot weld joint behavior itself. In a second step, tests of non-symmetrical two sheet joints (different gage and/or material) are of importance in order to determine a so-called 'rule of mixture'. The rule of mixture allows to calculate material properties and rupture parameters of non-symmetric joints, considering the weighting of thickness, yield strength and peak load capacity. In a last step, the rule of mixture has to be proved and complemented by means of three sheet joint experimental testing.

The detailed characterization of the spot weld is achieved by the determination of the material properties and diameter, as well as the identification of the rupture parameters. Two different types of physical tests have to be performed in order to obtain such information:

- metallurgical tests (spot weld material properties and diameter)
- coupon tensile tests (rupture parameters)

Both kinds of tests can be carried out for two and three sheet joints.

2.1 Metallurgical tests

The metallurgical sample consists of two or three sheets joint welded with a few spot welds and is used in order to study the microscopic properties of the joint. By carrying out such metallurgical tests the material properties and diameter of the spot weld can be determined. The proper preparation of metallographic specimens to obtain the spot weld microstructure requires a rigid step-by-step process. In sequence, the steps include sectioning, mounting,

grinding, polishing and etching. After this process, a microscopic examination follows: the hardness distribution of the joint can be extracted and three different subzones in the micro structure of the spot weld are identified: sheet basis material (BM), heat affected zone (HAZ) and nugget (Figure 1). These three different subzones are caused by the concentrated heat proceeding from the resistance spot welding process.

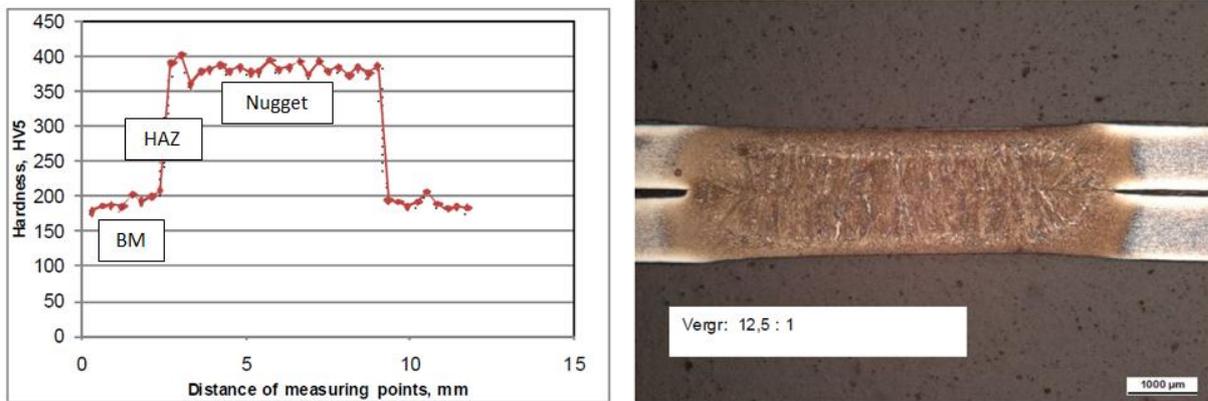


Figure 1 – Hardness distribution and metallographic specimen (DP600)

The hardness profile enables the calculation of the material properties of both HAZ and nugget (Figure 2). The yield curve of the basis sheet material is scaled by the hardness ratio:

$$\text{Scale Factor (SF)} = \frac{\text{Hardness nugget}}{\text{Hardness basis material (BM)}}$$

This information is taken into account and set as input in the FE model.

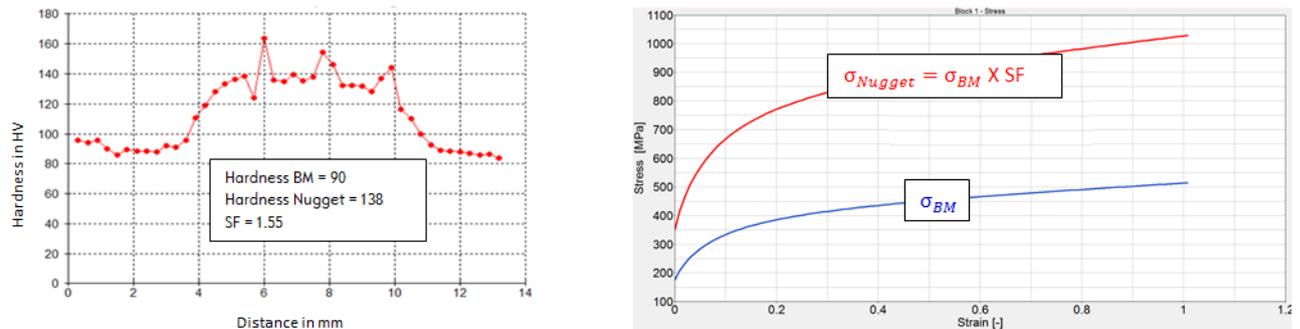


Figure 2 – Hardness distribution and BM and nugget yield curve (CR3)

The metallurgical cross-section also provides the information of nugget and HAZ diameter on the basis of the determined dimension of each weld subzone. The diameter is measured in three cutting angles 0°, 45° and 90° (Figure 3):



Figure 3 – Cutting angles for diameter measurement

It has to be emphasized that the study of metallurgical samples with three sheet spot welding cannot be overlooked. The metallographic specimen of a three sheet joint shows that the

HAZ and nugget diameter between the top and the middle sheet can be completely different than between the middle and the bottom sheet (Figure 4). Such results have to be considered in the FE simulations and are shown in the next paragraphs.

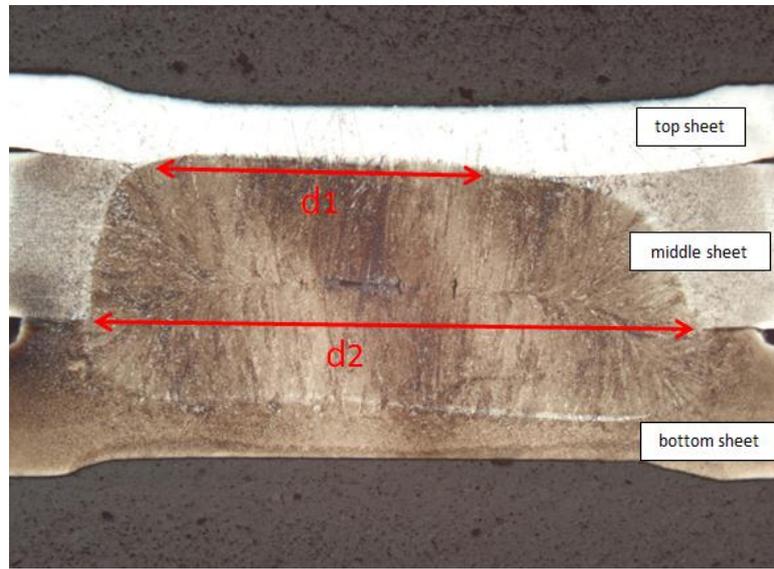


Figure 4 – Metallographic specimen (three sheets joint)

2.2 Coupon tensile tests

Apart from metallurgical tests, different coupon tensile tests under various kinds of load conditions have to be carried out in order to adequately determine the spot weld strength values. Conventionally, tensile-shear, cross-tension and coach-peel specimens have been performed for the estimation of strength characteristic of spot weld joints (Figure 5). However it is crucial to use extra specimen geometry with combined loading in order to be able to verify the FE simulation results. Coupon tensile tests are performed for both two sheet and three sheet joints.

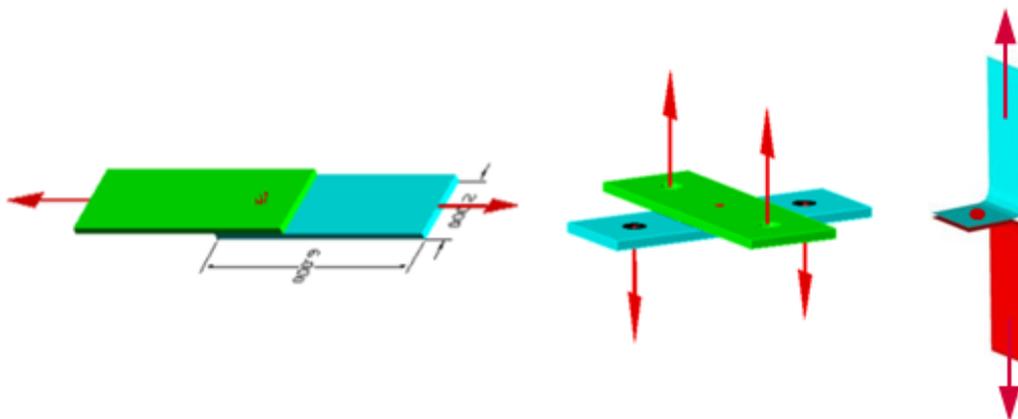


Figure 5 – Tensile-shear, cross-tension and coach-peel specimen

From the coupon tensile tests the force-displacement spot weld characteristic is extracted and the resultant peak force is captured. Figure 6 shows the force displacement curve for the three above mentioned specimen geometries.

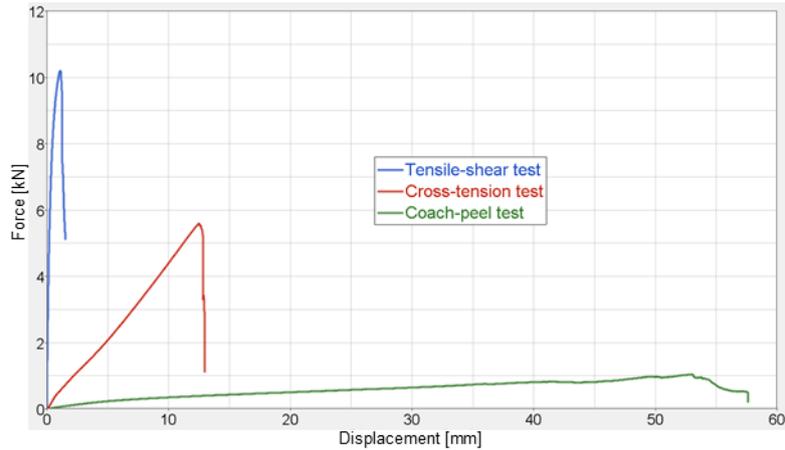


Figure 6 – Tensile-shear, cross-tension and coach-peel test results (DP600, 1.00mm)

Observing coupon test results, two remarkably different fracture modes of spot weld can be distinguished: nugget interfacial rupture and nugget pullout rupture (Figure 7). The pullout mode is generally the preferred fracture mode since the amount of energy absorbed by the weld is greater than in the case of interfacial fracture and has become the more common rupture mode in full vehicle crashes. Nugget pullout fracture involves fracture in the periphery of the weld within the HAZ or the base material rather than through the weld. Interfacial fracture is a less desirable fracture mode because a full separation of the joined sheets occurs as a result of a fracture through the weld, thereby providing less strength.



Figure 7 – Nugget pullout and interfacial fracture mode

3 FE MODELING

3.1 Spot weld modeling

In FE crashworthiness analyses the sheet metal is normally represented with shell elements and the spot welds with solid elements (Figure 8). Typically, a tied contact is used to

establish the connection among independent meshes; giving the solid weld elements a thickness that is half the sum of the thicknesses of the welded shell elements. This results in an artificial thickness of the spot weld model, which may lead to exaggerated bending moments. However, the bending moment can be corrected in the FE solver, so that during its calculation the true thickness of the spot weld is considered.

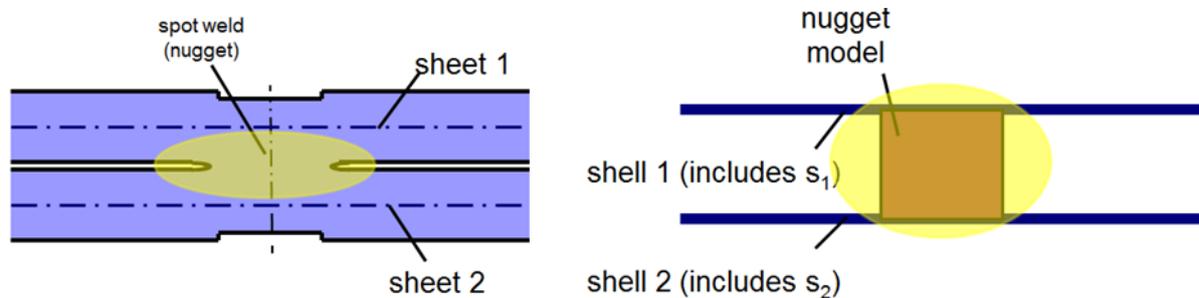


Figure 8 – Spot weld in the reality and in the simulation

The discretization of the spot weld (Figure 9) can be modeled by a simple solid element (hexahedron) or by any number of solid elements, building a spot weld assembly (cluster). The cluster modeling has some advantages compared to the single element weld because the tied contact is more robust, more mesh independent, and at the same time the usage of multiple solid elements allows a better representation of the complex mechanism of spot weld rupture.

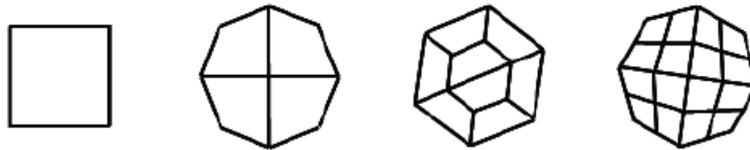


Figure 9 – Modeling of the spot weld (single hexahedron, cluster4, cluster8 and cluster16)

With a mesh size of the sheet panels between 3 and 4 mm, a weld discretization of eight solid elements is fine enough to represent the weld while not adding additional mass to the spot weld. The element length of the weld assembly should not be larger than the element length of the sheet panel. In this paper the 8 cluster representation is chosen in order to model the spot weld nugget.

It is important to consider the three different spot weld zones described in paragraph 2.1 in the FE model. Therefore, the nugget and the HAZ need to be modeled. There are many possibilities to represent the HAZ depending on the discretization of the nugget. In this paper the modeling of the HAZ comprises one homocentric annulus around the nugget with the HAZ diameter. On the basis of the hardness distribution the diameter of the HAZ can be approximated by scaling the spot weld diameter with a factor between 1.2 and 1.5 depending on the thickness combination of the joint. In order to avoid an element length too small for the shells, the HAZ is modeled by eight shell elements (elements alignment equal to the weld cluster), where the inner element ring is half of the outer element ring (Figure 10).

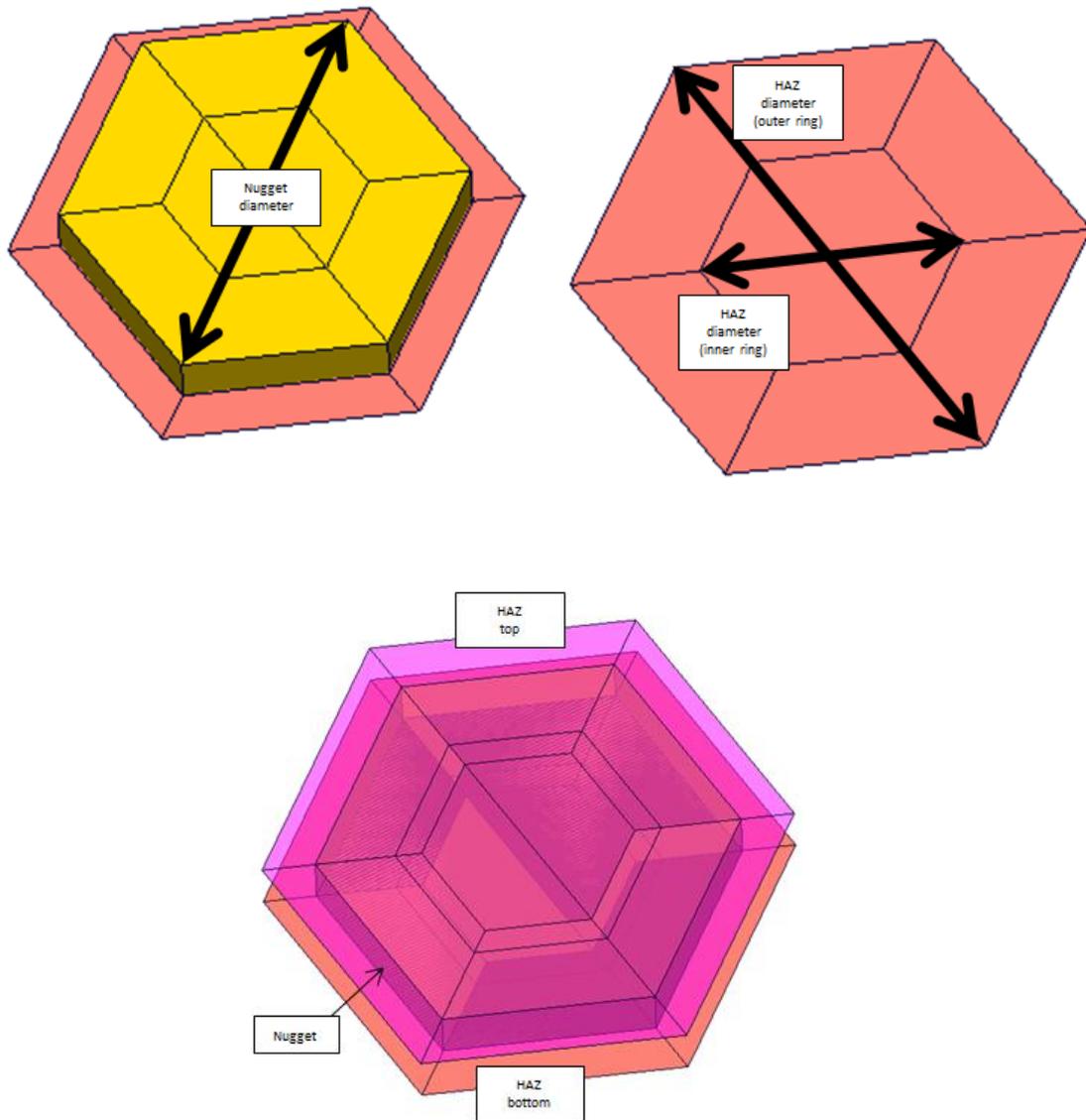


Figure 10 – Modelling of spot weld nugget and HAZ

3.2 Material modeling

In order to choose the appropriate material modeling approach to characterize the spot weld separation, the fracture mode of the spot weld has to be considered as well. Otherwise an incorrect modeling of the rupture mechanism may lead to over or under estimating the spot weld force.

In this case, the interfacial rupture of the nugget is modeled with a simple material model including a force or stress based rupture criteria. This approach is still the most commonly used. It simplifies the spot weld separation, which is equivalent to the rupture of the spot weld solid elements.

In contrast to the interfacial rupture, the much more complex tearing mechanism of the nugget pullout rupture requires a more comprehensive approach. In this case it is more suitable to model the rupture in or adjacent to the HAZ using more sophisticated material models. In this paper, a combined approach capturing both fracture modes is described in the next paragraphs.

4 ANSA SCRIPTING FUNCTIONALITY

4.1 General Requirements

As described in paragraph 3, different methodologies to discretize spot weld and spot weld rupture are available. Depending on the selected method, different spot weld rupture criteria are valid. These criteria are derived from validated coupon test and saved in the spot weld tool box. The kind of spot weld and HAZ realization as well as the material and rupture property parameter definition needs to be selected by the user within ANSA and the spot weld tool box.

For this selection process, the following information from the simulation model is required for each spot weld joint:

- Spot weld partner and stack up (Top/ Middle/ Bottom)
- Sheet thickness
- Base material properties (MID/ SIGY/ ETAN).

Within the spot weld tool box these data were used to calculate required material values and define spot weld joint specific values required for material rupture definition depending on rupture criteria:

- nugget material with rupture criteria (MID/ SIGY/ ETAN)
- HAZ material properties with rupture criteria (MID/ SIGY/ ETAN).

To enable the interaction between ANSA and the spot weld tool box a specific numbering scheme had to be implemented.

4.2 Implementation of Scripting Functionality

In order to achieve the FE-Representation as described in paragraph 3, a combination of the following pre-processing actions has to be performed:

- The realization of the spot welds using the SOLID-NUGGET representation, offered for spot welds by the ANSA Connection Manager (see reference 1). During this step, the hexa-elements are generated as well as the shell mesh on the flange is modified accordingly.
- The parallel call of user script, that performs additional actions on the FE-result, in a post-execution manner and automatically driven by the Connection Manager. The ANSA feature used is called Post realization script function. This is where the hexa-elements and the HAZ-shells are modified accordingly: Dimensions, Nomenclature, Numbering rules as well as the generation of additional solver keywords

For the purpose of this paper, focus will be given in describing the user script call as well as the basic steps of the algorithm that are followed:

- a) First step is to identify the parts involved in the spot weld connection, and categorize them according to their Flange sequence (top-middle-bottom sheet).
 - b) According to the Flange sequence, the equivalent thickness is calculated as well as the nominal diameter of the nugget.
 - c) Given these values, the diameter per flange pair is determined for the
-

hexa-nugget as well as for the shell elements representing the HAZ.

d) The dimensions of the hexas and the HAZ-shells are adjusted (their very geometry).

e) Properties and other solver keywords of the involved FE-elements are adjusted following rules: Nomenclature, Id-numbering directives and keyword field values (such as the actual connector properties).

4.3 Nomenclature and numbering rules

First the model assembly information regarding all connections within the model has to be captured. Depending on model information whether an ANSA databank with defined generic connector entity is available or a LS/DYNA input with respective contact definitions the procedure is more extensive.

To reduce the model size and to improve the model handling, same weld joints have to get the same property and material IDs. Therefore, the joint information needs to be saved for further processing. A nomenclature rule for the solid nuggets and HAZ shells was introduced (see Figure 11 **Fehler! Verweisquelle konnte nicht gefunden werden.**).

To distinguish between solid nuggets and HAZ shells a type identifier is defined by using the first text block. The identifier for the spot weld nuggets includes the number of joint partners (SPW3 = 3 layered joint / SWP2 = 2 layered joint) and the stack up information (sheet A/B/C). This is followed by the corresponding weld diameter which will be calculated as a function of sheet shell thicknesses. Last all partners of the weld joint are listed with the stack up position and corresponding shell property ID.

For HAZ shells the name includes as well the Identifier and the considered stack up position of the sheet. Then the zone diameter and the sheet thickness are listed followed again by all weld partners.

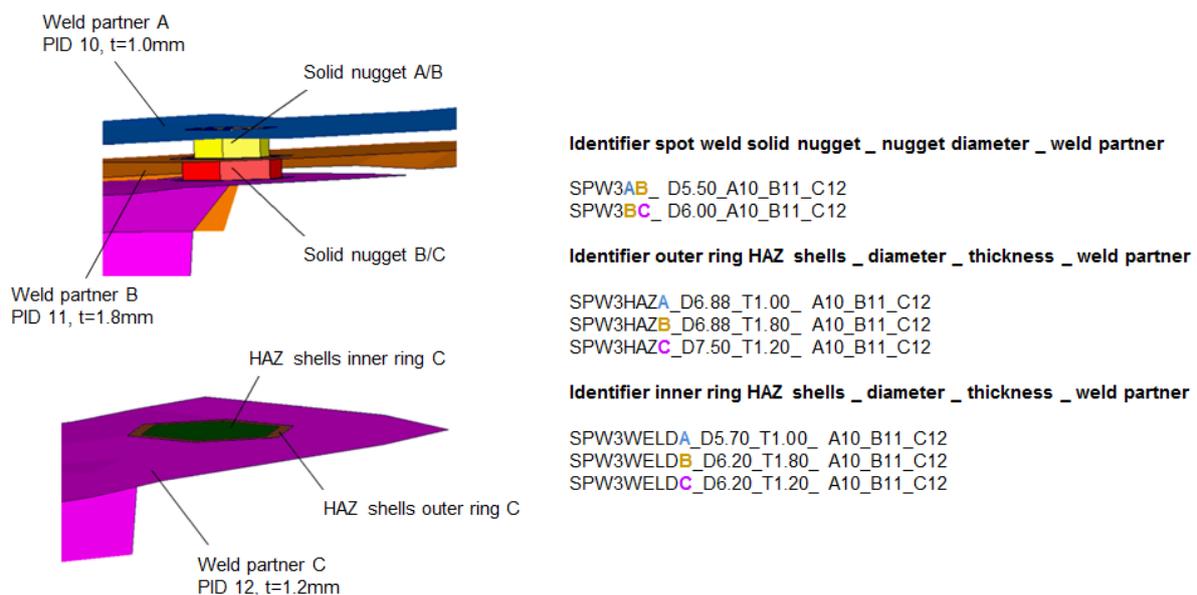


Figure 11 – Nomenclature rule for spot weld joints within ANSA

An equivalent numbering rule for the corresponding property and material IDs for solid nuggets and HAZ shells was specified which enables an improved model handling.

Using these rules ANSA is able to realize all welds by setting the connection post realization function to the new *Post realization script function*. For realization it is possible to select between different methods as described in paragraph 3. This enables the user to select the realization method corresponding to the coupon test validation models.

Property ID and name as well as material ID for solid nugget and HAZ shells according the defined rules will be then used as input parameters for the spot weld tool box. Within the toolbox the determination of all material relevant data as stiffness and rupture criteria occurs. Depending on selected method the required material cards will be written.

5 EXAMPLE

The following example is used to demonstrate how the application of more advanced weld modeling techniques with new ANSA functionality combined with validated material data can improve the prediction of structure performance.

5.1 Regulation and Test Rig Description for Belt pull

Fulfilling ECE-R14 regulations for seat belt anchorages is mandatory for vehicle type approval. This standard was established to ensure the integrity of the seat belt anchorage systems for effective occupant restraint.

Two types of test devices (pelvic and torso block) are placed onto the seat and belted without belt pretensioner and load limiter. The pull force is applied in a direction corresponding to the seating position at an angle of $10^\circ \pm 5^\circ$ above the horizontal plane of the vehicle. The seat belt anchorages and seat anchorage must withstand the specific loads for a prescribed hold time. The performance of the system is considered satisfactory if the system can sustain the maximum load. If this requirement is fulfilled permanent deformation or damage within the anchorage itself and the surrounding parts is permitted.

In order to study the impact of different spot weld modeling techniques on the structural performance, a principal test setup using a typical design of a vehicle center floor and seat attachments was established that mimics the ECE-R14 type of loading. Due to the simplified test set-up the behavior of individual spot welds could be monitored much easier leading to a better database for the latter model correlation.

5.2 Model validation

The most common modeling approach for spot welds is the discretization of the spot weld by a single solid element (Figure 12) without considering spot weld and material fracture.

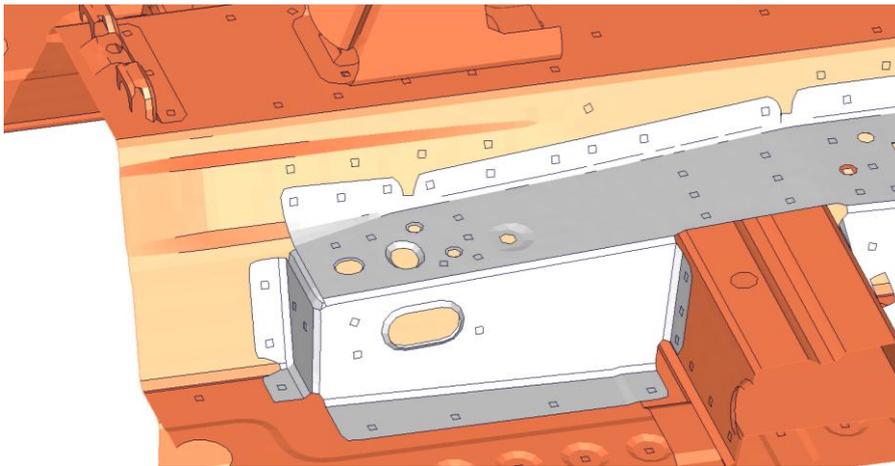


Figure 12 – Simulation model with simple spot weld definition (single hexahedron)

Using this method, the structural integrity assessment is done by evaluating the plastic strains and forces for each spot weld that might transfer high loads and comparing those to a set of limits (derived from principal spot weld tests) that might not be exceeded. The simulation result for the inner seat console of the passenger seat (here plastic strains) is shown in Figure 13.

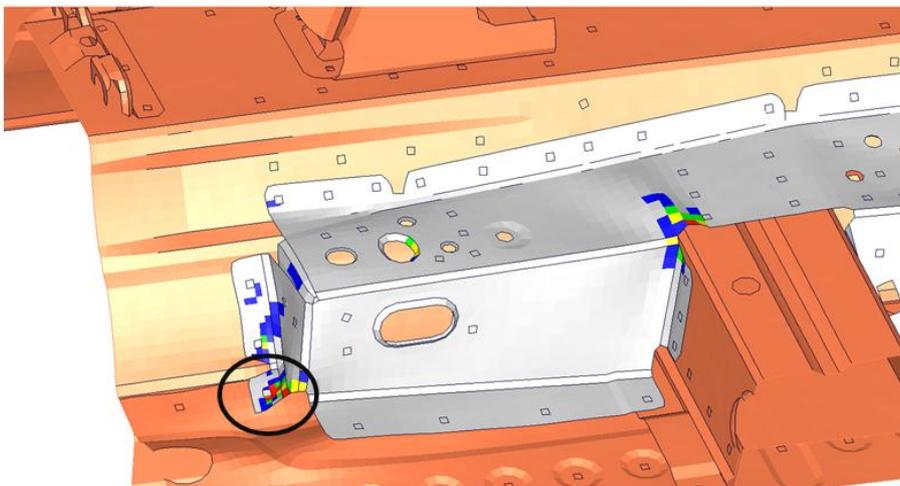


Figure 13 – Simulation results with simple spot weld definition (single hexahedron)
@ simulation end time

It is obvious that the weld connecting seat console and floor panel is highly loaded but there is no indication for an integrity loss. The expectation was that only one weld may rupture.

In contrast to this, the physical test using the principal setup showed a rupture of a larger number of spot welds mainly driven by nugget pullouts (Figure 14).



Figure 14 – Hard ware test correspond to simulation model

In order to validate the simulation model, different spot weld modeling methods with respective rupture criteria derived from coupon test validation were investigated.

From the example above, it becomes clear that spot weld modeling with one hexa element does not lead to satisfactory simulation results. Therefore, more advanced spot weld modeling as described in paragraph 3.1 is required. Figure 15, Figure 16 and Figure show simulation results for different spot weld modeling techniques. In all three cases, the weld nugget representation was changed from single hexahedron to a cluster consisting of 8 solid elements. But the models are different in the level of detail in geometrical spot weld representation.

In Fig. 16, all spot welds in the model have the same constant diameter of 5mm. This modeling technique is an improvement compared to the one hexa element modeling because it allows a better resolution of the stress state within the weld. But since all spot welds in the simulation model are modeled with the same diameter, this approach can't distinguish between "stiff" and "weak" spot weld connections.

This issue has been resolved by modeling weld nuggets with individual diameters depending on corresponding sheet joint gauges (Figure 16). This geometrical representation of the weld nugget is more realistic, because it is commonly known, that standard procedures of sheet metal welding lead to different weld nugget sizes. But still, this modeling approach is a simplification and therefore not generally sufficient to simulate spot weld behavior during vehicle crash impacts, especially when spot weld rupture due to weld nugget pullout has to be taken into consideration.

In this case, a better representation of the weld joint would be to include the HAZ into the spot weld model. The result of this modeling is shown in Figure 17, where the simulation results match the hardware test behavior very well in terms of rupture mode and carried loads. Significant improvement of structure performance assessment can be achieved when weld rupture is taken into consideration. Of course, in addition to HAZ meshing an appropriate material model for the HAZ has to be chosen to be able to model spot weld rupture due to nugget pullout. How to model material behavior including rupture of HAZ is not easy and still topic of research projects (FOSTA P806/A262: Characterization and simplified modeling of the fracture behavior of spot welds from ultra-high strength steels for crash simulation with consideration of the effects of the joints on component behavior" / Ref. 2).

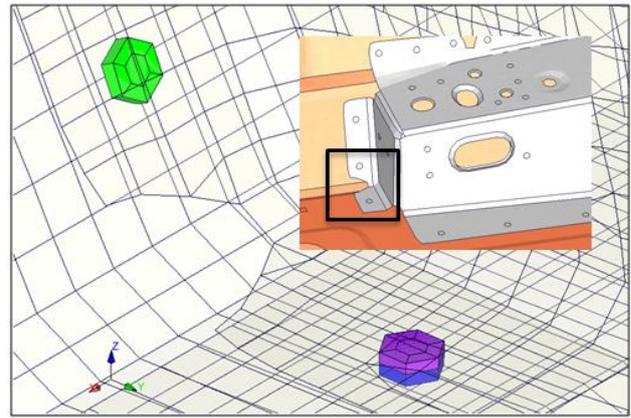
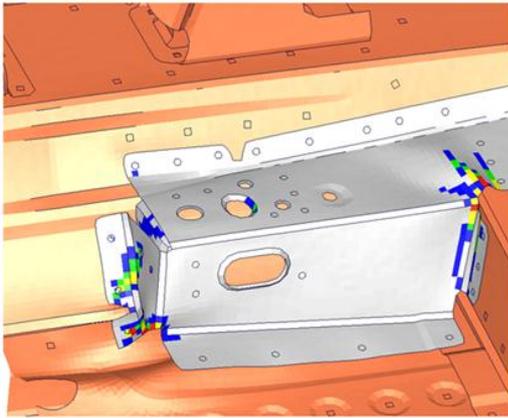


Figure 15 – Simulation results of weld cluster8 with constant nugget diameter (5mm)
@ simulation end time

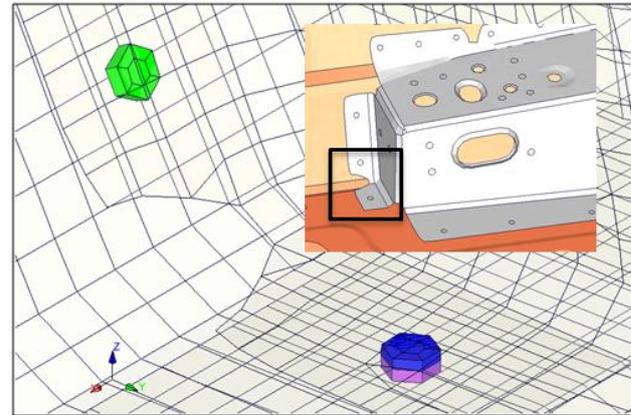
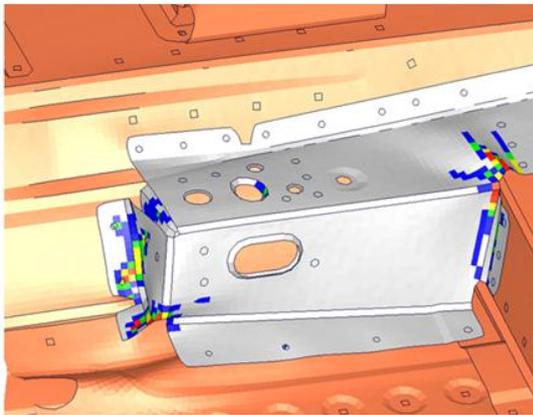


Figure 16 – Simulation results of weld cluster8 with thickness dependent nugget diameter
@ simulation end time

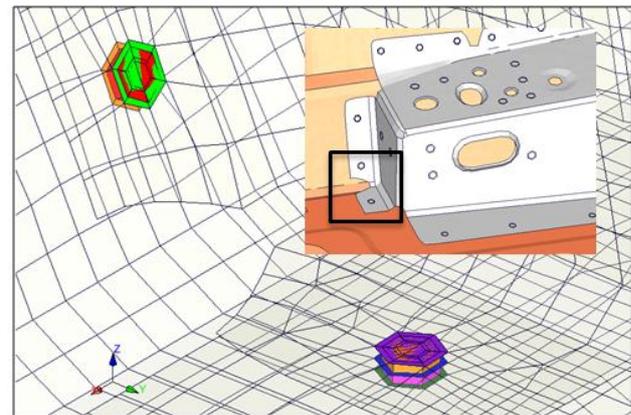
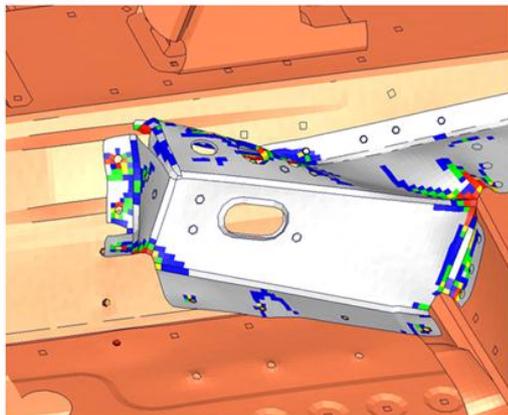


Figure 17 – Simulation results of weld cluster8 with thickness dependent nugget diameter and HAZ
@ simulation time at maximum carried load within hard ware test

Based on simulation models that are able to predict weld behavior correctly, design optimization can be performed by CAE methods. Figure 18 shows the results of this design improvement process in the simulation model and hardware test using weld cluster8 with thickness dependent nugget diameter and HAZ.

These simulation results show clearly that a more advanced spot weld representation is better suited to model complex spot weld behavior in vehicle crash events. With the newly developed ANSA Scripting functionality, it is possible to use these modeling techniques in an automated and efficient way for larger scale models.

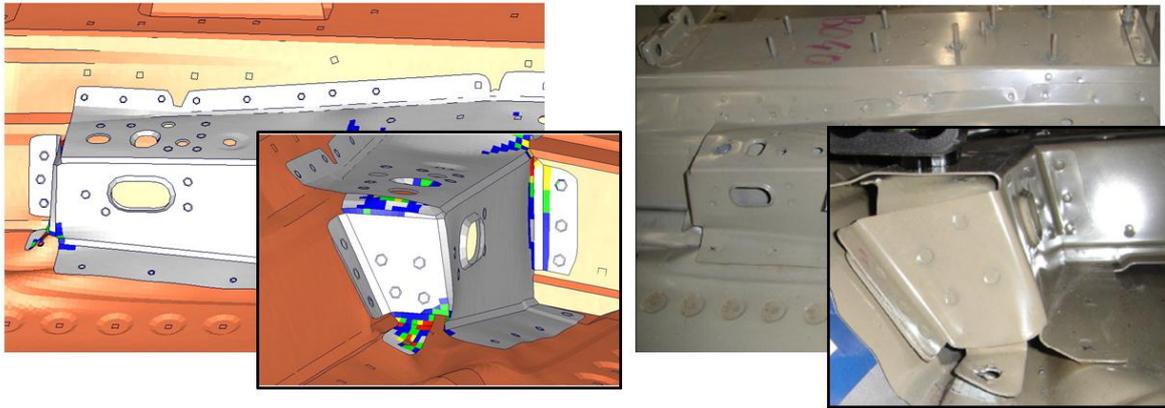


Figure 18 – Simulation results optimized design of weld cluster8 with thickness dependent nugget diameter and HAZ @ simulation end time / hard ware test

6 SUMMARY AND OUTLOOK

It was shown that structure integrity assessment may be improved when using more detailed spot weld modeling techniques. For that purpose, it is necessary to adjust the spot weld diameter and the respective HAZ diameter for each spot weld joint depending on sheet gauge and stack up. Further, it is essential to apply material properties for the weld nugget and the HAZ shells that are well suited to model spot weld behavior. From metallurgical and mechanical coupon testing, material weld stiffness properties can be derived in a straightforward manner and are managed within the spot weld toolbox. To derive appropriate parameters for weld joint rupture as additional content of the spot weld toolbox, is more complicated and still under development.

The implementation of the new weld simulation method with the consideration of weld partner dependent nugget diameter and HAZ into the vehicle development process requires besides the spot weld tool box a powerful pre-processor application to set up the simulation model fully automated. The new spot weld scripting functionality within ANSA offers the possibility of weld rupture definition over a large number of spot weld joints within a full vehicle simulation.

7 REFERENCES

- (1) ANSA version v14.1.0 User's Guide, BETA CAE Systems S.A.,
- (2) FOSTA P806/A262 "Characterization and simplified modeling of the fracture behavior of spot welds from ultra-high strength steels for crash simulation with consideration of the effects of the joints on component behavior"