Crash stable adhesives in application and simulation

Dr. Alexander Droste

DOW Automotive, Schwalbach, Germany

Abstract:

Structural adhesives have been introduced to increase the stiffness and crashworthiness, as well as to improve corrosion protection and sealing of the body-in-white in upper class car models and are now entering the segment of compact cars. Various numerical approaches are used to predict the mechanical responses for the different loading conditions applied to develop and optimize the 'bonded' car-body. Most often these approaches are limited to describe the complex material behavior of adhesives, especially in crash and post-crash analysis. Thus, in the past, choosing the adhesive material and placing and optimizing the bondline was often based on testing and design experience.

As one of the leading adhesive suppliers DOW Automotive is committed to support the OEMs and Tiers with suitable FEA approaches to improve the material selection process and reduce testing costs. In addition a reliable numerical prediction allows to design in the virtual development phase an optimized joint to get the most benefits out of the adhesive material. This will improve the usage of structural bonding also within the medium and lower car segments.

This article will give an overview about current applications, development and validation of the modeling approach using MAT_Gurson (#120) within LS-DYNA for the crash stable adhesive BETAMATE 1496/1496V.

Keywords:

structural adhesives, strukturelles Kleben, Gurson

1 Introduction

New material developments for crash stable structural adhesives open up new applications in the modern car body design. Especially the improved damage characteristic of these adhesives allows their usage in high dynamic loading conditions. To save development cost as well to allow up-front optimization in the vehicle development process, numerical tools like LS-DYNA need a suitable material behavior constitutive formulation to describe the material response. In addition to these material models, the numerical parameters like maximum element size, element formulation, etc. especially for the full vehicle simulation, have to be considered for balancing the accuracy and the calculation time.

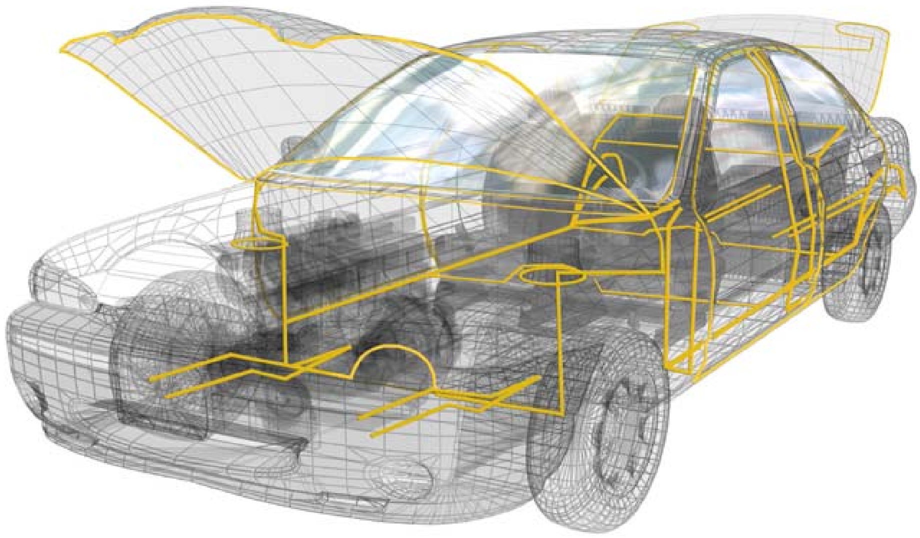

Figure 1: Potential structural adhesive bondline in the car body

Structural adhesives have been applied for body structures application as a thin layer between the substrates (0.2 – 0.5 mm bondline thickness - BLT) with a varying length of up to 150 m (Figure 1). Due to complex nature of adhesive material behavior and its influence on full vehicle response a need for establishing CAE methodology exists.

2 Material behavior description

In general the quality of an adhesive can be characterized by its ability to adhere to different often oily substrates. To save cost and to compete with other joining technologies like spot-welding, clinching, riveting minimal substrate surface preparation is required. The surface condition is one of the main aspects of the performance capability of a bonded joint. If the interface between the substrate and the adhesive is weak, neither the substrate nor the adhesive can meet the expected requirements.
Within this article it is assumed that interfacial failure does not occur and a bonded joint is always limited to its own material characteristic (cohesive failure) or to the substrate characteristic (substrate failure).

2.1 Different types of adhesive

In order to describe the mechanical behavior of a bonded part participating in vehicle components used for stiffness and energy management not only the (visco)-elastic-plastic behavior is significant. The mechanism of crack initiation, crack propagation and fracture leading to softening and failure has to be considered as well. The separation of bonded joint is of importance, as the energy management could be strongly influenced if two or more substrates are kept together or are separating within the load event.
Adhesives can be classified within different types. The five most widely used are epoxy, polyurethane, modified acrylic, cyanoacrylate and anaerobic. Additives or modifiers are used to improve certain properties like strength, load, temperature, solvent and/or creep. Adhesives used for body structrure applications are typicially one- or two component thermosets systems, which are curing at room- or elevated temperatures. Two component systems require careful proportioning and mixing. Some of

the structural adhesives are difficult to remove and/or repair. Structural adhesive bonds can be stressed to a high proportion of maximum failure load under service environments.
In summary there are various chemical families with varying mechanical- as well as process parameters and also with a wide range of costs.

2.1.1 Selection factors:

To select a suitable material for the required joint performance, different necessities and conditions have to be considered. Depending on its usage the following list should give an overview of selection factors for the adhesives:

- Substrates to be bonded: porosity, hardness, surface coating
- End-use requirements: stresses (construction, service), joint-types
- Temperature requirements: cure, end-use
- Exposure conditions: humidity, UV radiation, outdoor weathering
- Flexibility requirements
- Aging stability
- Aesthetic requirements: color, gloss
- Manufacturing conditions: materials handling system, processing
- Cost: waste, rejects, packaging, availability

To develop a new adhesive formulation, these factors will also be used for choosing the baseline polymeric system as well as the corresponding additives.

2.1.2 Adhesives mechanical behavior from brittle to ductile

A designer can select adhesives varying from brittle to ductile in their general mechanical behavior. By adding a toughener, the failure behavior can be modified towards a more stable post-critical material response (Figure 2).

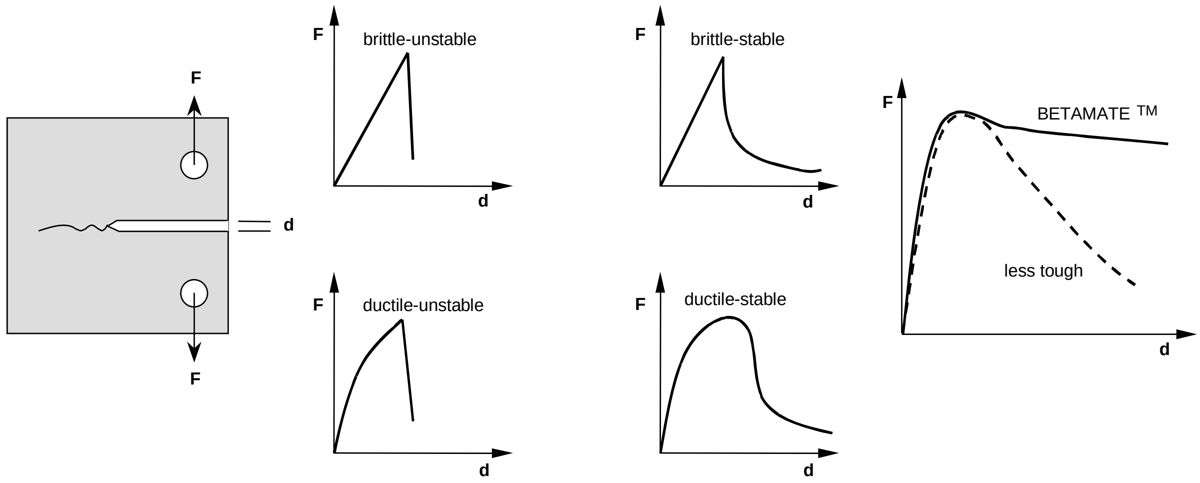

Figure 2: Adhesive CTS: crack initiation and propagation of different adhesive types

With the CTS (compact tension specimen) the crack initiation process as well as the crack propagation of different types of adhesives is examined quasi-statically. For the non-toughened materials it can be concluded that after reaching a certain load level, the crack initiates but also propagates instantaneous through the specimen leading to complete fracture and separation. For the stabilized (toughened) adhesives, the crack propagation behavior is modified towards a decelerating process and much more energy can be sustained before total failure occurs. In addition it is not favorable for a sudden loss of load bearing capacity in crash relevant joints. Thus, the ductile-stable behaving adhesives seem suitable for applications requiring higher degree of practical toughness and load-carrying capability. BETAMATE 1496/1496V is a one component epoxy adhesive treated with a special multiphase-rubber-toughened technology (Patent: EP0308664) to support high load bearing capacity and decelerated failure mechanisms, especially designed for joining structures participating in different crash scenarios.

As an example of the benefit using such a crash stable adhesive, Figure 3 compares a brittle epoxy bonded profile, a spot-welded profile and a profile bonded with BETAMATE1496 of a drop-tower testing.

a) brittle epoxy b) spot-welds c) toughened epoxy

Figure 3: Test results of dynamic drop-tower tests on a double hat section profile using a brittle adhesive, spot-welds and the crash stable BETAMATE 1496

In this example using a brittle epoxy or spot-welding has lead to separation of the parts during the impact, not being able efficiently absorb the impact energy. One the other hand, the toughened epoxy shows that the most efficient energy absorption take place when the steel profile undergoes axial plastic deformation without separation of bonded flanges.

2.2 Material characteristics for a crash stable structural adhesive

Depending on the requirements, the material characteristics have to be measured and benchmarked to support the material selection process as well as to identify the behavior and parameters required for CAE simulations. It should be taken into account that, related to complex stress fields in the adhesive layer, most adhesives act very local. Especially for benchmarking it has to be ensured that the load transfer into the joint is comparable. For the characterization and parameter identification process it is suggested to reduce the substrate influence as much as possible.
In addition to bulk adhesive characteristics examined by tension, compression and shear tests, static as well as dynamic component tests representing the application are the supporting information needed to identify and classify the performance behavior of the material model.

2.2.1 Lap-shear

To characterize an adhesive joint, most often the simple lap shear test is used (DIN 54451). For the material parameter identification the bonded area (overlap) of such a standard test is slightly extended and thick steel substrates are used to minimize rotational influences caused by the substrate deformation. Figure 4 shows the experimental and the simulation results of thick lap shear specimens with different bondline thickness.

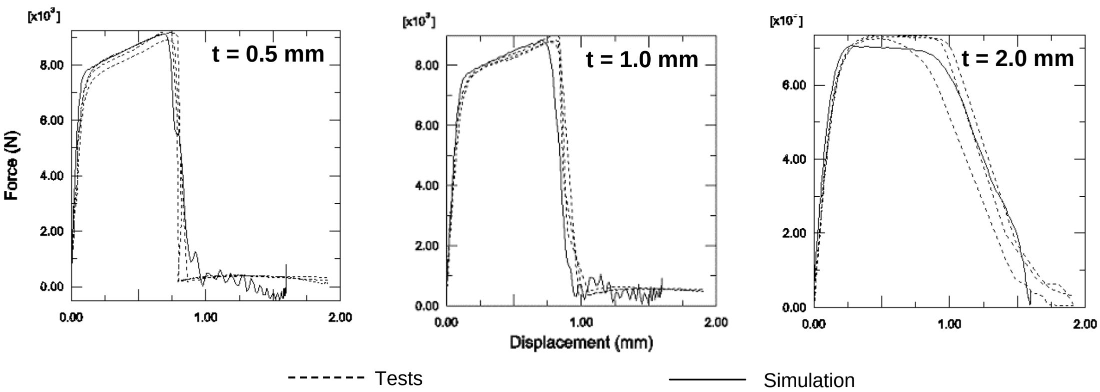

Figure 4: Experimental results for thick lap shear specimen tests of a crash stable adhesive and the simulation response using a detailed Gurson type material model, see Wocke [2], [3].

Comparing the test response with the simulation based on a Gurson material model and a detailed mesh representing the adhesive, the force-deflection behavior can be modeled accurately including the local propagating cohesive failure of the joint.
Changing the specimen geometry and/or the substrate material in a lap-shear test will lead to different shear strength levels due to changes of the local stress field in the bonded region. One has to take care in comparing documented material parameters of different sources, for example comparing the shear strength of an aluminum-steel with a steel-steel lap shear or comparing a bondline thickness of 0.5 mm with a 2.0 mm one.

2.2.2 Impact Peel

Another test, especially to judge the bonding capability under a dynamic loading, is the impact peel test (DIN ISO 11343). As the wedge is impelled dynamically through the two bonded steel substrates, very high local tension stresses occur in the bond - a critical load case for adhesives. Figure 5 sketches the testing setup and the results to evaluate a non-stabilized adhesive with a crash-stabilized one.

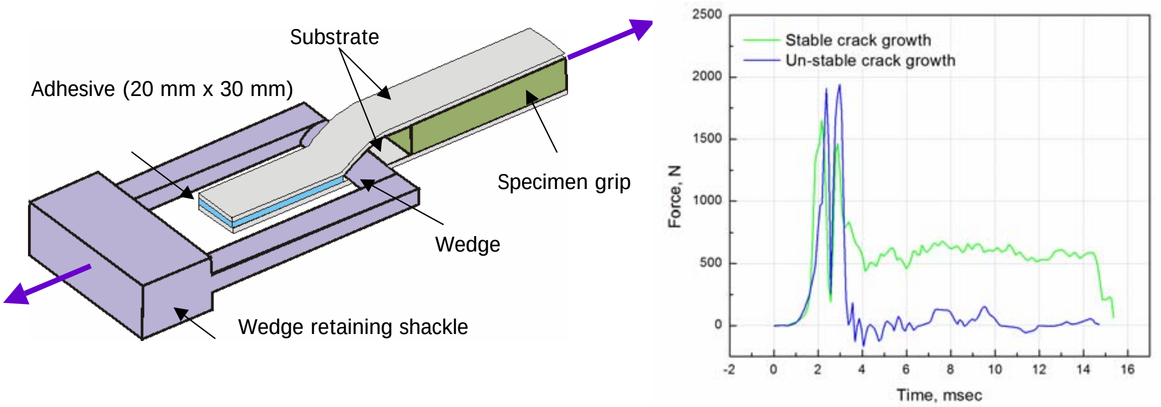

Figure 5: impact peel test and results for a crash stabilized and a non-stabilized adhesive

Evaluating a crash-stabilized adhesive against a non-stabilized one with the impact peel test, it can be easily seen that the crack growth is different. Non-stabilized adhesives fail after crack initiation instantaneously and the substrates separate. For the stabilized adhesive the crack front is more or less close to the wedge front. As the two substrates are still partially bonded, the steel has to deform and more impact energy can be absorbed. Furthermore, by changing the impelling speed, rate dependencies can be observed and a potential rate dependency could be taken into account for the material modeling. Figure 6 is giving a summary of different adhesive types for their impact peel strength depending on the stabilization treatment including the low temperature effects.

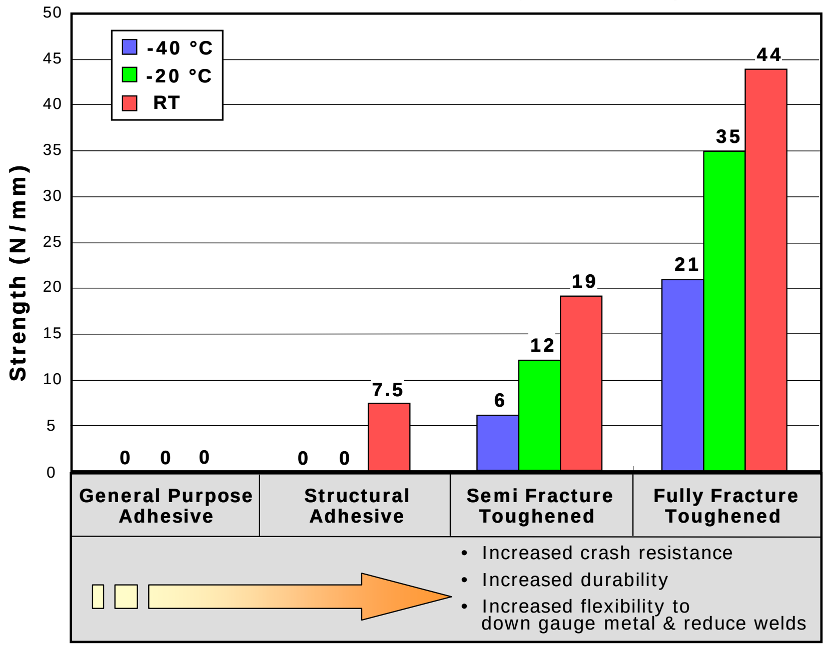

Figure 6: Impact peel strength of different adhesives including low temperature behavior

Regarding dynamic loading on safety relevant structures, general-purpose adhesives will not keep the substrates together. Non-stabilized structural adhesives can withstand a low energy impact, but at lower temperatures their resistance capacity is minimal. Structural-semi crash-stable adhesives could resist medium impact energy levels adequately. For higher impact levels, like they occur in the bonds of components participating in the crash load path, the crash stable adhesives fulfill the needed performance requirements and supporting also lower temperatures.

3 Material model

Screening of the available material models in LS-DYNA by extensive material testing and pre-simulation, the Gurson material model (MAT_GURSON #120) has been chosen to represent DOW Automotive's BETAMATE crash stable adhesives. The Gurson approach includes an acceptable representation of the general elasto-plastic response as well as the feasibility to include the complex damage mechanisms for the crash-stabilized adhesives. In addition, the Gurson approach is implemented in all main explicit FEA-programs, which offer a broad spectrum of usage.
Within the next LS-DYNA 971 releases also strain rate dependency is included. The Gurson flow function in LS-DYNA is defined as follows:

$$\Phi = \frac{\sigma_M^2}{\sigma_Y^2} + 2\, q_1\, f^* \cosh\left(\frac{3\, q_2 \sigma_H}{2\sigma_M}\right) - 1 - \left(q_1\, f^*\right)^2 = 0\,. \qquad (1)$$

Herein σ_M is the equivalent von Mises stress, σ_Y is the yield stress and σ_H is the mean hydrostatic stress, q_1 and q_2 are material constants. The damage behavior is related to the effective void volume fraction f*. Within the void volume fraction update, f_0-the initial void volume fraction, f_C-the critical void volume fraction and f_F-the void volume fraction at total failure control the porosity development. The void nucleation is described by f_N which is the void volume fraction of nucleating particles, ε_N is the mean nucleation strain and σ_N is the standard deviation of the normal distribution of ε_N. The interested reader is referred to the LS-DYNA keyword manual [1]. In addition, Wocke discuss the Gurson approach for DOW structural BETAMATE adhesives in [2], [3].

3.1 Model validation

As shown in Figure 4, the detailed approach (detailed by a fine discretization of the bondline) is representing the material behavior very well also for a varying geometry like the influence of the bondline thickness. For full car crash simulations a detailed mesh representing the bondline isn't acceptable, as the critical time step size would dramatically drop by the small adhesive element as well as by the number of elements used to represent the adhesive.

3.1.1 Macro-element

Focusing a macro-element size of 5 mm x 5 mm x BLT mm representing the adhesive, a full car simulation seems feasible. Nevertheless, the local crack initiation and propagation couldn't be examined like it would be with the detailed approach using macro-elements. The 'big' element is representing a homogenized failure on a large bond area, which also leads to less accuracy.
The material constants needed for the Gurson model have been slightly adjusted to represent the average failure mechanisms for such a larger bond area. Figure 7 is indicating the general approach of such a macro-element setup within LS-DYNA.

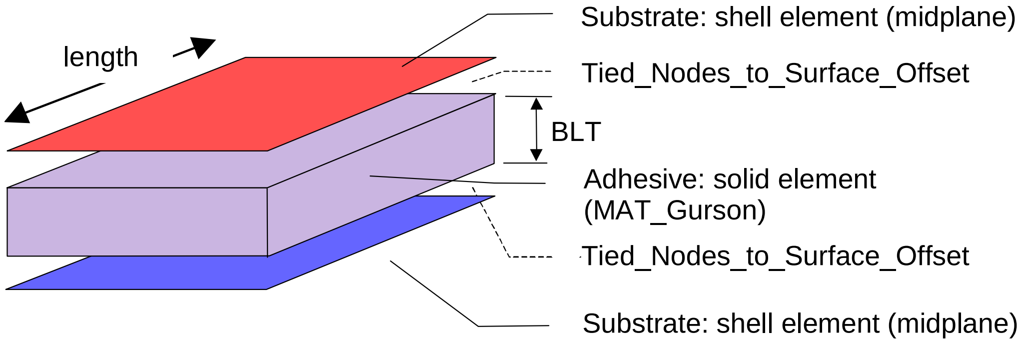

Figure 7: Macro-element approach – Connecting the adhesive representing solid element to the substrate representing mid-plane shells

As the bondline thickness has an influence on the 3D-stress field in the element, the material parameter set for the failure behavior of the Gurson approach is identified for a representative 3D volume. It is suggested to model the macro-element with the real geometrical value associated with the bond line thickness. It is certain that the direct connection of the macro element with the substrate representing mid-plane shell elements would have a positive effect on the calculation time, but such an approach would need a material parameter fit each time a change in substrate thickness takes place. Memhard et al. [4] discussed the mid-plane connection by calibrating the strength and failure parameter from the detailed approach to a replacement approach, however, further studies of this approach will have to be done on sensitivity and accuracy.
Also the macro-element approach need adjustments caused by the adhesive representing volume, but for a bondline thickness below 1 mm the influence is negligible (compare Figure 4), and sensitivity studies show that using the real bondline thickness one material parameter set can be used. Once more, in general the bondline thickness for a structural adhesive is between 0.2 – 0.5 mm.
To connect the adhesive representing element with the (standard) substrate shells, a tied nodes to surface contact with offset is suggested. The shell size of the substrates should be close to the solid contact surface size.

3.1.2 Application validation

As the approach is suggested to be used in real applications, a validation example was chosen to show the suitability of the Gurson material model and the macro-element approach on there potential to represent the structural adhesive. As discussed above, the crash-stabilized adhesive has been developed to establish a joint allowing two metal substrates to deform without separation of bonded flanges.
To validate the failure mechanism, a hat section simply closed-off with a flat steel sheet was chosen. Under high dynamic axial load the profile part starts to fold, whereas the backplate starts to peel-off. In Figure 8 the test setup for the axial crush is sketched.

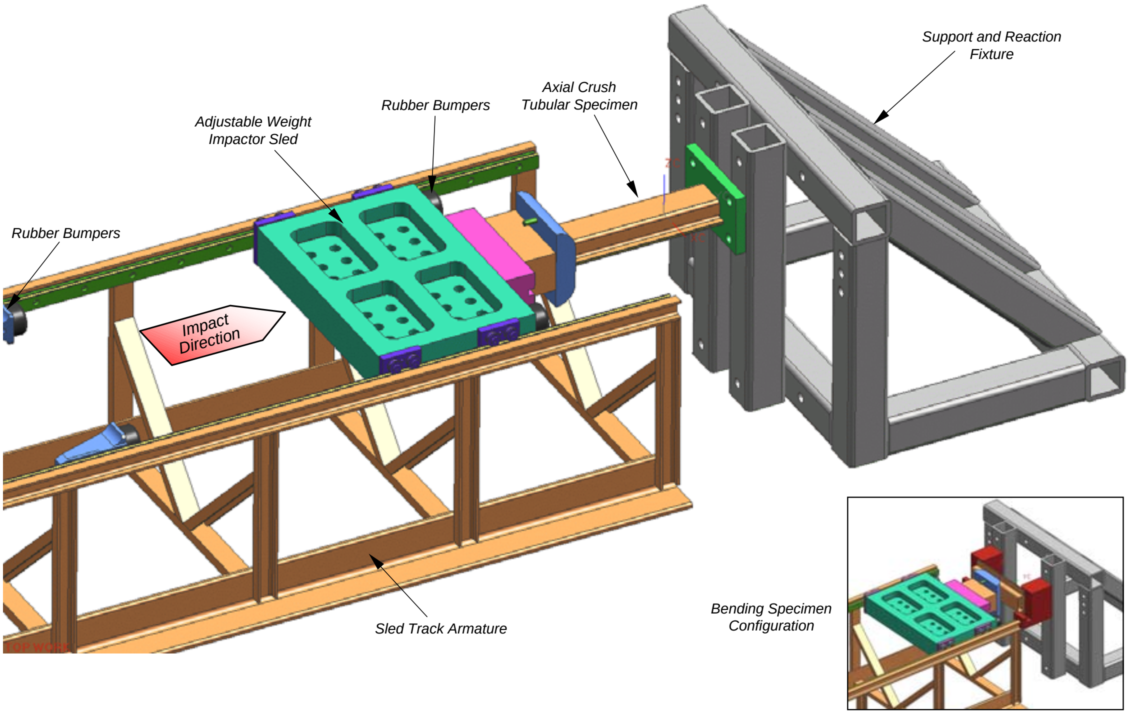

Figure 8: Test setup for the adhesive model application tests for axial crush and for a bending impact (small picture)

A sled with adjustable weight and speed is impacting a specimen mounted on a rigid support. Modifying the specimen support, the specimen could be impacted in a bending mode or, welded perpendicular to a support plate for axial loading. The deformation of the specimen is strongly dominated by the deformation of the steel substrates, only the axial configuration is leading to a cohesive failure of the adhesive, whereas the bending configuration was used to adjust the material model for the steel.
Figure 9 show the force-deflection result of the testing and the simulation of the axial crush test.

Figure 9: Force deflection results for the axial crush of a hat section closed by bonding with a steel plate

By the peel-off, cohesive failure within the adhesive layer occurs. Regarding the force-deflection response, the force level as well as the whole event is predictable within an error range of less than 20%.
The folding process of the profile is dominating the local force transfer to the adhesive elements and thus, controlling their failure. As the steel dominates the force-deflection response, the length of the failed bondline can be used to judge the quality of the Gurson approach with macro-elements. The experimental results show that the crack front stops close to the folds. This was depicted in the CAE simulations as well.
It should be emphasized that the validation example has been selected to verify the computational model at the extremes on its usefulness. A real body structure would be designed and dimensioned to avoid the failure of the adhesive.

3.2 Outlook

The accuracy and suitability of the adhesive modeling with the Gurson approach will be analyzed and discussed with the OEMs and Tiers on full-scale structures. These partners will have to define and provide feedback if the method can be used to get the benefits of modeling structural bonding – like weight optimization, spotweld reduction, etc. – as useable and accurate in the virtual development phase of a car.
Development activities are underway to elaborate a set of parameters needed for other grades of Dow Automotive adhesives including crash stable BETAMATE 1480 adhesive with the Gurson approach.

4 Summary

Discussing the capabilities of adhesives in the virtual development phase of structures participating in the crash energy management, it can be concluded that the accuracy level of a bonded joint should increase. Due to the complex behavior of the adhesive material, especially in crash, not only the prediction of the maximum force but also the failure mechanism including the softening and fracture behavior should be integrated into describing the behavior of such materials.
As numerous adhesives are available, the material model selection for crash simulation is discussed comparing different types of adhesives under static and dynamic loading. Within the material selection process, the benefits for crash-stabilized adhesives are related to the performance expectations and crash requirements. As the structure material is dominating the energy dissipation, the joint should keep the substrates together to get the most out of the energy dissipation from the substrates as well as to keep the structure integrity as long as possible.

To predict this behavior in an appropriate material model, material characterization and testing methods for the parameter identification have been provided. For crash-stabilized BETAMATE adhesives, DOW Automotive suggests to use MAT_Gurson representing the adhesive behavior.
Taking the critical timestep of a detailed discretization into account, a macro-element approach is suggested, to keep calculation times for e.g. full car crash simulations feasible. The representation of such a macro-element is discussed. Results of the methodology are validated with an axial crush test of a hat section profile closed by bonding with a crash-stable adhesive with a flat plate. This setup allows comparing the overall force-deflection (energy) as well as to appraise the quality of the failure model. For this type of component the accuracy of the model is acceptable, whereas for a full car usage the results are under development. DOW Automotive will continue to broaden the material models to the main BETAMATE grades used in crash relevant applications.

5 ACKNOWLEDGMENTS

Special thanks go to Colmar Wocke – DOW Engineering Simulation performing the development of the Gurson approach by using ABAQUS/Explicit as the development code. In addition the author want to thank Matt Turpin – DOW Lead Designer, Mansour Mirdamadi – DOW Global Technology Leader Body Engineered Systems, Scott Burr – DOW Automotive Material Science for their input and the testing work and finally Mustafa Ahmed – DOW Body engineered systems for the sensitivity studies.

6 Literatur

[1] Hallquist, J. et al.: LS-DYNA Keyword User’s Manual, Version 970, LSTC, April 2003, Livermore, USA

[2] Wocke, C. P.: Modeling Failure in a Modern, Toughened Epoxy Adhesive using Abaqus/EXPLICIT ,2004 Abaqus User’s Conference, May 2004, Boston, USA.

[3] Wocke, C. P.: Berechnung und Simulation crashstabiler Strukturklebstoffe, Adhäsion 3.06, Vieweg, 2006, p. 14-18

[4] Memhard, D. et al.: Entwicklung und Anwendung von Ersatzmodellen für die Modellierung von Klebverbindungen unter Crashbelastung, 4. LS-DYNA Anwenderforum, Bamberg, Germany 2005 – Crash I-Spotweld/Bonding, p. B-I-29