Implementation and simulation of local reinforcements of profile applications with changing cross sections

Implementierung und Simulation von lokalen Verstärkungen in Profilbauteilen mit veränderlichem Querschnitt

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Abstract:

The development of a vehicle structure is currently dominated by the concept of “light-weighting” driven by both fuel efficiency (Carbon dioxide emissions) and weight/cost reduction. To this end there is a strong desire for the utilization of material mix within the BIW structure (high- and highest strength-steels, aluminum and plastics). The related challenge is forming and joining these different substrates to build the most effective application including the use of reinforcements in critical areas.

The local reinforcement based on structural foam systems has become one of the main contenders for the optimization of the classical metal solution. The key driver behind this concept is the improved weight/performance ratio targeting buckling and folding prevention of thin pillar cross sections and profiles resulting in a more enhanced and efficient energy absorption system. Such benefits can directly translate into potential weight savings as the foam is only used in a local pillar area allowing the steel to efficiently sustain the loads and prevent buckling of the section without the need of unnecessary reinforcements or increased thickness.

Structural foam reinforcements and their effects can be analyzed effectively by the finite element method. Computer Aided Engineering (CAE) tools virtually allows the optimize use of materials and designs before building costly prototypes. To understand the predictability and accuracy of these simulations a verification and validation of the material model approach is clearly advantageous. In this study a closed section profile with and without structural foam is used to correlate the simulation with the corresponding dynamic 3-point bending test.

An example with an in-situ placement of structural foam reinforcement has been extended in the innovative application concept based on a T^3-Tube with variable cross sections by ThyssenKrupp Steel targeting a B-pillar profile. A side impact crash study will show the potential of such a T^3-Tube combined with the structural foam reinforcement.

Keywords:
Structural foam, B-Pillar application, reinforcements, high strength steel

1 Introduction

Safety performance, superior design features, good ride and handling characteristics, acoustic comfort and light weight vehicles are common trends and customer demands. All of these requirements need to be addressed by the body-in-white design and system engineering teams. The development and application of advanced CAE tools for new substrates and joining techniques have allowed these trends to be addressed by the following approaches:

1) "Material mix" in the body structure, such as high and ultra high strength steel grades in specific areas like B-Pillars or chassis rails.
2) The conceptual light weight design such as tailored rolled or welded blanks (B-pillar inner structures and closures).
3) Hydro formed structures (engine cradles or other chassis components).

The application of structural Polyurethane foam reinforcement within the above mentioned fields is highlighted in this report. Its effective deployment can lead to replacement of traditional metal reinforcements or improving the performance of an existing design while minimizing the vehicle mass and reduce the impact on overall program timing. Based on finite element simulation, the improvement in both buckling prevention and its influence on the load path need to be studied in detail. Thus, the proper foam selection with optimum mass can be engineered to deliver the optimal weight efficient solution. An indicative example of the potential of structural foam use in enhancing the capability within a BIW structure is shown for the Ford Taurus model in Figure 1.

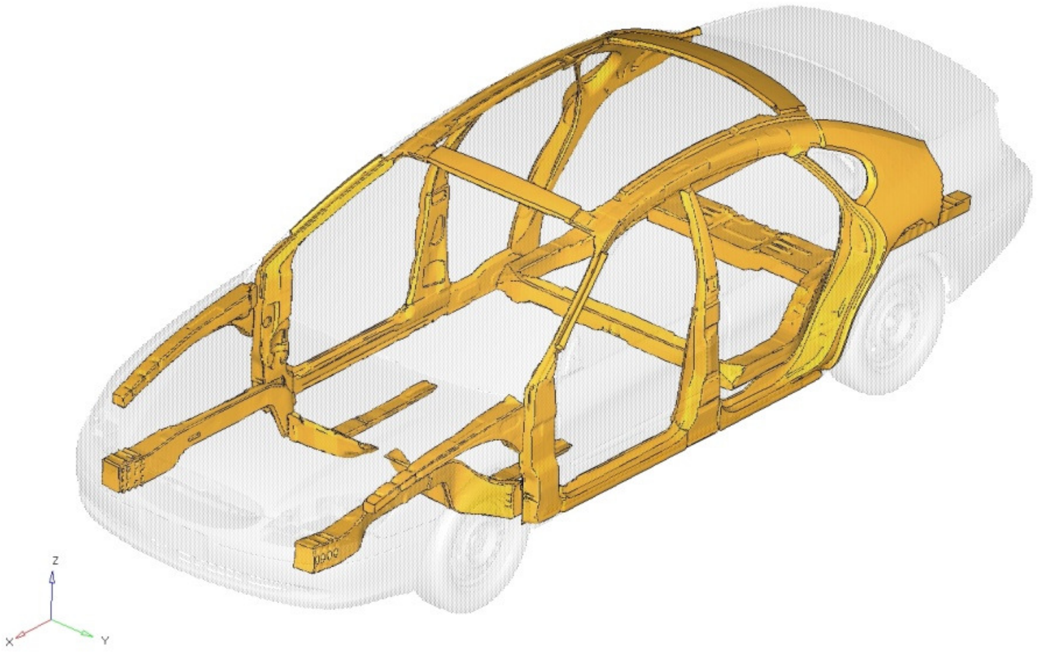

Figure 1: Foam filled cavities in the BIW of the NCAC Ford Taurus model [1]

Structural foam with a density of 400 g/l is modeled in all possible application locations in the Ford Taurus vehicle. This treatment has to be seen as artificial and should be used only for orientation of potential application areas based on the geometry which would allow a reasonable filling with such foam. The foam treatment is modeled in such a way to allow design of experiments (DOE) to be used to properly optimize the minimum amount and location of the foam for frontal and side impact crashworthiness as well as body stiffness analysis.

The approach to the application of structural foams to vehicle body design can be thought of as delivering scalable solutions. "Scale-Ability" may be summarized by the idea to have only one single/downgraded body platform and use bulk foams to scale performance needs for different vehicle derivates. In addition, bulk foams do also offer some flexibility when design changes need to be incorporated during the development – the bulk foam will fill any cavity shape and contour.

2 Material modeling

To achieve a good correlation and prediction of the mechanical behavior with numerical tools, it is necessary that for each specific load case, the geometry, the individual material descriptions and the joining concepts are correctly represented. It is essential that the material models capture the proper physical representation of the material behavior under loads. These models should be as accurate as possible without adversely affecting the overall computation time of full vehicle CAE models. In this section the material modeling of the examined materials will be discussed.

2.1 BETAFOAM™ 89100/89124R structural foam

BETAFOAM™ Structural Cavity-Filling Foam is a bulk applied Polyurethane foam designed to locally reinforce car body cavities that may bend and buckle under static and dynamic loads.

2.1.1 Working principle

The general working principle of such a foam system is shown in Figure 2. An untreated hollow beam would show local buckling effects in the applied loading area subjecting the beam to bending. The structural foam reinforcement improves the buckling resistance and allows better load transfer and energy absorption of the metal structure.

Figure 2: Buckling prevention, adhesion and failure mechanism of structural BETAFOAM™

Adhesion to the metal tube structure by the structural foam is a key attribute for its performance. The foam has significant strength to stabilize the hollow section and uniformly transfers the load from the applied location to the free ends of the beam with minimal variation of the beam sectional stiffness properties. The spread of this load allows steel material the opposite face to yield more effectively as compared to the untreated hollow beam. Within the discussed foam model this effect can only be taken into account by homogenization of the overall global material response.

2.1.2 Foam data

Two components are used to produce a high-density, carbon dioxide blown closed-cell rigid polyurethane foam, BETAFOAM™ 89100/89124R. These components were engineered to produce a 24 pcf (384 kg /m3) foam for increasing stiffness of body structure cavities. Foam is produced by the rapid impingement mixing of two components under high shear conditions. The foam has adhesion to primed (electro-coated) metal surfaces.

Structural BETAFOAM™ products range in density from approximately 200 to 600 g/l. The combined components cure within seconds at room temperatures to form a rigid, closed cell foam. Water absorption values of cured foam are well within typical ranges for synthetic materials (<2%). The reaction time is designed to secure short shot cycles. A designed physical “frothing” of the applied foam avoids uncontrolled leaking through openings and weld flanges. Exothermic release has also been engineered to be lower than normal heat generation compared to standard Polyurethane foams. The foam should be applied on coated structures to secure proper corrosion protection and good foam/substrate adhesion as already indicated by Figure 2.

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2.1.3 Processabilty and assembly

BETAFOAM™ can be applied using standard Polyurethane Reaction Injection Molding (RIM) dosing machines (Figure 3). These are well known from a number of automotive applications such as seat cushions, door liners, instrument panels, acoustic foams, body panels and run-flat tire inserts. The overall mixing system is computer controlled including weekend and service programs and data for individual shots can be easily integrated and tracked. Important process parameters are controlled and triggered for quality control and documentation. The movement of the mix head can be automated using standard robots and manipulators. The correct material placement can be confirmed for example by infrared detection of the exothermic reaction.

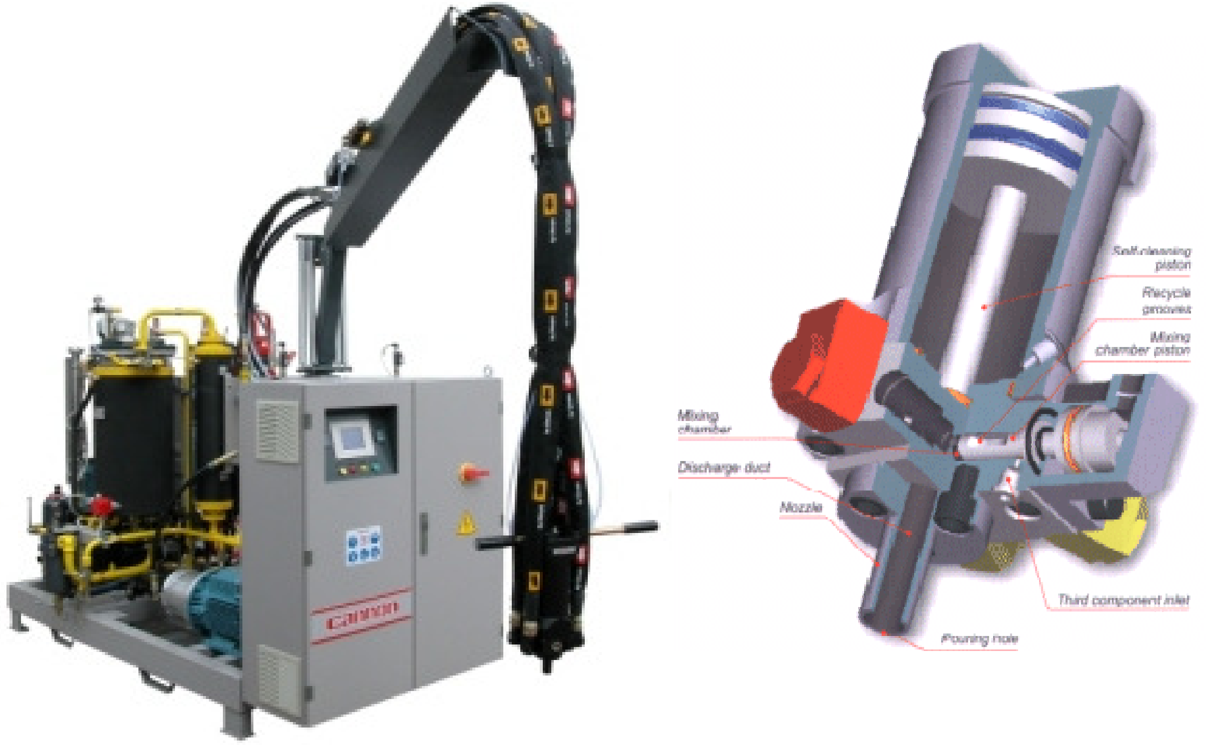

Figure 3: Standard Polyurethane dosing unit and scheme of a mix head

Applying structural foams in body structures involves slight process modifications in the car line compared to conventional reinforcement inserts:

- Typical shot weight varies between 200 - 1800 g
- The machine size depends on the shot weight / shot volume
- The foam is applied "into" cavities through an injection hole – the diameter varies between 20 - 30 mm
- Injection holes can be sealed using rubber plugs
- The foam should be applied "post-paint" and before a waxing where applicable
- Quality systems to check on shot matrix and foam location should be incorporated

2.2 Structural foam model

Practical CAE design optimization tools are valuable for design engineers to develop and validate a light weight efficient design. The design engineer can modify the geometry and material towards achieving vehicle program objectives. The reliability of this approach in many instances is contingent on having adequate validation of CAE assumptions with physical tests. To make this process more efficient, an accurate response of the virtual assembly under load, based on the material models used,

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need to be verified and validated. The approaches for BETAFOAM™ Structural Cavity-Filling Foam will be discussed in the following sections.

2.2.1 BETAFOAM™ model development

To quantify the typical foam behavior compression- and shear tests are performed on small samples; see Figure 4 and *Allan et al.* [2] and *Bilotto et al.* [3].

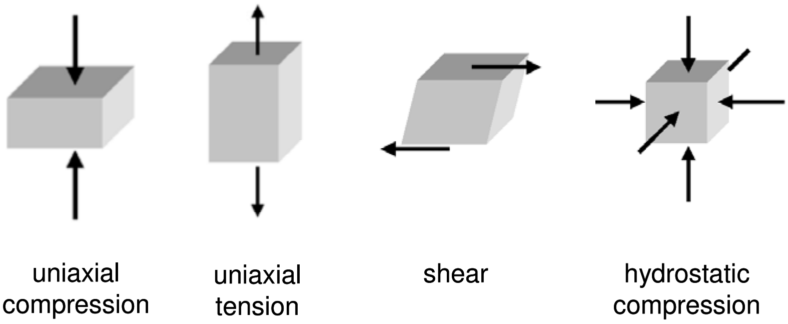

Figure 4: Standard testing for foam behavior characterization

The compression test is by far the most representative attribute. Tensile and shear tests are difficult in terms of sample preparation but may provide useful information about the failure behavior of the foam. Multi-axial tests in bi- or tri-axial-tests-cells, for example for hydrostatic compression, are even more complex to perform and therefore are most often neglected.

2.2.2 Foam Model Verification

As a result of these tests, load specific material responses are recorded as force-deflection pairs. These can be transformed into stress-strain data which in turn can be used for the material law and parameter identification. Baseline verification is used to correlate the test responses with the corresponding simulation results, see Figure 5 for LS-DYNA.

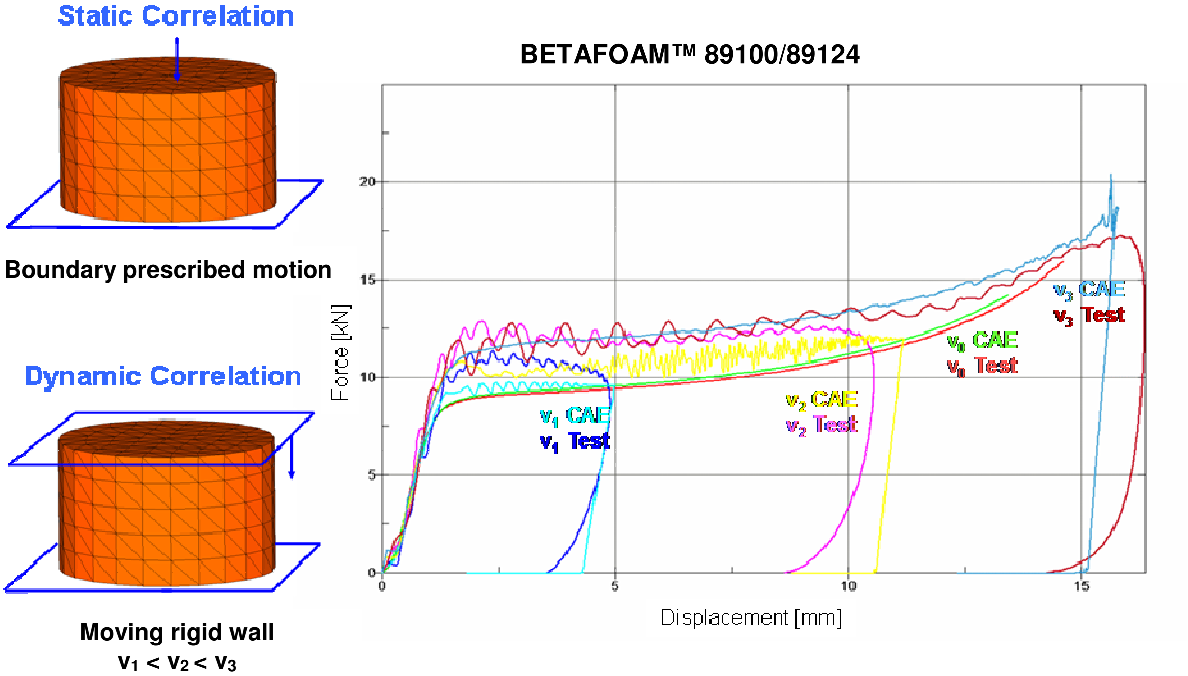

Figure 5: Model verification

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Depending on the finite element solver utilized, different material model approaches exist to describe the mechanical foam behavior. For structural BETAFOAM™ in almost all of the commercial available solvers the above information can be used to identify and select an accurate model.

2.3 Foam and steel model validation

As shown in the verification section the selected model correlates well under its main load case of compression for both static and certain dynamic conditions. However, in a real structure, a three dimensional stress state exists compared to such an 'ideal' compression state and this need to be described to an equivalent accuracy.

2.3.1 3-pt bending head section profile wo foam

Therefore a representative application test has been used to study the model response and evaluate the accuracy in such an environment. A profiled tube was used in a three-point bending test to show the effects of reinforcing cavities with BETAFOAM™ Structural Cavity-Filling Foam, as well as to show the predictive accuracy for the material model within a "real" case.

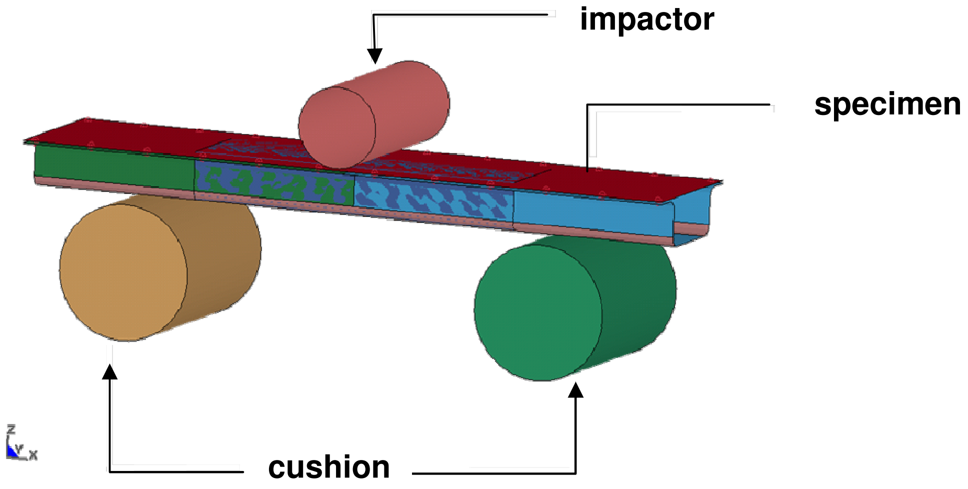

Figure 6: Three-point bending test configuration

For the validation, a hat section profile is closed by a spot-welded lock plate with dimensions of 60 x 30 x 400 mm, has been dynamically loaded with a cylindrical impactor, see Figure 6. The distance of the cylindrical supports is 250 mm. The impactor mass is 59 kg. The hat profile including the closing plate is made from HX 340 LAD steel with a sheet thickness of 1.58 mm.

This test focuses the stiffening effect of BEATFOAM™ in the cross section and the influence of the cavity treatment for the load bearing capacity. In addition, the compressibility of the foam is under examination to prevent a local failure of the steel. The foamed specimens have been reinforced in the center area in a length of 200 mm.

Within the first test series the baseline response of the HX 340 LAD has been measured to evaluate the model accuracy of the simulation without any foam treatment. The initial stress state as the result of forming history was not taken into account in the simulations. The test specimen has been manufactured by edge bending. In doing so, in the area of the bending radii the material thickness is slightly smaller than the average.

The result of the untreated foam profile shows a good correlation between simulation and experiment for the force peak, see Figure 7. The falling distance of the impactor was 1.30 m.

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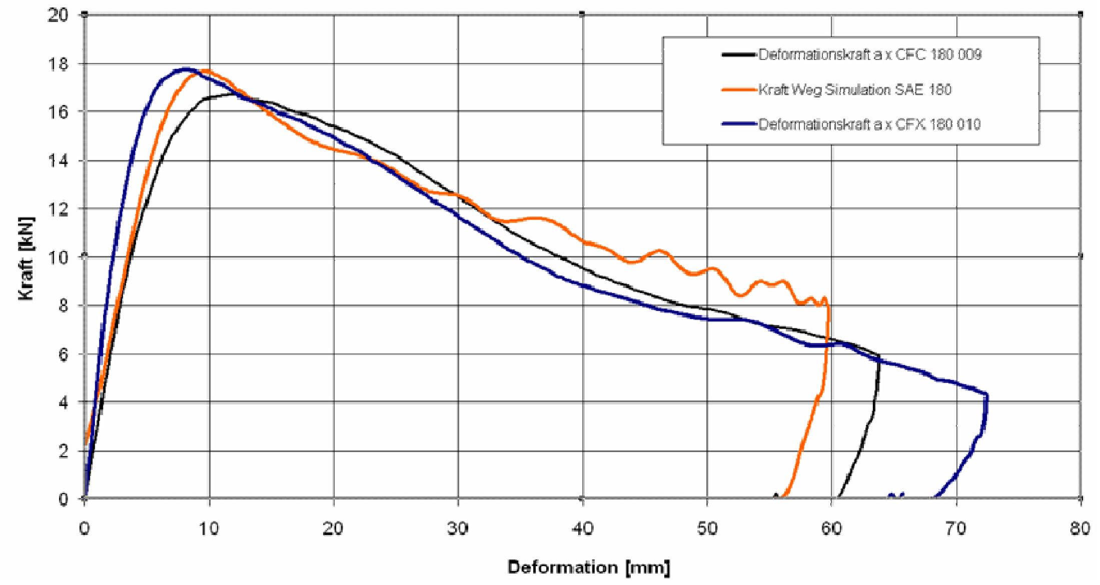

Figure 7: Force-deflection of the empty profile (1.30 m)

At the end of the force-deflection the simulation shows a slightly different behavior resulting in over-predicting the force level and under-predicting the deformation distance by approximately 13%. This is an acceptable value in regards of the missing manufacturing history details for the simulation model.

In the second test series the foamed specimens are examined under different impact speeds by varying the falling distance of the impactor as the height of 1.30 m did not show any significant deformation. Targeting a deformation behavior alike the empty profile a drop height of 2.00 m has been selected. This change of the kinetic energy was necessary to capture a significant plasticity behavior for the model correlation as shown in Figure 8.

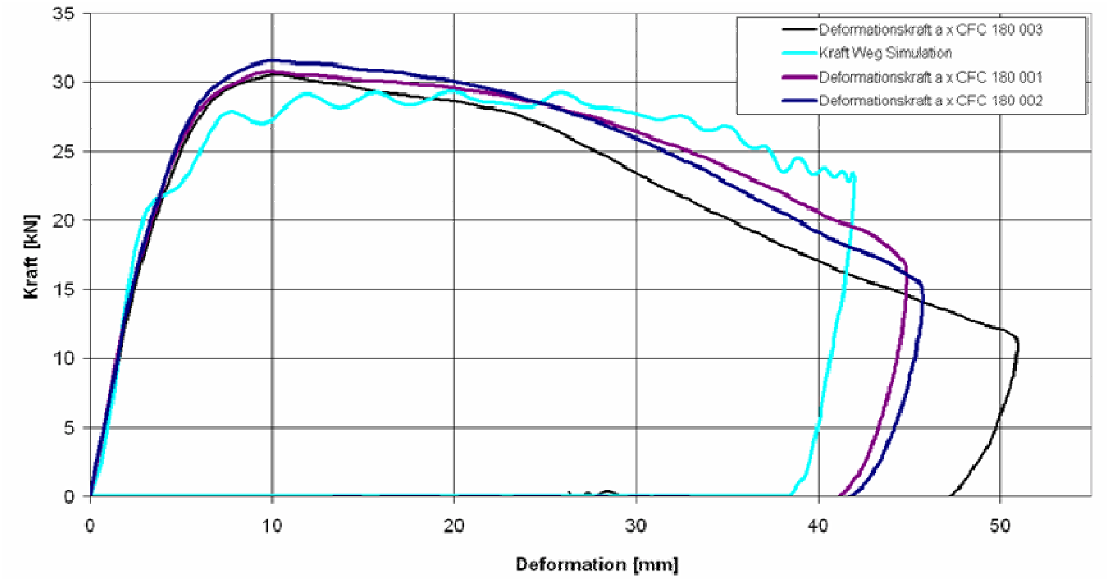

Figure 8: Force-deflection of the foamed profile (2.00 m)

Based on the simulation of the empty profile the focus was the validation of the application including the foam model. By correlation of the force-deflection behavior of the simulation and the test response, it can be seen that the first force peak in the simulation is reduced by approximately 6% and the overall deformation magnitude is under-predicted by 11%.

Based on these correlations of the energy absorption of the steel and the foam material it has been calculated that a 1.75 mm thick profile without foam would achieve the same force level as a foamed 1.35 mm thick profile using the same kinetic energy. Including the foam, a benefit of 20% weight saving potential has been calculated for equal performance.

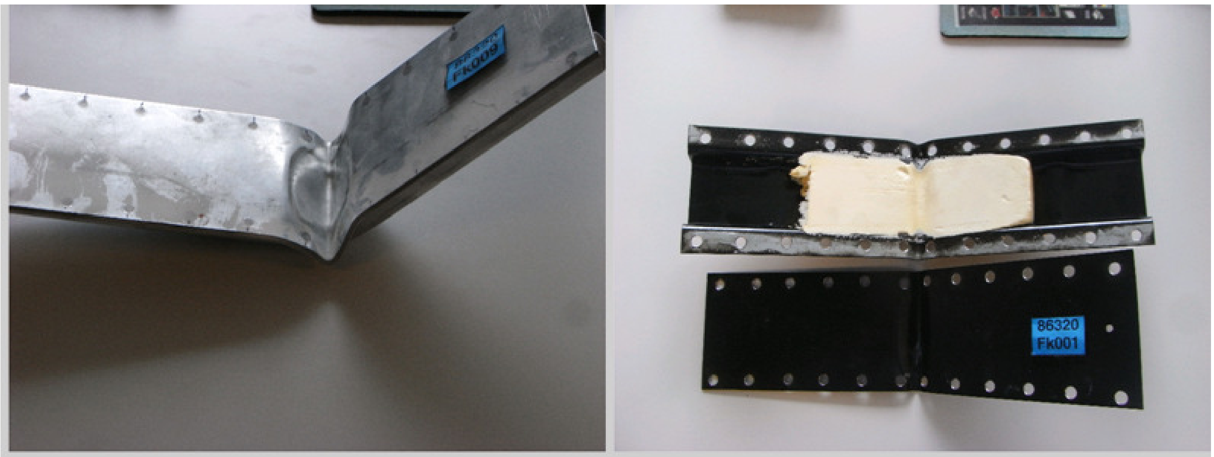

Figure 9: Deformation of the empty (FK009) and foamed profile (FK001)

In Figure 9, the hat profile and the closing plate without foam is shown left and the deformed part with the foam core is shown right.

3 IIHS side impact improvement with BETAFOAM

As occupant protection in frontal crashes improves, the relative importance of protection in side impacts has increased simultaneously. Related to the BIW design structural foams will allow further improving and optimization in the safety behavior of vehicles in such side impacts.

3.1 InCar B-Pillar concept

The idea of weight reduction in a vehicle made in conventional shell construction by using an optimized profile in the B-pillar section has been discussed with different OEMs. For the assembly of the profile the T³-technology [4] has been used. Outlined, in the T³ method a metal sheet will be formed by a multi-stage procedure and stamped on a supporting core as sketched in Figure 10.

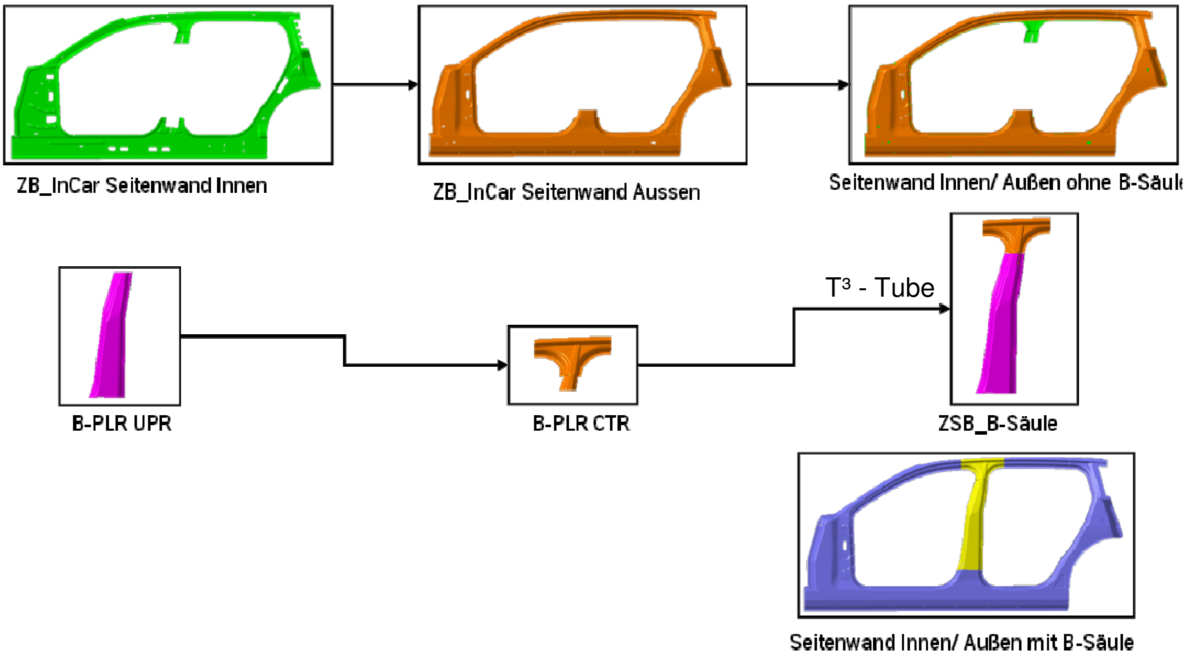

Figure 10: Assembly sequence – inner and outer side part

In summary, for the T^3-B-pillar tube, the original B-pillar section is cut out of the inner and outer side parts, leaving the rocker and roof T-joints for the assembly in place. In a second operation, an optimized B-Pillar T^3-tube is manufactured and then assembled on the connection parts by laser-welding. The bulk foam reinforcement would be applied after full assembly of the side part, after paint before wax.

The concept for achieving the challenges like performance, sealing concepts, assembly and the three-dimensional manufacturing of the B-pillar profile and weight targets for this application type will be shown using the InCar project [5].

Regarding the study of the three point bending correlation and the down-gauging potential, the combination of the T^3-technology together with the structural BETAFOAM™ reinforcement has been examined.

3.1.1 *Model Setup*

Based on the profile simulation and the correlation with the experiments of the real closed hat section profile, the InCar simulation model has been modified in the B-pillar section accordingly. A T^3-tube has been applied between the rocker and the roof rail. This tube has been locally reinforced with the location optimized BETAFOAM™ structural foam as illustrated in Figure 11 in the middle to upper B-pillar section. The testing conditions have been selected according to the IIHS side impact crash loadcase.

By substitution of the conventional shell construction with the T^3-tube not only design changes but in addition the assemblies, feasibility, sealing concepts etc. have also been addressed.

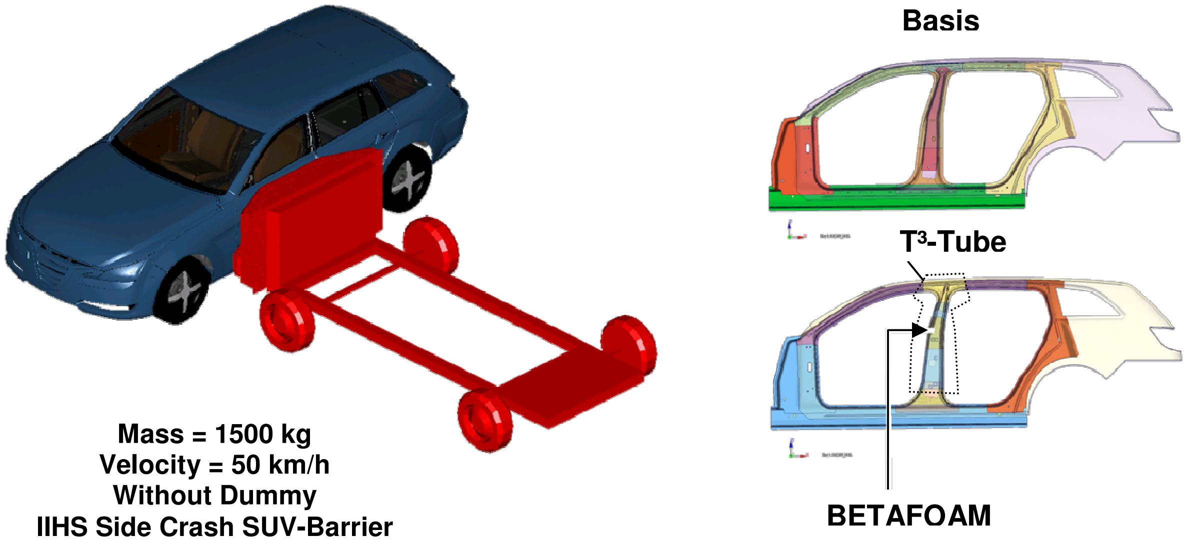

Figure 11: IIHS side impact – Conventional vs. foamed T^3-tube

These concepts are examined for the IIHS side impact loadcase as shown diagrammatically in the left of Figure 11. In the top-right section of Figure 11 the conventional base-structure is shown, while in the bottom-right a schematic of the foamed T^3-tube is given.

3.1.2 *Results*

Figure 12 shows the intrusion into the passenger compartment during side impact crash. In the top pictures, the baseline behavior is shown whereas in the bottom portion of Figure 12, the foamed T^3-tube response is captured. In general it can be seen that for both approaches a similar intrusion profile has been achieved.

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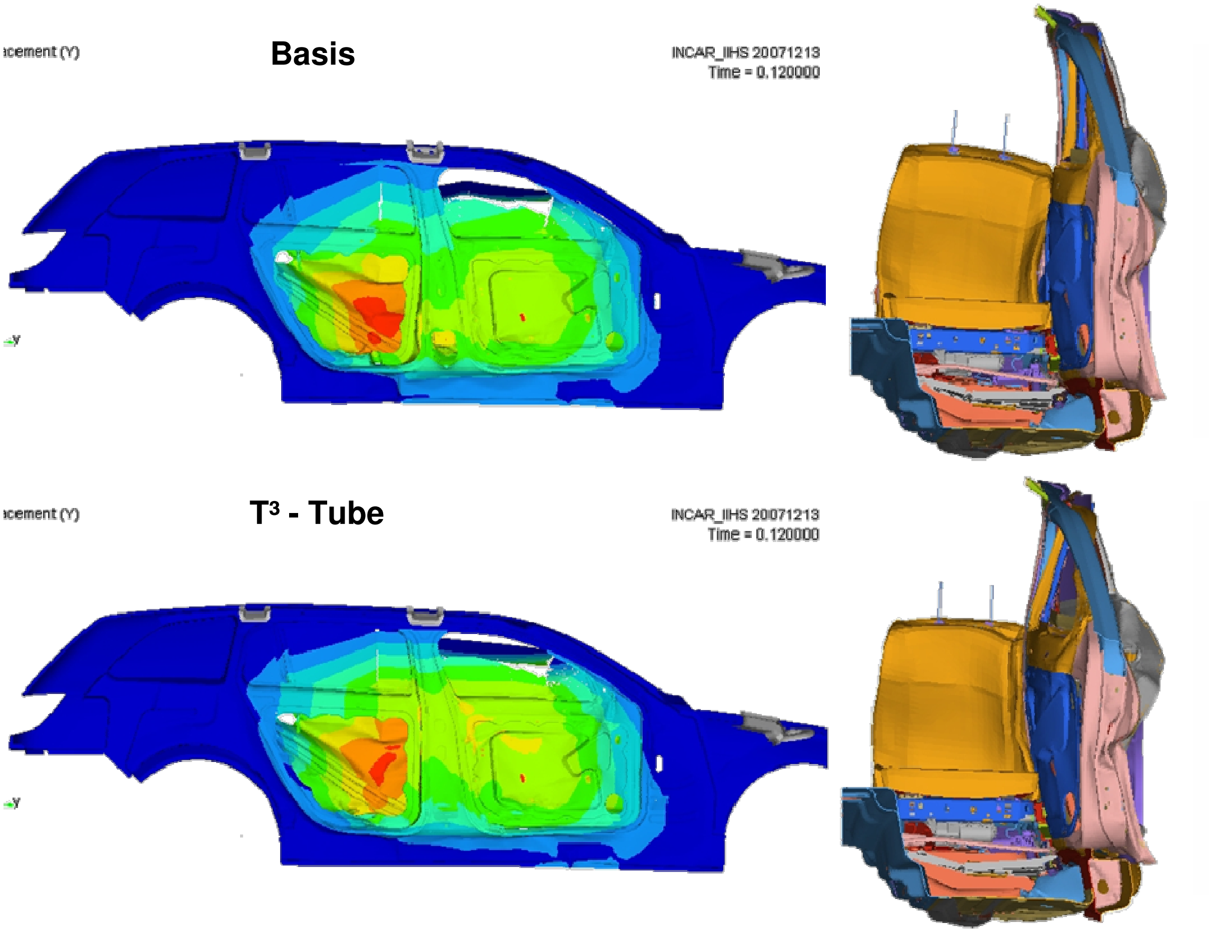

Figure 12: Comparison of the Intrusion - Conventional vs. T³ - Tube

It can be concluded via the simulation of the BETAFOAM™ reinforced T³-tube B-pillar that the crash requirements are met and that by combination of the conventional shell construction with local optimized profile structures in the B-Pillar section, a weight reduction of 15% would be possible.

4. SUMMARY AND OUTLOOK

Lightweight constructions are dominating the modern process for vehicle development. This is driven by desire for reduce fuel consumption and CO_2 emission. With this in mind the optimization of local reinforcements was discussed based on structural foam concepts. The introduction of the application of BETAFOAM™ technology, the associated manufacturing process, the material data and the material model for CAE usage has been provided and the model verification demonstrated.

By a three point bending of a spot-welded closed hat section profile made of HX 340 LAD steel the steel material and the foam material card has been validated. Using this validation example a weight saving potential for such profiles has been estimated by down-gauging the steel sheet thickness. The simulation accuracy is in a range of approximately 10% error relative to the test responses. This is related to the force peak prediction and the deformation depth of the dynamic three point bending.

Based on this, the material cards have been used to study the structural foam concept in combination with the T³-tube method. This T³-tube method has been introduced and examined by the replacement of a conventional B-pillar structure based on the InCar vehicle. An IIHS side impact scenario was used to further negotiate the performance of the foam reinforced tube but as well to analyze for example the

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overall feasibility, assembly and sealing concepts. In the side impact loadcase a comparable intrusion profile has been achieved. By this, a weight saving of 15% for the B-pillar section could be achieved.

Actually the verification of the 1.75 mm thick empty profile and the 1.35 mm thick foamed profile are in progress. A 20% weight saving by the combination of steel profiles with BETAFOAM™ is expected and would further develop the lightweight construction development.

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