Crash Performance Increase with Structural BETAFOAM™

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Abstract:

The choice of the right material and joining technique in the modern BIW-Design is driven by several factors. The international competition between the OEM's, new legislations concerning crash-requirements and the current development of fuel prices and the related customer interest in lower gas-consuming cars are just a few to be named. Even if we see from representatives from almost every material category – the full steel car body is still dominating. What has remarkably changed here is the move towards high- and highest-strength steel and "bake hardening"-grades.

A stiff and homogeneous body is the baseline for a car with excellent driving behavior and pleasant acoustical performance. The BIW-Designer is combining the following principles to meet flexural and torsion stiffness requirements:

- Build longitudinal and cross-car beams and useful profiles
- The use of high-strength steel grades and/or "Tailored Blanks"
- Optimization of joining technologies
- Avoid structural weak spots like hinges and profile constrictions
- Local reinforcements of surfaces and profiles

In addition, there is also the need to have an optimal performance of the body under the various load cases during a full car crash: Useful energy conversion in the profiles and rails while retaining the passenger compartment integrity. These design goals need also to be aligned with light-weight criteria. Future requirements concerning crash-performance and light weight needs will increase the demand for new materials and joining technologies. This article will discuss the opportunities to fulfill these requirements using polyurethane-foam based local reinforcements.

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1 Solutions for local body reinforcements

The idea to improve the car body stiffness and crash performance using local reinforcements is not new. In some cases, the need for such reinforcements is discovered quite late in the development process of a new platform. Going the “standard” way on modifying the material and or dimension of the identified weak structure is not always possible in that design stage. For a few years, the BIW designer has had the possibility of choosing solutions based on thermoplastic- and thermoset-materials so systems do offer advantages compared to standard solutions in terms of cost, weight and performance. Typical reinforcement areas in a BIW are shown in Figure 1.

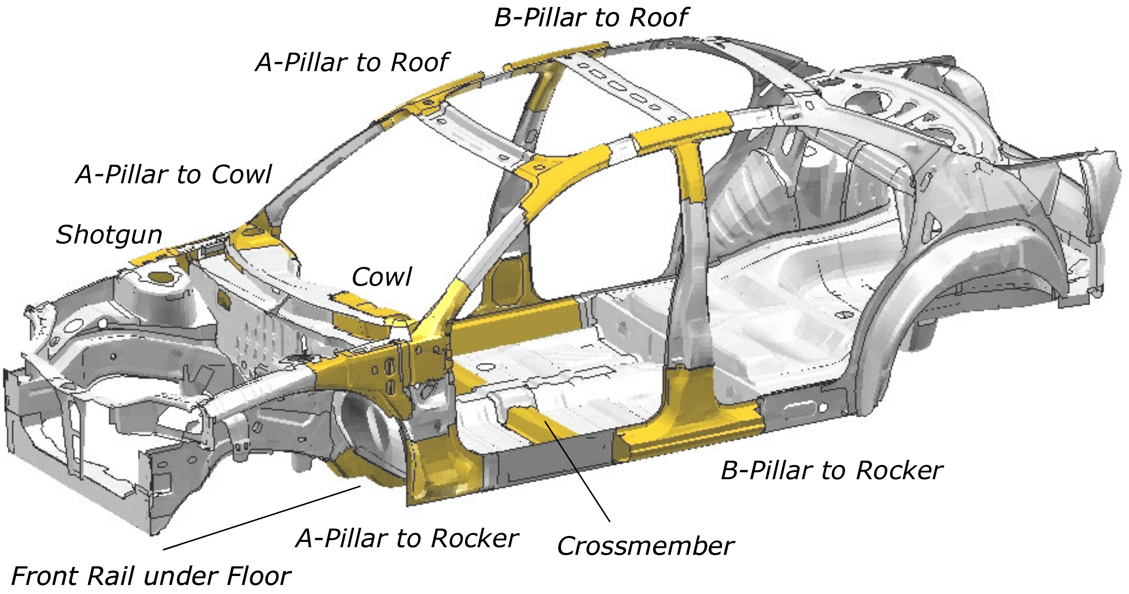

Figure 1: Application areas for structural foam

The whole potential of such a system can only be realized when it is designed early in the development process. Providing useful computational models and a deep material expertise is enabling the OEM to do so.

1.1 Reinforce with bulk Polyurethane-foams

Two-component polyurethane-foams are in use for a large number of applications in the automotive industry, e.g. seat cushions. Normally the raw-material PU is processed at tiers via molding tools to produce foamed parts. The part development and the production process itself are state-of the art. But the bulk PU-Foam can also be injected into body cavities. The applied foam will expand and cure in the cavity – based on the system reactivity it all takes place in a few seconds. Cost intensive molding tools are not needed – also the system is friendly when it comes to design changes for the reinforced section. Based on the density of the foam system and the shot-weight the designer can precisely improve the car performance in terms of stiffness, crash-resistance and also acoustic. Based on the density, DOW Automotive is grouping the PU-Foam offering in three performance categories:

- 32 g/l: Acoustic-foam
- 80 g/l - 288 g/l: Stiffness and NVH applications
- 288 g/l - 641 g/l: Improve crash- and energy-management

In order to gain maximum adhesion between the foam surface and the substrate material, it is recommended applying the foam on painted or E-coated surfaces. The incorporation of a foam station after the paint process is recommended at the OEM plant. The application to E-Coated sub-systems at a Tier is also a possible scenario. The adhesion on anti corrosion waxes has to be treated as unfavorable and therefore need to be de-considered in the planning process.

1.2 Application technologies for BETAFOAM™ bulk systems

BETAFOAM™ is a family of two-component polyurethane foam systems, with an A-component based on an MDI-Polymer or an isocyanate-prepolymer. The B-Component is a polyol-blend or a water/amine catalyst mixture. New formulations are able to significantly reduce the content of free "MDI" during the processing step that may reduce the need for ventilation systems, see also *Allan et al.* [2]. The predominant numbers of foam systems are low viscosity types that can be applied with high throughput rates. Due to the high reactivity of the system the foam expands and cures within seconds – the treatment of vertical locations is also possible.

The needed plant space and the expected investment do rely on a number of factors:

- Intended vehicle production volumes
- Number of local reinforcements and shot weights
- Type of application or foam system (acoustic-, stiffness- or crash-foams)
- Degree of automation
- Needed ventilation systems
- Process – and quality-control

This also points out that the process equipment and plant layout has to be taken into account early in the planning phase. Relative to flexible manufacturing already installed, foam stations can be carried over and adjusted for new platforms. There are various possibilities in terms of process- and quality control. An easy one is to check the location of the applied foam via sight holes or the possibility to locate the foam via an infrared scan due to the exothermic curing reaction of the foam. It is also strongly recommended to continuously having the process parameters of the machine protocol (Temperature, Pressure etc.) checked.

2 BETAFOAM™ in simulation processes

The correct representation of the foam material is a central point in the pre-development stage. Simulation tools like FEA are used in almost every case during that phase. A good accuracy between calculation and the real parts behavior implies also a good description of the boundary conditions. In the following, all BETAFOAM™ model data is related to fully cured foam.

2.1 BETAFOAM™ model development

To identify the foam behavior normally compression- and shear tests are performed on small samples, see Figure 2 and also *Allan et al.* [2] and *Bilotto et al.* [3]. Tensile tests are difficult in terms of sample preparation but may supply useful information about the failure behavior. Multi-axial tests in Bi- or Tri-axial-tests-cells, for example for hydrostatic compression, are even more complex to perform but can meaningful round of the tests setup.

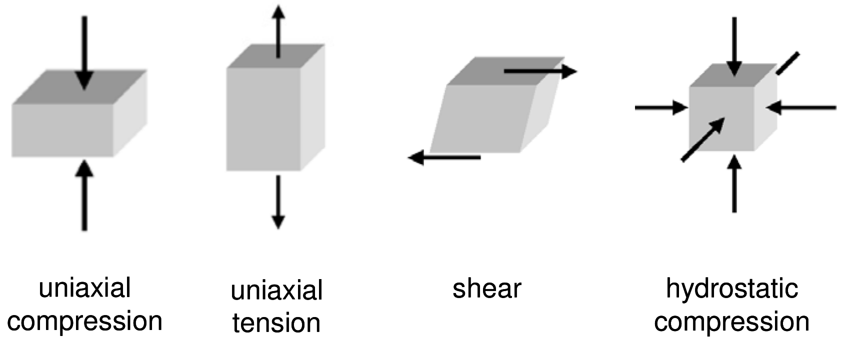

Figure 2: Standard foam testing

It is possible to perform static and dynamic tests in compression, ideal shear and tension mode. Due to the polymeric nature of polyurethane foam systems temperature behavior may also be of interest. Main goal is surely to identify the generic material behavior: elastic, viscous-elastic, elastic-plastic, etc. and find a fitting material model within the simulation program. If a suitable material model is available the performed tests can be used to identify the material card parameters. Validation tests are needed to judge the accuracy of the procedure.

2.2 Identification and Verification of the BETAFOAM^{TM} material model

In the following chapters BETAFOAM™ 89100/89124 with a density of 384 g/l is used as an example to validate the FEA calculation accuracy. For the structural foam, the material behavior is mainly driven by static or dynamic compressive loading. Brick and cylindrical shaped specimens have been used to evaluate the material behavior and parameter sets for the LS-DYNA MAT#163 – MAT_MODIFIED_CRUSHABLE_FOAM material card. This material model is dedicated to model crushable foam with optional damping and tension cutoff. The unloading is fully elastic and tension is treated as elastic-perfectly plastic at the tension cutoff value. The model includes strain rate effects. Next to the standard elastic parameters, like Young's modulus and Poisson's ratio, the yield stress versus volumetric strain at different strain rates have to be entered via tabulated input. These curves are directly related to the compression test curves and have to be only slightly fitted. Figure 3 shows the correlation between static and dynamic specimen testing and simulation.

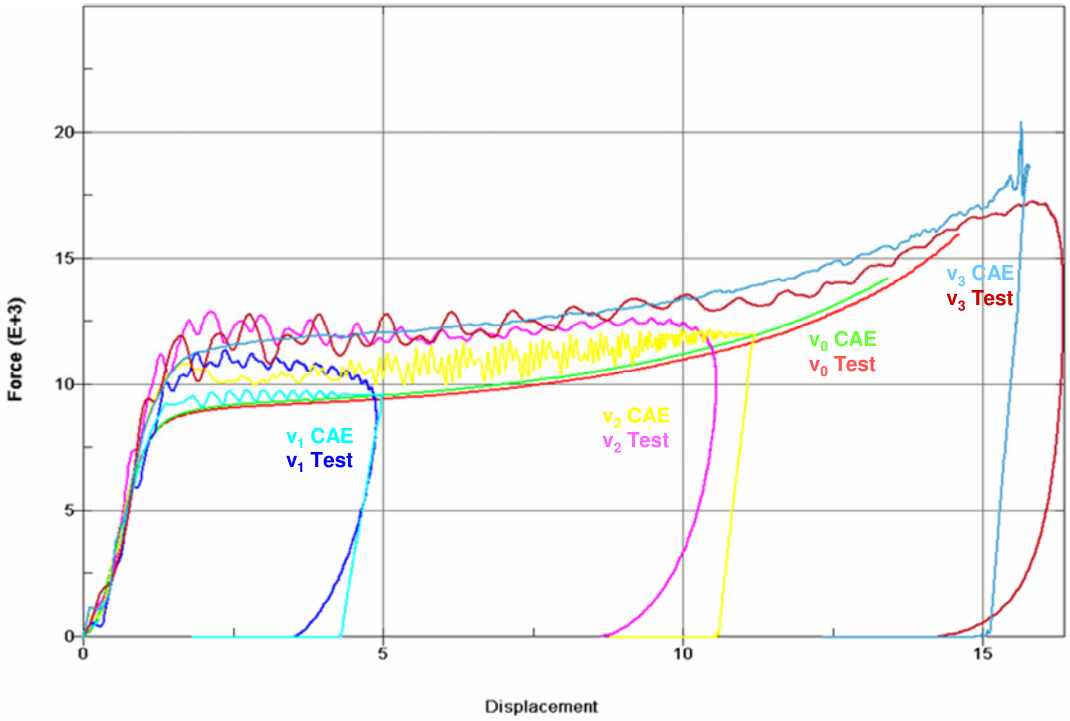

Figure 3: Force-Deflection correlation between specimen test and simulation

For the quasistatic setup, a constant velocity (v_0) was applied using the boundary prescribed motion on the head nodes of the specimen, whereas the dynamic testing has been performed using a moving rigid wall impacting the specimen. Three different initial velocities have been selected $v_1 < v_2 < v_3$. As the static correlation show a very good fit, the dynamic simulations for the lower speed are slightly underestimating the peak force levels. For the higher speed value the average behavior fits again well. For all cases the unloading behavior is capture accurately. For all cases the elastic stiffness is very well captured. As the strain rate effect is not that significant, the model seems to be feasible to fulfill the BETAFOAM^{TM} material representation in targeted applications. To validate this, further studies have been performed on applications and automotive parts. This validation will show the benefit on using the structural foam to either increase the performance or to optimize the structure.

2.3 Validation method for the BETAFOAM™ Model

The main goal of the model validation is to get a qualitative and a quantitative prediction of the reinforcement properties and the failure behavior of foam treated structures. Testing profiles without foam treatment are useful to check a correct representation of the boundary conditions. It will also be used as a baseline for benchmarking reinforced structures. Through the variation of the profile setup, various possible concepts for a material optimization process can be considered.

To compare simulation and testing results focusing the material model accuracy for the structural foam, the test setup should not be too complex to prevent problems on setting up the right boundary conditions and effects not directly related to the material to examine. In the following, a circular shaped tube is used in a three-point bending test to show the effects of reinforcing cavities with BETAFOAM^{TM,} as well as to show the predictive accuracy on using the material model within a “real” case.
Different setups have been examined to show the effects and the optimization potential to reinforce hollow structures most efficiently. As an un-reinforced structure under bending load starts to buckle, the impacting energy cannot be absorbed efficiently by the steel structure itself, see figure 4 - left. By filling the cavity with foam, the buckling is prevented, and the steel can deform most efficiently including the energy absorption due to plastic deformation, see figure 4 - right.

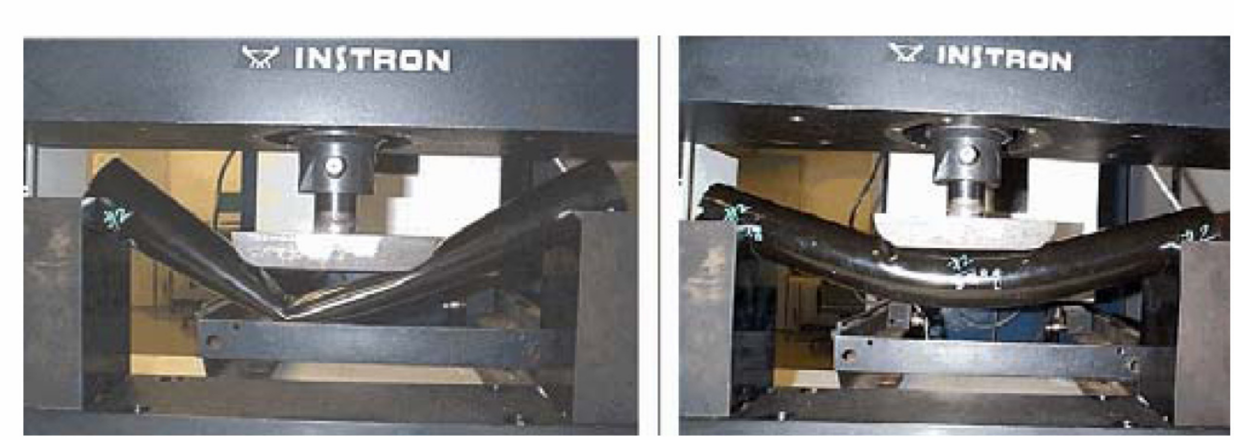

Figure 4: Load bearing capacity of an empty tube (left) and a foam filled tube (right)

The foam treatment of a single profile already shows an increase of the maximum load of 270% compared to the not foamed baseline. The absorbed energy was increased by 300%, which is a good indicator for possible optimization runs on wall thickness and design space reduction. An additional co-centric profile results in even higher load bearing capacity and leads in one case already to structural failure. This underlines the need for an accurate description of all involved components within the simulation. The equivalent Force-Deflection curves of the baseline tests and the simulations are shown in Figure 5.

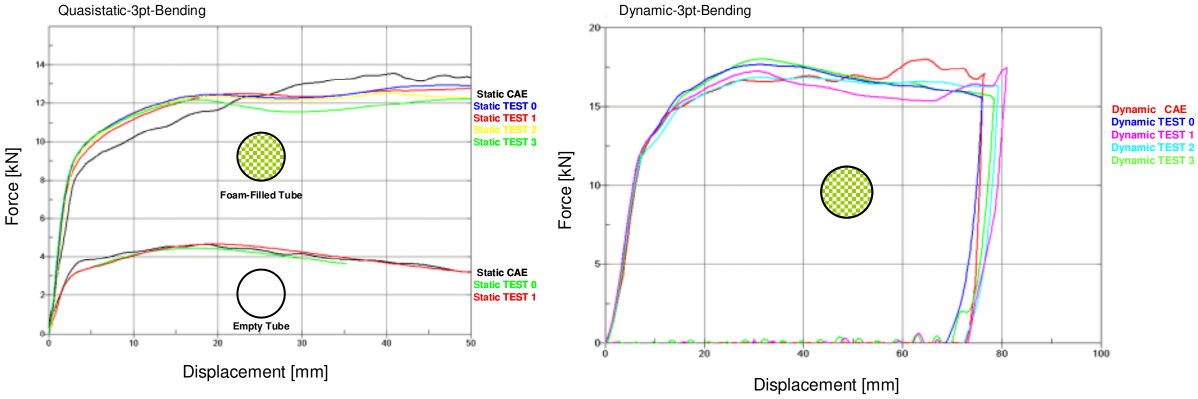

Figure 5: Quasistatic (left) and Dynamic (right) three-point bending tests and simulation correlation

Figure 5 shows the accuracy of such FEA-calculation for the simple foamed and not foamed profile in a 3-point bending load case. The calculation accuracy for the non-foamed and the foamed profile is very good – the material model is validated as usable for that load case, see also *Bilotto et al.* [3]. Besides static and dynamic bending tests DOW Automotive also performs axial compression tests using similar profiles where a similar accuracy level has been proven.

2.4 Full car crash simulations with BETAFOAM™

As the accuracy of the simulation has been shown above, the simulation of very complex crash scenarios with these material models is of interest. Figure 6 shows a crash simulation benchmarking (similar to FMVSS 208, 48 km/h). Target of this simulation is to benchmark the global deformation behavior, the front end stiffness, the buckling and bending mode of the front rail for the baseline (non-foamed) and the foam treated body.

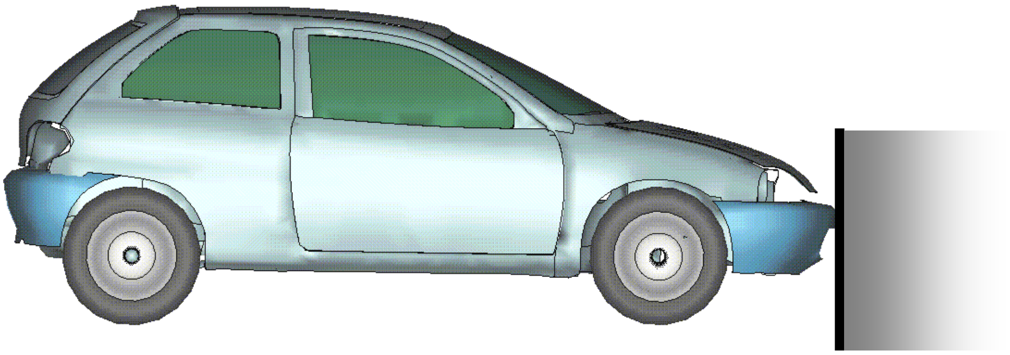

Figure 6: Geo Metro NCAC V. 2 model in a generic front crash analysis

The Geo Metro is an "older" model, available to show numerical studies on a full car scale without conflicting with individual secrecy agreements on more actual cars. For sure, it is not representing the state-of-the-art of modern cars, but the concept can be shown already by using this model. The foam treatment for the improvement is shown in Figure 7.

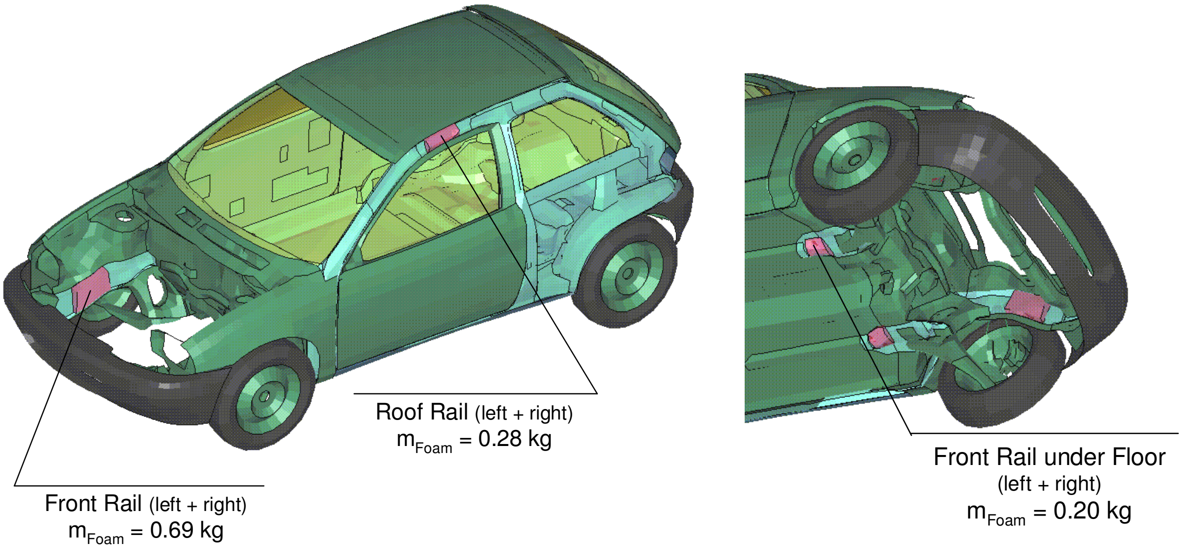

Figure 7: Foam treatment (2 kg) of the most critical cavities identified by the non-foamed simulation

The area which seems to be most effective has to be identified within an optimization study. As a result out of such a study, the roof rails, the front rails and the front rails under the floor have been identified to gain the most efficient performance increase without adding to much mass in the vehicle.

All in all, 2 kg of BETAFOAM™ 24 pcf have been used in this benchmark to gain a substantial effect in the crash event.

In Figure 8, the deformation within the frontal crash of the baseline (untreated) car and the car with BETAFOAM™ in the mentioned application areas is shown.

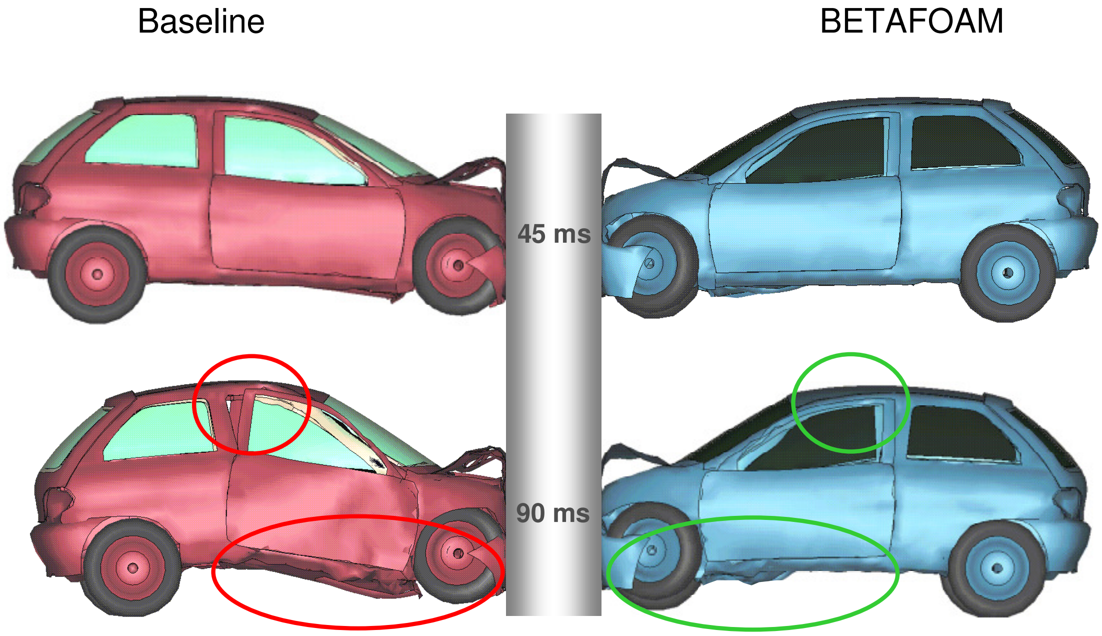

Figure 8: Baseline (red model-left) and foamed car (blue model-right) deformation in the frontal crash

The top pictures show the crash performance after 45ms – bottom pictures represent the deformation after 90ms of the crash event. As in the first 45 ms of the impact, there is not an obvious difference of the deformation behavior, but after 90 ms, the pictures show that the door of the baseline model has buckled strongly. Due to the strong deformation of the front end, the engine of the baseline model is indenting the firewall and affects the passenger cabin.

The improvements in the door and underbody areas regarding the foam treatment are obvious. The door and floor structure is less critical deformed. Also the engine intrusion has been resolved by using BETAFOAM™. This may represent the "important inches" in a real car crash situation.

The performance increase for the total deformation and specific to the front end deformation are given in Figure 9.

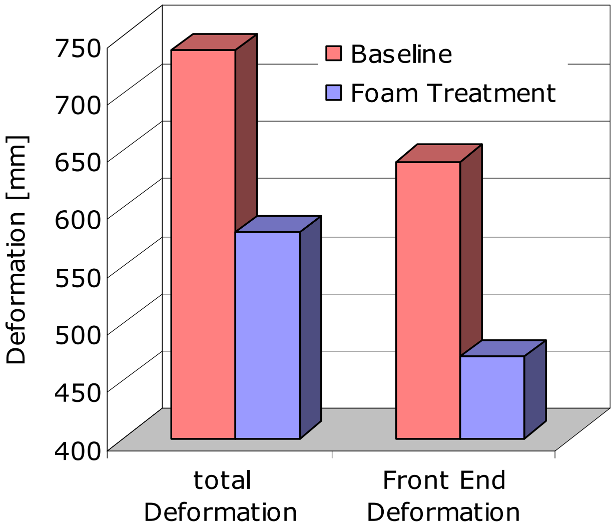

Figure 9: Deformation results of the performance increase using structural foam

The total vehicle deformation way of the baseline model counts: 736 mm and 640 mm for the foam treated car. Regarding the front end structure, the baseline model deformation is 578 mm whereas the foam treated model show 470 mm for the intrusion. The average deceleration of the baseline model is 15.2 g whereas the stiffer foam treated model is still close with 15.7 g. Adding the 2kg of structural foam has shown a significant improvement of the energy absorption for this frontal crash. One can think about the performance increase, but also to the potential to reduce weight and costs if the ~20% performance increase wouldn't be needed. The treatment would allow to down gauge steel or select less expensive steel grades, either to the material itself or to special manufacturing treatments.

3 Summary

The structural BETAFOAM™ technology represents an interesting possibility to locally reinforce the car body. Considering process and equipment needs, structural BETAFOAM™ offers the following advantages:

- Lower weight at same performance level.
- Reduce system cost: The reinforcements cost are basically dominated by the material cost and are lower compared to other local reinforcements.
- Design freedom/Flexible manufacturing: No need for expensive foaming tools – modification of the shot matrix will most likely cover that aspect.

Compared to bulk foam solutions the SFI-technology offers the following advantages:

- "Short term" integration is possible.
- No complex process equipment is needed in the vehicle line.
- Easy on site logistic at the OEM plant.

Thus, the discussed approach of structural foaming with BETAFOAM™ represents an ideal possibility to fulfill actual requirements in the automotive industry.

4 References

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