A New Method to Model Aluminium Honeycomb Based Crash Barriers in Lateral and Frontal Crash Load Cases

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Abstract:

Using Finite Element Method (FEM) it is possible to show and predict the behaviour of the vehicle's structure during a crash test. To ensure good simulation results compared to the reality it is not only necessary to correctly build up the FE-model of the vehicle, but to simulate the real behaviour of the crash barrier too. To meet this demand a new method for modelling and simulating crash barriers has been developed. This method is based on discrete beam elements to model the aluminium honeycomb structure. The major advantage of this method is the possibility to show realistic global and local deformation behaviour of honeycomb structures that includes all characteristic deformation modes. To ensure high quality crash barrier models an effort was done on testing and validating. Over all, the results of the validation work show a good accordance of the acceleration, the force results and of the deformation behaviour of all structures.

Keywords:

Aluminium honeycomb, discrete beam elements, automotive crashworthiness, side impact, IIHS, ODB,

1 Introduction

For the customer, passive safety is one of the most important reasons for the decision to buy a new car. To ensure high safety standards, passive safety is demonstrated in vehicle crash tests. Instead of vehicle to vehicle crash tests, one vehicle is replaced by an aluminium honeycomb based crash barrier. This barrier represents the front of a vehicle by the shape, the deformation behaviour and the energy absorption.

Using Finite Element Method (FEM) it is possible to show and predict the behaviour of the vehicle's structure during a previous mentioned crash test. To ensure good simulation results in comparison with reality it is not only necessary to correctly build up the FE model of the vehicle, but to simulate the real behaviour of the crash barrier too. Experience shows, that the deformation behaviour of the FEM crash barrier seriously influences the quality of the full vehicle simulation. Barrier models, which are currently used, show insufficiently reliable results. The modelling techniques are not able to show the characteristic deformation and failure behaviour of aluminium honeycomb. Moreover severe barrier deformation can cause serious instability problems of the models. That leads to an inaccuracy in the prediction of the vehicle safety during a virtually based development process. It has to be considered that CAE driven design processes are only feasible when the simulation delivers results with reliable prognosis quality.

The latter mentioned reliable prognosis quality can only be achieved when the FEM barrier model is of high quality concerning global and local deformation behaviour and stability [1]. To meet this demand a new method to model and simulate crash barriers has been developed. This method is based on discrete beam elements to reproduce aluminium honeycomb structures. The major advantage of this method is the possibility to show realistic global and local deformation behaviour of honeycomb that includes all characteristic deformation modes. Moreover this method ensures high stability even under severe deformation of honeycomb structures and is very efficient in terms of calculation time.

2 Deformation behaviour of aluminium honeycomb

The aluminium honeycomb structures used in crash barriers are anisotropic hexagonal structures made of thin aluminium foils. Caused by the structural shape, three principle directions T/L/W are observed (Figure 1). The T-direction has the highest load capability while L and W-directions are approximately 10 times weaker. Along these principle directions different characteristic deformation modes can be shown. Aluminium honeycomb structure, that is loaded in global T-direction shows a characteristic buckling and force-deflection behaviour, see Figure 2. At first the structure deforms elastically [2]. When the load reaches the critical compressive force, the structure buckles the first time. This is indicated by a distinctive peak. After that, the structure periodically buckles under constant load [2], [3].

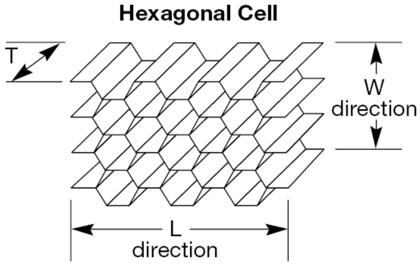

Figure 1: Principle directions of hexagonal honeycomb structure

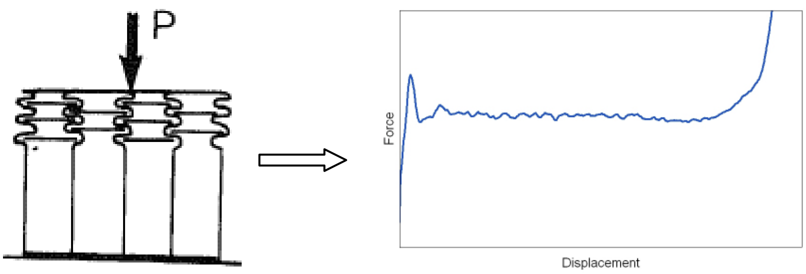

Figure 2: Buckling and force-deflection behaviour of T-directional loaded honeycomb structure [3]

Locally loaded, aluminium honeycomb structures show local failure behaviour of the aluminium foils in T-direction [4]. Failure is directly located at the perimeter of the body, that impacts. Beside local failure the loaded structure buckles as mentioned above. The unloaded structure keeps stable.

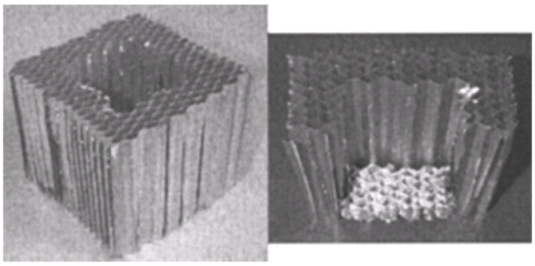

Figure 3: Deformation behaviour of T-directional locally loaded honeycomb structure [4]

Besides the typical deformation behaviour in T-direction, aluminium honeycomb shows typical behaviour in transverse direction too. A load in L-, W-, or mixed direction can cause local single deformation zones that propagate trough the structure (Figure 4) [5].

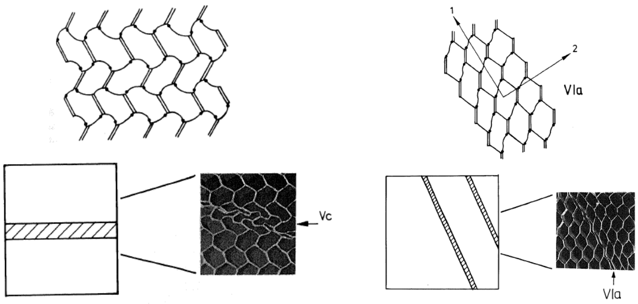

Figure 4: Principle deformation behaviour of transversely loaded honeycomb structure [5]

3 Methods to model aluminium honeycomb

3.1 State of the art

State of the art aluminium honeycomb models are based on 8-nodes solid elements [6]. With solids, a honeycomb structure is modelled as a continuum. This loss of structural information leads to inaccurate of the FE-model. The solid based model is not able to show principle, in-plane (L, W) deformation modes of real honeycomb structures. With special settings the characteristic buckling mode can be realized in global T-direction [7]. Nevertheless, it is not possible to reproduce the typical deformation behaviour of locally loaded honeycomb structures.

Despite the mentioned problem to show principle deformation modes with solid elements, it is possible to validate force-deflection or acceleration curves. Solid element based crash barrier models can at first sight show good results when crashed with full vehicle models. Although the simulated results seem to be quite good, the inaccurate deformation behaviour falsifies the force transmission to the tested specimen. It is hardly possibly to develop the vehicle's restrain systems based on the simulated results of the wrong loaded car structure. In fact, there is no possibility to ensure the prognosis quality of the virtually driven vehicle safety design process.

As a consequence in [8] and [9] honeycomb models made of shell elements used in crash barrier models were presented. The shell elements are used to directly model the honeycomb structure itself (Figure 5). By this method good results are achieved. Hence there is no loss of structural information in principle. The main problem of shell based honeycomb models is the small required discretisation of each edge of the hexagon. To show characteristic buckling mode in T-direction, in FEM the folding process of each cell wall during buckling strongly depends on the amount of elements per cell wall used. More elements mean better results, because the buckling mode will be shown quite more realistic.

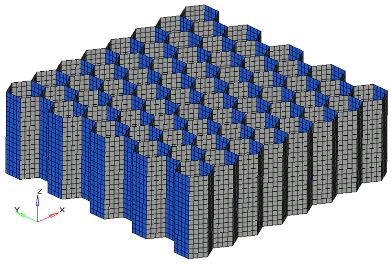

Figure 5: FE model of honeycomb structure based on shell elements

In principle, the amount of shell elements used in crash barrier models is essential to ensure economic behaviour. Hence the real cell size of the honeycomb structures will be increased to fulfil this requirement. Despite this procedure, the IIHS (Insurance Institute for Highway Safety) barrier model in [9] reaches 990.000 elements and the CPU-time is increased by 35 % related to a solid based barrier model. In fact, an extensive numerical effort was done to improve the result of the vehicle simulation compared to the reality.

3.2 Discrete Beam Method (DBM)

Based on the previously mentioned state of the art models a new Discrete Beam Method (DBM) to model honeycomb structures will be presented. The main aims of the DBM method are first to ensure the realistic directional deformation behaviour of anisotropic honeycomb structures, and secondly to reduce costs and CPU-time.

In principle, discrete beams are spring elements with six uncoupled degrees of freedom. The element itself consists of two nodes, whereas a third node is needed to initialise an elemental coordinate system (r,s,t). In fact, there is no physical connection between the nodes. To be able to model suitable deformation behaviour, MAT 68 (MAT_NONLINEAR_PLASTIC_DISCRETE_BEAM) in LS-Dyna is used. All six uncoupled DOFs show an elasto-plastic connection between load and deflection. Additionally, failure of all DOFs is possible. Moreover, the time step calculation of discrete beam elements is a big advantage concerning the usage for honeycomb structures. The time step is independent of a characteristic length and therefore constant [10].

In comparison to a shell based honeycomb model, the DBM leads to a simplified structured model of the hexagonal structure (Figure 6). In contrast to the shell method, each edge of the hexagon is resolved only with one element. Moreover, an increased cell size in order to reduce the amount of elements can be realised quite simple. All discrete beams of the model are assigned to characteristic element groups that depend on the principal beam orientation T, L, W of the honeycomb structure.

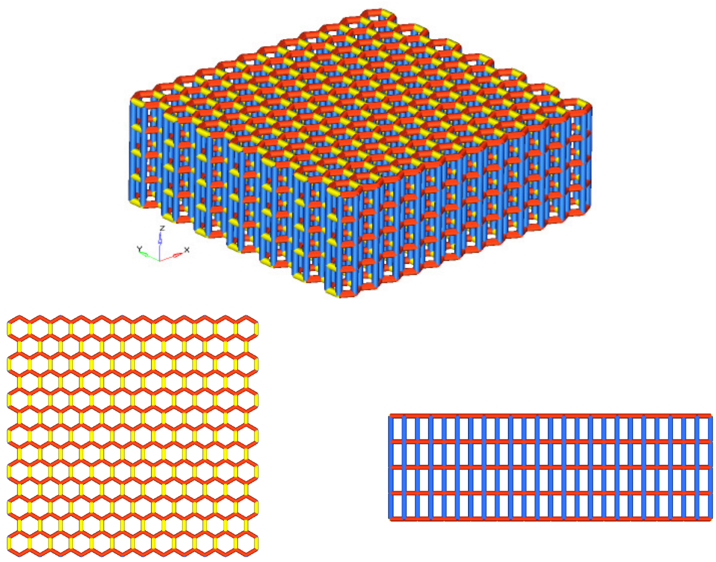

Figure 6: Iso, top and side view of honeycomb model based on DBM

In general, the DBM allows to qualitatively simulate the real characteristic deformation behaviour of honeycomb structures. First, this advantage is based on the ability to set up the load-deflection behaviour of all 6 DOFs. Secondly, each characteristic deformation mode observed is related to an element group. In Figure 7 the deformation behaviour of a DBM model under compressive and mixed (compression and shear) load is shown. In global T-direction, the beam elements fold in a locally layered manner. In principle, this deformation mode approximates the real behaviour of the structure. A mixed compression and shear load results in damaged areas on the top and bottom surface, while the rest remains nearly stable, which is the real characteristic deformation behaviour. Additionally to realistic global behaviour of the DBM model, local deformation behaviour can be modelled (Figure 8). As in reality, only the locally loaded structure will be damaged. In fact, the ability of realistic local failure of the model is the main advantage of the DBM.

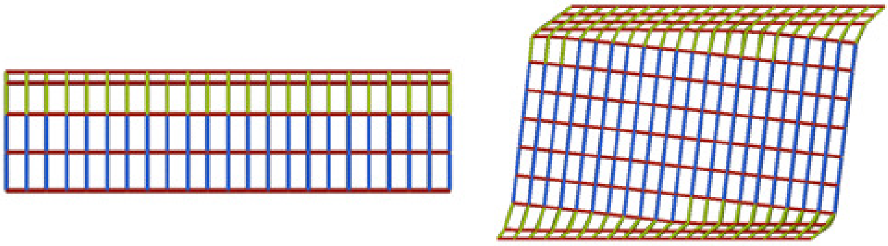

Figure 7: Characteristic deformation behaviour of T- and mixed directional loaded honeycomb model

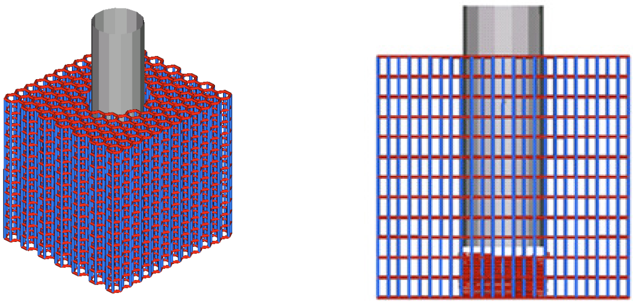

Figure 8: Characteristic deformation behaviour of T-directional locally loaded honeycomb model

4 Validation process of an IIHS side impact barrier based on DBM

The development process of the IIHS barrier model based on DBM honeycomb model is shown in Figure 9. To ensure a high quality crash barrier model an extensive effort was done on testing and validating components with different complexities by a step by step procedure.

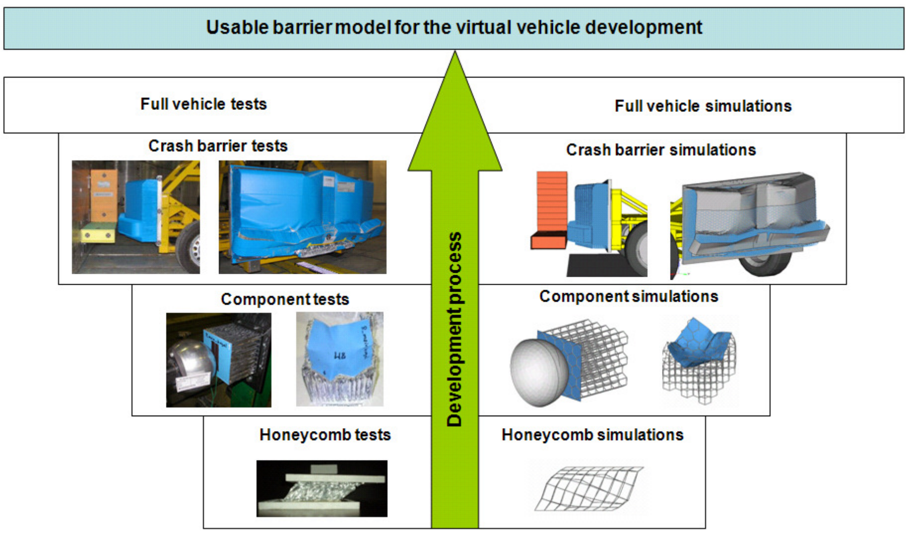

Figure 9: Development process of IIHS crash barrier model based on DBM

4.1 Validation of DBM based aluminium honeycomb model

The honeycomb validation is the fundament of the development process. Here, a lot of different tests were carried out to ensure a good overall deformation and force-displacement behaviour of the DBM based honeycomb model. The load cases include compression loads in all principle directions, angle dependent mixed (compression and shear) loads and local compression load in T-direction. For example two results of the honeycomb validation are presented. In Figure 10 the validation of the force-displacement curve and the related deformation behaviour of the DBM model loaded in global T-direction are shown. The simulated signal is nearly the same as the test result. Even the first buckling peak of the honeycomb structure is included qualitatively. As an example for mixed load, the result of a TW15° compressed model is shown in Figure 11. As in T-direction, the result of the simulation is comparable to the test.

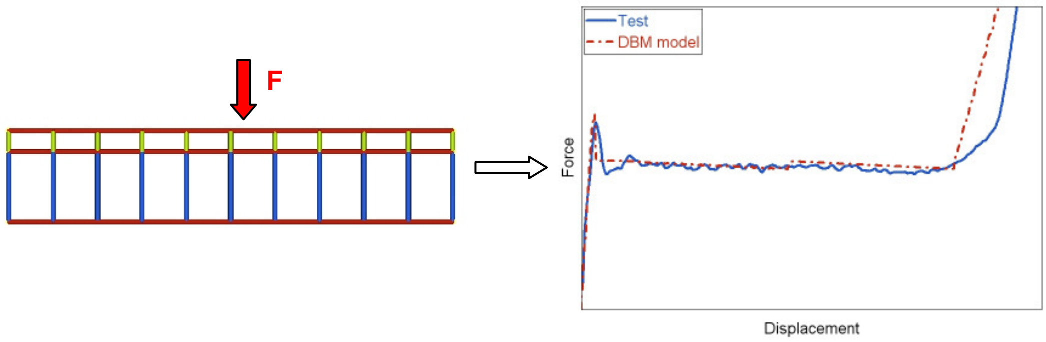

Figure 10: Deformation of T-directional loaded DBM model and validation of force-displacement curve

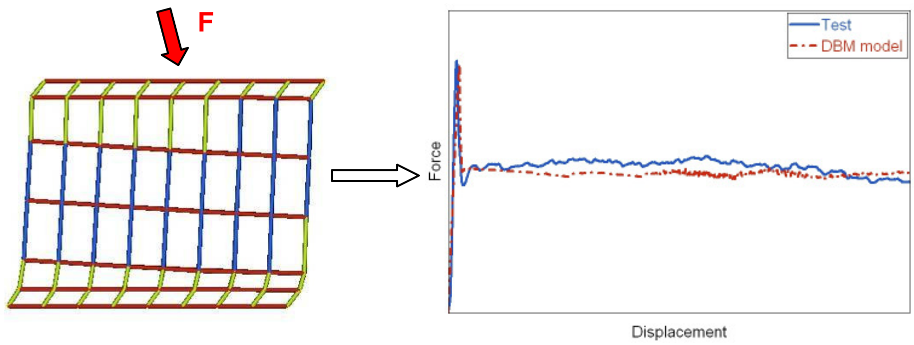

Figure 11: Deformation of TW15° loaded DBM model and validation of force-displacement curve

4.2 Validation of combined aluminium honeycomb and cladding sheet model

The deformation behaviour of a crash barrier is mainly influenced by the interaction of honeycomb structures and cladding sheets. Therefore a component validation was done. The test specimens and the FE models consist of a honeycomb cube with glued cladding sheet, cut from an IIHS barrier. Thereby, realistic deformation behaviour similar to the real crash barrier should be ensured. Thus specimens were dynamically loaded with different punches. As an example the sphere loaded specimen (Figure 12) is presented. The initial velocity of the sphere was 4,4 km/h. The force-displacement behaviour and the deformed FE model and test specimen are shown in Figure 13. The simulated force-displacement curve shows good correlation to both tests. The first peak of both force-displacement test signals shows a deviation of approximately 19 %. That is caused by the fact, that the first peak is related to the initial buckling of the honeycomb structure. This phenomenon seems to be highly dependent on structural tolerances. Additional to the simulated force-deflection curve, the deformation behaviour of the FE model meets the test result.

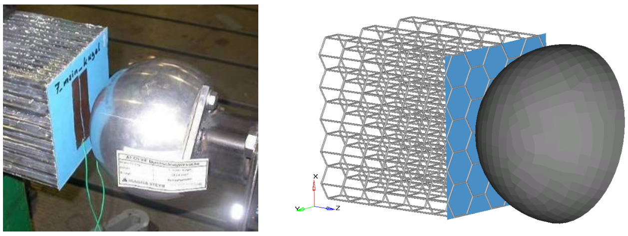

Figure 12: Initial state of sphere loaded specimen – test and FE model

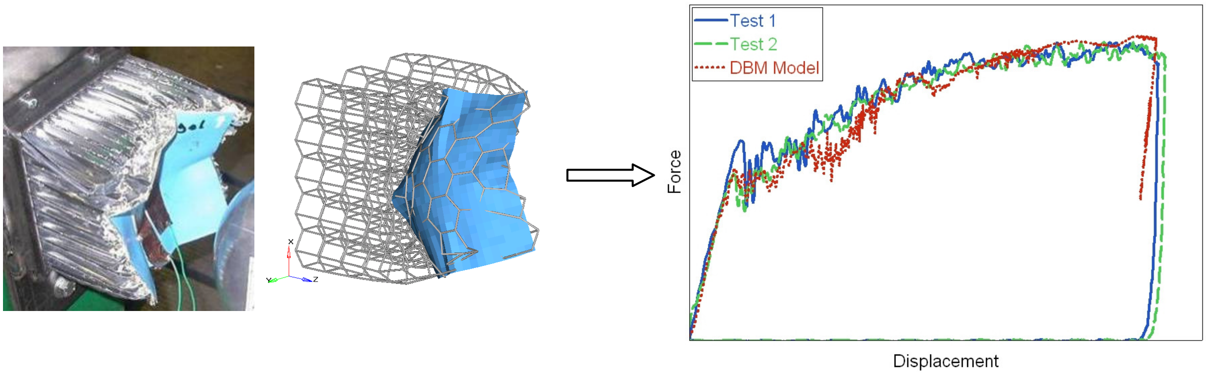

Figure 13: Validation of deformation behaviour and force-displacement curve

4.3 Validation of IIHS barrier model

Based on the validation results of the honeycomb structure and validation results of the component models, an IIHS prototype barrier model was set up. To reduce the number of elements, the original cell sizes of the honeycomb structures of the main and bumper blocks were increased by the factor of three. The entire barrier model consists of 214.000 discrete beam elements (honeycomb structure) and 196.000 shell elements (cladding sheets). The cladding sheets of the prototype model were meshed with a shell size of 6 mm to meet realistic localised deformation behaviour.

In general, the main request to the barrier model was to meet several load cases with a single model. The IIHS prototype barrier model was validated with seven different load cases. Different rigid barriers like rigid wall, poles etc. were hit by the crash barrier. In real side impact crash tests main deformations are caused by the rocker and the B-pillar. For this reason the results of the load cases 'rigid rocker' and 'three poles' are presented.

First the initial state of the load case 'rigid rocker' of the test and the FE model is shown in Figure 14. The mass of the moveable deformable barrier (MDB) was set to 1.500 kg and the initial velocity of the barrier was set to 25 km/h. The measured results of the test and the FE-model are shown in Figure 15. Over all, the IIHS barrier model qualitatively meets the test results. Moreover, the global deformation behaviour of the FE-model is comparable with the real crash barrier (Figure 16). Additionally, the barrier model was vertically cut in the middle and directly compared to the laser measured surface of the real deformed barrier (Figure 17). This comparison shows a good result of the barrier model too.

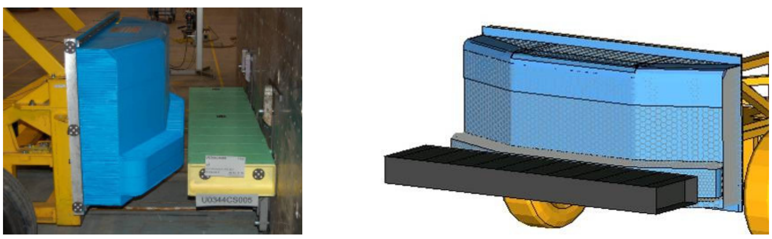

Figure 14: Initial state of load case 'rigid rocker': test and FE model

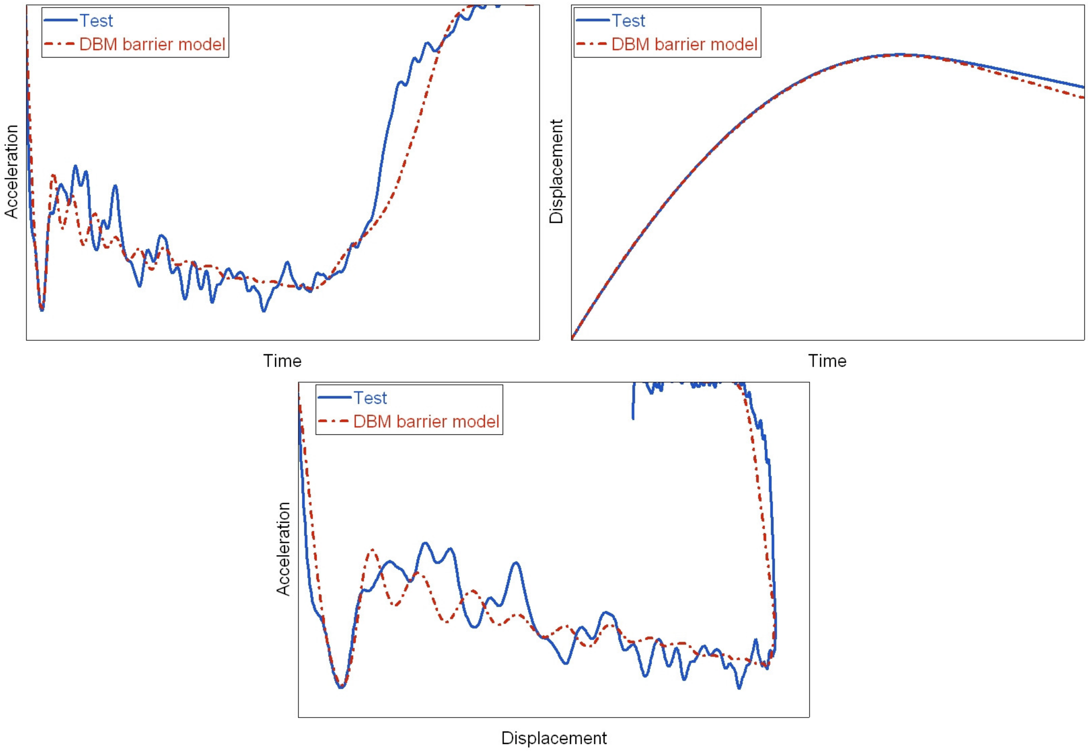

Figure 15: Validation of acceleration-time, displacement-time and acceleration-displacement curve

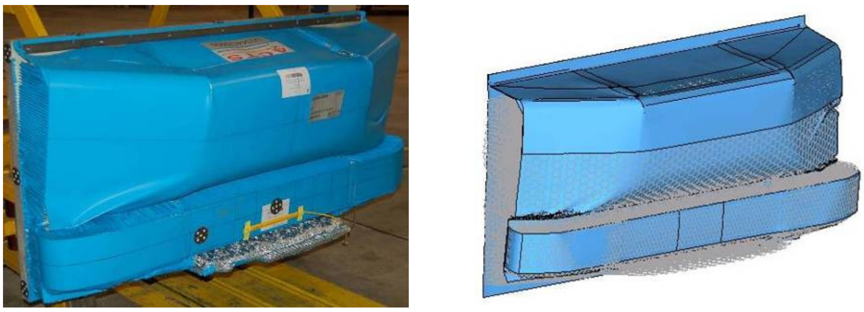

Figure 16: Comparison of deformation behaviour – test and FE model

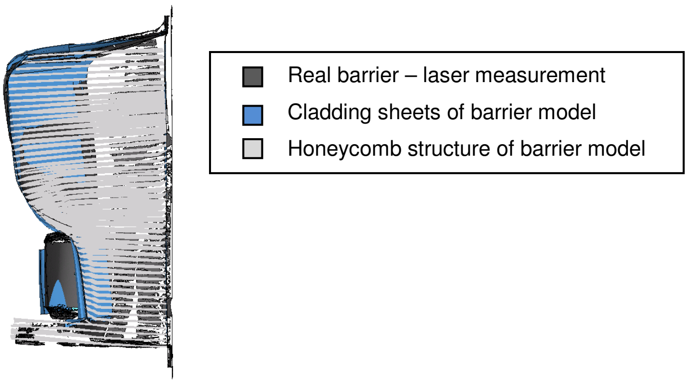

Figure 17: Overlay of deformed shape of real barrier with barrier model (vertical central cut)

The second barrier validation presented is based on the load case ‘three poles’ (Figure 18). Here, the initial velocity was set to 30 km/h. Over all, the simulated data (Figure 19) and the deformation behaviour (Figure 20) of the barrier model meet the test results.

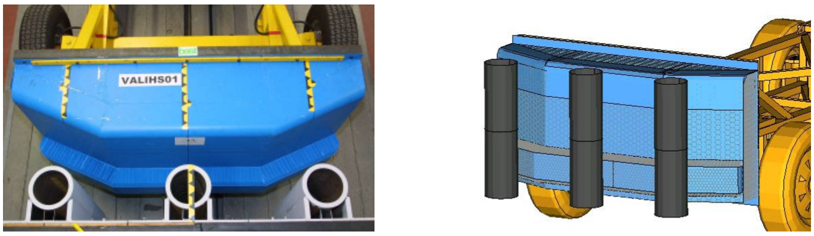

Figure 18: Initial state of load case 'three poles': test and FE model

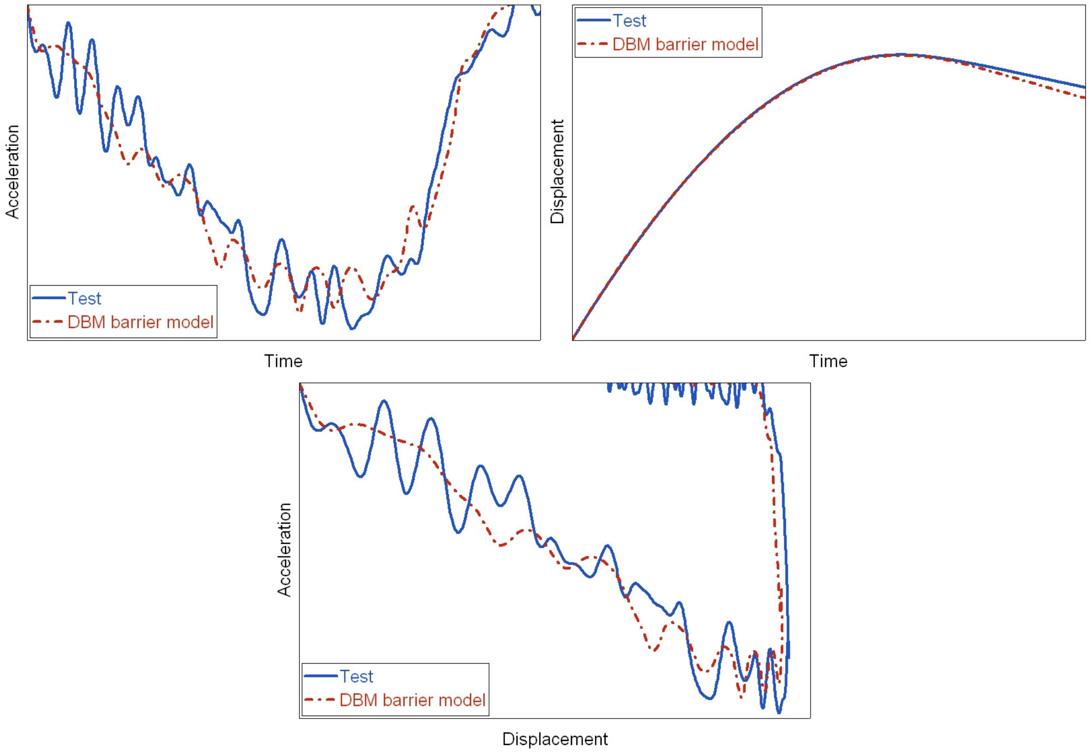

Figure 19: Validation of acceleration-time, displacement-time and acceleration-displacement curve

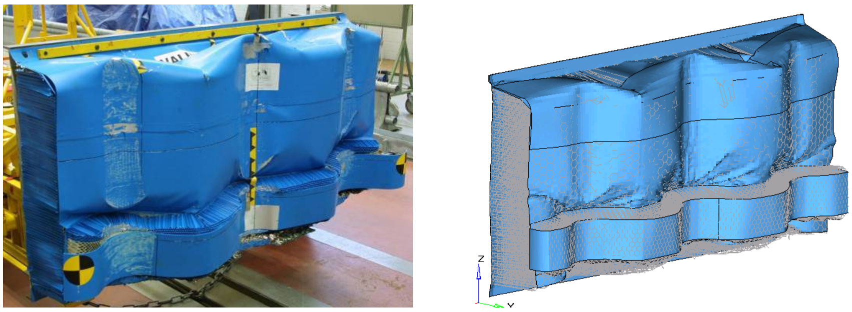

Figure 20: Comparison of deformation behaviour – test and FE model

In general some important factors to the quality of barrier models were identified during the validation work. A qualitatively validated FE model of the honeycomb structure does not guarantee perfect results concerning a crash barrier model. The failure behaviour of the sheet metals gluing and the failure behaviour of the sheet metals have a basic influence on the simulation results of the barrier model. Concerning all load cases, it is not possible to meet the behaviour of the glued sheet metals with one and the same barrier model. In principle, the mechanical properties of the glue highly depend on the production process of each barrier itself. Thus the IIHS barrier shows different failure behaviour of the glue even for similar tests. Nevertheless, failure of the sheet metals itself has quite more influence on the results. Concerning a correct validation of the barrier's displacement it is important whether there is crack propagation or not.

5 Outlook to ODB front crash barrier model based on DBM

The Offset Deformable Barrier (ODB) is the most important barrier to show the front crash behaviour of vehicles by now. Thus, this barrier is of main interest concerning the virtual development of vehicle safety. The main challenge of ODB FE models is to deal with severe local deformations caused by 40 % offset of the vehicle. State of the art FE models show problems like numerical instability or inaccurate local deformation behaviour, leading to incorrect folding of the vehicle's front structure.

To show the ability of DBM an ODB demonstrator model was set up. This model is based on the honeycomb structures of the IIHS barrier model because there was no possibility to validate the ODB honeycomb structures by now. Nevertheless real ODB and IIHS barrier nearly have the same energy absorption of the honeycomb structures. In Figure 21a the deformed ODB model and vehicle model (Ford Taurus [11]) are shown. To give more detail on the deformed ODB model, the whole model was cut horizontally (Figure 21b). In general the barrier model is able to show severe local honeycomb deformation without any problems of numerical instability.

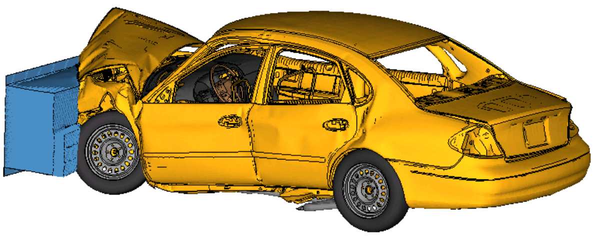

Figure 21: Crashed vehicle and ODB model

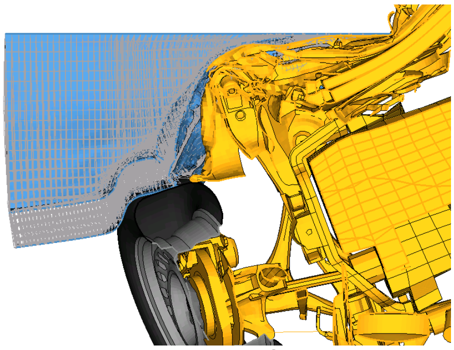

Figure 22: Vertical cut of ODB and front end

6 Conclusion

A new FE method to model aluminium honeycomb structures based on discrete beam elements has been developed. Starting from detailed tests the aluminium honeycomb model was validated. Special focus was given to realistic global and local deformation behaviour of honeycomb structures. Especially the ability of realistic local failure of the honeycomb structure and a constant time step are major advantages. Moreover, a component validation was done to ensure realistic combined deformation behaviour of honeycomb structures and cladding sheets. Finally, a prototype model of the side impact IIHS barrier has been set up and was validated based on seven load cases with different rigid barriers. Two load cases, the 'rigid rocker' and the 'three poles' are presented in this paper. In general the barrier model shows quite good results compared to the tests. Although the aluminium honeycomb model is qualitatively good, special attention has to be given to local phenomena like sheet metal failure and glue failure. To obtain high quality barrier models these local phenomena have to taken into account. Additional to the IIHS barrier model an ODB demonstrator model has been set up and real the deformation behaviour is shown by the model. In summary, the discrete beam method ensures high stability even under severe deformation of the honeycomb structure without any problems of numerical instability.

7 Acknowledgement

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