Alternative Model of the Offset Deformable Barrier

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Summary:

The offset deformable barrier consists mainly of honeycomb blocks with highly anisotropic behaviour. These parts are made from several layers with aluminium foil that is glued and stretched to form the honeycomb structure. Simple compression tests show high stiffness and strength when the cell structure is folded while both stiffness and strength are significantly lower when the deformation mode is mainly bending of the thin foil. Remember that the strength of a honeycomb block is mainly determined by the width/thickness ratio of the cell walls.

Therefore, shell elements are used to model the honeycomb structure, and an alternative model of the offset deformable barrier is made. Note that scaling is used extensively to limit the number of elements and thereby the computational time that is required. Both simulations and tests show that the typical deformation mode involve also transverse displacement of barrier parts, and when the honeycomb structure is folded this may be seen as the interaction between local and global buckling. This model seems able to predict both the force level and the transverse force components that are important to represent when designing bumper systems with respect to high-speed performance.

Keywords:

Automotive Crashworthiness, Offset Deformable Barrier (ODB), Aluminium Honeycomb,
Shell Elements and Material 24

1 Introduction

Numerial simulations are extensively used to predict the amount of vehicle deformation under offset frontal collisions. Therefore, it is crucical to properly represent the properties of the offset deformable barrier (ODB). Remember that the main parts of this barrier is made of aluminium honeycomb, and in an offset frontal collision this material is compressed not just allong one axis, but also in the oblique direction. For aluminium honeycomb the compresion property along its strong axis is well known, while less work has been carried out to investigate the properties connected to other deformation modes. Kojima et al. [1] have performed compresseion tests on aluminium honeycomb blocks that were cut with varying orientation relative to the strong axis. As expected, the zero-degree test shows the highest value measured, while the test pieces cut at angles of 60 degree or more, shows compressive stress less than one tenth of the zero-degree referance. Thus, in order to represent the variation in compressive strength, they have in collaboration with Livermore software Technology Corporation (LSTC) incorporated a new yielding function into the material model MAT126 [1].

Also this paper focus on the compression properties of aluminium honeycomb, but shell elements are used to model the behaviour that is seen as the interaction between local and global buckling when folding the cell structure. Note that scaling is used extensively to limit the number of elements and thereby the computational time that is required, and an alternative model of the offset deformable barrier is made. Finally, a comparisom is made between the numerical prediction and the test result from collision with the offset deformable barrier from Cellbond.

2 Scaling

The frontal offset barrier from Cellbond has both main block and bumper elements in honeycomb made of aluminium 3003 foil with thickness 0.076 mm. Both density and crush strength is governed by the cell size that is 19.14 mm and 6.4 mm for the main block and the bumper elements, respectively. Figure 1 illustrates how honeycomb parts can be made from foil. It seems like the angle H is about 90 degrees, and the distance M where two foils are put together is nearly the same for both honeycomb densities. Thus, the distance L is varying, and the width to thickness ratio for this wall is one important parameter that governs local buckling of the cell structure. In the present study, the geometry of the numerical honeycomb representation is defined by four times six squares. This area may be seen as 24 shell elements in the cladding sheet, and the shell elements that make the honeycomb main block and the bumper elements may have common nodes as well, see Figure 1. Note that the mesh may be refined in such a way that four, nine or even more elements fits into one square, and the present part is scaled and repeated to form the whole barrier.

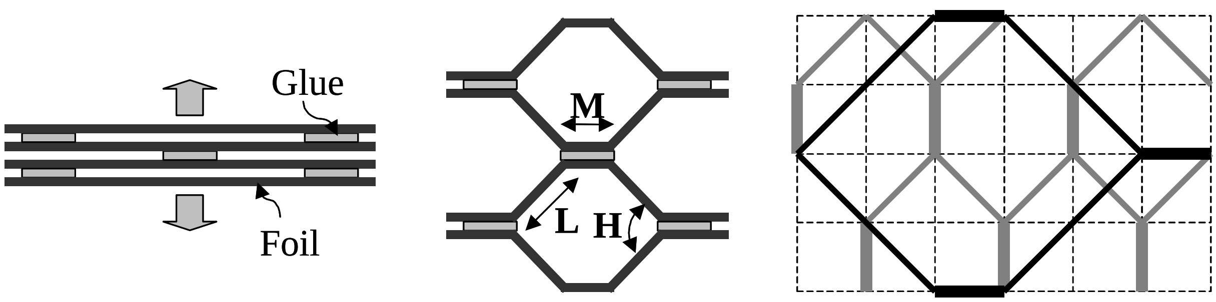
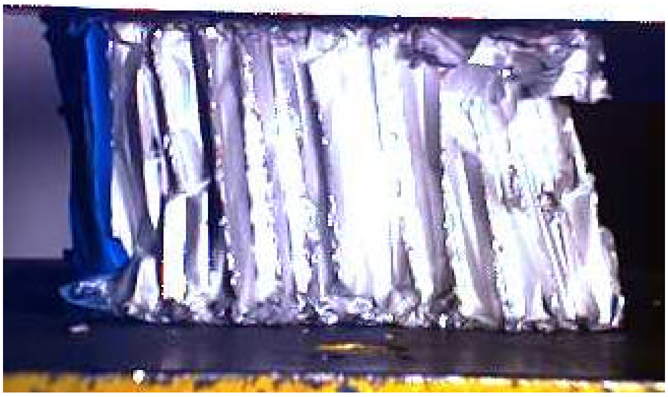


Fig. 1 Parameters that define the geometry of the honeycomb cell structure

A 150 mm aluminium honeycomb cube was cut out of the barrier core and compressed along its strong axis. The compressive strength was kept for about 50 mm movement of the loading bar, but then the measured force starts to drop, see Figure 2. This is herein explained as the interaction between local and global buckling when folding the cell structure. Note that this result gives a limitation when scaling the numerical model since the tendency to global buckling is reduced when the size of the honeycom cells is incresed. In addition, the computational resource is limited, and therefore a cell structure with small cells should not be modelled with a large number of elements forming the cross section of each cell. Thus, the main objective of the present study is to find an “optimal” scaling where the cell size as well as the number of elements to represent each cell is chosen to give the “best” representation of the offset deformable barrier related to the computational time required.



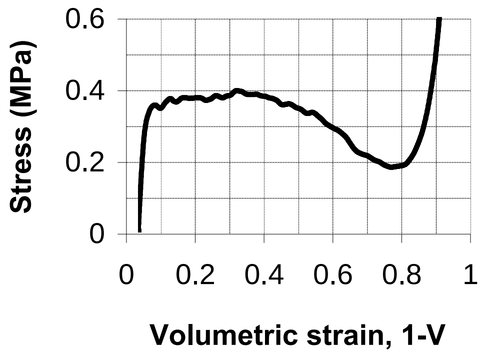
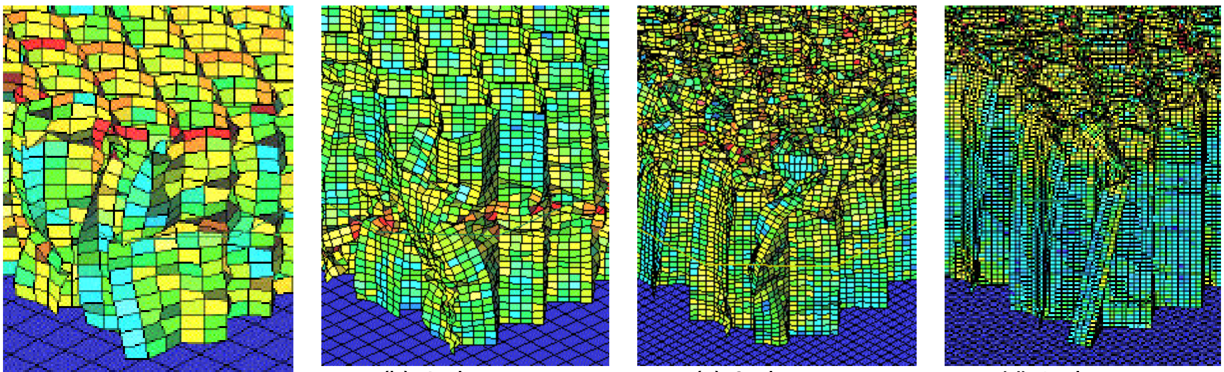


Fig. 2 Aluminium honeycomb compression test

A shorter variant of the compression test was modelled to investigate the influence of the number of elements over the cross section of the cells. Note that the parts that were put together with adhesive were modelled with two times the foil thickness. The numerical simulations were performed using the finite element code LS-DYNA [2]. The material properties were defined using von Mises yield criterion, the associated flow rule and nonlinear isotropic strain hardening following the values assumed for aluminium 3003 foil [3], see Table 1. The friction coefficient between the loading bars and the honeycomb specimen was chosen equal to 0.2. The results are presented in Figure 3 that shows the effective stress as well as deformed geometry after about 20 % compression of the initial volume. Note that fully integrated elements had to be used to avoid hourglass in the cases with only two or four elements over the width of each wall, and the specimen started to deform in the middle. The analyses with six or more elements over the same distance show progressive folding starting more or less from one end, and this corresponds to the behaviour observed in the experiment.

Table 1. Effective plastic strain and corresponding yield stress values adopted in MAT24

Strain	0.0	0.002	0.004	0.012	0.03	0.07	0.18	0.20
Stress	183	220	227	237	249	258	272	282

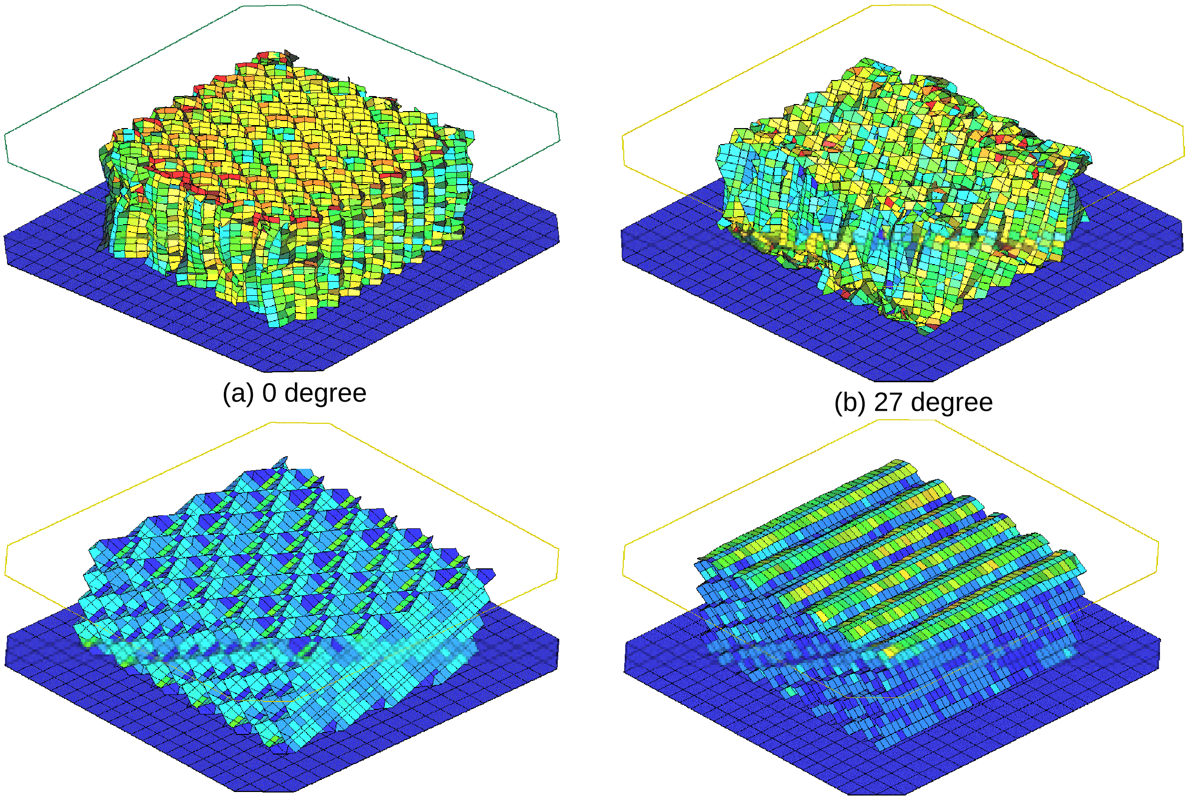


(a) 2 elements (b) 4 elements (c) 6 elements (d) 8 elements

Fig. 3 Simulations of aluminium honeycomb compression test – Effect of element size

Mohr and Doyoyo [4] have studied the local deformation modes of a honeycomb structure by using a mesh with 32 elements over the width of each wall. However, modelling of the whole barrier has the main focus herein, and the mesh should be as coarse as possible. It is therefore too coarse to properly describe the local folding mode, and the deformation mode is more like a mechanism model with plastic hinges following the borders between elements. This means that the global result is significantly influenced by the element orientation, and therefore, all the numerical specimens shown in Figure 4 have the same mesh except from some trimming at their edges. Note that the simulations were run without internal contact between shell elements representing the honeycomb parts.

The shorter variant of the compression test was also simulated with honeycomb pieces that where cut out with angles about 27, 63 and 90 degree relative to the main axis. Figure 4 shows the effective stress as well as deformed geometry after about 20 % compression of the initial volume. The simulations show that the cell orientation has great influence, and the deformation mode changes from compression of a cell structure in (a) to bending of thin walls in (d). This means that the compressive load drops, and with cell orientation 63 and 90 degree the effect is dramatically.

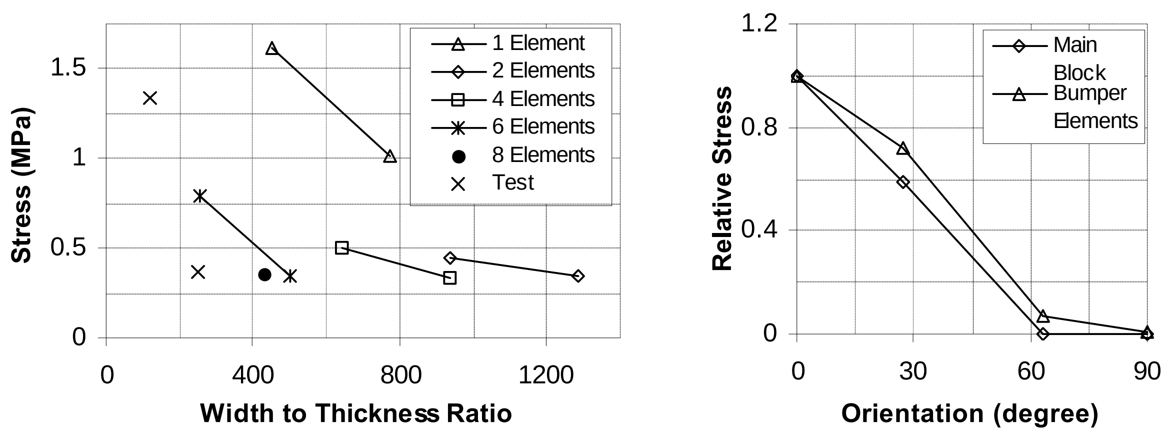


(a) 0 degree (b) 27 degree

(c) 63 degree (d) 90 degree

Fig. 4 Simulations of aluminium honeycomb compression tests – Effect of cell orientation

It seems like even this very coarse model is able to represent the global behaviour of the honeycomb cell structure, and then the scaling presented in Figure 5a becomes interesting. The numerical thickness is reduced to achieve the correct compressive stress, and this is shown as an increasing width to thickness ratio for coarser meshes. For the compression tests in Figure 4 this means the wall thickness in the numerical model is about one fifth of the real value, and this numerically increased slenderness seems to effectively reduce the strength for both the crushing and the bending modes. Figure 5b shows the predicted stress at 20 % volumetric strain as a function of cell orientation, and these numerical results corresponds well with experiments by Kojima et al. [1].

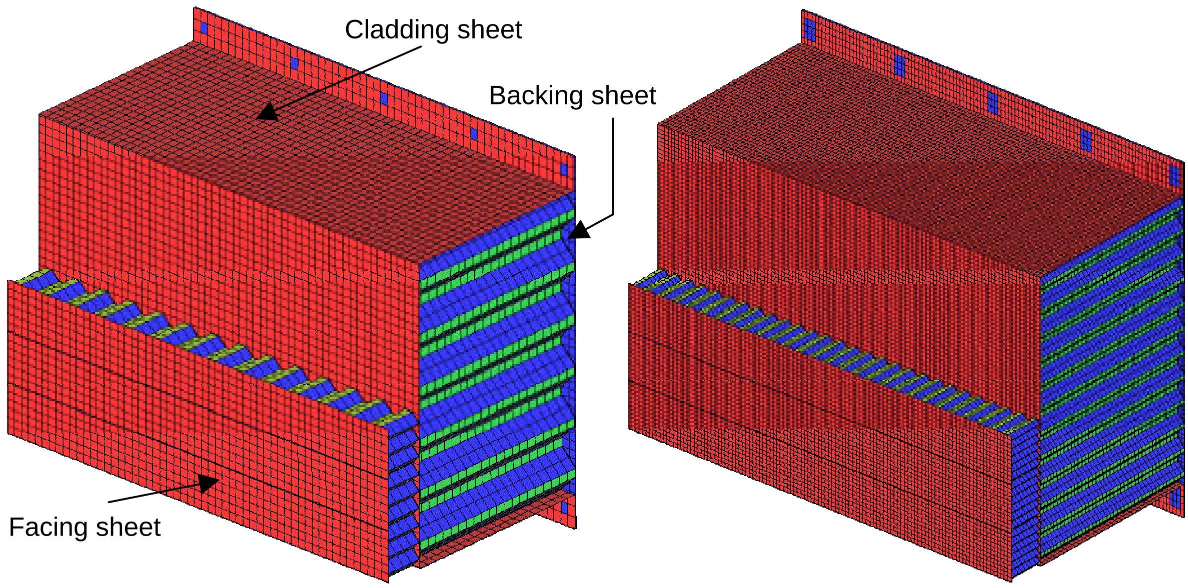


(a) Effect of mesh and width to thickness ratio (b) Effect of cell orientation

Fig. 5 Results from initial simulations to investigate scaling effects

3 Numerical Model

The present model of the ODB barrier is based on the cell geometry shown in Figure 1, and this patch is scaled and repeated to form the whole barrier. Note that for the base model with about 30 000 shell elements the cell size is enlarged about 5 and 6 times for the main block and bumper elements, respectively. In addition, the width to thickness ratio is increased to predict a reasonable crushing force with 18 mm shell elements. The foil material was defined by MAT24 in LS-DYNA [2] and the curve given in Table 1. Both the main block cladding and the bumper facing sheets were 0.8 mm thick, and yield stress 70 MPa and tangent stiffness 600 MPa were assumed for this aluminium plate material. The base model as well as a refined alternative with half the cell size is shown in Figure 6. The simulations were run with dt = $0.6\ 10^{-6}$ second, but the timestep was controlled by the bumper system that hits the barrier. In fact, the barrier model may be split one more time before dt is critical. This will give a realistic cell size, but the number of elements will be about half a million.



(a) Base mesh (b) Refined mesh

Fig. 6 Mesh alternatives with about 30 000 or 120 000 shell elements to represent the ODB barrier

The backing sheet was modelled as rigid and some elements in the cladding sheet were fixed to represent the bolts (unfortunately the test was run without steel strip). Contact was modelled between the shells representing honeycomb and the facing sheets, the cladding sheet and the backing sheet, and the friction coefficient was identified as parameter G in Table 2. Moreover, the contact between the impacting beam and be barrier was included with parameter F as friction coefficient, while no internal contact was established between the shells representing the honeycomb parts.

The adhesive was represented by one row of elements at each end of the honeycomb cells. These elements were not included in the contact definition, and their size was fitted to the contact thickness to directly support compression between honeycomb parts and the aluminium sheets. A simple bi-linear curve with yield stress like parameter C and tangent modulus 200 MPa was used to represent the tensile strength of the adhesive between the cladding sheet and the bumper elements, while the glue between the bumper elements and the facing sheet as well as and the main block to cladding sheet adhesive were assumed with yield stress like parameter E in table 2. It was assumed that the adhesive acts stronger when it is placed on a rigid surface, and yield stress equal to two times E was assumed for the main block to backing sheet adhesive. Note that a tied nodes to surface contact may be an interesting alternative.

Due to the coarse mesh the numerical specimen in Figure 3a reaches the densification face at about 65 % volumetric strain while the test shows the same at about 85 %; see Figure 2. Therefore, the failure flag in MAT24 is included as parameter D that effectively reduces the densification, but care should be taken since a low value can delete a lot of elements. The initial simulations also show a force peak to initialise the collapse mode, and the determination of the numerical thickness is derby depending on which force value that was used to calculate it. Thus, the numerical thicknesses that represent the main block and bumper elements were therefore chosen as parameter A and B, respectively, and a fractional factorial design [5] as shown in Table 2 was used to investigate seven parameters from only eight runs.

Table 2. The fractional factorial design used to effectively identify the main parameters

Runs	A	B	C	D = AB	E = AC	F = BC	G = ABC
1	-	-	-	+	+	+	-
2	+	-	-	-	-	+	+
3	-	+	-	-	+	-	+
4	+	+	-	+	-	-	-
5	-	-	+	+	-	-	+
6	+	-	+	-	+	-	-
7	-	+	+	-	-	+	-
8	+	+	+	+	+	+	+
+	0.070 mm	0.085 mm	90 MPa	0.6	110 MPa	0.60	0.60
-	0.065 mm	0.075 mm	80 MPa	0.8	90 MPa	0.40	0.40

Numerical simulations were performed with parameters at two levels as defined by the + and - signs in Table 2 where also the selected parameter range is given. The results are presented as the response curves in Figure 7 as well as the main effects in Figure 8.

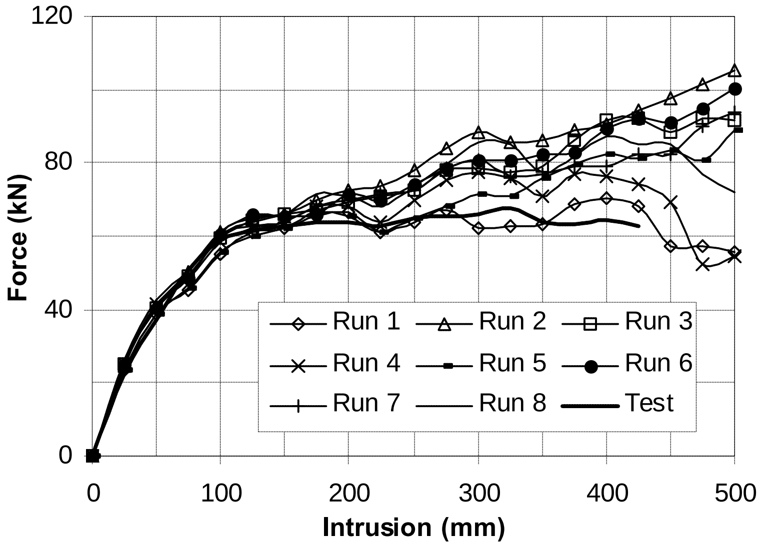


Fig. 7 Simulations of aluminium honeycomb compression tests

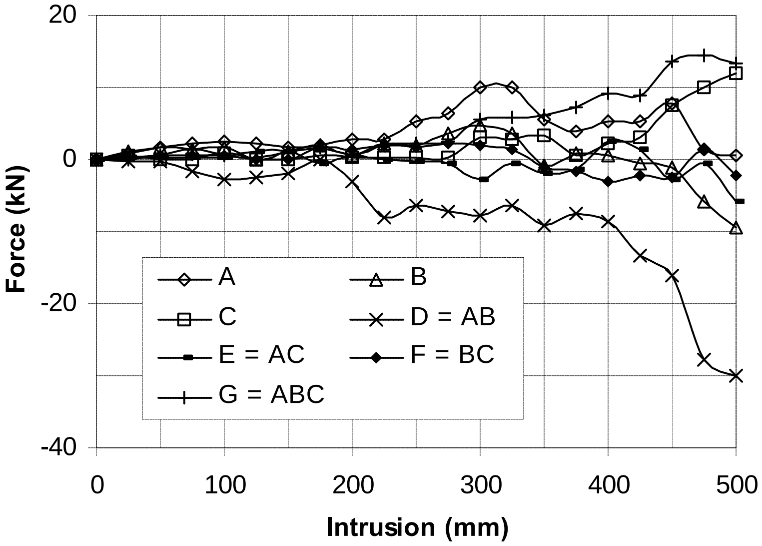
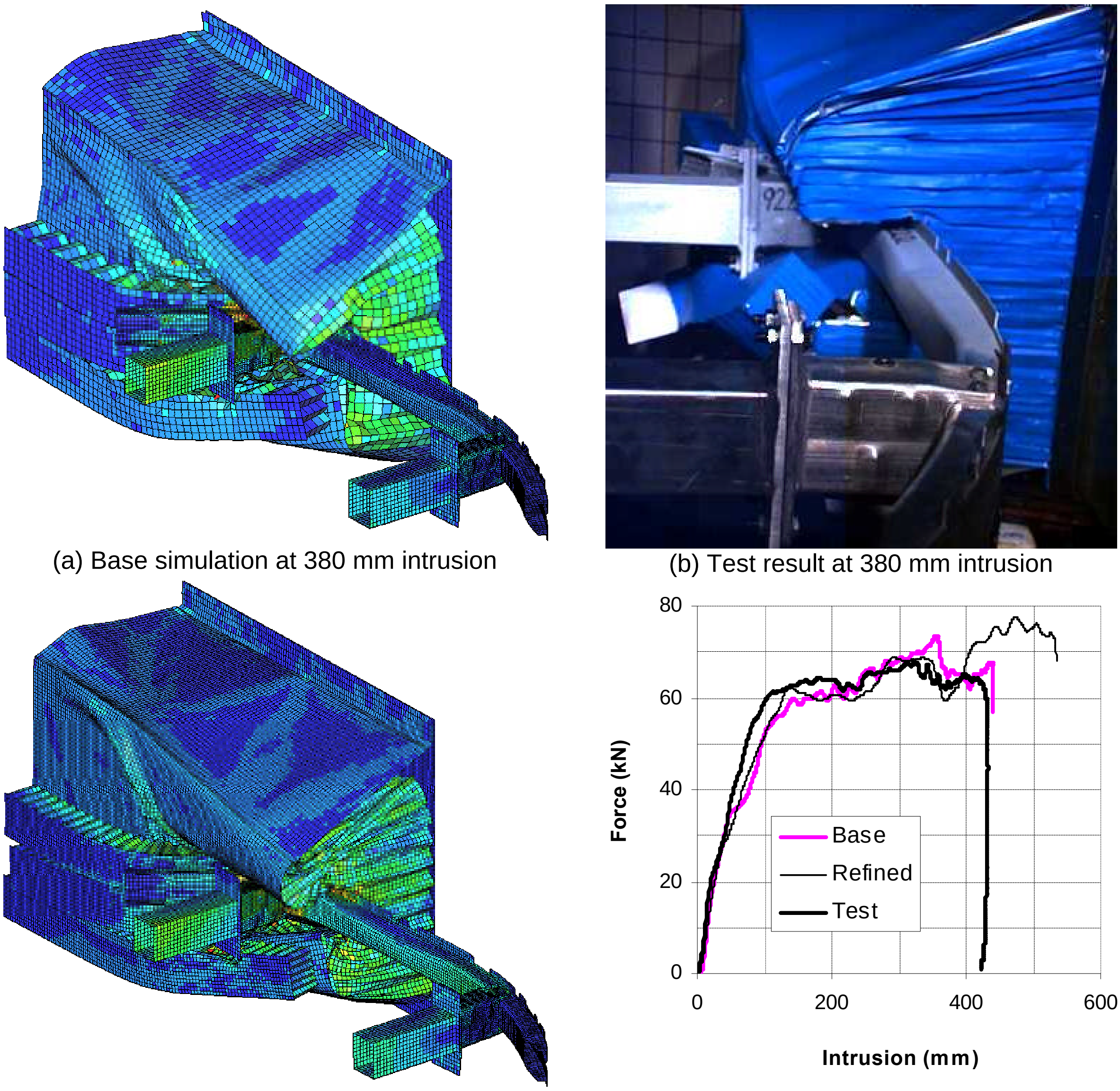


Fig. 8 Simulations of aluminium honeycomb compression tests

4 Discussion

The numerical study shows good correlation between Run 1 and the test result; see Figure 7. But, it seems like the simulations tend to overestimate the force level in the last part of the response curve. Parameter D, which is the failure flag in MAT24 seems to have a significant effect, and as shown in Figure 8, selecting this flag equal to 0.6 seems to be one way to keep the force level low. However, the main effect D is coupled with the interaction AB. Unfortunately, the high value for parameter B was chosen like 0.085 mm that corresponds to a width to thickness ratio about 847 in Figure 5 and indicate to low strength for the bumper elements. Hence, since also parameter A has an effect, it could be an idea to reduce A and increase B.

Simulations were run with A = 0.55 mm, B = 0.95 mm, C = 90 MPa, D = 0.65, E = 110 MPa, F = 0.6 and G = 0.4. Both the base and the refined mesh were run, but the thicknesses were halved for the latter one. Both the test and the base simulation were run with impact velocity 4.99 m/s, and they can be compared directly. Note that the refined simulation was run with impact velocity 8.33 m/s. Both test and simulations show some crack propagation in the upper part of the adhesive between the main block and backing sheet. Moreover, the bottom bumper element is bended up and thereby hit by the crashbox end plate. Then, at about 360 mm intrusion the free end at the two upper bumper elements starts to move out from the main block, and a force peak is observed.



(a) Base simulation at 380 mm intrusion

(b) Test result at 380 mm intrusion

(c) Refined simulation at 380 mm intrusion

(d) Response curves

Fig. 9 Simulations and test of an aluminium bumper system that impacts the ODB barrier

Both numerical models show the same overall deformation mode. But the refined mesh seems to more closely represent some details as the wrinkles at the cladding sheet or the vertical contraction seen at the upper part of the main block. However, these details may also be a result of higher impact velocity. It may be seen in Figure 9 that the cladding sheet corner remains in the simulations while it is nearly not visible on the real barrier at 380 mm intrusion. This may indicate that some elements representing the adhesive at the corner should be removed and thereby allow a rounded and flexible cladding sheet corner without smaller element to represent it.

In the present simulations the adhesive was modelled with yield stress about 100 MPa and tangent modulus equal to 200 MPa. But remember that, due to the scaling, these values should be about five times too high since they referred to a numerical thickness that is about one fifth of the actual wall thickness.

The testcar movement is free during the last part of the crash event, and its rotation influences the energy input into the bumper system. Thus, the boundary conditions are complex since the car rotation is influenced by parameters like its inertia, friction coefficients and force components that are again a result from the barrier as well as the beam deformation. Herein both the test and the base simulation show that the final car rotation was about five degrees. The crashbox is designed to fold in a local mode, but the bumper system also has to resist eventual transverse force components that may lead to a global buckling mode. Also the internal forces that are set up between the rails may influence the crash box behaviour, and herein the rail components give boundary conditions that have to be taken into account. Therefore, the testcar was instrumented to measure the bending moments in both rails during the crash event, and the maximum values are given in table 3. The simulation tells that the force component in Y-direction is less than 16 kN, but this is shown as 25 kN and –9 kN for the left and right rails, respectively. But by comparing the values in Table 3 it seems like the numerical simulation slightly overestimates the internal forces in the rails.

Table 3. Maximum values for bending moments defined by cross section planes through the loadcells

	Left side M_Y	Left side M_Z	Right side M_Y	Right side M_Z
Test	2.7 kNm	-5.9 kNm	0.6 kNM	1.0 kNm
Simulation	2.8 kNm	-7.5 kNm	0.6 kNm	1.8 kNm

5 Conclusion

In a frontal offset collision the honeycomb material is compressed not just along its strong axis, but also in the oblique direction. Thus, when the honeycomb structure is folded this may be seen as the interaction between local and global buckling of the cell structure. The idea was therefore to make an ODB model based on shell elements, and by studying compression tests on specimens that are cut out with varying orientation and use extensive scaling it seems possible to achieve this. The presented model with about 30 000 shell elements seems able to predict the global response for at least one test, and it may easily be refined to represent the more local behaviour as well.

6 Literature

[1] Kojima S., Yasuki T., Mikutsu S., Takatsudo T.: "A Study on Yielding Function of Aluminium Honeycomb", 5th European LS-DYNA Users Conference
[2] Hallquist J.: "LS-DYNA Version 970, Keyword Users Manual", Livermore Software Technology Corporation, April 2003
[3] Hatch J E (editor): "Aluminum, Properties and Physical Metallurgy", American Society for Metals, 1984, page 371-372
[4] Mohr D., Doyoyo M.: "Deformation-inducted folding systems in thin-walled monolithic hexagonal metallic honeycomb", International Journal of Solids and Structures 41, 2004, page 3353-3377
[5] Box G. E. P., Hunter W. G., Hunter J. S.: "Statistics for Experimenters", John Wiley & Sons, 1978, 652 pp

