FROM COMPLEX 3D-FOAM PARTS TO READY LS-DYNA INPUTDATA IN LESS THAN ONE HOUR?

EXAMPLES FROM OCCUPANT SIMULATION AT DAIMLER CHRYSLER

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Abbreviations:

H8	hexahedron 8-node brick element
IP	integration point
K	stiffness
T4	tetrahedron 4-node brick element

Keywords:

foam, meshing, tetrahedron, hexahedron, energy absorption

Abstract

Foam parts are used abundantly in automotive safety. The occupant simulation group at Daimler-Chrysler in particular needs to model the behaviour of padding and dummy parts for the numerical simulation of vehicle side impact and FMVSS201 interior head-impact. A common problem is the geometrical complexity of the parts involved.

In the quest for a faster and easier way to represent these bulky, complex geometries with finite elements, the use of the 4-node tetraeder element in LS-DYNA was systematically investigated. At first we examined the response of the T4 (4-node tetrahedron)-element under simple load cases such as pure shear and uniaxial compression. The behaviour of the classical hexagonal (H8) element was compared to the T4 element in different (regular and free) meshing configurations. The same procedure was applied in a second phase to a combined shear-compression load case and a simple impact load case with a cylindrical penetrator. The conclusion of this work was that although some care must be taken in the use of T4-elements, the element seems to be failsafe in conditions where compression is the dominant deformation mode.

In a brief application overview, the important savings that can be achieved in the model preparation phase due to the use of T4 elements are illustrated. An example of FMVSS201 head-impact is used to show that the differences in results with respect to a hexagonal mesh are within a range that is acceptable for engineering applications.

A summary and conclusions complete the paper.

1 Introduction

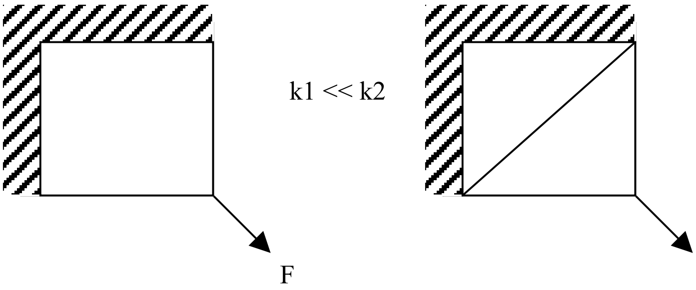
The low stiffness and high deformability of foams make these materials particularly attractive for use as energy-absorbers or comfort-enhancers. Some other properties of foams add to their suitability for use in automotive structures such as low density and the potential to mold almost any shape. The numerical simulation of foams, which is a necessary part of safety investigations, is inherently approximate since the foam cell structure must be modeled as a 3D-continuum using brick finite elements and a material law that can only represent the macroscopic behaviour of the foam. The numericist faces many practical problems that require pragmatic engineering solutions. Such problems include the selection (or development) of a material law capable of reproducing the foam's response under 3-dimensional dynamic loads causing high or at least medium deformations and the generation of finite element models that give a smooth representation of the complex undeformed and deformed geometries of the foam structure. From a numerical point of view, foams are best classified according to their unloading behaviour. We can then distinguish between recoverable (reversible) foams requiring elastic material laws and crushable (irreversible) foams that are obviously better simulated using material laws of the elasto-plastic type. Most automotive foams are entirely or at least largely recoverable (with the exception of certain PU-foams used as energy-absorbers) and important efforts have been made recently to develop material laws for this class of foams that allow inclusion of a large amount of experimental information /1/. This has lead to a rather universal approach towards the use of material law 83 (Fu Chang Foam, /2/) for the simulation of recoverable foam parts in automotive safety applications. We have also followed this approach in the paper below. The second problem is concerned with the generation of brick element meshes of foam parts with a typically very complex geometry. These meshes need to be sufficiently fine to capture the high deformations that will occur in the component. A stable and accurate solution can only be expected on condition that the hexahedron brick elements are of good quality: element aspect ratios are severely limited and mesh generation is accordingly time consuming since it must largely be performed manually. In this paper we investigate an approach allowing for fast automatic mesh generation using a tetrahedron finite element and leading to substantial time-savings.

2 Comparison of tetrahedron and hexahedron elements for general and compression-dominated load cases

2.1 Quasistatic shear load on a steel dice

In this test a steel dice is clamped on two sides, the opposite ridge is loaded by a force that grows linearly in time and then keeps a constant level. The dice is modeled using a single 8-node brick element that will be divided into 6 4-node tetrahedron elements.

It is known from experience with shell elements that splitting a 4-node element in two triangular elements will considerably stiffen the response in such a situation :



The rationale behind this load case is to check for similar effects caused by the use of tetrahedron elements. The results based on an elastic dice are shown in Fig. 1 below. Plotted are the displacements as a function of time for the nodal point at which the force is applied.

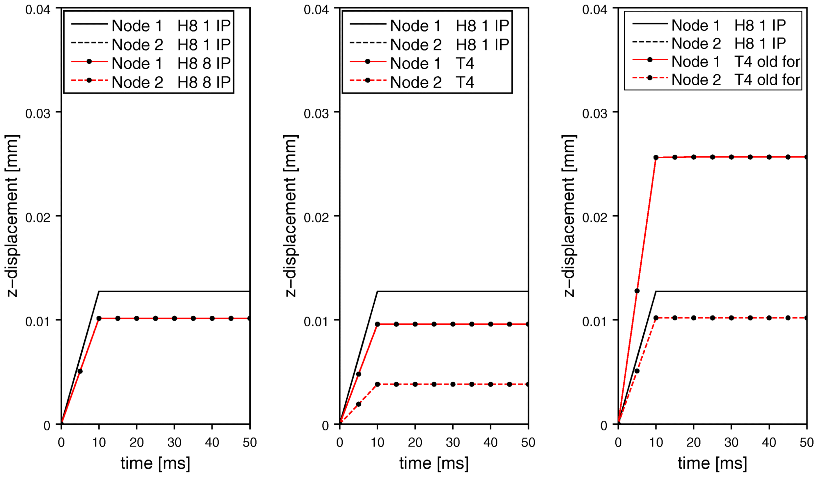


Figure 1: Displacement under Shear Load for an Elastic Dice

For the fully integrated 8-node hexahedron we obtain displacements that are about 15% lower then the corresponding results obtained using a (standard) underintegrated element. In view of the zero-energy modes that may occur in the single integration point element, this is not surprising.

The mesh consisting of 6 4-node tetrahedron elements also behaves stiffer then the single hexahedron but looses the symmetry of the problem: whereas the result in one nodal point nearly corresponds to the values that were obtained with the fully integrated hexa, the other node exhibits less then half of that displacement. The results are thus too stiff and to a certain degree mesh-dependent.

When degenerated hexahedrons are used in the same configuration as the tetrahedron elements, the results in terms of nodal displacements are again non-symmetric and the mesh now actually behaves too weak on one side of the dice. This is a first indication of the unreliability of this approach.

The effects that were noticed here for very small (elastic) displacements, can be dramatized by using an elasto-plastic material model and loading the dice slightly above the yield point. Upon yielding, a fast increase in displacement occurs as long as the force-load grows in time. The final displacements thus depend upon when exactly the von Mises stresses in each element reach the value of the yield stress. Results for the displacements in the nodal point where the load is applied are shown in Fig. 2 below .

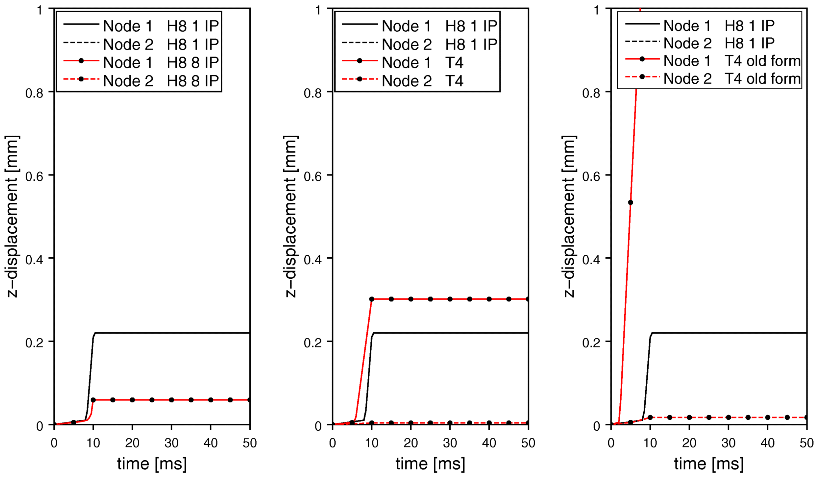


Figure 2: Displacement under Shear Load for an Elasto-Plastic Dice

It can be seen that the difference in results between 8-node fully- and under-integrated elements increases drastically. Obviously this is an effect that would be much smaller if a ‘reasonable’ mesh were to be used to treat this problem.

When using tetra-elements however, one side of the cube always remains nearly undeformed, meaning the yield point is never reached. On the opposite side, the mesh is more flexible then a single hexahedron. In the particular case of degenerated hexahedrons, the error reaches nearly 1000%.

Although this test is not physical, (the meshes used are certainly not at all suitable to study the problem of shearing a steel dice) it allows for some interesting observations about element behaviour. The first conclusion is that the tetrahedron should be used with some care, in particular the overly stiff behaviour under shear loads is similar to the behaviour of linear triangle elements and should be neutralized.

2.2 Dynamic compression test at 2.75m/s on an open-cell soft foam cube

Since we intend to use the tetrahedron element to simulate the compression and energy-absorption of foam parts, we will directly test it’s compressive behaviour in conjunction with a material law used to simulate rate-dependent reversible foams. We chose material law 83 in LS-DYNA, which was developed originally by Fu Chang and has found wide acceptance for modeling foams in the engineering community.

A droptower test was executed at a constant speed of 2.75m/s to provide a physical reference. The material used was a 40g/l seat foam. The drop mass was chosen large enough in order to guarantee a constant dropspeed for very high strains (almost 90%), beyond this point the velocity drops sharply to zero and the engineering strain rate can no longer be considered constant. A stress-strain relationship was derived from the test results for the range with constant engineering strain rate and material law 83 in LS-DYNA was modified in order to allow the direct input of stress-strain curves measured at constant engineering strain rate (or constant dropspeed). For further information about the modification on material law 83 see /1/.

Simulations of this test were performed using the standard underintegrated hexahedron element and with three different meshes using 4-node elements. The first mesh was obtained by splitting every hexa-element into 6 tetrahedron elements (regular T4). The second was obtained from an automatic mesh option for tetrahedron elements in a preprocessor (free T4). The third 4-node mesh corresponds to the first one, but degenerated hexahedron elements (old formulation in LS-DYNA) are used rather then real tetras.

The obtained results correlate well with the test and are very close to each other, with the exception of the degenerated 8-node elements that accumulate considerable error and must be deemed unusable for this type of problems. In Fig. 3 below the experimental and different numerical results are compared in terms of force-displacement characteristic of the foam. Comparisons are performed globally and separately for the low stress region.

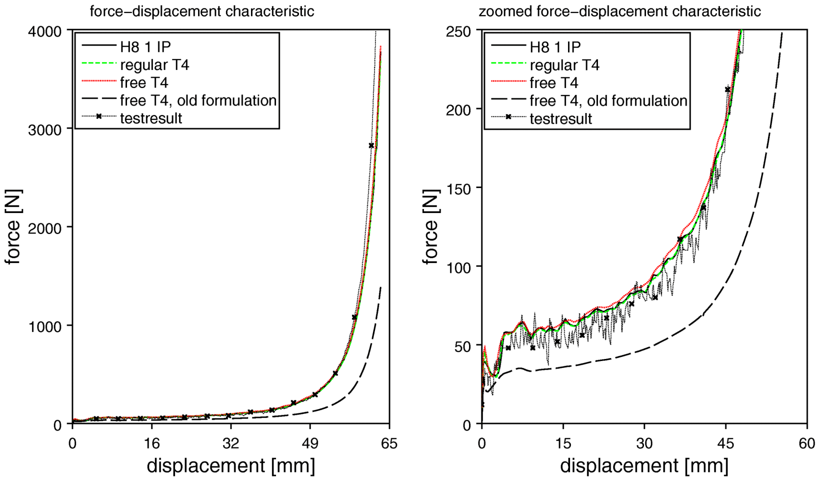


Figure 3: Force-Displacement Characteristic for a Soft Foam under Dynamic Compression

From this test, it can be seen that tetrahedron elements yield a response that is not mesh-dependent in any way and are fully equivalent to the standard underintegrated hexahedron, for problems of uniaxial compression.

2.3 Quasistatic shear-compression test on an open-cell soft foam cube

In view of the element test cases on the dice (chapter 2.1), it is necessary to investigate the influence of the shear stiffness on the energy-absorbing behaviour of foam parts. In order to achieve this, a quasistatic combined shear-compression test was performed by compressing a skewed foam cube. Both normal and tangential force were measured.

This test was simulated using the identical 4 meshes (1 8-node and 3 4-node) that were used in the analysis of the droptower test. The numerical and experimental results are shown in Figure 4 below for both normal and tangential forces.

Again the results obtained with the degenerated hexahedron were much too weak and can be discarded. Both tetra-meshes give results that are slightly stiffer then the 8-node hexahedron mesh. Concerning the normal (compressive) force all three results are somewhat weaker then the test result. The shear force is overestimated by the simulation for low and average strain values and underestimated at high strains (in the densification phase).

Although the simulation results are not very good with respect to testing as far as the tangential force is concerned, the normal force is rather well reproduced meaning the compressive strength of the foam is not strongly influenced by the additional shearing mode.
Both tetrahedron meshes yield identical results in this test, showing again no mesh dependency in their response.

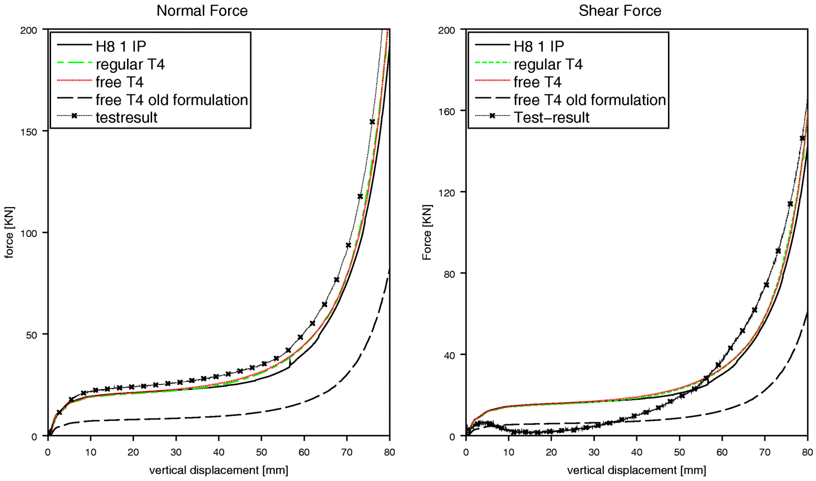


Figure 4: Force-Displacement Characteristic for a Soft Foam under Quasistatic Shear Compression

When energy values are compared, we see that the deformation energy in the tetrahedron mesh is slightly higher then the internal energy in the hexahedron mesh. This is due to the presence of an hourglass energy component in the hexahedron mesh (non-existant in 4-node elements) and to the slightly stiffer behaviour of the tetrahedron elements in this particular test. (see Figure 5 below).

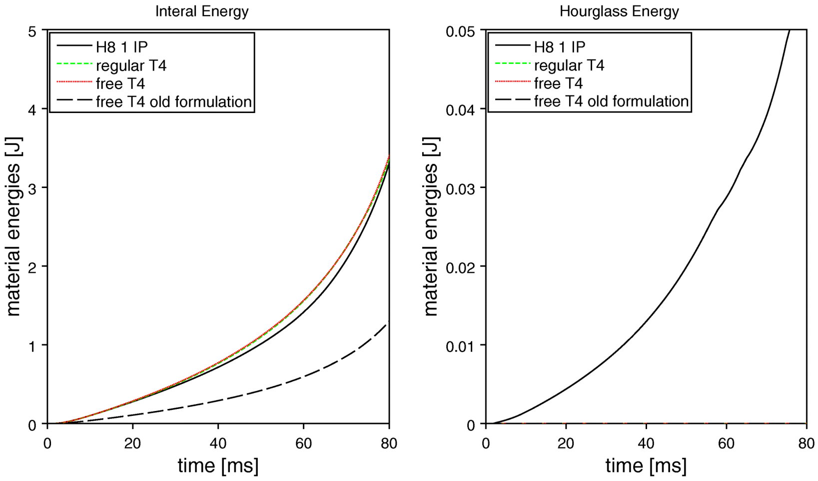


Figure 5: Energy Absorption for a Soft Foam under Quasistatic Shear Compression

2.4 Cylinder-droptest at 3.00m/s on an open-cell soft foam cube
To build a final reference load case, the 3-dimensional dynamic response of a foam part was examined. The load selected was a cylinder droptest causing compression and a complex deformation pattern in the foam part.

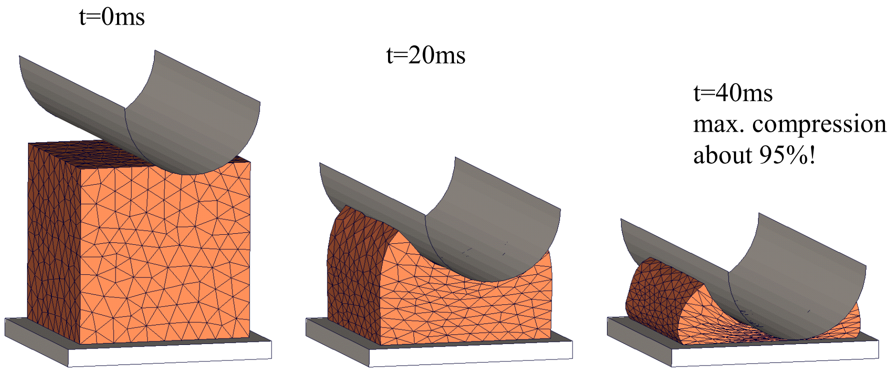


Figure 6: Animation Sequence for the Simulation of a Cylinder Drop Test with Automaticly Meshed Tetrahedron Elements

As in the two previous cases, 4 different meshes were used to simulate this test (for which there was no physical reference). A comparison of the impact forces on the cylinder (shown in Figure 7) shows that:

1. The hexahedron and the automatically meshed tetrahedron element yield similar results
2. The tetrahedron mesh obtained by splitting every hexahedron element in 6 4-node elements gives a force peak that is about 20% too high
3. The mesh consisting of degenerated hexahedron elements yields a result that is about 50% too stiff and will again be discarded

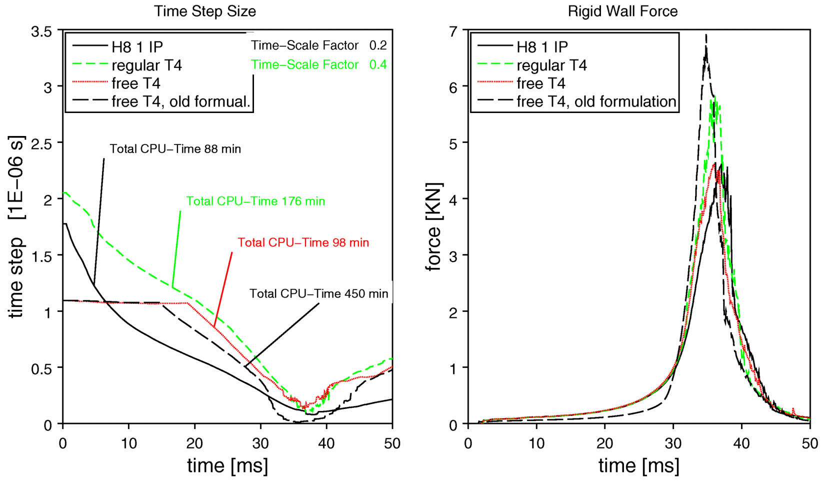


Figure 7: Time Step Size and Impact Force for a Soft Foam in a Cylinder Drop Test

When the energy-absorption in the foam block is considered (see Figure 8 below) it can be seen clearly that the degenerated hexahedron elements allow too much compression in the early stages of the deformation and consequently generate higher impact force levels (shown as tangents to the energy curves) in the densification phase.

In this case, involving a rather complex 3-dimensional state-of-stress, it can no longer be said that the tetrahedron element gives results that are fully mesh-independent. In particular the ‘regular’ mesh that was obtained by splitting every hexahedron in 6 tetrahedrons automatically seems to stiffen the response.

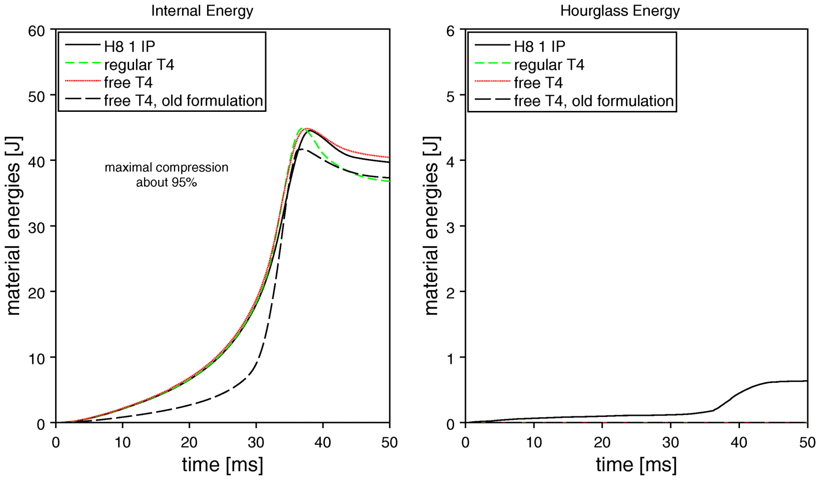


Figure 8: Energy Absorption for a Soft Foam in a Cylinder Drop Test

When the evolution of the explicit timestep is considered, (Figure 7), we see that the hexahedron and the regular tetrahedron mesh both have an initial timestep that is close to 2 microseconds. For the 4-node meshes that were obtained by automatic meshing, this value is reduced to nearly half (about 1 microsecond). However, the minimal timestep reached for high compressive strains of about 95% is very similar for all meshes and lays around 0.2 microseconds. This is drastically different only for the degenerated hexahedrons. These elements behave too weak initially resulting in a higher final compression corresponding to a higher peak force and a lower minimal timestep (about 0.1 microseconds). The cpu-time needed increases accordingly. An inspection of the timestep evolution is sufficient to demonstrate again the unsatisfactory behaviour of the degenerated hexahedrons.
Since the number of elements needed in the free mesh is much lower then in the regular mesh though, total cpu-time is smaller when a free (automatic) mesh is used and is actually comparable to the cpu-time needed by the hexahedron mesh.

3 Comparison of mesh generation for complex 3-dimensional geometries using hexahedron and tetrahedron elements

When automatic meshing of tetrahedron elements is used the mesh generating effort involved in modeling foam parts can be all but eliminated. As an example we can mention the model of an A-pillar padding part (see figure 9) that was completed in about 5 minutes using the automatic meshing capability of SYSMESH and took 12 hours of meshing time when hexahedron elements were used. The tetrahedron mesh consists of about 12.000 T4-elements and the hexahedron mesh of about 3.500 H8-elements. A similar example concerns the model of a roofrail padding. Most dramatic was the difference in the modeling of the pelvic-foam part of the US-SID (see fig. 10). Precise scanning of the real geometry revealed a part of extraordinary complexity with many transitions between regions that were to be modeled with a different number of brick layers. The manual modeling using hexahedron elements of this pelvic foam was considered practically unfeasable: the cost would simply be too high. Using a tetrahedron automatic mesh the model was completed in roughly one hour.

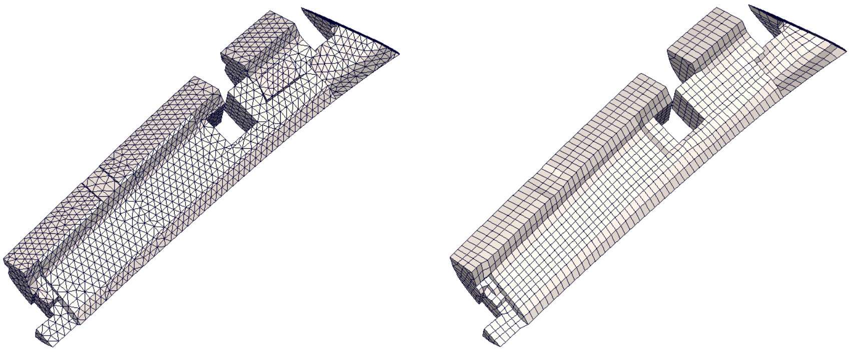


Figure 9: A-Pillar Padding Tetra- versus Hexaheadron Meshes

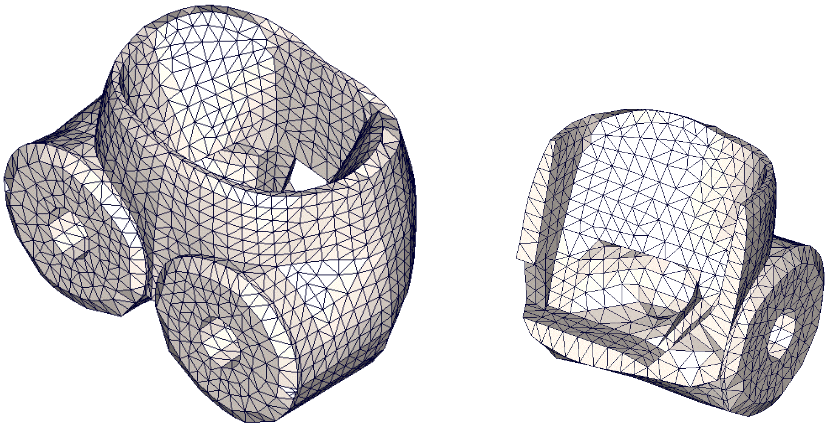


Figure 10: USSID-Pelvic Foam Tetrahedron Mesh

4 Comparison of hexahedron and terahedron elements in a real-life simulation of an energy-absorbing foam part concerning FMVSS201 head-impact on an A-pillar trim

As an example of real life application, we show a simulation of head impact according to the FMVSS201 regulation on a vehicle A-pillar. The A-pillar trim and the underlying padding are modeled as well as the structural parts (see Figure 11).

The foam padding block was modeled using the standard hexahedron and a free (automatic) tetrahedron mesh as described in chapter 3. Differences in head-acceleration and head-velocity obtained in the two simulations are within a normal spread that could be expected to exist between to experiments as can be seen in Figure 12 below.

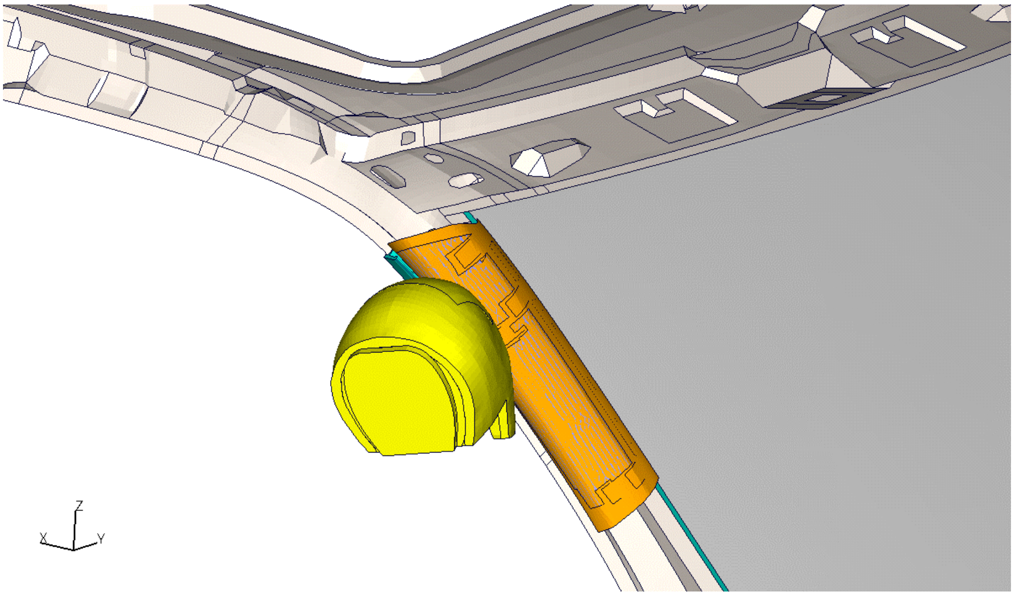


Figure 11: FMVSS201 A-Pillar Head Impact – Numerical Model

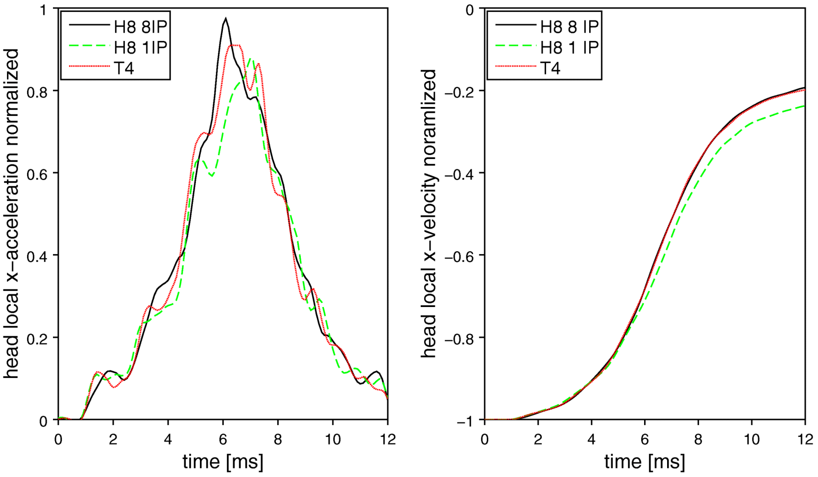


Figure 12: FMVSS201 A-Pillar Head Impact – Head Accelerations and Velocities

Comparison of the energy values shown in Figure 13 bellow, shows that the energy-absorption in the tetrahedron mesh is very close to the sum of internal and hourglass energies in the hexahedron mesh.

It would be useless to discuss which one of these numerical results is better. From an engineering point of view, they are both good enough to make decisions concerning the structure and that is all that counts. An additional simulation using fully integrated hexahedron elements was performed and yielded results for the head acceleration and head-velocity that are actually closer to the tetrahedron element then to the underintegrated hexahedron. Obviously no over-optimistic conclusions should be drawn from this.

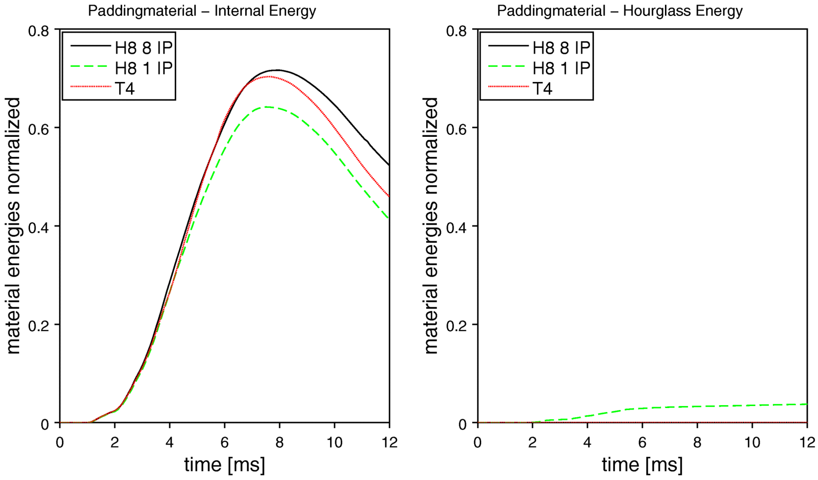


Figure 13: FMVSS201 A-Pillar Head Impact – Energy Absorption in Padding Block

5 Summary and Conclusions

A systematic comparison between hexahedron and tetrahedron elements using test cases of increasing complexity has shown that the poorer element quality of the tetrahedron is not a major issue when large compression and energy-absorption in foam parts are simulated. The consequent time savings in mesh generation are important and the obtained results seem accurate enough to be useful in an engineering context. In particular it was observed that the free automatic meshing at least does not seem to reduce the accuracy of the tetrahedron element versus the use of regular, structured meshes. It should be emphasized again that only the suitability for a very particular application of the tetrahedron element was investigated in this paper rather then it's general properties.

In a way the use of tetrahedron elements for the simulation of foam parts is a decision that is consistent with the use of the Fu Chang material law. The input data for the Fu Chang law consist of non-linear stress-strain curves describing the foam's measured response under uniaxial tensile and compressive dynamic loads. Exactly these load conditions are represented impeccably by the tetrahedron elements. It is therefore felt that the added loss in accuracy is mainly on the shear behaviour, for which no experimental information is processed directly by the material law anyhow.

6 References

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/2/ LS-DYNA User's Manual Version 940, LSTC, June 1997.