CHARACTERIZATION AND COMPONENT LEVEL CORRELATION OF ENERGY ABSORBING (EA)

POLYURETHANE FOAMS (PU) USING LS-DYNA MATERIAL MODELS

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ABSTRACT

Polyurethane (PU) foams are one of the most widely used countermeasures for head impact protection. For accurate prediction of the head injury parameters, studies were conducted to establish a reliable LS-DYNA[1] material model to characterize PU foams. A 5.0pcf (80.09 g/l) PU foam was characterized using four different material models available in LS-DYNA for simulating foams, namely MAT_LOW_DENSITY_FOAM (MAT57), MAT_CRUSHABLE_FOAM (MAT63), MAT_BILKHU_DUBOIS_FOAM (MAT75) and MAT_FU_CHANG_FOAM (MAT83)[1]. The Finite Element Analysis (FEA) results were compared with the physical test results.

The FEA material model resulting from the characterization procedure was validated using a component level, head impact correlation study. A simple side rail section was extruded about the SR1 target point and was impacted with a standard headform at an initial velocity of 15mph. Three different cases were investigated; baseline model with body-in-white (BIW) only, BIW with 18mm foam and BIW with 22mm foam. The Head Injury Criterion (HIC)[2] and acceleration curves from the simulation were compared with the physical tests.

INTRODUCTION

Occupant head impact protection is one of the major concerns in automotive safety design. Head impact countermeasures are used to reduce the rate of deceleration of the head when it impacts different points inside a vehicle during a crash, namely, pillar trims, headliners, side rails and seatbacks. Several countermeasures are used in the auto industry to reduce injury to the head. PU foam is one of the most common head impact countermeasures used in the industry. Foams are widely used as energy absorbers and comfort enhancers due to their lightweight, low stiffness and the ability to take large compressive strains. It is quite versatile in energy absorption because of the several deformation modes that it can undergo; cell -wall bending, elastic buckling, plastification and rupture. Most of the foams are open or closed cell structures and the mechanical properties vary widely, depending on the geometry and density. As foam can absorb significant impact energy, and also because of their capability to provide good comfort, their applications in the auto industry are wide-ranging. They include door and pillar padding, headliner reinforcements, seat cushions, bumpers, and dummy components.

FEA is widely used to simulate the behavior of foam. The foam thickness recommendations, given by FEA engineers are very crucial for packaging space decisions and HIC numbers. Effective characterization of foam is one of the major tasks in head impact FEA. LS-DYNA is a popular tool used for this purpose. It is a non-linear, explicit FEA solver, and it has different numerical material cards available. The foam material models available in LS-DYNA have to be evaluated prior to the use in an impact test simulation. This is achieved by comparing the acceleration values and force-deflection response obtained from the simulation to the physical test. The physical tests are conducted by the foam suppliers on foam samples of standard thickness and desired density. Based on the level of correlation with different material cards, the best material model will be chosen.

APPROACH

The scope of this paper can be outlined in two major steps:

1) Characterize foam material by correlating acceleration and force-deflection parameters of FEA with test results, for PU foam of 5.0pcf (80.09 g/l) density and 22mm thickness, at an impact velocity of 15mph. Four different material cards in LS-DYNA were studied, namely MAT57, MAT63, MAT75 and MAT83.

2) Correlate a physical head impact test performed on a uniform cross-section side rail flange with 18mm and 22mm PU foam attached to it.

In LS-DYNA, foams can be categorized by two macroscopic behaviors. They are reversible (recoverable) and irreversible (crushable) characteristics. The reversible foam material has nonlinear elastic behavior and undergoes rupture in tension. The irreversible foam material has elastic-plastic behavior and undergoes failure in tension and shear. To reliably simulate the foam's macroscopic behavior, five minimum requirements are recommended by Kikuchi [3].

1. Uni-axial, Quasi-static compression test.
2. Uni-axial, Quasi-static tension test.
3. Simple Shear test.
4. Hydrostatic compression test.
5. Uni-axial dynamic compression test.

Material Characterization

Methodology. The loading that foam sections undergo in case of head impacts resulting from a vehicle crash, is dynamic and compressive in nature. Hence, material model characterization was done for the uni-axial dynamic compression case only. Physical tests for high-speed foam compression were conducted and strain-rate dependent material properties were obtained from these tests. The tests were conducted on 5.0pcf PU foam blocks of 18 and 22mm thickness, at an impact speed of 10, 12 and 15mph. The in-vehicle crash tests are performed at 15 mph and hence the material characterization was investigated at that speed. The idea was to input the force-deflection characteristics obtained from the physical tests into the CAE simulation. This was done by using the stress-strain curves based on foam geometry, obtained from physical test. Once the FE analysis was done, the force-deflection characteristics from the simulation were studied and compared with the actual force-deflection characteristics from the physical tests. Four different cases were simulated for the material cards mentioned above, and results were compared to find the material model that best simulates the foam.

Finite Element Model. The FE model of the set-up is shown in Figure 1. A flat steel plate impacts a foam block that is supported on a rigid fixture. The steel impactor hits with an initial velocity of 15mph in the Z direction. The finite element model of the foam and the rigid impactor were created by solid brick elements. In LS-DYNA, element type 2, which is the fully integrated solid element formulation, was used for the foam, and type 1, the constant stress solid element formulation, was used for the impactor. The mass of the impactor was 15.6lbs, and the impact speed of 15mph was studied for material model comparison.

CONSTRAINT_SURFACE_TO_SURFACE algorithm was used to simulate the contact between the foam and the impactor. The foam block was supported at the bottom using a RIGID_WALL contact formulation. MAT_ELASTIC was the material card used for the steel plate and for foam, the card was different in each of the four cases.

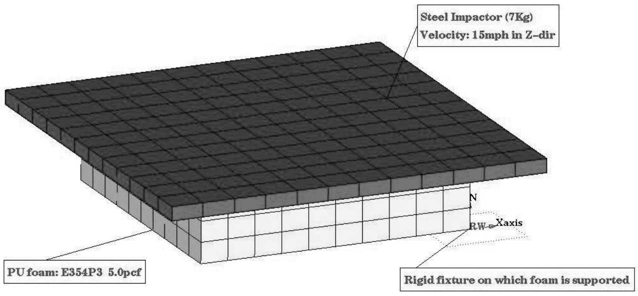

Figure 1. Finite Element Model of the test set-up.

Uniform Cross-Section Head Impact

Methodology. The results obtained from the foam characterization process were used in a real head impact simulation to understand the behavior of the foam materials. A simple side rail section was extruded about the SR1 target point and was impacted with a standard headform at an initial velocity of 15mph. To develop the confidence in the methodology, the side rail section, without foam, was impacted first. 18mm and 22mm foam blocks were added on the side rail section, and the head impact results were compared to study the effects of foam in a real physical head impact test. This correlation study validated the foam material models, so that they can be used with confidence in full system level, head impact simulations.

Finite Element Model. The finite element model of the test set-up is shown in Figure 2. A typical cross-section of the side rail profile at SR1 target point was extruded to 510mm and was impacted with a standard FTSS[4] headform at 15mph. The direction of the headform motion was along the Y-axis, and the orientation of the headform relative to the side rail flanges was 18 degrees. The uniform cross-section side rail was modeled using fully integrated shell elements (type 16), and the foam using brick elements (type 2). The side rail flanges were constrained in all the degrees of freedom at both side edges. The inner side rail flange was 1.5mm thick and the outer flange was 2.5 mm thick, and both the flanges were spot welded at regular intervals. Mild steel was used for side rail flanges and the LS-DYNA material card used was MAT_LINEAR_PIECEWISE_PLASTICITY (MAT24)[1]. The foam block was attached to the side rail flange using common nodes.

The FTSS headform is modeled with a series of solid and shell element layers. The skull and the forehead impact zone are modeled with shell elements (type 2) and the skin is modeled with solid elements. A null surface is created on the skin for defining the contact area. The acceleration of the headform is calculated at its center of gravity (CG). A local coordinate system is modeled using beam elements to define the CG of the headform[4].

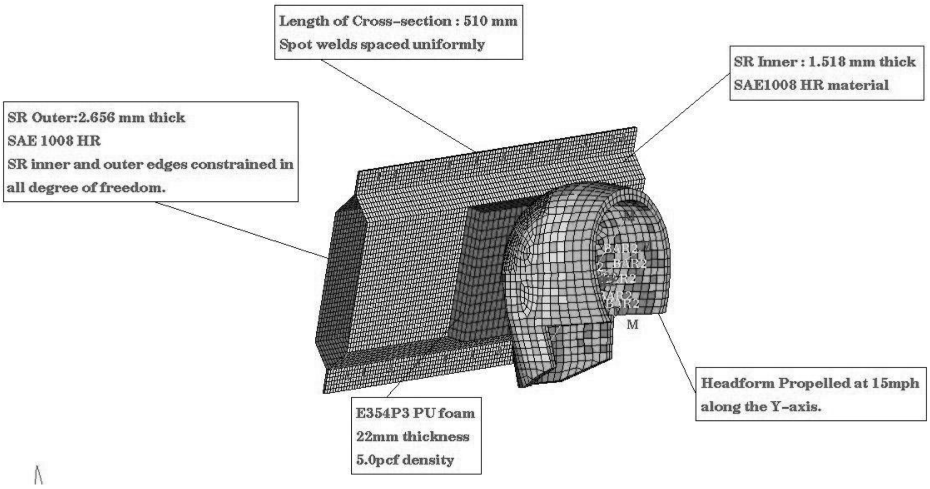

Figure 2. CAE modeling for head impact on uniform cross-section side rail flanges.

RESULTS AND DISCUSSIONS

Material Characterization

Figure 3 and Figure 4 shows the acceleration-time characteristics of the material cards that were investigated. Figure 3 clearly shows that MAT63 and MAT75 did not show good correlation with the physical test. The peak deceleration numbers as well as the pattern of the curves were quite different than the test. While the test peak

'g' (deceleration in terms of gravity) value was 216g; the maximum 'g' for MAT63 and MAT75 was 224g and 257g respectively.

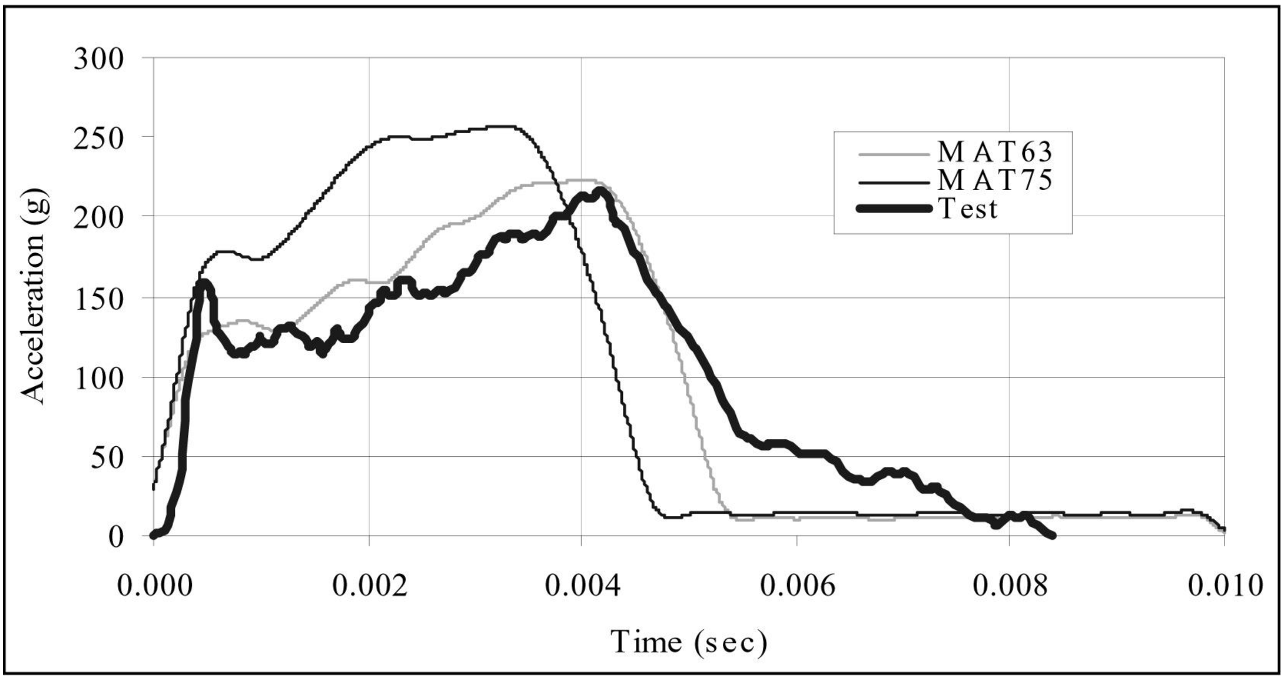

Figure 3. Comparison of acceleration-time response for MAT63 and MAT75 cards.

The pattern of the deceleration curve for MAT57 and MAT83 shown in Figure 4 shows excellent correlation with the test results. The peak 'g' values for MAT57 and MAT83 were 210g and 190g respectively. The behavior is best captured by MAT57 material model. The unloading phase also correlated very well, whereas in MAT83 the unloading behavior was quite different than the test results.

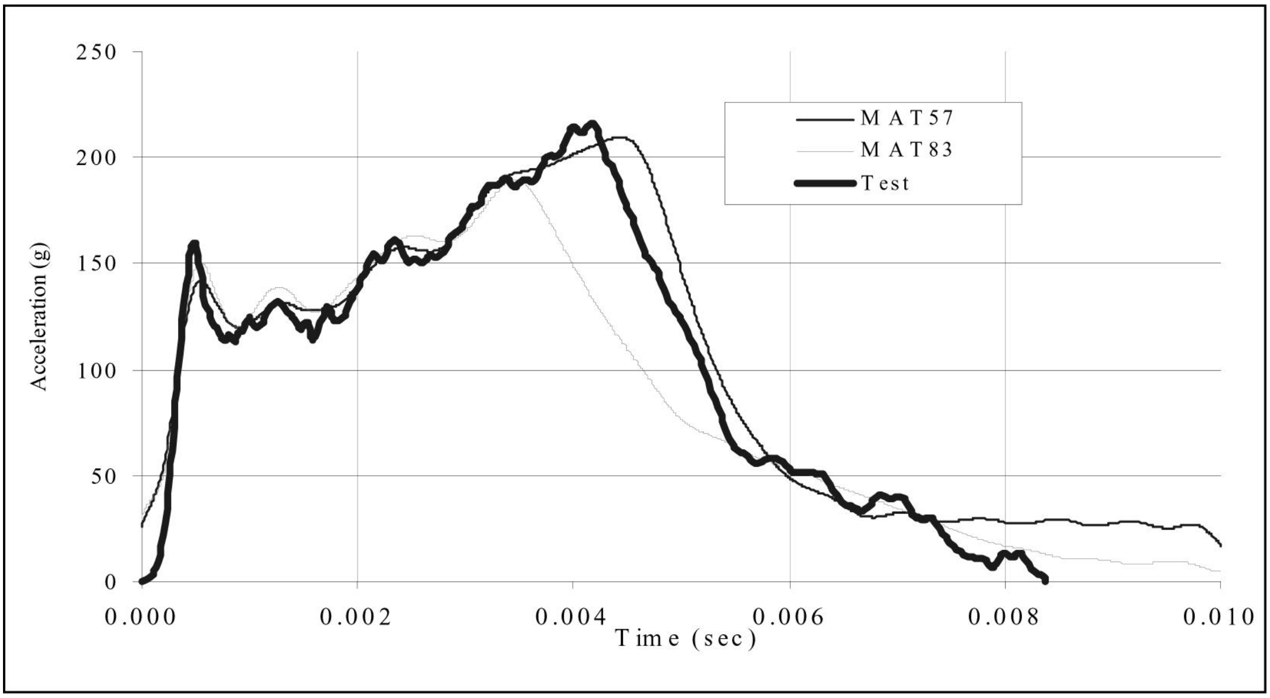

Figure 4. Comparison of acceleration-time response for MAT57 and MAT83 cards.

Force-Deflection characteristics for the different material models are compared in Figure 5 and Figure 6. The nature of the acceleration curves are pretty much reflected in the force-deflection response too. The comparison of force values in Figure 5 clearly shows that the peak force values for MAT75 were not even close to the test results.

Although, peak force values for MAT63 matched closely with test results, the nature of the curve was totally different. The test peak force value was 15,155N, whereas peak forces for MAT63 and MAT75 were 15,610N and 18,000N respectively.

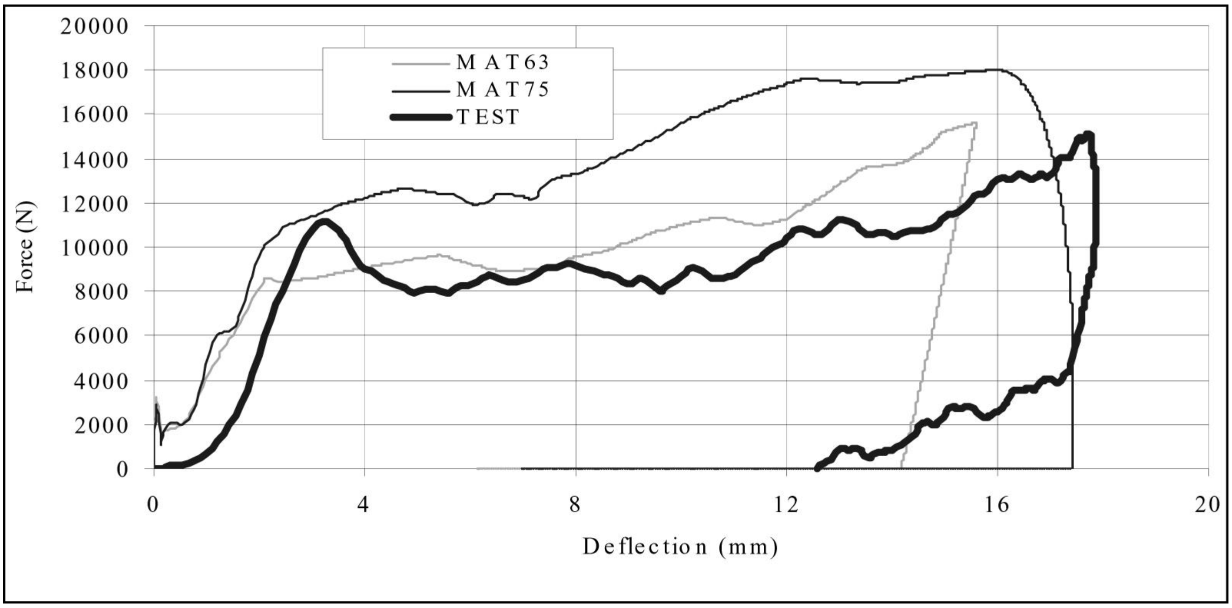

Figure 5. Comparison of force-deflection characteristics for MAT63 and MAT75 cards.

Figure 6 shows the force-deflection response for MAT57 and MAT83. In case of MAT83, although the loading phase was quite similar to test results, the unloading path did not match. The peak force value was 13392N. MAT57 demonstrated excellent correlation with test results, in terms of both the curve pattern as well as the peak force value. The unloading path was also very close unlike in MAT83. The peak force value in this case was 14,622N.

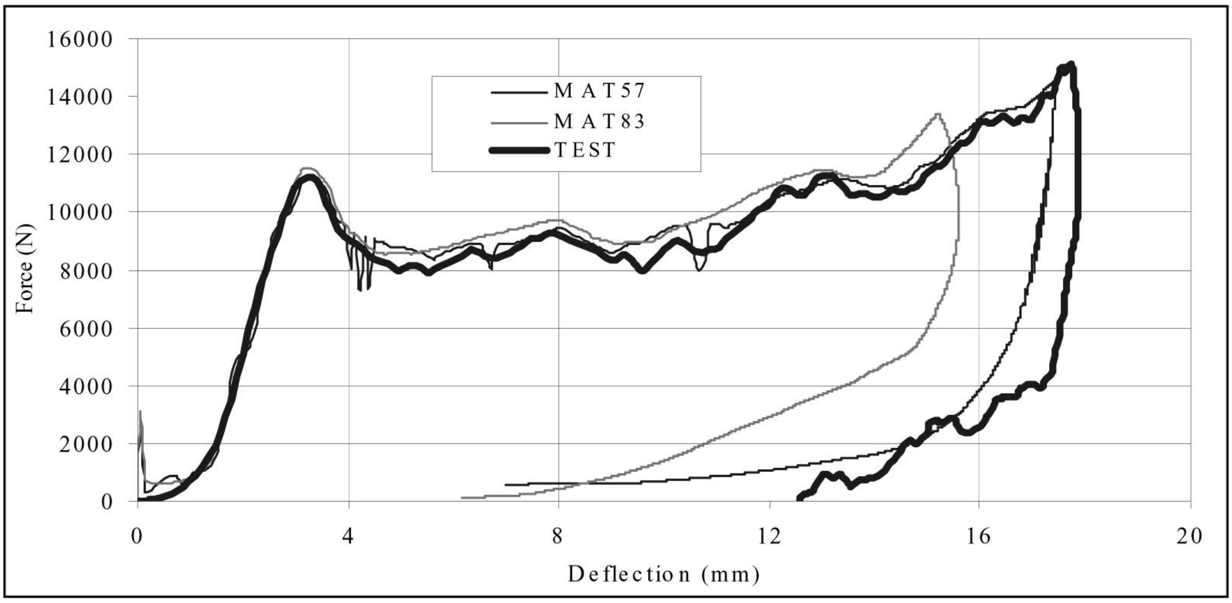

Figure 6. Comparison of force-deflection characteristics for MAT57 and Mat83 cards.

Uniform Cross-Section Head Impact Correlation

The side rail BIW impact was first correlated with physical test results to ensure a reliable full vehicle model. Comparison of test and FEA results for the side rail impact is shown in Figure 7. The nature of the simulation curves matched very well with the physical test. The HIC(d) value obtained from the physical test was 1105 and FEA correlated well, with a value of 1092. The test peak 'g' value was 181g and the FEA result was 179g.

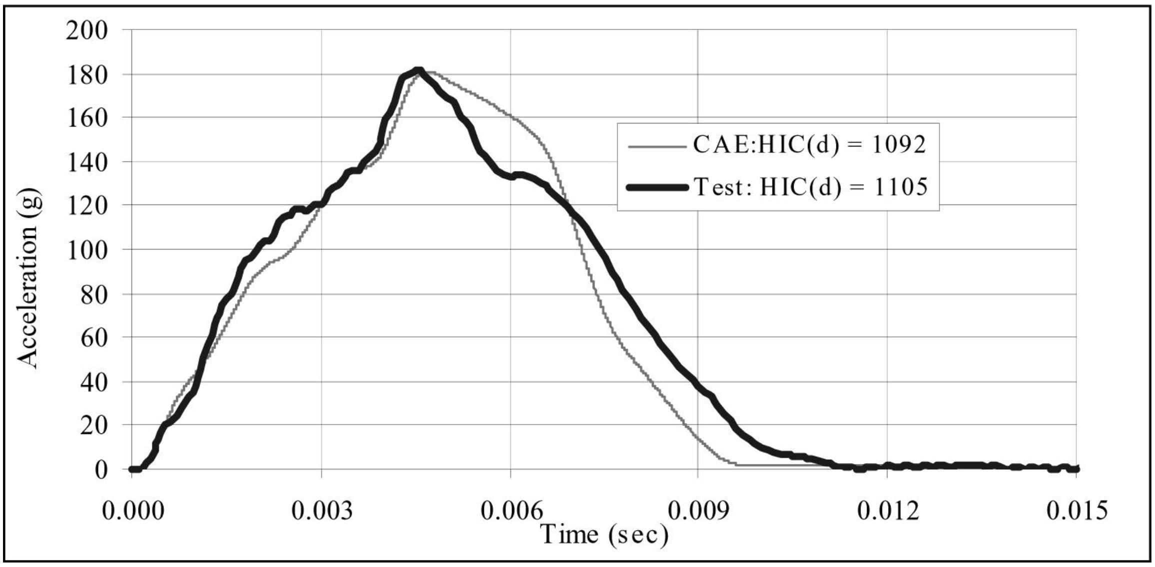

Figure 7. Comparison of acceleration curves for uniform cross-section BIW impact.

Figure 8 shows the comparison of test and FEA results for the 22mm foam impact. The foam characterization results showed that MAT57 and MAT83 simulated the foam well. Hence, both MAT57 and MAT83 material cards were used in the foam simulation. The results for MAT57, in terms of HIC(d) numbers and nature of the acceleration curve, were very close to the test results. The HIC(d) value for the physical test and MAT57 was 840 and 815 respectively. The peak 'g' value for the physical test and MAT57 was 132g and 136g respectively. The results for MAT83 are also shown in Figure 8. The HIC(d) value in this case was 738, and peak 'g' value was 125g. Comparing HIC(d) values and the nature of the curves, MAT57 simulates the foam characteristics better than MAT83. The 'g' value for MAT57 was also very close to the value for the physical tests.

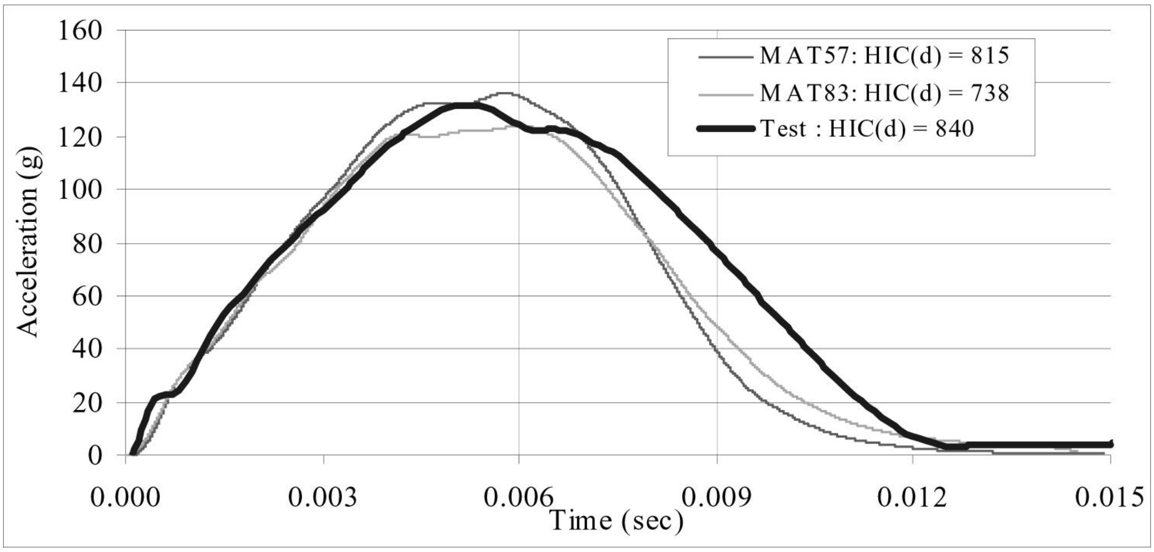

Figure 8. Comparison of acceleration curves for the foam impacts.

SUMMARY

From the results, MAT57 and MAT83 were the two material cards that showed good correlation with physical test values. These are the two cards that are most commonly used in the industry to simulate foams. The following is a summary of the different parameters required and their recommended values, in setting up these material cards.

MAT57 (MAT_LOW_DENSITY_FOAM)

This material card is for low-density foams such as seat cushion padding. Based on the studies discussed above, this card can also be confidently used for simulating PU foam. This card is very robust in its application and it is relatively easy to modify its parameters.

The following data are needed from the material suppliers to set up this card.

1. Young’s modulus
2. Density
3. Nominal Stress–Strain curve
4. Tensile cut-off stress

Most of the parameters used in this card are default values at the initial correlation stage. The following options have to be examined for better results.

1. The stress-strain curve given by a material suppliers may not be sufficient since the measuring device in test lab cannot capture the densification part of foam compression. Therefore, if needed, the curve can be extrapolated using 3rd order hyperbolic function in the densification area.
2. The hysteric unloading characteristic can be controlled by ‘HU’ option. This factor can vary from 0.0 to 1.0. If using 1.0, foam unloads rapidly and loses hysteresis. Therefore, it is recommended to start from a value of 0.01.
3. For the decay constant (b), a value close to 0.0 results in slow creep in unloading. It is recommended to use 0.0 as default.
4. The option ‘SHAPE’ can control the dissipation characteristics. If the foam has hysteresis unloading behavior, use a value less than 1.0. Using more than 1.0 will increase dissipation.
5. The damping effect of the foam material can be controlled with the option ‘DAMP’. The recommended range of damping coefficient is from 0.01 to 0.25.
6. For Young’s Relaxation Modulus (Ed) and decay constant (b1), use default values.

MAT83 (MAT_FU_CHANG_FOAM)

The following data are needed from material supplier to set up the card.

1. Young’s modulus
2. Density
3. Nominal stress – strain curve (as a function of strain rate)
4. Tensile cut-off stress

Different curves are used for the different strain rates. The following options have to be examined carefully for better results.

1. Stress-Strain curves can be defined as a function of strain rate. For numerical stability, curves should not cross over and must be smooth. One unloading curve can be included in the table at a zero strain rate. This curve should be taken from a lower strain rate, stress-strain curve.
2. Stress-strain curve should be checked to see if it starts with concavity or convexity. They should start with Young's Modulus that has convexity characteristics.
3. Depending upon the test lab facilities, strain rate can be determined as either true constant strain rate or engineering strain rate. The SFLAG option can be used based on the type of stress-strain data.
4. If the ED is less than Esteel, ED = 10Efoam is recommended for stability.
5. For the tensile cut-off stress, 0.0 is recommended.
6. No bulk viscosity in option BVFLAG is recommended.
7. It is recommended to turn on the viscous hour-glassing option.
8. It is recommended to use default values for other parameters.

Foam material models in LS-DYNA are summarized in Table1 to assist in selecting the relevant ones depending on the application. LS-DYNA has 12 foam material models available in its material library. Based on the foam characterization and head impact work discussed in this paper, and also considering the industry practices, following is a brief summary of the suggested LS-DYNA material card to be used for specific applications.

Table 1. Summary of LSDYNA foam material cards[3]

Foam Type	Characteristics	LS-DYNA card
Soft PU	$30 < r < 60$ (g/l) a. Reversible b. Hysteric	Mat 57 Mat 83
Comfort foam (PU)	$60 < r < 70$ (g/l) a. Reversible with slow recovery b. Highly damped c. High rate effect d. High thermal sensitivity	Mat 62 Mat 83
EA-PU (Reversible)	$50 < r < 110$ (g/l) a. Reversible with slow recovery and damping b. Possible permanent deformation c. Crush strength not uniquely related to density	Mat 57
EA-PU (Irreversible)	d. Plastic part of stress-strain curve in compression is horizontal e. Rate effect	Mat 63, 53, 26, 75, 5, 10
Expanded Particle foam	$20 < r < 200$ (g/l) a. Reversible with slow recovery and damping b. Crush strength determined by density c. Plastic part of stress-strain curve in compression has a slope d. Rate effect	Mat 83

Simulation of foam is not easy due to the inherent variability in its material properties. Understanding the right material model to use for a specific type of foam is very essential. The foam characterization method discussed in this paper is an effort in this direction. The PU foam is about 80% recoverable. This characteristic cannot be perfectly represented by any of the current LS-DYNA material models. Therefore, two of the fully recoverable and two of the crushable material cards were identified for correlation. The results clearly showed that, out of the four material cards chosen, only two of them could simulate the foam really well. The material cards were then tested in a real head impact simulation and they correlated well with the physical test results. Hence, before any foam material card could be used with confidence in head impact simulations, they need to be characterized by correlating with component level physical tests. Then, good confidence can be developed in predicting the head injury parameters predicted.

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