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Optimization of Expanded Polypropylene Foam Coring to Improve Bumper Foam Core Energy Absorbing Capability

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ABSTRACT

To design a cost, weight, and energy efficient bumper foam energy absorber, it is important to consider optimizing the shape of coring employed in the design of the system. In this paper, a number of foam coring patterns are studied by both empirical and analytical methods. The size and shape of proposed core designs are studied in detail with consideration given to several different densities of expanded polypropylene (EPP) foam. Using the finite element method of structural analysis, it is possible to have an inside look at the stress distribution during deformation of foam structures. An optimization study using the finite element method is conducted using the energy absorption ratio as an efficiency parameter. Several coring patterns are studied and recommended for bumper foam core design based on high energy absorption efficiency and low tear stress.

INTRODUCTION

EPP foam is of a closed-cell type and is commonly used to absorb energy in automobile bumper systems. In this application, the energy absorption characteristics of the foam are directly related to the loading that the bumper reinforcement beam and body frame rails receive. To date, most of the design latitude in using this foam has involved varying the density and the thickness as a means to change the energy absorption characteristics. To further optimize the bumper system design using EPP foam, however, it is necessary to look at shape variation. That is the subject of this paper.

EPP foam absorbs energy through the bending or buckling of cell walls. As a result, the energy absorption characteristics of a particular block of foam depend on its density, the ambient temperature, and the impact speed (strain rate). Each of these dependencies are documented in the literature.

EPP foam is available in a variety of different densities. Four common densities were chosen for this study. Several physical properties (at room temperature and quasi-static strain rates) for each of these densities are listed in Table 1.

Table 1: EPP Foam Properties by Density

Density (g/l):	20	44	60	80
Young's Modulus (MPa):	75	215	320	470
Poisson's Ratio:	0.00	0.03	0.04	0.03
Yield Strength (MPa):	2.4	7.7	10.0	14.1

EPP foam is strain-rate sensitive with higher stiffness at higher rates of strain. The properties listed in Table 1 are for a quasi-static strain rate, which corresponds to the test conditions discussed in this paper. Figure 1 provides a comparison between the stress versus strain curves for quasi-static (60 mm/min) and dynamic (15 km/h) loading conditions of a 60mm X 60mm X 60mm solid 80 grams/liter foam block.

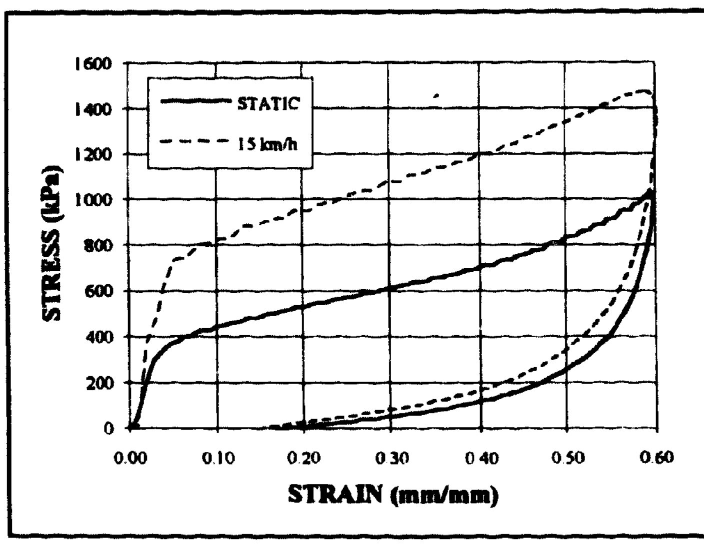

Figure 1: Static and Dynamic Loading of 80 grams/liter EPP Foam

HISTORY

BUMPER REQUIREMENTS - The design of a bumper system must take into account a variety of demands imposed by governmental standards (U.S. Federal Motor Vehicle Safety Standards-FMVSS, Canadian Motor Vehicle Safety Standards-CMVSS, Gulf Coast Coalition, and Korea), consumers' wants (Insurance Institute for Highway Safety-IIHS, Consumer's Union), and OEM standards. A common denominator among these demands is that the bumper system should protect the rest of the vehicle during multiple impacts. Impacts are performed using pendulums and barriers.

ENERGY ABSORBING DEVICES - Ten years ago, nearly all cars sold in the U.S. had bumper systems which utilized some type of stroking ("shock absorber") energy absorber or low speed crush bracket mounted between the bumper beam and the body frame rails. Most of the energy from an impact is absorbed in these stroking devices by forcing a fluid, gas, or gel through small orifices. Energy absorption characteristics could be controlled by changing the orifice geometry. This paper will not discuss crush brackets except as a comparison to foam energy absorbers.

Now, ten years later, more than 40% of the 1994 model year car bumper systems in the U.S. use some type of foam energy absorber. This increased use of foam energy absorbers in bumper systems reflects the current weight reduction imperatives in OEMs. A foam energy absorber system can save significant weight over a stroking absorber because of its low density. However, as illustrated in Figure 2, the energy absorption efficiency (defined below) of a foam absorber is less than a stroking absorber (a hydraulic absorber is shown as an example). Stroking absorbers are more efficient because they quickly reach a pre-defined load and remain near that load throughout the stroke. Foam absorbers load more slowly initially and provide an increasing level of load throughout their stroke. Both types of absorbers will have an abrupt increase in stiffness at the end of their travel. Changing the foam energy absorber to perform more like the stroking energy absorbers is the motivation for this study.

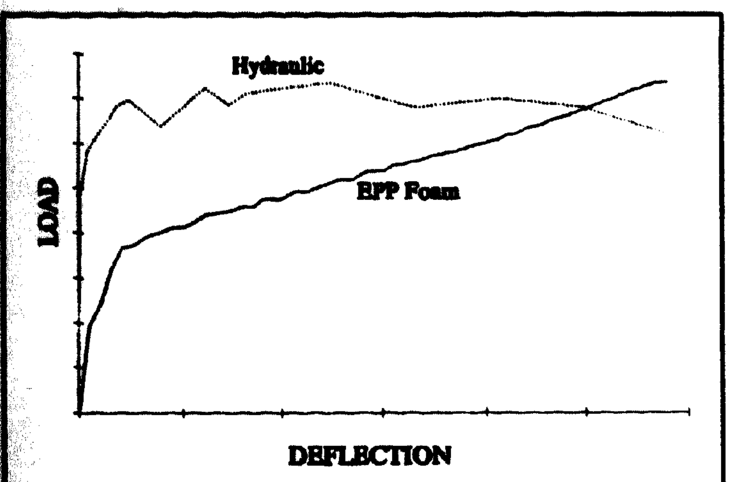

Figure 2: Foam and Stroking Energy Absorber Loading

TECHNICAL BACKGROUND

Figure 3 contains a loading curve generated by compressing one of the samples in this study. In addition to the stress, three other curves are plotted versus strain. These curves identify the energy absorbed per unit volume (Unit Energy, E_{abs}), the efficiency (η), and the rate of change of stress ($d\sigma/d\varepsilon$). These are defined as:

$$E_{abs} = \int_0^{\epsilon} \sigma(\epsilon')d\epsilon' \quad (1)$$

$$\eta = \frac{E_{abs}}{E_{max}} = \frac{E_{abs}}{\sigma \times \epsilon} \quad (2)$$

where σ is the stress for a given amount of strain, ε is the current strain (ε' is an integration variable), E_{abs} is the energy absorbed up to the current strain, and E_{max} is the maximum amount of energy which could have been absorbed assuming a constant maximum stress out to the current strain (a box curve).

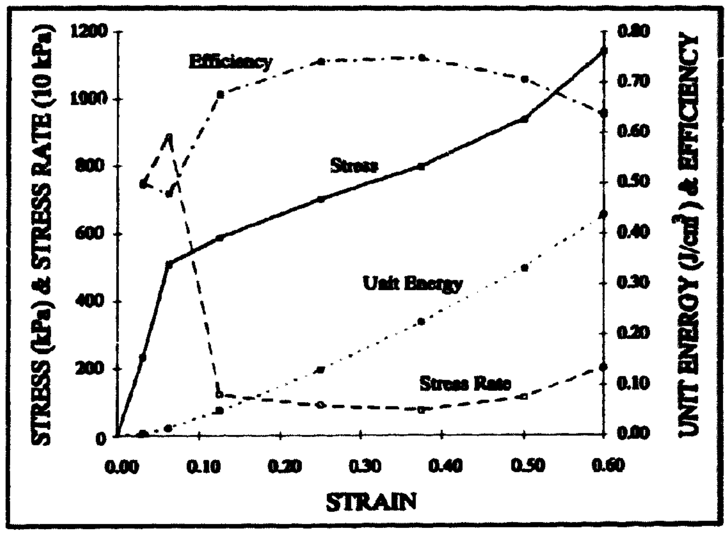

Figure 3: Test Sample Loading

In low-speed impacts, the amount of energy which must be absorbed by the bumper system is related to the vehicle mass and speed. Without changing either of these parameters, an increase in the efficiency of the energy absorber will allow this energy to be absorbed:

- In less distance (lower strain), or
- With lower maximum force.

Lower maximum strain would allow a thinner absorber to be used, reducing the overall bumper overhang. Lower maximum force would be helpful in cases where frame rail strength is dictated by the bumper impact.

A final factor of interest is the rate of change of stress (Stress Rate, $d\sigma/d\varepsilon$). Notice that this term mirrors the efficiency, since it is basically a measure of how flat the curve is. A flatter curve will demonstrate a more perfect absorber: high efficiency and low $d\sigma/d\varepsilon$. We will discuss only efficiency through the rest of this paper.

METHODOLOGY

In order to better understand the effects of foam coring on energy absorbing characteristics a laboratory test was conducted by BASF AG HSB/ZEW in Germany. In addition, a Finite Element Method analysis was performed by the Bumper Core Technology group at Ford Motor Company in the U.S.

TEST SPECIMENS - All test specimens consisted of (80mm X 80mm X 80mm) cubes with shapes cut out of the base along one axis. Three types of cutouts were used: Rounded (circular arches), pointed (gothic arches), and triangular. These cutouts were made in various sizes in order to fully understand the geometric effect. Figure 4 shows the ten tested cutout geometries.

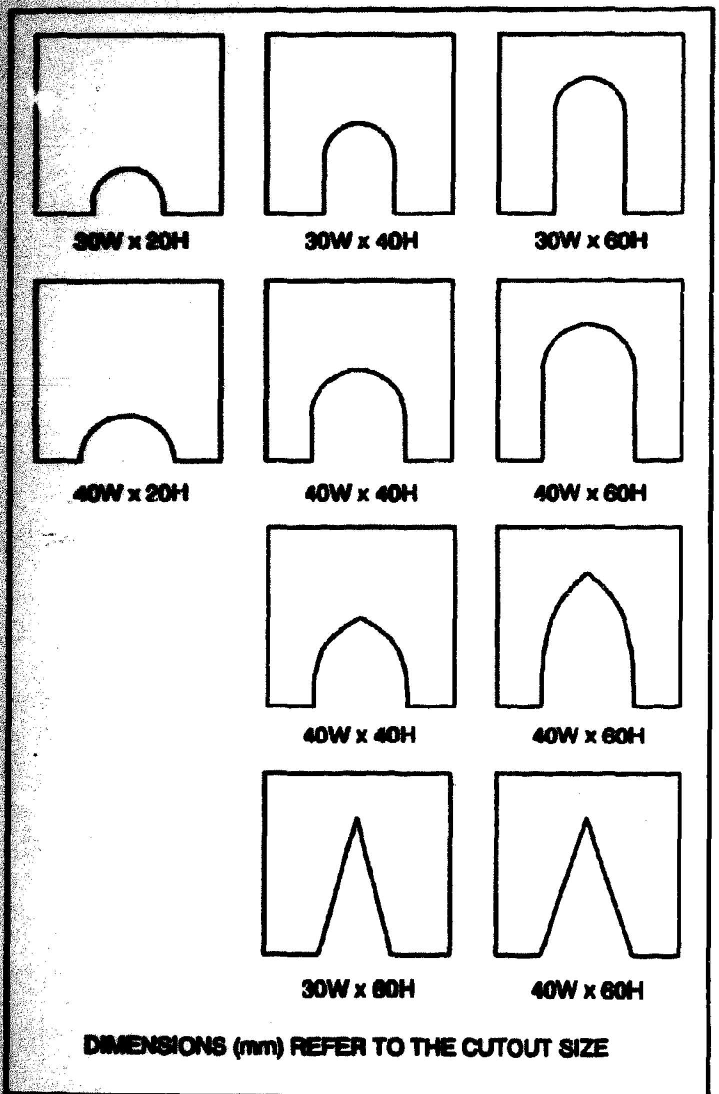

Figure 4: Foam Cutout Geometries

LABORATORY TESTING - A total of forty-four cubes were tested: Ten cutout shapes plus a solid cube for each of four densities (20, 44, 60, 80 grams/liter). Each cube was subjected to quasi-static (60 mm/min) compression at room temperature on a spindle press. The force and displacement were measured throughout the test and recorded on an XY recorder. Prior research has indicated that EPP foams tend to experience permanent damage after 60% strain, so these tests were concluded when deformation reached 48 mm (60% strain).

Data analysis consisted of digitizing the recorded load-deflection curves and converting them to engineering stress-strain plots (NOTE: as shown in Table 1, Poisson's Ratio for EPP foam is very small (less than 0.05); thus engineering stress and strain are nearly equivalent to true stress and strain). Digitized stress was numerically integrated using equation (1) to generate the unit energy, E_{abs} for strain from 0 to 60%. These results are reported in the next section.

FINITE ELEMENT METHODOLOGY - Four sample blocks were chosen for analysis using the finite element method of structural analysis. These samples were chosen with the most efficient (without cracks) dimensions for each cutout shape (rounded arch, pointed arch, and triangular), as determined by the laboratory testing.

- Solid (no cutouts)
- 30mm X 20mm Rounded Arch
- 40mm X 60mm Pointed Arch
- 30mm X 60mm Triangle

In each case a full solid model was developed and analyzed using Abaqus Finite Element software on a Cray 90 Series supercomputer. The analysis used a static non-linear implicit method with reduced integration elements. The tops of the blocks were modelled as a frictionless free surface while the bases were fixed with a rough surface condition (restricting horizontal motion). To avoid numerical instabilities, the bases of the cubes were constrained (and perhaps over-constrained) vertically to the surface. The material type was *FOAM and the elements were C3D8R. *FOAM requires the following material parameters which were determined by testing:

- Poisson's Ratio
- Logarithmic Bulk Modulus
- Yield Pressure in Hydrostatic Compression
- Strength in Hydrostatic Tension
- Yield Stress
- Logarithmic Plastic Bulk Modulus
- Ratio of Flow Stress in Tri-axial Tension to Tri-axial Compression

Output from the Finite Element Method consisted of load, displacement, and Von Mises stress for all elements in the models. Data analysis involved converting the load and displacement at the top of the blocks to stress and strain. Then the stress was numerically integrated using equation (1) to generate the unit energy and efficiency. Also, Von Mises stress contour plots were produced to provide tear stress comparisons between the geometries. These results are reported in the next section.

RESULTS

LABORATORY TESTING - Table 2 lists the efficiency (η) for each tested cube at 60% strain. An asterisk (*) indicates cases in which the foam cracked; we did not include these samples in our analysis.

FINITE ELEMENT METHODOLOGY - With the exception of the pointed arch core model, the finite element method results were in reasonable agreement with the test data. Figures 6 through 9 provide comparisons between the load vs. displacement plots for the modelled and tested

Table 2: Test Sample Efficiencies at 60% Strain

CUTOUT	W (mm)	H (mm)	EFFICIENCY (η) FOAM DENSITY (g/l) 20	44	60	80
NONE	0	0	0.48	0.60	0.56	0.63
ROUND ARCH	30	20	0.45	0.57	0.58	0.59
	30	40	0.49	*	*	*
	30	60	*	*	*	*
	40	20	0.44	0.55	0.57	0.60
	40	40	*	0.52	*	*
	40	60	*	*	*	*
POINTED ARCH	40	40	0.49	0.53	0.55	0.55
	40	60	*	0.59	0.65	0.90
TRI-ANGLE	30	60	0.52	0.61	0.66	0.68
	40	60	0.50	0.60	0.62	0.64

cubes. These comparisons and the reasons for the pointed arch exception are discussed in the next section. Figure 5 shows the deformed FEM models of each of these cubes at 35% strain. Again, except for the pointed arch case, these are representative of the deformation seen in the testing.

DISCUSSION

COMPARISON BETWEEN TESTING AND FINITE ELEMENT METHOD - The Finite Element Method load-displacement plot results match those of the tested samples except for the pointed arch. One possible reason for this mismatch can be seen in Figure 5. In each modelled case, the base of the cube remains flat and does not lift off the simulated lower plate of the test device. This condition was required for numerical stability of the analysis, but it does not represent the actual testing condition. In fact, videos of the testing indicate that the inner edges of the legs of the pointed arch samples tend to lift off the lower plate of the test device. This lifting allows the legs of the test specimen to buckle much easier, which means that it would take less force to further displace the top of the specimen.

Since the numerical instability mentioned above is specific to the finite element method software used, we plan to try a different software which can more closely model the actual constraint conditions. Unfortunately, we did not have time to complete this additional analysis before publication.

BENEFITS OF FOAM CORING - Coring can provide three major benefits to bumper foam energy absorbers:

- Increased Efficiency
- Lower Cost and Weight
- Reduction in Local Loading of Reinforcement Beam

We will discuss each of these in turn.

Increased Efficiency - Increased efficiency, while maintaining the same total energy absorption, can be helpful in bumper designs through one of two ways: (1) Reducing maximum frame rail loads while not increasing foam stroke

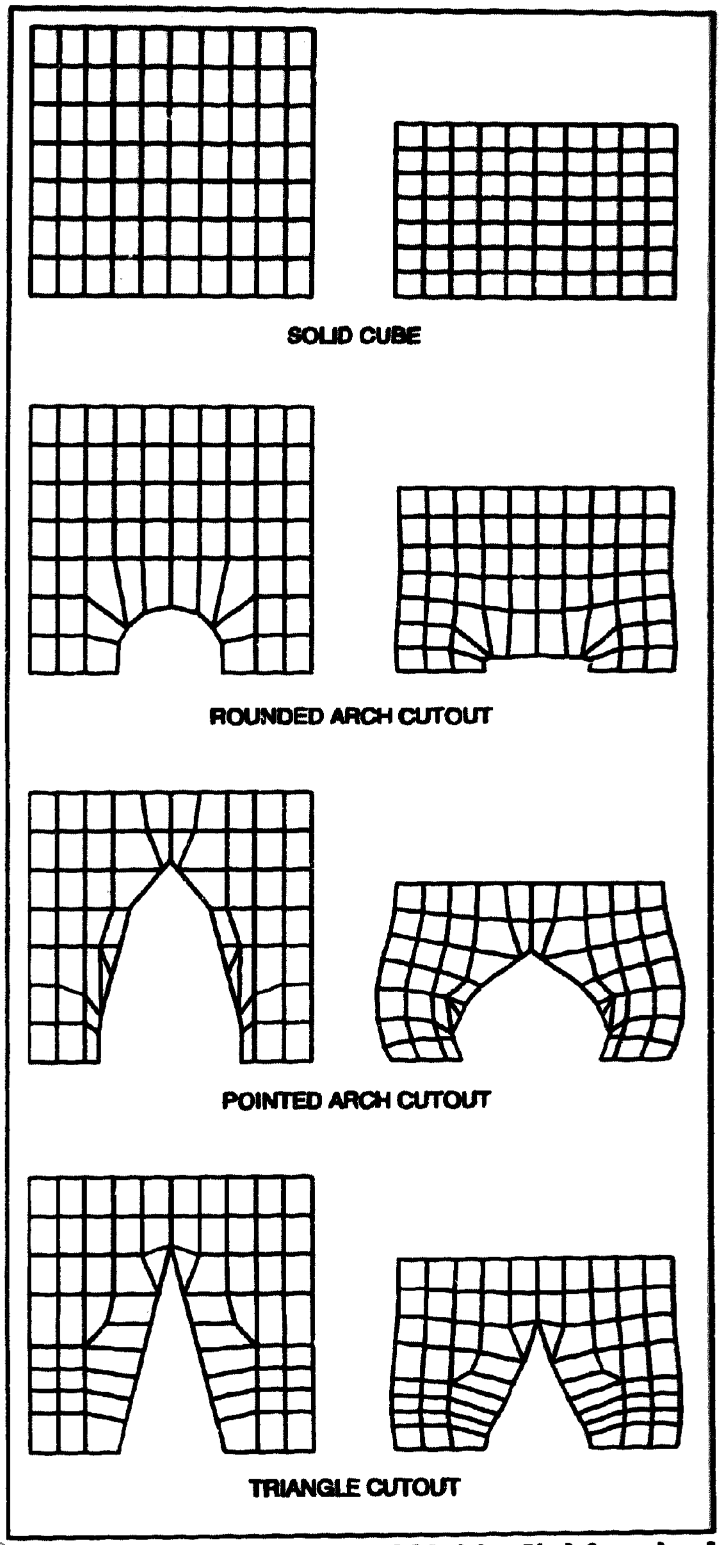

Figure 5: Finite Element Method Models: Undeformed and With 35% Deformation

distance, or (2) Reducing foam stroke distance while not increasing frame rail loads.

The reduction of frame rail loads is shown in Figure 10 by comparing three test samples of differing densities and cutouts which each absorbed 54 Joules of energy in 30 mm of deflection. In this case, the most efficient absorber has the smallest peak load. If a bumper system is excessively loading the frame rails, selective foam coring can reduce the

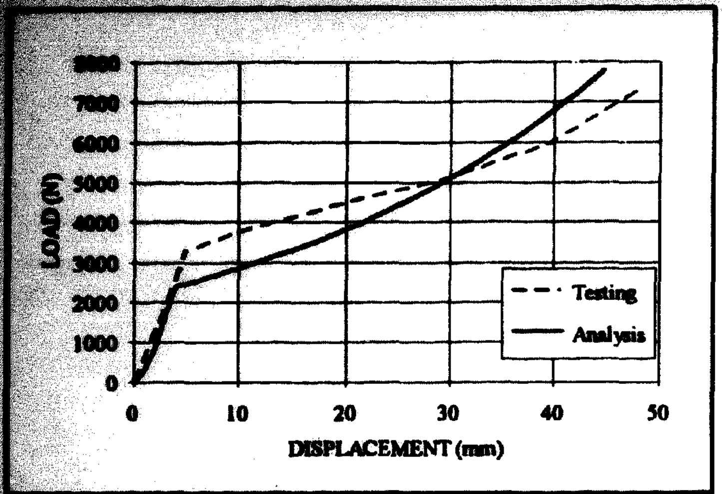

Figure 6: Solid Foam Block Load vs. Deflection

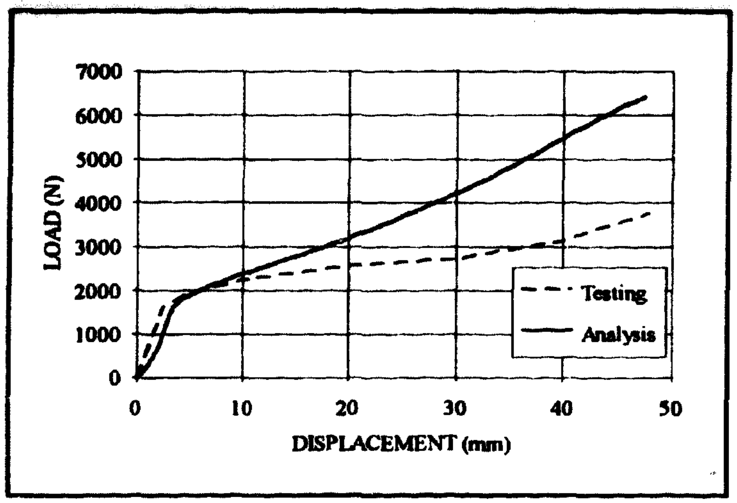

Figure 8: 30mm X 60mm Triangle Load vs. Deflection

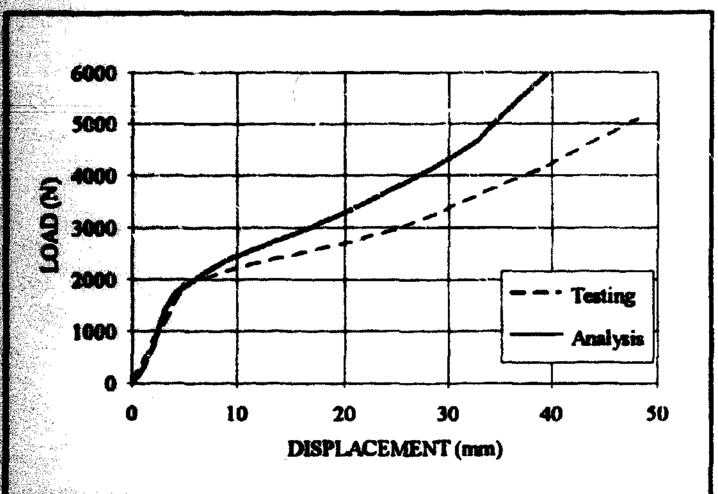

Figure 7: 30mm X 20mm Round Arch Load vs. Deflection

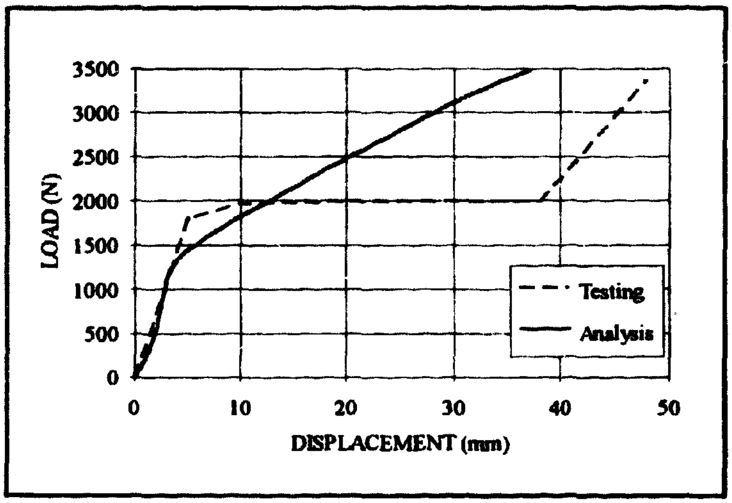

Figure 9: 40mm X 60mm Pointed Arch Load vs. Deflection

peak load without significantly reducing the total energy absorbed. We have observed this benefit for strains up to 40%; however, at higher levels of strain the peak loads for all samples absorbing the same energy tend to converge.

The reduction of foam stroke distance is shown in Figure 11 by comparing two test samples which absorbed 87 Joules of energy with a maximum load of 3000 Newtons. The cored 80 grams/liter foam block is more efficient and experiences 9.5 mm less deflection. Although it has a mass 12.7 grams greater than the solid 44 grams/liter foam block, it is still 5.8 grams less than a solid 80 grams/liter foam block which would typically have been used without coring to reduce the stroke distance. The loading curve for the solid 80 grams/liter foam block is also shown in Figure 11 for comparison: not only does it weigh more, but it also imparts a much higher (undesirable) peak load.

Lower Cost and Weight - Less material results in lower cost and weight for the system: Selective foam coring can be used to reduce the amount of material used in a foam energy absorber. The results of this study indicate that a foam absorber can be cored without an increase in density as long as the system can accept a greater deformation in absorbing the same energy. During testing only one of the pointed arch or triangle cored blocks experienced cracking. By contrast, more than half (see Table 2) of the round arch cored blocks cracked during the loading. Foam coring should be designed with these results in mind.

Reduction in Local Loading of Reinforcement Beam - A reduction in localized loading of the reinforcement beam has been observed in practice. By locally coring out the back of the foam, a concentrated load on the face will be spread out on the bumper beam. Although data was not presented, this concept was utilized on the 1994 Ford Thunderbird.

EFFICIENT FOAM CORING DESIGNS - Among the tested foam core geometries, the (40mm X 60mm) pointed arch and (30mm X 60mm) triangle were the most efficient, surpassing the efficiency of a solid block of the same density. However, the drawback of this increased efficiency is that it takes greater distance to absorb the same amount of energy. This is because the increase in efficiency comes about by reducing the overall level of force required to deform the block. As we discussed above, this problem can be dealt with by using higher density foams. There may be manufacturing difficulties with producing higher density foams--these need to be investigated.

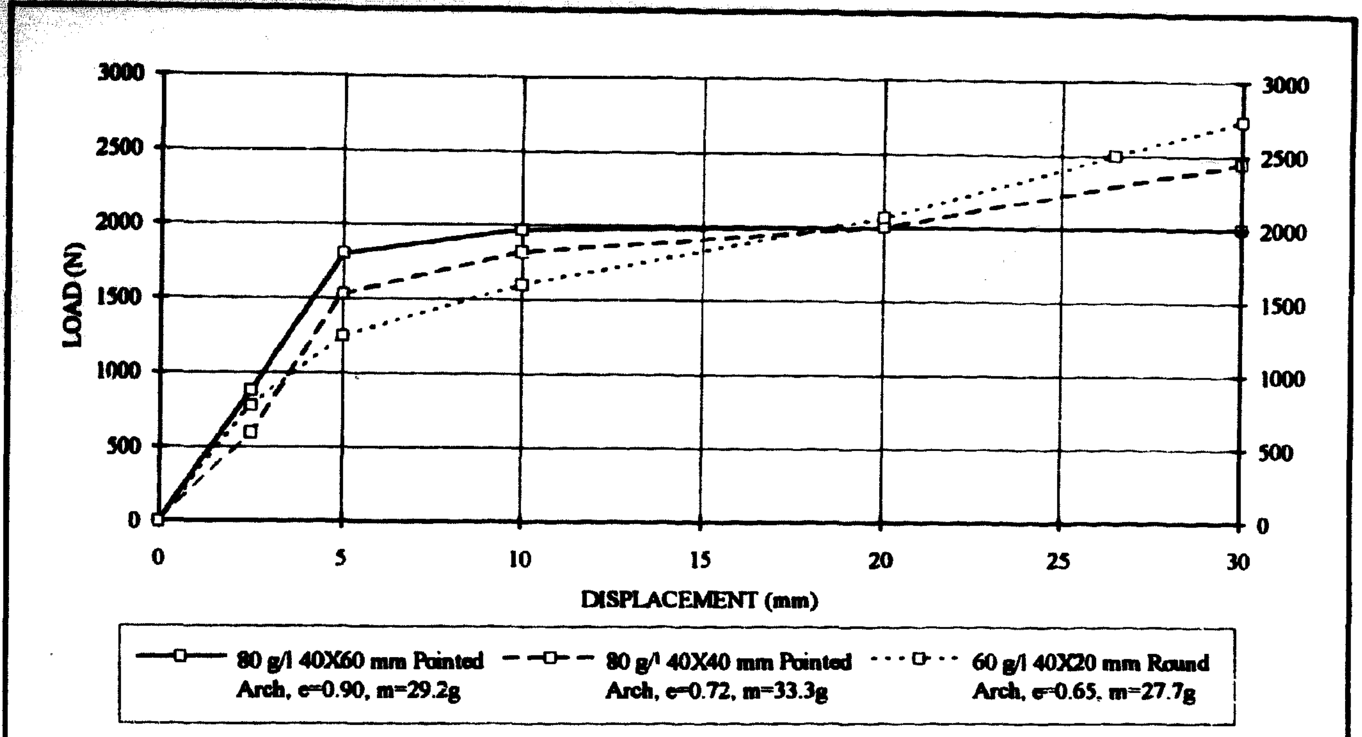

Figure 10: Peak Loads in Foam Blocks Which Absorb 54 Joules in 30 mm Displacement

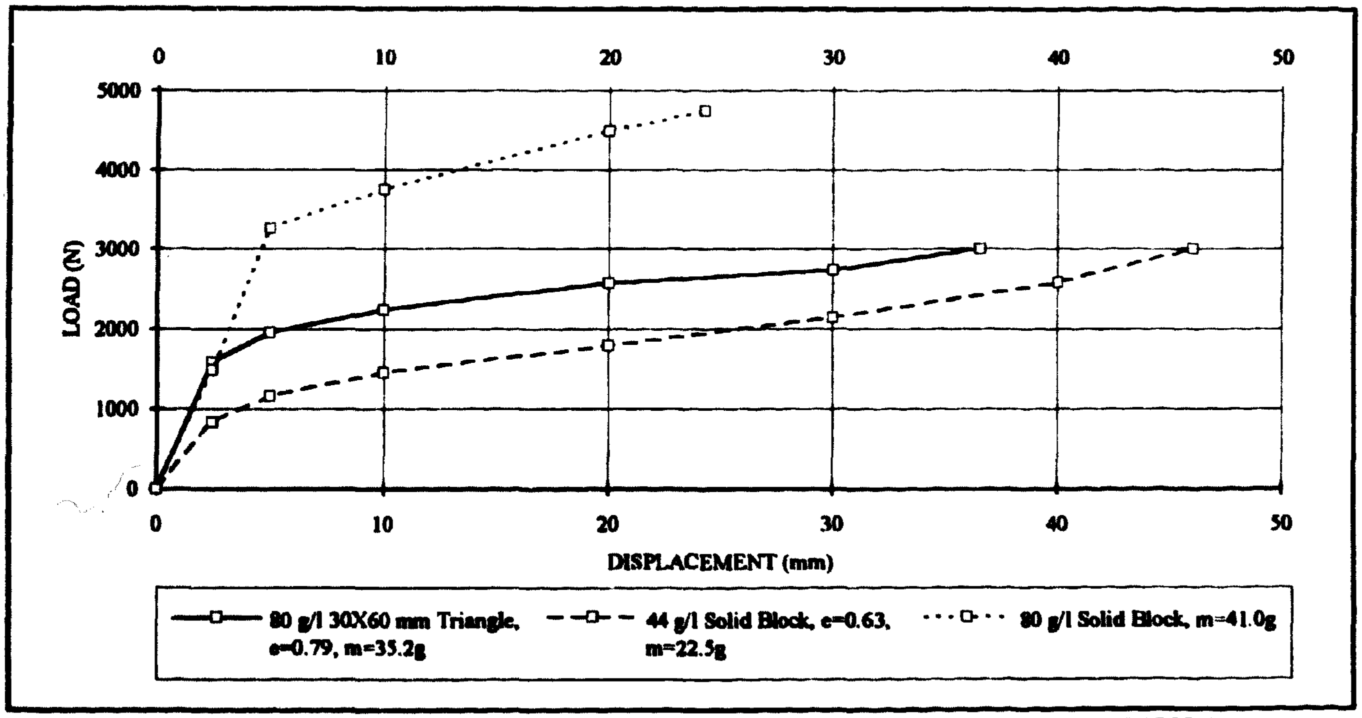

Figure 11: Displacements in Foam Blocks Which Absorb 87 Joules With a Peak Load of 3000 Newtons

APPLICATIONS

CURRENT APPLICATION - Some of these results are realized on the 1994 Ford Thunderbird rear bumper foam. In response to concerns about localized loading of the bumper beam, BASF AG proposed a cored foam design. Lorro Incorporated (the foam energy absorber supplier) performed tests on this proposal and found that the cored design reduced the initial loading spike and provided a more efficient energy absorption with minimal increase in stroke. At the same time, this design was lower weight and less costly than a solid foam energy absorber.

FUTURE APPLICATIONS - With minimal cost and weight effects, selective coring of higher density foams can absorb the same amount of energy at the same deflection with a lower peak load. This can be critical for optimizing the design of the front and rear vehicle structures. Also, higher density cored foams will absorb the same amount of energy with the same peak load at less deflection. This can reduce bumper shelf width, creating greater design flexibility.

Foam energy absorber coring has applications outside of bumpers as well. EPP foams are being employed in occupant protection systems by several OEMs..

CONCLUSIONS

- The primary conclusion of this study is that coring can improve the efficiency of bumper foam energy absorbers. This result leads to increased foam design latitude:
  - Selective coring is an additional tool in changing foam energy absorbing characteristics for design optimization.
  - More efficient energy absorption can result in reduced maximum frame rail loads or reduced bumper system stroke.
- Of the coring shapes studied in this project, the (40mm X 60mm) pointed arch and (30mm X 60mm) triangle were the most efficient. However, the most efficient core shape may be dependent on the entire foam absorber geometry. It is recommended that an optimization study is performed for each foam system to determine the best shape for foam coring. A triangular or pointed arch shape should be used as a starting point in the process.
- If a vehicle can tolerate a greater foam stroke, coring of the same density foam can save cost and weight without risk of foam cracking. The pointed arch and triangle core shapes have less risk of cracking than the rounded arch.

ACKNOWLEDGEMENTS

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