A STUDY ON ENERGY ABSORPTION CHARACTERISTIC AND HEAD INJURY PERFORMANCE ACCORDING TO THE CHARACTERISTIC OF COUNTERMEASURES AND SPACE BETWEEN INTERIOR AND BODY STRUCTURES

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ABSTRACT

It is important to adopt proper countermeasure strategies, i.e. energy absorbers (EA), in order to meet the Upper Interior Head Impact requirements of FMVSS201 S6.2 (FMVSS201U) which assesses head injury by impacting a Free Motion Headform (FMH) to upper interior parts. The understanding of the energy absorbing characteristic for each kind of countermeasures is a stepping stone to optimize the head injury performance. This paper reviews general features of foam and plastic types of countermeasures with respect to raw material and manufacturing process, and highlights merits and demerits from the point of view of design flexibility. Energy absorbing characteristics based on static component crush testing are considered and these characteristics are also compared quantitatively by investigating energy absorbing efficiency of the countermeasures.

Lastly, sensitivity analysis is conducted to study the relationship between the space and head injury performance according to types of energy absorbers using finite element analysis (FEA).

Range of Types of Energy Absorber to be Considered

Types of foam and plastic energy absorbers are mainly used as a countermeasure for improving FMH performance, and EA countermeasures that use metal such as corrugated tubes and stamped sheet metal are excluded from this paper.

Categorizing EA as raw material and manufacturing process

There are mainly two kinds of foams, molded type and expanded. An example of the former is Polyurethane (PU) foam that is mixed and injected directly into a mold. The final products are obtained after curing in a high temperature oven.
For the latter case, using polystyrene as a raw material, the manufacturer provides a fixed size of plank by expanding process then final products are obtained by wire cutting the plank as its shape.
In addition, there are other types of EAs using plastic resin as a raw material and adopting thermoforming or injection molding as the manufacturing process. In the thermoforming process, desired EA structures are procured by heating up a sheet of polypropylene plastic, for example, then vacuum forming over a die. The final component is then die cut to the final shape. Lastly an energy absorber that has thin walled structure, usually lattice shape, is obtained by conventional injection molding process using polypropylene or other plastic resins.

In the following sections, the merits and demerits of each EA countermeasure type are reviewed.

Type 1. Molded PU Foam
The design flexibility of final parts is one of the merits of molded PU foam as a result of the molding process. Mechanical properties are generally uniform throughout the part. Prototype parts may be cut or machined from larger molded blocks without necessitating prototype tooling. However PU foam does have limited range of crush load, as compared to other EA countermeasures. In addition, when the mold tooling is set, modification of the tooling is limited.

Type 2. Expanded Polystyrene Foam
A significant advantage of expanded Polystyrene is that it provides high energy absorbing efficiency and stable crush properties along the axis of extrusion. The wire cut process requires no tooling to produce final production parts. However complex 3D geometry is not feasible with a wire cut process. In addition, the cost per part is dependent upon the number of parts cut per plank. The number of parts obtained per plank is highly dependent on the part size and geometry. Therefore, the cost per part can significantly increase as overall part yield decreases.

Type 3. Thermoformed Plastic
In contrast with the molded foam type of EA, thermoformed plastic geometries can provide a good range of crush load. The typical forming process,

vacuum forming, has positive and negative design attributes. The process enables various nominal thickness of the raw sheet material with minimal tool changes. However, this process does have limits in the amount of curvature of the base geometry. In addition, the variation of thickness in height direction is not uniform so the exact thickness distribution must be estimated or measured off or tooled parts.

<u>Type 4. Injection Molded Plastic</u>

Like the thermoformed plastic, injection molded EA countermeasures also have a range in adjustment of crush load and very little limitation on parts design except manufacturing requirements such as minimum thickness and draft angle. But tooling needs long lead time, carving the tool into the shape of lattice is time consuming work, and tool modification is very restricted.

The summarized characters for each kind of EAs are summarized on the Table 1. And typical shapes of each type of EAs are shown in figure 1.

Table 1.
Summary of EA as raw material and manufacturing process

	Type 1	Type 2	Type 3	Type 4
Raw Material	PP/EPP	Poly-styrene	PP	PP/ABS
MFG Process	Molding	Extruding & Wire cut	Thermo-forming	Injection Molding
Tooling Lead time	'+'	N/A	'0'	'-'
Flexibility Medication of Tooling	'0'		'0'	'-'
Flexibility Part design	'+'	'-'	'0'	'+'

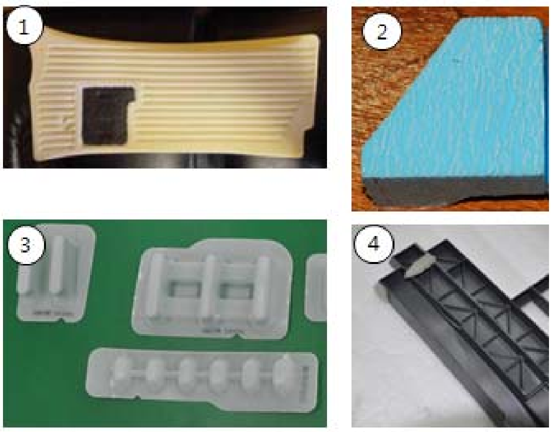

Figure 1. Types of Countermeasure
1. Molded PU Foam, 2. Extruded Poly-styrene Foam, 3. Thermoformed Plastic, 4. Injection Molded Plastic

Energy Absorbing Characteristics and Efficiency

To examine energy absorbing characteristics of the four types EAs, quasi-static crush tests were performed. The size of the test specimen for type 1 and 2 are 30x30x50 (mm) and 30x30x60 (mm), respectively. Figure 2 shows nominal stress and strain. Both EAs show densification. Stress increases quickly as the foam becomes dense at 0.68~0.78 range of strain. We define a design stress, as a stress level whose value is maintained steady state. Type 1 has 20% variations, while type 2 has 70% variations in both product families. This means that type 2 EA gives more options to choose from a crush load perspective.

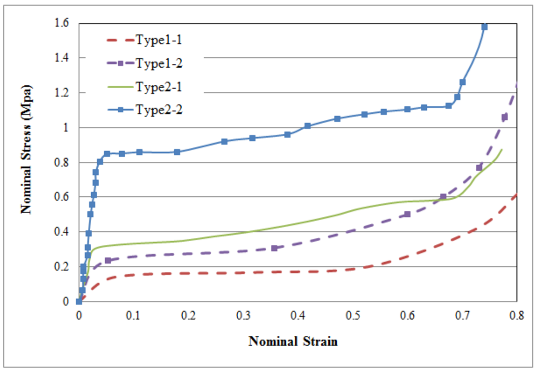

Figure 2. Nominal Stress vs Strain (Type 1, 2)

Figure 3 shows the energy absorbing feature of plastic EA's (type 3 and 4) crushed with a rigid plate. The crush loads are normalized with each peak force and are considered to identify the energy absorbing characteristic for the case of the EAs that do not have uniform cross sections.

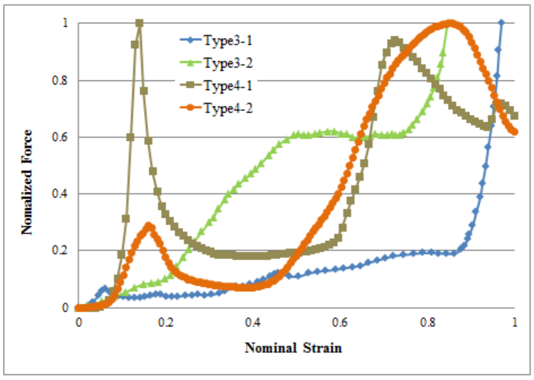

Figure 3. Normalized mean force vs Strain (Type 3, 4)

Critical strains at densification and design forces can vary drastically according to its geometry, even for the same types of EA. Type 4 shows a characteristic that exhibits a high force level at the beginning of deformation and then decreases by more than 50%

when fracture occurs.

Until now it has been observed that EAs have their own crush characteristic according to their raw material and geometry; therefore, it is necessary to evaluate the characteristic quantitatively. In previous research, G.G Lim et al. suggested Pulse Waveform Efficiency defined as a ratio of maximum to net area of a load-displacement curve derived from deceleration and time, shown in equation 1. The concept defines the efficiency; however, it gives only the ratio of total absorbed energy to an ideal amount; it does not explain the relationship between the efficiency and the amount of deformation, that is when maximum efficiency is achieved and the densification occurs as a part is deformed.

So equation 2 and 3 show the definition of modified parameter in terms of stress and strain, and equation 2-1 and 3-1 in terms of force and strain. Equation 3 and 3-1 show that the design values are updated with current ones if the current values exceed initial design ones. The efficiencies calculated based on equation 3 or 3-1are show in figure 4 for each type of EAs.

$$\eta_1 = \frac{\int_o^{u\,max} f\,du}{f_{max} u_{max}} \qquad (1).$$

$$\eta\_{modi} = \frac{\int_o^t \sigma_{design}\,d\varepsilon}{\sigma_{design} \cdot \varepsilon} \qquad (2).$$

$$\sigma_{design} = \sigma \; if \; \sigma_{design} \geq \sigma \qquad (3).$$

$$\eta\_{modi} = \frac{\int_o^t f_{design}\,d\varepsilon}{f_{design} \cdot \varepsilon} \qquad (2\text{-}1).$$

$$f_{design} = f \; if \; f\sigma_{design} \geq f \qquad (3\text{-}1).$$

Type 2, having rectangular cross section with polystyrene, shows good energy absorbing efficiency. More than 60% of its efficiency is reached within 0.11 strain, and the efficiency continues to increase to 80% until 0.67 range of strain. Meanwhile the maximum efficiency and the critical strain of type 1 are 80% and 90% compared to type 2 EA's, respectively under the same cross section condition.

Type 3, adopting thermoforming process using PP as raw material, shows various energy absorbing behavior according to its structures and 35 to 39% level of efficient until 0.6 strain range. Type 4 also shows a wide range of behavior similar with type 3 EA. The maximum efficiency is reaches 47 to 60% of strain.

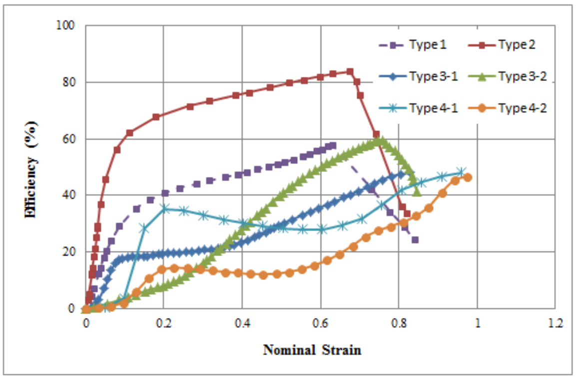

Figure 4. Energy of Absorbing Efficiency acc. to types of EAs

Considerations on the Efficiency

The efficiencies in figure 4 show only examples of each type of EAs with similar cross sections to introduce energy absorbing efficiency so the behaviors and efficiencies do not fully represent the full range of each type of EA countermeasure.
And the efficiency does not explain the absolute value of crush load, which is an important factor considering head injury performance because it is expressed as ratio. These factors, geometry and crush load of EA, are considered on the following topic.

Reviewing FMH behavior and Sensitivity Study with Full Vehicle CAE Analysis

Head injury and head form behavior are compared for 6 cases of EAs on a B-pillar upper roof area as per the protocol of FMVSS 201u with LS-DYNA 971 r511. Case 1 through 4 have same figure of solid block while case 5 and 6 have thin walled structure, however, all cases have the same coverage volume. The load deflection characteristic and efficiency are shown in figure 6 and 7. This crush characteristic of each EA is obtained with rigidly modeled FMH under the same condition of FMVSS201u testing. An example of the setting up configuration is shown on figure 5.

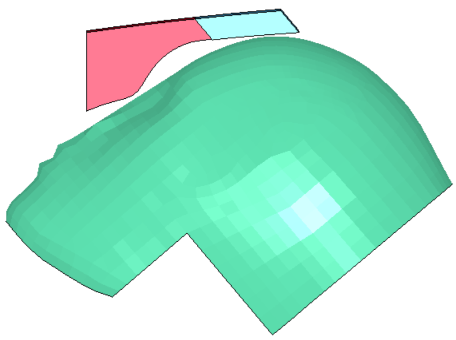

Figure. 5 Configuration for crush characteristic analysis

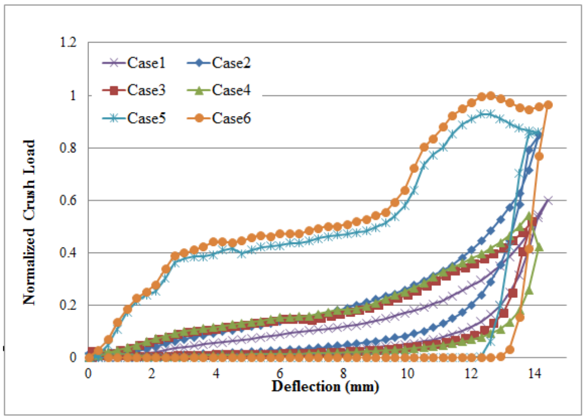

Figure. 6 Normalized crush load and deflection characteristic

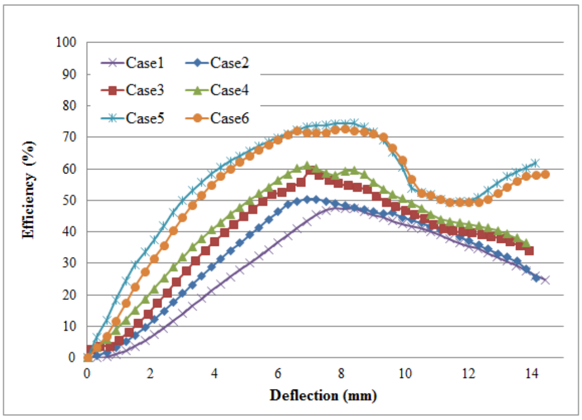

Figure. 7 Energy Absorbing Characteristic

EAs of Case 5 and 6 EA show higher energy absorbing efficiency and also higher crush load than the other cases as shown in table 2. But the foam, FMH in case 6 has the least amount of intrusion due to high crush load and results in a higher HIC(d) result. Table 2 shows normalized HIC(d) response according to efficiency and crush load.

Table 2. HIC(d) according to types of EA

	Mean Efficiency	Crush Load (%)	HIC(d) (%)
Case 1	21.6	23.3	110
Case 2	24.7	27.6	104
Case 3	31.2	27.6	101
Case 4	30.	32.0	100
Case 5	52.7	82.9	101
Case 6	49.3	100	113

To investigate head injury variation in reducing countermeasure space for the types of EAs, a sensitivity study is performed. The space is reduced by 25% and 50% to current gap by offsetting head liner surface. To minimize re-modeling of head liner, only the forehead area of surface is modified. Figure 8 shows the profile of modification. The impact conditions such as the position of FMH and impact location is adjusted as the headliner offset as per FMVSS201u targeting process. The height of EAs are also modified to accommodate the gap

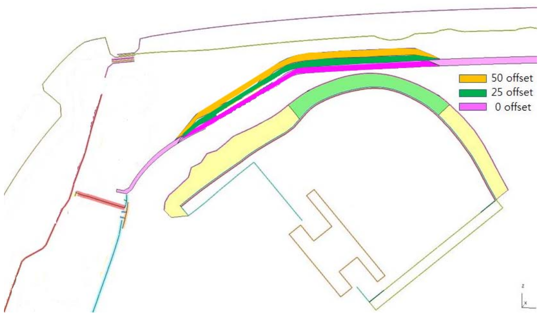

Figure.8 Section of Vehicle lateral direction

Table3. HIC(d) variation according to Energy Absorbing Space

	Baseline (0 offset)	25% offset	50% offset
Case A	100	110	116
Case B	100	116	126
Case C	100	122	134
Case D	100	123	143

Foam types of CMs, case A and B, show less variation than plastic types', case C and D. The case D, which has thin walled structure shows up to 43% more sensitive response than the others.

CONCLUSION

1. Manufacturing process and advantages and disadvantages in accordance with the process are reviewed for foam and plastic type of energy absorbers as a stand point of FMVSS201u.
2. Energy absorbing efficiency is presented as a parameter to evaluate load-deflection characteristic of examples of each type of EA countermeasure.
3. Energy absorbing efficiency and crush load should be considered together when assessing head injury performance.
4. Plastic type of EA shows sensitive response as the countermeasure space reduced.
5. This study has a limitation as below and further studies are required to cover the below topics;
 - Many different design elements affect the energy absorbing characteristic such as various geometry, wall thickness and wall pattern and are not fully considered in this paper.
 - The phenomenon that different efficiency and

crush load achieve similar HIC(d) values is not fully explained and does require further study.

References

1) Federal Motor Vehicle Safety Standard :49 CRF PART 517) “FMVSS 201u - Occupant protection in interior impact”

2) G. G. Lim, C. C. Chou, R. N. Patel, S.A. Shahab, and P.J. Patel “Estimating the Minimum Space to Meet Federal Interior Head Impact Requirement”, SAE 950333

3) LS-DYNA User’s Manual, Version 971, Livermore Software Technology Corporation (LSTC), May 2007.