Effect of Aluminium Foam Density on the Energy Absorption Characteristics of S-rail structure

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Abstract

In the past few decades big emphasis is given on energy absorbing members in automotive structures to meet the NCAP (New Car Assessment Programme) requirements in passenger car safety. Many design and material changes are being incorporated to improve the vehicle safety. Structures which are filled with foam have shown better energy absorbing behaviour compared to the bare tube structures. Studies have also shown that the density of foam influences energy absorption behaviour of the structure. In the present work, S-rails structure has been considered to evaluate the energy absorption characteristics of S-rail filled with different densities of aluminium foam and wall thickness. Energy absorption behaviour of S-rail without foam and with foam of 92%, 81% and 74% porosity is studied at a speed of 17.77m/s (64 km/h) as per NCAP standard. Foam filled S-rails absorbs 55% more energy compared to baseline model of S-rail. Energy absorbed by wall of S-rail alone when filled with foam is 40% more than wall of baseline model because of interaction effect. S-rail with 81% porosity and wall thickness of 1.5E-3 m (1.5 mm) weighs 30% less than baseline model. It is thus observed that foam filled S-rails structures can be used for vehicle weight reduction with better energy absorption.

Key Words: Foam Filled Structures, S-rail Structure, Energy Absorption, Foam Density, Passive Safety

1. INTRODUCTION

S-rails, is one of the most important component in automobile for crash energy absorption. S-rail as shown Fig. 1 is equipped with the crash box at the front end of the vehicle which is designed to absorb energy and decelerate the vehicle to stop. S-rails are manly made of thin sheet of 2 to 3 mm thickness which carries 10% of the total car weight.

![Fig. 1 S-rail structure](image)

The structural impact mechanics and crashworthiness are the most important factors in vehicle crash analysis. Generally crashworthiness is defined as the ability of vehicle to avoid the injury to occupants or damage to the survival cabin by withstanding impact force. Crashworthiness is the behaviour of the structure or vehicle when it collides with another vehicle or an object [1].

Foams shows unique characteristic where they can gradually undergo a huge strain distortion while keeping a low stress level prior to the densification region.

A typical stress-strain curve of foam materials has three regions first elastic region then plastic region where stress rises gradually and cells of foam deforms, and finally densification region in which cell boundaries touches each other and foam shows bulk like character (Fig. 2) [3]. Even though the foam filled tubes show great characteristics for energy absorption, it may undergo global bending [4]. For foam filled tube global bending depends on density of foam and the geometry of tube. For square tubes foam density of more than 320 kg/m³ [4] and for circular tubes foam density of more than 770 kg/m³ can cause bending [5]. Foam density should be adequately low to prevent global bending mode and adequately high to rise the energy absorption ability.

![Fig. 2 A typical stress-strain curve for foam materials](image)

The mutual effect among the tube and foam filler rises the energy absorption capability of foam filled tubes. Many studies on foam behaviour have shown that foam filled members have higher energy absorption capability and a mean load than the sum of foam and a tube separately (Fig. 3) [6]. Study by Reid has shown that foam filled tube is found to enhance the energy absorption of steel tube by 40% to 60%.

![Fig. 3 Interaction effect of a foam-filled circular tube](image)
This interaction effect between foam and the tube depends on the material properties and the geometry factor. An empirical formula considering interaction effect for average crushing load of foam filled circular tubes (Pmf) [6].

\[ Pmf = Pme + \sigma_p Af + C_{avg} \sqrt{\frac{\sigma_y \sigma}{\gamma}} \quad \text{eqn. (1)} \]

Where,
- \( Pme \) = The mean crushing load of an empty tube
- \( \sigma_p \) = Foam plastic stress
- \( C_{avg} \) = Co-efficient of Interaction effects

In the present study, CAD model is built using CATIA. FEA is developed using Pre-processor tools (Hypermesh/ LS-Dyna Prepost) and the results were analysed using post processor tool (LS-Post process / HyperView) as shown in Fig. 4.

![Flow Diagram of the procedure](image)

**Fig. 4 Flow Diagram of the procedure**

Crash analysis of S-rail structure is simulated for 17.77 m/s speed for the baseline study and foam filled with different foam density and wall thickness. Comparison of energy absorption by Foam, S-rail and overall energy absorption were analysed.

### 1.1 Boundary Conditions

Frontal impact behaviour of the vehicle is studied at 17.77 m/s (64 km/h) velocity according to Euro NCAP standard. [7] Boundary conditions applied for the S-rail structure simulation is shown in the Fig. 5.

![Boundary conditions for the S-rail structure](image)

**Fig. 5 Boundary conditions for the S-rail structure**

### 1.2 Material Properties

The wall of S-rail is defined with (*MAT_024) in LS-DYNA which is piecewise linear elastic plastic material model. Material properties are as follows:
- Yield stress (\( \sigma_y \)) = 401.4 MPa
- Poisson ratio (v) = 0.3
- Young’s modulus (E) = 210 GPa
- Density (\( \rho \)) = 7809 kg/m³

Stress strain value obtained from tensile test carried out according to AS1391-1991 [2]. Figure 6 shows stress-strain curve in plastic region which is taken for the simulation.

Deshpande and Fleck material model (*MAT_154) is used for defining the crush behaviour of foam (Table 1) similar to Zaini Ahmad’s work [2].

### Table 1. Material parameters for the Alulight aluminium foam

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case:1</th>
<th>Case:2</th>
<th>Case:3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity, %</td>
<td>92</td>
<td>81</td>
<td>74</td>
</tr>
<tr>
<td>( \rho ), g/cm³</td>
<td>0.22</td>
<td>0.534</td>
<td>0.71</td>
</tr>
<tr>
<td>( \sigma_{ps} ), N/mm²</td>
<td>2.14</td>
<td>12.56</td>
<td>22.18</td>
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<tr>
<td>( \alpha )</td>
<td>2.12</td>
<td>2.12</td>
<td>2.12</td>
</tr>
<tr>
<td>( \alpha _N/mm²</td>
<td>169</td>
<td>1544</td>
<td>4295</td>
</tr>
<tr>
<td>( \gamma _1 ), N/mm²</td>
<td>2.45</td>
<td>1</td>
<td>6.438</td>
</tr>
<tr>
<td>( \gamma _2 )</td>
<td>2.5</td>
<td>1.62</td>
<td>1.33</td>
</tr>
</tbody>
</table>

### 1.3 Contact Definition

Contact between S-rails and the bumper has been defined, as Automatic surface to node contact. Similarly the contact between bumper and the rigid wall is defined as automatic surface to surface contact. For foam filled condition contact between S_Rail wall and the foam is defined as automatic surface to surface contacts were defined as per literatures obtained.

### 2. RESULTS AND DISCUSSIONS

#### 2.1 Energy Balance Curve

In present analysis the theoretical kinetic energy is 143 kJ. The kinetic energy is 143 kJ which is within the 5% of the theoretical kinetic energy. Maximum internal energy absorbed by the S-rail system is equal to 55 kJ in 20 ms which is very less than the maximum kinetic energy which implies that the more deformation is needed to absorb the energy. Figure 7 shows the energy balance curve of baseline model.

![Energy balance curve for baseline model](image)

**Fig. 7 Energy balance curve for baseline model**

#### 2.2 Internal energy of S-rail

Internal energy of S-rail with bumper is shown in Fig. 8. Initially bumper absorbs impact energy and then passes to S-rails. Bumper absorbs total of 25 kJ of energy whereas S-rails absorbs 35 kJ of energy during the crash.
2.3 Comparison results of Foam Filled S-rail

2.3.1 Energy absorbed by Foam

The optimum foam density which gives maximum internal energy for S-rails filled with Aluminium foam is obtained by analysis. For analysing the energy absorbed by different components, internal energy plots for foam, wall and entire S-rail with foam were obtained.

Figure 9 shows the Energy absorbed by foam only for foam porosity of 92%, 81% and 74%. For 92% porosity foam maximum energy absorbed is 10 kJ whereas for 81% and 74% porosity foam it is 29 kJ and 32 kJ respectively.

2.3.2 Energy absorbed by S-rail Tube

Energy absorbed by the bare S-rail is plotted in Figure 10. Energy absorbed by the S-rail wall without foam is 30 kJ whereas energy absorbed by wall with foam filled with 92%, 81% and 74% of porosity is 51 kJ, 55 kJ and 60 kJ respectively.

2.3.3 Overall Energy absorbed by S-rail

The overall energy absorbed by the S-rail is plotted in Fig.11. This contains energy absorbed by S-rails tube alone and foam. S-rail without foam absorbs 55 kJ of energy whereas S-rail with foam (92%, 81 % and 74% porosity) absorbs 110 kJ, 120 kJ and 121kJ of energy. 81% of porosity foam absorbs 120 kJ of energy and it is 10 kJ more energy compared to that of 92% porosity foam. It is observed that as the density increases, deformation mode of foam filled structure also changes [6]. 74% porosity foam absorbs 1 kJ more energy than 81 % foam but it can result in adding more weight to the structure. By selecting 81% of porosity for filling in S-rail 65 kJ more energy absorption can be achieved compared to baseline model.

2.4 Energy balance curve for S-rail with 81% porosity foam

Figure 12 shows energy balance curve for S-rail with 81% porosity foam, total kinetic energy is 145 kJ, whereas total energy absorbed by the S-rails is 120 kJ. Most of the kinetic energy is consumed by the S-rails by deformation this implies that the foam Filled S-rails shows better results during crash simulation.

2.5 Changing thickness of Foam filled S-rail with 81% Porosity

In order to have less weight of S-rail with foam, tube thickness of the S-rail is decreased compared to that of the baseline model. Energy absorption behaviour is obtained with wall thickness of 2.5, 2, 1.5 and 1 mm.

Energy absorbed by foam with 81% of porosity with different tube thickness is plotted in Fig. 13. 30 kJ of total energy is absorbed when thickness is 2.5 as well as for 2 mm, whereas 25 kJ of energy is absorbed by 1.5 mm thickness. When thickness is reduced to 1 mm, energy absorbed by foam is reduced to 17 kJ.

Figure 14 shows the comparison of energy absorbed by S-rail tube alone with different thickness. 55 kJ, 49 kJ and 37 kJ is the energy absorbed by foam filled S-rail tube with 2.5 mm, 2 mm, and 1.5 mm thickness respectively which is more than the energy absorbed by S-rail without foam and 2.5 mm wall thickness.
Energy absorbed by foam filled S-rail wall with 1 mm thickness is 18 kJ which is less compared to 29 kJ energy absorbed by S-rail without foam.

Figure 15 shows the comparison of energy absorbed by S-rail with different thickness. 121 kJ, 103 kJ and 81 kJ is the energy absorbed by foam filled S-rail with 2.5 mm, 2 mm, and 1.5 mm tube thickness respectively which is more than energy absorbed by S-rail wall without foam and 2.5 mm wall thickness. Energy absorbed by foam filled S-rail with 1 mm thickness is 31 kJ which is less compared to 57 kJ energy absorbed by S-rail without foam.

Figure 16 shows energy balance curve for S-rail with 81% porosity foam and 1.5 mm tube thickness. Initial kinetic energy is 138 kJ and the total energy absorbed by S-rail is 83 kJ which is more than S-rails without foam and 2.5 mm thickness. Thus it is possible to get better energy absorption without significant changes in the weight and cross section of the S-rail structure.

3. CONCLUSIONS

- Baseline model of S-rails absorbs 55 kJ of energy which is less than half of initial kinetic energy, this implies the cabin or occupant space deforms more than safety limit
- S-rails filled with foam absorbs 110% more energy compared to S-rails without foam.
- 81% porosity foam gives better result in terms of energy absorption and it also carries less weight
- Energy absorption increases with increasing relative density of foam until the critical value of density after which foam filled tube tends to bending which reduces the energy absorption. Here 92% porosity foam filled S-rail absorbs 10% more energy compared to 81% porosity foam, but 81% and 74% porosity foam filled S-rail absorbs same amount of energy because 74% porosity foam tends to be bending.
- Energy absorbed by S-rail without foam is 40% less than the energy absorbed by foam filled S-rail tube alone, which is because of interaction effect.
- Foam filled S-rail can be used by reducing the wall thickness. S-rail with 81% porosity foam and 1.5 mm tube absorbs 15% more energy than S-rail without foam. It weighs 30% less than the bare S-rail structure.

REFERENCES