

Aluminium foam for automotive applications

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Abstract

One of the most important targets in vehicle design is passive safety; this more and more stringent requirement leads the designer towards new vehicle architectural solutions and innovative materials. Aluminium foams are a new class of materials with promise an improvement of vehicle crashworthiness, combining the properties derived from the cellular structure, in particular the lightness, with the typical behaviour of metals.

This paper deals with the application of aluminium foam as the filler of a generic crashbox structure aiming at the improvement of the energy absorbing efficiency. With reference to a medium size car and on the basis of a complete set of design formulae developed in a previous investigation carried out by SIMLAB at the Norwegian University of Science and Technology, a crashbox mock-up was designed. Both static and dynamic compression tests were carried out on the crashbox simulacrum as well as on a complete vehicle front-end assembled using a commercially available bumper cross-beam. The experimental results validated the recently developed design formulae and highlighted the potential benefits of the aluminium foam based crashbox.

1. Introduction

Many of today's vehicles incorporate deformable energy absorbing elements within the vehicle structure. These elements, which represent the crushable zone, manage the collision energy for protection of the rigid passenger cell. For low speed impact, the traditional solutions for the front-end of a vehicle are able to absorb the impact energy at up to 3-5 km/h, while for speeds exceeding this limit the chassis is deformed plastically.

With the introduction of a crash absorber structure between the chassis and the bumper, it is possible to increase the above mentioned speed limit up to 15 km/h. In this case the passengers' safety is not a target, due to the low speed, but the attention is paid to an easy and cheap repair of the vehicle.

It is only in recent years that new production methods have been developed making aluminium foams attractive for high volume markets such as the automotive industry sector.

In this work, the application of aluminium foams for filling a crashbox is investigated experimentally. Due to the high efficiency guaranteed by the foam, this application offers the following potential advantages in comparison to other solutions:

- weight saving,
- reduction of the crashbox dimensions.

2. Terminology

Appendix A illustrates the typical behaviour of an axial energy absorber undergoing crushing [1]. The force-displacement, $F-d$, relationship may be integrated to obtain the absorbed energy E . For a given displacement d , F_{max} is the largest force occurring in the interval $\{0, d\}$ whereas F_{avg} is the average force of the same interval. The relative deformation of the absorber is given by the deformation capacity D_C ($D_C \equiv d/l$).

The crush force efficiency A_E is the ratio of the absorbed energy E to that of an ideal, perfect plastic absorber of constant collapse force F_{max} . A value of A_E close to 100 % indicates an absorber with good qualities. Another dimensionless parameter is the total efficiency T_E which is a quantity proportional to the ratio between absorbed energy E and maximum force F_{max} (see Appendix A). Hence, a given energy absorber shows optimum energy absorbing properties at a deformation d_{max} where the total efficiency T_E has a maximum value.

3. Design formulae

Prior to the current investigation, a complete set of design formulae was developed based on an experimental activity at the Norwegian University of Science and Technology. Figures 1, 2, 3 summarise the results. Full details can be found in Refs. [1-3]. When designing foam filled crash boxes the value of F_{avg} and F_{max} has to be linked to the geometric and material properties of the crash box. For a square box column the geometric properties are the outer width b and the wall thickness h , whereas the material properties comprise that of both box column wall as well as the foam filler. In order to keep the model parameters to a minimum, both the box column wall strength and foam strength are each described by a single strength. As given in Figure 1, the characteristic stress σ_0 of the crash box is taken as the average of the stress at 0.2% plastic strain $\sigma_{0.2}$ and the ultimate stress σ_U . The material properties of the foam are given by the plateau stress σ_f (evaluated as energy absorbed at 50% strain divided by deformed distance). As illustrated in Figure 2, there is an exponential relationship between foam density and plateau strength.

It is evident from Figure 4 that the design formulae consist of three parts. By closer inspection it is seen that the first part amounts to the well-known formula for the resistance of a non-filled crash box. The second term is simply the uniaxial resistance of the foam core, whereas the third term describes the increased force level due to the coupling effect between crash box and foam filler. The additional constants needed in order to describe the interaction effect are $C_{avg} = 5.5$ and $C_{max} = 2.5$. In order to determine the maximum force of the foam filled crash boxes, the level between average and maximum force of a non-filled crash box (A_{E0}) and that of the foam core A_{Ef} has to be measured. For the non-filled crash box this value was

experimentally determined to be $A_{E0} = 0.56$, whereas the foam core had an efficiency of approximately $A_{Ef} = 0.85$.

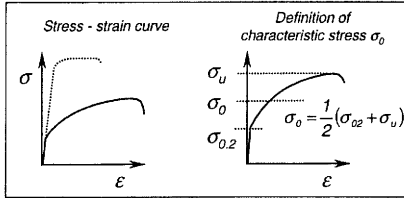


Figure 1.
Definition of the material properties of crash box material (extruded material)

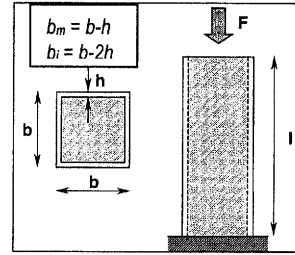


Figure 3. Geometry

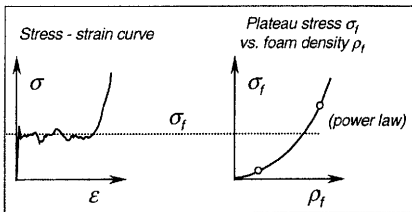


Figure 2. Typical foam material properties

Average force:

$$F_{avg} = 13.06\sigma_0 b_m^{1/3} h^{5/3} + \sigma_f b_i^2 + C_{avg} \sqrt{\sigma_f \sigma_0} b_m h$$

Maximum force:

$$F_{max} = \frac{13.06}{A_{E0}} \sigma_0 b_m^{1/3} h^{5/3} + \frac{1}{A_{Ef}} \sigma_f b_i^2 + C_{max} \sqrt{\sigma_f \sigma_0} b_m h$$

Figure 4. Design formulae

4. Crashbox mission

The crash box concept is motivated by the large amount of car crashes taking place at velocities below 15 km/h. Thus, owners of cars that manage to absorb the energy during these impacts in a localised and controlled manner strongly benefit from decreased insurance rates as a result of low repair costs. Therefore, the mission of the component is to avoid plastic deformation of the vehicle body frame during low speed impacts. The deformed structure should be easily interchangeable in order to reduce the cost and time for repairing.

A standardised crash test, defined by the Allianz Center for Technique (ATZ), is generally adopted to evaluate the behaviour of cars in low speed impacts. According to this standard, the vehicle is rated on the base of repair costs after a crash against a rigid barrier with 40% of contact overlap at a speed of 15km/h.

In the experiments this standard was simulated giving the desired value of energy to the drop hammer. It was calculated as the energy of a vehicle of 1000 kg (B segment) at a speed of 15 km/h, reduced by a factor because the energy is absorbed also by other components of the front of the vehicle. The targets were:

- energy to absorb: $E = 5000 \text{ J}$
- maximum force: $F_{max} = 55 \text{ kN}$
- max crashbox length $l_{max} = 210 \text{ mm}$

5. Design and experimental investigation

According to the previously described design formulae and the component mission, a simulacrum of a crash box was designed (Figure 5). The prototypes were manufactured from a commercially available extruded aluminium (Al6060 - T6) profile. The aluminium foam filler, supplied by Hydro Aluminium, was AlSi7MgCuNi + 15 % of SiC_p, having a nominal density of 0.19 kg/dm³. The foam cores were machined to fit the extrusion cavity without clearance so that no adhesive was needed. An aluminium flange was welded to the bottom side of the extrusion to simulate the real fastening to the chassis. Prototypes of a complete front-end were manufactured from two crashboxes and a cross-beam, joined together by bolted junction (figures 6, 7). The cross-beam was of a commercially available type produced for the European market.

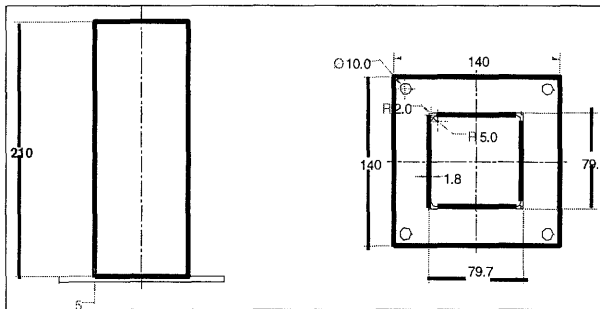


Figure 5. Crashbox geometry and dimensions

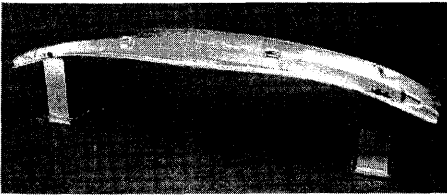


Figure 6. Crashboxes

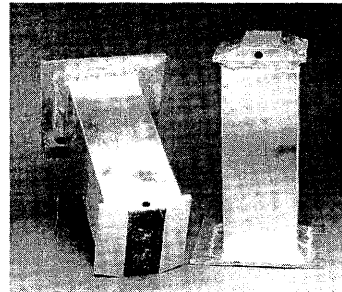


Figure 7. Front-end simulacrum.

Both the simulacra, the crash box and the complete front-end, were characterised by static and dynamic compression tests. In details, the following tests were performed:

- static compression tests on single crash boxes
- dynamic compression tests in the form of crash tests on single crash boxes and crash tests on the complete front-end simulacra in accordance with the “Allianz” test standard.

All the experimental results are summarised in Table 1.

Test ⁽¹⁾	Max Force [N]	Absorbed Energy [J]	A _E	S _E	T _E
Static compression on non-filled crashbox	38938	3505	0.56	0.76	0.43
Static compression on filled crashbox	51891	5490	0.74	0.69	0.51
Dynamic compression on filled crashbox	57356	4744	0.74	/	/
Dynamic compression on complete front end (Allianz test)	54847 ⁽²⁾	5704 ⁽²⁾	0.58	0.58	0.34

(1) Average value over 3 tests

(2) Maximum force and absorbed energy are related to the most stressed crashbox.

Table 1: Experimental results

Static compression tests on the single crash box

The average force during the deformation of the filled crashbox is nearly twice that of the non-filled crashbox (see figures 8, 9). Correspondingly, the maximum force is about 30% higher. Moreover, it was observed that the sum of the energy absorbed by the two components separately (crashbox and foam) is lower than the energy absorbed by the filled crashbox. Both the previous considerations lead to an increase in the energy absorbing efficiency of the filled crashbox. This effect is due to the positive interaction between the elements that increases the folds number and leads to an increase in the energy absorption capability (see figure 10, increasing in subtended area). The increase in the number of folds is also visible in the figures as a decrease in wavelength. Details on this behaviour can also be found in Ref. [1].

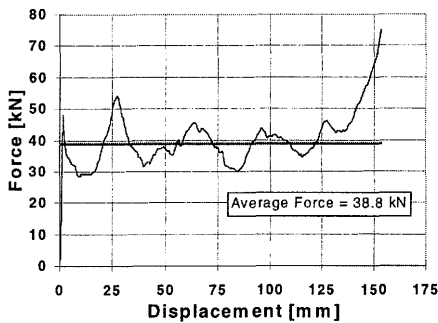


Figure 8. Static compression - foam filled crashbox.

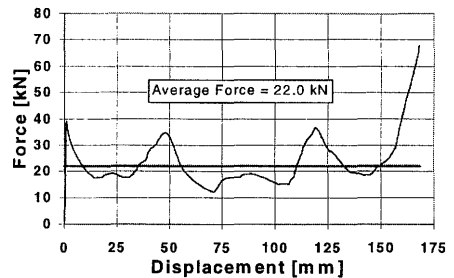


Figure 9. Static compression - non-filled crashbox

Dynamic compression tests

The dynamic tests were carried out by a drop hammer. During the compression, a load cell located under the specimen (the crash-box) measured the force, whereas 3 accelerometers, placed on the hammer, were used to record the acceleration.

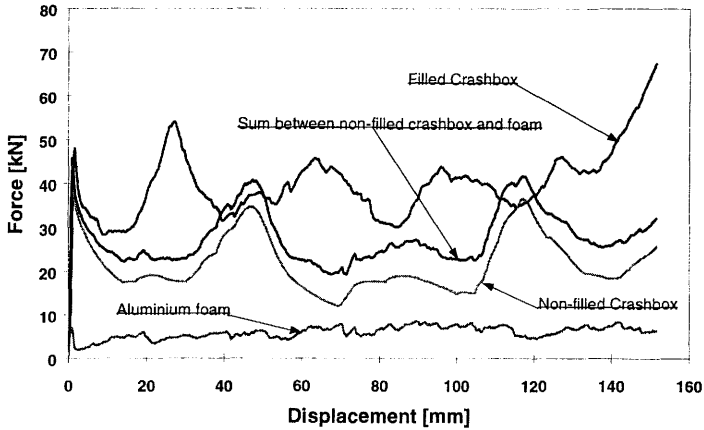


Figure 10. Interaction between crashbox and foam.

Crash test on the single crash box

The results are well correlated with those of static compression in terms of efficiency A_E ; the materials did not show any strain rate sensitivity (Figure 11), nor did dynamic inertia effects significantly influence the results. Ref. [1] describes more thoroughly the dynamic loading of these components.

Owing to the experimental layout, the crashbox did not reach complete densification. For the same reason, the energy absorbing capacity of the tested crash boxes is actually higher than the energy input of the current tests.

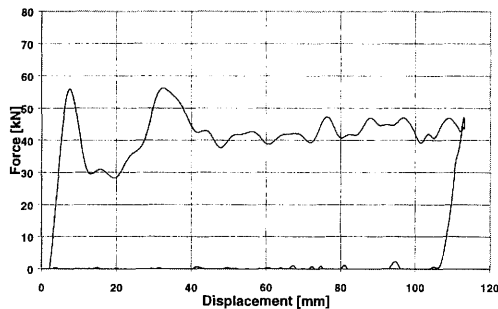


Figure 11. Crash test on filled crashbox.

Crash tests on the complete front-end simulacrum in accordance with the “Allianz” test standard.

The results of the “Allianz” test are in agreement with the design target (figure 12). As for the single crash boxes, the front-end structure was able to absorb more than the total amount of energy that is involved in this crash standard. The maximum force measured was also lower than the design value. The energy absorbing efficiencies were in a range of $\pm 10\%$ of the design value. No rupture were observed neither in the cross beam nor in the crashbox.

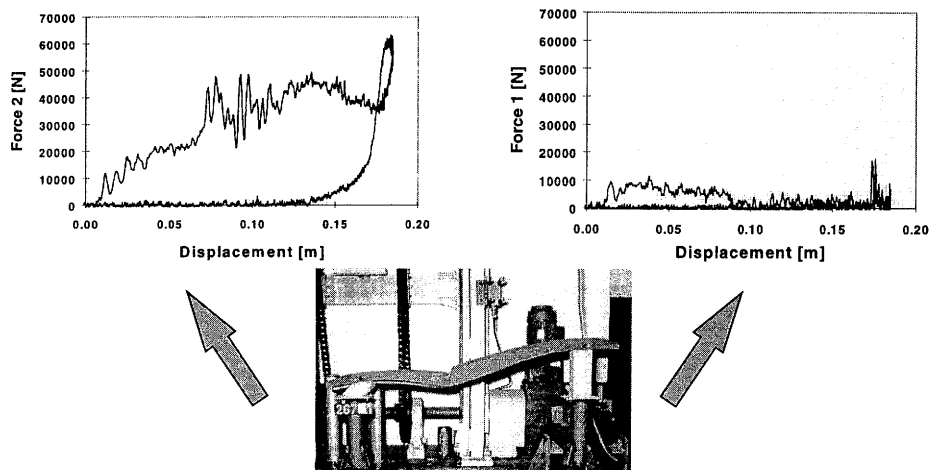


Figure 12. Crash test – Simulation of Allianz test

6. Conclusions

An experimental investigation of the behaviour of a bumper system based on aluminium foam filled crash boxes has been undertaken. It was found that existing design formulae applying to aluminium foam based crashboxes resulted in an overall good agreement compared with the experiments. Furthermore, the tests carried out revealed that both the single crashbox and the complete front-end satisfy the design constraints in terms of energy absorption, maximum force transmitted and dimensions.

Taking also into account the results of an additional study described in Ref [3], the application of aluminium foam as the filler of an energy absorbing structure (crashbox) guarantees the following advantages (with reference to the design targets fixed in the studied case):

- Weight saving approximately 10%
- Crashbox length (minimum shortness required) reduction of about 30%
- Crashbox volume reduction, approximately 60%.

References

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Appendix A

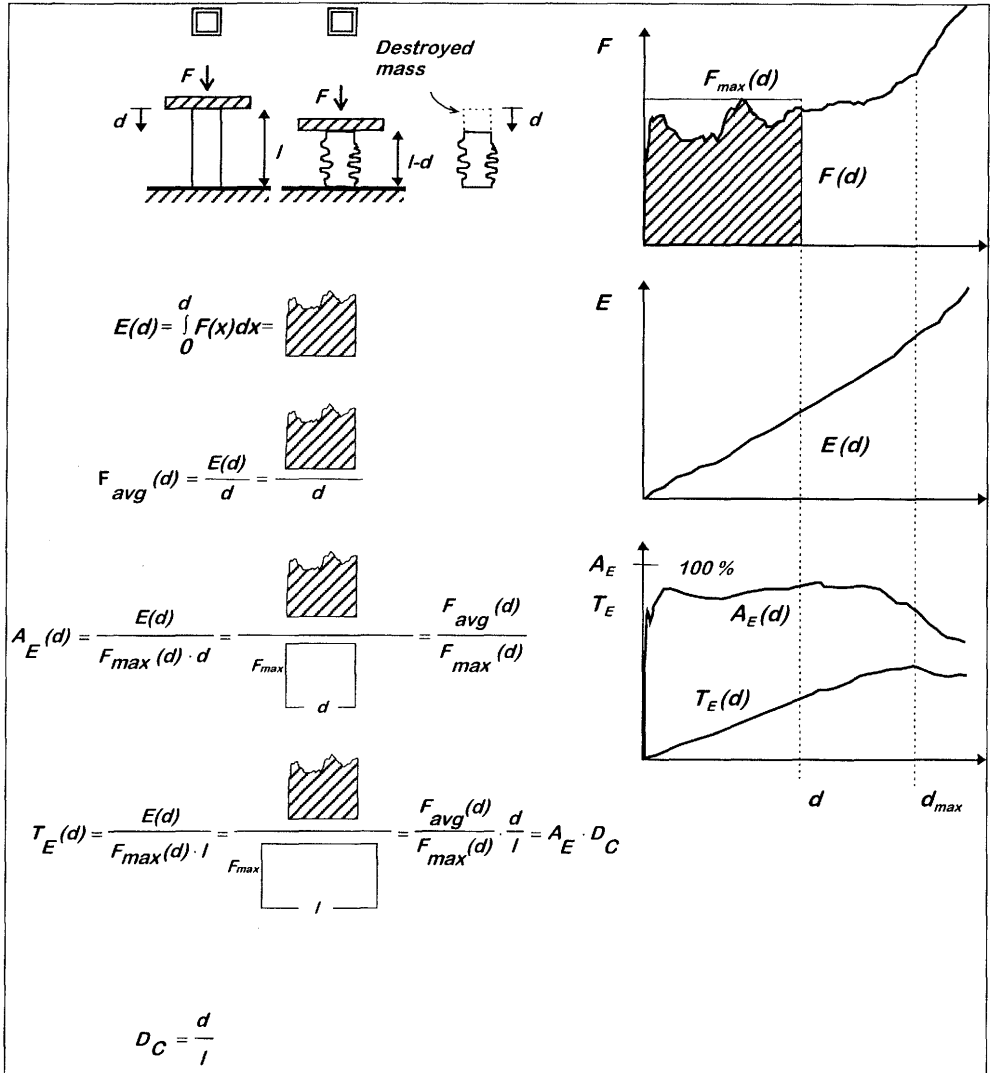


Figure A.1. Terminology