IMPROVED VEHICLE PERFORMANCE THROUGH LOCAL REINFORCEMENTS

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Abstract

Two preformed foam types (XPS and PMI) and one injected 2C-PUR foam have been evaluated on their reinforcing effect in metal profiles based on bending and impact tests. Surprisingly, the PMI foam showed significantly higher energy absorption-to-weight ratios for the low-density variant compared to the high-density variant. Due to the rather low density of the XPS foam, this material had no effect on the mechanical properties of the metal profiles. Furthermore, the filling degree of the injected foam appeared to have a significant positive effect on energy absorption during impact.

1 Introduction

1.1 Background

With the ever more stringent restrictions concerning fuel consumption and emission rates, it is difficult for modern vehicles to fulfill both the high safety requirements and the customer's expectations as to comfort. Accordingly, there is considerable interest in local reinforcements that can improve the vehicle's structural and/or acoustic performance and at the same time have a positive effect on weight reduction.

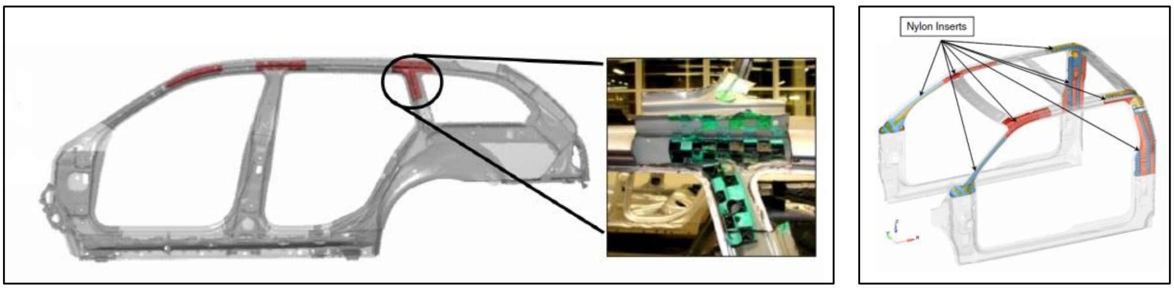

Figure 1: (left) Application of structural foam in the side frame of the BMW5 Touring series [1] - (right) Possible application of nylon inserts in A and C pillar [2].

For integration in the bodywork of passenger cars quite a few techniques are already being applied, such as the injection of polymer foams or custom-made inserts as illustrated in Figure 1. However, this is not the case for the trucks, buses and industrial vehicles (TBI) industry. Indeed, simple "copy/paste" actions for applications that are used in passenger cars are not feasible as for this branch of the automotive industry different production volumes, manufacturing methods and additional requirements apply. As a result, there are still significant opportunities for development and innovation in this area of transportation.

1.2 Prior results

In a previous Flanders' DRIVE project, "A Lightweight Functional Door Demonstrator", the behaviour of polyurethane foams in steel profiles under bending impact was evaluated [3]. Apart from a significant change in deformation behaviour, as can be seen on the left in Figure 2, a clearly higher energy absorption was noted with the use of polyurethane memory foams, with values up to 2.5 times higher than the energy absorption of rigid in-situ polyurethane foam. Figure 2 also shows the force/displacement graph. The sudden force drops seen in the graph are due to the cracking of the memory foam inside the steel profile during the impact. These results encouraged further research into the effect of foam reinforcements.

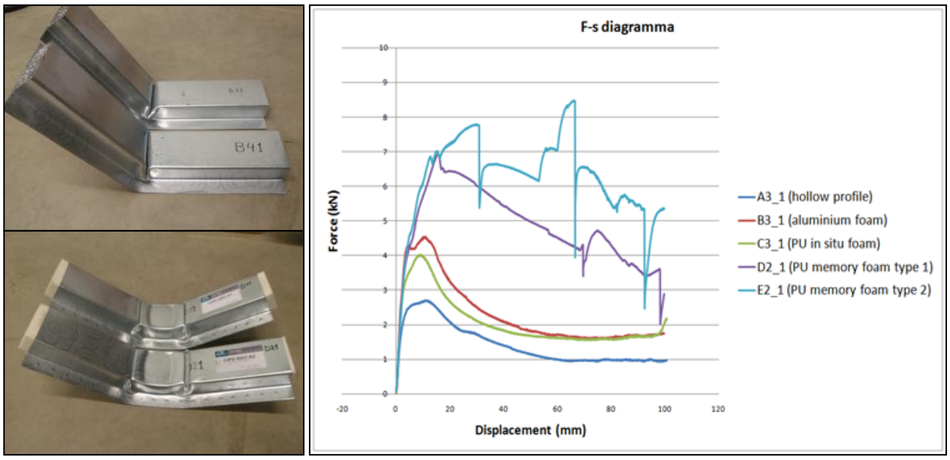

Figure 2: Polyurethane foam filled steel profiles after impact testing. Top left: rigid in-situ foam – bottom left: memory foam. Right: force/displacement graph of U-beams filled with different foams. The two upper graphs illustrate two types of polyurethane memory foams with different densities [3].

Hence, in the project "Enhanced Vehicle Performance via Structural Reinforcements", supported financially by the Flemish Government, a large-scale research has been initiated into the possibilities of different technologies to enhance hollow (metal) structures and thin body panels with respect to their mechanical and acoustic performance. Given the interest in a reliable prediction of the costs and environmental impact associated with these technologies, a thorough cost-benefit analysis is being implemented as well, comparing the achieved gains (stiffness, crash resistance, noise reduction, extra functionalities, etc.) with the additional costs and possible environmental penalties. These findings will then be validated based on use cases from industrial partners[1].

This paper focuses on a selection of polymer foam filled hollow structures and their mechanical behaviour.

[1] Following partners take part in the project "Enhanced Vehicle Performance via Structural Reinforcements": PSS, hegge ID, Vitalo, VDL Bus Roeselare, Voxdale, CNH, Sapa RC profiles, Recticel, LMS, Thule.

2 Methodology

First, several known reinforcing technologies are screened and rated from a qualitative perspective with respect to various features subdivided into mechanical, physical and processing-related issues. Also cost concerns, such as material cost, required investments and operating cost, are taken into account. Technologies that are taken into consideration are metal profiles filled with several foams (of a polymeric or metal nature) or with custom-made reinforcing inserts, profiles made of fibre-reinforced polymers and tailored welded profiles.

Based on the overall rating result, the most promising technologies are selected for further testing. In a first stage, 'tailored' or 'custom-made' technologies are omitted from the general evaluation, which led to a selection of nine foam materials to be processed into metal profiles, i.e. XPS foam, PMI foam, PA foam and several polyurethane and epoxy foams. To optimize the number of tests required in a statistically sound way the 'Design of Experiments' principle is applied. With this method, not every parameter combination requires testing to allow drawing conclusions, tests are limited to a well-defined set of parameter combinations only. Accordingly, the number of experiments that must be carried out to allow drawing reliable conclusions can be restricted to a minimum.

3 Experimental procedure

3.1 Material

As mentioned before, tests are performed on foam filled metal profiles. Several parameters are taken into consideration – those relevant for this paper are listed in Table 1 and will be explained below. All tests are performed on round, open-ended profiles, made of aluminium (6060 T66, extruded) or steel (S235JR, cold formed, welded). The profiles have a length of 700 mm, an outer diameter of 30mm and a wall thickness of 1.5mm or 3mm.

Entity	Parameter	Description
Profile	Profile material	Steel or Aluminium
	Wall thickness	1.5mm or 3mm
	Section geometry	Round
	Profile ends	Open
Filling	Filling material	XPS foam, PMI foam or PU foam
	Adhesive	No
	Foam density	Low or High
	Filling degree	Empty, Half or Full
	Foam location	In

Table 1: Overview of tested product parameters.

The foams that are discussed in this paper are extruded polystyrene (XPS) foam, developed for impact applications, polymethacrylimide (PMI) foam and a basic two-component polyurethane (PU) foam. The XPS as well as the PMI foam have been supplied in preformed shapes, which are then inserted in the metal profiles. No adhesive is applied. Two densities of XPS foam are evaluated: 37 kg/m³ and 42 kg/m³. Also two densities of PMI foam are evaluated: 31 kg/m³ and 110 kg/m³. The PU foam is injected in-situ into the metal profiles.

The foam has a free density of ca 55 kg/m³, therefore only one density is tested. The effect of the filling degree has been evaluated as well: the properties of empty profiles are compared to completely filled profiles (100% filling) and profiles that are only filled in the middle section (50% filling).

3.2 Tests

All specimens are subjected to four-point-bending tests to determine stiffness and maximum load capacity and to low-velocity, flexural impact tests to determine the amount of energy absorbed during impact. Additional buckling tests will be performed as well, but these results are not yet available at the moment. Every specimen is thus made in nine fold: three samples for bending tests, three samples for impact tests and three samples for buckling tests.

3.2.1 Four-point bending

The distance between the outer supporting points of the four-point bending test amounts to 650 mm and the distance between the inner loading points equals 100 mm. The test is carried out at a displacement rate of 1 mm/sec. Both the supporting and loading surfaces are rounded (R=10mm) and rotating to minimize friction effects.

A typical load/displacement graph of a foam filled sample is displayed in Figure 3. Maximum load and stiffness values are determined as indicated in this figure. Both absolute properties and properties relative to weight are analysed (referred to as “specific load” or “specific stiffness”).

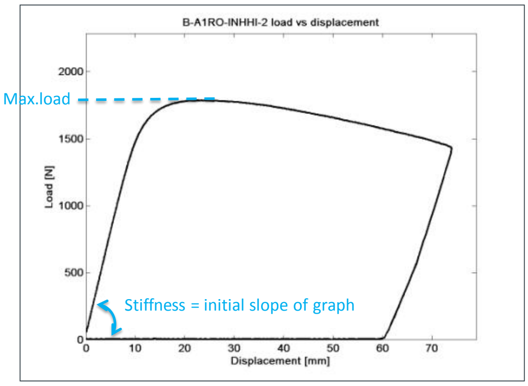

Figure 3: Typical load/displacement graph during four-point-bending of a foam filled metal profile.

3.2.2 Low-velocity Impact

The outer supporting points of the impact test are positioned at a distance of 650 mm from one another. The impactor is situated in the middle, with a profile diameter of 254 mm, in accordance with FMVSS 214. The supports are rounded (R=10mm) and rotating. The displacement rate is set at 2 m/s.

A typical impact graph of foam filled samples is displayed in Figure 4. The energy absorption is calculated between two fixed displacement points. Also a weight-specific energy absorption value is calculated, referred to as “specific energy absorption”.

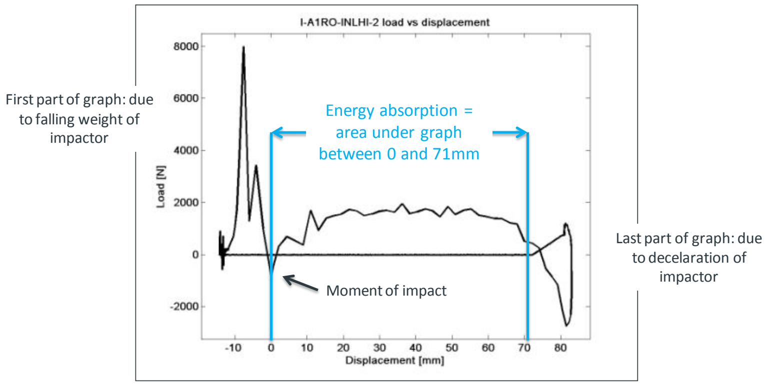

Figure 4: Typical load/displacement graph during low-velocity impact on a foam filled metal profile.

4 Results

4.1 Polystyrene foam filled structures

The bending and impact properties of XPS foam filled profiles are analysed in more detail using the Design of Experiments method to identify the parameters that have a significant impact on the bending properties. It can be concluded that the bending properties of XPS foam filled profiles are mainly determined by profile parameters (material and wall thickness). As expected, thicker profiles have higher absolute values for load and stiffness and steel profiles perform better than aluminium profiles. However, when weight is taken into account, the specific load properties of aluminium outperform those of steel, as illustrated in the left graph of Figure 5.

The specific stiffness of XPS foam filled profiles is furthermore (negatively) influenced by the filling degree, which means that the XPS foam adds more weight without adding any stiffness to the structure (Figure 5).

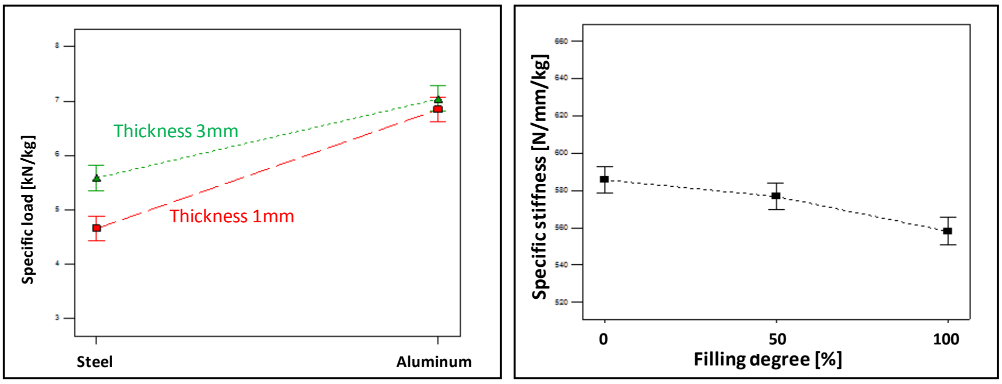

Figure 5: Graphic representation of some significant effects in XPS foam filled profiles. Left: the specific load values of aluminium profiles are higher than those of steel profiles, regardless of filling degree. Right: the specific stiffness decreases with increasing filling degree for XPS foam filled profiles, regardless of the respective profile parameters.

Parameters that have a significant effect on the energy absorption during impact of XPS foam filled profiles are limited to profile material and wall thickness, as illustrated in Figure 6.

Thicker profiles have higher absolute properties, but when weight is taken into consideration, thinner profiles are superior. Steel performs better than aluminium, but this relation reverses when weight is taken into account.

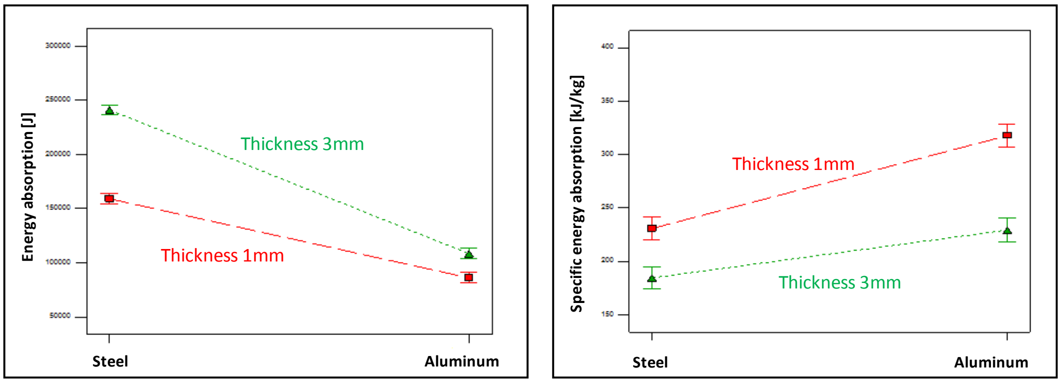

Figure 6: Graphic representation of the effect of profile parameters on energy absorption (left) and specific energy absorption (right) of XPS foam filled profiles during impact

4.2 Polyurethane foam filled structures

Again, the Design of Experiments method is used to identify the parameters that have a significant influence on the bending properties of PU foam filled profiles. The results show that bending properties of PU foam filled structures are determined by profile parameters as well as by filling degree. As already observed with XPS foam, thick-walled and steel profiles have higher absolute properties than thin and aluminium profiles respectively. But, when weight is taken into account, aluminium profiles achieve significantly higher load values, although the specific stiffness values remain lower compared to steel. Furthermore, partly filled profiles are optimal as for the achieved absolute maximum load; it is also shown that specific stiffness decreases with increasing filling degree, indicating that the foam adds weight without significantly improving the stiffness of the structure. This is illustrated in Figure 7.

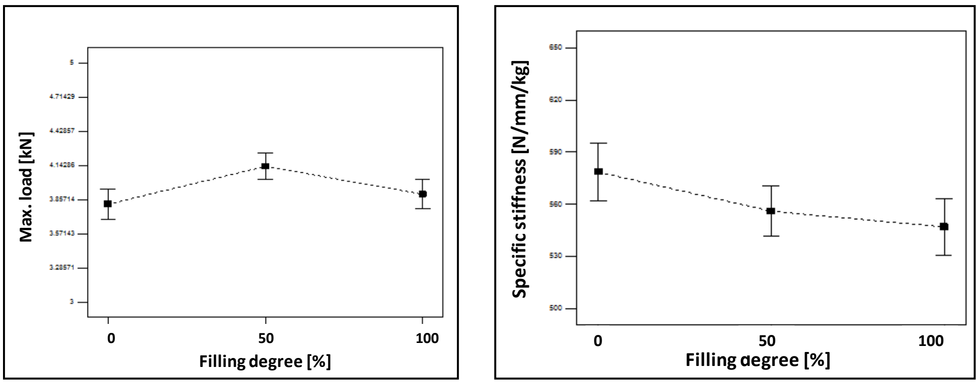

Figure 7: Graphic representation of some significant effects in PU foam filled profiles. Left: half-filled profiles achieve a higher maximum load regardless of profile parameters. Right: the specific stiffness decreases with increasing filling degree for PU foam filled profiles, regardless of profile parameters.

Additionally, the impact results show that the energy absorption of PU foam filled profiles is influenced by the profile parameters (material and wall thickness) as well as by the filling degree. It is again clear that thick profiles, as well as steel profiles, absorb more energy than thin and aluminium profiles respectively. But when weight is taken into account, thin profiles and aluminium profiles have a higher specific energy absorption value. Moreover, the specific energy absorption of thin profiles as well as of aluminium profiles is highest for empty profiles, whereas thick profiles and steel profiles benefit most from a 100% PU foam filling. This is illustrated in Figure 8.

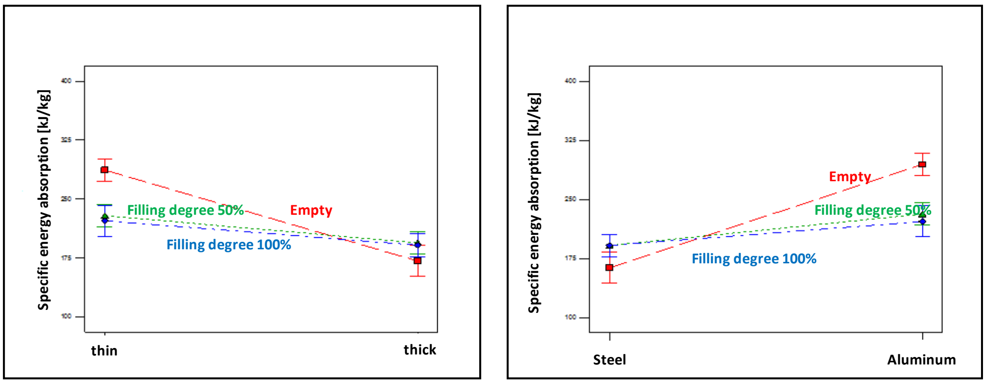

Figure 8: Graphic representation of the effect of profile parameters on the specific energy absorption of PU foam filled profiles during impact. Left: effect of wall thickness and filling degree – Right: difference between steel and aluminium profiles.

4.3 PMI foam filled structures

The Design of Experiments method is once more used to identify the parameters that have a significant effect on the properties of PMI foam filled profiles. Analogous to XPS and PU foam, the bending properties of PMI foam filled tubes are determined mainly by profile parameters, such as material and wall thickness. As far as specific stiffness is concerned, the filling degree has an adverse effect.

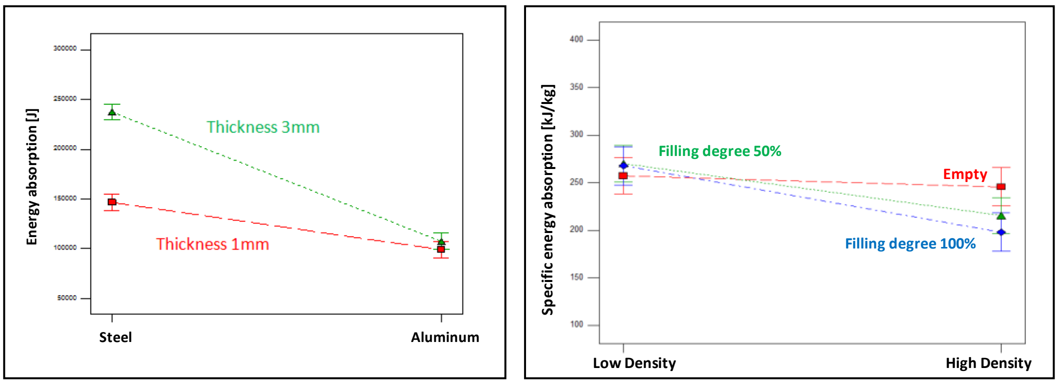

Figure 9: Graphic representation of the effect of profile parameters on the energy absorption of PMI foam filled profiles during impact. Left: effect of material and wall thickness on the absolute energy absorption– Right: effect of foam density and filling degree on the specific energy absorption.

With respect to the energy absorption, PMI foam filled profiles during impact can be compared to XPS foam filled profiles. The profile material and wall thickness have a significant influence on the energy absorption: thick and steel tubes absorb more energy than thin and aluminium tubes respectively, as shown in the left-hand graph of Figure 9. When weight is taken into account, it is shown that high-density PMI foam results in a negative effect compared to empty profiles. This is illustrated in the right-hand graph of Figure 9.

5 Conclusion and future work

Round metal profiles are filled with XPS foam, PMI foam and PU foam and the bending and impact properties have been determined. As expected, the profile parameters (material and wall thickness) play a significant role in the mechanical properties for all foam filled profiles. Stiffness, load and energy absorption of XPS filled profiles are not influenced at all by the foam filling, moreover a negative effect is noticed when weight is taken into account. Also PMI foam seems to have little effect on the bending and impact properties of metal profiles. On the other hand, the performance of PU filled profiles is significantly better than that of empty profiles despite the low density of the foam. Probably, the fact that this particular foam is in-situ injected, as opposed to the XPS and PMI foams that are inserted as preformed shapes, results in a better adhesion between foam and metal substrate. This in turn results in a better load transfer and thus in a measurable effect of the filling degree. It is expected that foams with a higher density that are properly adhered to the metal profile, will show a significant positive impact on the overall bending and impact properties.

Please note that the conclusions are based on experiments that were performed on relatively narrow profile dimensions with a high wall thickness. The choice for this geometry was partly driven by the industrial case studies. Accordingly, the conclusions are based on a rather small part of possible profiles and results might be different for other profile geometries.

Further short-term steps in this research include the evaluation of additional polymer foams, such as epoxy foam and other types of PU foam. Also the effect of the respective foams on the buckling behaviour of the profiles will be tested. Next to hollow metal structures, sandwich panels with different foam cores will be evaluated as well. In addition, the Eco Audit™ Tool, which is an add-on tool to Granta's CES Selector, is used to calculate the environmental impact of each of the technologies. Finally, the Part Cost Model, a newly developed tool from Granta Design, is used to make cost estimates. This way, a complete cost-benefit analysis as well as an environmental evaluation will be available for all researched technologies.

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