Quasi-static bending of thin-walled beams with different fillers under extreme load for solving the problems of crashworthiness

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Abstract. In this paper, there are issues related to the choice of elemental modelling of thin-walled beams with various types of fillers for quasi-static bending loading, which causes washing of beams and filler, as applied to the optimal design. The objects of research are thin-walled beams made of aluminium AMG6 contains fillers made of aluminium foam, epoxy resin and composite (consisting of Poraver balls and epoxy resin). One of the best fillers for solving the problems of crashworthiness is requiring expensive technological equipment for filling. Epoxy resin is a fragile material, but inexpensive, affordable and technologically “convenient”. In addition to the influence of the filler on the mechanical properties of beams, the effects of the constrained behaviour of the material of the filler under the bending loading of beams are investigated with Zwick Z100 (for hollow thin-walled beams made of aluminium and the same beams with fillers). The paper presents the results of numerical calculations and the results of the experiment (the error of calculations does not exceed 8%). The most rational is the ratio between the indicators of energy intensity - the mass is aluminium-foam (with an increase in the mass of the sample by 2.1 times the mechanical properties reach 10 times). The remaining fillers give significantly worse results for the same parameters. To assess the effectiveness of the use and creation materials for the refinement of the cabins and car bodies according to the crashworthiness.

1. Introduction

The requirements to ensure both active and passive safety of people in the car are the most important now. Vehicle structures that perceive external impact during an accident, including shock, should be lightweight, durable and capable of absorbing energy so that living space around people is preserved [1–13]. During the collision, frame-type elements of cabs and car bodies, made primarily by welding thin-walled profiles in a closed loop, lose their bearing capacity under the influence of bending loads [14–16]. A similar character of deformation is obtained during three-point bending of a thin-walled beam, therefore, this article addresses issues related to modelling the behaviour of beams under extreme transverse quasistatic loading (causing beam and filler crushing) for subsequent interpretation of the results obtained on more complex cab and body models as applied to crashworthiness.

Thin-walled beams in the process of such bending are usually very significantly deformed at the point of contact up to the formation of a plastic joint. To achieve optimal ratios of mechanical properties during bending and structural mass, it is advisable to use a filler in the form of a foamy
material, for example, aluminium-foam. Chen [17] performed an optimization to minimize the weight of the structure, which is filled with a porous material. He showed that aluminium-foam is a good energy-absorbing material. Chen [18] also studied the behaviour of foam-filled profiles during bending and proved that aluminium-foam increases the energy-absorbing properties of the structure. Hanssen [19] experimentally investigated the bending behaviour of foam-filled profiles and found that the foam filler significantly changes the local patterns of beam deformation. In articles [20, 21], issues related to the application and optimization of the properties of aluminium-foam for the refinement of elements of cabs and car bodies in order to meet the requirements for passive safety are considered. It is shown that the use of filler allows you to achieve the specified requirements with a minimum increase in mass.

The main problem limiting the massive use of foam-filled construction of cabs and bodies is related to production issues. Modern technologies for the manufacture and processing of aluminium-foam are complex and expensive, which leads to an increase in the cost of production; therefore, in this work, we also consider alternative options for fillers. One of them is epoxy resin—a cheap and affordable material and due to its excellent infusion properties, it can be “pumped” under pressure into the frame elements of cabins, which greatly simplifies and reduces the cost of production and assembly technology.

Particular attention is paid to the numerical modelling of the mechanical properties of fillers using the finite element method (FEM) and the LS-DYNA program (including the development of rational finite element models and material modelling). Two types of materials are compared: cellular elastic-plastic (aluminium-foam), which allows large deformations to fracture and brittle (epoxy resin), which has high strength in a limited range of deformations.

To assess the errors of solutions, corresponding bench experiments were carried out.

Comparison of materials with different mechanical properties is necessary to determine the limits of their applicability of cars crashworthiness and to predict the required properties of promising fillers.

2. Mathematical model

2.1. Modelling of filled aluminium beams in LS-DYNA

To study and compare the mechanical properties of cellular elastoplastic and brittle materials, the problem was posed of quasistatic loading of an aluminium beam with a filler. This problem was solved in an explicit statement by the finite element method in the LS-DYNA program. FEM of beam with filler is shown in Figure 1. The proposed type of element is eight nodal, constant stress solid and the base size of the element is 2 mm, which is typical for high-precision models [22]. This type and size of the element is best suited for solving the problems of three-point beams bending with filler [23], including multivariate and optimization [24]. The beam material (aluminium alloy AMg6) was modelled by the MAT_PLASTIC_KINEMATIC “map” with isotropic hardening (material parameters are summarized in Table 1). The diameter of the beam is 40 mm, the wall thickness is 3 mm, the length is 270 mm, the distance between the supports for three-point bending is 200 mm.

The solution to the problem in the LS-DYNA was carried out for the following types of beams:
- hollow beam;
- beam filled with epoxy resin;
- beam filled with aluminium-foam.

Aluminium-foam in LS-DYNA is described by the model proposed by Deshpande and Fleck MAT_DESHPANDE_FLECK_FOAM [25]. This model allows to simulate the mechanical properties of the foam material without directly modelling the pores, which significantly reduces the time spent on the preparation of the calculation and computer time counting.

Three variants of aluminium-foam with densities of 50 kg/m$^3$, 430 kg/m$^3$ and 800 kg/m$^3$, respectively, were compared in [26, 27]. The mechanical properties of the epoxy resin were set
according to the data presented in Table 1 and based on research [28]. Material model MAT_PLASTICITY_POLYMER with the condition of destruction upon reaching a strain of 8%.

![Fig. 1. FEM of filled beam and a loading device](image)

| Parameters                  | Aluminum AMg6 | Epoxy EL with hardener EL 152 MLR | Poraver |
|-----------------------------|----------------|-----------------------------------|---------|
| ρ, kg/m³                    | 2460           | 1100                              | 390     |
| E, GPa                      | 71             | 3.2                               | –       |
| σ₀, extension, MPa          | 250            | –                                 | –       |
| σₑ, extension, MPa          | 385            | 74                                | –       |
| σₑ, bending, MPa            | –              | 110                               | –       |
| σₑ, compression, MPa        | –              | 100                               | –       |
| δ₅, %                       | 11             | 8                                 | –       |

Table 1. Mechanical properties of the materials

This article simulates two “extreme” types of materials in which elastoplastic and brittle properties are pronounced. Other types of materials (including composite) with properties not very different from those considered can also serve as a filler for frame-type elements of cabs and car bodies. For adequate modelling of such materials, it is necessary to know the dependences of stresses on deformations for a specific load (tension, compression, bending). Such dependencies are best obtained by the experimental method [29].

The calculation time was limited to 0.1 second at a loading speed of 0.5 m/s in LS-DYNA. The dependence of strain-rate was not taken into account.

The obtained load curves are shown in Figure 2. The numerical result of the deformed state of the beam is shown in Figure 3.
Fig. 2. Numerical impact force curves for the foam-filled beam

- aluminum-foam (800 kg/m$^3$)
- aluminum-foam (430 kg/m$^3$)
- aluminum-foam (50 kg/m$^3$)
- epoxy
- hollow
The numerical results are in Table 2.

Table 2. Results of numerical analysis

| Material                  | Mass, g | Maximum force, kN |
|---------------------------|---------|-------------------|
| Hollow beam               | 250     | 14,1              |
| Epoxy filled beam         | 520     | 32,3              |
|                           | 267 (50 kg/m³) | 14,2      |
| Foam filled beam          | 396 (430 kg/m³) | 22,5      |
|                           | 521 (800 kg/m³) | 5140     |

An analysis of the results showed that brittle materials (epoxy resin) have relatively high strength in a small deformation range, in contrast to cellular elastoplastic materials (aluminium-foam), which remain operational during significant deflections and, as a result, absorb more energy during deformation, which is more important property for solving the problems of crashworthiness.

Aluminium-foam with a minimum density (50 kg/m³) does not significantly improve the flexural rigidity of the structure. When the filler density is increased to 800 kg/m³, the perceived force increases by 10 of times, and the mass by 2.1 times.

2.2. Verification of theoretical provisions

In order to verify, experiments were carried out for a hollow aluminium beam and a beam filled with epoxy resin. In addition, we studied the mechanical properties of beams filled with polyurethane foam and a composite material consisting of Poraverball filler and EL epoxy binder with an EL 152 MLR hardener shown in Figure 4.

In addition to the influence of the filler on the mechanical properties of beams, effects were studied in the constrained behavior of materials in the case of three-point bending. The ends were welded with rectangular aluminum plates in beams with a composite material and epoxy resin (four beams).

Fig. 3. Numerical deformation pattern for the filled beam

Fig. 4. Test beams:

a — hollow beam; b — polyurethane foam-filled beam; c — composite material-filled beam; d — epoxy-filled beam
Three-point bending tests were performed on a Zwick Z100 universal testing machine. The test beam and universal machine are shown in Figure 5.

![Zwick Z100 testing machine and test beam](image)

**Fig. 5.** Zwick Z100 testing machine and test beam

The experiment was carried out as follows:

– a gradually increasing quasistatic load was applied to the beam using an indenter with a rounded end. Load application speed 20 mm/min.

– the amount of applied force was measured depending on the movement of the beam using special sensors and software.

The experimental results are shown in the graphs of Figure 6 and Table 3, and the picture of the deformed state of the beams is shown in Figure 7.
Fig. 6. Experimental and numerical impact force curves for:
a — hollow beam; b — polyurethane foam-filled beam; c — composite material-filled beam; 
d — epoxy-filled beam
Fig. 7. Beams after full-scale experiment

Table 3. Results of the experiment

| Beam type                        | Number            | Mass, g | Maximum force, kN |
|----------------------------------|-------------------|---------|-------------------|
| Hollow beam                      | 1                 | 239     | 14,73             |
|                                  | 2                 | 238     | 14,1              |
|                                  | 3                 | 239     | 14,58             |
|                                  | 1                 | 241     | 14,27             |
| Polyurethane foam-filled beam    | 2                 | 240     | 14,28             |
|                                  | 3                 | 238     | 14,48             |
|                                  | 1                 | 413     | 23,79             |
| Composite material-filled beam   | 2 (with welded ends) | 451   | 23,18             |
|                                  | 3 (with welded ends) | 457   | 22,44             |
|                                  | 1                 | 514     | 35,35             |
| Epoxy-filled beam                | 2 (with welded ends) | 543   | 33,21             |
|                                  | 3 (with welded ends) | 545   | 31,42             |

3. Result and discussion
Analysis of the experimental results shows that the use of the proposed FEM allows to achieve acceptable results in accuracy. The error in the values of the maximum force does not exceed 8%.

In the case of a hollow beam, the loading curves for the three beams and the calculation practically coincide. The polyurethane foam-filled beam does not increase the stiffness, the loading curves in this case are comparable with the loading curves for a hollow beam.

As follows from the graphs (Figure 6 a, b) for displacements greater than 20 mm, the load acting on the beams decreases and, therefore, in both cases, the structure loses its bearing capacity.

On the other hand, the composite material as a filler allows to increase the stiffness of the beam by 1,6 times. The use of plugs at the ends of the beam does not introduce significant changes in the mechanical properties of the structure. The mass of the composite material filler is 200 g. The appearance of “teeth” on the graph is assumed to be associated with the destruction of Poraver balls and a short-term decrease in the rigidity of the entire model until neighbouring balls come into interaction and the structure begins to work again as a whole. The refinement of the frame elements of the cabs with such fillers is technological, but the effect of filling is not as significant as in the case of aluminium-foam.

Epoxy filler gives a more substantial increase in stiffness 2,23 times. In the process of deformation, the brittle resin is destroyed, as evidenced by the characteristic drops in strength on the graph. A specimen without plugs collapsed with more force than the other two, but with less strain. This is due to the fact that cracks appeared in the epoxy resin, it lost its bearing capacity and, as a result, began to extrude through the free ends of the beam. In all cases, the samples collapsed with smaller deformations (Figure 8) than in the case of using foam, therefore, despite the greater strength of the brittle material, its energy intensity is lower due to smaller deformations. Therefore, the use of brittle materials in the field of crashworthiness is not advisable (in addition, the mass of epoxy is relatively large — 275 g).
4. Conclusion

Based on the research, the following conclusion can be made:

1. The developed finite-element models make it possible to effectively predict the elastic-plastic behavior of a thin-walled beam (aluminum alloy AMg6) with a filler (aluminum-foam, EL epoxy resin with hardener 152 MLR, composite material) at the limit of three-point bending (error does not exceed 8% compared with the experiment).

2. The use of aluminum-foam gives the best results in the ratio of energy capacity — mass. The maximum perceived force during bending is 10 times greater than when using other types of fillers.

3. The use of epoxy resin increased the bending stiffness of the structure 2.23 times compared with a hollow beam, while the mass increased 2.1 times.

4. The use of a composite consisting of Poraver balls and a binder in the form of an epoxy resin made it possible to increase the flexural rigidity of the structure by 1.6 times, while the mass increased by 1.8 times.

The use of brittle materials does not have a significant effect from the point of view of crashworthiness, therefore, they are not recommended for solving issues related to ensuring
crashworthiness of automobiles, in contrast to elastoplastic foams (which lose their bearing capacity under significantly large displacement).

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