Crashworthiness design of truck’s cabin using topological and parametric optimization

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Abstract. In the given work the basic problems of search of optimum parameters of a cabin of the truck based on parametrical and topological optimization for the purpose of maintenance of requirements on crashworthiness under the international rules and reception of its minimum mass were considered. The article presents the developed finite element models of the cabin and drummer in relation to the optimization tasks, allowing to obtain results with acceptable accuracy and minimum time of solution when using LS-OPT and LS-TaSC programs with LS-DYNA solver. Steel linings and a foam filler are used to reinforce the cabin. In order to solve the problem and more fully assess the impact of parameters, several options were considered to refine the cabin. Topological optimization was carried out in order to obtain a picture of the best distribution of filler on the frame of the cabin. Parametric optimization was carried out by selection of filler properties (aluminium foam) and thickness of structural elements of the cabin. As a result, the passive safety requirements were achieved with optimal mass distribution as a result of combined use of linings and filler. The cabin’s mass increase was 20%.

1. Introduction

Increasing the requirements of ensuring the passive safety of people in the car is the most important task for designers working in this field [1–5]. Increase in the number of cars, speed of traffic on city streets and highways, growth of load-carrying capacity of newly developed cars [6–9] leads to necessity of creation the truck cabins that meet the requirements of passive safety with minimum mass and enough crashworthiness.

Passive safety testing is a complex and expensive task, so it is advisable to use the capabilities of modern computational analysis based on computer modelling to reduce the time and cost of design development. This kind of problems are solved by the finite element method (FEM) using an explicit method of solving differential equations.

Modern software packages allow solving highly non-linear problems with contact interaction between structural elements. They implement various optimization algorithms, including those based on hybrid cellular automata method (HCA) for topological optimization and various variation algorithms for parametric optimization.

In this paper, topological and parametric optimization was carried out to select the parameters of aluminium foam and the properties of the elements of the frame type cabins to achieve the requirements for crashworthiness under international rules and at the optimal value of mass. The main problem in solving optimization problems associated with the impact is the machine calculation time (from a few days to several weeks). The LS-TaSC and LS-OPT programs with the explicit LS-DYNA solver were used for the solution, which gives good results in terms of the ratio of accuracy to
computational time. Similar problems were solved in the works [10–13], but they do not give the
methods of searching for the optimal parameters for the truck cabs from the standpoint of

The purpose of the work is to meet the requirements of the passive safety rules of the truck cabin
and minimize mass due to the optimal distribution and selection of aluminium foam parameters and
thicknesses of frame type elements in the cabin.

2. Mathematical model

2.1. Analysis of the stress-strain states of the cabin during crashworthiness tests

Crashworthiness test are designed to simulate real-world emergency scenarios. In the case of trucks,
these situations include frontal impact, rear-end impact of the braked load, and tipping over of the
truck cabin. In accordance with VVVFS 2003:29, the crashworthiness of the cabin is verified by the
following tests, as shown in Figure 1: static load on the cabin roof; front impact by a cylindrical
drummer on the top front corner of the cabin; right-angle impact by a rectangular drummer on the rear
wall of the cabin.

The truck cabin is considered to have passed all types of tests under the following conditions:
– The supporting structure of the cabin or parts, as well as the fastening units, have not been
damaged, and no significant cracks or deformations have occurred;
– There is still living space in the cabin for the driver and passengers;
– When dynamically loaded (impacted), the entire impact energy is consumed (absorbed) by the
cabin without the drummer slipping over the roof.

The object of research in this paper is cabin of a truck. The cabin is shown in Figure 2, a. The FEM of the cabin is shown in Figure 2, b. The size of the finite element is 35 mm, the number of elements is 28521. Cabin elements were modelled mainly by 4-knot shell elements such as Belytschko-Tsay. The thickness of internal and external panels is 1 mm, the cabin spars are 4 mm. Cabin material is steel 08kp with kinematic hardening, cabin mass 250 kg.

To check the performance of the cabin, a calculation was made to assess compliance with the
requirements of passive safety rules. In this article the most complicated mode for the design is
considered: drummer impact test with the mass of 1000 kg with the initial speed of 7,6 m/s on the
front post of the cabin at an angle of 15°.
Figure 2. Object of research:

a — 3D model; b — FEM at the moment of pendulum impact

The time of calculation in the LS-DYNA program is 41 minutes, which in case of solving the optimization problem is acceptable from the point of view of time, provided that the deformation character is identical to the experimental one. With a larger finite element size, the resulting calculation error does not produce adequate results [14]. If more accurate FEMs are used, the calculation time is increased many times, resulting in excessive time consumption. The calculation results are shown in Figure 3.

Figure 3. Cabin results:

a — FEM in the final phase of impact; b — stress Mises; c — deformed state of the cabin

Results show that the residual life space is significantly less than the required values. Extensive plastic deformations have arisen in the design, the doorway has been severely deformed, and collapse zones are observed at the points where the thresholds are connected to the front of the cabin.

Based on the analysis carried out, the aim was to find optimal solutions for the cabin in order to meet the requirements for crashworthiness and minimize mass.

In order to achieve this objective and to better assess the effect of the parameters, the approach of sharing an aluminium foam filler in frame type elements and linings has been considered.

2.2. Topological optimization

In order to optimally distribute the filler (aluminium foam) over the cabin frame, a topological optimization was carried out for the three loading modes (VVFS 2003:29) shown in Figure 4.

To solve the problems of crashworthiness was created FEM, consisting of shell elements (cabin) and solid elements (such as tetra 10 — aluminium foam). The whole set of solid elements constitutes the design space, which is involved in topological optimization. The size of the element is 35 mm (at the place of impact and stress zones, the size of the element is 10–15 mm), and the number of
elements is 67890. The aim of the optimization is to provide living space in the structure and to minimize mass. The main objective of the calculation is to obtain a picture of the optimal distribution of the material in the cabin frame in the event of impact loading with a drummer.

Optimization was carried out by the hybrid cellular automata method (HCA) in the program LS-TaSC, as one of the most effective for such problems [15–18]. The results of topological optimization are presented in Figure 5.

Results show that the main elements that transmit the load on the brackets of the cabin to the frame, when hitting the front drummer are the floor and side members. Aluminium foam must be in the cavities along the contour of the doorway, tightens the structure, preventing the emergence of plastic hinges when hitting the post. Frame-type elements of the front panel reinforced with filler close the door apertures and spars into a single contour, thus uniting the structure into a single whole.

The following conclusions can be drawn from the analysis of the results:

– It is necessary to fill the cavities around the doorway and the front panel with aluminium foam;
– The cabin floor and spars are the main elements that transmit the impact load on the brackets of the cabin to the frame;

The use of medium level FEM for the topological optimization task at the preliminary stage of development allows getting the best picture of the filler distribution by the volume of the cabin with acceptable computational time consumption.

2.3. Parametric optimization

Based on the results of topological optimization and comprehensive analysis of the stress-strain state of the cabin, the variant of distribution of filler (aluminium foam) and linings on the design of the cabin was considered.
To obtain a solution to the optimization problem, the cabin was divided into several parts (subzone) and filled with aluminum foam. The division into subzones allows to limit the number of variable parameters in such a way that their number was enough to obtain appropriate results at the minimum cost of estimated time. Based on preliminary studies, the subzones around the doorway, windscreen, spars and the rear wall of the cabin were identified. In addition to the filler, the doorways and the front part were reinforced with linings. The thickness of the spars also varied to increase the crashworthiness of the cabin. The scheme of division of the structure into subzones is shown in Figure 6.

The aluminum foam in the program LS-DYNA is described by the model proposed by Deshpande and Fleck [19]. In this model, the properties of the filler depend on the density, which allows it to be used to solve optimization problems, choosing density as a variable parameter. The use of this model in relation to structural optimization problems is presented in [20–22].

The variable parameters are the density of foam aluminum $\rho_i$, which varies from 100 kg/m$^3$ to 800 kg/m$^3$, and elements of frame type with variants of thickness $t_j$: 0.1 mm; 1 mm; 2 mm; 3 mm; 4 mm. They are analogous to the linings, increasing the crashworthiness of the cabin, all parameters vary independently of each other. The aluminum foam fills the area around the doorway and the subzone under the windscreen. The use of aluminum foam increases the crashworthiness of thin-walled closed profiles [23], such as truck cabin racks.

Based on previous analysis, the maximum displacement of the rack at the checkpoint should not exceed 350 mm (the checkpoint is the node on the rack that has the maximum movement). The optimization was solved by using metamodel (Radial basis function) and adaptive simulated annealing algorithm (ASA). The optimization results are in Table 1.
Table 1. Results of combined optimization of foam density and lining’s thickness

| Aluminum foam | $\rho_1$ | $\rho_2$ | $\rho_3$ | $\rho_4$ | $\rho_5$ | $\rho_6$ | $\rho_7$ |
|---------------|---------|---------|---------|---------|---------|---------|---------|
| Density, kg/m$^3$ | 800 | 100 | 680 | 100 | 120 | 435 | 640 |
| Lining | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_7$ |
| Thickness, mm | 4 | 1 | 0.1 | 0.1 | 0.1 |
| Mass, kg | | | | | | 306 |
| Displacement of the checkpoint, mm | | | | | | 358 |

It is necessary to avoid extensive plastic deformation of the subzone $\rho_1$ and $\rho_3$ to fill with aluminum foam with a density of 800 kg/m$^3$, 680 kg/m$^3$, respectively, and to strengthen the front post with a 4 mm lining, in order to meet the requirements for the crashworthiness of the cabin when hitting the front post by a drummer. As a result, displacement of the checkpoint does not exceed the specified value of 350 mm, and the cabin mass is 306 kg.

3. Result and discussion

Table 2 shows the results for basic and advanced cabin variants.

Table 2. Comparison of basic and advanced cabin variants

| Displacement of the checkpoint, mm | Cabin’s mass, kg | Mass increase, % | Satisfying safety standards |
|-----------------------------------|-----------------|-----------------|---------------------------|
| Basic cabin                       | 850             | 250             | -                         | No                         |
| Cabin with fillers and linings    | 349             | 306             | 22                        | Yes                        |

After optimization, the cabin was modified for practical use. Filler zones $\rho_4$, $\rho_5$ and frame type elements with a thickness of 0,1 mm were removed from the structure, and the $t_1$ element was replaced by a 4 mm equivalent stiffness overlay.

As a result of the final modification, the cabin has become compliant with the requirements for crashworthiness, but the mass of the cabin has increased by 20% to 300 kg compared to the original design.

4. Conclusion

The use of the proposed combined approach (topological optimization for the distribution of filler and parametric optimization of the thicknesses of linings and aluminum foam parameters) allowed to achieve the specified properties of crashworthiness of the truck cabin design with a minimum increase in mass (20%).

Application of the approach based on the division of the task into subtasks allowed us to increase the efficiency of the solution of the optimization task.

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