Virtual modelling of the crash cushion operation with projected destruction

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Abstract. The article discusses a technique for virtual modeling of the process of deformation and fracture of the structure of a crash cushion, which is used to protect the places of road works, which occurs when a car hits the device during a road accident. The peculiarity of the approach consists in taking into account and modeling the processes of fracture of special energy-absorbing elements used in devices for absorbing impact energy due to the directional destruction of these elements.

1. Introduction
Pull and mounted type crash cushions (often called a truck-mounted attenuator (TMA)) are the effective devices to protect the places of road works and prevent severe consequences in case of a road traffic accident, which occur when a car hits these places (figure 1) [1]. The kinetic energy of an uncontrolled car hitting at high speed is absorbed by means of special energy-absorbing elements integrated in the crash cushion structures, including crash cartridges, often with a cell structure, and/or structural elements with directional projected destruction.

Figure 1. Protection car with attached crash cushion.

In case of a road traffic accident the car hits the crash cushion directly (frontal impact) or at a certain angle, and deformation of the crash cushion energy-absorbing elements made as cell cartridges
is described in [2]. The behavior mechanics of crash cushions and cell energy-absorbing elements was analyzed by a virtual testing approach with the use of virtual modelling in Ls-Dyna Software.

In some structures of crash cushions special devices are used, either along with cell cartridges or independently, which absorb energy through destruction losses, provided that the mechanics of such destruction shall certainly be predictable.

Modelling of crash cushion deformation and destruction, as well as the impact energy absorbing based on the used destruction forecast for special elements requires consideration of the fracturing process in case of a dynamic impact, which complicates the modelling task. Let us consider an example of such device (figure 2 (a), (b)), where the structure of energy-absorbing elements is comprised of rectangular tubes of various thickness with stress raisers (1) and special knives (2, 4) with most of them located inside the tubes.

![Figure 2. Main cushion elements: (a) assembled cushion, (b) knives.](image)

The device operates under the following principle: the coming car hits the front frame of the crash cushion (3 on figure 2), which is rigidly connected with the cushion knives (2). The frame starts pushing the knives forward, and they react on the tube (1) along the cutting surface (4). Since the cutting surface is much wider than the tube, the fracture starts growing on the edges with the growth direction determined by the grooves and initial cutting in the tube as the stress raisers (figure 3).

![Figure 3. Stress raisers at the tube edges: (a) tube initial geometry, (b) operating principle.](image)

In this structure the kinetic energy produced when the car hits the frame is further used for the generation of free surfaces during the increase in fractures, which develop from stress raisers and directionally grow further, as well as for the knife friction with the tube surface, the plastic deformation of the tube sheet bending, and the plastic deformation of the front frame and the cushion bearing part. Since the fracture growth represents one of the main processes, let us consider it in detail.
2. Fracture Growth Modelling

A cohesive element with the linear softening law and bilinear fracture boundary stress law were used for the fracture growth modelling. These were related to the free energy velocity through the following expressions:

\[ G_I = T \cdot \frac{u_n}{2}, \]
\[ G_{II} = S \cdot \frac{u_t}{2}. \]

\( G_I, G_{II} \) is the free energy velocity by the fracture opening type I and II; \( S, T \) are the standard and tangential force vectors at the fracture boundary; and \( u_n, u_t \) are the fracture opening distances.

In order to set the model, the free energy velocity at the fracture opening, force vectors, as well as maximum material movements before opening were to be determined. These parameters were determined by the element-free Galerkin method (EFG) [3], as it provides for a high-precision destruction process modelling.

A part of the tube with symmetric boundary conditions for movements was considered for the tube operation modelling with the use of EFG methods. 1/4 part of the tube start was taken for the investigation. The model operating results are shown on figure 4.

![Fracture opening. EFG Model.](image)

Figure 4. Fracture opening. EFG Model.

The model provided for the calculation of force vectors at the fracture boundary, a J-integral [4] (figure 5) describing the free energy velocity by both types, as well as for the measurement of the fracture opening distances.
Figure 5. Fracture opening. EFG model: (a) surface forces, (b) J-integral contour.

Once the data required to set the operation of cohesive elements were received, they were uploaded to the model. The model operating results are shown on figure 6.
Figure 6. Operation of the FEM model with cohesive elements with 5-mm grid.

In order to estimate the solution accuracy, the operating results of the EFG model were compared to the FEM models with the elements of 1 mm and 5 mm based on the efforts imposed on the tube by the knife. These results are shown on figure 6.

When analyzing the charts, it is apparent that the EFG model creates greater effort on the moving element than the FEM, especially on the stable fracture opening section. Maximum model difference is observed between EFG and 1 mm FEM and constitutes 15 percent. The 5 mm FEM model creates slightly greater efforts upon stabilization and has a difference of 6%. In general, such model accuracy can be considered as acceptable (figure 7).

Figure 7. Forces: EFG (red), 1 mm FEM (green), 5 mm FEM (blue).

3. Entire cushion model
All elements described above were united into a general cushion model (figure 8). A basis was set for the model, through which no cushion or car parts can penetrate.
Figure 8. Assembled cushion model before impact.

The modelling and testing results are compared on figure 9. Good visual similarity of models can be observed.

Figure 9. Visual comparison of the model operation and experiment results.
To compare the model and the experiment, 3 parameters were used: the length of the barrier after deformation, amplitude values of accelerations in the center of gravity, and moving the front surface of the car. These parameters were chosen, as it was they who were specified in the report of the American crash test center. In the course of the quantitative comparison, the maximum movement of the car bumper under the impact was 3.97 m. Based on the testing results, the cushion moved by 3.89 m. The difference in the results was 2.1%.

When comparing the car accelerations in the center of gravity averaged for 10 ms, longitudinal and lateral accelerations were equal to 17.69 g and 4.11 g, respectively. Their values during the acceleration modelling were 17.5 g and 5.81 g. The difference in the results was 1.1% and 41%. The last difference is 1.8 g which is small in absolute terms when compared with other accelerations.

4. Conclusions
Virtual modelling of the crash cushion operation under the car impact has shown satisfactory results when compared to the field tests. Good visual consistence is observed between the model and tests. The quantitative comparison criteria demonstrated the difference of maximum 10% for all parameters, except for the lateral acceleration. The latter differed by 41% in the model against the field tests (4.11 g when tested and 5.89 g in the modelling), which was probably due to the different position of the wheel mounting mechanism compared to the tests.

References
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