DOI: 1 10.32056/KOMAG2020.2.1

Dynamic analysis of thin-walled structures as energy absorbers

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Keywords: numerical analysis, impact energy, energy dissipation, thin-walled structure

Słowa kluczowe: analiza numeryczna, energia uderzenia, rozpraszanie energii, struktura cienkościenna

Abstract:

In this work, a FEM dynamic analysis of the energy absorbing system was carried out on the example of a thin-walled column loaded with impact of mass. The results of the numerical analysis of the impact of the column cross-sectional shape and the notch on the amount of impact energy absorbed are presented. Modeling of phenomena occurring during impact is a very complex task, because it is necessary to analyze a complicated process in which geometric and physical nonlinearities and contact problems occur. Model preparation and calculation using the finite element method (FEM) is currently the most reliable method of modeling impacts. The results of numerical analyzes discussed in the paper were carried out using the special MSC.Software.

Streszczenie:

W niniejszej pracy przeprowadzona została analiza dynamiczna układu pochłaniającego energię na przykładzie cienkościennej kolumny, obciążonej udarem masy. Przedstawiono wyniki analizy numerycznej wpływu kształtu przekroju poprzecznego kolumny oraz karbu na wielkość pochłoniętej energii uderzenia. Modelowanie zjawisk zachodzących podczas uderzenia jest bardzo złożonym zadaniem, gdyż należy przeprowadzić analizę procesu, w którym następują nieliniowości geometryczne i fizyczne oraz problemy kontaktu. Przygotowanie modelu i przeprowadzenie obliczeń przy użyciu metody elementów skończonych (MES) jest aktualnie najbardziej wiarygodną metodą modelowania uderzeń. Omówione w pracy wyniki analiz numerycznych uzyskano przy wykorzystaniu specjalistycznego programowania firmy MSC.Software.

1. Introduction

Society is becoming increasingly aware of the need for designing the safe components and systems to reduce the tragic consequences arising in various types of car, airplane or natural disasters. In the second half of last century there was a significant development of the so-called impact engineering. Structural dynamics studies have contributed to a better understanding of the phenomenon of energy dissipation during impact. It was observed that thin-walled components such as plates, coatings, pipes, columns, etc., used in car assemblies, aircraft and ship hulls, during impact are usually subjected to compression and undergo large displacements, which may even exceed the permissible values twice. Therefore, many tests and computer simulations base on analysis of the systems consisting of thin-walled components [1, 2, 3].

It is obvious that, in the future, the transportation structures will be designed to withstand bumps and accidents. In the current trend for production of lightweight structures, weight of the components is reduced, while more tough requirements are put to designers as the standards for structures become more demanding. It is possible to design absorbers that will be able to dissipate energy in a safe way for people or load [4, 5].

The finite element method (FEM) is the most reliable method of modelling the impacts in which complex structures can be involved [4, 15]. Preparation of the model and calculations is time consuming, because it requires integration of a very large system of motion equations over time that can reach up to several hundred thousand degrees of freedom. However, computer simulations reduce the number of prototypes and thus reduce the cost of crash tests. In addition, when using FEM much more virtual tests can be carried out, which allows a better understanding and better designing of energy absorbers [8, 9].

In the discussed research work, MSC.Software, i.e. MSC.Dytran and MSC.Patran, was used, allowing relatively easy and quick modelling and analysis of mechanical systems absorbing the impact energy. Detailed information on the software used can be found in [10, 11, 12].

2. Energy absorption process

Energy during impact is absorbed by the absorber as kinetic energy is converted into other forms of energy. In energy absorbers, where large displacements occur, dissipation of energy is possible due to plastic flow of material, the formation of brittle cracks or friction. Then, the reversible, elastic part of the deformation energy is negligible [4, 7]. A typical relationship force-displacement, also known as crushing characteristics, in energy absorbing mechanical systems is shown in Fig. 1.

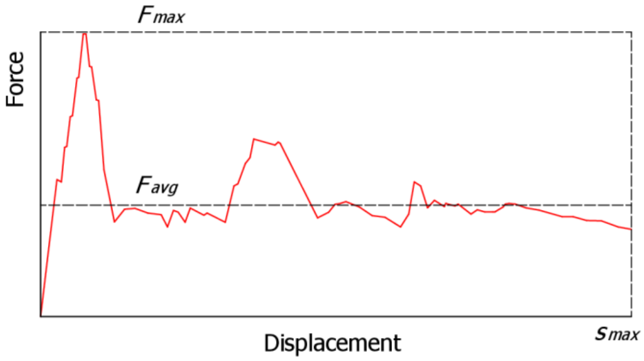


Fig. 1. Relationship between force and displacement (sample crushing characteristics)

The maximum force in the crushing process is marked as F_{max} [N], while the maximum permanent displacement as s_{max} [m]. Energy absorbed by the absorber in the Ω area (regardless of the type of processes involved) equals to the work of the external load:

$$W = \int_0^{S_{max}} F(s)ds = \int_{\Omega} E_{dys} d\Omega \tag{1}$$

Work of the external load W [J] can be expressed as:

$$W = F_{avg} s_{max} \tag{2}$$

where: F_{avg} [N] is an average crushing force.
Averaged absorbed energy is approximately equal to work of the external load:

$$E_{dyss} \approx W \tag{3}$$

3. Requirements put to energy absorbers

In the case of an impact between a moving object (with a given initial speed) and a rigid stationary wall creates forces, stresses and deformations resulting from this impact. Various types of tests and computer simulations lead to a possibility of controlling and routing the energy flow through the system [6, 13-19].

The test results enable to design structures meeting the following requirements:

- stable and controllable method for dissipation of kinetic energy impact,
- limited deformation of the protected volume for working people and equipment,
- limited accelerations and forces during impact – what is especially important when assessing the safety level for vehicles users [20, 21].

These are the three main requirements, ranked according to the criterion of their importance for energy absorbers. To a large extent they are associated with the type of structures that they have to protect. If the first requirement is not met, it certainly leads to failure to meet the other two. Consequently, kinetic energy is not absorbed in the part of the structure intended for this, and thus with a very high probability there will be penetration into the protected zones, and the level of acceleration will exceed the allowable value [5].

4. Criteria for comparison of energy absorbers

The criteria presented below are used in comparison of different absorbers and assessment of their effectiveness. They describe in the best way the absorbers in which energy is absorbed through progressive axial compression [7, 22].

- Specific energy E_s [J/kg]

$$E_s = \frac{E_{dyss}}{m} \tag{4}$$

This is the ratio of dissipated energy E_{dyss} [J] to the absorber mass m [kg]. Only a part of the absorber involved in dissipation of energy is considered.

- Density of dissipated energy E_d [J/m^3]

$$E_d = \frac{E_{dyss}}{V_0} \tag{5}$$

This is the ratio of energy dissipated by the absorber E_{dyss} [J] to its initial volume V_0. If this coefficient is high it means that structure of the device is compact.

- Average crush intensity σ_{avg} [Pa]

$$\sigma_{avg} = \frac{F_{avg}}{A_0} \tag{6}$$

This is the ratio of average crushing force F_{avg} [N] to the initial surface area of the absorber A_0 [m^2].

- Crush force efficiency AE

$$AE = \frac{F_{max}}{F_{avg}} \tag{7}$$

This is the ratio of maximum crushing force F_{max} during energy dissipation process to the average crushing force do F_{avg}. If this ratio is close to 1, such absorbers have advantageous, flat crushing curve.

- Stroke efficiency SE

$$SE = \frac{s_{max}}{H_0} \tag{8}$$

This is the ratio of maximum displacement of the absorber s_{max} to its initial height H_0 [m].

Proper design of energy absorbers can significantly reduce the risk of injury or death, as deformations and accelerations are directly related to the type and operation of energy absorbers. In connection with the above, an additional comparative criterion for absorbers has been introduced in this paper, related to the probability of head injuries. These injuries are caused by the formation of linear or angular accelerations and by bending and stretching the spinal cord in the area of connection with the brain. The most commonly used criterion, which determines the probability of suffering head injuries, is HIC (head injury criterion). HIC exceeding 1000 is considered to be dangerous [5].

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a dt\right]^{2.5} (t_2 - t_1) \tag{9}$$

where:

t_1, t_2 – times determining the beginning and the end of the head's contact with the obstacle or the time interval for which the HIC value is the highest [s], a – acceleration acting on a head [ms^{-2}].

5. Numerical tests

Modelling of phenomena occurring during an impact is a very complex task. Complicated process, in which there are geometrical and physical non-linearities and contact problems, has to be analysed. Model preparation and calculations using the Finite Element Method (FEM) is a complicated task, but it is currently the most reliable method for modelling the impacts [6, 7].

FEM dynamic analysis of the energy absorbing system was carried out on the example of a thin-walled column hitting a rigid wall. Based on the [2, 3, 14], a numerical task was developed in which a column, loaded with an additional mass of 300 kg, hits a rigid wall at an initial speed of 30 km/h. The diagram of the analysed system is shown in the Fig. 2.

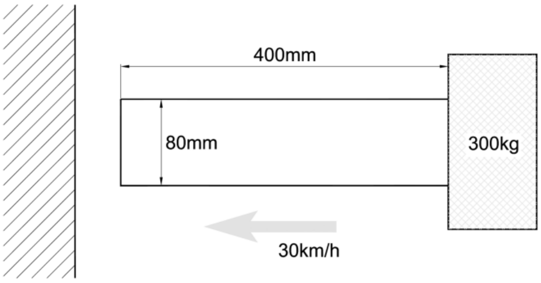


Fig. 2. Diagram of the analysed system column – wall

The column was modelled of aluminium AA 6063 T7 of the following parameters: *Young modulus* E=6.9E+10 Pa, density ρ=2720 kg/m^3 *Poisson* coefficient ν=0.3. Elastic-plastic material *ElasPlast (DMATEP)* with *True Stress vs Plastic Strain* model, available in *MSC.Dytran* was used. The method for defining the material properties is discussed in [21].

6. Impact of a column cross-section shape on amount of dissipated energy

To compare the impact of the cross-sectional shape of the structure on the amount of dissipated energy as a result of impact, the simulations were carried out on three column models. Model 1 is a square column (80 mm side), 2-circular model (ø80 mm) and 3-triangular model (equilateral triangle with 80 mm side). All columns have an equal wall thickness of 3 mm and a height of 400 mm. More information on the effect of column cross-section on the amount of energy dissipated can be found in [10]. Fig. 3, 4 and 5 present subsequent phases of deformation of the analysed models.

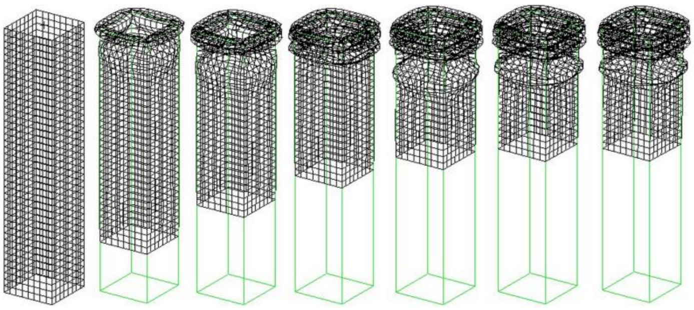


Fig. 3. Subsequent phases of deformation – model 1

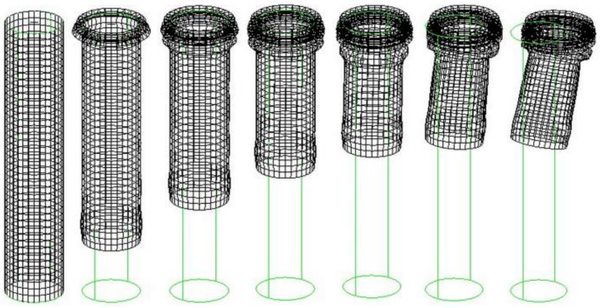


Fig. 4. Subsequent phases of deformation – model 2

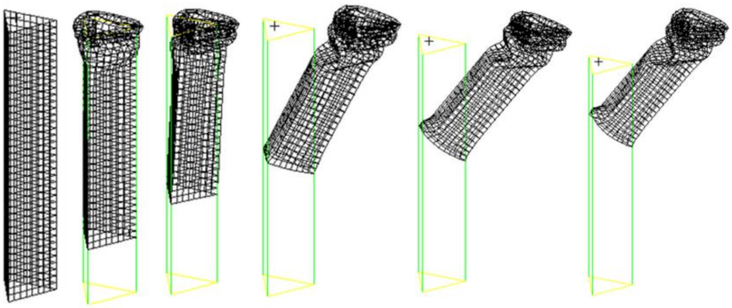


Fig. 5. Subsequent phases of deformation – model 3

In a result of column buckling - Model 3 (Fig. 5), the process of dissipation of impact energy is interrupted, while the crushing force and acceleration are small. The test proves that the column with triangular cross-section in comparison with other models is the least absorptive structure and the most susceptible to buckling. Therefore, model 3 will not be considered in further analyses.

To present the impact of shape on amount of dissipated energy, the following parameters were compared in models 1 and 2: crushing characteristics (Fig. 6) and acceleration in a function of time (Fig. 7).

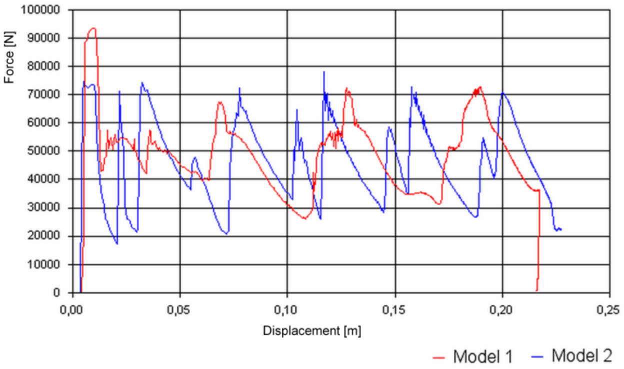


Fig. 6. Crushing characteristics in models 1 and 2

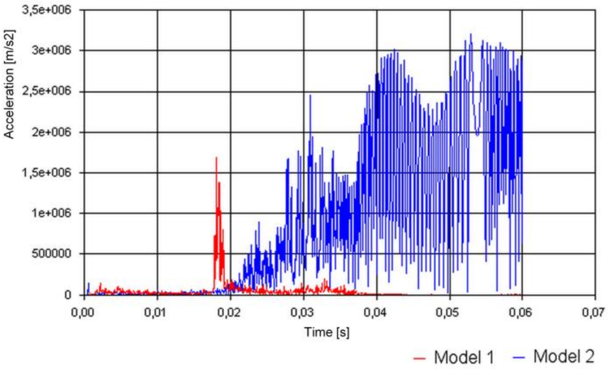


Fig. 7. Acceleration time process in models 1 and 2

Peak crushing force, shown in Fig. 6, indicate for the formation of subsequent impact waves in columns. Crushing force in model 1, at the moment of impact into the wall, was higher by 20 kN than in the model 2, however it was dissipated and dropped to 0. In Fig. 7, after 0.018 s, an increase in the acceleration can be observed in both models, probably due to the material strengthening, which in turn hindered the formation of another wave of column deformation. While in model 1 the deformation process is stable and the accelerations are close to 0, in the case of model 2 there is a gradual increase in acceleration, which is the result of column buckling.

Based on the averaged crushing force and maximum permanent displacement from the relationship (2), the work of the external load was calculated, which according to the relationship (3) is equal to the energy absorbed by the column. The results are presented in Table 1.

Table 1. Parameters characterizing the amount of dissipated energy

	Model 1	**Model 2**
F_{avg} [kN]	46.191	40.688
s_{max} [m]	0.215	0.261
E_{dyss} [kJ]	9.931	10.619

The analysis shows that model 1 (square column) in comparison with models 2 (column with cylindrical cross-section) and 3 (column with triangular cross-section) has the greatest ability to dissipate energy and is characterized by high stability of the deformation process. In addition, in model 1 there is less accidental acceleration, which, except for one dangerous impulse, gradually decreases to 0. So, further analysis was performed only on the square column model.

7. Impact of notches on the absorber surface on the amount of dissipated energy

To increase the energy dissipation capacity, notches were introduced on the absorber surfaces. Notches with dimensions 7 x R3.5 mm were placed on opposite walls of the column at a distance of 15 and 30 mm from the face. Three thin-walled prismatic columns were analysed: two with two notches (models 4 and 5) and one with four notches (model 6), Fig. 8. Column dimensions: cross-section 80 x 80 mm, height 400 mm, wall thickness 3 mm.

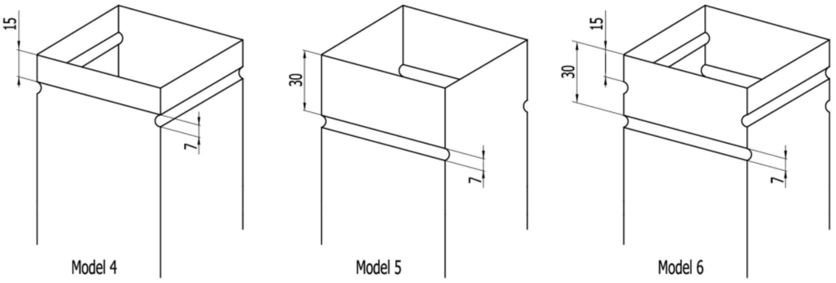


Fig. 8. Columns with notches (models 4, 5 and 6)

Fig. 9, 10 and 11 show the subsequent stages of deformation of models 4, 5 and 6, resulting from the columns hitting a stationary wall, in the selected time intervals (from 0 to 0.065 s). The process of deformation of columns 4 and 6, as in model 1, is stable. Introduction of a notch resulted in a significant increase in a deformation of the columns and thus had a positive effect on the amount of dissipated energy. However, too large distance of a notch (0.03 m) from the front surface of the column caused, in model 5, an unstable deformation process, and as a consequence the column buckled already in the first time interval of the analysis, interrupting the energy dissipation process. Therefore, model 5 will not be considered in further analysis.

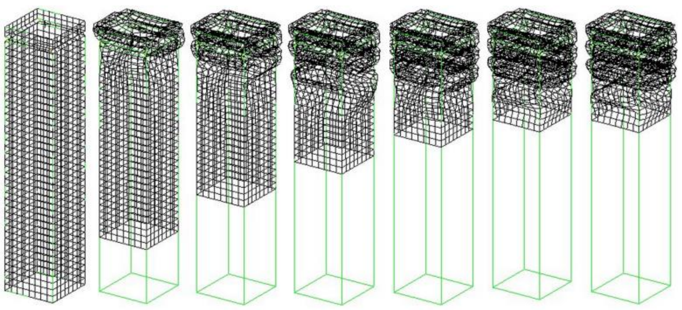


Fig. 9. Subsequent stages of deformation - model 4

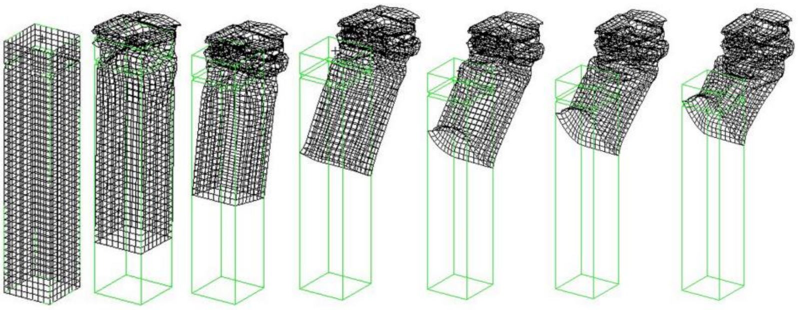


Fig. 10. Subsequent stages of deformation - model 5

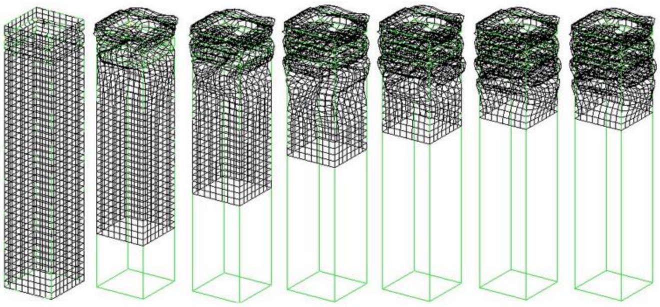


Fig. 11. Subsequent stages of deformation - model 6

For presentation of a notch impact on amount of dissipated energy, time processes of crushing force (Fig. 12), acceleration (Fig. 13) and kinetic energy (Fig. 14), in models 1, 4 and 5 were compared.

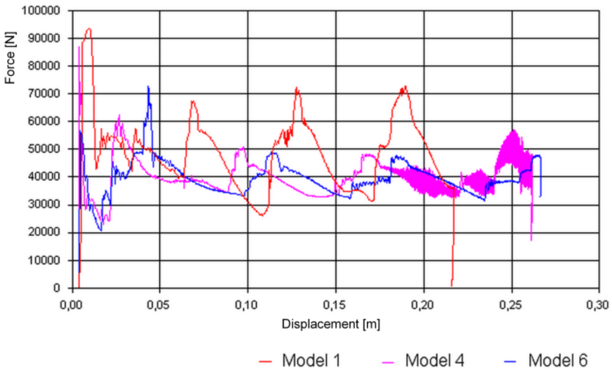


Fig. 12. Crushing characteristics in models 1, 4 and 6

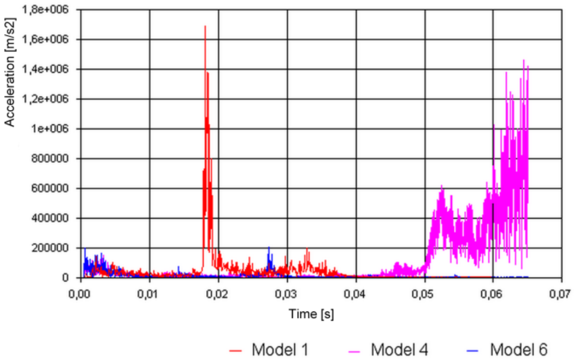


Fig. 13. Time processes of acceleration in models 1, 4 and 6

Analysis of time processes, presented in Fig. 12, 13 and 14, it clearly shows that the use of notches limits the forces and accelerations generated during a collision. However, in the case of model 4, in the final phase of deformation there were large force fluctuations, which resulted in a significant increase in acceleration in the column to values dangerous for the protected persons and structures. The introduction of the second notch in model 6 caused that both crushing force (Fig. 12) and acceleration (Fig. 13), compared to other models, were much lower.

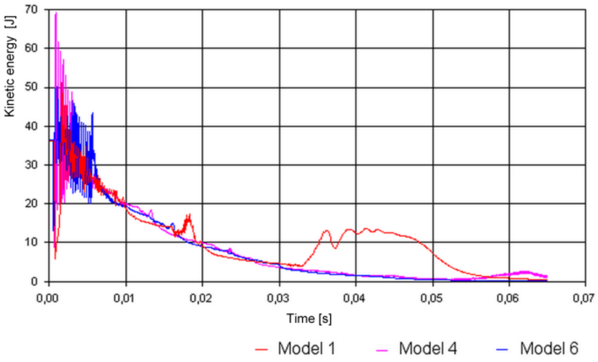


Fig. 14. Distribution of kinetic energy in time in models 1, 4 and 6

Distribution of kinetic energy in time in the discussed models, presented in Fig. 14, confirms advantageous impact of notches in energy dissipation process The column with two notches, model 6, was most advantageous also when analysing dissipation of kinetic energy.

Values of the characteristic parameters of the analysis, i.e. the average crushing force and the maximum permanent displacement, were used to calculate, from the relationship (2), the work of the external load, which according to the relationship (3) is equal to the energy absorbed by the column. The results from analysis of models 4 and 6 were compared with the results of model 1, as shown in Table 2.

Table 2. Parameters characterizing the amount of dissipated energy

	Model 1	**Model 4**	**Model 6**
F_{avg} [kN]	46.191	40.688	40.433
s_{max} [m]	0.215	0.261	0.268
E_{dyss} [kJ]	9.931	10.619	10.836

The criteria for assessing and comparing the effectiveness in dissipation of energy for models 1, 4 and 6 were determined. Results are given in Table 3.

Table 3. Energy absorbers comparison criteria

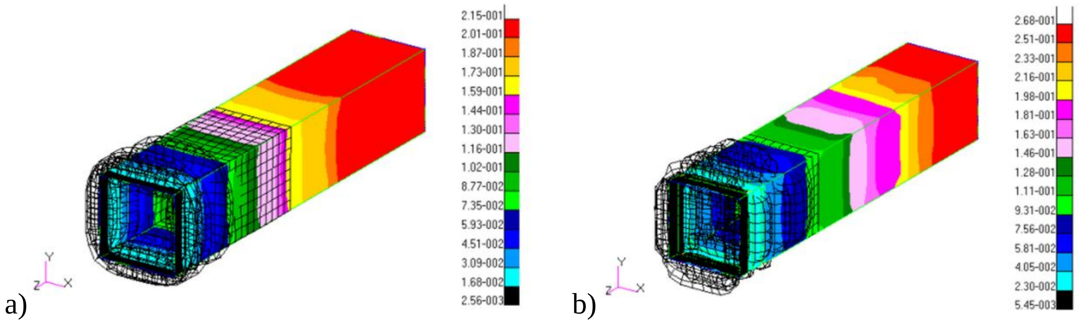
	Model 1	**Model 4**	**Model 6**
E_s [kJ/kg]	9.878	10.563	10.713
E_d [MJ/m^3]	26.840	28.548	29.286
σ_{avg} [MPa]	0.186	0.164	0.163
AE	2.042	2.135	1.800
SE	0.537	0.652	0.67

In models 4 and 6, similar results were obtained (Tables 2 and 3), therefore, in order to justify the need of using two notches on the column surfaces, an additional criterion was introduced - the HIC (head injury criterion), calculated from the relationship (9). The *HIC* for models 1, 4 and 6 is given in the Table 4.

Table 4. *HIC* criterion

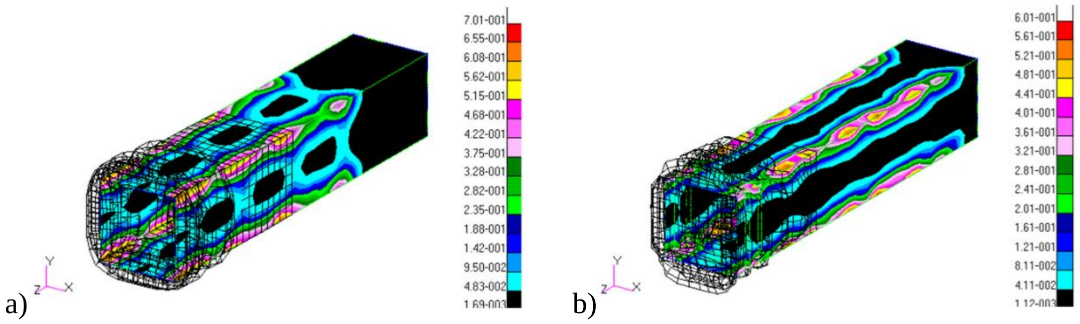
	Model 1	**Model 4**	**Model 6**
HIC	2.083E10	3.96E13	8.27E8

The analysis shows that the introduction of notches improves the energy absorption capacity of the presented models and limits forces and accelerations. Based on the results in Table 3, it can be seen that models 4 and 6 absorb almost 9% more of impact energy than model 1. This is due to greater deformation (shortening) of the columns equipped with notches. Comparison of displacement and deformation in columns 1 and 6 is shown in Fig. 15 and 16.



a) b)

Fig. 15. Mapping of displacement: a) model 1, b) model 6



a) b)

Fig. 16. Mapping of deformations: a) model 1, b) model 6

In addition, in notched columns the average crushing forces are about 12% lower than in the smooth column. The assessment of the effectiveness of the analysed models (Table 4) proved that model 6 shows the greatest energy dissipation capacity. Model 4 has slightly worse energy absorption properties. The use of an additional criterion, which is *HIC* (Table 4), allowed selecting the best solution among the analysed structures, which is model 6, which had the lowest *HIC* criterion.

8. Conclusions

Numerical analyses of the impact of the cross-sectional shape of the column and notches on the amount of dissipated energy from the hit of the column on a stationary wall as well as computer simulations allowed to draw the following conclusions:

- Shape of the structure cross-section significantly affects the amount of absorbed energy. Model 1 (square column) compared to models 2 (column cylindrical cross-section) and 3 (column with triangular cross-section) in collision with the wall shows the greatest ability to dissipate energy and is characterized by high stability of the deformation process. In addition, in model 1 there is less accidental acceleration, which, except for one dangerous impulse, gradually decreases to 0.

- The introduction of notches on the surface of the column significantly increases its ability to absorb energy and limits the acceleration and forces generated during impact. The results in Table 1 clearly show that models 4 and 6 (notched columns) absorb almost 9% more impact energy than model 1 (smooth column). In addition, in notched columns the average crushing forces reached about 12% lower value than in the smooth column. The assessment of the effectiveness of the analysed models (Table 3) confirmed the correctness of the use of notches, because models 4 and 6 obtain much better results than model 1. The application of the *HIC* criterion (Table 4) enabled the selection of the model with the highest absorption properties - model 6.

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