Numerical analysis of the thin-walled structure with different trigger locations under axial load

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Abstract. This paper presents the results of the numerical analysis of thin-walled structures with a square cross-section. Aluminium models contain different types of triggers and distance to the base. Postbuckling analyses were compared with the form of the buckle to find the most beneficial location of the trigger. The study problem was approached with FEM Abaqus. Numerical analysis results are shown in the Load–Shortening diagram. The data obtained during numerical analysis were used to determine the crushing efficiency indicators such as SE, CLE, TE. The aim of the research was to obtain the best efficiency indicators for the tested positions of triggers.

1. Introduction
One of the most important factors in the transport industry is passenger safety. For years, the construction of thin-walled profiles has been evolving in order to improve their efficiency or, as it was originally thought, to absorb the greatest amount of energy. As early as in the 1980s, Wierzbicki and Abramowicz [1] dealt with the mechanism of thin-walled structures destruction, where they described the behaviour of plastic joints for thin-walled structures with a square section. The mathematical model of energy-absorbing structure destruction has been described in detail [2,3,4]. The studies have shown that the length of a plastic hinge is relative to the wall thickness and the width of the profile. Along with evolving knowledge of thin-walled model analysis, not only the energy absorbed by the specimen, but also the maximum forces generated by the model during the test proved to be an important aspect of the impact tests. Peak crushing force (PCF) [5,6], was an important factor in the impact analysis. Generating excessive overload could kill the passengers, despite the model absorbing a very large amount of energy. The initiation of crushing was managed by the holes incorporated in the profile in order to reduce its stiffness locally and induce to crush at a given point.

Nowadays, examination often concern thin-walled elements made of composite materials [15, 16]. In this type of profile, the most important factor influencing the form of buckling and the mechanism of destruction is the layout of laminate layers. Due to the multiplicity of composite layer layouts, artificial neural networks are used [14]. Prediction has become a popular tool with the development of software.

Another way of initiating crushing at a selected location and decreasing the peak crushing force generated, most frequently, in the initial stage of crushing, was to crush the side walls [7, 10]. Trigger made in such a way allowed for easy formation of the first fold. With the development of technology, models with fillings began to appear in order to increase the efficiency of the absorber. At the turn of the 20th century two Hanssen’s papers [8, 9] were published in which aluminium profiles with foamed
aluminium filling were described. There, the dispersed energy increased, however, it did not affect the maximum destructive force. Similar conclusions can be drawn from the study by Mohammadiha et al. [11], where the aluminium profile was filled with a honeycomb structure. This material increased the amount of absorbed energy, but due to its structure it could slightly increase the PCF due to increased stiffness in the direction of impact.

The effectiveness of crushing is influenced by the position of the triggers. Such tests were conducted by Ferdynus [12, 21], where the initiator in the form of dents was placed on the top and bottom of the sample. In the studies, there was no arrangement of the triggers from intermediate distances, which would give a full picture of the influence of the position of the triggers on the coefficients of effectiveness.

The scientific team of the Department of Machine Design and Mechatronics has extensive experience in performing analyses of finite element methods [17-20]. Researchers of the department are engaged in numerical analyses of various areas of mechanical engineering.

2. Energy absorption indicator

In order to correctly interpret the results of the dynamic analysis, it is necessary to describe the course of crushing with several parameters. The coefficients describing the impact analysis can be obtained by analysing the force - shortening diagram. An exemplary characteristic describing the crushing is shown in figure 1.

![Figure 1. Exemplary force – shortening diagram of a thin-walled structure [13].](image)

The main quantity determining the crush is the absorbed energy, which is defined as the area of the surface under the function, and is given by the equation (1).

$$EA(d_s) = \int_0^{d_s} F(x) \, dx$$  \hspace{1cm} (1)

where the $d_s$ is crushing distance, and the $F(x)$ is crushing force given as a function.

Another factor is Specific Absorbed Energy (SEA), which is energy per unit mass (2).

$$SEA = \frac{EA}{m}$$ \hspace{1cm} (2)

These two values are not direct measures of crashworthiness. There are several other coefficients that help to understand the process of crushing thin-walled profiles.

To determine the first factor it is necessary to determine the Peak Crushing Force (PCF) which is the maximum force and the Mean Crushing Force (MCF) which is given by formula 3.
The crash load efficiency is determined by comparing the mean crushing force with the peak crushing force and is given by the formula below.

\[ CLE = \frac{MCF}{PCF} \times 100\% \]  

(4)

The value describing the crush length is SE, which compares the length of the specimen after crushing with its initial length.

\[ SE = \frac{U}{L_o} \]  

(5)

The last factor is TE (6), which is the product of CLE and SE. The coefficient was first described by Hanssen [9]. Nowadays, it is often used in literature to describe the crushing process.

\[ TE \% = CLE \times SE \]  

(6)

3. Numerical analysis

The numerical analysis was carried out using Abaqus CAE. The subject of research was the aluminium column with a different type of trigger. The models were generated as a shell element. The square section of the specimen is 40x40 mm, and the length of the column is 200mm. The shell thickness is 1.2mm. The model has a notch in various configurations. The length of notch is changing from 10 to 40mm, as well as the location of the trigger from 20 to 180mm. Every described dimension is presented in figure 2.

The boundary conditions were defined using the top and the bottom plates. The energy was simulated as a mass assigned to the reference point as well as the speed of the top plate. Both plates were connected to the column with tie contact option. The numerical discretisation was related to the use of the appropriate mesh type. In this analysis, two types of elements were used: S4R is a 4-node, quadrilateral, stress–displacement element with reduced integration, and the other element – R3D4, has 4 nodes within a single element, and 3 degrees of freedom in each node. The column was subjected
to impact load of kinetic energy $E=1500\text{J}$, which corresponds to the mass of $m=60\ \text{kg}$ dropping with initial velocity $V=7.071\ \text{m/s}$.

The material model of aluminium is based on elastic-plastic characteristics. The elastic properties are described by two coefficients – Young’s modulus, and Poisson’s Ratio. Plastic ones are defined by bilinear characteristics. Material data are presented below in table1.

**Table 1.** Aluminium column material properties (own study).

| Al-6061 aluminium material properties |               |
|--------------------------------------|---------------|
| Density                              | 2700          |
| Young Modulus [MPa]                  | 70000         |
| Poisson ratio $\nu$ [-]              | 0.33          |
| Yield point $R_e$ [MPa]               | 200           |
| Tensile Strength $R_m$ [MPa]          | 279.98        |
| Elongation $A\%$ [%]                 | 5.98          |

The analysis was modelled in two steps. The first one is a buckling analysis, the second one is a dynamic analysis based on the model obtained in the first step.

4. Results of numerical analysis

The group of tested models was a column with a trigger in the form of a 10-mm-long cut-out at the edges. A variable parameter was the distance between the centre of the trigger and the base of the element. The distance changed from 20 mm to 180 mm. The behaviour of the model in the different stages presented below will allow a better understanding of the energy absorption process.

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**Figure 3.** Force – Shortening diagram and stages of impact crushing of the specimen C10-30.
The force shortening diagram (figure 4) below allows indicates which models absorbed the energy most quickly, which translates into crushing efficiency indicators. The mechanism of damage to the structure is the same for all models. The first fold occurs in the place of the trigger. Differences in the shortening result from the fact that the defect is implemented into the model by the mode of buckling (figure 5).

![Figure 4. Characteristic curve force shortening for models with 10-mm-long trigger.](image)

The models that absorbed energy the fastest are those that have the initiator of the crushing at a distance of 50 mm and 110 mm from the base. The model that has been shortened the most during the dynamic analysis is the one with the trigger located at 170 mm from the base. The biggest shortening results in the worst ST and MCF ratio. These results allow us to state that the position of the trigger affects the form of buckling and thus changes the course of the impact crush.

![Figure 5. Different mode of the buckle a) 20 mm to the base b) 50 mm to the base.](image)
The presented buckling forms show that locating the trigger too close to the bottom plate causes the first fold’s potential to be underutilised. Positioning the initiator 30 mm higher causes the plastic hinge to form in the place where the trigger occurs and free folds to appear above and below the crush initiator.

5. Studies of crashworthiness indicators
To obtain a complete image of the analysis, use the indicator described in the second chapter. Coefficients based on the characteristics of the crush behaviour together with data from the previous chapter will determine the most advantageous position of the trigger.

![Graph showing CLE and SE factors for a sample with a 10 mm trigger.](image)

**Figure 6.** The CLE and SE factors for a sample with a 10 mm trigger.

The graph above shows that the models with the best CLE factor are the columns with a 30 mm, 130 mm, and 160 mm distance triggers. This indicator is based on both the height of the force peak as well as the average force during the analysis. The lowest value was obtained for models with a trigger located near the top plate (170 mm, 180 mm).

The highest SE factor was reached by the model with the initiator located at 170 mm from the base. Other models achieved an index of approximately 0.51. The model achieves the best results when the CLE is the largest and the SE the smallest. The models that received the best combination of indicators are 30 mm, 110 mm and 160 mm.

![Graph showing TE coefficient for the specimen with a 10-mm trigger.](image)

**Figure 7.** TE coefficient for the specimen with a 10-mm trigger.
The last coefficient is the value resulting from the multiplication of CLE and SE. The course of TE (figure 7) values changes depending on the position of the trigger. The highest values of the coefficient are around 30 mm, 80 mm, 130 mm and 160 mm.

6. Conclusions
This paper presents the numerical analysis of a thin-walled profile. The sample had a trigger in the form of a 10-mm-long cut-out. The distance between the trigger and the base changed from 20 mm to 180 mm every 10 mm. The change of initiator's position did not affect the PCF force, the value fluctuated around 42.5 kN for all models. The analysis showed that placing the cut-out too close to the top plate has a negative effect on its performance. The CLE is about 11% higher for the 160–mm model than for the 170–mm model. The maximum difference in shortening the models was 17 mm, i.e. 8.5%. The TE coefficient reaches its maximum for models with distances of 30 mm, 80 mm, 130 mm, 160 mm. Placing the trigger between the optimal values reduces the efficiency of the applied trigger.

7. References
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