Numerical analysis of porous materials subjected to oblique crushing force

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Abstract. This article presents an analysis of porous materials subjected to oblique loading. The analysis was carried out with the Abaqus software using the finite element method. The material model used for numerical analysis was Crushable Foam. The subject of the study involved solid elements located on a base with a variable angle of inclination. The values of the base angle were 15, 30, 45, 60 degrees. All samples were loaded with the same boundary conditions. During the test, the normal and shear forces were determined. The crushing efficiency indicators were calculated from the measured forces. The aim of the tests was to define the distribution of forces in the foam element.

1. Introduction
In times of rapid development of transport technology, it is necessary to continuously improve the safety of passengers and transported goods. Porous materials are modern materials used to increase the passive safety of vehicles [1, 2]. Due to their structure, they are able to absorb significant amounts of energy and improve the crushing efficiency of the structure [3, 4]. Porous structures are obtained in two ways, physical and chemical. The physical method consists in the injection of gas into a pool with liquid metal [5]. The second way is to induce a chemical reaction during which the gas starts to emit. Alporas is a popular method, the principle of operation of which is to add TiH$_2$ which – as a result of the hydride breakdown – emits gas [6, 7]. The foaming methods of metals and macromolecular plastics are gaining popularity owing to the ease of the production process and the ecological aspect, which is the possibility of processing chips and post-production waste. Due to the structure of the foam, open and closed pore scan be distinguished [8]. In the case of open pore structures, this type of foam can be infiltrated with the materials with different properties. In this way, metal-ceramic foam scan be obtained. Composite foams are widely used in the marine industry. Numerical analyses are commonly employed in the study of composite materials [9–11]. They have good energy-absorbing properties while maintaining non-flammable materials [12]. The materials with a porous structure have found application in motor vehicles. Especially in crash-boxes, where thin-walled profiles are filled with foam materials. The first works concerning the phenomenon of energy absorption of aluminum foams appeared at the end of the 20th century [13, 14]. Then, the researchers started to work on the mechanism of destroying foamed materials. Thin-walled profiles were filled with aluminum foam to check their energy-absorbing properties [15, 16]. Both static and dynamic loading of the profiles show their energy potential but they are not able to determine the distribution of forces in the foamed material. Nowadays, many newly developed porous materials are inspired by nature. Porous structures are applied in medicine where open
pore implants are used. It is particularly important for osteointegration to occur due to the bone that is growing over the implant to form a connection similar to the natural one [17–19]. Furthermore, neural networks are often used today to read the non-linear relationships between properties [20, 21].

The coefficients used to analyze the crushed foam data are Peak Crushing Force (PCF), Mean Crushing Force (MCF), Crushing Load Efficiency (CLE) [22]. Where PCF is highest force detected during crush, MCF is the energy absorbed by model divided by the crushing distance and CLE is division of MCF and PCF. In addition, modern structures are created, which increase the energy efficiency of the crumple zone. The materials of this type are called auxetic foams. A characteristic feature is the negative Poisson's ratio [23, 24]. The materials increase their cross-section during stretching. This behavior is due to its structure, where the cell wall collapse inside is formed under pressure. During impact, auxetic foam increases its density locally to compensate for the impact force [25, 26]. However, in order to determine the stress distribution and to better develop the mechanism of destruction, the cells of the test were subjected to oblique crushing of porous materials.

2. Finite element method

The analytical test was performed using the Abaqus software. The foam model was placed on a platform the angle of which to the ground changed between 15-60° in 15° steps (Figure 1). The dimensions of the porous material are 20 by 40 mm. Owing to the variable inclination of the base, the stress distribution in the structure can be easily checked. During the numerical analysis, two types of AL (Aluminium-Alporas), and PET (Poly(ethylene terephthalate) foams were used [27–29].

![Figure 1. Dimensions of the tested sample.](image)
The discretization process performed in the Abaqus software has applied a mesh with a density of 2 for the foam element and 3 for the tups (Figure 2). This fine subdivision for foam element allowed achieving high accuracy of the results. Due to the non-deformable character of tup, its mesh density is lesser. The time of the dynamic analysis has been specially set so that the crush in the elastic-plastic range is fully registered until the force exceeds the Peak Crushing Force (PCF). A detector collecting the values of the forces determined during the analysis was defined at the reference point in the base. During the analysis, normal and shear forces were collected on the OY and OX axis directions, respectively. Furthermore, during numerical analysis, the following values were detected at reference points: velocity, displacement, force.

3. Results of numerical analysis

3.1 Static analysis
The subject of the research was metal foam (aluminum) and polymer foam (PET). The samples were placed on a base inclined at an alpha angle from 15-60 degrees. The foam load during static analysis was modeled by determining the displacement in Y direction. The deflection was between 10mm and 25 mm depending on the inclination of the bottom.
Table 1. Results of static crushing of foamed materials.

| Model | EA   | PCF  | MCF  | CLE    |
|-------|------|------|------|--------|
| S15-AL | 25.6107 | 5.73255 | 2.11498 | 0.36894 |
| S15-PET | 17.2885 | 2.35284 | 1.72885 | 0.73479 |
| S30-AL | 26.4129 | 5.45489 | 1.97879 | 0.36275 |
| S30-PET | 26.7771 | 2.65063 | 1.80492 | 0.68094 |
| S45-AL | 27.0946 | 4.83465 | 1.72815 | 0.35745 |
| S45-PET | 25.2862 | 2.25497 | 1.48447 | 0.65831 |
| S60-AL | 25.976 | 3.08417 | 1.24848 | 0.4048 |
| S60-PET | 28.3244 | 1.75739 | 1.17754 | 0.67005 |

Shear Forces

| Model | EA   | PCF  | MCF  | CLE    |
|-------|------|------|------|--------|
| S15-AL | 4.81229 | 1.14765 | 0.39741 | 0.34628 |
| S15-PET | 3.94523 | 0.56334 | 0.39452 | 0.70033 |
| S30-AL | 10.314 | 2.07746 | 0.7727 | 0.37194 |
| S30-PET | 10.9996 | 1.00336 | 0.7333 | 0.73086 |
| S45-AL | 16.3746 | 2.72167 | 1.04441 | 0.38374 |
| S45-PET | 15.4796 | 1.3756 | 0.90876 | 0.66063 |
| S60-AL | 25.2728 | 2.94837 | 1.21468 | 0.41198 |
| S60-PET | 27.8905 | 1.70174 | 1.1595 | 0.68136 |

Observing the results presented in the table above, it can be see that the foam shows a change in behavior due to a change in the inclination angle. In the case of aluminum foam, the energy absorbed in the shear direction increases with the change of angle, while the same energy is absorbed in the normal direction. The mean and peak crushing forces decrease in the normal direction and increase in the shear direction.

![Normal Forces](image_url)

**Figure 3.** Description of normal forces in static analysis.
The characteristics presented in Figure 3 show the relationship between force and shortening for the normal direction. The values were collected at a reference point in the base during the static analysis. For both AL and PET foams, force peaks with the displacement of about 3mm can be observed. Furthermore, the forces in both foams show a similar trend.

![Figure 4. Description of shear forces in static analysis.](image)

Polymer foam takes on loads in the tangential direction to a greater extent than metal foam. Despite being twice as dense, it has a similar energy efficiency, as can be seen in Figures 3 and 4 as well as in Table 1.

### 3.2 Dynamic analysis

During the dynamic analysis, the porous material was loaded with energy defined by assigning a mass of 50kg and a velocity of 1.5 m/s to the tup. Stress distribution in the foam cross-section was investigated.

While analyzing the data presented in Table 2, it can be seen that the values of forces in the normal direction generate energy at a similar level. Despite the increasing slope of the base, the energy does not differ by more than 10%. Due to the tilt of the base, the value of the tup insert displacement increases, so a decrease of the MCF can be observed.
Table 2. Results of dynamic crushing of foamed materials.

| Model | EA   | disp  | PCF   | MCF   | CLE   |
|-------|------|-------|-------|-------|-------|
| S15-AL. | 46.8941 | 15.1025 | 13.8949 | 3.10506 | 0.22347 |
| S15-PET | 49.2734 | 18.875 | 8.08776 | 2.63847 | 0.32623 |
| S30-AL. | 47.412 | 16.4784 | 13.2517 | 2.87722 | 0.21712 |
| S30-PET | 54.2343 | 20.9599 | 8.16391 | 2.58753 | 0.31695 |
| S45-AL. | 43.6555 | 19.1478 | 11.4509 | 2.27992 | 0.1991 |
| S45-PET | 50.8889 | 25.2008 | 5.84287 | 2.01934 | 0.34561 |
| S60-AL. | 45.6366 | 26.1729 | 8.21042 | 1.74366 | 0.21237 |
| S60-PET | 52.2735 | 33.5531 | 4.40244 | 1.55793 | 0.35388 |

Shear Forces

| Model | EA   | disp  | PCF   | MCF   | CLE   |
|-------|------|-------|-------|-------|-------|
| S15-AL. | 9.1309 | 15.1025 | 3.02123 | 0.6046 | 0.20012 |
| S15-PET | 9.1926 | 18.875 | 1.45153 | 0.4926 | 0.33936 |
| S30-AL. | 18.6768 | 16.4784 | 5.00397 | 1.13341 | 0.2265 |
| S30-PET | 21.0996 | 20.9599 | 3.16146 | 1.00666 | 0.31842 |
| S45-AL. | 25.1422 | 19.1478 | 6.61426 | 1.31306 | 0.19852 |
| S45-PET | 30.7297 | 25.2008 | 3.88643 | 1.21939 | 0.31376 |
| S60-AL. | 41.5921 | 26.1729 | 7.78949 | 1.58913 | 0.20401 |
| S60-PET | 49.0098 | 33.5531 | 4.23897 | 1.46066 | 0.34458 |

Figure 5. Description of normal forces in dynamic analysis.
Observing the characteristics shown in Figure 5 shows the difference in the crushing behavior. Aluminum foam, as the base tilt increases, significantly enhances the peak crushing force (PCF), which occurs by a very short cut, absorbing little energy in this area. The polymer foam exhibits a different behavior, with a change of angle the maximum force (PCF) increases more smoothly and for a longer shortening, thus enhancing the energy gain.

![Graph showing shear forces in dynamic analysis](image)

**Figure 6.** Description of shear forces in dynamic analysis.

The shear forces determined during dynamic loading reach the maximum values of 14 kN for aluminum foam and 8 kN for PET foam (Figure 6). The shortening values for the foam are 20 mm and 35 mm, respectively. As with the collected normal forces, the characteristics for the tangential forces in the case of aluminum foam have a large peak in a very short time, which adversely affects the performance and only slightly increases the energy efficiency of the porous material. PET foam reaches its maximum value in a much longer time, i.e. at a greater shortening of the model, thus absorbing more energy at a given stage. It is worth noting that PET foam achieves a similar energy efficiency at half density.

4. Conclusions

This article presents the tests of porous materials subjected to static and dynamic oblique loading. The specimen dimensions are 20 mm by 40 mm and the base angle is in the range of 15-60 degrees. The foamed materials used in numerical analysis are AL and PET. During static loading, the foams show similar energy efficiency, but PET foam has a better CLE indicator due to lower maximum forces detected during crushing. This is noticeable for both normal and shear forces. The difference in efficiency (CLE) is about 10 percentage points. For dynamic crushing under the same boundary conditions, PET foam absorbed about 10-15 percent more energy. In addition, in the case of the shear forces, the greater the angle of inclination, the greater the difference in energy absorbed in favor of the polymer foam. To sum up, both foams show good energy-absorbing properties, however, despite double the density, PET foam absorbed more energy in both normal and shear directions. This shows that there are other material factors which have a significant impact on the hardening of the foam.
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