Blast resistance of panels made of profiles filled with granular materials

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Abstract

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With the increasing threat of terrorism and threat to human life by the explosions, blast resistant design of special structures such as magazines, explosives storage facilities, major embassies, buildings with high traffic and strategic centres and security is a necessity. On the other hand, the weight of these structures is important and design of a shelter using light-weight materials is very crucial. Aluminium can be assembled as hollow and portable parts to form a protective wall filled with Granular materials. Since aluminium has high blast resistance, it has often been used in protective structures as both empty and mass-filled panels in combination with other materials like ceramics. In this paper, numerical study of both empty and mass-filled aluminium panels filled with granular materials as a protective wall structure in containers is carried out using ABAQUS. Different cases have been studied and the comparison between them demonstrated that the combination of aluminium panels and granular materials have better performance regarding dissipated energy.

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1. Introduction

The risk of terrorist attacks is gradually increasing, and many innocent people around the world are injured, or even killed by these attacks. Design and building of various structures against these attacks and blast loads are crucial for modern society in order to protect and secure its citizen [1]. Aluminium alloys are one of interesting materials in the design of lightweight protective structures as protection against accidental loads, terrorist attacks or in international operations.

Currently, large amounts of equipment and personnel are sent into highly risked regions of the world with non-operating infrastructure. The troops and crew will be especially vulnerable in the time during the establishment of new camps. Therefore, it is important to set up camps with sufficient
protection within a shortest possible period of time. Since, the protective elements should be transported in long distances in most cases, thus the weight of the system is a critical parameter. This inhibits the application of traditional shelter systems, and thus new designs using lightweight materials become a key issue. From the material viewpoint, light metal aluminium may give an equally good or even better ballistic protection per unit weight compared to traditional steel due to aluminium’s low density, high specific strength, and high specific energy absorption. The ballistic perforation resistance of different materials has been studied in Refs. [2-5]. However, it should be noted that aluminium also has disadvantages compared to steel regarding structural impact [6]. Since thin aluminium plates have a rather poor ballistic performance, they often appear in layered or spaced structures, in extruded products or in combination with other materials (such as ceramics). Reviews on the subject of ballistic perforation resistance of aluminium structures can be found in Børvik et al. [4,6,7].

Many alloys can be extruded into closed-cell panels with integrated construction details for simplified mounting. The cells can then be filled with a local granular material to increase the blast resistance. Børvik et al. [8,9] experimentally and numerically investigated the ballistic and blast load response of a 20 ft ISO container used as shelter in international operations and protected with aluminium panels filled with a local mass. They showed that that the proposed system was able to meet all requirements with a good margin of safety. They later conducted numerical simulations of an unprotected same container exposed to a blast load of 4000 kg TNT at 120 m standoff distance using the three different approaches. To validate and discuss the results, the simulated response of the container is compared to available data from a full-scale blast test under such conditions. They indicated that the Lagrangian approach gives better results than the fully coupled Eulerian–Lagrangian approach when the design blast load was solely based on ConWep calculations [10].

The present paper numerically studies the blast resistance of a standard container retrofitter with aluminium panels and filled with granular materials using ABAQUS package. Different cases have been studied to obtain the best case as a protective structure for application in containers in order to withstand blast loading.

2. Modelling

2.1 Model geometry

The model studied here consists of a one-piece sections with different dimensions designed as a panels for use in containers against blast loadings. All of the models consisted of three main following parts as shown in Figure 1:
1) **Panel:** All the panels with specified cross-sections having thickness of 13 cm and different length and widths are modelled as arc or closed plates using Shell elements in order to taken into account nonlinear effects due to the large shear under blast loading.

2) **Fillers:** The fillers with triangular cross-sections located inside the empty panel are modelled using Solid elements in ABAQUS.

3) **Frame:** Regarding that the frame of studied structure is made from steel profiles, thus Shell element are used for modelling. Figure 1 shows the frame model.

![Frame model](image)

**Fig. 1:** The different parts modelled in ABAQUS

### 2.2 Materials properties

Aluminium, steel and sand are the materials used in the present study and their properties are given in Tables 1 to 3, respectively.
Table 1: Mechanical properties of aluminium

<table>
<thead>
<tr>
<th>Young's modulus</th>
<th>Shear modulus</th>
<th>Bulk modulus</th>
<th>Poisson ratio</th>
<th>Mohs hardness</th>
<th>Vickers hardness</th>
<th>Brinell hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 GPa</td>
<td>26 GPa</td>
<td>86 GPa</td>
<td>0.35</td>
<td>2.75</td>
<td>167MPa</td>
<td>245 MPa</td>
</tr>
</tbody>
</table>

Table 2: Mechanical properties of steel

<table>
<thead>
<tr>
<th>Young's modulus</th>
<th>211 GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus</td>
<td>82 GPa</td>
</tr>
<tr>
<td>Bulk modulus</td>
<td>170 GPa</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 3: Mechanical properties of sand

<table>
<thead>
<tr>
<th>Density</th>
<th>1700 (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>3200 (N/mm²)</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.05</td>
</tr>
</tbody>
</table>

2.3 Blast loading

Calculations of the blast load on structures have normally been carried out using an Eulerian method, e.g.[11–13], where it is assumed that the blast loaded structure behaves as a rigid body. Then, the obtained loading has been used together with some simplified analytical models [14,15] or design manuals [16,17] to calculate the structural response. On the other hand, the structural response due to blast loads may be simulated using a Lagrangian finite element formulation, e.g. [18–20], often by use of a simplified blast load description (based on ConWep [21] or similar).

The ABAQUS software can compute the pressure resulted from TNT explosion on the surface, thus in order to define blast loading, an external point is considered as the explosion source point and the TNT amount is defined at that point [22, 23]. Then, CONWEP is used to calculate the resulted pressure value from TNT explosion at specified distance and exert it on the plate.
3. Results and discussion

In this section, the results of Ref. [8] are used to validate the ABAQUS results. Then, the modelled panel is attached to a frame of a container as a rigid body and is exposed under the blast loading of 4000 kg TNT at stand-off distance of 20 m. The panels are modelled with aluminium and steel without fillers and the results including displacement, strain energy and dissipated energy are studied. Later, the aforementioned panels considering granular materials as fillers are investigated at the same conditions. In the next part, a container with dimensions of 6×2.5×2.5 m$^3$ are fully modelled under blast loading and its results are compared with a conventional one manufactured from a common plate. Then the complete container is investigated under different blast loads and the results are analyzed and the proposed configurations for various applications are evaluated.

3.1 model validation

The studied model is as one-piece sections with different dimensions used as a protective structures in a container for resisting blast loads. The results of Børvika et al. [8] are used for validation. For simulation, a source point at the distance of 42 m from panel is created and the load equal to 8000 kg TNT is applied to it. The comparison of deflection-time diagrams for the panel are shown in Figures 2 and 3. As it can be seen, the results are in good agreement.

![Fig. 2: Deflection-time results for the panel in LS-DYNA [8]](image-url)
3.2 Container with aluminium and steel panels

In this section, the container frame made from steel profiles with thickness of 10 cm is modelled and steel and aluminium panels are attached as tie (Figure 4). Then, the blast load equal to 4000 kg TNT at distance of 20 is applied. Figure 5 illustrates the stress distribution at different points of the modelled panel. The panels are modelled using aluminium and steel without fillers and their results including displacement, strain energy and dissipated energy are reported as depicted in Figures 6 to 8. In the next stage, the aforementioned panels containing granular materials as fillers are studied at same conditions. As can be seen from Figure 6, displacement of aluminium panel is two times larger than that of steel panel. Figures 7 and 8 also shows that the absorbed energy in aluminium panels is about two times higher compared to steel panel.
Fig. 5: Stress distribution at steel and aluminium panels without fillers

Fig. 6: Displacement-time variation at steel and aluminium panels without fillers

Fig. 7: Strain energy-time variation at steel and aluminium panels without fillers
3.3 Container with aluminium and steel panels filled with granular materials

In this section, the previous model with the same geometry and blast loading is considered. Here, the effect of using fillers is taken into account. The stress distribution results are demonstrated in Figure 9.

It can be seen in Fig. 10 that the filled panel with aluminium is modelled at its displacement is 17 cm (same as the displacement of steel panel without fillers). The strain energy-time and kinetic energy-time diagrams show that the amount of absorbed energy in the steel with fillers is near to aluminium’s. The amount of absorbed energy in the aluminium panel is almost 100% higher than steel panel, while this difference is lower than 20% for the case with filler and this indicates extreme dissipation of energy in fillers.
3.4 energy dissipation rate in fillers

As it can be seen in the following figures, the amount of energy dissipation in fillers in aluminium panels is four times that of steel panel.
Fig. 13: Dissipated energy-time variation at steel panels with fillers

Fig. 14: Dissipated energy-time variation at aluminium panels with fillers

Fig. 15: Comparison of dissipated energy-time variation at gravels with steel and aluminium panels
Fig. 16: Comparison of dissipated energy-time variation at steel and aluminium panels

3.5 Comparison of aluminium container with filler against conventional container

As it is shown in Figures 17 and 18, a conventional container with aluminium plates and a container with aluminium panels and fillers are subjected to same blast loading. The results obtained demonstrate the superiority of aluminium panels.

Fig. 17: Stress distribution and deformation of a conventional container

Fig. 18: Stress distribution and deformation of a container with aluminium panel
Fig. 19: Comparison of displacement-time variation for conventional container and container with empty panel

3.6 Container with aluminium panel including fillers under varying blast loads

In this section, container is completely modelled and is subjected to various blast loads of 500 kg, 2500 kg, 5000 kg and 10000 kg TNT. The results are depicted in following Figures. As it can be seen, the deformation rate is directly proportional to the weight of explosives.

Fig. 20: Stress distribution in the modelled container for different TNT loads
3.7 effect of arch aluminium panels

The displacement and the amount of applied blast load results in the following models specifies that using arch aluminium panels lead to better blast resistance results.
Conclusions

In this paper, a lightweight protective concept for a standard container used as shelter in international operations is presented. The protection is based on using aluminium and steel panels which are fixed to the container. The effect of using granular material to increase their ballistic and blast load resistance is numerically investigated using ABAQUS. The major obtained results are as following,

- Despite lower weight of aluminum compared to steel, it showed better blast resistance characteristics.
- Granular materials have high energy dissipation ability, thus they have excellent performance in constructing blast resistant structures in combination with other materials.
The comparisons demonstrated that the combination of aluminum panels and granular materials have better performance regarding dissipated energy.

The simulation results indicated that the arc panels have better performance compared to flat panels.

At last, it can be stated that aluminium panels are proposed to be used in protective structures as blast resistance.

References


[21]. US Army Engineers Waterways Experiment Station. ConWep – conventional weapons effects. USA; 1991.
