Numerical response of aluminium plate (6061-T6) under dynamic loadings.

Nassier A. Nassir¹ ² and Ayad K. Hassan¹

¹ Materials Engineering Dept., University of Technology, Baghdad, Iraq
² Email: 130076@uotechnology.edu.iq

Abstract. The response of aluminium plates (6061-T6) under low velocity impact is investigated numerically using ABAQUS software package. Firstly, the effect of the sample thickness on the perforation resistance of the aluminium plates is undertaken. It was shown that the perforation behaviour of the plates investigated increases with the target thickness and the maximum resistance to perforation, for the range of thicknesses investigated, was achieved using 4 mm thick panels. In order to capture the influence of the projectile shapes on the perforation behaviour, the aluminium plates were impacted with different head shapes impactors. The results showed that plates impacted with a flatted impactor offer the highest perforation resistance. Moreover, the results showed that changing the size of the targets has no significant change on the dynamic behaviour of the plates investigated in this study. Finally, it is suggested that the finite element models developed in this study can be used to capture the effect of the geometric and loading conditions of aluminium plates under perforation by low velocity impact.

Keywords: Aluminium (6061-T6), ABAQUS, impact, perforation

1. Introduction

In aircraft industry, the reduction of the cost is the main concern in many airlines manufactures and this can be achieved by controlling many factors such as maintenance cost, fuel consumption, service life and number of passengers. All the aforementioned requirements can be achieved by reducing the weight of the structural materials used. It is found that weight reduction of the structure by three to five times is more effective than increasing its mechanical properties such as damage tolerance and tensile properties [1]. As a result of the attracting mechanical properties of composite structures compared to metals, i.e. strength to weight ratio, specific stiffness and excellent resistance to fatigue as well, these materials have used extensively in the primary and secondary load bearing components in aerospace applications [2]. Composite structures are considered to be the suitable materials for designing the wings and fuselage structures. However, composite materials offer some disadvantages such as low impact properties, high cost production, and relatively hot/wet stability [1,3]. Since the late of 1920s, the aluminum alloys have been used mainly as airframe materials due to their relatively low cost and strength to weight ratio, where weight needs to be minimized. Advanced aluminum alloys are widely used in aerospace application where the fracture toughness, high fatigue performance and super-plasticity, high damage tolerance and durability are required. Due to their corrosion resistance, good weldability and high recycling potential, aluminum alloys
offer an excellent potential in in marine and automotive sectors. Moreover, these kinds of alloys exhibit a
good level of strength by using heat treatment. Aluminum alloys, as high-performance materials, are
considered to be one of the most easily fabricated materials [4,5]. Aluminum alloys are mainly used in the
aeronautical industry such as the frames of fuselage, bulkheads, engine blades and aircraft wings [6-8]. During
services, aluminum alloys may be subjected to impact loadings by foreign bodies such as bird strike and
runway debris which can cause a serious damage in the structural materials. Therefore, the structural
behaviour of these materials needs to be examined under such kinds of loadings. Low-velocity impacts and
high-velocity impacts are the types of the dynamic loadings. The term of low-velocity impact is used when
the structural materials subjected to big masses with a small velocity. In the high velocity impact loadings,
the materials exposed to low mass projectiles with high velocity such as gun bullets. Although the complete
failure could not happen, the damage panels may require to replace instead of repairing [9].
The impact behaviour of metals under various loading conditions were conducted by many researches. A
review on the perforation and penetration behaviour of structures impacted by free falling projectiles with
high velocities can be found in [10,11]. The perforation resistance of squared and rectangular plates of mild
steel impacted with different projectile shapes was studied by Jones et al. [12]. The results showed that the
hemi-spherical projectile exhibit the largest perforation energy and the blunt impactor require the smallest
energy for perforation, whereas, the perforation energy obtained for the sample impacted with conical
projectiles was slightly less that those impacted with hemi-spherical projectile.
The experimental and numerical characterizations of aluminium plates (AA5083-H116) were conducted by
Grytten et al. [13]. The finite element part was conducted using LS-DYNA software. The results showed
good agreement between the experimental and numerical data. Fagerholt et al. [10] studies the behaviour
of AA5083-H116 plates under dynamic loadings numerically and experimentally. The dynamic response of
clamped circular plates of aluminium, copper and mild steel under blast loading was conducted Habaei [14].
The process parameters of the mid-point deflection thickness ratio were well predicted using GMDH-type
networks. It can be seen from the literature that extensive experimental and numerical studies have been
 undertaken to investigate different types of aluminium alloys under high velocity impact. However, the
response of these structures against low velocity impact still need more investigations. Therefore, this work
aims to investigate the dynamic response of aluminium ally (6061-T3) under low velocity impact at various
test conditions.

2. Finite element modelling
In this study, numerical simulations using ABAQUS /Explicit were developed to predict the perforation
resistance of the aluminium alloys used in aircraft industry. Here, the aluminium alloy was modelled as an
elasto-plastic with rate dependent behaviour. Here, due to the ambient conditions, the temperature effects
are neglected. The model of Johnson-Cook material was employed in the following form [15,16]:

$$\sigma = \left[ A + B (\dot{\varepsilon}_{pl})^n \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0} \right) \right]$$  \hspace{1cm} (1)

in which the constants of A, B, C and n are the material parameters, $\dot{\varepsilon}_{pl}$ and $\dot{\varepsilon}_0$ refers to the equivalent and
reference strain rate. $\dot{\varepsilon}_{pl}$ denotes to the equivalent plastic strain. The following formula refers to the damage
in the Jonson -Cook model.

$$D = \sum \left( \frac{\Delta \varepsilon_{pl}}{\varepsilon_f} \right)$$  \hspace{1cm} (2)

where, $\Delta \varepsilon_{pl}$ is the increment of equivalent plastic strain during an increment in loading.
$$\varepsilon_f^{pl} = [D_1 + D_2 \exp (D_3 \sigma^*)] \left[ 1 + D_4 \ln \left( \frac{\sigma^{pl}}{\sigma_0} \right) \right]$$  \hspace{1cm} (3)

Here, $D_1$, $D_2$, $D_3$ and $D_4$ are the material parameters, $\sigma^*$ is the mean stress which normalised by the equivalent stress.

Table 1 shows the Johnson-Cook model parameters for the aluminium alloy (6061-T6) used in this investigation. The elastic properties of the aluminium alloy used was defined in the terms of Young modulus and passion ratio. The values of density, Young modulus and passion ratio were taken as 2690 kg/m$^3$, 73.1 GPa and 0.3, respectively.

The projectile was modelled as a rigid body without deformation. The interaction between the projectile and the aluminium plates was defined as surface to surface contact between the node set of the plate and the projectile surface. The contact properties between the projectile and the aluminium plate is illustrated in Table 2. In this simulation, a fully fixed squared plates with various dimensions and thicknesses are considered. In order to minimize the CPU time and the associated cost, only one half of the plates was modelled as shown in Figure 1. The aluminium plates were meshed using eight-noded solid brick elements (C3D8R) with reduced integration and hourglass control, whereas, four-noded bilinear quadrilateral rigid elements (R3D4) were used to mesh the projectile. The initial velocity of the impactor was applied in the normal direction of plates.

**Table 1.** Johnson-Cook parameters of aluminum alloy (6061-T6) [16].

| Material (Al) | A (MPa) | B (MPa) | n   | C   | D1   | D2   | D3   | D4   | Tensile strength (MPa) |
|--------------|---------|---------|-----|-----|------|------|------|------|------------------------|
| 6061-T6      | 324     | 114     | 0.42 | 0.002 | 0.13 | 0.13 | -1.5 | 0.011 | 332                    |

**Table 2.** Contact properties between the indentor and aluminium plate.

| Contact algorithms | Mechanical constrain formulation | Friction formulation | Contact stiffness (MPa) | Pressure -overclosure |
|--------------------|---------------------------------|----------------------|------------------------|-----------------------|
| Contact pair       | Kinematic                        | Penalty              | 1                      | linear                |

![Figure 1. Loading and boundary conditions of the aluminium plate.](image)
3. Results and discussion

Here, the results are presented in terms of force history (time-force) and displacement history (time-displacement). The data were then combined in the form of force-displacement. Typical force history and displacement history of the squared plate investigated under impact loading is presented in Figure 2. It can be seen from the figure that the traces are highly oscillatory due to the dynamic nature of the test. The trace of force-displacement can be divided into three parts. Initially, there is a small change in the force values with the displacement and the relationship is non-linear (up to 1mm). This can be attributed to the initial contact between the rigid projectile and the target. Then the force values increase rapidly with the displacement due to the membrane effect of the aluminium plate. Once, the force reaches to the maximum value (peak force), it decreases gradually as the projectile start to penetrate the target. The perforation stages for aluminium plate (4 mm thick) is shown in Figure 3.

![Figure 2](image)

**Figure 2.** Force history (a), displacement history (b) and force-displacement (c) of aluminum plate impacted centrally by a hemi-spherical projectile.
The initial part of this investigation focused on the effect of the plate thickness on the perforation response of aluminium alloy (6061-T6). Figure shows the force-displacement relationship of aluminium plate with various thickness (i.e. 0.5 mm, 1 mm, 2 mm and 4 mm) impacted with a hemi-spherical projectile (3.56 kg) with a diameter of 10 mm. The range of the applied velocity was between 4 to 6 m/s. All traces showed similar patterns; the force values increase with the displacement before dropping at the onset of the perforation. It can also be noted that, as the thickness of the plates investigates increases, the maximum and total displacement increase. The effect of the target thickness on the peak forces is presented in Figure. The figure showed that that values of the peak forces increased with the target thickness and the relationship between them is non-linear. For example, target with thickness of 4 mm offers a peak force value of 11978 N which is ten times higher than those offered by the thin plates (i.e. 0.5 mm thick).
Figure 4. Force-displacement traces for aluminum alloy (6061-T6) with various thicknesses impacted with a hemi-spherical projectile. The projectile diameter=10 mm.

Figure 5. Force versus thickness for aluminum plates subjected to low velocity impact. The energy absorbed by the targets investigated can be determined by calculating the areas under the force-displacement traces. The perforation energy values were calculated and plotted against sample thickness as shown in Figure 4. From the figure, it is clear that as the thickness increases, the energy required to perforate the targets increase. For example, the energy required to perforate the thickest plates (i.e. 4 mm) is approximately twenty times higher of that required to perforate the thinnest plate (i.e.0.5 mm). The numerical failure modes of aluminium plates with various thicknesses after full perforation by the projectile

\[ y = 281.59x^2 + 1846.7x + 72.008 \]
\[ R^2 = 0.9998 \]
(i.e. hemi-spherical with diameter of 10 mm) is presented in Figure 6. It can be noted from the figure that all targets exhibit similar failure modes in terms of cracks initiated in the rear surface of the plate. Then, these cracks propagate to give a cross shape as the full perforation of the targets by the projectiles is obtained.

![Figure 6](image1.png)

**Figure 6.** The perforation energy against sample thickness for aluminum plates under impact loading.

![Figure 7](image2.png)

**Figure 7.** Predicted failure modes for aluminum plates after full perforation.
The next part of this work focused on investigation the effect of projectile shapes on the perforation resistance of aluminium plates (i.e. 1 mm thick). Here, the diameter of 10 mm was used for the different projectile head shapes to facilitate comparisons. The projectile mass and velocity values were 3.56 kg and 4 m/s, respectively. Three head shapes are used in this investigation and these being hemi-spherical, conical and flatted projectiles, as shown in Figure 8. Perforation resistance of aluminium alloy (1mm thick) impacted with different projectile head shapes is presented in terms of force-displacement traces as shown in Figure 9. It is clear from the figure that all targets exhibit similar initial stiffness and this can be attributed to the small contact area between the projectiles and the targets at the beginning of the interaction between them. Then, targets impacted with flatted projectile show the highest values of stiffness and peak forces due to the largest contact area and therefore the high resistance offered by the targets against the impactor. It is interesting to mentioned that plates impacted with conical and hemi-spherical projectile show approximately similar peak forces and a similar observation to that made elsewhere on plates of mild steel [12]. However, the largest displacement was recorded for targets impacted with conical shape due the small interaction area between the target and impactor resulting weak resistance to penetration and perforation.

Figure 8. Projectile shapes used in this investigation.

Figure 9. Force-displacement traces for aluminium alloy under low velocity impact with different shapes.
This part of the study investigates the effect of the target dimensions with constant thickness of 1 mm on the perforation behaviour of the aluminium alloy (6061-T6). Three plate dimensions were employed and these being 100 mm, 200 mm and 400 mm. Again, only half model was used for saving the CPU time. These plates were impacted with a hemi-spherical projectile (10 mm diameter), as shown in Figure 10. The projectile mass and velocity values were 3.56 kg and 4 m/s, respectively. The force-displacement traces of aluminium alloy investigated under low velocity impact with different head shapes are shown in Figure 10. From the figure, it is interesting to note that target with dimension of 100 mm^2 exhibits the highest stiffness value due to the short distance between the impact region and the boundary condition. Similar conclusion was observed for fibre metal laminates based on aluminium alloy and glass fibre reinforced epoxy by Fan et al [17]. These results confirmed that near boundary condition regions are more serious than far regions. It can also be noted from the figure that there is no significant change in the values of peak force and perforation energy when the targets impacted near or far the boundary conditions as shown in Figure 10.

Figure 10. Assembly of the aluminum plates with various dimensions, 50 mm (a), 100 mm (b) and 200 mm(c) impacted with a hemi-spherical projectile with dimension of 10 mm.
4. Conclusion

Numerical simulations using ABAQUS/Explicit software have been developed to predict the perforation resistance of aluminium alloy (6061-T6) under low velocity impact. It has shown that changing the thickness of the plate has a significant effect on the perforation resistance of the panels investigated. However, the target size showed no significant change in the response of the plates investigated in terms of peak force and perforation energy values. The effect of the head shapes of the impactor on the perforation behaviour...
has also been investigated. The results showed that targets impacted with a flattened projectile exhibit the highest stiffness and peak forces. It can be concluded that the finite element models developed were capable to capture the effect of the geometric and loading conditions on the perforation resistance of aluminium plates (6061-T6).

References

[1] T. Dursun and C. Soutis, “Recent developments in advanced aircraft aluminium alloys,” Mater. Des., vol. 56, pp. 862–871, 2014.
[2] N. Nassir, Z. W. Guan, R. S. Birch, and W. J. Cantwell, “Damage initiation in composite materials under off-centre impact loading,” Polym. Test., vol. 69, pp. 456–461, 2018.
[3] N. Nassir, R. S. Birch, W. J. Cantwell, Q. Y. Wang, L. Q. Liu, and Z. W. Guan, “The perforation resistance of glass fibre reinforced PEKK composites,” Polym. Test., vol. 72, pp. 423–431, 2018.
[4] N. E. Prasad and V. V Kutumbarao, Aerospace materials and material technologies. Springer Science+Business Media Singapore, 2017.
[5] P. Vasanthakumar, K. Sekar, and K. Venkatesh, “Recent developments in powder metallurgy based aluminium alloy composite for aerospace applications,” Mater. Today Proc., vol. 18, pp. 5400–5409, 2019.
[6] R. Ghajar, S. M. R. Khalili, M. Yarmohammad Tooski, and R. C. Alderliesten, “Investigation of the response of an aluminium plate subjected to repeated low velocity impact using a continuum damage mechanics approach,” Fatigue Fract. Eng. Mater. Struct., vol. 38, no. 4, pp. 475–488, 2015.
[7] Z. Huda, N. I. Taib, and T. Zaharinie, “Characterization of 2024-T3: An aerospace aluminum alloy,” Mater. Chem. Phys., vol. 113, pp. 515–517, 2009.
[8] Z. Huda, N. I. Taib, and T. Zaharinie, “Characterization of 2024-T3: An aerospace aluminum alloy,” Mater. Chem. Phys., vol. 113, pp. 515–517, 2009.
[9] D. Kreculj and B. Rašuo, “Review of impact damages modelling in laminated composite aircraft structures,” Teh. Vjesn., vol. 3, pp. 485–495, 2013.
[10] E. Fagerholt, F. Grytten, B. E. Gihleengen, M. Langseth, and T. Borvik, “Continuous out-of-plane deformation measurements of AA5083-H116 plates subjected to low-velocity impact loading,” Int. J. Mech. Sci., vol. 52, no. 5, pp. 689–705, 2010.
[11] M. E. Backman and W. Goldsmith, “The mechanics of penetration of projectiles into targets,” Int. J. Eng. Sci., vol. 16, no. 1, pp. 1–99, 1978.
[12] N. Jones, R. S. Birch, and R. Duan, “Low-velocity perforation of mild steel rectangular plates with projectiles having different shaped impact faces,” J. Press. Vessel Technol. Trans. ASME, vol. 130, no. 3, pp. 0312061–0312068, 2008.
[13] F. Grytten, T. Borvik, O. S. Hopperstad, and M. Langseth, “Low velocity perforation of AA5083-H116 aluminium plates,” Int. J. Impact Eng., vol. 36, no. 4, pp. 597–610, 2009.
[14] B. Hyman, “Prediction of Deformation of Circular Plates Subjected to Impulsive Loading Using GMDH-type Neural Network,” Int. J. Eng., vol. 27, pp. 110–117, 2014.
[15] T. P. Vo, Z. W. Guan, W. J. Cantwell, and G. K. Schleyer, “Modelling of the low-impulse blast behaviour of fibre-metal laminates based on different aluminium alloys,” Compos. Part B Eng., vol. 44, pp. 141–151, 2013.
[16] J. Zhou, Z. Guan, and W. Cantwell, “Numerical modelling of perforation impact damage of fibre metal laminates,” ICCM2014, pp. 1–12, 2014.
[17] J. Fan, W. Cantwell, and Z. Guan, “The low-velocity impact response of fiber-metal laminates,” J. Reinf. Plast. Compos., vol. 30, pp. 26–35, 2011.