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Ballistic impact analysis of double-layered metal plates

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Abstract. In the present study, ballistic impact analysis of double layered circular metal plates with different arrangements were investigated numerically using the finite element method. Nine different double layered plates configuration consist of steel 4340 (st), Aluminium 2014-T3 (Al), or titanium Ti-6A1-4V (Ti) having the same thickness were considered in this study and the energy absorption capability of each configuration were determined and compared. In order to validate the results obtained via the numerical method, an experimental ballistic test utilising a single stage gas gun was performed on single layer Al plates using a blunt projectile. It was found that the results obtained from numerical analysis agree well with the experimental results, which confirmed the accuracy of the numerical analysis procedure. The non-linear explicit finite element analysis employing Johnson-Cook plasticity material model coupled with was carried out using ABAQUS commercial package. A parametric study was conducted to determine the best configuration in terms of the energy absorption capability under ballistic impact. It was observed from the analysis that the double layered plate with titanium (front plate facing the projectile) and steel 4340 (back plate) produced the highest energy absorption with 279.72 J. However, the highest specific energy absorption (SEA) was given by titanium (front) and Aluminium (back) plate with 2830.45 J/kg.

1. Introduction

The design and development of armour plates for protection against ballistic impact has long been of interest in military and civilian applications [1]. A multi-layer configuration that consisted of several parallel plates is proposed to replace the design using monolithic or single plates. When a single plate is replaced by several layered thin plates, the order, thickness and the number of layers will affect the failure modes, which leads to difference of ballistic resistance between various target configurations [2]. Although there were a number of research dealing with the ballistic behaviour of multi-layered plates [3-9], their scope was limited when compared to studies of monolithic plates. Moreover, the studies conducted on multi-layered armour plates using numerical analysis is also scarce [10-17]. Thus the study of multi-layered plates remains an open research topic since the conclusive results of their performance have not been obtained to date.

In this research, ballistic impact analysis of double layered circular metal plates with different order were investigated numerically using finite element method using nine different double layered plates configuration consisted of steel 4340 (st), Aluminium 2014-T3 (Al) or titanium Ti-6A1-4V (Ti) [18].

The thickness of each plate is assumed to be the same and the plates are assumed to be in contact with each other. The energy absorption capability of each configuration was determined and compared in order to determine the most optimum configuration.

2. Methodology

The current research is conducted based on tasks and stages as shown in Figure 1. The work is started with the fabrication of the Al 2024-T3 single plates, whose dimensions are in accordance to the NIJ standard requirement. A parametric study is carried out on nine different configurations for the double layered circular plates (50mm diameter and 3mm thickness for each layer) using the specific notation shown in Table 1. Finally, the optimum configuration based on specific energy absorbed is determined using the numerical analysis.

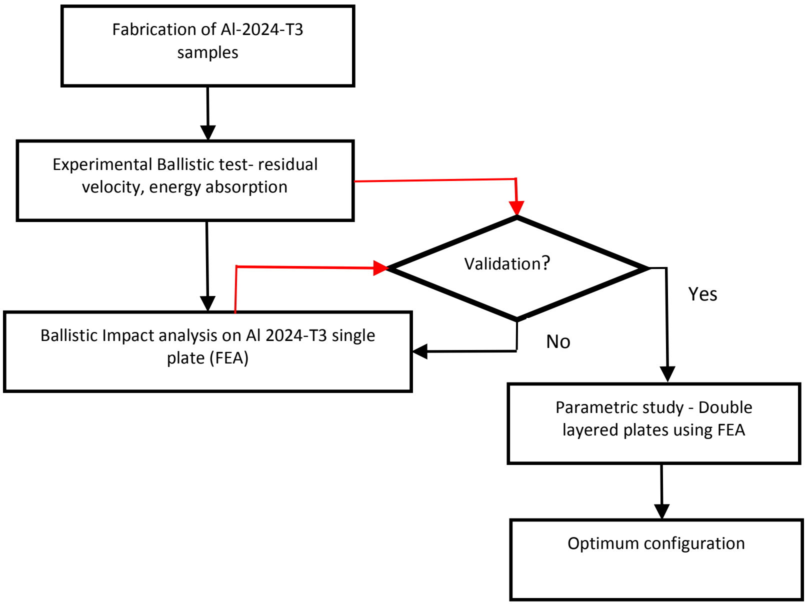

Figure 1. Flowchart for the overall research work

Table 1. Configuration for the double layered plates

Material (Front plate-Back plate)	Configuration
(Steel-steel)	*C1*
(Aluminium-aluminium)	*C2*
(Titanium-titanium)	*C3*
(Steel-titanium)	*C4*
(Titanium-aluminium)	*C5*
(Steel-aluminium)	*C6*
(Titanium-steel)	*C7*
(Aluminium-titanium)	*C8*
(Aluminium-steel)	*C9*

2.1. Experimental ballistic impact

A single stage gas gun was used to conduct the experimental ballistic test in which the projectiles were launched at different pressures and velocities, shown in Figure. 2. The test setup was developed based on NIJ NIJ-018.01 standard [19], as shown in Figure 3. The impact energy absorption was determined using the principle of conservation of energy, i.e. the change in kinetic energy by the projectile before and after the impact is equivalent to the energy absorbed by the plate.

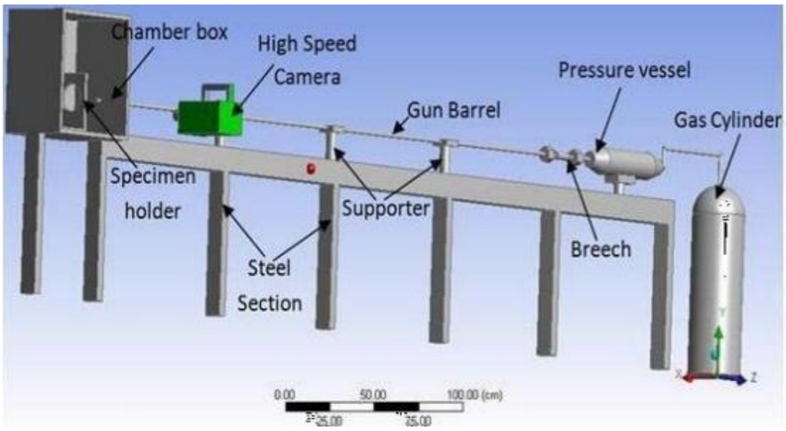

Figure 2. Gas gun tunnel instrument for impact test

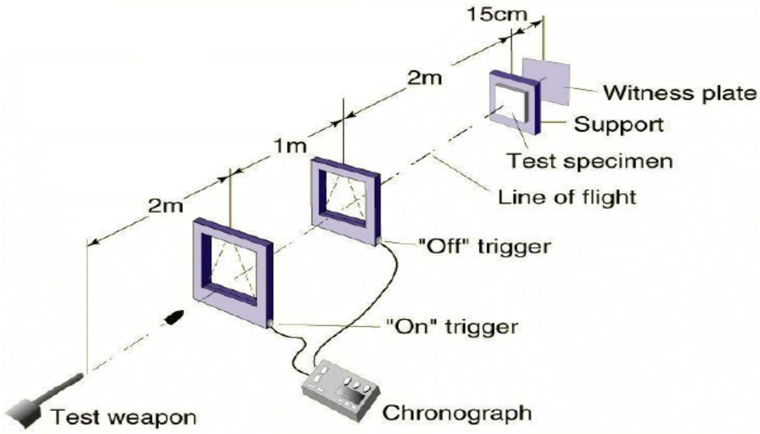

Figure 3. Ballistic test setup following the NIJ standard

Square targets with sides of 4 inches were fixed to a thick base plate by means of four bolts that were arranged in specimen holder in the target chamber box, as demonstrated in Figure 2. The test was done on a single square (100mm x 100mm x 3mm) monolithic aluminium 2024-T3 plate subjected to a blunt mild steel projectile with a diameter of 4.5 mm and 13.07mm length. A high speed camera was used to record the process of projectile penetrating target and the projectile motion. From the digital images, the travelled distance and projectile velocity before and after penetration were obtained. With these information, energy absorption by the plate can be estimated using the conservation of energy principle. The results obtained from this test served as a validation against the numerical results.

2.2. Numerical analysis

A numerical analysis using ABAQUS v6.13 finite element analysis software was used in the present study to investigate the ballistic performance of double layered plates having different arrangements as presented in previous Table 1. The two plates in each configuration are assumed to be in contact with each other using general contact formulation [20]. The non-linear dynamic explicit analysis has been employed in ABAQUS to accurately simulate the ballistic impact behaviour.

The Johnson & Cook plasticity formulation [21], which defines the flow stress as a function of the equivalent plastic strain, strain rate and temperature, was employed in the numerical simulations in

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order to predict damage behaviour in metal plates due to impacted projectile. The following relation in Eqn. 1 expresses the dynamic flow stress, where A, B, m, and n are material parameters, T, T_r, and T_m are temperature, room temperature and melting point, and $\dot{\varepsilon}_0$ is a reference plastic strain rate.

$$\sigma_e = [A + B(\varepsilon_e^p)^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right], \quad (1)$$

In the Johnson–Cook failure model [22], a damage parameter D is defined as in Eqn. 2,

$$D = \int \frac{1}{\varepsilon_f} d\varepsilon_e^p. \quad (2)$$

When D reaches 1, the failure occurs so that element will no longer withstand the tension and then will be deleted in simulations. Failure strain ε_f is defined in Eqn. 3, where d_1, d_2, d_3, d_4 and d_5 are material constants and P is hydrostatic pressure [22].

$$\varepsilon_f = \left(d_1 + d_2 e^{d_3 \frac{P}{\sigma_e}}\right)\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_0}\right)\right]\left[1 + d_5\left(\frac{T - T_r}{T_m - T_r}\right)\right], \quad (3)$$

Many studies show good agreements between predictions of Eqn. 3 and the experimental results of the steel and aluminium alloy at high strain rate [23, 24]. The yield surface parameters and failure strain parameters for Al 2024-T3, Ti-6A1-4V and Steel 4340 are given by Table 2 and Table 3, respectively. Table 4 presents the mass of each material and the projectile. These values are required to compute the energy absorb and the specific energy absorption of the double plates.

Table 2. Yield surface parameters Al 2024-T3, Ti-6A1-4V and Steel 4340 [17, 22]

Material	**Al 2024-T3**	**Ti-6A1-4V**	**Steel 4340**
Parameter	**Value**	**Value**	**Value**
A	368.986 MPa	1097.962 MPa	792 MPa
B	683.973 MPa	1091.964 MPa	510MPa
N	0.73	0.93	0.926
M	1.7	1.1	0.014
C	0.0083	0.014	1.03

Table 3. Failure strain parameters for Al 2024-T3, Ti-6A1-4V and Steel 4340 [17, 22]

Material	**Al 2024-T3**	**Ti-6A1-4V**	**Steel 4340**
Parameter	**Value**	**Value**	**Value**
d_1	0.112	-0.090	0.05
d_2	0.123	0.270	3.44
d_3	1.500	0.480	-2.12
d_4	0.007	0.014	0.002
d_5	0	3.870	0.61

Table 4. Mass of specimen and projectile

Specimen	**Mass (kg)**
Al 2024-T3	0.0283
Ti-6A1-4V	0.0451
Steel 4340	0.0798
Projectile	0.00675

3. Results and discussion

This section discusses the results obtained from the validation of impact damage on the aluminium plate along with the energy absorbed by the plate from both experimentally and numerically. Finally, a parametric study for the nine different configurations mentioned above using three different materials (aluminium, titanium and steel) were carried out and discussed.

3.1. Validation

The results obtained from the experimental ballistic test as well as the numerical analysis are shown in Table 5. It can be observed that the results obtained via FEA agree well with those obtained from the experiments. The small percentage differences observed in the results, i.e. 3.54% and 6.73% for the residual velocity (Vout) and the energy absorbed, respectively, proves that the numerical simulation scheme (FEA) was employed with high accuracy and validity. Figure 4 shows the damage plates after impact for three different initial velocities or gauge pressures.

Table 5. Comparison between numerical and experimental results

Gage pressure (bar)	V_{in} (m/s)		V_{out} (m/s)		Energy absorption (J)	
	Exp.	FEA	Exp.	FEA	Exp.	FEA
10	155.30	155.30	No penetration	No penetration	-	-
15	191.04	191.04	No penetration	No penetration	-	-
44	272.38	272.38	189.83	183.10	128.77	138.07
			% difference		% difference	
			3.54		6.73	

(a) No penetration (b) No penetration (c) Plugging mode

Figure 4. Post-impact damage of Al-2024-T3: (a) V_{in} = 155.3 m/s; (b) V_{in} = 191.04 m/s; (c) V_{in} = 272.38 m/s

3.2. Parametric study

A parametric study using FEA was performed to determine the optimum plate configuration in terms of its energy absorption. From Table 6, it is found that double plate with configuration C7 (Titanium-steel) gives the highest energy absorbed with 279.72 J whereas C5 (Titanium-aluminium) possesses the greatest SEA with 2830.45 J/kg. The high energy absorbed by the C7 plate is attributed the high density of the steel combined with the high strength-to-weight ratio of the titanium alloy. On the other hand, the highest SEA in C5 configuration means impact strength-to-weight ratio of this configuration is the best compared to all other configurations given in Table 1. From this results, it can be concluded that Titanium alloy plays a major role in improving the high velocity impact resistance subjected to blunt projectile especially when used as the front plate facing the projectile. Figures 5 to 8 illustrate the FE results for selected plate configurations under the projectile impact.

Table 6. Results of parametric study using ABAQUS (V_{in} = 500m/s)

Configuration	**V_{out} (m/s)**	**Energy absorbed (Joule)**	**Specific energy absorbed (energy absorbed/mass of a plate (layer)) J/kg (SEA)**
C1	418.9	251.5	1575.714
C2	458.3	134.86	2382.685
C3	423.1	239.54	2655.986
C4	429.0	222.61	1782.225
C5	434.1	207.75	2830.45
C6	442.4	183.205	1694.773
C7	408.8	279.72	2239.551
C8	437.3	198.34	2702.18
C9	412.5	269.47	2492.784

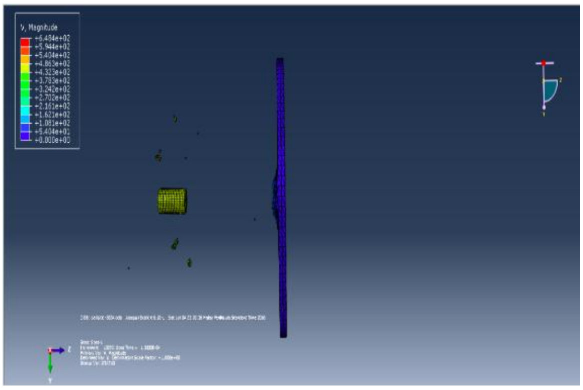

Figure 5. Perforation of aluminium-titanium plate

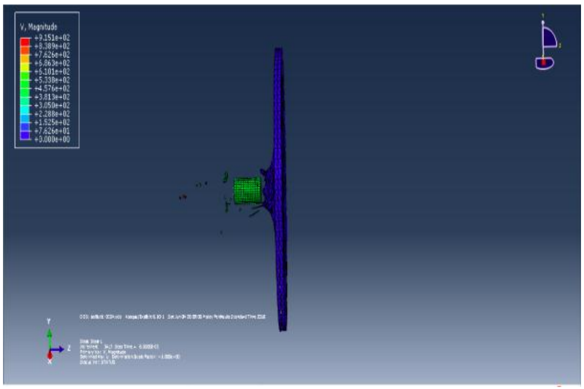

Figure 6. Perforation of titanium-aluminium plate

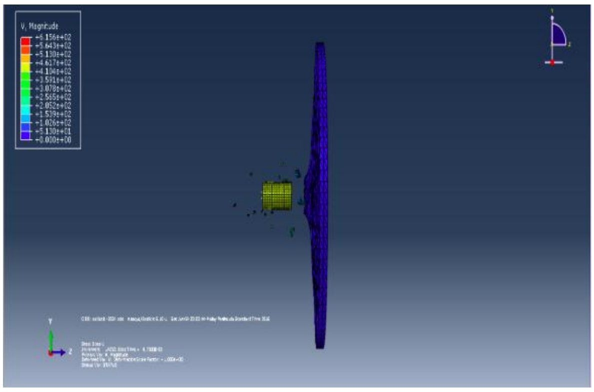

Figure 7. Perforation of steel-titanium plate

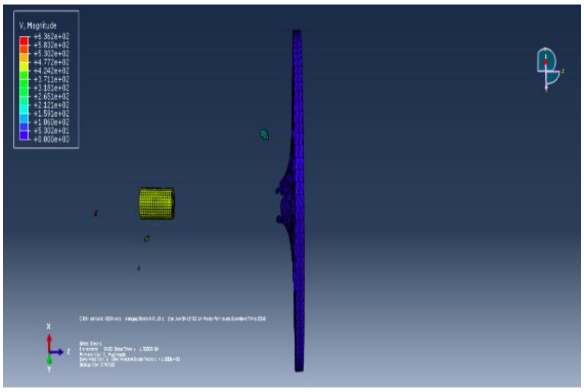

Figure 8. Perforation of aluminium-aluminium plate

4. Conclusion

In this study, the ballistic impact analysis on nine different types of double layered metal plates was investigated by numerical simulation based on the finite element method. Validation of the numerical simulation scheme incorporating the Johnson-Cook damage model was successfully carried out by comparing the numerical results of monolithic aluminium 2024-T3 plate with that of the experimental ballistic test. In the parametric study, it was observed that "titanium-aluminium" specimen yielded the highest specific absorbed energy (SAE) due to the combination of low density (aluminium alloy) and high strength (titanium alloy) characteristics of the double-layered plate. It can be generally concluded that by replacing the either steel or aluminium layer with titanium led to the increase in the SAE.

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