Original Article

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A study on the response of single and double circular plates subjected to localised blast loading

Abstract
The response of single and double layered steel plates to localised air-blast loading was examined. Two configurations, both comprising fully clamped circular plates with a 200 mm exposed diameter, were considered: 4mm thick single and (2+2) mm double layered plates. The localised air-blast loading was applied by centrally detonating discs of PE4 plastic explosive. Similar failure modes were evident in the single and double plate configurations, namely, Mode I (large inelastic deformation) and Mode II (capping failure along with deformation) responses. The double plates exhibited larger midpoint deflections than the single plates, and partial tearing of the front plate in the double plates was observed at a lower impulse than in the single plates. However, complete capping of both plates in the double plate configuration occurred at the same charge mass as for the single plates, implying that both configurations offer equivalent protection from capping failure as a result of this type of localised blast loading. A metallographic study of the deformed and torn plate regions did not reveal any phase transformation in the steel. It was also found that the 2 mm thick plates exhibited larger increases in grain size than the 4 mm thick plates.

Keywords
Blast loading; plates; HSLA steel; deformation; Microstructure

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1 INTRODUCTION

Conventionally, High Strength Low Alloy (HSLA) steels are considered as a basic construction material for armour systems due to their high hardness and enhanced yield strengths. In recent years, the potential of multi-layered plates to improve the performance of structures subjected to projectile impact has been investigated by various researchers.

Marom and Bodner (1979) performed ballistic tests on layered targets of 6061-T aluminium alloy beams (using 0.22 calibre projectiles at a velocity of 375 m/s) and found that equivalent mass multi-layered beams were more effective in resisting perforation than single beams. Corran et al. (1983) tested mild steel, stainless steel and aluminium plates and showed that layered shielding exhibited superior ballistic resistance to a single plate once the total thickness exceeded a critical value. Woodward and Cimpoeru (1998) reported results from impact tests using conical and blunt nosed projectiles on layered 2024-T351 aluminium plates. The layered system comprising two plates of equal thickness provided the highest ballistic limit for both nose shapes.

However, Radin and Goldsmith (1988) reported results from normal impact tests on multi-layered targets of different thickness and showed that the ballistic resistance of the equivalent mass single target was greater than that of the layered systems. Similarly, Almohandes et al. (1996) found that single plates were more effective than laminated plates when impacted by 7.62 mm standard bullets, in the thickness range 1-8 mm. Plates comprising fewer laminates were more effective than those containing many laminates. Zukas and Scheffler (2001) also concluded that layering reduced the ballistic performance of systems when the overall thickness was relatively low.

Teng et al. (2007); Teng et al. (2008) reported results from a numerical study on the protection performance of double-layered metal shields against different projectile using ABAQUS/Explicit. The study indicated improved ballistic resistance of 8–25% by using double-layer configuration against flat-nose projectile. Dey et al. (2007) found that double-layering the target caused an increase of 40 – 50% in ballistic limit velocity (V50) compared to a single target of equal thickness when impacted by blunt projectiles. In case of ogival nose projectile, the single target offered better protection, but the difference in perforation resistance was only 10– 15%.

The change in failure mode from predominantly brittle “shear plugging” (in thick plates) to more ductile response (in layered plates) is the reason for the improved ballistic limit – the ductile structures were able to absorb more energy before rupturing than the equivalent mass brittle plates Dey et al. (2007). However, not all multi-layered structures exhibited enhanced impact performance, as the relative performance was dependent upon various factors, including the projectile geometry and the overall thickness of the protective structure. Since layered steel plates have been shown to give improved ballistic performance under certain circumstances Dey et al. (2007); Teng et al. (2007); Teng et al. (2008), it is useful to ascertain the effect of layering for blast performance. There have been many investigations into the blast performance of single steel plated structures to localised blast loading, for example references Chung Kim Yuen and Nurick (2000); Jacob et al. (2004); Nurick and Radford (1997). The authors are unaware of similar investigations into the blast response of multi-layered steel plates, except for some attempts at tuning blast/impact response through layering of a thick armour structure (to modify the stress wave transmission through the plates by choosing materials with differing damping frequencies, for example Rahimzadeh et al. (2015)).

The failure modes of structures subjected to uniformly distributed blast loading were first classified by Menkes and Opat (1973) at various intensities of impulse. Similar failure modes were also observed for clamped circular plates Teeling-Smith and Nurick (1991) and for square plates Nurick and Shave (1996); Olson et al. (1993) subjected to uniform blast loads. Nurick and Radford (1997) reported that localised blast loading resulted in plate deformation that was characterised by an inner dome superimposed on a larger global dome. At higher impulses, tearing in the central area of the plate occurred with further increase in impulse after the onset of thinning. The tearing observed was characterized by a cap torn away from the plate. The “capping” failure Mode was subdivided by Nurick and Radford (1997).

Mode I - large inelastic response
Mode Itc - large inelastic response with thinning in central area
Mode II*c - partial tearing in the central area
Mode IIc - complete tearing in the central area - capping
Mode II - complete tearing at the boundary

This article presents preliminary results from blast loading experiments on layered plates and equivalent thickness single steel plates subjected to localised air-blast loading. These results are part of a wider study planned to consider the influence of layering in plates of different thicknesses. In the present study, the failure modes and deformation profiles of single and double plates with a combined thickness of 4 mm were compared. Results from air-blast loading experiments on Domex 550 MC steel plates in two configurations, namely, single (4mm thick) and double plates of equal thickness (2+2) mm, the post-test inspections and metallographic investigations are reported.

2 MATERIAL TESTS

High-strength low-alloy (HSLA) steels are a group of low-carbon steels that use small amounts of alloying elements to attain higher yield strengths in the as-rolled or normalised condition. These steels have higher strength than as-rolled carbon steels and are usually 20 to 30% lighter than carbon steel with the same strength. The high yield strength can be obtained at lower carbon content levels. The weld-ability of many HSLA steels is comparable to or better than that of mild steel Society (1982). Hence, HSLA steels are used in a wide variety of applications, such as cars, cranes, bridges, roller coasters. The properties can be tailored to specific applications by the combination of composition and structures obtained during processing. These steels have fine grain size microstructure due to micro alloying of Vanadium, Niobium and Titanium. The yield strength usually varies with grain size according to the well-known Hall-Petch equation, shown in Eq. (1). Fine grains have larger grain boundary areas that impede dislocation motion. Domex 550MC is a hot rolled, cold forming steel that is produced by a thermo-mechanical treatment process and meets the demands for steel S550MC in EN 10149-2 (SSAB, 2018) (Last access Aug 2018). The chemical composition of Domex 550MC steel is listed in Table 1.

$$\sigma_y = \sigma_o + K_y/\sqrt{d} \tag{1}$$

where σ_o and K_y are constants for a particular material and d is the average grain diameter.

Table 1: Chemical composition of Domex 550MC steel (SSAB) (Last access Aug 2018)

Elements	Wt. %	Elements	Wt. %	Elements	Wt. %
Iron	97	Carbon	0.12	Aluminium	0.015
Manganese	1.80	Silicon	0.1	Sulphur	0.010
Vanadium	0.2	Niobium	0.09		
Titanium	0.15	Phosphorus	0.025		

The mechanical properties of the Domex 550MC steel were determined according to the ASTM standards Standard (2013). The samples were cut from 2mm thick steel plates and were tested at a nominal strain rate of 4.2 × 10-4 /s on a Zwick universal testing machine. Three samples were tested at each cross-head speed. The average mechanical properties were: 533 MPa yield strength, a 605 MPa ultimate tensile strength and a 20% elongation to failure. Hardness tests were performed on samples prepared for metallographic study and the average hardness was 230 HV.

3 BLAST EXPERIMENTS

All tested plates were used in as-received condition. The 400 mm by 400 mm square plates were bolted between two 12mm thick annular steel clamps with an exposed diameter of 200 mm. The annular clamps acted as a rigid boundary and fixed the plate to the ballistic pendulum. The whole clamped assembly was mounted in front of the ballistic pendulum, similar to previous blast loading experiments reported in Chung Kim Yuen and Nurick (2000); Jacob et al. (2004); Nurick and Radford (1997); Nurick and Shave (1996); Teeling-Smith and Nurick (1991). A photograph of the ballistic pendulum and attached target plates is shown in Figure 1.

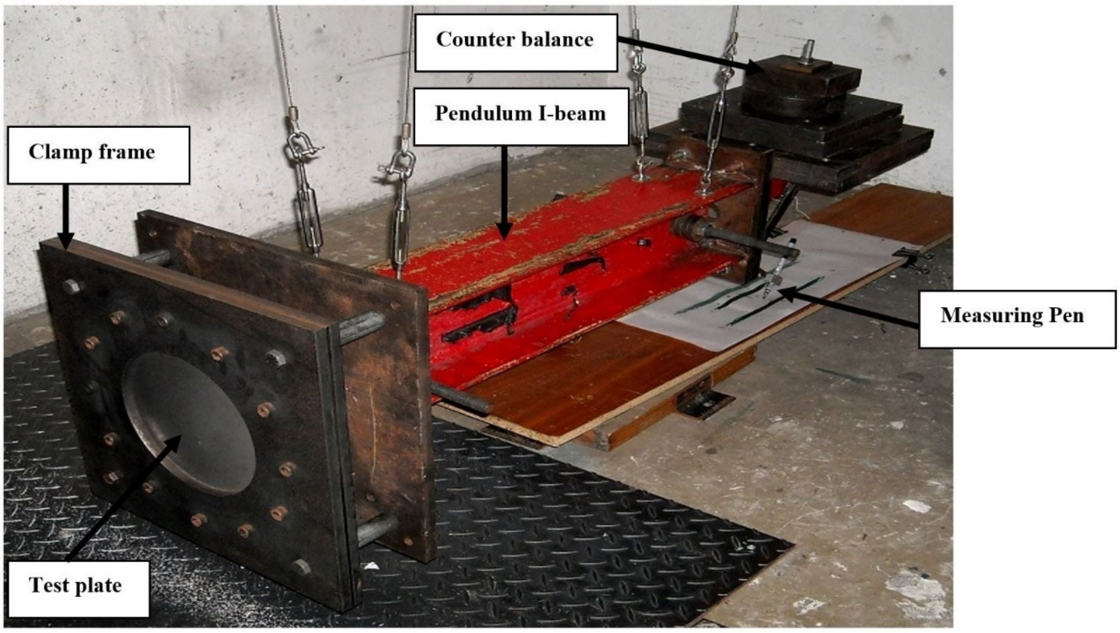


Figure 1: *Photograph of test plate attached to ballistic pendulum*

The PE4 explosive, in the form of a 33 mm diameter disc, was mounted on a 12 mm thick polystyrene foam pad and centrally positioned onto the plate. A 1g leader was used to connect an electrical detonator to the centre of the explosive disc. The approximate burn speed of PE4 is 7500 m/s Balden and Nurick (2005). The explosive mass was varied by adjusting the charge height. The results of the blast tested single plates are presented in Table 2, and the results of double plates are shown in Table 3. In the post test examination, the deformation profile, permanent midpoint displacement, tearing and capping were measured. A metallographic study was performed to investigate the effect of adiabatic heating during plate deformation and tearing. The effect of the blast loading on the grain size of the microstructure was also examined.

Table 2: Results of 4mm monolithic plate subjected to localised blast loading

Test No	Charge mass (g)	Impulse (Ns)	Permanent midpoint deflection (mm)
SA041209SA	7 + 1 = 8	22.0	10.4
SA041209SB	15 + 1 = 16	38.1	17.9
SA041209SC	22.5 + 1 = 23.5	45.4	24.4
SA081209SD	29+1= 30	57.7	29.5 Partial tearing
SA151209SE	36.5 + 1=37.5	63.4	Hole Ø = 20 - 22mm

Table 3: Results of 4mm (2+2) double plates subjected to localised blast loading

Test No	Charge mass (g)	Impulse (Ns)	Permanent midpoint deflection of front plate (mm)	Permanent midpoint deflection of back plate (mm)
SA071209DG	7+1= 8	20.2	12.3	12.8
SA071209DH	15+1=16	36.1	21.8	22.5
SA071209DI	22.5+1=23.5	45.6	28.0	28.7
SA151209DJ	29+1=30	59.9	30.5 partial tearing	Capped
SA151209DK	36.5+1=37.5	61.0	Capped Hole Ø = 28.5	Capped Hole Ø = 29.5

3.1 Post-test failure inspection

Photographs showing mid-line cross-sections of the blast tested plates in single and double configurations (with increasing impulses from bottom to top) are shown in Figures 2 and 3, illustrating the deformation and tearing behaviour at various charge masses. Large inelastic deformation in both configurations increased with increasing impulse. The permanent midpoint deflections, measured using a height gauge, of double plates are slightly greater than the single plates as shown in Tables 2 and 3.

A laser scanner was used to capture the deformed shape of the plate. The deformation profiles from the boundary to midpoint were extracted from the data. Figure 4 shows the deformation profiles of the single plates. At low impulses (22 Ns), the deformation was limited to the central portion of the plate, while at higher impulses the deformation extended towards the boundary. Figure 5 shows the deformation profiles of double plates where the displacements were less localised, with higher displacements near the boundary (when compared to the single plate profiles in Figure 4). It is observed from Figure 3 that the deformed profile shape for the front and back plates were very similar until the point of fracture, varying by less than 1 mm. It was, hence, considered unnecessary to replicate the displacement profiles in another figure for the back sheet.

Failure Mode I (large inelastic response) and Mode Itc (large inelastic response with thinning in central area) responses were observed. At lower impulses below 36 Ns, no significant thinning was observed (that is, Mode I failure occurred). Above 36 Ns, the thinning was observed in the central plate region, agreeing with observations in ref [10], over a diameter smaller than the charge diameter (that is, Mode Itc was observed). Reduction in thickness was easier to observe in the thicker single plate, as shown in the cross-section photographs in Figure 2.

The plate responses were classified with respect to the onset of tearing (that is, the transition between the failure Mode I and Mode II, defined as Mode II* by Langdon et al. (2005)). The impulse at which Mode II* occured was defined as the threshold impulse. A comparison of the single and double plate deformation profiles, shown in Figures 6 and 7, showed that the Mode I profiles were similar in shape but with different magnitudes of permanent displacement. Prior to capping, double layered plates exhibited greater deformations at equal charge masses, as indicated in Figures 6 and 7a. Further increase in charge mass led to partial tearing (Mode II*c) in the central area of the plate, as illustrated in the photographs shown in Figure 8. Mode II*c failure occurred at a lower charge mass in the double plates. For example, the single plate subjected to a 23.5 g charge mass exhibited a midpoint deflection of 24.4 mm (Mode I only) while the double plate midpoint deflection was 28.0 mm with partial tearing of the front plate.

Partial tearing in both single and double plates was found at higher impulses (45-60 Ns) over a 29 mm diameter circular ring (smaller than the charge diameter). As tearing commenced and impulse increased, the deformation profiles of the two configurations are similar in both shape and magnitude, as shown in Figure 7b. For double plates, the front plate (exposed to charge) was partially torn (that is, Mode II*) whilst the back plate exhibited capping. Photographs of the double plate response are shown in Figures 8d and 8e. Although the double plates exhibited Mode II*c failure in the front plate at a lower charge mass, the complete rupture of single and double plate configurations occurred at the same charge mass (37.5 g). This means that the single and double layered configurations offer the same protection from this type of localised air-blast loading.

Mode IIc (complete tearing) was noted for impulses above 60 Ns as shown in Figure 8f for the double plate and Figure 8b for the single plate. The cap diameters were smaller in the single plates (from 20 mm to 22 mm) compared to the double plate cap diameters (28.5 mm to 29.5 mm). The holes in double plates were more rounded whereas the single plates exhibited petalling type failure. Boundary thinning and tearing were not observed during the present study due to the localised nature of the loading.

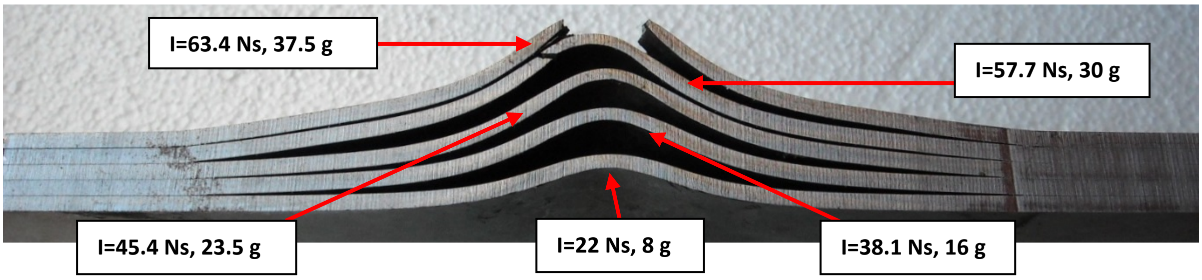


Figure 2: *Photographs of the cross-sections of blast tested single plates*

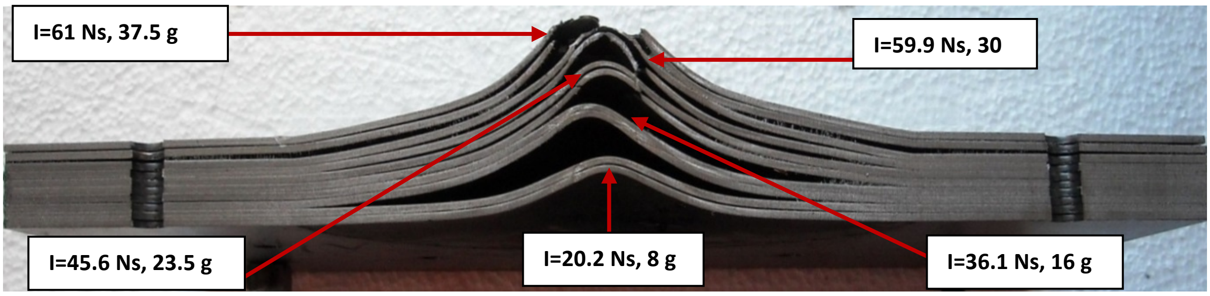


Figure 3: *Photographs of cross-sections of blast tested double plates*

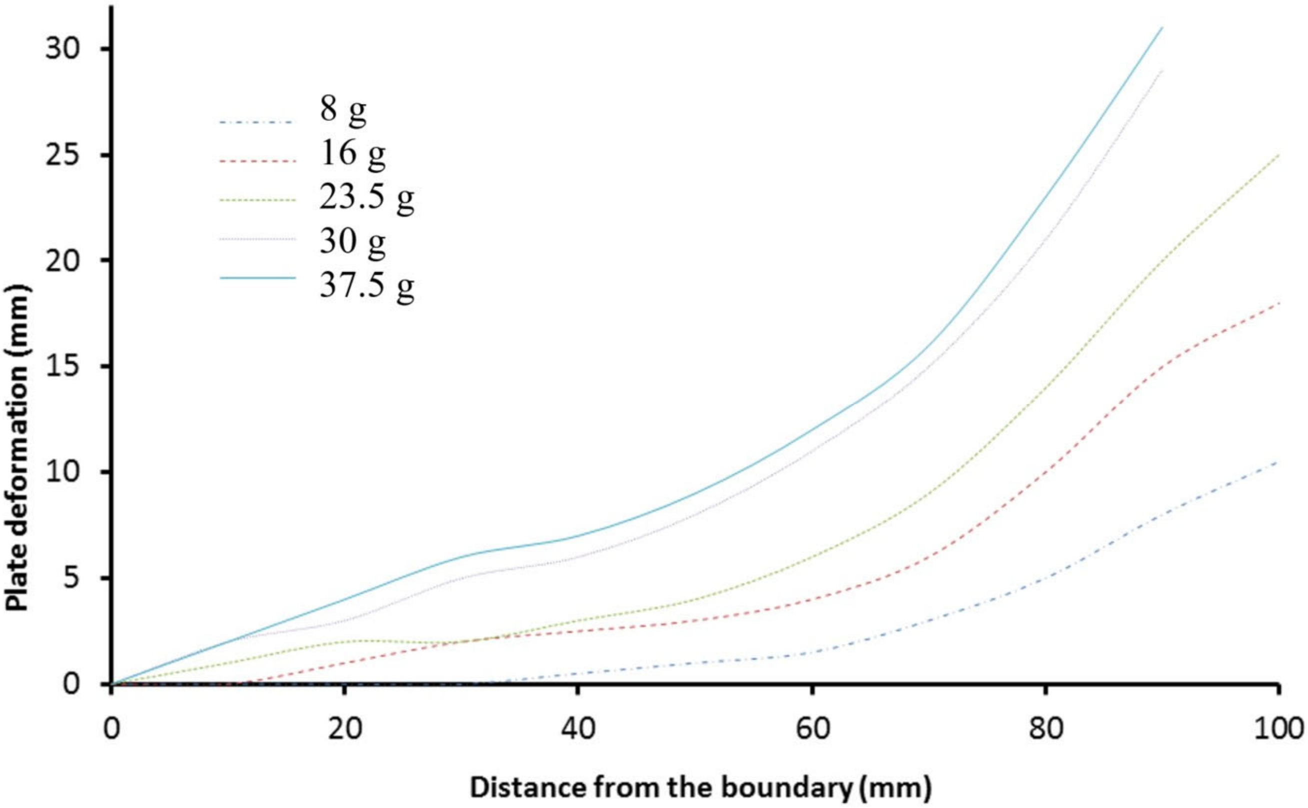


Figure 4: Deformed plate profiles for single plates subjected to blast loading

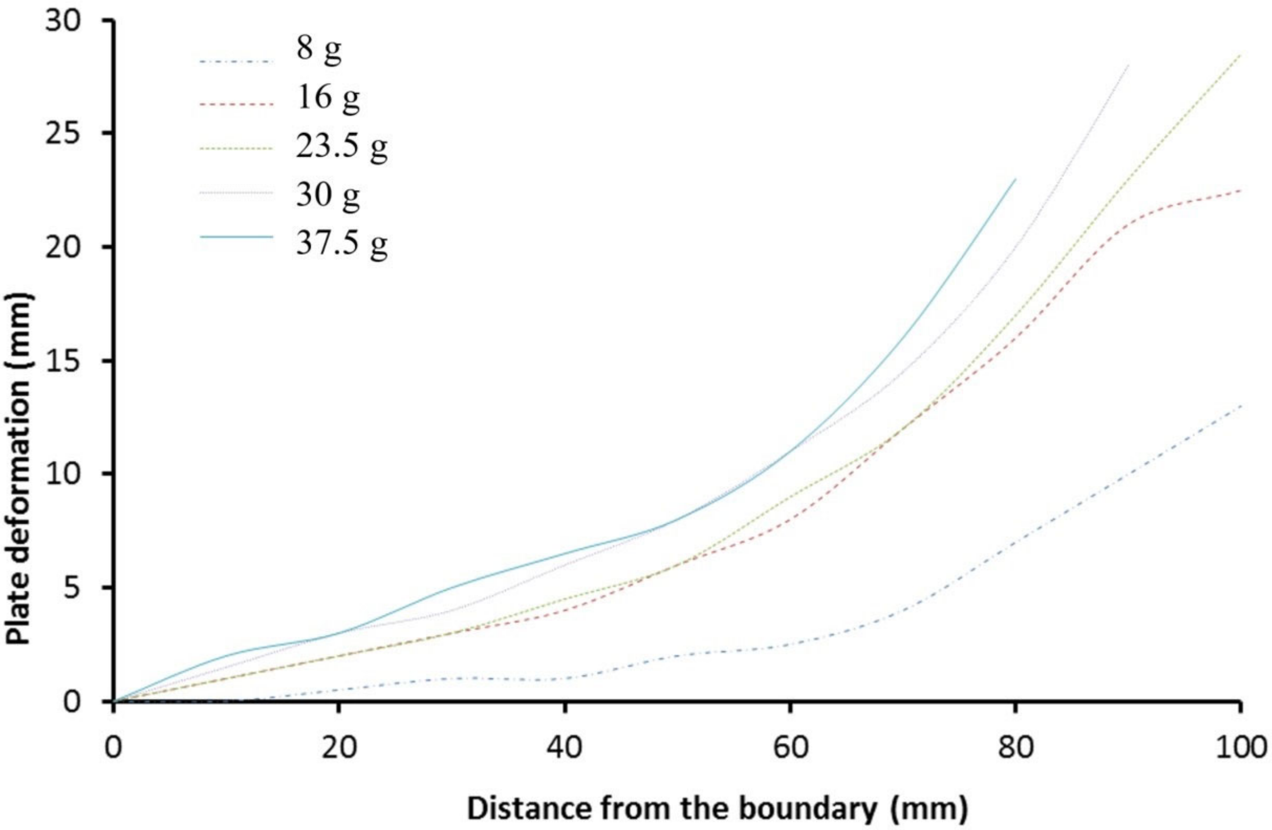
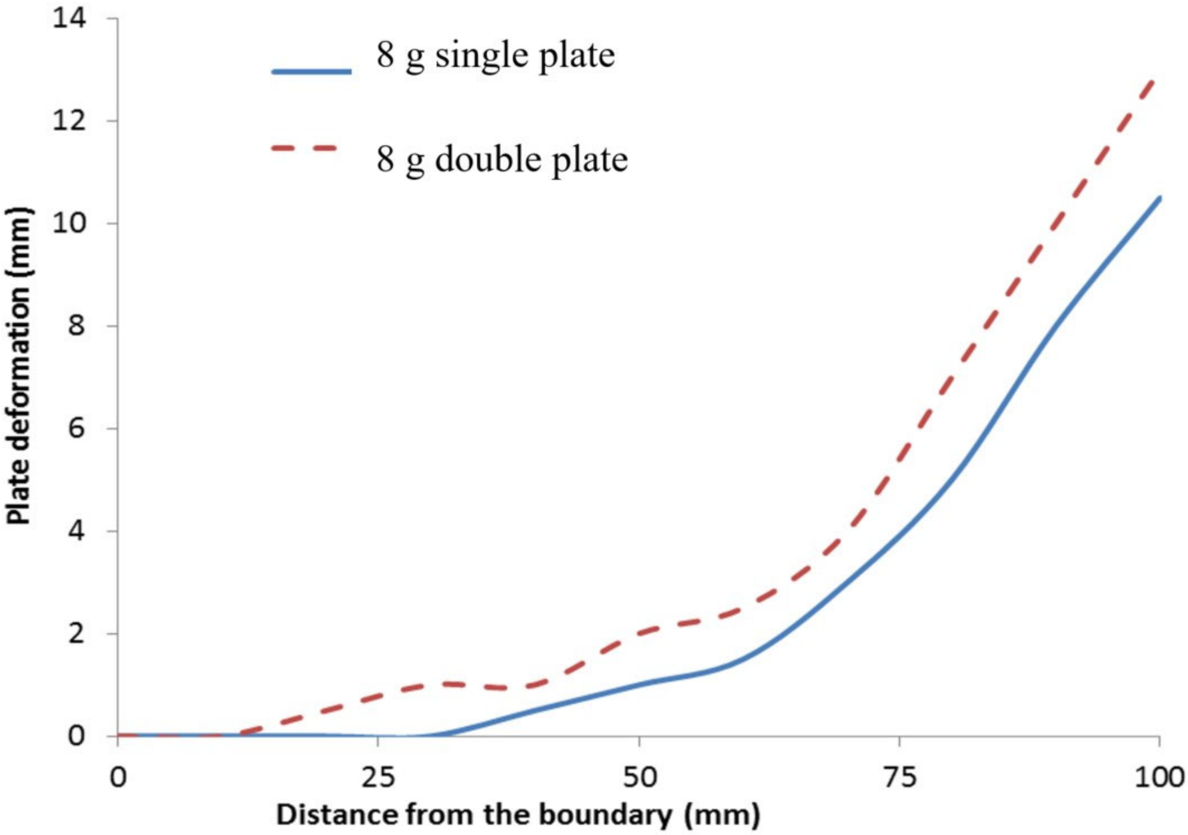


Figure 5: Deformed front plate profiles for double (2+2) mm thick plates subjected to blast loading



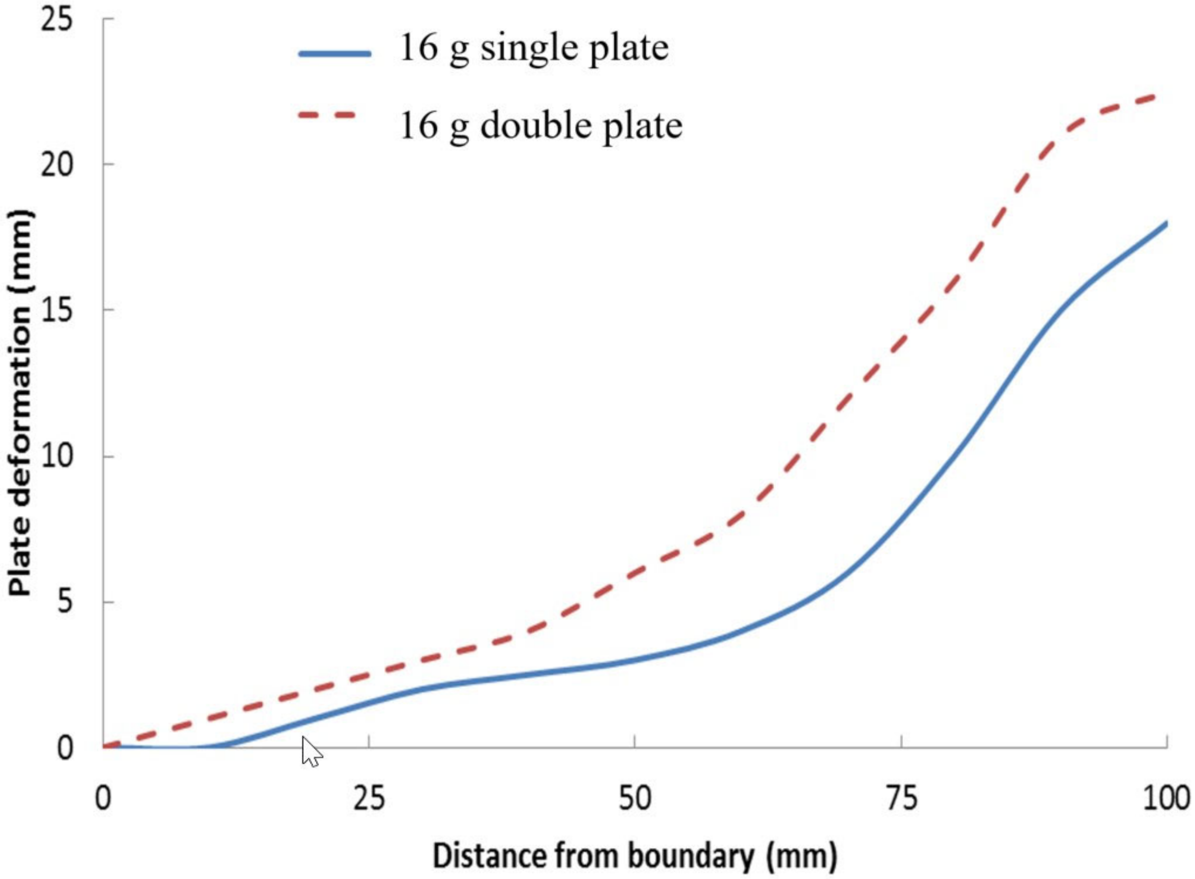
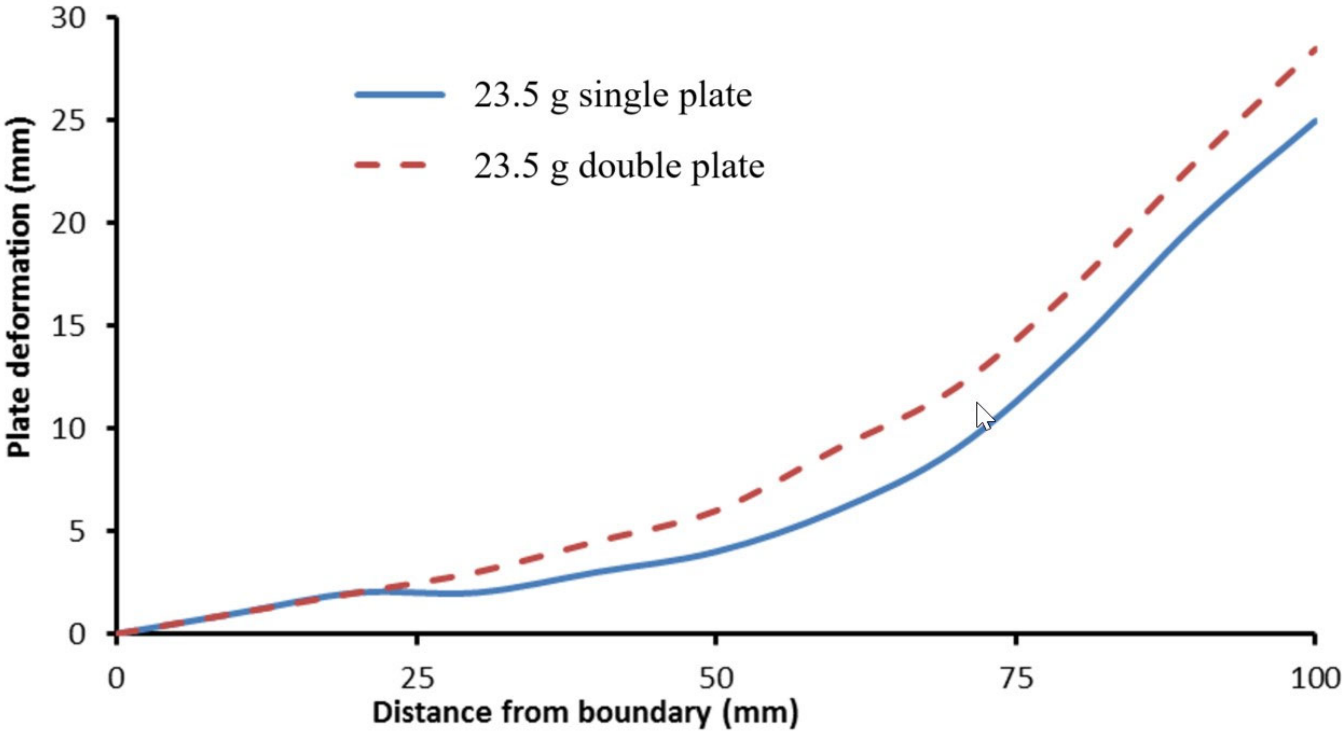


Figure 6: *Deformation profiles of single and double (front) plates subjected to (a) 8 g detonations (b) 16 g detonations*



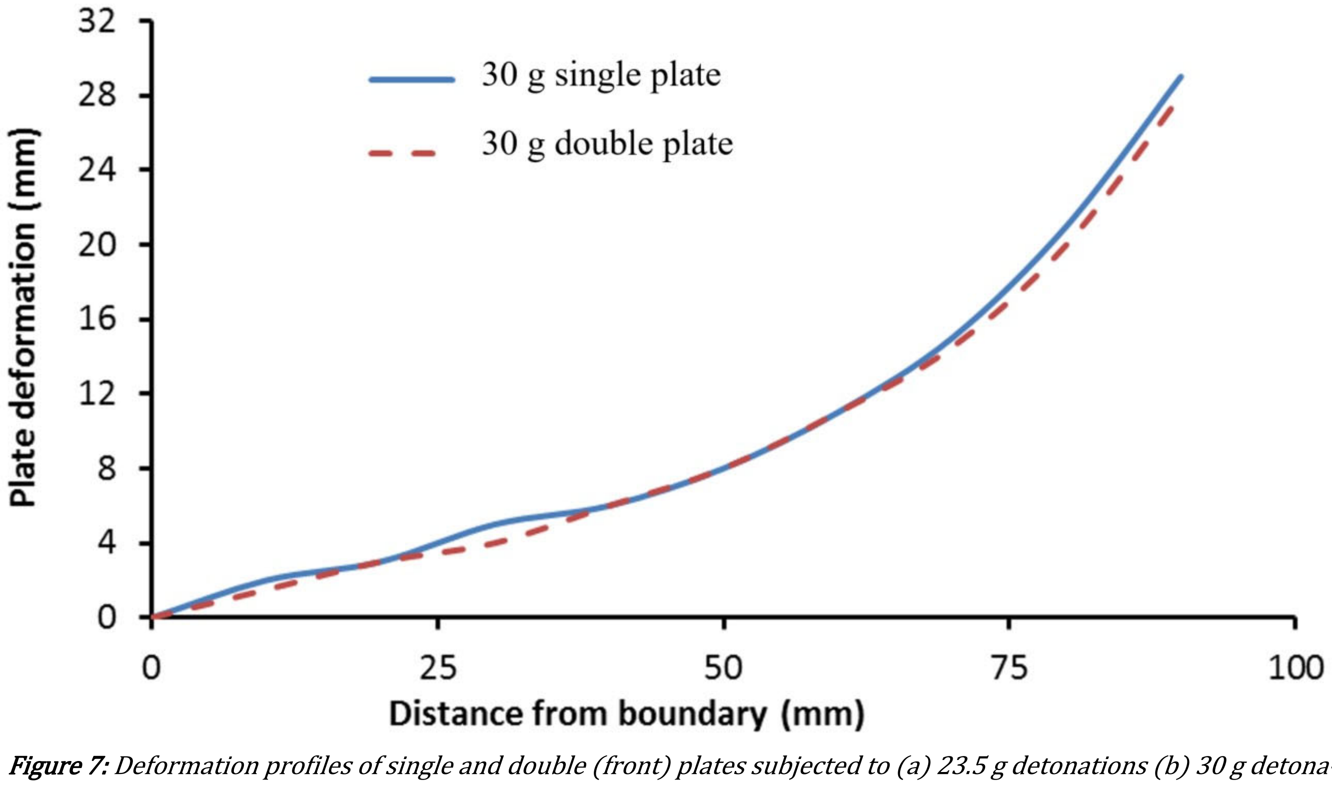


Figure 7: *Deformation profiles of single and double (front) plates subjected to (a) 23.5 g detonations (b) 30 g detonations*

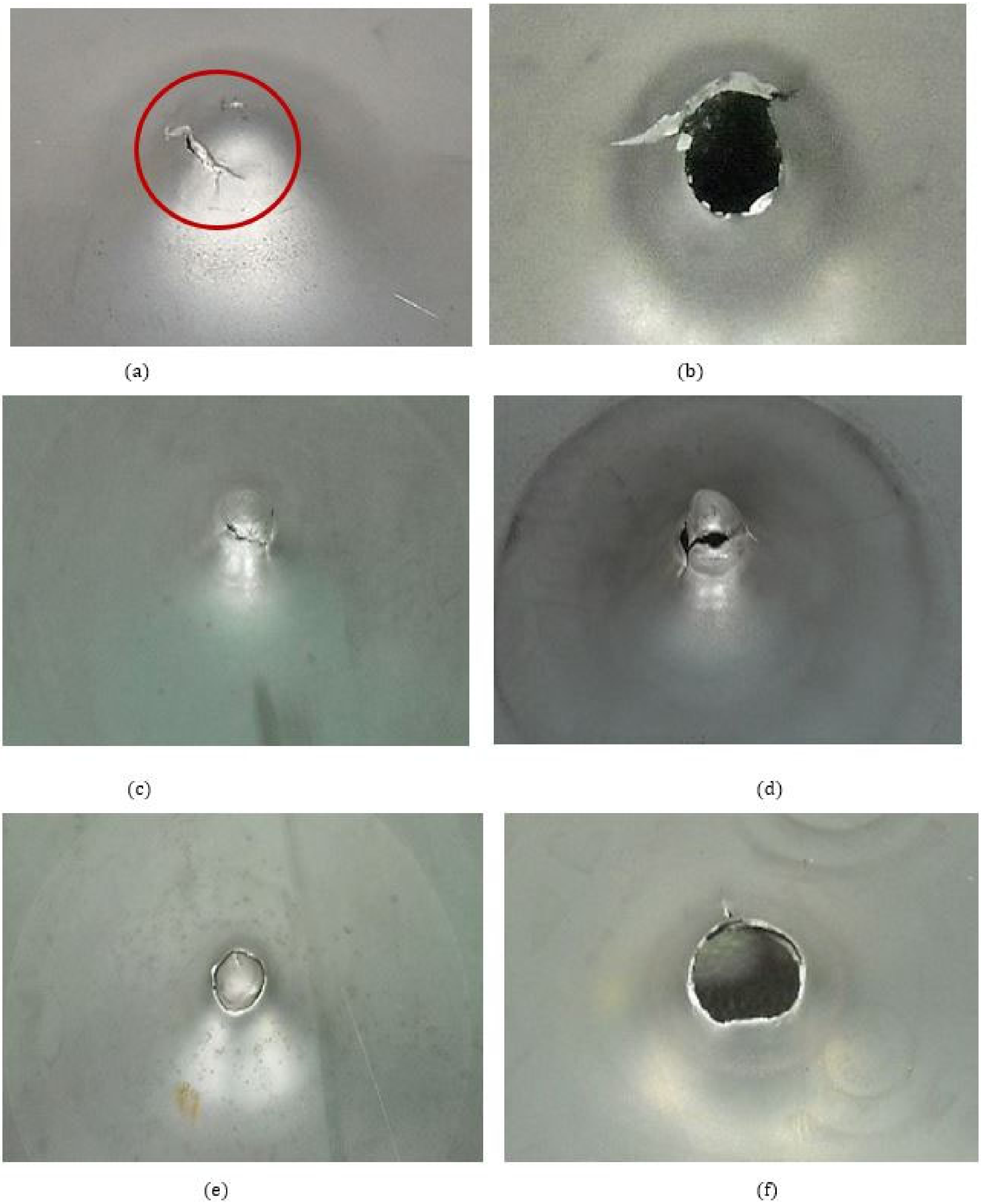


Figure 8: Photographs of plates exhibited partial tearing or capping failures (a) Single plate, 30 g PE4 (b) Single plate, 37.5 g PE4 (c) Double, front plate, 23.5 g PE4 (d) Double, front plate, 30 g PE4 (e) Double, back plate, 30 g PE4 (front plate showing under the back plate) (f) Double, back plate, 37.5 g PE4

3.2 Metallographic observations

Metallographic studies of the single and double plates were performed before and after the blast tests on samples cut from the central region of the deformed and torn plates (that is, near the fractured edge of the capped plate). The samples for microscopy were carefully obtained from the area of interest by using coolant during the cutting process to avoid heating. The samples were mounted and mechanically polished, following standard metallographic techniques. In order to reveal different phases, polished samples were etched in a 2% nital solution for approximately 35 seconds.

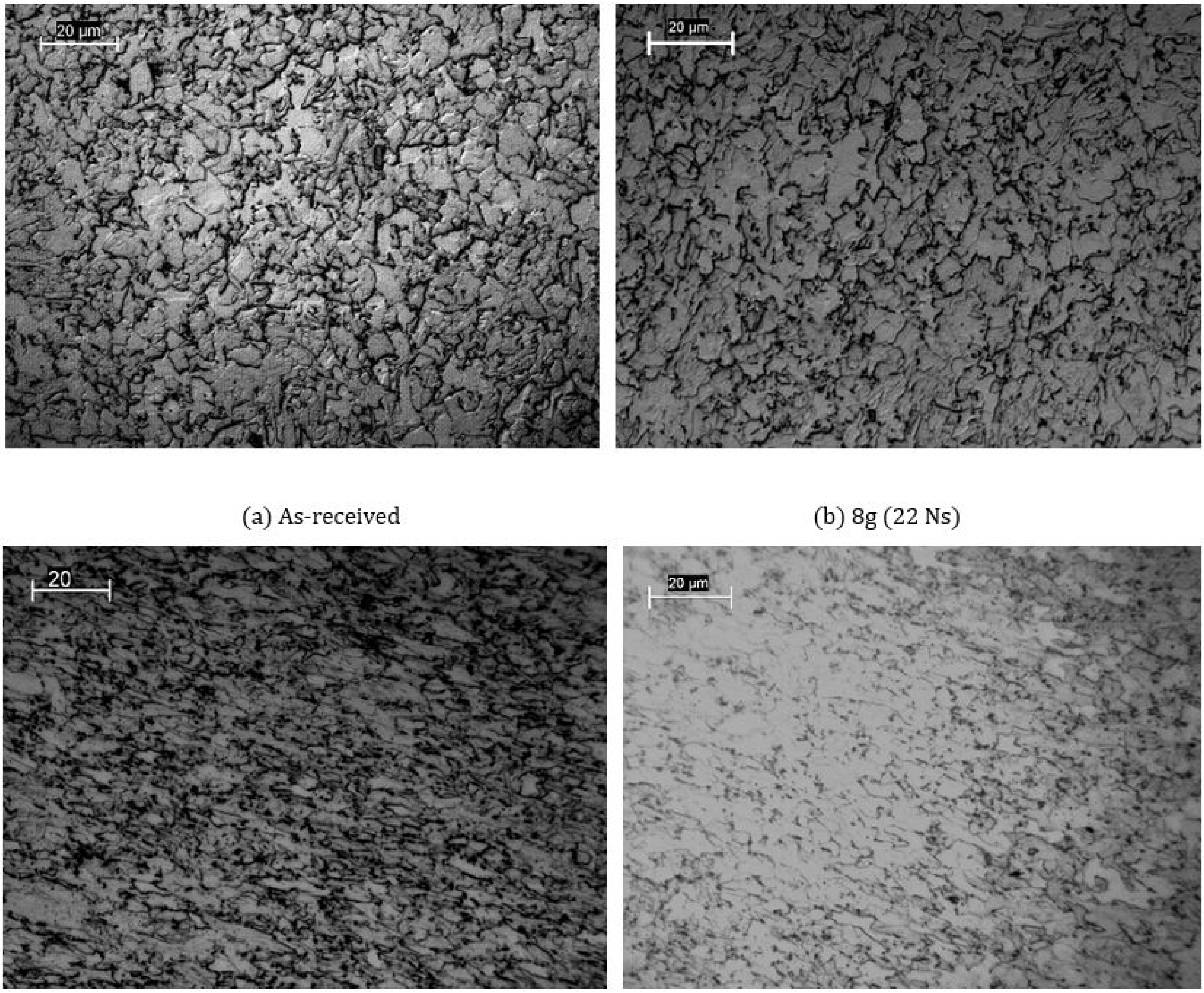
The microstructure of virgin 4 mm and 2 mm thick plates, shown in Figure 9(a) and Figure 10(a) respectively, consisted of fine equi-axed grains of ferrite and a minute quantity of pearlite at the grain boundaries. Figures 9(b, c, d) and Figures 10(b, c, d) show the microstructures of deformed grains from plate samples subjected to increasing impulses. These deformed grains are due to plastic deformation during blast loading. The grain size was measured along the deformation direction (radially towards the charge diameter) to study the effect of increasing impulses on microstructures.

The average grain sizes of the as-received 4mm thick plates were larger than the 2mm thick plates (7.5 and 4 microns respectively). The average grain size of the 4 mm and 2 mm thick samples from plates subjected to different impulses are shown in Tables 4 and 5 respectively. In the case of double 2 mm thick plate, the grain size of both the front and back plates were measured. No significant differences in grain size were observed. The deformed grain sizes of the 4 mm and 2 mm thick back plates were found be similar to each other, and increased with increasing charge mass. A graph of mid-point deflection thickness ratio versus normalised grain size, shown in Figure 11, indicated that the initial increase in grain size of 2 mm back plate was greater than of 4mm thick plate. The final grain size was similar in both plates when approaching capping failure. The normalised grain size increases in the plates were linear with increasing impulse, as shown in Figure 12. In case of 2 mm thick back plates, the initial increase in grain size is greater than in 4 mm thick plates, whereas at higher impulses increase in grain size is linear with the impulse as shown in Figure 12.

The plate microstructures along the capped edges were mainly composed of a ferritic phase, as shown in Figure 9(d) and Figure 10(d). There was no evidence of a transformed region in microstructure as a result of heat generated during tearing, unlike that reported by Raftenberg and Krause (1999). The modelling of localised blast loaded mild steel plates reported by Langdon et al. (2005) and Wiehahn et al. (2000) assumed adiabatic heating and used temperature to define the onset of Mode IIc failure in the plates; both Wiehahn et al. (2000) and Langdon et al. (2005) reported maximum temperatures of 765 °C in the torn regions while 650 °C was considered to represent the torn regions. The microstructural findings herein indicate that the actual temperatures in the torn regions of the plates (presumed to be due to adiabatic heating) did not reach the melting temperature.

Table 4: Average grain sizes of 4mm single plate (measured radially towards the plate centre)

Charge mass (g)	Average grain size (microns)	Standard Deviation	Maximum grain size (microns)	Minimum grain size (microns)	Normalised grain size
As-received	7.5	1.9	12	4	1
7 + 1 = 8	9	2.2	25	6	1.2
15 + 1 = 16	11	3.4	21	7	1.5
22.5 + 1 = 23.5	12	3.8	22	7	1.6
29+1= 30	13	4.5	24	5	1.7
36.5 + 1=37.5	14.2	4.5	23	8	1.9



(a) As-received (b) 8g (22 Ns)

(c) 23.5g (45.4 Ns) (d) 37.5g (63.4 Ns)

Figure 9: *Microstructures of 4mm thick plates subjected to various charge mass detonations (etched in 2% nital)*

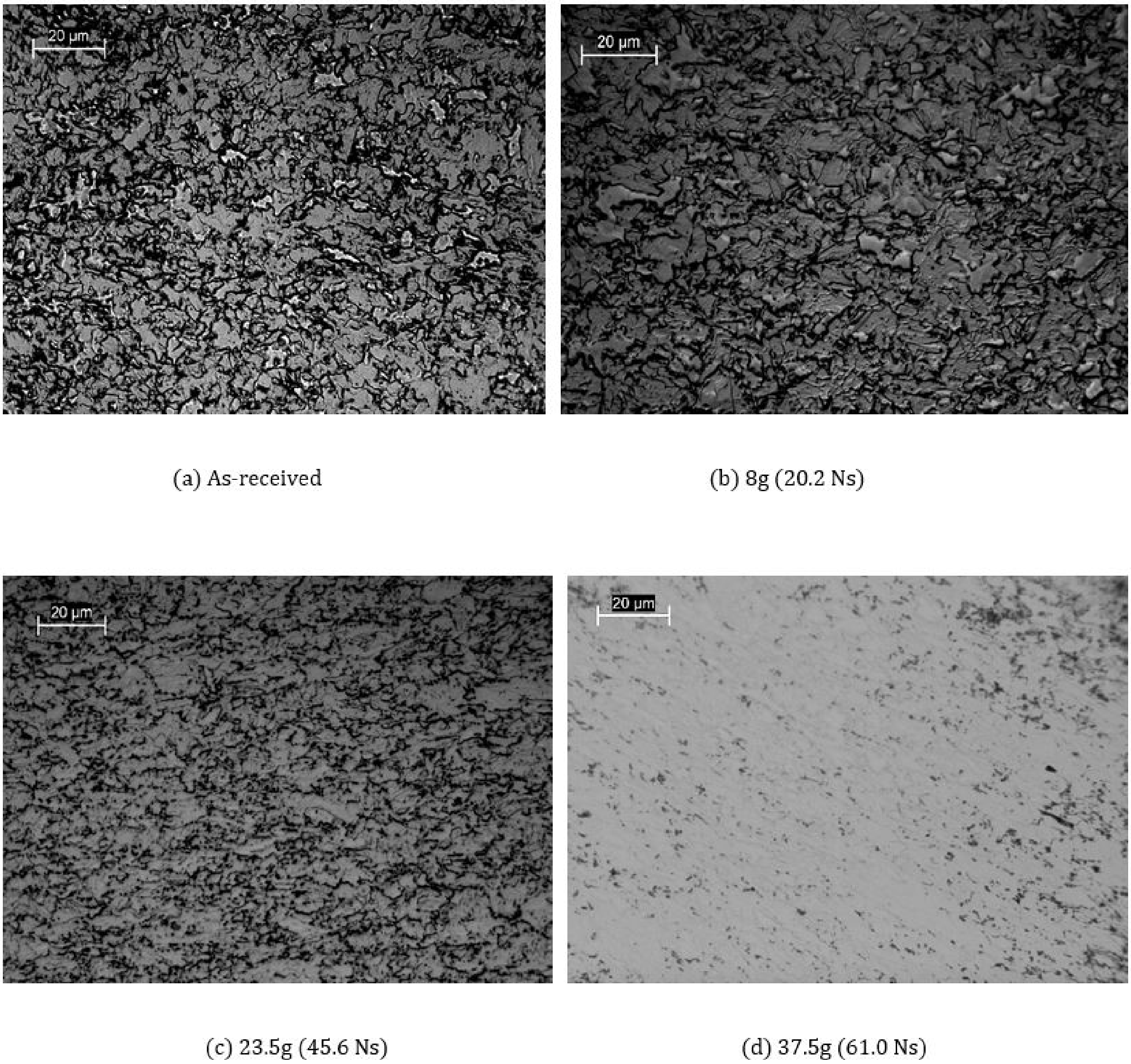


Figure 10: *Microstructures of 2 mm thick back plate subjected to various charge mass detonations (etched in 2% nital)*

Table 5: Average grain sizes of 2 mm thick back plate (measured radially towards the plate centre)

Charge mass (g)	Average grain size (microns)	Standard Deviation	Maximum grain size (microns)	Minimum grain size (micron)	Normalised grain size
As-received	4	1.6	11	3	1
7 + 1=8	10	2.46	16	6	2.4
15 + 1=16	---	---	---	---	----
22.5 + 1=23.5	13.3	3.6	21	6	3.2
29+1=30	14.3	3.9	23	8	3.4
36.5+1=37.5	15.1	4.1	23	8	3.5

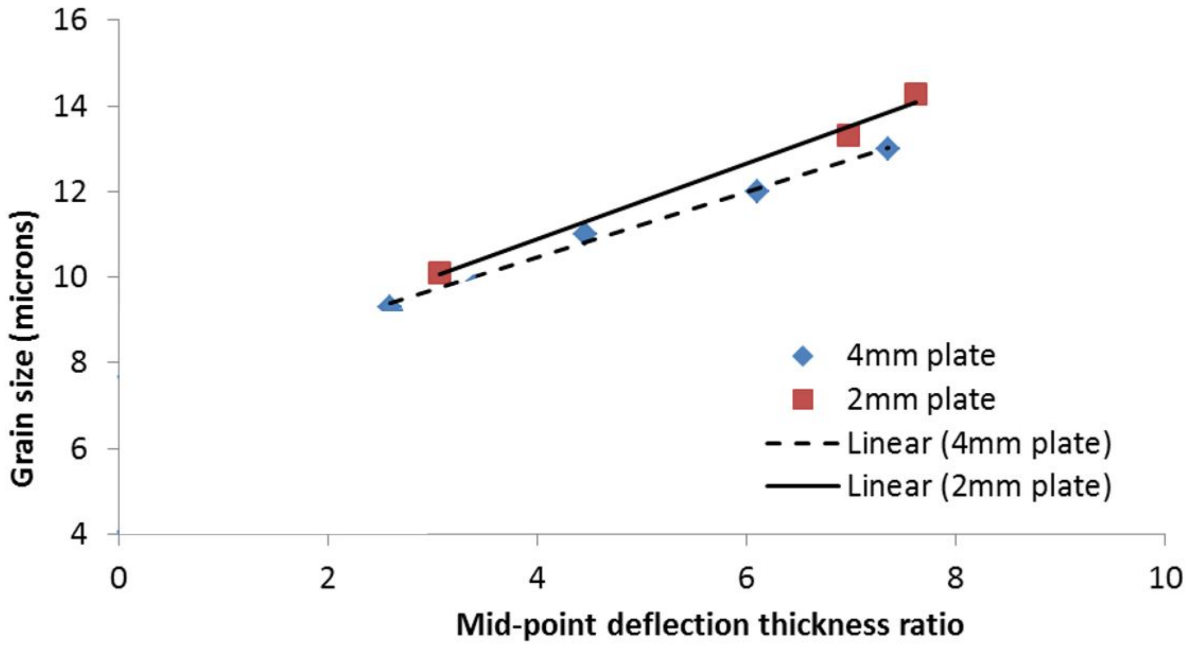


Figure 11: Graph of grain size versus mid-point deflection thickness ratio

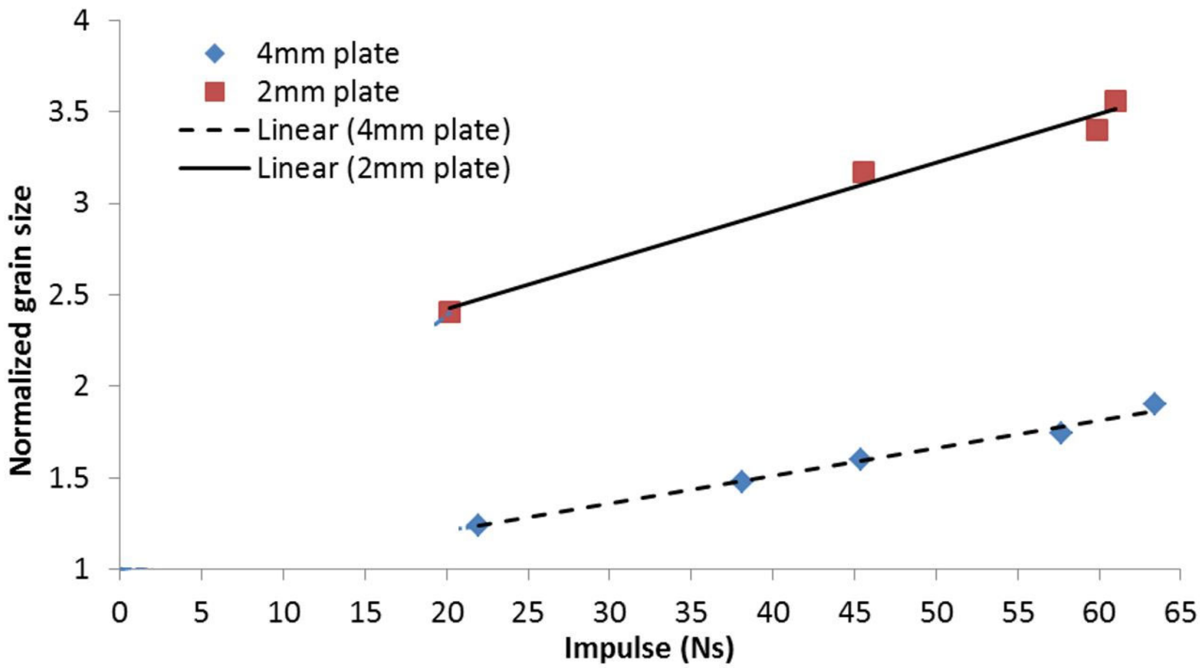


Figure 12: Graph of normalised grain size versus impulse

4 CONCLUSIONS

The experimental work reported herein has shown that similar failure modes (Mode I, Mode II*c and Mode IIc) were evident in both the single and double plate configurations. The double plates exhibited slightly larger midpoint deflections than the single plates. Partial tearing of the front double plate was observed at a lower impulse than in the single plates. Complete capping failure of both plates in the double plate configuration occurred at the same charge mass as for the single plates. It is therefore concluded, that for this particularly loading threat, both the single and double plate configurations offered equivalent protection from capping failure. A metallographic study of the deformed and torn regions of the plates did not reveal any phase transformation in the steel. This meant that adiabatic heating during tearing did not induce temperatures that approached the melting temperature of the steel. No significant differences in grain size were observed for the front and back 2 mm thick plates. It was also found that the 2 mm thick plates exhibited larger increases in grain size than the 4 mm thick plates.

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References

Almohandes, A.A., Abdel-Kader, M.S., Eleiche, A.M., (1996). Experimental investigation of the ballistic resistance of steel-fiberglass reinforced polyester laminated plates. Composites Part B: Engineering 27, 447-458.

Balden, V.H., Nurick, G.N., (2005). Numerical simulation of the post failure motion of steel plates subjected to blast loading. International Journal of Impact Engineering 32, 14-34.

Chung Kim Yuen, S., Nurick, G.N., (2000). The significance of the thickness of a plate when subjected to localised blast load. 16th International Symposium on Military Aspects of Blast and Shock, (MABS 16), 491-499.

Corran, R.S.J., Shadbolt, P.J., Ruiz, C., (1983). Impact loading of plates — An experimental investigation. International Journal of Impact Engineering 1, 3-22.

Dey, S., Børvik, T., Teng, X., Wierzbicki, T., Hopperstad, O.S., (2007). On the ballistic resistance of double-layered steel plates: An experimental and numerical investigation. International Journal of Solids and Structures 44, 6701-6723.

Jacob, N., Chung Kim Yuen, S., Nurick, G.N., Bonorchis, D., Desai, S.A., Tait, D., (2004). Scaling aspects of quadrangular plates subjected to localised blast loads - experiments and predictions. International Journal of Impact Engineering 30, 1179-1208.

Langdon, G.S., Chung Kim Yuen, S., Nurick, G.N., (2005). Experimental and numerical studies on the response of quadrangular stiffened plates -Part II- subjected to localised load. International Journal of Impact Engineering 31, 85-111.

Marom, I., Bodner, S.R., (1979). Projectile perforation of multi-layered beams. International Journal of Mechanical Sciences 21, 489-504.

Menkes, S.B., Opat, H.J., (1973). Tearing and shear failures in explosively loaded clamped beams. Experimental Mechanics 13, 480-486.

Nurick, G.N., Radford, A.M., (1997). Deformation and tearing of clamped circular plates subjected to localised central blast loads. Recent developments in computational and applied mechanics: a volume in honour of John B. Martin, 276-301.

Nurick, G.N., Shave, G.C., (1996). The deformation and tearing of thin square plates subjected to impulsive loads-an experimental study. International Journal of Impact Engineering 18, 99-116.

Olson, M.D., Fagnan, J.R., Nurick, G.N., (1993). Deformation and rupture of blast loaded square plates - Predictions and experiments. International Journal of Impact Engineering 12, 279-291.

Radin, J., Goldsmith, W., (1988). Normal projectile penetration and perforation of layered targets. International Journal of Impact Engineering 7, 229-259.

Raftenberg, M.N., Krause, C.D., (1999). Metallographic observations of armor steel specimens from plates perforated by shaped charge jets. International Journal of Impact Engineering 23, 757-770.

Rahimzadeh, T., Arruda, E.M., Thouless, M.D., (2015). Design of armor for protection against blast and impact. Journal of the Mechanics and Physics of Solids 85, 98-111.

Society, A.W., (1982). Welding Handbook, Metals and their Weldability.

Standard, A., (2013). Standard Test Methods for Tension Testing of Metallic Materials, Desingation: E8/E8M – 13.

Swedish Steel (SSAB), S.S., (Last access Aug 2018). http://www.ssab.com.

Teeling-Smith, R.G., Nurick, G.N., (1991). The deformation and tearing of thin circular plates subjected to impulsive loads. International Journal of Impact Engineering 11, 77-91.

Teng, X., Dey, S., Borvik, T., Wierzbicki, T., (2007). Protection performance of double-layered metal shields against projectile impact. Journal of Mechanics of Materials and Structures 2.

Teng, X., Wierzbicki, T., Huang, M., (2008). Ballistic resistance of double-layered armor plates. International Journal of Impact Engineering 35, 870-884.

Wiehahn, M.A., Nurick, G.N., Bowles, H.C., (2000). Some insights into the mechanism of the deformation and tearing of thin plates at high strain rates incorporating temperature dependent material properties. Structures Under Shock and Impact VI (SUSI VI), 207-220.

Woodward, R.L., Cimpoeru, S.J., (1998). A study of the perforation of aluminium laminate targets. International Journal of Impact Engineering 21, 117-131.

Zukas, J.A., Scheffler, D.R., (2001). Impact effects in multilayered plates. International Journal of Solids and Structures 38, 3321-3328.