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Experimental investigation and simplified modeling of response of steel plates subjected to close-in blast loading from spherical liquid explosive charges

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Experimental investigation and simplified modeling of response of steel plates subjected to close-in blast loading from spherical liquid explosive charges

Abstract

Detonations of nitromethane spherical charges have been carried out to study close-in blast loading of steel plates and the effectiveness of several protective solutions. Three types of bare steel plates, namely mild steel, high-strength steel, and stainless steel were subjected to explosive blast loading. Steel plates of the same type with polyurea coating and composite covers were also subjected to localized blast loading. During an explosive field trial, the blast pressures and displacements of steel plates were measured. Additionally, loading of steel plates by the impinging detonation products was captured by high-speed video recordings. This experimental program has produced results which can be used to calibrate numerical models and to refine the simplified models for predicting blast loads and response of structural elements due to close-in detonations. The effectiveness of polyurea coating for enhancing blast protection of steel plated structures is discussed. The engineering-level model for predicting the blast impact impulse of the detonation gases from the charges in close proximity from the target is introduced and validated using the experimental results obtained during the course of the explosive trials.

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1 **EXPERIMENTAL INVESTIGATION AND SIMPLIFIED MODELING OF**
2 **RESPONSE OF STEEL PLATES SUBJECTED TO CLOSE-IN BLAST LOADING**
3 **FROM SPHERICAL LIQUID EXPLOSIVE CHARGES**

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5
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21 **Abstract**

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Keywords: Impulsive loading; Near-field blast; Protective design; Liquid explosive.

1. Introduction

Blast induced effects can be broadly classified into two distinct categories, namely “near field detonation” and “far-field detonations”. Due to the portability of small charges within a constrained container such as a back pack or a parcel and likelihood of reaching near to the targets, close-in detonations has become a major treat to the structures and personnel.

However, the response of structures subjected to near-field detonations has received less focus within the research community. The near-field region is defined here as the region within 15-20 radii (for an equivalent spherical blast source) of the face of the explosive with which the blast loading is affected by local phenomena such as the expansion of the detonation products and after burn. These phenomena are not observed in the far field blast loading regime. Therefore, the mechanism of near-field detonation and blast loading is more complex than that of far-field blast loading.

Some recent investigations done by Ngo et al. [1] and Remennikov and Uy [2] on concrete filled hollow steel tubes reported the failure mechanism and possible pressure regime development during a near field detonation event. Ngo et al. [1] has identified two

major phases of structural deformation during near field detonations of concrete filled hollow steel beams. Localized damage has dominated the initial phase of the deformation while global deformation occurred afterwards. It has also emphasized that if the structural element can sustain this initial impulse, it can survive the possible damages caused by the detonation. Remennikov and Uy [2] presented the experimental results of explosive tests conducted on hollow and concrete filled tubular columns. They also demonstrated the effectiveness of the simplified engineering-level models for predicting the response of steel tubular elements to a near-field blast impulse. It was observed that the columns failed due to localized damage caused by the detonation rather than global deformation. Besides, several other researchers have reported the possible consequences due to close-in detonation on structural elements [3-4]. Above mentioned recent studies highlight the importance of further research into the close-in detonation effects by focusing on possible damage mitigation measures.

Polyurea has been widely investigated as a suitable material in blast and impact mitigation. Raman et al. [5] conducted a study on the applicability of concrete-polyurea composite as a retrofitting material for concrete structures against blast loads. Three different charge weights (0.1, 0.5 and 5 kg) of ammonite explosives were used at different stand-off distances. Both polyurea coated and uncoated concrete panels were used in the test program. Crack propagation, out-of-plane deformation, and failure patterns of the panels were investigated and reported. Further, a numerical investigation was carried out using the LS-DYNA [5] finite element code to simulate the experimental program. The results showed

that polyurea coating positively contributed to the resistance of structural elements against blast pressure. Ackland et al. [6] reported an experimental and numerical investigation performed on steel–polyurea composite plates subjected to blast loads. However, the results reported in this work have shown a negative influence of polyurea coating on deformation of the steel plates. The bare plates performed better in terms of out-of-plane deformation than the polyurea–steel composite plates. When the polyurea thickness increased, the deformation also increased under the same blast load. The reason for ineffective performance of polyurea coating has been identified as the debonding of the coating from the metal layer during the blast event. This can be considered as the only experimental and numerical investigation that has reported a negative outcome of the application of polyurea. In addition, authors have effectively used polyurea coating as an effective mechanism to mitigate impact loads [7-8]. This material has shown a great potential as an impact and blast mitigating component of the protective structures. This experimental program aims to consolidate the authors' previous experiences with using polyurea coating in blast and impact applications and improve the effectiveness of polyurea coating for steel plated structures subjected to close-in blast loads.

This study investigates the behavior of steel plate structures with three different steel types under close-in blast loading conditions while focusing on potential damage mitigation techniques through additional polyurea protective coatings. It also focuses on presenting an engineering-level analytical models in predicting the damage caused by close-in blast loading. This work further validates the analytical model for predicting the close-in detonation blast

impulse, which has previously been applied and validated by the authors for the response of steel tubular columns [2]. Once validated through experimental and numerical studies, the proposed blast impulse model can be effectively used for predicting blast induced damage for a wide range of structural components.

2. Experimental Setup

2.1 Test rig

The test rig for explosive loading of steel plates is shown in Fig.1(a). The test rig was manufactured from welded steel plates with thicknesses of 16 mm and 25 mm. The overall dimensions of the rig are 1000 mm x 1000 mm x 800 mm. The steel plate specimens were placed on the top surface of the rig and clamped using the steel flange and twenty seven M24 high-strength bolts. The effective surface area of the plate exposed to the blast source is 700 mm x 700 mm as shown in Figure 1(b). The test rig was supported by three rectangular hollow sections at the bottom and placed on leveled and compacted soil foundation. The total mass of the rig was nearly 500 kg which provided sufficient inertia to the rig to prevent excessive movements during close-range detonations of the explosive charges. Plates coated with polyurea on both front and rear surfaces were used in the test program. Two different coating thickness (6 mm and 12 mm) were used in order to observe the effectiveness of the coating thickness. Figure 1(c) shows as test setup used with a polyurea coating on the front surface.

114 Figure 1(d) depicts expanding detonation products and initial stages of formation of the shock
115 wave in the blast tests presented in this paper.

(a)

(b)

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(c)

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(d)

128 Figure 1: (a) Test rig for explosive loading of steel plates; (b) plate dimensions (c) test setup

129 with the polyurea coated plate (pilot test) (d) fireball and air-blast shock wave.

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2.2 Explosive charges

The aim of the testing program was to generate blast loading on the steel plates from 1 kg NEQ TNT spherical charges with central detonation. Manufacturing of perfectly spherical charges from TNT or other solid explosives is not a trivial task. To overcome difficulties with manufacturing spherical charges, it was suggested [10] to use sensitized Nitromethane (NM) as the high explosive material considering that its TNT equivalency is 1.0 as given in [11]. The non-fragmenting plastic spherical casings with a diameter of 120 mm and thickness of 1mm were manufactured from nylon using 3-D printing technology (Figures 2(a) and (b)).

Nitromethane is considered as a liquid explosive. Nitromethane is relatively insensitive and must be initiated by a strong ignition source. The shock front produced by Nitromethane is well formed and produces blast loads with approximately 100% TNT equivalency [11]. The plastic spherical casings were manufactured with a detonator well for inserting and positioning centrally the electric detonators.

Two ways of positioning the charges to achieve the required standoff were compared in the tests. A series of tests was carried out with a spherical charge supported by a cardboard tube cut to the required length as can be seen in Figure 2(a). This arrangement presented a significant 'shock focusing effect' which will be discussed later. Another series of tests was performed by suspending the charges from steel cables using nylon strings as shown in Figure 2(b).

(a)

(b)

Figure 2: Nitromethane spherical charges: (a) supported by cardboard tube; (b) suspended with strings.

2.3 Steel plate specimens

All steel plate specimens had dimensions 1000 mm x 1000 mm and 10 mm thickness. The

thickness of the plates was chosen based on the results of pre-test numerical simulations so that to avoid rupture failure of the test plates.

The experimental program included three types of steel plates to compare their performance under near-field blast loading. Bluescope XLERPLATE Grade 350 steel was chosen as the baseline material due to its widespread availability and for comparison with the previous blast test results [3]. High-strength steel BISPLATE 80 from Bisalloy Steel Group Limited was selected due to its potential applications in protective structures. Grade 304 austenitic stainless steel was selected due to its excellent ductility and energy absorption which makes this steel a good candidate for use in security and protective structures applications. Table 1 summarizes the typical mechanical properties of the steels used in the trial. Figure 3 provides the engineering stress-strain diagrams for XLERPLATE 350 and BISPLATE 80 steels obtained by tensile testing of the standard steel specimens using the universal testing machine Instron under quasi-static loading rate. Note that a full stress-strain diagram for the stainless steel was not available at the time of preparing the paper.

Table 1: Typical mechanical properties of steel plates used in explosive trial

Steel/Grade	Tensile Strength (MPa)	Yield Strength 0.2% Proof (MPa)	Uniform Elongation (%)
Bluescope 350 XLERPLATE	480	356	30
Bisalloy BISPLATE 80	773	715	8
304 Stainless Steel	—	325	—

Figure 3: Stress-strain relationships for normal strength and high strength steel plate specimens.

2.4 Polyurea coating

Polyurea used in this study was Eraspray ESU630D[®], supplied by Era Polymers Pty Ltd., Australia. High strain rate tensile tests on the polyurea sample were conducted in order to obtain the stress–strain properties of the material at different strain rates. A comprehensive study on the high strain rate behaviour of Eraspray ESU630D[®] at high strain rates has been reported in Mohotti et al. [7]. In addition, authors have effectively used polyurea-aluminium plate system in reducing the damage caused by low and high speed projectiles [8]. The well-established Mooney–Rivlin material model has shown reasonably good representation of the stress–strain behaviour of the material under individual strain rates. Therefore, Mooney–Rivlin material model was used in the finite element model to represent the

stress-strain behaviour of polyurea. True stress-strain behaviour of the polyurea used in this test program is presented in Figure 4.

Figure 4: Stress-strain relationships for polyurea [7].

2.5 Instrumentation

Blast pressure time histories were recorded making use of a blast data recording system developed by the University of Newcastle (UoN). Netherton et al. [12] describes the system's components, which are summarised as:

- A sensor sub-system that includes piezoelectric gauges (PCB Model 113A), gauge support discs, and instrumentation support frames.
- A data collection sub-system that includes an integrated electronic piezoelectric excitation power supply unit and a 24-channel, 2 MHz data acquisition and storage unit.

The measurement of the peak dynamic deformation of the plate was achieved by means of a mechanical comb-like device that was similar to the device described by Neuberger et al. [13]. The teeth of the comb possess a gradually decreasing height as depicted in Figure 5(a). When positioned under the dynamically deflecting plate, the long teeth are permanently bent while those that are shorter than the maximum deflection remain intact. Figure 5(b) shows deformed mechanical gauges for HS-1 and SS-1 test configurations.

(a)

(b)

Figure 5: Mechanical gauge for measuring peak deformation of plates: (a) installation in the test rig; (b) samples of deformed gauges for HS-1 and SS-1.

2.6 Experimental program

The experimental program consisted of nine test configurations. Bare steel plates were used as a reference for the coated plate configurations. Three groups of steel plates MS, HS and SS were used in the test program and each specimen was designated according to its number in the steel type group (e.g. SS-1, HS-1, MS-1) as shown in Table 2. These configurations were used to compare the performance of each grade of steel subjected to the same amount of explosive energy from the charges placed at the stand-off distances of 110 mm and 150 mm.

Test configuration 5 (MS-2) was used as the reference for the configurations 6 (MS-3) and 7 (MS-4) where the polyurea coating was applied on the top surface of the mild steel plates. For the test configurations 5-9, the standoff distance was fixed as 150 mm. Several studies have been conducted to find out the effectiveness of polyurea coating when it is applied to the surface opposite to the blast source or the surface facing the blast source [5,6]. However, no clear comparative evidence has been reported in order to reach a conclusion on the effectiveness of the polyurea coating as a front or back side protective shield. Therefore, in this study polyurea coating was used as both front and back side protective shield. In configurations 6 and 7, mild steel plates were sprayed with 6 mm and 12 mm thick polyurea coating as a front side protective shield.

BISPLATE 80 plates were used in configurations 8 (HS-3) and 9 (HS-4) with 6 mm and 12 mm thick polyurea coatings. In configuration 9, BISPLATE 80 plate was sprayed with 12 mm thick polyurea coating at the back side of the plate. Those were used for the comparison

236 with the coated mild steel plates with the similar coating arrangements.

237 Table 2: Description of test configurations

Test configurations	Steel plate material	Protective polyurea coating	Charge support/suspension	Stand-off distance, mm
1 (SS-1)	SS Grade 304	-	Cardboard tube support	110 mm
2 (HS-1)	BISPLATE 80	-	Cardboard tube support	110 mm
3 (HS-2)	BISPLATE 80	-	Suspension	110 mm
4 (MS-1)	XLERPLATE 350	-	Suspension	110 mm
5 (MS-2)	XLERPLATE 350	-	Suspension	150 mm
6 (MS-3)	XLERPLATE 350	6mm (top)	Suspension	150 mm
7 (MS-4)	XLERPLATE 350	12 mm (top)	Suspension	150 mm
8 (HS-3)	BISPLATE 80	6mm (top)	Suspension	150 mm
9 (HS-4)	BISPLATE 80	12mm (bottom)	Suspension	150 mm

238

239 3. Analysis of experimental results

240 3.1 Response of bare steel plates to close-range suspended charges

241 Responses of bare steel plates used in the test configurations were assessed based on their
 242 permanent (residual) plastic deformation. Table 3 demonstrates the deformation profiles of
 243 the bare steel plates after being subjected to close-range detonation of the 1 kg NM charges
 244 suspended over the center of the plates at the standoff distances 110 mm and 150 mm. In order
 245 to determine the plate deformed profiles and the residual deformations, a 3-D scanning
 246 system was used. The 3-D scanned images of the deformed steel plates are included in Table 3.

Using the specialized software Geomagic Qualify, the scanned images of the steel plates were digitally processed and the deformation profiles and the peak residual deformations at the center of the plates were determined. The peak residual deformations are summarized in Table 3 and will be used in the subsequent sections for validating the analytical and numerical models of plate response to close-range blast impulses.

Table 3. Experimental results for bare steel plate specimens (suspended charges)

Test # Plate Material	3D scanned view of deformed plates	Deformed plate profile	Residual deformation (mm)
MS-1 XLERPLATE 350			102
MS-2 XLERPLATE 350			64.0
HS-2 BISPLATE 80			57.6

Analysis of the results in Table 3 demonstrates that the performance of high strength steel plate HS-2 was superior to the mild steel plate MS-2 in resisting the near-field blast loading from a 1 kg NM charge at the standoff distance 110 mm (scaled standoff distance $0.11 \text{ m/kg}^{1/3}$). The residual deformation was reduced by about 43% by replacing the steel with a characteristic yield stress of 350 MPa with the high strength steel with a characteristic 0.2% proof stress of 690 MPa.

Another important observation can be drawn by comparing the performance of the two mild steel plates MS-1 and MS-2 where the variable parameter was the standoff distance. It shows that even small change in the standoff distance from 110 mm to 150 mm (scaled standoff distances from $0.11 \text{ m/kg}^{1/3}$ to $0.15 \text{ m/kg}^{1/3}$) in the close-in detonations could produce significant damage mitigation by reducing the plate residual deformation by nearly 40%.

3.2 Response of steel plates with polyurea coating

The effectiveness of the polyurea coating was assessed by comparing the residual deformations of the bare steel plates MS-2 and HS-2 with the coated steel plates. The standoff distance was selected as 150 mm to ensure that no major fracture failures occurred in the steel plates after the detonation. Polyurea has a relatively low melting temperature of 270°C . After burn will result in high temperature in the steel plate which, in turn, will soften the steel plate and melting the polyurea layer as shown in Figure 6. This makes polyurea layer less effective when it applied on the front face of the plate which faces the blast source.

Figure 6: Melting of polyurea layer when applied on the front t surface facing the blast source.

Configurations MS-3 and MS-4 represent the plates with 6 mm and 12 mm polyurea coatings, respectively, applied to the surface facing the charge. The peak residual deformation produced by MS-3 plate was 55.6 mm, and the peak residual deformation of MS-4 plate was 52.6 mm. **Figure 7** provides comparison of damage for plates MS-2, MS-3 and MS-4. It can be observed that both configurations MS-3 and MS-4 with the polyurea coating on the front face of the plate delivered only modest reductions between 13 and 18 percent to the plate damage compared to the bare plate configuration MS-2.

Figure 7 shows that the most effective approach to mitigating damage of the steel plates from the near-field detonations was applying a 12 mm polyurea coating to the back side of the HS-4 steel plate that was not directly exposed to the flow of gas detonation products. In comparison with the mild steel plate MS-2, it appears that substituting the steel with higher strength steel and applying a 12 mm polyurea coating to the back side of the plate could produce a reduction of about 62% in the plate permanent deformation.

Table 4. Experimental results for bare steel plate with polyurea coating (suspended charges)

Test # Plate material	3D view of deformed shape	3D scanned profile	Residual deformation (mm) (3D scanned)
HS-3 BISPLATE 80 6 mm polyurea coating (top)			45.8

HS-4 BISPLATE 80 12 mm polyurea coating (bottom)			24.4
MS-3 XLERPLATE 350 6 mm polyurea coating (top)			55.6
MS-4 XLERPLATE 350 12 mm polyurea coating (top)			52.6

Figure 7: Effect of polyurea coating for MS and HS steel plates (MS-2: bare plate, MS-3: 6 mm polyurea coating facing explosion, MS-4: 12 mm polyurea coating facing explosion, HS-2: bare plate, HS-3: 6 mm polyurea coating facing explosion, HS-4: 12 mm polyurea coating on opposite side from explosion)

4. Focusing flow of detonation gases with weak media

As shown in Figure 2(a), the cardboard tube stands were used in several tests to position the spherical NM charges at a standoff distance of 110 mm above the steel plates. The effect of the cardboard tube stands on the steel plate response is presented in Figure 8. It is evident from Figure 8(a) that the cardboard tube stand acted as a blast focusing device that resulted in the concentrating of blast energy within the tubular stand and penetration of the high-strength steel plate HS1 by the hot detonation gases. The depth of localized penetration was about 5 mm. Figure 8(b) demonstrates the response of the stainless steel plate SS-1 due to detonation of a spherical charge supported by a cardboard tube stand. One can notice the blast focusing effect that resulted in the localized penetration of the plate. Figure 8(c) shows a close-up view of the localized damage of the plate.

The experimental results have provided the evidence that blast focusing could be achieved by manufacturing blast focusing devices from such weak media as cardboard. Furthermore, it has been confirmed that tubular cardboard stands are capable of focusing energy of explosion of a spherical charge and force the explosion products out along the axis of the tubular stand. The amplified and concentrated blast energy can be used for transforming the blast flow from spherical explosive charges for penetrating targets in military and civilian applications.

(a)

(b)

(c)

Figure 8: Effect of cardboard stands: (a) response of BISPLATE 80 steel plate HS-1; (b) response of stainless steel Grade 304 plate SS-1; (c) close-up view of plate localized damage.

The results for test configurations SS-1 and HS-1 where the spherical charges were supported by the cardboard rings are presented in Table 5. Direct comparison can be made for the steel plates HS-1 and HS-2 as in both configurations the standoff distance was 110 mm. It can be noticed that the configuration with the cardboard stand, HS-1, produced damage that is about 10% larger than for the charge centrally suspended over the plate, HS-2, at the same standoff distance, in addition to significant localized damage within the diameter of the cardboard ring support. Table 5 also presents the peak dynamic deflections of the steel plates HS-1 and SS-1 determined using the mechanical gauges described in Section 2.5.

Table 5. Experimental results for bare steel plate (cardboard charge supports)

Test # Plate material	3D view of deformed shape	Deformed plate profile	Residual deformation (mm)	Mech. gauge (mm)
HS-1 BISPLATE 80			65.7	73
SS-1 Stainless steel Grade 304			85.3	93

5. Analysis of blast pressure records

Multiple pressure-time histories were captured for 17 independent explosive shots, via four blast gauges per shot, each of which were located alongside the test-rig; see Figures 1(a) and 1(b). Gauge location #01 is the furthest to the left within Figure 1(a), with gauge #2 to the

right of #1, then #3 to the right of #2, whilst #4 is the furthest right within the image. The intent was not to observe blast pressures on the test-rig itself; rather, the recorded values are useful in terms of calibrating the modelling of blast waves in the vicinity of the actual test-rig, such that NEQ, air temperature and pressure are appropriately considered. The data is also extremely useful in terms of recording spherical free-air bursts from bare Nitromethane and confirming statistical parameters for the NEQ of the explosive compound as used.

Figure 9 shows initial stages of the fireball formation and expansion of the gas detonation products (**Figure 9(a)**) followed by the formation of the shock waves in the air (**Figure 9(b)**) which were recorded by pressure gauges #1 through 4. **Table 3** presents data from the gauges for shots #15 through 17 representing three tests involving free air detonation of 1kg spherical Nitromethane charges. The charges were suspended from a wire at a height of 2.5 m above the ground surface. This ensured that the blast wave arrived first at the blast pressure gauges measuring incident blast overpressures without being contaminated by the reflected shocks.

Figure 9: Free air detonation of spherical 1 kg NM charges: (a) initial spherical expansion of

detonation products 1.3 msec after detonation; (b) spherical shock wave in air recorded by high-speed camera 10 msec after detonation(distance to the camera about 50 m).

Figure 10 shows the experimental trace for shot #17 as example of pressure-time histories recorded by the incident pressure gauges, with relevant blast parameters – peak pressure, positive and negative phase impulse, arrival time and second shock arrival time – labelled. Some features could be identified from the pressure time history. Firstly, the peak pressure can be clearly identified since the pressure gauges did not show any adverse ringing effects. Secondly, the second shock can be seen to arrive at around 3.5 msec after detonation. This is caused by successive reflection of the shock wave off the air/explosives interface shortly after detonation. It can be noticed that a tertiary shock arrived at around 6.0 ms after detonation due to reflection of the primary shock off the ground surface, however it can be discounted since it affected only the negative phase part of the blast pressure curve.

Figure 10: Example of recorded blast pressure-time histories, explosive shot #17 for gauge #2.

The TNT equivalence of an explosive is given as the equivalent mass of TNT required to produce a blast wave of equal magnitude to that produced by a unit weight of the explosive in question. Currently, there is a lack of information in the literature on the TNT equivalence of Nitromethane. Table 3 also contains the predicted peak incident overpressures and impulses from a 1 kg TNT spherical charge calculated by the computer program CONWEP which is based on the Kingery-Bulmash model [19]. It can be seen that the experimental incident overpressures exceed with the measured incident overpressures from 1 kg Nitromethane charges by 12 to 34 percent with an average incident pressure equivalency of 1.26. TNT

equivalency for incident impulse is found to be nearly 1.0 based on the twelve free-air spherical bursts of the NM charges. An averaged value of pressure and impulse equivalency can be assumed as 1.13 for spherical Nitromethane charges in far-field blast events.

Table 6. Recorded blast data for free-air bursts of 1kg NM.

Shot #	Gauge location:	Stand-off distance, m	1 kg spherical Nitromethane charge (measured)		1 kg spherical TNT charge (Kingery-Bulmash model, free-air burst)		Ratio NM / TNT	
			Peak Incident Pressure, kPa	Peak Incident Impulse, kPa-msec	Peak Incident Pressure, kPa	Peak Incident Impulse, kPa-msec	Incident Pressure	Incident Impulse
15	#1	2.106	195.8	86.01	174.7	88.16	1.120	0.976
	#2	1.800	345.4	97.24	246.6	101.4	1.400	0.959
	#3	2.455	164.9	82.98	124.8	76.88	1.321	1.079
	#4	3.251	89.24	59.27	69.38	59.92	1.286	0.989
16	#1	2.062	241.9	94.02	181.9	89.62	1.330	1.049
	#2	1.736	354.9	94.02	267.6	104.9	1.326	0.896
	#3	2.401	162.0	84.09	130.3	78.26	1.243	1.074
	#4	3.227	89.02	63.16	70.41	60.32	1.264	1.047
17	#1	2.032	218.5	94.27	187.9	90.81	1.163	1.038
	#2	1.768	285.2	100.41	256.8	103.1	1.111	0.974
	#3	2.436	159.2	81.87	126.3	77.27	1.260	1.060
	#4	3.253	93.19	61.41	69.29	59.89	1.345	1.025
Average							1.26	1.01

6. Blast Impact Impulse Model (BIIM)

The analytical approach is based on the model of instantaneous detonation of the spherical; explosive charge located at a distance h from the flat surface of the target. The assumed mechanism of the expansion of the gas detonation products in vacuum behind the rarefaction wave propagating with velocity W is depicted in Figure 11. These assumptions are valid within the distance $r_0 \leq h \leq (10 \div 15) r_0$. Thus, for a 1-kg NM charge the analytical model of

close-in detonation is expected to be valid for standoff distances up to 600-900 mm from the target surface.

Figure 11. Model of expansion of detonation products for close-in detonation of spherical high-explosive charge at standoff distance h from the target surface.

The blast impact impulse of the elementary mass of the detonation products with the flow tube with an area dS and inclined to the target at an angle of α can be written as follows:

$$dI = (1 + k_r) u_0 dm \cdot \cos \alpha \quad (1)$$

where k_r is the coefficient of restitution for the particles of the gas detonation products striking the target. It is known that $k_r = 1$ for perfectly elastic collision, and $k_r = 0$ for perfectly inelastic collision.

The specific blast impulse acting on the target due to the flow through a stream tube with the

413 cross-sectional area dS can be determined using Eq.(1) as

$$414 \quad i = \frac{dI \cos \alpha}{dS} = (1 + k_r) u_0 \cos^2 \alpha \cdot \frac{dm}{dS}. \quad (2)$$

415 The coefficient of restitution for the gas particles can be determined by analyzing the limiting

416 case when the spherical charge is in contact with the target as this provides the known

417 pressure at the point of contact ($\alpha = 0$) equal to the mean detonation pressure $p_0 = \rho_0 u_0 W$. It

418 has been shown [20] that the coefficient of restitution can be determined as

$$419 \quad k_r = \frac{W}{u_0} \quad (3)$$

420 and, therefore Eq.(2) can be transformed to the following expression for the specific blast

421 impulse

$$422 \quad i = (W + u_0) \cdot \cos^2 \alpha \cdot \frac{dm}{dS} \quad (4)$$

423 In Figure 12, Ω is the solid angle of a cone of expanding gas detonation products approaching

424 the target at the angle of incidence α . From the definition of the solid angle, the area of a

425 spherical cap on the sphere with radius r_0 is defined as

$$426 \quad dS_0 = r_0^2 \Omega \quad (5)$$

427 Hence, the mass of the detonation products within the cone of the gas detonation products can

428 be determined from the following expression

$$429 \quad dm = \frac{1}{3} dS_0 r_0 \rho_0 = \frac{1}{3} \Omega r_0^3 \rho_0 \quad (6)$$

Figure 12. Model for calculating impulse of impinging detonation products for near-field blast loading conditions.

At a distance r from the center of the charge, the cross-sectional area of the stream tube is determined as

$$dS = r^2 \Omega \quad (7)$$

where $r = h/\cos \alpha$ and $\cos^2 \alpha = h^2/r^2$. Substituting these expressions into Eq.(4), we get the following expression to calculate the specific blast impulse transferred to the target at a distance r from the center of the charge

$$i(r) = (W + u_0) \cos^2 \alpha \cdot \frac{\Omega r_0^3 \rho_0}{3 \Omega r^2} = \frac{W + u_0}{3} r_0^3 \rho_0 \frac{h^2}{r^4} \quad (8)$$

where W is the velocity of rarefaction wave in the detonation products, u_0 is the particle velocity of the expanding detonation products flying away from the surface of the charge, ρ_0 is the initial density of the explosive material, r_0 is the radius of the spherical charge, h is the distance from the center of the charge to the target, and r is the distance from the center of the charge to a position on the target where the blast impulse is determined.

Eq.(8) can be transformed to a more convenient form for predicting the blast impulse at any location on the target plate by taking into account that the spherical charge mass $C = 4/3\pi r_0^3 \rho_0$ and $r^4 = (h^2 + x^2)^2$. Hence,

$$i(x) = \frac{(W + u_0)C}{4\pi} \cdot \frac{h^2}{(h^2 + x^2)^2} \quad (9)$$

Figure 13 depicts the distributions of blast impulses over the steel plate for two standoff distances of 110 mm and 150 mm as predicted by the analytical model of close-in detonation. From Figure 13, one can notice that the blast loads acting on the steel plates are highly localized with about 80-90 percent of the blast energy being transferred to the steel plates within a radius of 150 mm from the center. This fact will be used later for simplified engineering modelling of the steel plate response for close-in high explosive detonations.

Figure 13: Blast impulse predictions using BIIM model of close-in detonation.

458

459 In order to validate the blast loads predicted by the analytical model of close-in detonation,
460 the analytical blast impulses will be applied to the MS, HS, and SS steel plates to determine
461 their dynamic response and compare with the experimental data for these plates.

462

463 **7. Simulation of response of steel plates using Blast Impact Impulse Model (BIIM)**

464 *7.1 Initial nodal velocities to simulate blast impact*

465 The three types of steel plates were modelled using the finite element program LS-DYNA.

466 The steel plates were modelled using 4-node Belytschko-Tsai reduced integration shell

467 elements. The steel plate model size was 700 x 700 mm. The model was fully restrained on all

468 four edges. Similar to the “blast impact” approach introduced by Remennikov and Uy [2] for

469 modelling close-in explosion loading on the steel tubular columns, the blast impulses

470 calculated using the analytical model for the plate nodes were converted to the initial velocity

471 boundary conditions applied to the nodes of the steel plate. The initial nodal velocities were

472 estimated using the specific blast impulse from Eq.(9) and the tributary mass areas to the

473 nodal points of the plate as

$$474 \quad v_0(x) = \frac{i(x)}{\rho_{pl} t_{pl}} \quad (10)$$

475 where ρ_{pl} is the density of material and t_{pl} is the thickness of the steel plate. The initial

476 velocities were calculated for the standoff distances 110 mm and 150 mm and their

477 distribution over the plate is shown in Figure 14. The calculated initial nodal velocities were

applied to the nodes using *INITIAL_VELOCITY_NODE command in LS-DYNA as demonstrated in Figure 15.

Figure 14: Distribution of initial nodal velocities for standoff distances 110 mm and 150 mm.

Figure 15: Vectors of initial nodal velocities for 1 kg NM charge at 150 mm standoff.

7.2 Modelling high-strain rate effects

Severe impact of impinging detonation products on the steel plate will produce a rate of deformations in the material several orders of magnitude higher than that under quasi-static loading conditions. Strain-rate hardening effects in the finite element computations were considered using two models. The Johnson-Cook model [15] was previously used by Ackland et al. [6] for modelling response of the similar mild steel plates XLERPLATE 350 under close-in detonation. Various attempts to use the Johnson-Cook parameters from [6] with the proposed BIIM model were unsuccessful in generating reasonable predictions of the steel plate response. Instead, strain-rate hardening was incorporated using the Cowper-Symonds strain hardening model [16], which scales the yield stress as shown

$$\sigma_{yd} = \sigma_y \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{p}} \right] \quad (11)$$

where σ_y is the yield stress at constant rate, σ_{yd} is the dynamic yield stress, $\dot{\epsilon}$ is the effective strain rate, and C and p are strain rate coefficients to be determined based on test data. Table 7 presents coefficients for the Cowper-Symonds model. According to Paik and Thayamballi [14], the Cowper-Symonds coefficients for Mild steel in Table 7 were determined experimentally using the steels with yield stresses between 189.6 MPa and 283.0 MPa, and for High tensile steel the yield stresses were between 313.8 MPa and 522.9 MPa. Hence, in this numerical study the Cowper-Symonds coefficients $C = 3200$ 1/sec and $p = 5$ were adopted for modelling high-strain rate effects for MS and HS steel plates.

Table 7. Sample coefficients for the Cowper-Symonds equation [14].

Material	C (1/s)	p	Reference
Mild steel	40.4	5	Cowper & Symonds [16]
High tensile steel	3200	5	Paik et al.[17]
Stainless steel 304	100	10	Forrestal & Sagartz [18]

Figure 16 presents the time histories for the mild steel plates MS-1 and MS-2 subjected to an impulsive load from a 1-kg NM spherical charge at 110 mm and 150 mm standoff calculated by LS-DYNA using the initial nodal velocities presented in Figure 15. Figure 17 compares the time history of the response of the high strength steel plate HS-2 with the experimental residual deformation. It can be noticed that the predicted residual deformations for all analyses steel plates match the experimental values very closely which can be used to validate the loading predicted by the BIIM.

Figure 16: Comparison of displacement time histories predicted by the BIIM loading model

with experimental residual deformations of MS-1 and MS-2 plates.

Figure 17: Comparison of displacement time histories predicted by the BIIM loading model with experimental residual deformation of HS-2 plate.

7. Summary and conclusions

An explosive field trial was conducted to investigate the response of steel plates due to close-in blast loading from high explosives. The aim of the testing program was to subject the steel plates to blast loading from 1 kg NEQ TNT spherical charges. This was achieved by employing sensitized nitromethane as the liquid high explosive and manufacturing plastic spherical charge casings using 3-D printing technology.

The responses of three types of steel plates, namely mild steel Grade 350, high strength steel, and stainless steel Grade 304 were determined to the near-field blast loading conditions.

The performance of the plates was assessed based on the final deformation profiles that were

determined using 3-D scanning of the deformed steel plates. The mild steel plates resulted in the highest residual plate deformations. High-strength steel BISPLATE 80 plates demonstrated 60% reduction in the peak deformation compared to the mild steel plates. Stainless steel Grade 304 plates achieved 26% reduction in the peak deformations compared to the mild steel plates.

Experimental investigation was conducted to evaluate the effect of spray-on polyurea coating applied to the front and back surfaces of the plates subjected to the near-field blast loading. Steel plates were sprayed with two thicknesses of polyurea coating of 6 mm and 12 mm. It was evidenced that there was no considerable mitigation effect on the peak deformations of the steel plates with the 6 mm polyurea coating applied on the front face compared to the bare steel plates. It was also observed that polyurea layer melted near the center of the plate due to the excessive heat of the detonation gases which may have affected the overall effectiveness of polyurea coating in reducing deformation response of the steel plate to the close-in blast loads. The effect of 12 mm coating applied to the back surface of the steel plates was more pronounced in terms of reducing overall damage, in particular in combination with replacing the material from mild steel to high strength steel.

The Blast Impact Impulse Model (BIIM) is presented in this paper for predicting the blast impulse for close-in detonation of a spherical explosive charge. The model is based on the hypothesis of instantaneous detonation that was presented by the authors in their work on explosive breaching of concrete walls [21]. Under the condition of instantaneous detonation,

all explosive charge particles are assumed to stay stationary and hold the original volume of the explosive charge. After the instantaneous detonation, the gas detonation products begin to expand. The particles located on the outer surface of the charge begin flying away first. Following the outer surface particles, the particles located on the successive interior surfaces start progressively flying away so that the boundary between the moving particles and the stationary particles is moving inside the charge with some velocity. This paper presents the original derivation for the specific blast impulse acting on the target in the close proximity from the charge. The BIIM allows for rapid generation of the blast effects on the targets due to close-in detonations by converting the specific blast impulses into the initial velocity boundary conditions applied to the nodes of the steel plate. The predicted residual deformations for all analyzed steel plates matched the experimental values very closely which contributes to the validation studies of the engineering-level modelling of close-in blast loading effects on structures undertaken by the authors in the previous studies.

One of the objectives of the trial was to better understand the effect of different approaches to positioning spherical charges at the required close-range standoff distance. It was experimentally confirmed that the blast energy of a spherical charge can be transformed and focused by the tubular supporting elements made from such weak media as cardboard. This effect requires further investigation and may find applications in military and civilian situations where target localized penetration with small charges may be required.

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