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Alex M. Remennikov

University of Wollongong, alexrem@uow.edu.au

Edward Gan

University of Wollongong, ecjg428@uowmail.edu.au

Tuan D. Ngo

University of Melbourne

Michael Netherton

University of Newcastle

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THE DEVELOPMENT AND BALLISTIC PERFORMANCE OF PROTECTIVE STEEL-CONCRETE COMPOSITE BARRIERS AGAINST HYPERVELOCITY IMPACTS BY EXPLOSIVELY FORMED PROJECTILES

Alex Remennikov^{*1}, Edward C. J. Gan², Tuan Ngo³, and Michael D. Netherton⁴

¹Centre for Infrastructure Protection and Mining Safety, University of Wollongong, Wollongong, NSW 2522, Australia, e-mail: alexrem@uow.edu.au

²Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2522, Australia, e-mail: ecjg428@uowmail.edu.au

³Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC, 3010, Australia, e-mail: dtngo@unimelb.edu.au

⁴Centre for Infrastructure Performance and Reliability, The University of Newcastle, Callaghan, NSW 2308, Australia, e-mail: michael.netherton@newcastle.edu.au

Abstract

Explosively formed projectile (EFP) is one of the most severe explosive and impact loading threats for civil infrastructure and military vehicles. Currently, there is no effective means of protection for military vehicles and infrastructure facilities from EFPs. This paper presents the experimental results of the hypervelocity impact of EFPs on steel-concrete (SC) barrier systems of finite dimensions. The SC barrier units tested were broadly representative of the type of protective SC units used in the expedient construction of barriers for mitigating improvised explosive device (IED) and EFP threats to critical infrastructure facilities. The response of non-composite, partially-composite and fully-composite SC barrier units was studied. All studied protective systems were capable of terminating the high-velocity projectiles effectively through the combined action of the concrete core and steel faceplates. The data gathered from these tests is also intended to further the understanding of impacts on SC composite structures at speeds greater than 1000 m/s and for the calibration of numerical models of EFP formation and its interaction with steel-concrete targets. 3D numerical simulations were performed to better understand the various stages of EFP interaction with the SC composite barriers and develop recommendations for their design optimisation. No previously published results on the EFP terminal ballistic performance of SC composite structures of finite dimensions have been found in the open literature.

Keywords: Explosively formed projectiles, hypervelocity impact, steel-concrete protective structures, terminal ballistic

1 INTRODUCTION

Improvised explosive devices (IEDs) present a significant challenge to conventional armour systems and civil engineering infrastructure. One type of IED that has been particularly difficult to defeat using conventional protective measures is known as explosively formed projectiles (or EFPs). EFP warheads are commonly found in conventional anti-tank weapons. They are also regularly used by insurgent forces against armoured vehicles in conflict-affected countries. The energy of EFPs is significantly greater than that of large calibre ammunition, such that a threat is posed to the occupants of armoured vehicles both by perforation and spalling of the armour.

One such EFP device is schematically illustrated in Figure 1, wherein a high explosive is placed in a tube holder having an open end. A dish-shaped metallic liner, typically copper, is placed at the open end with its concave surface facing outward, so that the high explosive is enclosed within the tube behind the metallic liner. This improvised device is positioned so that the concave surface of the copper dish faces the target. When detonated, the explosive shock wave hits the liner at the apex first and the high pressure remains there longer than around the rim where the detonation front arrives later [1]. This turns the liner into an essentially super-plastic shape by turning it inside out and driving it forward with the apex in front until the entire disc has folded in on itself to form a slug. The final geometry of the slug (Figure 1) is determined by stretching and collapse deformation modes caused by a combination of higher velocity of the liner elements near the axis and initial curvature of the liner.

Figure 1: Formation of an explosively formed projectile (EFP)

Relatively limited research has been published in the open literature on defeating this threat [2]. Instead, the bulk of research has been focused on investigating the protection of armour against conventional shaped charges and long-rod penetrators, which are very different in their penetration mechanics to an EFP. Existing publications in the area of EFPs predominantly addressed performance and penetration of steel armoured solutions with a direct application to the protection of armoured vehicles such as armoured fighting vehicles and infantry mobility vehicles. The resistance of conventional structural components to hypervelocity impacts by EFPs has not been previously studied systematically and is not a well understood phenomenon.

Some recent work describing the flight, and destructive capabilities of EFP experimentally and numerically have been noted. For example, Wu et al. [3] numerically simulated the entire process of slug formation, flight and the penetration of a 60 mm calibre EFP on a 25 mm steel target. It was found that the projectile was able to easily penetrate the steel target before breaking into chips and bursting away. Liu et al. [4] studied ballistic performance of monolithic and composite structures including three-layered in-contact and spaced mild steel targets and found that the multi-layered targets with the thinner sub-structures in front and thicker sub-structures at back are

superior to resist the penetration of the copper EFP. Hu et al. [5] assessed the impact performance of EFP on concrete targets. Various EFP parameters (e.g. liner and explosive materials) were evaluated and it was concluded that the configuration with a copper liner and Composition B explosive resulted in maximum penetration into concrete.

Figure 2 shows the reinforced concrete walls breached by a 300 mm diameter EFP demolition device [6]. The EFP breached the first two concrete wall targets and had sufficient energy to topple a third wall (not shown). Bookout and Baird [7] conducted an extensive experimental program on unreinforced concrete targets of 600 mm thickness impacted by a 100 mm calibre EFP. Their experimental results demonstrate that an EFP is capable of destroying and penetrating substantial unreinforced and reinforced concrete targets.

Figure 2: Destructive force of EFP experienced by reinforced concrete wall targets [6]

Steel-concrete protective structural solutions are common in nuclear installations as the primary containment system for some reactor types. Bruhl et al. [8] proposed a three-step method for designing steel plate composite (SC) walls subjected to missile impact. This method can be used to compute the minimum required steel plate thickness for SC walls to prevent perforation from missile threats with initial velocities between 20 m/s and 230 m/s,

and missile weights up to around 2000 kg. For parameters outside of this range, the validated finite element analysis approach is recommended for conservative evaluation.

Hashimoto et al. [9] carried out an experimental study on the behaviour of RC panels reinforced with steel plates subjected to missile impact as part of a project on designing nuclear-related facilities for extreme loading conditions such as an accidental aircraft crash or terrorist attack. In their experiments, the missile velocities were in the range of 140 m/s to 270 m/s. One of the main findings of this study was that a concrete panel with a steel plate on its rear face had higher impact resistance than a reinforced concrete panel. When used on the front face of a concrete panel, a steel plate was less effective compared to the concrete panels with steel cladding on the rear side.

Performance of steel tubular structures and panels filled with concrete as protective structures have been studied by Remennikov et al. [10, 11]. Remennikov and Uy [10] experimentally investigated the failure modes of concrete-filled steel tubular elements due to contact and near-field detonation of TNT charges. Remennikov et al. [11] carried out an investigation into the response of axially restrained non-composite steel-concrete-steel (SCS) sandwich panels subjected to blast and impact loads, and demonstrated the high effectiveness of steel-concrete sandwich panels as protective barriers against high-speed vehicle impacts and close-range blasts. Ngo et al [12] carried out a comprehensive, non-linear three-dimensional numerical analysis the concrete-filled square tubular columns subjected to blast loading due to close range detonation of the TNT charges and highlighted the beneficial effect of concrete as an infill material in protective composite structures.

The performance of steel-concrete structural elements has been extensively studied experimentally, analytically and numerically for high-speed vehicle impacts, as well as far-field and near-field high explosive (HE) detonations and contact charge detonations.

However, the performance of concrete structures clad with steel face plates when subjected to hypervelocity impacts in excess of 1000 m/s produced by such IED threats similar to EFPs is uncertain. This study investigates the possibility of utilising concrete units clad with steel face plates for infrastructure protection against EFPs. The presented experimental program includes EFP testing of steel-concrete protective systems with different construction types to evaluate their effectiveness in mitigating IED-EFP threats to built infrastructure. The experimental results are subsequently used for calibrating numerical models of EFP penetration into the steel-concrete protective barriers.

2 EXPERIMENTAL SETUP AND TEST PROGRAM

The EFP device design was based on the recommended empirical design parameters for the explosively formed projectiles [1, 6]. The EFP consisted of carbon fibre-reinforced polymer (CFRP) casing and a copper liner as shown in Figure 3. CFRP was used for the casing to provide a high level of confinement while having a lower likelihood of generating safety hazards due to fragmentation than steel casing. The CFRP casing was manually packed with the Composition B explosive (60/40 mixture of RDX and TNT, density: 1600 kg/m³, detonation velocity: 8,050 m/s) and closed from one end with the plastic end cap. At the other end of the CFRP tube, the copper liner was placed so as to ensure an intimate contact with the high explosive fill. An electric detonator was inserted through the plastic cap into the explosive fill and used for initiating the EFP device.

Figure 3: Schematic view of an EFP device

The steel-concrete targets were tested in the blast trial range facility shown in Figure 4(a). The distance between the firing position of the EFP devices and the targets was 6 meters. Previous studies of the EFP formation [1] have shown that the complete development of the EFP requires less than 400 μ s, which means that the selected distance between the firing position and the target is acceptable. A 1.5 m x 2.5 m board with black and white stripes was positioned between the firing position and the targets to assist with the measurements of the projectile velocity with a high-speed camera, which was positioned in front of the board and perpendicular to the projectile's flight path. Figure 4(b) demonstrates the installed EFP device prior to testing. The welded steel tubular adjustable mounts were used for precisely positioning and targeting the devices.

Figure 4: Experimental setup for: (a) EFP testing of targets and measurement of the velocity of high-speed projectiles; (b) EFP device installation prior to firing

The steel-concrete sandwich units had dimensions 0.5 m (W) x 0.5 m (H). The SC units consisted of front and rear steel face plates, and a concrete core. Three groups of SC units were constructed to develop a better understanding of the effects of concrete strength, strength of the steel face plates, and the connection or “composite action” between the concrete core and the steel face plates. The test matrix, unit IDs and material properties of the steel faceplates and the concrete cores are detailed in Table 1. In Table 1, BISXX refers to a high-strength steel plate of Grade XX manufactured by Bisalloy Steels in Australia [13], and NSC and HSC refer to normal- and high-strength concrete, respectively.

The first group of SC units included a baseline design BIS400-NSC-150, which consisted of an NSC concrete core with a compressive strength of 42 MPa and the high-strength steel face plates. The face plates and the core were not mechanically connected apart from the chemical bond developed between the steel and concrete during the curing process. The concrete core of BIS400-NSC-150 was not reinforced. The SC unit BIS500-NSC-REO also did not have the steel plates connected to the core but its concrete core was reinforced with steel meshes and shear links. This type of SC unit was expected to demonstrate the effectiveness of steel lining and reinforcing the concrete core. Since no connectors were used in this protective system design, we will refer to it as “non-composite” in this paper.

The second group of SC units addressed several parameters such as concrete strength, steel strength and the effect of tying the steel face plates internally and externally. This group included six test unit designs, namely BIS80-NSC, BIS80-HSC, BIS400-NSC, BIS400-HSC, BISHH-NSC and BISHH-HSC. Two concrete mix designs were used for filling the sandwich block to yield normal strength concrete and high strength concrete cores. The front and rear steel plates were connected with three internally welded ties bars

with a diameter 8 mm for holding the steel plates in place during concrete pour. Additionally, in some designs the externally welded steel straps were used to introduce some degree of composite action between the steel plates and the concrete core. As such, this group of protective units is referred to as “partially composite” in Table 1 and in the remainder of this paper.

The third group of SC units addressed the effect of fully restraining the steel face plates against outward motion caused by high-intensity stress waves propagating through the layered media (steel-concrete-steel). Units of BIS500-NSC-BOLTS were designed with four high-strength bolts of 16 mm diameter through the thickness of the block. This group is referred to as “fully composite” to reflect that this design provides a strong mechanical connection between the steel face plates and the concrete core.

Table 1: Test matrix and properties of steel and concrete components of barrier units

Unit ID	Steel face plates		Concrete core			Connection between core and plates
	Thickness [mm]	Yield strength [MPa]	Thickness [mm]	Compressive strength [MPa]	Reinforcement	
BIS400-NSC-150	9.5	1320	150	42	No	Chemical bond
BIS80-NSC	9.5	830	300	40	No	Ties and straps
BIS80-HSC	9.5	830	300	75	No	Ties and straps
BIS400-NSC	9.5	1320	300	40	No	Ties and straps
BIS400-HSC	9.5	1320	300	75	No	Ties and straps
BISHH-NSC	9.5	1640	300	40	No	Ties and straps
BISHH-HSC	9.5	1640	300	75	No	Ties and straps
BIS500-NSC-BOLTS	9.5	1400	300	42	No	HS through bolts
BIS500-NSC-REO	9.5	1400	300	42	10 mm bars @ 100 mm mesh both faces	Chemical bond

3 MOTION ANALYSIS OF EFP PROJECTILES

The velocity of the projectiles was estimated using motion analysis of the high-speed video

footage recorded during the EFP firings. The velocity of the projectile significantly affects the projectile's ability to penetrate a target due to the squared velocity value in the kinetic energy equation. In this experimental program, the velocity tests used a Memrecam HX-3 high-speed camera to collect video recordings of the projectile's path. The Memrecam HX-3 high-speed camera was set to 25,000 frames per second (fps). The black and white striped Zebra board was placed 3.0 meters away from the firing position and parallel to the projectile's path. The black and white stripes were 100 mm wide.

Figure 5 shows a typical snapshot where the flying EFP could be clearly identified as it was passing a white stripe of the Zebra board. By tracking the flight of the projectile over several frames recorded every 40 microseconds, the velocity of the EFP was calculated. The average projectile velocities are summarised in Table 2. These average velocities are comparable with the similar EFP design described in [7] where a velocity of 1317 m/s was determined using C-4 explosive fill.

Table 2: Summary of EFP parameters and calculated velocities

Group of SC blocks	Ave. explosive fill mass [g]	Ave. mass of copper disk [g]	Ave. EFP velocity [m/s]
#1 ("non-composite" blocks)	1380	460	1228
#2 ("partially composite" blocks)	850	536	1198
#3 ("fully composite" blocks)	1358	460	1215

Figure 5: High-speed video recording used for motion analysis of projectile velocity

The soft recovery system was developed to capture the projectiles in the tests without the targets. Based on previous experience with capturing similar EFP slugs, the soft recovery system utilised 12 hay bales placed behind the targets as shown in Figure 6(a), followed by the sand section. One of the recovered projectiles is shown in Figure 6(b). The recovered projectile has an air cavity that begins at the tail and progresses forward into the projectile, which is difficult to observe. The presence of the air cavity confirms that the slug did not collapse completely during the formation process as shown in Figure 1.

Figure 6: (a) soft recovery system; (b) recovered slug

4 PERFORMANCE OF STEEL-CONCRETE (SC) PROTECTIVE SYSTEMS

4.1 Performance of SC Unit with Unreinforced Core and Unrestrained Face Plates

The resistance of SC units with unrestrained faceplates to hypervelocity impacts by the EFPs was investigated first. As mentioned previously, the face plates were connected to the concrete core only through the chemical bond developed during the curing process. The target unit BIS400-NSC-150 is shown in Figure 7(a).

Figure 7: Target unit BIS400-NSC-150: (a) view before impact; (b) initial contact between the copper projectile and front steel plate; (c) initial horizontal crack in the concrete; (d) separation of the front and rear steel plates

The target unit was subjected to a hypervelocity impact by a projectile flying with a velocity of 1200 m/s. The high-speed impact of a copper projectile into a front steel plate results in localised melting of both metals and increased luminosity as depicted in Figure 7(b). Figure 7(c) demonstrates an initial response of the target unit where the steel faceplates start moving away from the concrete core and the concrete core develops a large crack in the central horizontal plane.

The outward motion and separation of the steel face plates can be explained by complex interactions between the compressive and release stress waves at the interfaces between the concrete core and the steel plates. As Figure 7(d) depicts, failure of the BIS400-NSC-150 unit resulted in fragmentation of the concrete core into large projectiles flying with a high velocity, which are capable of inflicting secondary damage in the protected targets.

Despite severe damage of the SC protective unit with unrestrained steel face plates, the EFP did not penetrate into the rear steel plate thereby indicating that it was fully arrested by the 150 mm thick concrete core. Based on the experimental observations, the SC blocks with the mechanically unrestrained liners can be used as protective barriers against EFPs but their failure response might produce large steel and concrete projectiles, as well as associated secondary fragmentation hazards to the protected targets.

The subsequent sections in this paper will present the options for improving the overall performance of the SC protective units as protective barriers against explosively formed projectiles.

4.1 Performance of SC Unit with Unreinforced Core and Partially Restrained Face Plates

High-speed cameras were used to record the ballistic response of the steel-concrete protective systems. Images obtained from high-speed video recordings were helpful in diagnosing the damage sequence of the target elements as well as any experimental

anomalies. Several frames from the high-speed recordings, marked by an approximate time after impact, are shown in Figure 8. Figure 8(a) shows an EFP just prior to impacting on the front steel plate. The increased luminosity at 0.60 ms (Figure 8(b)) is due to impact of the projectile on the steel plate and melting of the metals in the impact zone.

By the approximate time of 1.0 ms after impact, the concrete core experienced severe shear cracking originating from the front surface of the concrete core at the point of impact and propagating through the entire thickness of the concrete core. Figure 8(c) also shows that the front steel plate receives the impulse in the direction opposite to the direction of impact, which results in fracture at the connections between the steel welded straps that were holding the steel plates and the concrete core together, and the front steel plate. After the tensile fracture of the steel welded straps, the front steel plate starts moving away from the concrete core that also continues to shatter into multiple fragments of concrete as shown in Figure 8(d).

Figure 8: High-speed video frames showing the interaction between an EFP slug and the target at various stages: (a) EFP slug (red circle) prior to impact (time = 0 ms); (b) Impact on the front steel plate (time = 0.60 ms); (c) initial cracking of the concrete core (time = 1.0 ms); (d) target disintegration by EFP slug (time = 5.0 ms)

The typical global failure mode of the steel-concrete protective units of finite dimensions is demonstrated in Figure 8. All six “partially composite” protective units responded to the hypervelocity impact by the EFP in a similar fashion regardless of the steel plate grade and the concrete core strength. For all targets, the projectile impacted the block within 50 mm of the central point. The impact of the projectile resulted in the perforation of the front steel plate and the complete destruction of the concrete core for both normal strength and high strength concrete specimens. The concrete that formed the core of the protective unit scattered around the test site as shown in Figure 9.

One of the important findings of these tests was that the rear steel plate did not receive any damage for all six targets. This finding indicates that the front steel plate and the concrete core effectively absorbed the kinetic energy of the EFP, thereby protecting the rear steel plate from any damage. This finding has important consequences for the development of an effective protective system from EFPs based on sandwich construction, such as steel plates with a concrete core.

Figure 9: Typical failure mode of SC “partially-composite” sandwich blocks after high-speed impact by EFP

The front and rear steel plates of the steel-concrete sandwich targets performed differently in these tests. The steel plates that faced the EFP were perforated by the projectiles forming slightly elongated holes with a maximum dimension of approximately 60-65 mm. The hole dimensions were similar for all three grades of high-strength steel plates used for the targets. A typical front steel plate after impact is shown in Figure 10(a).

Table 3 summarises the projectile penetration dimensions for the three types of high-strength steel used for the front plates and two concrete grades. It can be observed that the penetration dimensions are very similar for all three types of steel and not affected by the concrete strength.

(a) (b)

Figure 10: Steel face plates of the sandwich targets after impact by EFP: (a) perforation of the front steel plate; (b) intact rear face steel plate

Rear steel plates did not receive any damage after the EFP impact on the sandwich target. The rear steel plate separated from the front plate due to fracture of the steel straps and rod connectors welded between the two plates as shown in Figure 10(b). In all these tests, the rear plates were not displaced from the testing location, which indicates that no direct loading was transferred onto these plates by the impacting projectile. Based on these experimental observations, it can be concluded that the tested designs of steel-concrete sandwich blocks may be proposed as effective protective structures for mitigating the highly destructive effects of EFPs on infrastructure and critical structural components.

Table 3: Comparative performance of front steel plates of different steel grades

Plate perforation dimensions	Front steel plates 9.5 mm / Concrete strength		
	BIS400-NSC	BIS80-NSC	BISHH-HSC

Minimum	60 mm	55 mm	55 mm
Maximum	70 mm	65 mm	67 mm

4.2 Performance of SC Unit with Unreinforced Core and Fully Restrained Face

Plates

To investigate the effect of fully restrained steel faceplates, the SC protective system was developed with four high-strength bolts of 16 mm diameter as shown in Figure 11(a). The concrete core had a thickness of 300 mm and a compressive strength of 42 MPa. The high-

strength bolts were designed to prevent outward motion of the steel face plates by estimating momentum of the steel plates from the measured outward velocities and their masses.

Figure 11(b) depicts a target unit BIS500-NSC-BOLTS after being struck by an EFP flying with a velocity of 1200 m/s. The failure mode for the BIS500-NSC-BOLTS unit included perforation of the front steel plate and complete disintegration of the concrete core. The rear steel plate was intact thereby indicating that the EFP was arrested by the concrete core. The high-strength bolts effectively restrained the steel face plates against outward motion with only minor plastic deformation around the bolt holes.

Figure 11: Target unit BIS500-NSC-BOLTS: (a) Before impact by EFP; (b) After impact by EFP

The performance of the target units with fully-restrained steel face plates demonstrated that these units can be effective as protective barriers for mitigating hypervelocity impacts by explosively formed projectiles.

4.3 Performance of SC Unit with Reinforced Core and Unrestrained Face Plates

Steel liners and jackets are widely used for retrofitting reinforced concrete structural elements against the effects of blast and impact. A target unit BIS500-NSC-REO (Figure 12(a)) was developed to investigate the effect of a steel mesh reinforced concrete core on the

overall performance of the SC protective system subjected to hypervelocity impacts by EFPs. The reinforced details included two welded steel meshes of 10 mm deformed bars with a spacing of 100 mm in both directions. The concrete cover was 20 mm for both steel meshes. The meshes were connected with shear links made from the same reinforcing bars to form an effective confining cage for the concrete core.

As can be observed in Figure 12(b), the EFP penetrated the front steel plate approximately 50 mm from the centre. The front steel plate separated from the concrete core. The concrete core after the EFP impact is shown in Figure 12(c). Even though the concrete core damage is quite extensive, one can notice the significantly improved overall performance of the reinforced core compared to that of the SC blocks with an unreinforced concrete core presented in Sections 4.1-4.2. It appears that lateral confinement afforded by steel meshes and steel shear links is an effective mechanism for reducing fragmentation of the concrete core following a hypervelocity impact by EFPs.

Figure 12(d) shows that the rear steel plate remained bonded to the concrete core and did not experience any damage. This observation indicates that the reinforced concrete core of 300 mm thickness effectively terminated the EFP and absorbed the shock impulse produced by the EFP hypervelocity impact. These experimental results provided an important design outcome; that the SC protective system with a reinforced concrete core is an effective means of protection from hypervelocity EFP impacts with reduced fragmentation hazards from the protective barrier.

Figure 12: Target unit BIS500-NSC-REO after impact by EFP: (a) View of the block prior to testing; (b) Perforated front plate; (c) View from the impact side after EFP impact; (d) View from the rear side after EFP impact

5 NUMERICAL SIMULATION OF THE INTERACTION OF EFP WITH STEEL-CONCRETE PROTECTIVE BARRIER UNITS

5.1 Description of Computer Models

In this study, computer simulations were performed using the ANSYS Autodyn 17.1 [14] software. Full 3D models were developed to study the ballistic performance of various configurations of barrier units (see Figure 13). The impact response of spaced steel plates was first investigated to establish the maximum perforation capacity of the slug formed from a 100 mm calibre EFP device. Next, the effect of a concrete core sandwiched in between two parallel steel plates is investigated. In an effort to optimise the design of the barrier unit, several variations were numerically investigated. The variations included modelling SC units with concrete cores with varying thicknesses (e.g. 150 mm, 100 mm, and 100 mm), and the removal of the front face plate. Recommendations for future designs of barrier units to protect against EFPs are then made based on the conclusions drawn from the entire study.

Figure 13: Computational domain used for: (a) hypervelocity impact of spaced steel plates; (b) penetration of steel-concrete target sandwich block

The EFP slug was modelled based on the exact geometry of the actual slug recovered from the field test for maximum accuracy (see Figure 14). This was achieved by digitising the actual projectile using a 3D-scanner and importing into Autodyn as a 3D surface mesh. The EFP slug as well as the concrete core was defined with the Smooth Particle Hydrodynamics (SPH) meshless Lagrangian formulation [14]. In comparison, conventional Lagrangian grids

would typically suffer from severe grid distortions and tangling. However, it is to be noted that the SPH method is computationally expensive and is less efficient than conventional methods and should therefore be employed sensibly [15].

Figure 14: (a) Recovered EFP slug; (b) EFP slug discretised as SPH mesh for interacting with targets

The front face steel plate was discretised with the Arbitrary Lagrangian-Eulerian method (ALE) [14] to account for extremely high pressures and large deformations caused by hypervelocity impact. This method allows for the grid to be moved and remapped accordingly during the calculation process. This essentially minimises grid distortions and therefore reduces the occurrence of numerical instabilities normally experienced by “pure” Lagrangian grids while still allowing the overall calculation to be performed efficiently [15].

Interaction between all ALE and SPH parts was defined using the external gap contact algorithm [14]. A summary of the discretisation methods used to define the various parts in the computer models is given in Table 4.

Table 4: Summary of discretisation methods used in the numerical models

Part	Spaced steel plates	Steel-concrete target sandwich blocks		
		50 mm concrete core	100 mm concrete core	150 mm concrete core
EFP	5639 SPH nodes	5639 SPH nodes		
Concrete core	N/A	100k SPH nodes	200k SPH nodes	300k SPH nodes
Steel plates	150k hex ALE elements	100k hex ALE elements		

5.2 Material Constitutive Modelling

In the numerical models, the strength behaviours of the EFP slug and steel plates are represented by the Johnson-Cook material model (refer to equation (2)) which describes the strength behaviour of metals experiencing large strains, high strain rates, and high temperatures which is suited for the high velocity impact of the present problem [14].

$$\sigma_y = (A + B\varepsilon_p^n)(1 + C\ln\dot{\varepsilon}^*)(1 - T_H^m) \quad (2)$$

where σ_y is the yield stress while A , B , C , n , and m are the material constants. ε_p and $\dot{\varepsilon}^*$ are the effective plastic and normalised effective plastic strain rate, respectively. $T_H = (T - T_{room}) / (T_{melt} - T_{room})$ represents the homologous temperature where T_{room} and T_{melt} are the room and melting temperatures, respectively.

The P-alpha equation of state model developed by Herrmann [16] was utilised to represent the compaction behaviour of the concrete blocks, accounting for the relationship of material compaction over a wide stress range while simultaneously giving reasonable definition of compaction process for levels of low stress [14]. This is defined in equation (5):

$$\alpha = 1 + (\alpha_i - 1) \left[\frac{p_s - p}{p_s - p_e} \right]^n \quad (5)$$

where α is the material porosity, p_e is initial compaction pressure at porous compaction, α_i is porous compaction while p_s is solid compaction pressure, at full compaction (i.e. $\alpha = 1.0$), and n is the compaction exponent.

RHT (Riedel-Hiermaier-Thoma) concrete strength model is used to describe the dynamic loading of the concrete blocks [14]. This strength model combines the plasticity

and shear damage model in which the material deviatoric stress is limited by a generalised failure surface of the form of equation (6).

$$f(P, \sigma_{eq}, \theta, \dot{\epsilon}) = \sigma_{eq} - Y_{TXC(P)} * F_{CAP(P)} * R_3(\theta) * (F)_{RATE(\dot{\epsilon})} \quad (6)$$

where Y_{TXC} accounts for the fracture surface, F_{CAP} accounts for reduction in deviatoric strength under porous compression, R_3 is the third invariant dependence term which represents the difference between compressive and tensile meridian, $(F)_{RATE}$ is the strain rate effect which is represented with increases in fracture strength with plastic strain rate. Table 5 summarises the equation of states (EOS) and material models used to define all the parts in the numerical models. While, Table 6 and Table 7 present the material parameters of the parts imported from the Autodyn material library [14].

Table 5: Summary of EOS and material models

Part	Material	Equation of state	Strength model	Failure model
EFP slug	Copper	Linear	Johnson-Cook	None
Concrete block	Normal strength concrete	P alpha	RHT concrete	RHT concrete
Steel plates	High hardness high strength steel	Linear	Johnson-Cook	None

440 **Table 6: Material parameters of EFP and steel plates**

Parameter	EFP slug	Steel plates
Material	Copper	Steel
Density [g/cm ³]	8.960	7.830
Equation of state	Linear	Linear
Bulk modulus [kPa]	1.290E8	1.590E8
Specific heat [J/kgK]	-	477.000
Strength model	Johnson-Cook	Johnson-Cook
Shear modulus [kPa]	4.600E7	8.180E7
Yield stress [kPa]	9.000E4	6.800E5
Hardening constant [kPa]	2.920E5	5.100E5
Hardening exponent	0.310	0.260
Strain rate constant	0.025	0.014
Thermal softening exponent	1.090	1.030
Melting temperature [K]	1356	1793

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442 **Table 7: Material parameters of concrete blocks**

Parameter	Equation of state	Parameter	Strength model	Parameter	Failure model
	P-alpha		RHT concrete		RHT concrete
Material	Concrete	Shear modulus [kPa]	1.670E7	Damage constant, D1	0.040
Density [g/cm ³]	2.750	Compressive strength (fc) [kPa]	3.500E4	Damage constant, D2	1.000
Porous density [g/cm ³]	2.314	Tensile strength (ft/fc)	0.100	Minimum strain to failure	0.010
Porous sound speed [m/s]	2920	Shear strength (fs/fc)	0.180	Residual shear modulus fraction	0.130
Initial compaction pressure [kPa]	2.330E4	Intact failure surface constant A	1.600		
Solid compaction pressure [kPa]	6.000E6	Intact failure surface exponent N	0.610		
Compaction exponent	3.000				
Bulk modulus [kPa]	3.527E7				

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5.3 Numerical Simulation of EFP Impact on Steel-Concrete Sandwich Targets

Using a Coupled Multi-Solver Approach

In an effort to obtain quantitative as well as qualitative understanding of the penetration performance of the EFPs for steel and concrete targets, the penetration of EFP into multiple steel plate targets and steel-concrete sandwich blocks was studied numerically using ANSYS Autodyn 17.1. Simulation results will be validated using experimental observations in Section 4 and high-speed video recordings of the experiments.

5.3.1 Ballistic Performance of Spaced Steel Plates

Impact response of spaced steel plates was investigated so as to establish the maximum perforation capacity of the explosively formed projectile formed from a 100 mm calibre EFP device. The 9.5 mm thick high-strength steel plates were spaced 150 mm apart as shown in Figure 13(a). The plates have dimensions of 500 mm x 500 mm. The EFP slug was assigned an initial velocity of 1200 m/s based on the results of motion analysis of the high-speed video recordings of the flying EFPs from the field explosive trials.

Figure 15 presents the simulation results for the interaction analysis of the EFPs and the spaced steel plates. The results indicate that the EFP flying with a velocity of 1200 m/s is likely to perforate two consecutively placed 9.5 mm thick steel plates and will be terminated by the third steel plate which will experience plastic bulging deformation but without perforation damage. As demonstrated by Figure 15(d), the penetration and perforation process occur in about 1 millisecond leading to the termination of the projectile. The results also show that the numerical model correctly captures the thermo-hydrodynamics processes where the copper projectile explosively bonds with the steel plug upon initial impact transient. This behaviour is confirmed experimentally and is discussed in the subsequent sections.

Figure 15: Interaction of the EFP with spaced steel plates: (a) perforation of first plate; (b) perforation of second plate; (c) deformation of third plate; (d) evolution of the EFP projectile velocity during the interaction with the three spaced steel plates

5.3.2 Ballistic Performance of 150 mm “Non-Composite” SC Blocks

As evidenced by the results presented in Figure 15, an explosively formed projectile flying at a velocity of 1200 m/s is likely to perforate two parallel 9.5 mm steel plates. Therefore, two steel plates with a concrete infill is investigated next so as to assess their performance when subjected to the hypervelocity impact by an EFP. The 3D model of the steel-concrete (SC) target unit with concrete infills of either 50 mm, 100 mm, and 150 mm is shown in Figure 13(b). This model includes two high-strength steel plates modelled using ALE formulation and a concrete infill and copper EFP discretised with SPH. The target unit was modelled as non-composite panel with the steel plates and the concrete infill interacting only through the

contact interfaces between them. Just like before, the impact velocity of the projectile of 1200 m/s was taken from experimental motion analysis.

Figure 16 compares the concrete core damage at 0.062 ms instant after impact between the experimentally recorded damage (Figure 16(a)) and numerically predicted damage contours (Figure 16(b)). The concrete core damage initiated at the impact location as well as through formation of cracks at the central horizontal and vertical planes of the block. At this time instant, the front and rear steel plates just started separating away from the concrete core which correlates well with the numerically predicted steel plate velocities in Figure 18(b).

Figure 16: Concrete damage at $t = 0.062$ ms after impact: (a) initial horizontal crack from high-speed video recording; (b) predicted concrete damage by AUTODYN model at 0.062 ms (blue – intact material, red – fully fractured material)

Analysis of the numerical results provided information on the mechanics of EFP penetration into a steel-concrete (SC) sandwich target. By plotting the time histories of displacements and velocities for the projectile and steel plates, it is possible to better understand the interaction between an EFP and the targets subjected to hypervelocity impacts.

Figure 17: SC target panel response (with 150 mm concrete infill): (a) penetration depth of EFP travelling into concrete core; (b) EFP penetration in the SC “non-composite” panel (concrete infill is not shown) after 1 ms

It can be observed from Figure 17(a), that it takes about 1.5 ms for the EFP to penetrate through the front face steel plate and full depth of the 150 mm concrete core. By this time, the projectile becomes moulded into a typical “mushroom” shape and is depicted in Figure 21. Analysis of the projectile and rear face plate velocities indicates that after 1.0 ms their velocities will attain approximately 35 m/s (Figure 18(a)) and 17 m/s (Figure 18(b)), respectively. The rear steel plate attains velocity due to the compressive wave induced by the impact impulse that travels through the concrete core and reflects from the steel-concrete interface. This finding explains why the rear steel plate was intact in the experiment – by the time the EFP had reached its resting position, the rear plate had already separated and flown away from the concrete core.

The graph in Figure 18(b) also confirms the observed behaviour of the front steel plate after getting struck by an EFP. After an initial impact transient which imposes very high pressure on the front steel plate in the impact zone, the front steel plate bounces back in the direction opposite to the impact. The acquired momentum is sufficiently high to fracture tension ties between front and rear steel face plates in “composite” designs of the sandwich

blocks. These qualitative observations are also supported by the high-speed video recording in Figure 16(a) and observations of the failure modes discussed in Section 4.

Figure 18: Interaction of the EFP with 150 mm SC target: (a) evolution of the EFP projectile velocity; (b) average velocities of front and rear steel plates in the non-composite SC block

Behaviour of the concrete confined between the front and rear steel plates is characterised by rapid progression of damage originating from the point of impact, firstly across the concrete thickness, and then spreading towards the block edges. Figure 19 presents the evolution of contours for concrete damage after EFP impact. At $t = 1.0$ ms, the EFP is practically terminated by the concrete. Similar to the experimental observations, the concrete core of the SC block is fully damaged and the projectile retains its “mushroom” shape in the process of concrete penetration.

Figure 19: EFP penetration into 150 mm concrete core and evolution of concrete damage ($t = 0.2$ ms, 0.5 ms, 1.0 ms) (0 – intact material, 1 – fully fractured material)

Numerical simulations also allow for a better understanding of the localised concrete behaviour in the vicinity of the EFP which is otherwise not possible with experimental measurement techniques. A material compression variable *COMPRESS* in Autodyn provides information on the changes in material density resulting from localised compressive pressures exerted by the EFP slug. The material compression variable *COMPRESS* is calculated as the natural logarithm function of the ratio of the current material density to the original density $\ln(\rho/\rho_0)$. Thus, *COMPRESS* = 0 represents the original material density and *COMPRESS* = -0.5 represents the reduction (i.e. softening) of about 40% from its original value. Figure 20 illustrates the progression of changes in the concrete density as the projectile penetrates into the concrete core. It can be observed that as the EFP travels through the concrete core, it leaves behind a cylindrical volume of crushed and pulverised concrete with a density of about 60-75% of the original concrete density. On the other hand, the concrete in front of the projectile is densified by 5-10% of the original density and continues providing its contribution towards terminating the EFP.

Figure 20: EFP penetration into 150 mm concrete core and changes in concrete material compression variable $COMPRESS = \ln(\rho/\rho_0)$ ($t = 0.2$ ms, 0.5 ms, 1.0 ms)

Figure 21 validates the final shape of the explosively formed projectile after penetrating through the steel-concrete target. The SPH model of the EFP slug (Figure 21(a)) simulated the final deformed shape quite realistically – capturing all important features and overall dimensions of the EFP slug recovered after the tests (Figure 21(b)). The model reproduced the typical “mushroom” form of the projectile, the final mass, and the steel fragment bonded to the copper projectile during the initial stage of hypervelocity impact on the front steel face plate.

Figure 21: (a) Final shape of SPH model of the EFP after penetration into concrete; (b) recovered copper slug with steel plug bonded to the copper slug. Mass of the recovered slug is 425 g

5.3.3 Ballistic Performance of 100 mm “Non-Composite” SC Blocks

Following the findings of the previous section where an explosively formed projectile flying at a velocity of 1200 m/s is successfully terminated by a 150 mm thick concrete core sandwiched in between two steel plates, a parametric study is performed to investigate the ballistic performance of SC blocks when the thickness of the concrete core is varied (i.e. 100 mm and 50 mm) as well as when the front face steel plate is absent.

Figure 22 illustrates the process of the EFP interaction with an SC block with a 100 mm thick concrete core. At the initial stages of the front face steel plate perforation and initial penetration into the concrete core, the ballistic performance of SC block is similar to that of the SC block with a 150 mm thick concrete core. Major differences in the ballistic performance however, can be observed after about 0.6 ms from the initial impact, when the EFP comes into contact with the rear face steel plate. For an SC block with a 100 mm concrete core, it appears that the terminal ballistic performance is controlled by the presence of the rear face steel plate. The velocity of the EFP after penetrating through the concrete core is relatively low and is not sufficient for perforating the rear face steel plate. However,

for the EFPs with higher initial impact velocities than 1200 m/s, a thicker rear face steel plate would need to be selected to avoid possible perforation damage.

Figure 22: EFP penetration into 100 mm concrete core and changes in concrete material compression variable $COMPRESS = \ln(\rho/\rho_0)$ ($t = 0.0$ ms, 0.3 ms, 0.6 ms, 0.8 ms)

As can be seen from Figure 23(a), the EFP velocity curve becomes nearly flat at $t = 0.8$ ms as both the EFP and the rear steel plate have acquired the same outward velocities. Analysis of the velocities of the front and rear steel plates shown in Figure 23(b) indicates that the plates acquired outward velocities of about 7 m/s and 27 m/s, respectively within 0.8 ms after impact.

Figure 23: Interaction of the EFP with 100 mm SC target: (a) evolution of the EFP projectile velocity; (b) average velocities of front and rear steel plates in the non-composite SC block

5.3.4 Ballistic Performance of 50 mm “Non-Composite” SC Blocks

In order to evaluate minimum required thickness for the concrete core to fully terminate an EFP impacting an SC block at a velocity of 1200 m/s, a model of an SC block with a 50 mm thick concrete core was employed. Figure 24 presents the stages of EFP penetration into the SC block with a 50 mm thick concrete core. Due to the relatively thin layer of concrete, the concrete in front of the EFP becomes crushed and its density is reduced even prior to the full penetration of the front face steel plate by the EFP. The compressive pressure exerted by the EFP on the concrete is transferred to the rear face steel plate causing its bulging. At $t = 0.37$ s, the EFP comes into contact with the rear face steel plate – by this time its velocity is relatively low and therefore not sufficient to perforate the rear face steel plate.

Figure 24: EFP penetration into 50 mm concrete core and changes in concrete material compression variable $COMPRESS = \ln(\rho/\rho_0)$ ($t = 0.0$ ms, 0.06 ms, 0.10 ms, 0.37 ms, 0.72 ms)

Figure 25(a) shows the evolution of the projectile velocity during its penetration into an SC block with a 50 mm thick concrete core. Interestingly, it can be observed that the EFP velocity becomes terminated much faster and at a higher rate compared to the SC blocks with thicker concrete cores (Figure 18 and Figure 23). The faster termination of EFP could be attributed to the faster “activation” of the rear face plate due to the thinner concrete core. Even before complete perforation of the front face steel plate by the EFP, the rear face plate has already become deformed and already started contributing to the termination of the EFP.

While the rear face steel plate experiences large plastic localised bulging without rupture for an EFP with an initial impact velocity of 1200 m/s for this SC block configuration, a faster EFP (e.g. 1800 m/s or higher) could cause the rear face steel plate to be perforated.

Analysis of the velocities of the front and rear face steel plates presented in Figure 25(b) indicates that the plates would move away from the concrete core at velocities of about 6 m/s and 34 m/s, respectively within approximately 1.0 ms after impact.

Overall, a 50 mm concrete core may be recommended as the minimum thickness for the SC protective barriers. Since the thickness of the rear steel plate becomes a controlling design

parameter to prevent perforation damage by an EFP, the designer may need to consider increasing the plate thickness for cases with EFP impact velocities exceeding 1200 m/s.

Figure 25: (a) evolution of the projectile velocity during penetration of 50 mm SC block; (b) average velocities of front and rear face steel plates in non-composite SC block

5.3.5 Ballistic Performance of 100 mm “Non-Composite” SC Block Without Front Face Plate

As evidenced by the results presented in Sections 5.3.3 and 5.3.4, the contribution of the rear face steel plate becomes critical for the overall penetration resistance of the SC barriers when the concrete core thickness is reduced. On the other hand, as observed from the multiple experiments, the front face steel plate always becomes perforated by the EFP regardless of its ultimate strength or hardness. Therefore, an additional parameter modelling was performed where the front face steel plate was removed from design of the SC barrier units to see its effects.

Figure 26 presents the different stages of concrete damage at $t = 0.06$ ms, 0.15 ms and 0.80 ms after direct EFP impact. It can be observed that the EFP impact causes violent outburst of concrete fragments ($t = 0.8$ ms) in the direction opposite to the impact. Furthermore, the concrete resistance causes erosion of the EFP which can be clearly seen at $t = 0.15$ ms. This phenomenon was not observed in the SC barrier designs with the front face steel plate. The EFP erosion can be explained by observing the progression of concrete damage for the SC blocks with and without front face steel plate (e.g. Figure 19 and Figure 26).

In Figure 19, one can notice that the concrete becomes fully fractured when an EFP is penetrating through the front face steel plate. In this case, the EFP would travel through concrete core that has already experienced strain-softening behaviour and would therefore have less shear strength to contribute to the resistance of the EFP. Contrary to this behaviour, when the front face is absent from the design (see Figure 26), the EFP would travel through concrete which is only minimally damaged from the initial impact ($t = 0.06$ ms) and would therefore possess more resistance against the EFP. Significant EFP material erosion can be observed to have occurred by the time the EFP penetrates through the entire thickness of the concrete core ($t = 0.15$ ms).

Figure 26: EFP penetration into 100 mm concrete core (no front steel plate) and evolution of concrete damage (0.06 ms, 0.15 ms, 0.80 ms)

The contours for the Autodyn material compression variable, *COMPRESS* also confirms the above observed phenomena. As depicted in Figure 27, from the initial stages of EFP penetration into the concrete core, a cloud of loose concrete fragments is formed that fly outward with high velocity. At $t = 0.08$ ms, the EFP is broken up into multiple copper fragments, and concrete behind the EFP forms into a cloud of flying fragments which are partially contained by the rear face steel plate.

Figure 27: EFP penetration into 100 mm concrete core (no front steel plate) and changes in concrete material compression $COMPRESS = \ln(\rho/\rho_0)$ (0.06 ms, 0.15 ms, 0.80 ms)

Despite initially having a slower rate of deceleration of the EFP velocity as compared to other SC barrier configurations with a front face plate (see Figure 30), analysis of the projectile velocity time history as presented in Figure 28(a) shows that the EFP is still effectively terminated by the SC barrier unit at about 0.8 ms after impact.

The graph in Figure 28(b) shows that the rear face steel plate would move away from the concrete core at an average velocity of 38 m/s (at $t = 0.8$ ms) after being hit by the EFP.

Figure 28: (a) evolution of the projectile velocity during penetration of 100 mm concrete panel (without front steel plate); (b) average velocities of rear steel plate in non-composite SC blocks

5.3.6 Optimisation of SC barrier configuration

Based on the results of experimental and numerical studies presented above, a number of observations can be made to help for optimizing designs of the SC protective barriers. Comparison of the EFP deceleration curves in Figure 29 for several designs of steel-concrete-steel protective units and a protective system based on spaced steel plates demonstrates the advantages of utilising the concrete infill between the steel plates for terminating hypervelocity impacts by EFPs. Depending on the thickness of the concrete core and the EFP impact velocity, the following mechanisms and phases of EFP deceleration have been identified:

- (1) **Phase 1** – Deceleration by the front face steel plate. A 9.5 mm thick steel plate provides deceleration to about 70% of the initial impact velocity of the EFP. It takes about 0.1 ms for the EFP to fully perforate the ruptured steel plate and exit into an air with a velocity of about 800 m/s as shown in Figure 29 (Curve 1).
- (2) **Phase 2** – Deceleration by the front face steel plate – concrete interface. When the steel plate is backed by the concrete core, the rate of deceleration remains nearly

constant as the EFP starts penetrating into the concrete core.

(3) **Phase 3** – Deceleration by the concrete core. The onset and rate of concrete core penetration by the EFP is determined by the concrete core thickness. When the concrete thickness is comparable in size with the EFP major dimensions, the EFP is effectively constrained between the steel plates which results in an earlier onset of Phase 3 and higher deceleration rate (Curve 2 in Figure 29). When the concrete core is sufficiently thick to fully terminate the EFP (Curve 4 in Figure 29), the deceleration continues with an average rate of 330,000 m/s/s until the full stop of the EFP.

(4) **Phase 4** – Deceleration by the rear face steel plate. The EFP – rear face steel plate interaction plays an important role for the SC protective units designed with the concrete core thickness that is not sufficient for full termination of the EFP within the concrete core. In this case, the EFP comes into contact with the rear face steel plate and the EFP and the rear steel plate start moving together. By this stage, the EFP velocity is not sufficient for perforating a 9.5 mm steel plate but it could cause large localised bulging deformations in the steel plate.

Figure 29: Comparison of EFP deceleration for SC block designs with 50, 100, and 150 mm concrete thicknesses

The optimal design of the SC barrier units should consider uncertainties associated with the EFP calibres and their velocities. In the tests presented in this paper, a 100 mm calibre EFP device was used. In real life scenarios, an EFP device could have a diameter up to 400 mm and use thinner metal liners thus producing EFPs with much higher velocities and mass that those considered in this study. Therefore, design of SC protective units should consider a number of design parameters such as an aerial density required, type of infrastructure to be protected, maximum EFP velocity, cost and availability of the materials, and ease of installation.

Table 8 summarises the ballistic performance of the SC units analysed in this study. Based on an aerial density as an objective function for optimising SC protective units, the spaced steel plate armour system appears to be the most economical due to its lowest aerial density. On the other hand, terminating larger diameter EFPs flying with higher velocities than that considered in this study may require increasing the number of steel plates to 5 or more which may not be practical and could increase the aerial density of the armour to the levels comparable to the steel-concrete protective systems.

Table 8: Summary of ballistic performance of SC protective units

SC block configurations	Aerial density [kg/m ²]	Ballistic performance	EFP velocity after barrier penetration [m/s]	Average velocity of front face plate [m/s]	Average velocity of rear face plate [m/s]
2 steel plates [*]	149.1	Perforation	210	-	-
3 steel plates [*]	223.7	EFP termination by 3 rd plate	0.0	-	-
2 plates [*] + 150mm concrete core	509.2	EFP termination by concrete	0.0	7.0	17.0
2 plates [*] + 100mm concrete core	389.2	EFP termination by concrete and rear face plate	0.0	7.0	27.0
2 plates [*] + 50mm concrete core	269.2	EFP termination by concrete and rear face plate	0.0	6.0	34.0
100mm concrete core + 1 plate [*]	314.6	EFP erosion, termination by concrete and rear face plate	0.0	No plate	38.0

^{*} Note: all steel plates in this table are 9.5mm high-strength steel plates

As evidenced by extensive experimental and numerical results presented in this paper, the optimal design for the SC protective units that delivers reliable terminal ballistic performance appears to be related to providing sufficient thickness of a concrete infill between the steel plates that could decelerate and terminate the EFP within the concrete core and prevent the

EFP from coming into contact with the rear steel plate. Generally, high-velocity outward movement of the rear face steel plate should be prevented in the design of SC protective systems to avoid injuries to personnel or damage to infrastructure protected by the SC units. The experimental results presented in Section 4 have proven the effectiveness of reinforcing the concrete core with steel meshes and using high-strength through bolts for minimising outward motion of the face plates.

Designing the SC barriers to terminate the EFP within the concrete core would also provide an additional safety margin where the rear steel plate is utilised as the last line of defence should the front face steel plate and the concrete core are fully penetrated by the EFP. Based on this design philosophy, a SC unit with a 150 mm thick concrete core appears to be the optimal design for ballistic protection from an EFP attack with a velocity of 1200 m/s.

Additional mass minimization could be achieved by utilising the SC units that do not include a front face steel plate. This design would rely only on the concrete resistance to decelerate the EFP and the rear face steel plate as a liner to prevent full penetration of the SC barrier. The deceleration curves for the 100 mm SC blocks with and without front steel plates are compared in Figure 30. It can be inferred from the graph that without the front face steel plate the EFP is decelerated by the concrete core less effectively and comes into contact with the rear face steel plate earlier than that for the other designs. Significant disadvantage of this SC protective unit design is highly hazardous concrete fragments produced by the shattered concrete core that fly outward with very high velocity. This failure mode of the SC units without the front steel plate makes this design generally not satisfactory for protecting personnel and infrastructure from the EFPs.

The concrete core sandwiched in between two steel face plates provides the most significant contribution to the aerial density of the SC protective units. Mass of the concrete

core could be substantially reduced by using lightweight concrete with density 1450 kg/m^3 as described by Soheli and Liew [17] in application to the SC sandwich slabs subjected to impact load. Effectiveness of adding steel fibres into the concrete core to reduce brittleness of concrete due to high-speed impact loads is an additional direction for future research into optimisation of the SC barrier units.

Figure 30: Comparison of EFP deceleration for 100 mm thick SC block designs with and without front face steel plate

6 CONCLUSIONS

Use of steel-concrete systems is common for protective structural systems requiring a high level of protection from various forms of IEDs. No work has been done up until now to understand the response of steel-concrete sandwich systems to hypervelocity impacts

by EFPs. EFP is one of the latest and most destructive warheads and IEDs for which no adequate protection has been developed so far. Relatively little research has been published on defeating this threat.

Nine steel-concrete target units of finite sizes with different grades of high-strength steel plates, concrete core strength and degree of composite action were subjected to hypervelocity impacts to evaluate their capabilities in terminating EFPs. The experimental results confirmed the high destructive capacity of EFPs and their ability to demolish steel-concrete elements of substantial sizes. The following specific conclusions can be drawn based on the hypervelocity impact tests of the SC protective systems:

1. The steel face plates in the SC protective units acquire sufficient momentum to fly away from the concrete core and become secondary projectiles after being struck by the EFP.
2. Steel face plates with a yield strength varying from 600 MPa to 1600 MPa and variable hardness were used in the tests. The steels with higher strength and/or hardness did not show an appreciable difference in the dimensions of the entry hole or the overall terminal ballistic performance of the SC systems to the EFP impacts.
3. SC protective units were designed with nominally normal strength concrete (NSC) and high-strength concrete (HSC) cores. There was no appreciable difference in the penetration performance of the sandwich units with NSC and HSC unreinforced cores subjected to hypervelocity EFP impacts.
4. To maintain the integrity of the SC sandwich units, the use of high-strength steel through bolts was found to be a most effective means to resist the outward accelerated motion of the steel face plates.

5. It has been verified experimentally that reinforcing the concrete core with steel meshes connected with shear links is an effective means for maintaining sufficient integrity of the concrete core.
6. EFP simulations using hydrocodes and experimentally validated numerical models provided important insights into the interaction of steel plates and a concrete core with the EFP, which is important for understanding the penetration mechanics of steel-concrete structures by EFPs.
7. Numerical simulations have demonstrated an important contribution of the rear face plate for catching EFPs after their penetration through the concrete core for relatively thin SC unit designs. Minimum threshold for terminating the EFPs by the concrete core appears to be around 150 mm thick concrete core for a 1200 m/s EFP impact. For higher impact velocities (up to 2200 m/s), further experimental and numerical studies are required to establish the minimum thickness of the concrete core.

Although all steel-concrete protective systems were substantially damaged by the EFPs, the important outcome of this work is that the steel-concrete protective systems are capable of providing effective protection against an EFP threat. In all tests, the rear steel plate remained intact indicating that a combination of a steel plate and a concrete layer of an optimal thickness may provide effective protection against hypervelocity impacts by EFPs. Further studies are required to evaluate the effects of hypervelocity impacts on common steel and concrete structures, and methods of protection from this type of threat.

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