1-1-2012

Utilising non-composite steel-concrete-steel panels for protective structures

A M. Remennikov
University of Wollongong, alexrem@uow.edu.au

S Y. Kong
University of Wollongong

Brian Uy
University of Western Sydney, brianuy@uow.edu.au

Abstract

A high-performance protective structure utilising non-composite steel-concrete-steel (SCS) sandwich panels for protecting buildings and facilities against close-range detonation of VBIEDs and heavy ve-hicle impacts has been developed. Unlike other existing composite sandwich panels, no shear connec-tors between the steel faceplates are utilised to construct protective panels in order to simplify the con-struction process. The concrete core of the panel is included to provide the mass for increased inertia effects, and the steel faceplates are designed to develop tensile membrane resistance at large displace-ment to dissipate impulsive energy. The energy dissipation capability and high ductility of the axially-restrained non-composite SCS panels have been verified through a series of high energy impact tests on scaled panels using the drop hammer facility at UoW. High-fidelity finite element models for the pro-tective barriers were developed and subjected to close range detonation of high explosive using the non-linear explicit dynamics code LS-DYNA. Using the validated modelling techniques, a full-scale blast barrier structure composed of non-composite sandwich panels and steel posts was studies for its performance to provide resistance against close range bomb explosion. It was established that the non-composite SCS barrier construction could provide a highly effective means for protecting critical facili-ties and personnel against effects of an external bomb attack.

Keywords

structures, composite, utilising, steel, non, concrete, panels, protective

Publication Details

Remennikov, A. M., Kong, S. Y. & Uy, B. (2012). Utilising non-composite steel-concrete-steel panels for protective structures. 2012 Australasian Structural Engineering Conference (pp. 1-8). Australia: Engineers Australia.

Utilising non-composite steel-concrete-steel panels for protective structures

A. M. Remennikov*, S.Y. Kong* and B. Uy**

** Faculty of Engineering, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong NSW 2522, Australia (E-mail: alexrem@uow.edu.au)*
*** Institute for Infrastructure Engineering, University of Western Sydney*
Locked Bag 1797, Penrith NSW 2751 Australia (E-mail: b.uy@uws.edu.au)

ABSTRACT
A high-performance protective structure utilising non-composite steel-concrete-steel (SCS) sandwich panels for protecting buildings and facilities against close-range detonation of VBIEDs and heavy vehicle impacts has been developed. Unlike other existing composite sandwich panels, no shear connectors between the steel faceplates are utilised to construct protective panels in order to simplify the construction process. The concrete core of the panel is included to provide the mass for increased inertia effects, and the steel faceplates are designed to develop tensile membrane resistance at large displacement to dissipate impulsive energy. The energy dissipation capability and high ductility of the axially-restrained non-composite SCS panels have been verified through a series of high energy impact tests on scaled panels using the drop hammer facility at UoW. High-fidelity finite element models for the protective barriers were developed and subjected to close range detonation of high explosive using the non-linear explicit dynamics code LS-DYNA. Using the validated modelling techniques, a full-scale blast barrier structure composed of non-composite sandwich panels and steel posts was studies for its performance to provide resistance against close range bomb explosion. It was established that the non-composite SCS barrier construction could provide a highly effective means for protecting critical facilities and personnel against effects of an external bomb attack.

KEYWORDS
Protective structures; Composite structures; Blast resistance; Impact resistance.

INTRODUCTION
Composite steel-concrete-steel (SCS) or double skin composite structures consist of a concrete core connected to two steel faceplates using mechanical shear connectors. Crawford and Lan (2006) presented the design concept of non-composite SCS panels without shear connectors for resisting blast loading and provided experimental verification for the full-scale blast wall. Remennikov et al. (2010a, b) further evaluated the concept of non-composite SCS sandwich panels and established that this form of construction has high energy absorption capability, and viable economic and technological characteristics. In this concept, the mass of the concrete core provides inertial resistance, which is beneficial in resisting high-intensity impulsive loads. The imparted energy is dissipated by axial stretching of the steel faceplates and crushing of the concrete core. When the protective SCS panels are damaged, no hazardous projectiles are generated since the concrete core is confined by the steel faceplates. Additionally, the overall cost of construction is reduced by not providing shear connectors between the faceplates, thus simplifying their constructability and installation procedures.

Based on a comprehensive literature review, it was found that no studies so far have addressed a detailed analytical and experimental investigation of non-composite SCS sandwich panels with axially restrained connections. This study was initiated with the objective of providing insight into the behaviour of non-composite SCS panels under extreme loading, and to formulate recommendations for the design of axially restrained non-composite SCS sandwich panels as barrier structures for protection against high-speed vehicle impact and close-range detonation of high yield explosive devices. Preliminary results of axially restrained non-composite SCS panels subjected to impact loading reported by Remennikov et al. (2010a, b) demonstrated that the panels were capable of developing very high resistance through the tensile membrane mechanism in the steel faceplates at large deformation.

This paper presents the results of experimental investigation of the response of scaled models of axially restrained non-composite SCS panels subjected to the impact of a 600 kg free-falling drop hammer released from a height of 3 meters. The experimental data were used for calibrating the high-fidelity finite element (FE) models of SCS panels using the non-linear transient dynamic finite element program LS-DYNA. Using the validated FE models, a full-scale barrier structure composed of axially restrained non-composite SCS panels and steel posts has been numerically investigated in order to determine its performance under blast loads due to the close-range detonation of high explosives and high-speed vehicle impact.

METHODOLOGY

High energy impact tests on scaled models of SCS panels

The geometry and dimensions of a prototype full-scale non-composite SCS panel and its connection details are illustrated in Figure 1. The SCS panel design utilizes two steel faceplates, each with a thickness of 10 mm, and a concrete core with a thickness of 200 mm, such that the overall thickness of the panel is 220 mm. The length of the panel between the flared ends is 3500 mm, and the height of the panel is 3500 mm. The angle of the flared ends is 30 deg as shown in Figure 1. The panels are supported by a steel post system, with the keyed connections allowing restraining of the flared ends of the panel. The post is composed of a welded plate section with a pre-fabricated keyed connection, as shown in Figure 1(b). The bracing elements are used to limit the local plastic deformation of the post flanges due to the reaction force between the panels and the keyed connections, which can cause pull-out failure of the panel.

The dimensions of the post system were determined based on the optimum configuration of the keyed connections. To effectively restrain the in-plane movement of the panel and to prevent local bending deformation of the post flanges, an angle of inclination of 30 deg was chosen. Based on this angle of inclination, the required section depth of the post was selected as 600 mm for the 220 mm thick panel. The geometrical details of the post are illustrated in Figure 1(c). The height of the post was 3500 mm. The voids in the keyed connections were filled with 40 MPa concrete.

High-velocity impact tests were performed on six scaled models of non-composite SCS panels with different designs of the core and faceplates. The model scale was approximately 1:3. The performance of two panel designs — with a normal weight concrete core and with a lightweight concrete core — will be discussed in this paper. The Control panel (CP) design included the normal weight concrete core and mild steel faceplates. For the Lightweight core panel (LP) design, the panel was filled with lightweight concrete with a density of 1400 kg/m^3 and a concrete compressive strength of 11 MPa. The thickness of the mild steel faceplates was 3 mm, and the thickness of the concrete core was 80 mm. The length of the panel between the flared ends was 1250 mm.

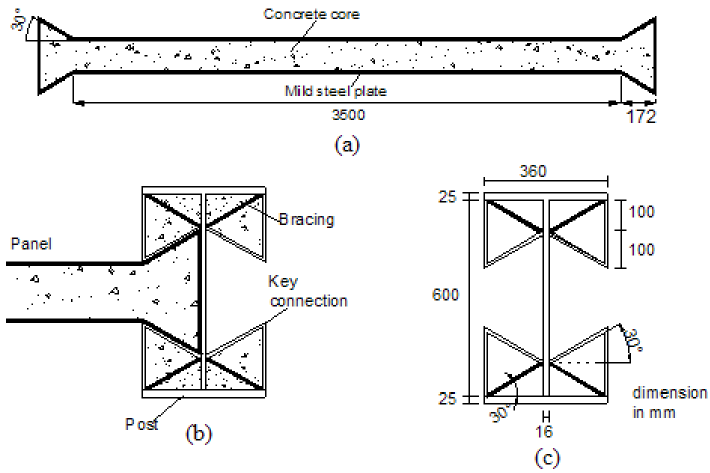

Figure 1. Geometry of the prototype barrier system components: (a) sandwich steel-concrete-steel panel with flared ends, (b) keyed connection details, and (c) dimensions of the post.

Validation of high-fidelity FE models

The explicit dynamics non-linear finite element code LS-DYNA was used to simulate the impact tests for non-composite SCS panels. In the FE models developed for this study, only a quarter of the experimental setup was considered due to the symmetry of the specimen, loading and support conditions. The axial restraints, including the keyed inserts, bolted connections, steel UC section, and steel I-beam were modelled in detail, as shown in Figure 2. A detailed description of the simulation techniques of non-composite SCS panels under drop mass impact can be found in Kong et al. (2012). From the convergence study, a mesh size of 10 mm was found to be appropriate for the concrete core and the steel faceplates. Fully integrated selectively reduced (S/R) solid element formulation was used to model the steel UC section, I-beam, and the bolts; while the concrete core of the panel was modelled using constant stress solid elements. The steel faceplates were modelled using Belytschko-Tsay shell elements.

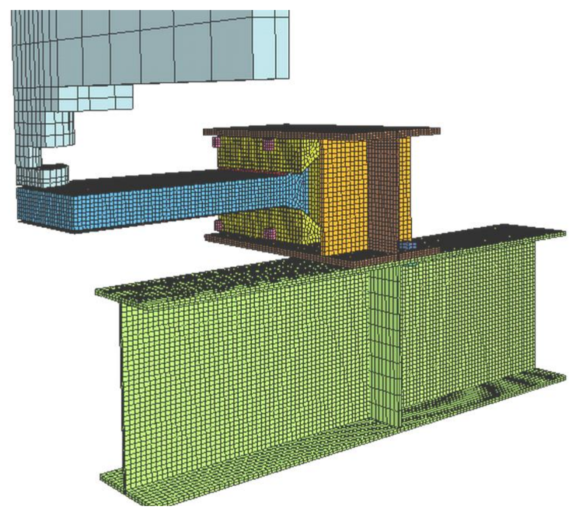

Figure 2. LS-DYNA model of experimental setup for SCS sandwich panels

The mild steel was modelled using the LS-DYNA Piecewise Linear Plasticity material model with a yield stress of 270 MPa. The non-linear behaviour after yielding was considered by defining the plastic stress-strain relationships according to the tensile coupon test results. The strain rate effects of the mild steel were considered in the model by specifying the Cowper-Symonds coefficients, which are 40.4 (D) and 5 (q). The impactor was assumed to be absolutely rigid since there was no deformation observed on the drop hammer during the tests. The steel UC section, I-beam and bolts were assumed to behave as elastic-perfectly plastic materials and were modelled using the LS-DYNA Plastic Kinematic material model (*MAT_PLASTIC_KINEMATIC). The yield stress for the UC section and I-beam was assumed to be 300 MPa, whereas a yield stress of 640 MPa was assumed for the high-strength bolts.

The Continuous Surface Cap Model 159 in LS-DYNA (*MAT_CSCM_CONCRETE) was used to model the concrete infill material. The density of the lightweight concrete was 1400 kg/m^3, and no aggregates were used in the mix. Single element simulation was carried out to evaluate the ability of the concrete model CSCM (*MAT_159) to generate parameters for the lightweight concrete. It was found that by using a density of 1400 kg/m^3 and a concrete compressive strength of 16 MPa, and by ignoring the aggregate size, the concrete model can generate a stress-strain curve with a compressive strength of 10.8 MPa and tensile strength of 0.9 MPa. It was assumed that this stress-strain relationship was appropriate for the lightweight concrete used in this study.

Numerically predicted contact forces and mid-span displacements are compared to the experimental results in Figures 3 and 4. From the comparison between the predicted and experimental load time histories, one can notice that the numerical models were able to predict the initial flexural response of the panels, followed by the tensile membrane resistance at large deformation. It shows that the numerical models have the capacity to predict the initial inertial effects and the flexural response of the panels quite closely. After that, the FE models could not predict the significant drop in the flexural resistance due to fracture of the concrete core. The FE models predicted the peak membrane resistance of 384 kN and 358 kN for the Control panel and the Lightweight Core panel, respectively. The predicted peak membrane resistance was 8 percent higher than the experimental results of both panels. The predicted maximum displacement for the Control panel was 182 mm, and 174 mm for the Lightweight panel. Therefore, the FE model underestimated the maximum displacement of the Control panel and the Lightweight Core panel by 9 and 11 percent, respectively. From the comparison of the numerical and test data for the impact load and maximum displacements, it can be concluded that the finite element model is capable of capturing the most important structural response characteristics of non-composite SCS panels.

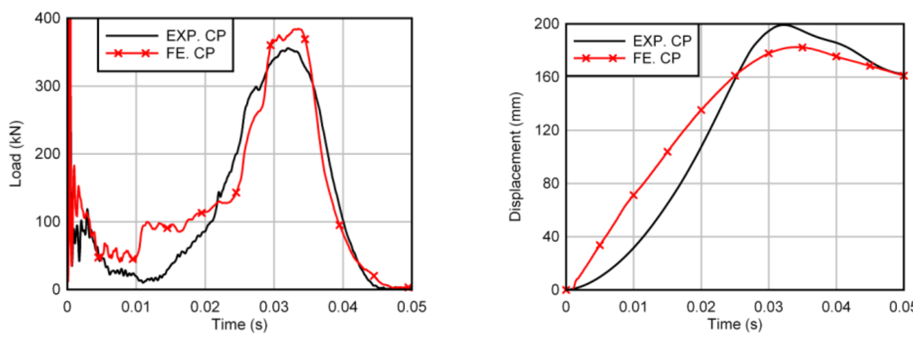

Figure 3. A comparison between the experimental and predicted results for the Control panel: (a) impact load time histories, and (b) displacement time histories.

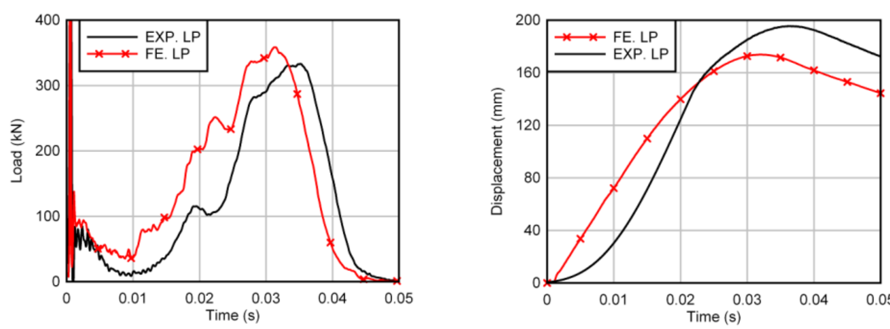

Figure 4. A comparison between the experimental and predicted results for the Lightweight core panel: (a) load time histories, and (b) displacement time histories.

Performance of the prototype protective barrier under close-range blast

Following the validation study for the FE models of the reduced-scale sandwich panels, a full-scale protective barrier based on the design features presented in Figure 1 was investigated for its performance under blast loading and vehicle impact. Two types of steel posts were investigated: 1) steel posts constructed from mild steel plates, and 2) steel posts utilizing high-strength steel plates. The static yield stress of mild steel and high-strength steel was 270 MPa and 690 MPa, respectively. The effects of the soil-post interaction were not considered in this study and it was assumed that the posts acted as cantilever beams. Figure 5 shows the FE model of the protective barrier wall system. Three panels were modelled: the centre panel positioned in front of the blast threat was modelled using a finer mesh size of approximately 25 mm, and the side panels were modelled using a mesh size of approximately 50 mm.

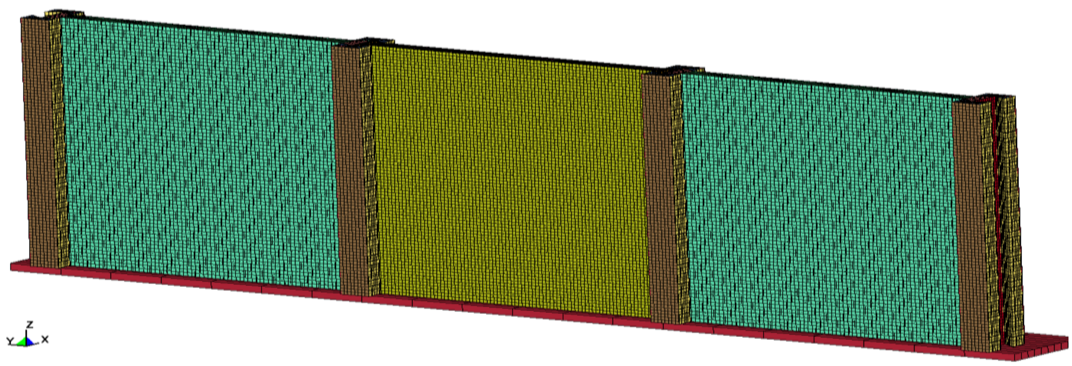

Figure 5. FE model of the modular barrier wall system.

The steel plates in the post were modelled using Belytschko-Tsay shell elements, whereas the concrete infill was modelled using constant stress solid elements. The Automatic-Surface-to-Surface contact algorithm was used to model the interaction between the panels and the keyed connections, with a dynamic coefficient of friction of 0.2. The mild steel and the high-strength steel were modelled using the Plastic Kinematic material model in LS-DYNA. Fracture strains of 0.25 and 0.15 were defined for the mild steel and high-strength steel, respectively. The concrete core material was modelled using the concrete model Damage Release III (Mat_72R3). The concrete infill in the posts and at the flared zones of the panels was modelled using the CSCM 159 material model. The concrete compressive strength was 40 MPa, and the strain rate effect of concrete was ignored. The Flanagan-Belytschko stiffness form with exact volume integration for solid elements (type 5) was used to control the hourglass energy in the concrete core.

The blast loads acting on the barrier structure were calculated by performing Computational Fluid Dynamics analysis of the blast wave interaction with the barrier structure utilizing the computer program Air3D (Rose, 2006). The reflected pressure time histories were applied to the front faceplate of the panels and the flanges of the posts, which were divided into segments ranging from 100 x 100 mm in the vicinity of the explosion to 250 x 250 mm at locations further away from the blast.

For the barrier supported by the mild steel posts, three blast loading scenarios were considered: 250 kg, 500 kg and 750 kg TNT at a stand-off distance of 5 m. The response of the barrier supported by the mild steel posts was similar when it was subjected to increased blast threat loading conditions. The response of the barrier can be exemplified by the response of the centre panel of the barrier subjected to blast loading due to the detonation of 500 kg TNT at a 5 m stand-off distance, as shown in Figure 6.

The centre panel and the supporting posts showed the most severe deformation as the charge was positioned on the ground surface, 5 m from the mid-span of the centre panel.

When subjected to the blast loading, the panels and the posts started responding almost simultaneously. At the early stage of response, the extensive damage of the concrete core near the posts can be attributed to the shear failure of the unreinforced concrete core. Moderate damage of the concrete was observed at the concrete infill in the flared zone of the panels. As panel deformation increases, the concrete is severely damaged and the front faceplate is separated from the concrete core. The rear faceplate is pushed in the direction of the blast loading by the concrete core and it starts yielding at the flared zone and the mid-span. At the maximum displacement, it was observed that no significant local bending deformation occurred at the supporting flanges, and the keyed connections were effective in restraining the in-plane displacement of the panel. The in-plane displacement of the posts was less than 10 mm.

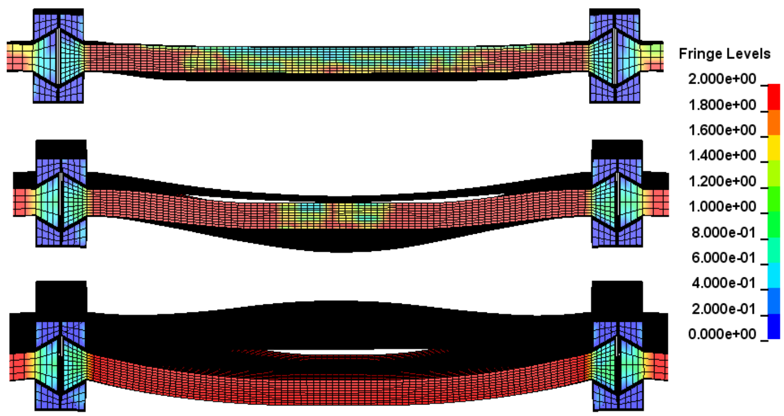

Figure 6. The response of the protective barrier with mild steel posts subjected to blast loading due to detonation of 500 kg TNT at 5 m stand-off distance.

Table 1 summarises the maximum displacements of the centre panel and of the posts supporting the centre panel. The maximum displacement of the panels and the posts increased as the blast loading increased. It shows that the maximum displacement of the centre panel was non-uniform along the height, with the maximum displacement being at the top edge. The maximum displacement at the bottom of the panel is found to be higher than that at the centre, due to positioning the charge near the ground surface. The centre panel showed the highest maximum displacement at the top due to the deflection of the cantilever posts. The rear faceplate yielded at the mid-span and the flared ends. When blast load energy is increased, plastic deformation starts concentrating at the flared ends. The maximum support rotation of the centre panel was about 20 deg when the barrier was subjected to a blast loading resulting from the detonation of 750 kg TNT at a stand-off distance of 5 m.

Table 1. Deformations of SCS panel and posts for the barrier supported by mild steel posts under increasing blast loading effects.

Blast Threat Scenario	Displacements of centre panel (mm)			Posts		Keyed connection	
	Bottom	Mid-height	Top	Displ. (mm)	Rotation (deg)	Displ. (mm)	Rotation (deg)
250 kg TNT at 5 m	243	240	269	83	1.4	2.8	0.65
500 kg TNT at 5 m	445	404	451	267	4.4	5.3	1.2
750 kg TNT at 5 m	652	577	677	490	8	9.2	2.2

For all the blast loading scenarios considered, the mild steel posts supporting the centre panel yielded and formed a plastic hinge at the base. When the barrier was subjected to a blast loading due to the detonation of 250 kg TNT at 5 m stand-off distance, the maximum support rotation for the post was 1.4 deg, and the maximum strain at the base was approximately 0.08. The maximum support rotation of the post increased to 4.4 deg and the maximum strain approached the fracture strain of mild steel when the blast threat increased to 500 kg TNT. Further increase of the blast threat to 750 kg TNT at a 5 m stand-off distance resulted in the fracture failure of the post keyed connections and the unzipping failure of the rear faceplate. The maximum angle of rotation for the keyed connection was 2.2 deg for the blast threat based on the detonation of 750 kg TNT at 5 m stand-off distance. These results show that the keyed connection design had sufficient capacity to provide axial restraint to the SCS panels. The failure of the posts is found to be the critical limiting parameter in the design of SCS barriers supported by posts utilizing mild steel plate elements.

Table 2 demonstrates the relative contributions of the SCS panels and posts to the overall blast energy absorption capability of the modular SCS barrier construction with axially restrained panels. It shows that about 50% of the initial blast energy is dissipated by the SCS panels when the posts utilize mild steel plates. The proportion of the blast energy absorbed by the SCS panels is increased to 70% when the panels are restrained by posts that utilize high-strength steel plates. The absorbed energy balance between the SCS panels and the posts remains fairly consistent for the range of blast threat scenarios shown in Table 2. These results also show that SCS panels supported by high-strength steel posts demonstrate higher effectiveness in resisting high intensity close-range blast loads, since they are capable of achieving a higher percentage of their theoretical capacity determined by the steel faceplate membrane mechanism.

Table 2. Proportion of blast energy absorbed by the SCS panels and steel posts.

Blast Threat Scenario	Proportion of blast energy absorbed by:			
	SCS panel (%)	Mild steel posts (%)	SCS panel (%)	High-strength steel posts (%)
250 kg TNT at 5 m	45.5	54.5	70.5	29.5
500 kg TNT at 5 m	29.6	70.4	78.0	22.0
750 kg TNT at 5 m	32.5	67.5	74.4	25.6
1000 kg TNT at 5 m	-	-	70.0	30.0

CONCLUSIONS

An extensive study on the dynamic response of non-composite steel-concrete-steel sandwich panels under impact and blast loading conditions has been undertaken. The experimental program was carried out to investigate the response of non-composite SCS panels under impact loading. Three-dimensional FE models of the impact tests were generated and validated against the experimental results. Based on the modelling techniques presented, the predicted peak tensile membrane resistance and peak mid-span displacements correlated well with the experimental results. Using the validated modelling techniques, a full-scale barrier structure composed of axially restrained non-composite SCS panels was subjected to blast loading and head-on impact by a single unit truck. Some conclusions based on observations made in this research can be summarised as follows:

1. High-speed impact tests on the reduced-scale axially restrained non-composite SCS panels confirmed the viability of this type of construction for achieving very high load carrying ca-

pacity through the tensile membrane mechanism in the steel faceplates. The panels demonstrated high ductility and an ability to sustain large support rotations of up to 18 degrees without collapse.
2. The infill materials have minor effect on the ultimate load carrying capacity of the axially restrained non-composite SCS panels. Utilisation of lightweight concrete or low-strength concrete as compared to the normal strength and normal weight concrete for the sandwich core would not significantly affect the performance at large deformation due to the prevailing contribution of the tensile membrane mechanism in the steel faceplates.
3. For the post and SCS panel barrier construction subjected to severe blast loading, a certain percentage of the initial kinetic energy of the panels is dissipated by the posts due to the interaction between the panels and the posts. As the blast energy is increased, the posts and the panels undergo large deformations, and the failure modes identified in this study are related to fracture of the steel plates at the bottom of the posts as well as unzipping of the rear faceplate. The use of high-strength steel for the posts is beneficial as they deform less than mild steel posts under the same blast loading condition, thereby facilitating more effective utilization of the steel plate membrane capacity.

ACKNOWLEDGEMENT
This research was supported under the Australian Research Council's Discovery Projects funding scheme (project number DP0879733) — this support is gratefully acknowledged. The authors would like to thank senior technical staff, Mr. Alan Grant and Mr. Ian Bridge for their assistance in conducting the experiments.

REFERENCES

Crawford J. E. and Lan S. (2006) Blast barrier design and testing. *ASCE Structures Congress*, St Louis, Missouri, USA.

Kong S. Y., Remennikov A. and Uy B. (2012). Numerical simulation of the response of non-composite steel-concrete-steel sandwich panels to impact loading. *Australian Journal of Structural Engineering*, **12**(3) (*in press*).

Remennikov A., Kong S. Y. and Uy B. (2010). Static and dynamic behaviour of non-composite steel-concrete-steel protective panels under large deformation. In: *Proceedings of The 4th International Conference on Steel & Composite Structures*, 23-23 July, Sydney, Australia.

Remennikov A., Kong S. Y. and Uy, B. (2010) Impact resistance of non-composite axially restrained steel-concrete-steel sandwich panels. In: *Proceedings of The 5th Civil Engineering Conference in the Asian Region and Australasian Structural Engineering Conference 2010*, 8-12 August, Sydney, Australia.

Rose T. A. (2006). *A Computational Tool for Airblast Calculations.* Air3D version 9 user's guide. Cranfield University, UK, DCMT.