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Performance of sandwich structure strengthened by pyramid cover under blast effect

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Abstract. The number of explosive attacks on civilian structures has recently increased. Protection of structure subjected to blast load remains quite sophisticated to predict. The use of the pyramid cover system (PCS) to strengthen sandwich structures against a blast terror has great interests from engineering experts in structural retrofitting. The sandwich steel structure performance under the impact of blast wave effect is highlighted. A 3-D numerical model is proposed to study the PCS layer to strengthen sandwich steel structures using finite element analysis (FEA). Hexagonal core sandwich (XCS) steel panels are used to study structural retrofitting using the PCS layer. Field blast test is conducted. The study presents a comparison between the results obtained by both the field blast test and the FEA to validate the accuracy of the 3-D finite element model. The effects are expressed in terms of displacement-time history of the sandwich steel panels and pressure-time history effect on the sandwich steel panels as the explosive wave propagates. The results obtained by the field blast test have a good agreement with those obtained by the numerical model. The PCS layer improves the sandwich steel panel performance under impact of detonating different TNT explosive charges.

Keywords: displacement; finite element analysis; field blast test; sandwich steel structure; TNT explosive charge

1. Introduction

Technologies provide blast protection for civilian structures (Aimone 1982, Liu and Katsabanis 1997, Fayad 2009, Mohamad 2006, Schueller 1991, Zhang and Valliappan 1990). There is a need to understand both dynamic interaction of blast loading with structures and shock mitigating mechanisms. Traditional lightweight materials such as foam and honeycomb core system are effective for blast protection applications because of their ability to mitigate shock blast wave transferred to structures due to terrorism (Liu and Katsabanis 1997, Gustafsson 1973, Technical Manual TM 5-885-1 1986, Technical Manual TM 5-1300 2008).

Iinterior panels are examples of composite structures (Dharmasena *et al*. 2008, Ming 2008). To better understand structural damage under dynamic conditions, there are many researches to study civilian structures (Fayad 2009, Mohamad 2006, Beshara 1994, Liane and Hedman 1999, Smith and Hetherington 1994). The composite structures become an engineering challenge to understand their performance against blast effect.

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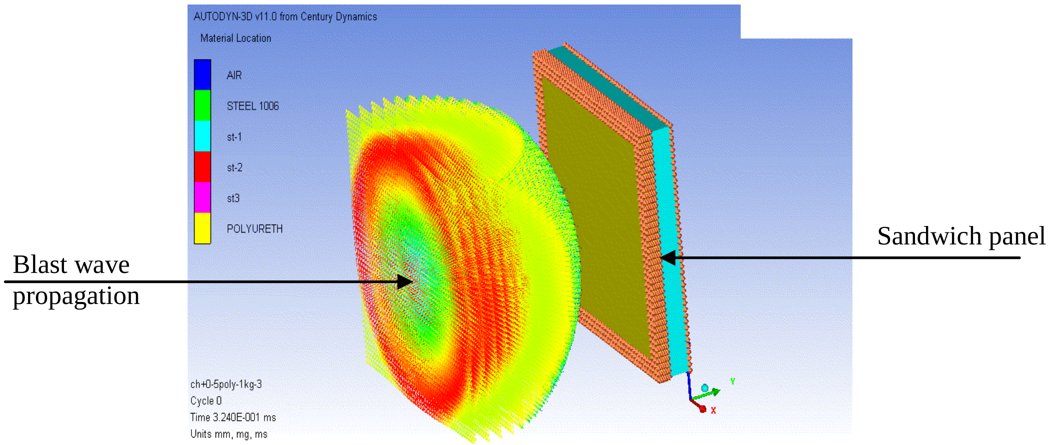
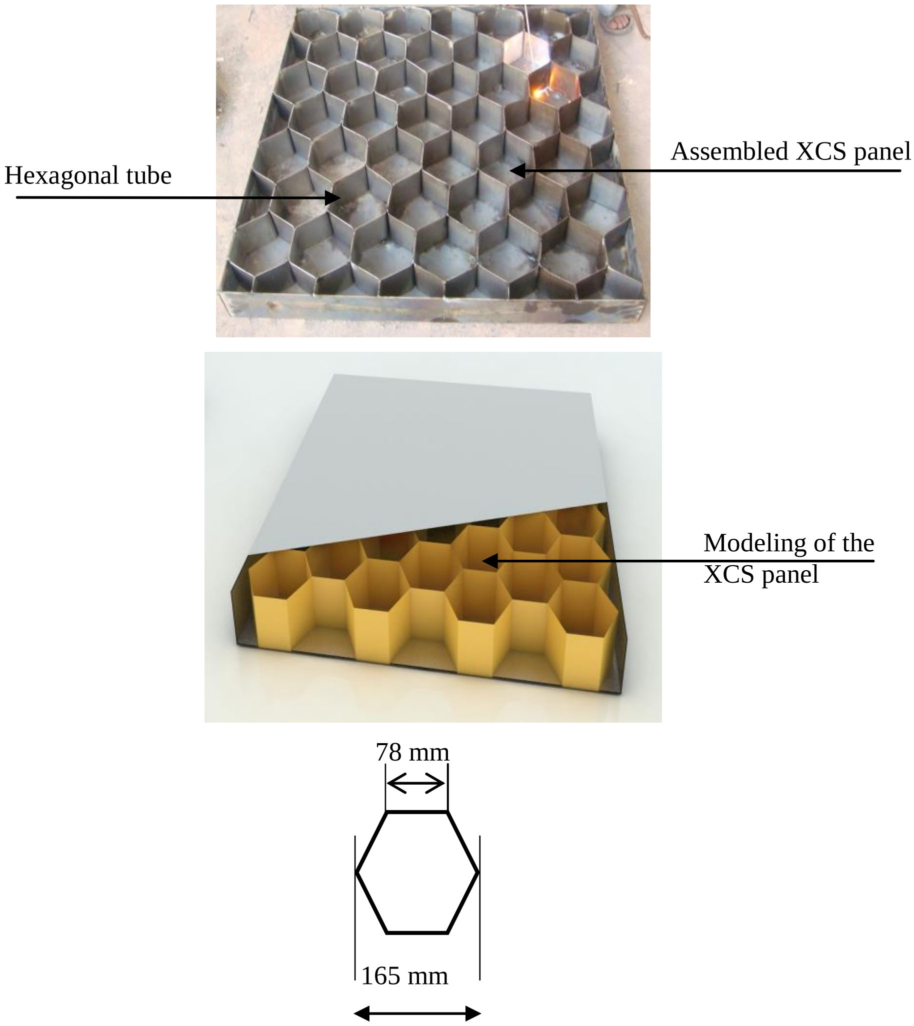


Fig. 1 Blast wave propagation hitting the sandwich steel panel

It is very expensive to conduct field blast tests in every site and sometimes it is impossible to carry out such field tests due to safety and environmental constraints (Dharmasena *et al*. 2008, Hao *et al*. 1998). However, a reliable numerical model validated against measured field data is an effective tool to analyze the structure performance under blast effect (Dharmasena *et al*. 2008, Hao *et al*. 1998, Ming 2008).

Chen and Chen (1996) investigated the dynamic soil-structure interaction phenomenon involved in shallow-buried flexible plate under impact load. They used the experimental and the numerical works to study the performance of the buried structure. Lu *et al*. (2005) used a fully coupled numerical model to simulate the response of buried concrete structure under subsurface blast. The responses of the buried structure obtained by 2-D numerical model at different points were compared by those obtained by 3-D numerical model. Trelat *et al*. (2007) studied impact of shock wave on structure due to explosion at altitude. They improved the understanding of interaction of blast waves with both ground and structure using both the FEA and the experimental work. Luccioni *et al*. (2009) studied craters produced by underground explosions. They discussed the accuracy of numerical simulation of craters produced by underground explosions. Ha *et al*. (2011) used carbon fiber reinforced polymer (CFRP) to strengthen structures against blast load. They conducted an experimental work on CFRP to strengthen RC panels under blast loading. Mazek and Mostafa (2013) used the rigid polyurethane foam (RPF) to strengthen sandwich steel structure under blast load. The field blast test was conducted. They used the finite element analysis (FEA) to model the sandwich steel structure strengthened by the rigid polyurethane foam under shock wave.

In this study, the performance of the sandwich steel panels strengthened by pyramid cover system (PCS) is highlighted under the impact of the blast wave effect. The 3-D numerical model is proposed using finite element analysis (FEA) to study the PCS performance to strengthen the sandwich steel panels, as shown in Fig. 1. Hexagonal core sandwich (XCS) steel panel is used to study blast mitigation based on constant sheet thicknesses of the PCS. Field blast test is also conducted to record pressure-time history of blast effect hitting the sandwich steel panel and to record maximum displacement at the centre point of the sandwich steel panel. The study presents a comparison between the results obtained by both the field blast test and the numerical model to validate the accuracy of the 3-D finite element analysis (FEA). The constitutive model for this



Cross section on each hexagonal tube
(1 mm thickness)

Fig. 2 Hexagonal core sandwich steel panel (XCS)

analysis contains elasto-plastic materials. An elasto-plastic model is employed to represent the performance of the sandwich steel panel and the PCS layer. The proposed model is programmed and linked to an available computer program Autodyn3D (2005). The sandwich panel model strengthened by the PCS is also implemented in a finite element code Autodyn3D. Current codes and regulations to estimate blast wave intensities due to outdoor blasting are also used in this study based on empirical methods (Gustafsson 1973, Technical Manual TM 5-1300 2008, Remennikov 2003). These empirical methods were obtained from observations and measurements in field blast tests.

The finite element model takes into account the effects of the blast load, the sandwich steel panel, and the PCS. The effects are expressed in terms of the displacement-time history of the

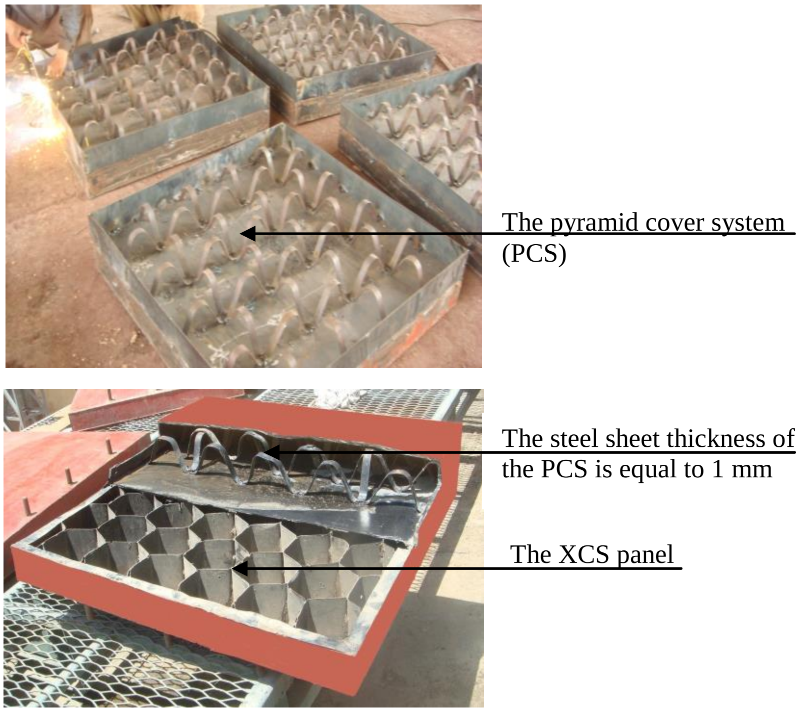


Fig. 3 Hexagonal core sandwich (XCS) panel strengthened by the PCS

sandwich panels as the explosive wave propagates. The 3-D nonlinear FEA is conducted to study the impact of the PCS on the sandwich panel performance based on different TNT charges. The behavior of the sandwich panel is investigated under the blast waves obtained from detonating 1-kg, 2-kg, and 3-kg TNT explosive charges at a stand-off distance (R) of 1 m.

Numerical results obtained by the FEA are compared with the data obtained from the field blast test. The numerical model can well predict the blasting-induced pressure on the sandwich panel. Displacement-time history of the sandwich panel strengthened by the PCS is also presented. Maximum displacements of the sandwich steel panels are recorded and computed by the author.

2. Field blast test

In this study, the field blast test is conducted to understand the sandwich steel panel performance based on different TNT explosive charges. The XCS steel panels are prepared and tested in this study. The dimensions for each hexagonal tube (1 mm thickness) of the internal core structure system in the sandwich steel panel are shown in Fig. 2. The outer covers of the sandwich steel panel are steel plates. The steel plates are square in shape of 1.0 m height, 1.0 m width, and 6 mm thickness, as shown in Fig. 2. The steel used in the sandwich steel panel is normal mild steel. The interior spacing (core spacing) between the steel plates of the sandwich steel panel is 10 cm.

The height of the PCS layer covering the sandwich steel panel is 10 cm with the same core spacing of the sandwich steel panel, as shown in Fig. 3. The length of the pyramid base is 20 cm. The outer covers of the PCS layer are steel plates. The thickness of the steel sheet for the pyramid

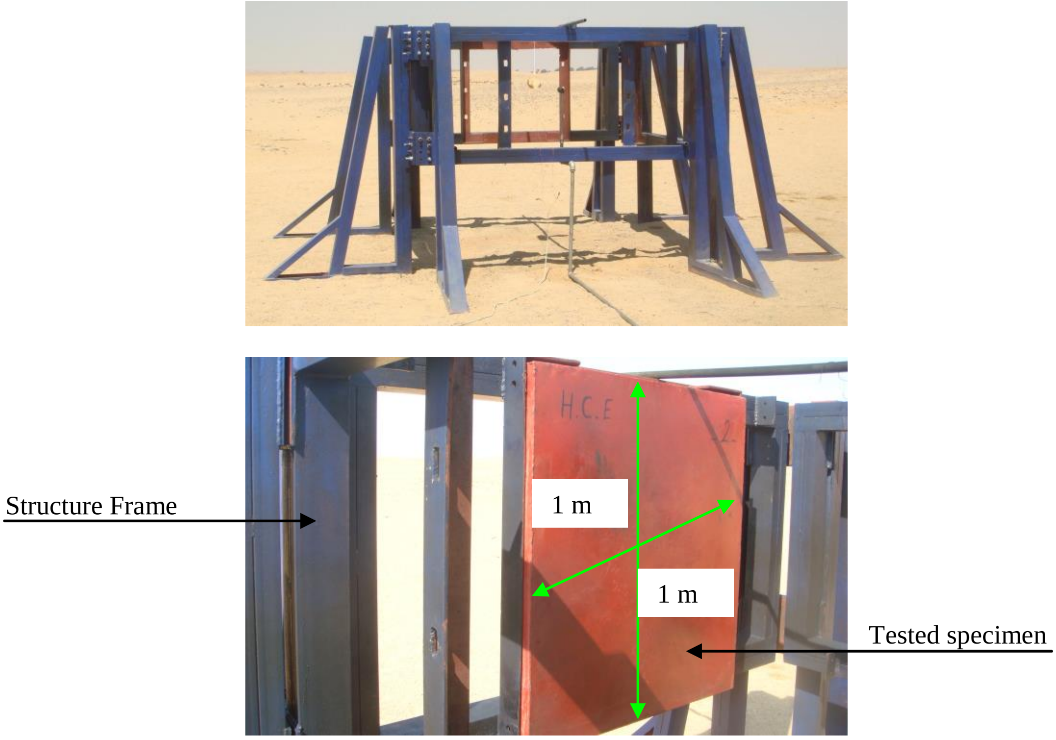


Fig. 4 Test rig

stiffener is 1 mm. The steel used in the PCS layer strengthening the sandwich panel is also normal mild steel.

The sandwich steel panel is subjected to 1-kg, 2-kg, and 3-kg TNT explosive charges, as shown in Fig. 1. The XCS panel strengthened by the PCS layer is also prepared and tested under different TNT explosive charges.

The previous specimens are prepared and assembled with special requirements to be tested against TNT explosives. A test rig is prepared and used to simulate the sandwich steel panel boundary in free air. However, the test rig also needs some precautions to satisfy boundary conditions for free air explosion. The dimension of the test rig is 2 m×2 m×2 m, as shown in Fig. 4. The members of the test rig are box sections composed from two channel 140 mm. These box members are welded face to face. Angles (70 mm×7 mm) are also welded to the box members in vertical and horizontal directions so as to support the tested specimens, as shown in 4. The height of the supporting angles is 1.0 m and their width is 1.0 m, as shown in Fig. 4.

The sensor interface PCD-30A is a voltagemeter that is connected with the personal computer so as to record pressure-time history hitting the sandwich steel panel due to blast effect, as shown in Fig. 5. The maximum displacements of the specimens are also measured under blast loading. LVDTs are placed at the centre of the sandwich steel panel. The sensors are used to record maximum displacement at the centre of the sandwich steel panel (point 1), as shown in Fig. 6. This device is capable of measuring voltage which is recorded and attached to control software. This system can measure four channels. The sensors are also attached on the center of the specimen's top surface (sandwich steel panel). The locations of the attached sensors are shown in Fig. 6 (point 1).

Field instrumentation devices Sensors

Fig. 5 Field blast system measurement devices

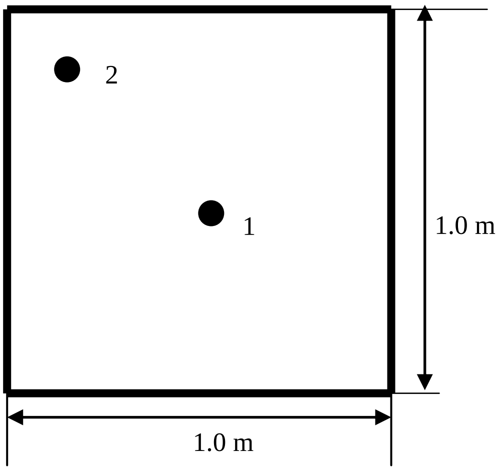


Fig. 6 Position of sensor located at the sandwich steel panel for points 1 and 2 (Field test and numerical model)

Fig. 5 shows the field instrumentation devices.

The XCS panel is subjected to blast pressure recorded at the case of 2-kg TNT explosive charge, as shown in Fig. 7. The high speed camera is also used to capture photos at 15000- 20000 frames/s. The photos of explosion with TNT charge of 2 kg are shown in Fig. 8.

3. Sandwich panel model

In numerical modeling, air and equivalent TNT explosive are simulated by Euler processor, as shown in Fig. 9. The air and the equivalent TNT explosive are assumed to satisfy the equation of state (EOS) of ideal gas (Hao *et al*. 1998). The sandwich steel panel and the PCS are modeled by the modified isotropic damage model and simulated by Lagrange processor, as shown in Fig. 9 (Hao *et al*. 1998; Wu *et al*. 1999). The whole domain, including the air media, the TNT explosive, the PCS, and the sandwich panel, is assumed to be symmetric in the X, Y, Z directions, as shown in Fig. 9. Transmitting boundary is used to reduce reflection of stress wave from the numerical

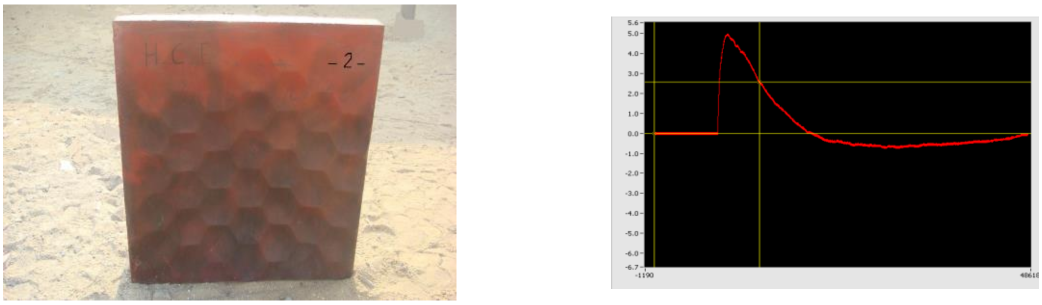


Fig. 7 The XCS steel panel subjected to 2-kg TNT explosive charge

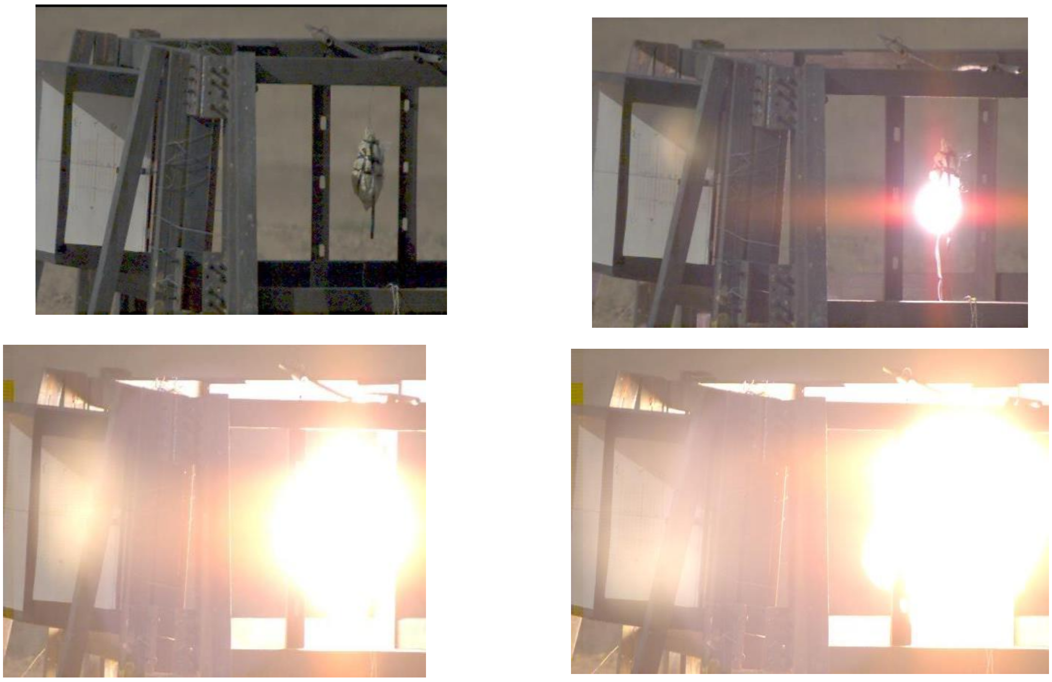


Fig. 8 Explosive scene by 2-kg TNT explosive

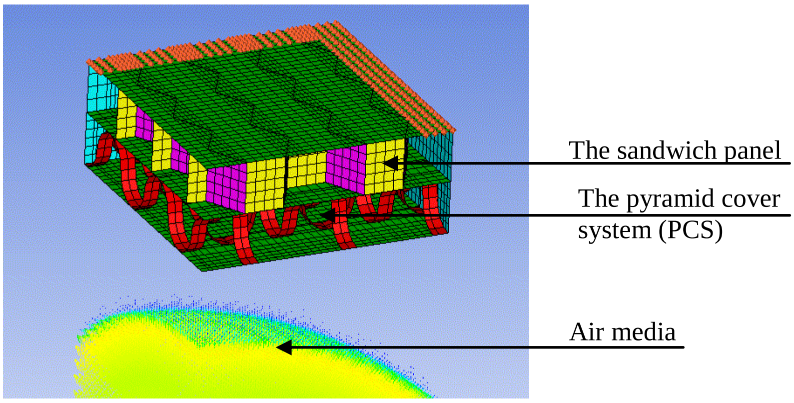


Fig. 9 3-D finite element model of the XCS panel strengthened by the PCS layer

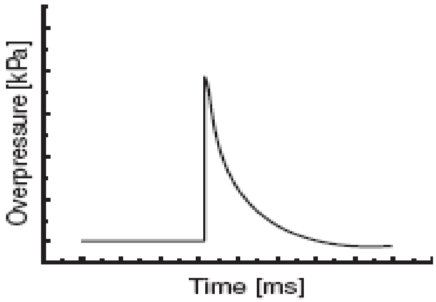


Fig. 10 Typical pressure time history in open air (after Gaissmaire 2003)

boundaries. The material constants of the standard constants of the air, the TNT explosive, the PCS, and the sandwich panel are obtained from the Autodyn3D material library. These include air mass density ρ=1.225 kg/m^3; air initial internal energy E_n=2.068×10^5 kJ/kg; and ideal air constant γ=1.4.

Shell element is used to model both the membrane (in-plane) and the bending (out-of-plane) behavior of the sandwich panel including the internal hexagonal core structure system and the PCS layer, as shown in Fig. 9. In this study, the sandwich panel strengthened by the PCS is modeled. 4-node rectangular shell elements are used for modeling the sandwich steel panel with each node having 6 degrees of freedom (three translations and three rotations).

The mechanical properties of the sandwich panel and the PCS are Poisson's ratio ν=0.3; averaged mass density of steel 7900 kg/m^3; elastic modulus E=2100 t/cm^2; and yield strength f_y=2400 kg/cm^2. The shear modulus of the steel depends on the elastic modulus E and Poisson's ratio ν. It should also be noted that viscous damping effect is neglected in the numerical simulation as its influence on high velocity explosion-type responses is insignificant (Hao *et al*. 1998, Wu *et al*. 1999).

The shell element interface is used between the sandwich panel and the PCS to ensure the compatibility conditions at the interface surface between them as well as the associated stresses and strains along the interface surface.

4. Numerical model analysis

The shock of the blast wave is generated when the surrounding atmosphere is subjected to an extreme compressive pulse radiating outward from the centre of the explosion. The pressure–time history of a blast wave can be illustrated with a general shape, as shown in Fig. 10 (Gaissmaire 2003). The illustration is an idealization for an explosion in free air, as shown in Fig. 10. Transient pressure being greater than ambient pressure is defined as the overpressure (P_s) (Smith and Hetherington 1994). The peak overpressure (P_s) is the maximum value of the overpressure at a given location. The rise time to peak overpressure is less than microsecond (Baker *et al*. 1983).

The study presents a comparison between the pressure-time histories obtained by the empirical method (EM) developed by Henrych (Beshara 1994), by the field blast test, and by the numerical model. The empirical method uses the scaled distance (Z) to calculate the peak overpressure, as written in Eq. (1) (Beshara 1994).

$$Z = \frac{R}{\sqrt[3]{W}} \tag{1}$$

Where; R is the stand-off distance from the centre of the explosion to a given location in meter and W is the weight of the explosive in kg.

The equations developed by Henrych (Beshara 1994) divide the analysis into three fields based on one-meter scaled distances (Z) as presented in Eqs. (2) to (4).

$$P_s = \frac{14.072}{Z} + \frac{5.540}{Z^2} - \frac{0.357}{Z^3} + \frac{0.00625}{Z^4}\ (bar) \quad \text{(for 0.05< Z<0.3)} \tag{2}$$

$$P_s = \frac{6.194}{Z} - \frac{0.326}{Z^2} + \frac{2.132}{Z^3}\ (bar) \quad \text{(for 0.3< Z< 1)} \tag{3}$$

$$P_s = \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3}\ (bar) \quad \text{(for 1< Z< 10)} \tag{4}$$

The scaled distance (Z) is also used to determine the positive duration time (T_s) and the positive impulse (i_s) by using Fig. 11 (Smith and Hetherington 1994).

The comparison between the results obtained by the field blast test, the empirical method, and the numerical model is conducted to assess the accuracy of the numerical model. One-kg TNT, two-kg TNT, and three-kg TNT explosive charges are applied at stand-off distance of one meter to obtain the pressure-time history hitting the sandwich panel by the EM, the numerical model, and the field blast test at points 1 and 2 (Fig. 6), as shown in Figs. 12 to 14. From these figures, it can be seen that the results obtained by the field blast test agree well with those estimated by both the numerical model and the EM.

5. Blast impact on performance of sandwich panel strengthened by PCS

The displacement-time history of the sandwich steel panel with hexagonal core sandwich (XCS) due to blast load is calculated using the 3-D FEA. The blast load affects the sandwich panel as shown in Fig. 10. The FEA is also used to calculate the displacement-time history of the sandwich panel strengthened by the PCS as structural retrofitting. The study discusses the impact of the PCS layer on the sandwich panel performance under the blast impact. Two cases of the XCS panel with and without the PCS layer are studied. For the first case, the XCS panel is modeled without using the PCS layer. For the second case, the XCS panel is modeled using the PCS layer.

One-kg TNT explosive is used to discuss the impact of the PCS layer on the XCS sandwich panel at points 1 and 2 (Fig. 6). The TNT explosive is located at the one-meter stand-off distance from the sandwich panel, as shown in Fig. 8. The pressure- time history hitting the sandwich panel is presented in Fig. 12. The displacement-time histories of the sandwich panels at points 1 and 2 for the two cases (Fig. 3) are computed to discuss the impact of the PCS layer. Fig. 15 shows the comparison between the displacement-time histories of the sandwich panels at point 1 for each case. Fig. 16 also presents the comparison between the displacement-time histories of the

Table 1 Maximum displacement at the centre of the sandwich steel panels (point 1) under different TNT explosives

Sample	TNT explosive (kg)	Maximum recorded displacement (mm)	Maximum computed displacement (mm)
XCS panel without PCS	1	4.4	4
	2	7.8	7.2
	3	10.5	9.8
XCS panel strengthened by PCS	1	2.4	2.2
	2	3.7	3.4
	3	5.8	5.3

Note: XCS is hexagonal core sandwich panel (XCS)

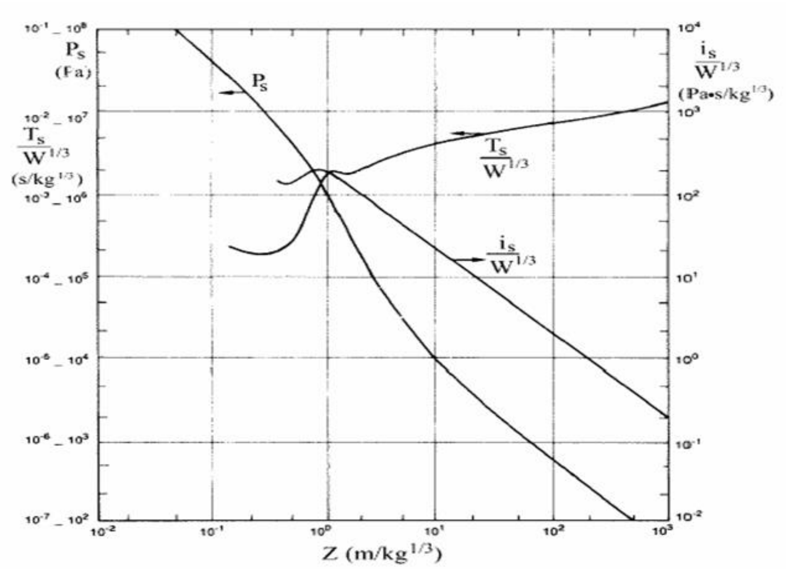


Fig. 11 Blast wave parameters for spherical charges of TNT explosive (after Smith and Hetherington 1994)

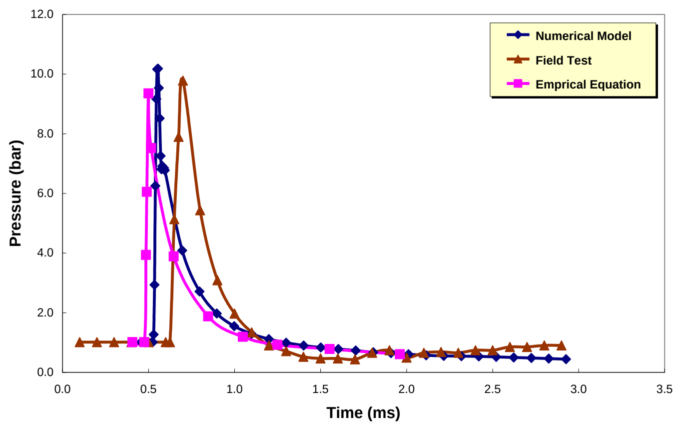


Fig. 12 Pressure-time history hitting the sandwich panel at point 1 based on 1-kg TNT explosive

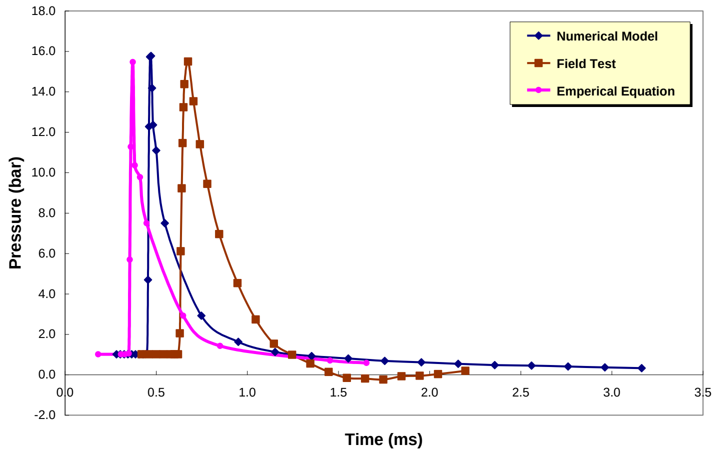


Fig. 13 Pressure-time history hitting the sandwich panel at point 1 based on 2-kg TNT explosive

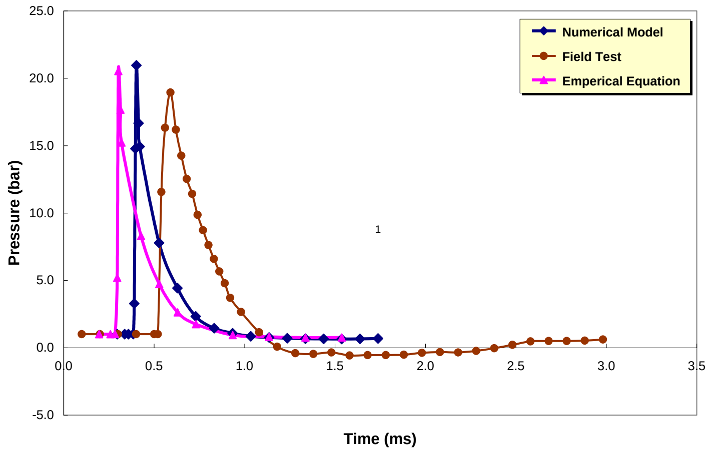


Fig. 14 Pressure-time history hitting the sandwich panel at point 1 based on 3-kg TNT explosive

sandwich panels at point 2 for each case. The maximum displacement of the sandwich panel at point 1 is also obtained by both the field blast test and the 3-D FEA as presented in Table 1. The comparison indicates that the response of the sandwich panel strengthened by the PCS layer is lower than the response of the sandwich panel without the PCS layer, as shown in Figs. 15 and 16 and as presented in Table 1.

Two-kg TNT explosive is also used to discuss the impact of the PCS layer on the sandwich panel at points 1 and 2 (Fig. 6). Two-kg TNT explosive is also located at the one-meter stand-off distance from the sandwich panel, as shown in Fig. 8. The pressure-time history hitting the sandwich panel is also presented in Fig. 13. The displacement-time histories of the sandwich panels at points 1 and 2 based on the two cases (Fig. 5) are also calculated to discuss the impact of the PCS layer. Fig. 17 shows the comparison between the displacement-time histories of the sandwich panels at point 1 for each case. Fig. 18 also presents the comparison between the

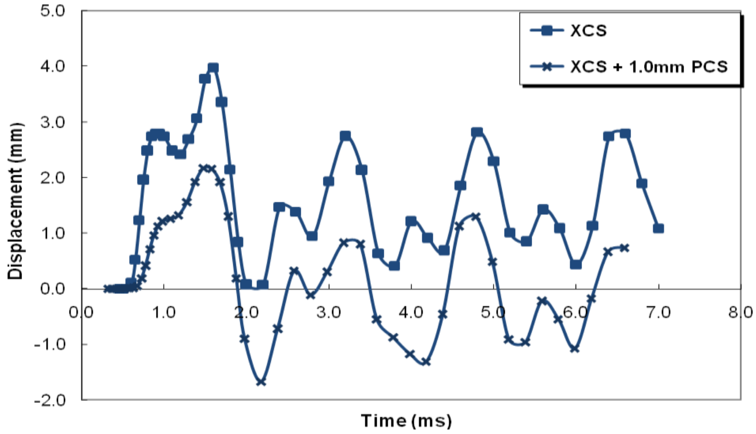


Fig. 15 Displacement–time history of the sandwich panel at point (1) for two cases (1 kg TNT)

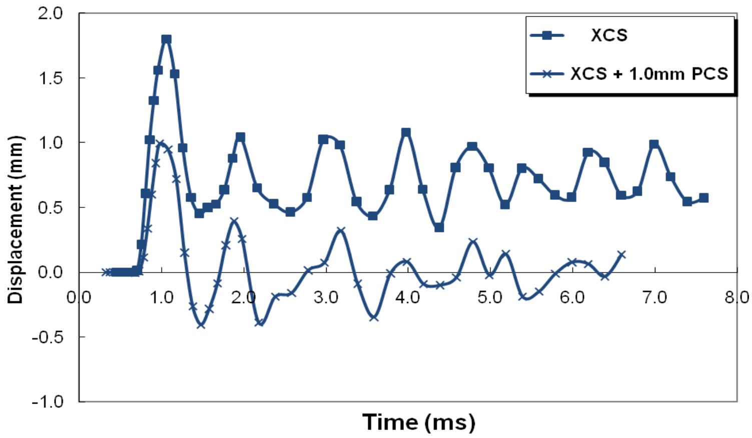


Fig. 16 Displacement–time history of the sandwich panel at point (2) for two cases (1 kg TNT)

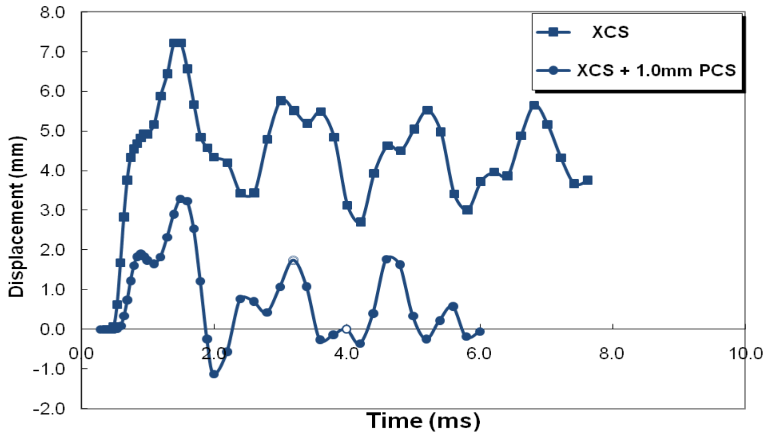


Fig. 17 Displacement–time history of the sandwich panel at point (1) for two cases (2 kg TNT)

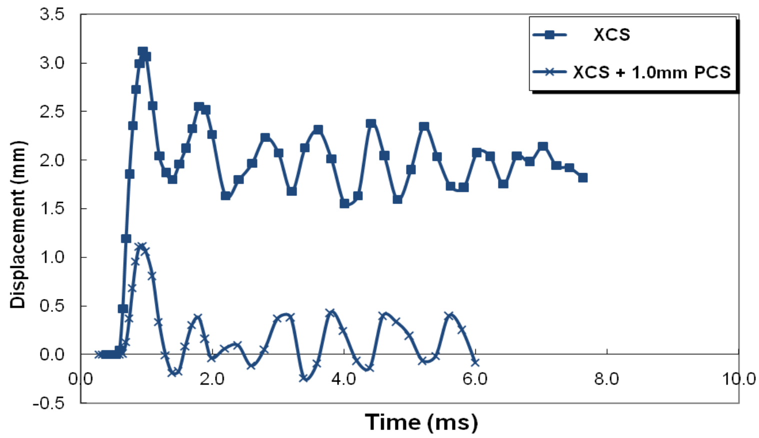


Fig. 18 Displacement–time history of the sandwich panel at point (2) for two cases (2 kg TNT)

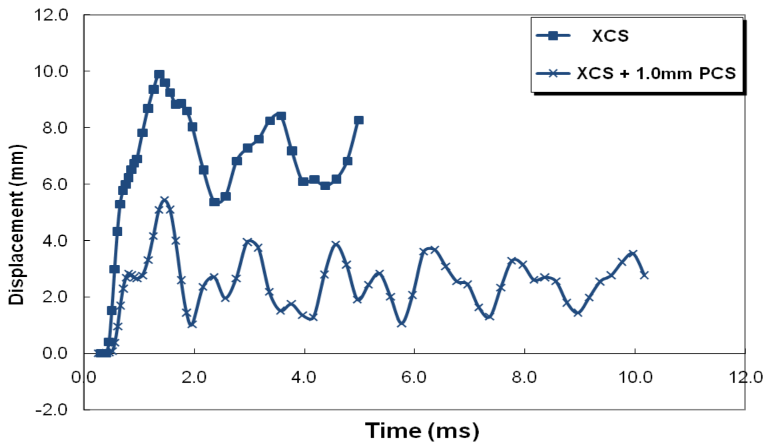


Fig. 19 Displacement–time history of the sandwich panel at point (1) for two cases (3 kg TNT)

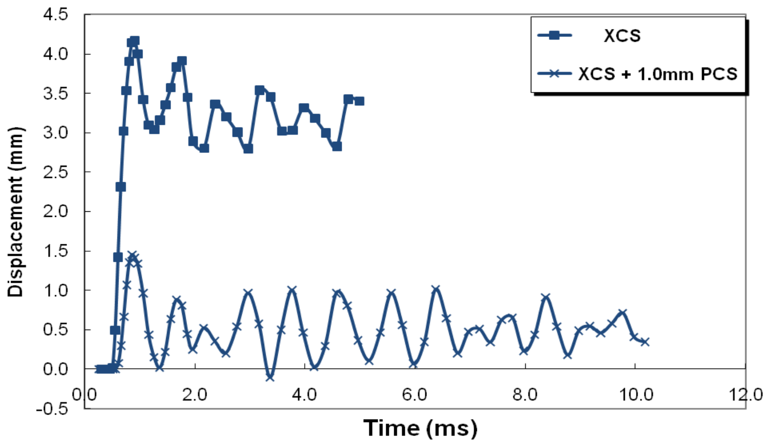


Fig. 20 Displacement–time history of the sandwich panel at point (2) for two cases (3 kg TNT)

displacement-time histories of the sandwich panels at point 2 for each case. The maximum displacement of the sandwich panel at point 1 is obtained by both the field blast test and the 3-D numerical model as presented in Table 1. The comparison also shows that the response of the sandwich panel strengthened by the PCS layer is lower than the response of the sandwich panel without the PCS layer, as shown in Figs. 17 and 18 and as tabulated in Table 1.

Three-kg TNT explosive is again used to discuss the impact of the PCS layer on the sandwich panels at points 1 and 2 (Fig. 6). The comparison again indicates that the response of the sandwich panel strengthened by the PCS layer is lower than the response of the sandwich panel without the PCS layer, as shown in Figs. 19 and 20 and as tabulated in Table 1.

6. Discussions

The difference between the performance of the sandwich steel panels with and without the PCS layer lies in the use of the PCS layer. The XCS panel (Fig. 2) is used to discuss the impact of the PCS layer on the performance of the sandwich steel panel. The field blast test is conducted to study the performance of the XCS panel strengthened by the PCS layer and to trace the pressure-time histories hitting the sandwich panel based on different TNT explosive charges. The pressure-time history hitting the sandwich panel and the maximum displacement of the sandwich panel are recorded. The trends of the pressure-time histories obtained by the field blast test, the numerical model, and the empirical method are the same trend as those presented by Gaissmaire (2003). Based on the field blast test, there is a good agreement between the recorded and the computed maximum displacement of the sandwich panel. The FEA gives a better estimation of the response of the sandwich panel strengthened by the PCS.

In general, the sandwich steel panels play an important role to resist the blast load. The PCS layer improves the performance of the sandwich steel panel. Therefore, the PCS layer increases the sandwich panel stiffness and then reduces the displacement of the sandwich panel compared to the sandwich panel without the PCS layer. The PCS has a large amount of strain energy which can absorb the kinetic energy of the blast wave propagation. Based on the field blast test and the FEA, the PCS reduces the maximum displacement of the sandwich steel panel up to 45%. Finally, the performance of the sandwich panel is highly dependent on the geometrical properties of the PCS layer which is used as a structural retrofitting.

7. Conclusions

The field blast test is conducted to study performance of the XCS panel strengthened the PCS layer. A 3-D numerical model is also used to predict the performance of the sandwich panels strengthened the PCS layer under the blast effect. In this study, the performance of the sandwich panel strengthened by the PCS layer is modeled and analyzed using the 3-D FEA. The following conclusions can be drawn regarding the performance of the sandwich panels strengthened by the PCS layer under the impact of the TNT explosives.

• Based on the field blast test and the empirical method developed by Henrych (Beshara 1994), the 3-D numerical model gives a better estimation of the pressure-time history hitting the sandwich steel structure.

• The pressure-time histories calculated by the 3-D numerical model is in reasonable agreement with those obtained by both the field blast test and the empirical method developed by Henrych (Beshara 1994).

• The pressure-time history profile of the sandwich steel panel calculated by the numerical model has the same trend as that presented by Gaissmaire (2003).

• The 3-D finite element model can be successfully used to analyze and estimate the performance of the sandwich steel panels strengthened by the PCS layer based on the field blast test.

• The response of the XCS steel panels strengthened by the PCS layer is reduced up to 45% with respect to that of the XCS steel Panel without the PCS layer.

Therefore, the pyramid cover system (PCS) layer can be used as structural retrofitting to absorb the energy of the blast wave propagation hitting the sandwich steel panels.

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