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Experimental and numerical studies of non-composite Steel–Concrete–Steel sandwich panels under impulsive loading

Yonghui Wang [*], J.Y. Richard Liew, Siew Chin Lee

Department of Civil and Environmental Engineering, National University of Singapore, Singapore

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ABSTRACT

The performance of non-composite Steel–Concrete–Steel (SCS) sandwich panels under impact-induced impulsive loading was experimentally and numerically studied in this paper. Two SCS sandwich panels with different core depths were tested and the impulsive loading was applied in the laboratory by utilizing an inflated high pressure airbag to transfer the impact load from dropped projectile onto the panels. The deformation modes, applied pressures, displacement and strain responses of the panels were determined in the test. A combination of bending and shear deformation mode was observed in the SCS panel with thinner core while there was minimal visible deformation in the thicker panel. The maximum and permanent deformations of the panel with thicker panel were significantly reduced due to the increase in resistance and mass. Debonding between grout core and bottom plate was also noted in both panels during impact from the strain–time histories. Following the test, Finite Element (FE) models were constructed and verified against the test data to simulate the tests. It was shown in the FE analysis that the steel plates absorbed more energy due to its higher strength and ductility as compared to the grout core under the impact-induced impulsive pressure loading.

1. Introduction

Steel–Concrete–Steel (SCS) sandwich structure, which consists of a concrete core connected to two external steel face plates using mechanic shear connectors, exhibited superior ductility and strength than conventional reinforced concrete structures. The potential applications of SCS structures under static, impact and blast loadings have been demonstrated in various studies [1–9]. In the past, the SCS was applied to sustain static and impact loadings while more recently, the application has been extended to protective layer against blast loading due to its high energy absorbing capacity and scabbing protection [5–9]. An example of such application is shown in Fig. 1 [7]. Most reported works on SCS including those in Refs. [1–9] involved the use of mechanical shear connectors while there is a lack of study on the performance of non-composite SCS sandwich panel under blast loading [8] and its energy absorbing performance was not fully understood. Hence, laboratory test using drop-weight projectile and numerical analysis using nonlinear LS-DYNA Finite Element (FE) code, which has been widely applied to simulate blast and impact response of civil infrastructure, including concrete [4,10–15], steel [16,17] and sandwich structures [18–20], were carried out in the current study to investigate the response of non-composite SCS sandwich panel under impact-induced impulsive loading and to determine its energy absorbing performance.

Field blast test is a direct method to apply blast loading onto structures [7–11,21–23]. It is generally expensive and requires remote testing site. Other method like shock tube is comparably less costly and can be better controlled but is only available at few laboratories worldwide. Besides, the test is restricted by the specimen size and the applied loading has relatively longer duration as compared to field blast, especially for close-in detonation [24,25]. In the absence of field blast test and shock tube facilities, Mostaghel [26] developed a simple non-explosive test to generate impulsive loading by using a membrane formed inflated airtight chamber mounted to a frame system. A plate was dropped onto the membrane from various heights to achieve the required impulse magnitude and duration. This method was adopted by Chen and Hao [27] and the airtight chamber was replaced with inflated airbag to apply impulsive loading on multi-arch double layered panels. Remennikov et al. [28] also adapted this method to test columns under impulsive loading. Although the impulsive loading duration that can be obtained was relatively longer as compared to actual blast induced loading, the test using airbag is simple and can be conducted in the laboratory. Hence, a similar

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[*] Corresponding author.
E-mail address: wangyonghui@nus.edu.sg (Y. Wang).

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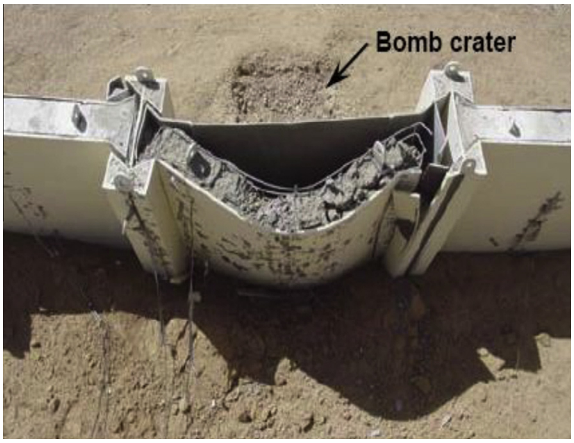

Fig. 1. SCS sandwich panel as blast wall [7].

concept was adopted in the current study by using high pressure airbag to test the SCS sandwich panels under impact-induced impulsive loading. The airbag was charged with initial pressure of 100 kPa before impact to reduce the impulsive loading duration to 0.042–0.049 s, which were shorter than those reported in Refs. [27,28] (round 0.1 s) and close to that of a gas explosion.

2. Experimental study

2.1. Design of specimens

Two SCS sandwich panels with different core depths of 50 (SCS50) and 75 mm (SCS75) were fabricated from mild steel plates that were fillet welded together to form the outer skin as shown in Fig. 2. A 32 mm (1¼ inch) inlet pipe with stopper ball valve and a 32 mm (1¼ inch) outlet pipe with threaded cap were provided at the side and end plates of the panels for pumping of cement grout into the core during casting. The schematic drawing of the panel is shown in Fig. 3 and the details are summarized in Table 1.

2.2. Test setup and instrumentation

The instrumented drop-weight impact test machine that was used to apply the impact-induced impulsive loading in the laboratory is shown in Fig. 4. A hydraulic controlled mechanical hoisting system is utilized to raise the projectile up to 4 m drop height. Once the winch brake is released, the projectile, which has an adjustable weight of 500–1200 kg, will slide down freely along the vertical guide rails. The SCS panel was placed below the projectile and simply supported on two 80 mm diameter bars support with clear span of 900 mm, as shown in Fig. 5. The inflated height of the airbag between the 1000 mm × 1000 mm × 30 mm thick impact plate and test panel was kept at 160 mm by using two wood beams that were inserted between the frame and impact plate. The airbag was charged with 100 kPa initial pressure before impact. Even though the change in contact area between airbag and test panel was expected to be less significant with higher initial pressure of airbag, the 100 kPa initial pressure was selected such that the midpoint displacement of specimen was minimal (less than 2 mm) and within the elastic range. Wet paint was applied to the bottom surface of the inflated airbag which was not in contact with the panel before test. As the wet paint would leave a marking on the panel after impact, the maximum contact area during impact could be determined. The inflated height of 160 mm was selected based on trial tests and kept as small as possible since an inflated airbag with lower compressibility, which can be defined as the ratio of compression distance of airbag, ΔH, to change of air pressure, ΔP, will generate impulsive loading with shorter duration.

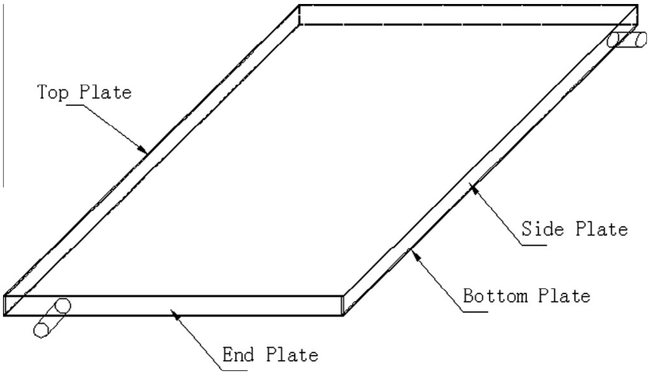

Fig. 2. Notation for SCS sandwich panel.

A digital circuit in combination with laser emitters and photodiodes was used to measure the impact velocity of projectile just before the impact and also to trigger the data acquisition system by the 16-channel Oscilloscope 1 with sampling rate setting of 1 MHz as shown in Fig. 6. The Dytran high frequency 2300 V Low Impedance Voltage Mode (LIVM) pressure sensor was connected to the inlet pipe of the airbag to capture the air pressure and three quartz force rings on the same plane with total capacity of 1050 kN were attached to the projectile to record the impact force. The displacement and strain responses of the specimen were respectively measured by using potentiometers and strain gauges at the positions shown in Fig. 7. The signals from the photodiodes, pressure sensor, quartz force rings and potentiometers were captured using Oscilloscope 1 while the strain gauge readings were recorded by the 16-channel Oscilloscope 2 with the same sampling rate setting of 1 MHz. Oscilloscope 2 was triggered by strain gauge S0 at the mid-span.

2.3. Test results and discussions

The SCS50 and SCS75 sandwich panels were subjected to impact by an 800 kg projectile that was dropped from the height of 3.7 m. The impact force, air pressure, deformation and strain responses were measured in the test and are discussed as follow.

2.3.1. Impact force and air pressure

The recorded impact force–time histories between the projectile and impact plate are plotted in Fig. 8. Multiple contacts between the two can be seen from the plots as the heavier projectile continued to move downward and hit the impact plate again multiple times after their first contact. The air pressure–time histories, which represent the impulsive loading acting on the panel, are plotted in Fig. 9. The measured loading durations on the SCS50 and SCS75 panels are 0.049 s and 0.042 s, respectively, which were shorter than those reported in Refs. [27,28] (about 0.1 s). The shorter duration could be attributed to the higher initial pressure and drop weight used in the current test. The recorded impact velocity (V), maximum impact force (F_{max}), impact impulse (I) and maximum air pressure (P) in both tests are summarized in Table 2. The impact impulse was obtained by integrating the impact force–time history shown earlier in Fig. 8. From Table 2, it appears that the SCS75 panel with higher resistance and mass absorbed higher impact impulse under the same impact condition.