Full scale field testing of trapezoidal core sandwich panels subjected to adjacent and contact detonations

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ABSTRACT: Corrugated-core sandwich panels are efficient protective structures that can absorb blast/impact energy through plastic deformation. A relatively non-expensive folding technique is used to manufacture the core to different topologies. Literature survey revealed that the dynamic response of metallic trapezoidal corrugated-core sandwich panels subjected to near-field/contact detonations has not yet been thoroughly investigated. Hence, the aim of this study is to examine, with field tests, if trapezoidal core sandwich panels can protect a pre-cast concrete target from adjacent/contact detonations. The performance and damage behavior of two pre-cast RC slabs were assessed with and without aluminum sandwich panels. The two slabs were subjected to 4 detonations ranging from close to contact explosions. The study concludes that the implemented sandwich panel is not suitable for near-field or contact detonations and might be a protective solution for far-field explosion scenarios.

1 INTRODUCTION

The need for more robust systems of protection is of vital importance due to this increasing risk of explosive attacks (Al-Rifaie and Sumelka, 2017). Exposure of civilian facilities to explosion scenarios cannot be entirely avoided, but the effects of such accidents can be greatly mitigated by the use of protective systems, such as sandwich panels. To absorb the energy from blast/shock/impact, sandwich panels are used as sacrificial structures. They are usually made up of an inner-core sandwiched between two plates. The inner-core can be classified as either cellular or corrugated. The blast energy dissipation of such panels is based on the plastic deformation of the core.

Cellular cores can be metallic foams (Nowak et al., 2017), honeycomb structures (Li et al., 2014) or auxetic topologies (Al-Rifaie and Sumelka, 2019, Al-Rifaie and Sumelka, 2020) that are efficient but relatively expensive to produce (3D-printing). This may restrict their uses to particular fields, such as the aerospace field, biomedical engineering and military equipment. Corrugated core sandwich panels have been suggested as an alternative due to their high longitudinal stretching, shear strength and energy absorption properties (Zhang et al., 2015, Wiernicki et al., 1991). To manufacture the corrugated layers, a relatively non-expensive folding technique is used. The geometric topologies can be triangular, sinusoidal, rectangular or trapezoidal-shaped (Al-Rifaie et al., 2021). The later proved its performance compared to other topologies (Rong et al., 2018).

The performance of sandwich panels (with trapezoidal core) subjected to far-field explosions was generally perceived by researchers, either numerically or through real field testing. However, according to the authors' survey, the dynamic response of metallic trapezoidal corrugated-core sandwich panels subjected to near-field/contact detonations has not yet been thoroughly investigated. Hence, the aim of this study is to investigate, with field tests, if

trapezoidal-core sandwich panels can protect a pre-cast concrete target from adjacent/contact detonations.

2 CASE STUDY

2.1 Sandwich panel properties

The panel used in this research is composed of 8 trapezoidal corrugated layers manufactured using cold-form press technique. The directions of the corrugated layers is cross-arranged (0°/90°), as better energy absorption can be achieved compared to the regular-arranged (Al-Rifaie et al., 2021). The 8 aluminum layers are neither welded, nor bolted together. They are hold by a C-shaped aluminum frame. The layer itself has a thickness of 1.5 mm while the frame has 2 mm. Figure 1 shows the geometrical properties of the aluminum sandwich panel and its trapezoidal corrugated core. The sandwich panel has exterior dimensions of 1000x1000x163 mm. Two sandwich panels of this type were used in this research. The aluminum material properties are listed in Table 1.

2.2 The RC slab

As mentioned earlier, the sandwich panels are supposed to protect a concrete target from contact or adjacent detonations. Two 3000x1500x145 mm pre-cast RC slabs were used. Each slab is simply supported on 2 concrete supports. The slab is reinforced with upper and lower layers of similar reinforcement. Each layer has longitudinal main reinforcement of $\varnothing 10\text{mm}@150\text{mm}c/c$

Figure 1. Geometrical properties of the aluminum sandwich panel and its trapezoidal corrugated core where: a) Top view, b) Section A-A, c) One layer and d) Produced panel.

Table 1. Material properties of the aluminum, reinforcing steel and concrete used in this study.

Material	Grade	Young's Modulus	Poisson's Ratio	Strength		Density ρ
		GPa	-	MPa		kg/m ³
Aluminum	6063-T5	70	0.3	$F_y = 130$	$F_u = 175$	2700
Steel reinforcement	B500A	200	0.3	$F_y = 500$	$F_u = 650$	7850
Concrete	C35/45	34	0.17	$F_{cu} = 35$	$F_t = 3.2$	2430

Figure 2. The reinforced concrete slab with its reinforcement details.

and transverse reinforcement of $\emptyset 10\text{mm}@200\text{mm c/c}$, as shown in Figure 2. The material properties for the concrete and the reinforcements are listed in Table 1. The test scheme and loadings are discussed in details in the flowing sections.

2.3 Experimental setup

The sandwich panels are supposed to protect the concrete slab from contact or adjacent detonations. To see the difference, two detonations (1st and 2nd) were performed on a bare slab (Figures 3a and 3b). Then, two other similar detonations (3rd and 4th) were conducted with the addition of the proposed sandwich panels (Figures 3c and 3d). The two pre-cast RC slabs were put on four concrete blocks/supports with 800x800x1600 mm each. The bearing area of the slab is 100x1500 mm on each end, giving a clear slab span of 2800 mm. The four detonations were done in sequence, one after the other with about an hour gap in between to analyze the performance and record the results. Each of the 4 detonations had mass of 1 kg of TNT and was positioned 750 mm far from adjacent slab edges. The stand-off distance for 1st and 2nd detonations (the distance between upper slab surface to the centroid of the explosive device) were 200 mm and 160 mm, respectively (Figure 3b). The stand-off distance for the 3rd and 4th detonations were less, as sandwich panels were glued to the slab, leaving only 40 mm and 0 mm, respectively. The 4th detonation can be considered as a contact detonation attached directly to the sandwich panel's front layer.

The incident and peak reflected over-pressure generated from those 4 explosions, cannot be estimated using the well-known Kingery–Bulmash graphs/empirical equations. The reason is that they are close-range or contact blasts, where at this zone, more complex phenomena take

Figure 3. Field testing scheme with and without proposed sandwich panels. a) Top view-without panels, b) Side view-without panels, c) Top view-with panels and d) Side view-with panels.

place due to afterburning and the violent outflow of the detonation gases (Novak et al., 2016). In other words, the pressure-time curve is not a single peak followed by exponential decay of Friedlander equation. There are limited test data available that might be used to validate the parameters for near regions (Baranowski et al., 2016, Bogosian and Heidenreich, 2012). Based on the mass of the TNT (W in kg) and stand-off distance (R in meters), the scaled distance $Z = (R)/\sqrt[3]{W}$ can be calculated as 0.2, 0.16, 0.04 and 0 m/kg^{1/3} for 1st-4th detonations, respectively. Those Z values are less than the minimum scaled distance 0.4 m/kg^{1/3} required to avoid close-range detonations (Rigby et al., 2015). Based on literature, the peak reflected over-pressure can roughly be estimated as 200, 500, 700 and 900 MPa for the 1st-4th detonation, respectively.

The 1 kg of TNT, refers to the situation when industrial infrastructural elements, such as gas cylinders, are located at a close distance from the structural elements. For example, in case of accidental explosion of 20L of propane cylinder or 20L of acetylene cylinder, they release blast energy equivalent to that of 0.82 kg and 0.86 kg of TNT, respectively (Studziński et al., 2021, Sielicki et al., 2017).

3 RESULTS AND DISCUSSION

3.1 Behavior of RC slab without aluminum panels

In general, the RC slab was able to resist the 1st and 2nd detonations without excessive damage. Figure 4 shows the behavior of the slab to the 1st (Figures 4a and 4b) and 2nd (Figures 4c and 4d) detonations. The upper surface, maintained its integrity, with minor erosion to its surface directly under the centroids of the explosive devices (Figures 4a and 4c). The sides of the slab showed no visible cracks, although micro-cracks may exist. The bottom surface revealed concrete

Figure 4. The failure mechanisms of the RC slab (without aluminum panels) subjected to 2 field detonations of 1 kg of TNT each, 1st and 2nd, a) 1st detonation, top concrete surface behavior, b) 1st detonation, bottom concrete surface behavior, c) 2nd detonation, top concrete surface behavior, d) 2nd detonation, bottom concrete surface behavior.

spalling and part of the reinforcement is visible (Figures 4b and 4d). The mid-span deflection was recorded as 3 mm. The aim of the addition of the sandwich panels in the next section is to see if the tension damage at the bottom surface of the slab would be reduced/prevented.

3.2 Behavior of RC slab with the sacrificial aluminum panels

Based on the testing scheme presented in Figures 3c and 3d, the two panels were glued to the top surface of the concrete (Figure 5a). When the 3rd detonation was first performed, the panel (with mass of 45.2 kg) was lifted and shifted 17.6 m away from the explosion location. The panel frame and the layers were also separated (Figure 5b). A circular local punching shear failure is the dominant behavior of the panel through all its 8 layers (Figures 5c-e). The adjacent panel, at this stage showed minor deformations due to the 3rd detonation (Figure 5b). When the 4th detonation was then performed, a similar panel behavior was observed, although the IED was in a complete contact with the frontal layer of the panel. These results agreed with (Kevin et al. (2013)) that contact detonations have extremely high pressures for just microseconds leading to local shear and punching failure.

The behavior of the concrete slab (with aluminum panels) is shown in Figure 6. The upper surface, under compression, was more deteriorated (Figures 6a and 6c). The bottom surface (under tension) showed bigger areas of spalling with long visible longitudinal and transverse cracks (Figures 6b and 6d). The sides of the RC slab were also cracked with visible damage (Figure 6e). The mid-span deflection was 73 mm. It can be noticed that the addition of sandwich panels worsen the situation rather than protecting the slab. The cracks, damage and deflection were all more. The weight of the two panels (~90 kg) and hence the kinetic energy from those panels might be the reason. Therefore, this study concludes that this type of sandwich panels may be protective in far-field explosion scenarios, but not for close or contact detonations.

Figure 5. The failure modes of the aluminum panel after 3rd detonation.

Figure 6. The failure mechanisms of the RC slab (with aluminum panel) subjected to 2 field detonations of 1 kg of TNT each. a) 3rd detonation, top concrete surface behavior, b) 3rd detonation, bottom concrete surface behavior, c) 4th detonation, top concrete surface behavior, d) 4th detonation, bottom concrete surface behavior, e) Side view of the concrete slab showing cracks and damage.

4 CONCLUSIONS

In this study, the performance and damage behavior of two pre-cast RC slabs were experimentally assessed with and without aluminum trapezoidal-core sandwich panels. The two slabs were subjected to 4 detonations ranging from close to contact explosions. Results showed that the behavior of the slabs was worse with the addition of those panels. More tension damage/cracks were observed. The study concludes that this type of sandwich panels cannot resist close or contact detonations and might be a protective solution for far-field explosion incidents.

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