



# Effectiveness of FRP sandwich panels for blast resistance



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## ABSTRACT

Nowadays, sandwich panels are recognized for their importance in various technical fields especially in aeronautics, automotive, and structural engineering. Light-weight composite material can be used in sandwich panels due to having high stiffness-to-weight ratio. In this study, a numerical model has been conducted to study the effectiveness of fiber reinforced polymer (FRP) sandwich panels under blast effect. Results of numerical model are validated with experimental field tests in the literature. A new inner core configuration is proposed. In the experimental field test, inner core configurations were honeycomb shaped and sand was used as filling material. Newly proposed core configuration is formed of a combination of woven and honeycomb shapes and sand is used as a filling material. The two performance parameters considered in this study are the amount of energy absorbed by panels and their peak deformation. In order to track the enhancement of the panels' performance, a parametric study has been conducted. Moreover, the effect of changing the filling materials has been investigated. A good agreement between the numerical results and the experimental measurements has been realized. Finally, the analyses have revealed that using the new core configuration noticeably enhances FRP panels' behavior under blast loads.

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## 1. Introduction

Recently, blast loads resulting from accidental or intentional events adversely affect different structures and threaten their occupants. Normally, conventional structures are not designed to resist blast loads. Therefore, it is important to give due attention to the design and retrofit of structures against blast loads. Currently, the possibility of providing an adequate level of protection without changing people lifestyle and daily routine through building structures that are more similar to bunkers are one of the main controversial challenges facing researchers.

One of the solutions considered is using maneuverable blast walls to shield buildings and other structures against blast loads. Maneuverable walls act as a reflective surface for blast waves that reduces the blast effect on the targeted building. During higher severity events, maneuverable walls are erected around structures as a first line of defense, increasing stand-off distance. The two main factors taken into consideration for designing maneuverable walls are the ease of assembly and portability. Zhou and Hao [1] studied numerically the effectiveness of blast barriers in reducing blast effect. They stated that while placing a barrier between an explosion and a building, the peak reflected pressures and

impulses created on the surface of a building are reduced, and the arrival time of blast wave is delayed. Such maneuverable walls are beneficial for constructing temporary vital facilities such as barracks and hospitals [2]. Furthermore, these temporary structures can be used in hazardous industrial fields that are vulnerable to blast such as petrochemical industry. In industrial fields, man-made accidents can create explosions that are accompanied with other phenomena such as fire and impacts caused by explosion-borne missiles [3].

The most efficient light-weight maneuverable walls are usually made of sandwich panels [4]. Sandwich panels are composed of three layers; upper skin, inner core, and lower skin [5]. The inner core can have several forms such as honeycomb cores, corrugated cores, truss cores, Z-cores, C-cores, I-cores or solid foam cores. One of the best sandwich panels that are used for maneuverable walls is manufactured from fiber reinforced polymer (FRP) composites. FRP have many advantages that make it highly used as it has high strength-to-weight ratio, resists corrosion, and are easily handled and fabricated. The main factor controlling the behavior of FRP sandwich panel during manufacturing is the core stiffness [6]. The upper and lower skins are bonded to the core by an adhesive polymer such as epoxy resin to form the FRP panels. According to Davalos et al., Alagusundaramoorthy et al., and Ji et al. [7,8], the deflection is the main factor that controls the design of FRP panels. However, changing the inner core topology has significant

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effect on the performance of the whole panel [9]. Davalos and Chen [10] reported that buckling and pure compression failure are the two failure modes usually observed for honeycomb FRP panels. Recently, Rejab and Canwell [11] stated that for corrugated core sandwich panels, the buckling of the core cells is observed as an initial failure. Xiong et al. [12] indicated that the failure modes for pyramidal truss FRP cores are layers' debonding, face layer crushing, face layer wrinkling, core member buckling, and core member crushing. Du et al. [13] stated that for Z-pin reinforced polymer foam core, two failure modes occurred; a series of pins are pulled out from the face layers and cracks in the foam. Chen and Davalos [14] showed that the number of bonding layers and the thickness of the core are the main factors controlling the maximum shear strength achieved.

In the last two decades, the dynamic behavior of sandwich panel under blast loading has been the area of investigation for many researchers. Xue and Hutchinson [15] stated that it is way better to compare the blast effect resistance of a well-designed sandwich panel with a solid panel having the same weight. In addition, they have proven that the sandwich panel dissipates significantly more energy than a solid plate of the same material and mass due to the ability of the core truss structure to deform plastically. Fleck and Deshpande [16] studied different sandwich core topologies under the effect of both; air and water blast. They concluded that the best performance is obtained by the diamond-celled core sandwich beam due to the longitudinal strength provided by the core. Jacob et al. [17] mentioned that the main factors that increase the energy absorption capabilities are mainly; the decrease in the FRP density, the increase in strain capacity, and the increase in the fracture toughness of the inter-laminar. In this regard, Zhou et al. [18] concluded that the increase in the core density slightly increases the panel's ultimate load and the energy absorption capacity. Also, Langdon et al. [19] stated that debonding between layers, perforation of the panels, bending and stretching of the glass fibers, and spalling of the back layers highly increase the energy absorption resulted from blast loads. Furthermore, Langdon et al. [20] stated that the delamination, core compression, and fiber fracture increase the energy absorption of the sandwich panels. Su and McConnell [21] stated that energy absorption capability of the composite sandwich panels is highly affected by the density and the tensile strength. Also, they concluded that the failure in the middle core is not only acceptable, but rather desirable as it increases the energy absorption. Hoemann [2] studied experimentally the behavior of FRP sandwich panels under blast loads and fragmentation. During the experiment, four sandwich panels with different inner core configurations and the same weight of explosives were tested. The inner core configurations were formed from different orientations of the honeycomb shape and were filled with sand. It was noticed that the shear flow controls the overall performance of the panels. Arora et al. [22] studied glass fiber reinforced polymer (GFRP) sandwich structures subjected to blast loads. They demonstrated that, under blast explosion, displacement and in-plane strain data can be reliably obtained for GFRP sandwich panels. Jackson and Shukla [23] stated that the damage to the front face negatively affects the performance of the sandwich composite more than the damage to the back face sheet. Tekalur et al. [24] demonstrated that increasing the stitching density significantly reduces the damage occurred in the sandwich panels.

Using sandwich panels with filling materials improves their behavior [25]. In this regard, Børvik et al. [26] investigated aluminum sandwich panels to be used in protecting a 20 ft ISO container. The results showed that ballistic and blast load resistance were enhanced when using granular material as a filling material. Zhang et al. [27] studied analytically and numerically the compressive strengths and dynamic response of corrugated sandwich

plates with unfilled and foam-filled sinusoidal plate cores. They concluded that filled foams can significantly increase the normal compressive strengths of the corrugated sinusoidal plate cores. Yan et al. [28] studied Sandwich panels having metallic corrugated cores under three-point bending, once without filling material and another time using foam as a filling. As a result, bending stiffness, initial failure load, peak load, and sustained load-carrying capacity after peak failure were increased on using foams as filling material. Yazici et al. [29] concluded that maximum deflections can be reduced by more than 50% upon using filling material.

This paper presents numerical evaluation of the effectiveness of a proposed FRP sandwich panel in resisting blast loads. Hoemann [2] experimental tests have been used to validate the finite element model. A parametric study has been conducted to examine more variations of the studied parameters. Also, the effect of changing filling materials has been investigated. The conducted studies aim to achieve better enhancements for the panels resisting blast loads.

## 2. Numerical model validation

Based on the experimental work conducted by Hoemann at Tyndall Air Force Base, Florida [2], a numerical model has been simulated. The numerical results have been compared to the experimental measurements for validation. The dynamic nonlinear explicit software ANSYS AUTODYN [30] has been used for the numerical model simulation. The software is suited to solve fluid dynamics equations and simulate three-dimensional blast wave propagation with multiple reflections and refraction. Fig. 1 is a schematic representation of the numerical model. It shows the interaction of the incident wave and the reflected wave resulted from explosion. Following the experimental work setup of Hoemann [2] shown in Fig. 2, the center of explosion is 10.7 m from the simulated panel and is elevated at 1.8 m from the ground surface. The modeled panel is 1800 mm height (Y-axis), 2600 mm width (Z-axis), and 360 mm thickness (X-axis). In the experimental test [2], the four panels were exposed to the same explosion at the center of the four tested panels and at the corner of each panel, whereas in the numerical simulation in this paper, each panel is simulated separately and the explosion is applied at the corner of each panel following the experimental setup.

The FRP panels are defined as Lagrangian elements while the air domain is defined as Euler elements. Contrary to Eulerian analysis, in the Lagrangian analysis no material movement between two elements would occur in case of deformation, whereas in Eulerian analysis, a material movement occurs between mesh elements. On the other hand, filling materials are defined as Smooth Particle Hydrodynamics (SPH). SPH is a gridless Lagrangian technique, therefore it is suitable for modeling filling material to avoid mesh tangling problems. The TNT explosion is simulated by using the remapping method (e.g. [31]) to imitate the reflection and diffraction of blast loads. In the remapping method, the initiation of explosion is modeled as 1D wedge with fine mesh (0.25 mm

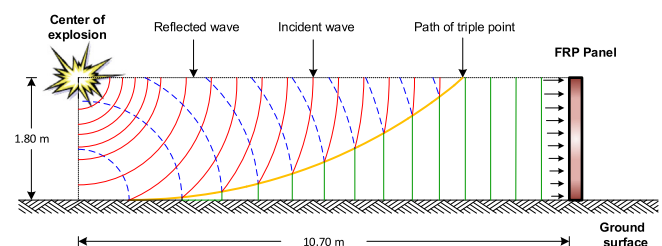


Fig. 1. Schematic of numerical models.

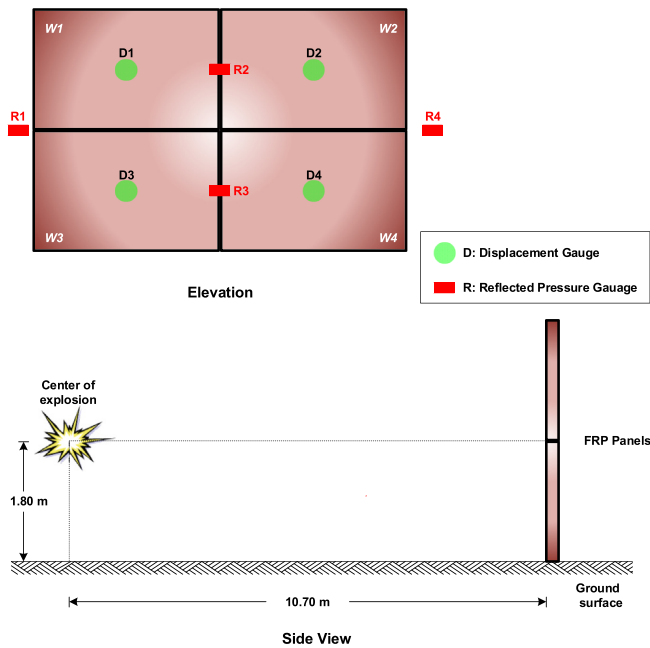


Fig. 2. Schematic of the experimental models. adapted from Hoemann [2].

thickness) to obtain higher accuracy with minimum processing time. On the other hand, the propagation of explosion is modeled as 3D model with mesh size of 30 mm and aspect ratio of 1.0 based on convergence studies that aim to keep the models within a computationally manageable range.

The Orthotropic equation of state (EOS) was used to model FRP material. The strength model parameter used is the Orthotropic Yield, whereas the failure model parameter used is the Orthotropic Softening. In this study, fiber orientation and layers' delamination are not taken into consideration. Lagrange and Euler elements exchange impulses at their interfaces. To simulate the interaction between the FRP structure and air domain, the interaction is defined as fully coupled where Lagrange elements interact dynamically with Euler elements. On the other hand, the interaction between the Lagrange FRP element and SPH filling materials is defined as gap contact, where the interaction follows conservation of angular and linear momentum [32]. Hinged boundary conditions are applied along the full height to the two vertical sides of the modeled FRP panel. Whereas the bottom and top elements of the modeled panel are set to be free. A bonded contact is used for joining the nodes of the FRP panels. By default, the bonded contact is unbreakable unless a stress failure criteria are defined [32]. In this study, stress failure criteria are defined as the maximum normal stress limit is 9.6 MPa and the maximum shear stress limit is 36.4 MPa, as per the manufacturer data sheet [33].

Fig. 3 shows the pressure time history of the experimental field test [2] and the numerical model. Four gauges were installed during the experimental tests (R1 to R4) as shown in Fig. 2. Gauge R3 was considered as a defective gauge. As for the numerical model, the pressure gauge is located at the wall panel center  $(x, y, z) = (10.7, 0.9, 1.3)$  m where the peak pressure value is 1215 kPa. Such value is nearly the same as the average reading of the three field pressure gauges. Fig. 4(a)–(d) presents the experimental and numerical deflection time histories of the four considered panels (W1 to W4). W1 and W2 (thin panels) are of the same dimensions, yet, they differ in inner core configurations. However, W3 and W4 (thick panels) have the same inner core configurations as W1 and W2, but differ in dimensions. During the experimental test, W1, W2, W3 and W4 were filled with sand. As shown in the figures, the numerical model showed good agreement with the experimen-

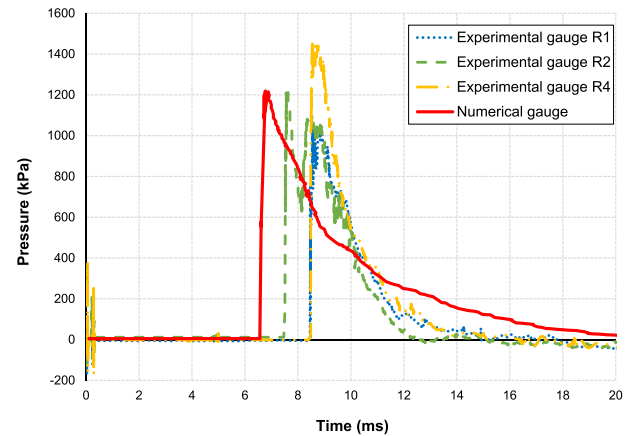


Fig. 3. Experimental [2] vs numerical pressure time histories.

tal test until reaching the rebound phase with maximum deviation ranges between 3% and 18%. However, a discrepancy was noticed after reaching the rebound phase. Such discrepancy might be due to the failure of the clamping anchorage joints upon reaching the panels' rebound phase in the experimental test. Whereas during the numerical simulation, such failure has not been taken in consideration and boundary conditions remain the same during the whole analysis. An early rebound phase was noticed for W3, which can be attributed to the fact that W3 has a stiff core thus it deflects in its elastic range, which results in partial bond failure and the stored energy is recovered during the rebound phase [2].

### 3. Proposed FRP sandwich panel

The proposed FRP panel is formed of a new inner core configuration, which is formulated from a combination of woven and honeycomb shapes. In order to compare the analyzed results, the same amount of FRP material used in W3 and W4 has been maintained. Also, the modeled FRP panel has the same dimension and has been filled with sand as the thick panels (W3 and W4). Fig. 5 shows the inner core configuration for W3 and W4, where the core of W3 is represented by "TRW axis" while the core of W4 is represented by "PW axis". Sinusoidal core layers similar to the layers used in the experimental panels (W1 to W4) form the inner core configuration. Sinusoidal core layers are used as layers for the honeycomb shape or cutting strips for the woven shape. Fig. 6 illustrates the FRP sandwich panel with the two main inner core configurations considered in the analyses, woven and honeycomb shapes. Configuration (a) consists of perpendicularly interlaced strips that form the woven shape. "WV2-1 strips" represent Configuration (a). It consists of two strips from the sinusoidal layer in the longitudinal direction and one fill from the sinusoidal strip in the transverse direction. On the other hand, configuration (b) – represented by "RW axis" – is formed of sinusoidal layers that are separated by flat layers in between, forming a honeycomb shape. The inner core configurations are formed of four layers of WV2-1 and one layer of RW. Each two layers are separated with a flat layer. These four layers are divided into two layers at the top (TL) of 110 mm total thickness and other two layers at the bottom (BL) with the same total thickness. In between the TL and BL, the RW layer is placed with a thickness of 120 mm.

The main objective of the proposed FRP panel is to enhance the behavior of the FRP panels used in the experimental tests under blast loading. The decrease in the panel's peak deflection and the increase in its energy dissipation (ED) are the two main factors for enhancing the panel's behavior. The panel's peak deflection can represent the panel's level of damage [34]. For the simulated

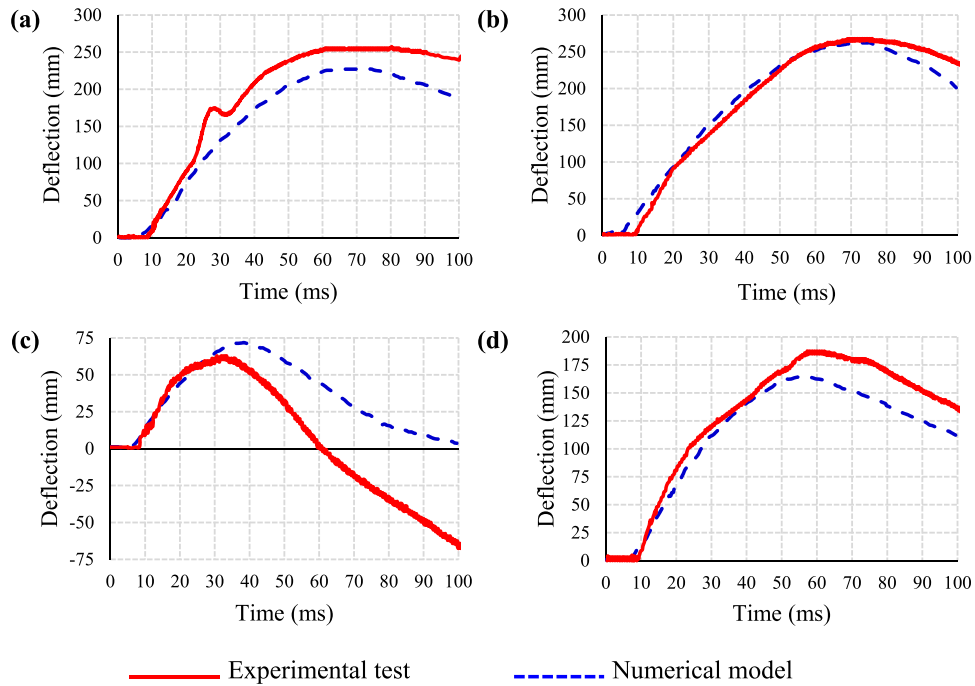


**Fig. 4.** Numerical model validation against experimental results [2] for (a) W1, (b) W2, (c) W3, and (d) W4.

#### FRP Sandwich Panel

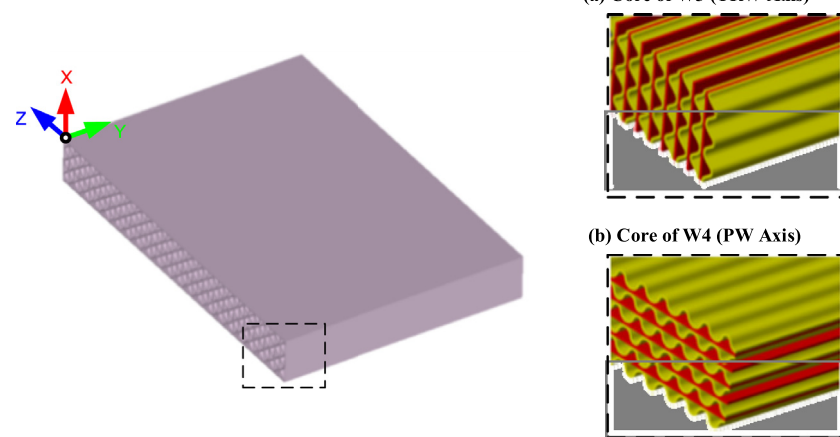


**Fig. 5.** Inner core configurations of the validated FRP sandwich panel; (a) core of W3 and (b) core of W4.

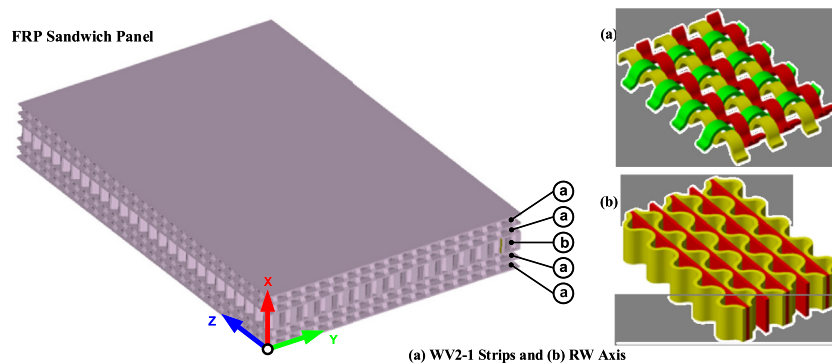


**Fig. 6.** Inner core configurations of the proposed FRP sandwich panel; (a) WV2-1 Strips and (b) RW Axis.

test panels, W3 has a peak deflection value of 72 mm, maximum chord rotation,  $\theta_{\max}$  of  $3.2^\circ$ , and energy dissipation of 121 J. Accordingly, W3 is a stiff panel of low deflection and low energy dissipation capability. On the other hand, W4 has a peak deflection value of 163 mm,  $\theta_{\max}$  of  $7.2^\circ$ , and energy dissipation of 268 J. Therefore, W4 is a soft panel of high deflection and high energy dissipation capability. Fig. 7 represents the time history of the central point deflection for the FRP panels; the proposed panel (W5) with the simulated thick test panels (W3 and W4). As shown in the figure, the peak deflection of the new proposed panel W5 is 67 mm reduced by 7% comparing to W3 and by 59% comparing to W4 which decreases the value of  $\theta_{\max}$  to  $2.95^\circ$ . Besides, an increased arrival time of peak deflection has been achieved. Whereas, under the same conditions, it is noticed that the energy dissipation of W5 is 256 J; 111% increase and 4% decrease have been realized compared to W3 and W4, respectively. From the four studied FRP shapes (TRW axis, PW axis, RW axis, and WV2-1 strips), RW axis is the stiffest shape as the core is aligned with the loading direction however it has low energy dissipation [35]. On the other hand, the woven shape represented by WV2-1 has high energy dissipation capabilities with a reasonable strength, as interlacing the strips forming the woven shape allows a good distribution of stresses. Therefore, combining the stiff core RW with WV2-1 in W5 resulted in having low-peak deflection as W3 and high-energy absorption as W4.

The effect and efficiency of geometrical shapes on the modes of failure of the three sandwich cores used in W3, W4, and W5 was compared. The results showed that the expected modes of failure for the TRW axis shape are: failure due to buckling of the flat vertical layers, failure due to crushing of the flat vertical layers, or bond failure between the flat vertical layers and its attached sinusoidal layers. In this shape (TRW), failure due to buckling of vertical plates is expected to occur in later stages after a bond failure between flat vertical layers and sinusoidal ones takes place first. This is attributed to the increase in critical buckling load capacity as a result of the multiple points of fixation between the sinusoidal layers along the vertical layer depth. In this study, a shear failure occurred which resulted in partial bond failure between the flat vertical layers and its attached sinusoidal layers. Whereas for the PW axis shape, three modes of failure are expected, which are: bond failure between horizontal sinusoidal layers and horizontal flat layers, fiber tensile/compression failure of the horizontal flat layers, or compression and wrinkling failure of the sinusoidal FRP layers. In this study, a complete bond failure is detected between the core layers due to the shear load transfer. Finally, for the proposed shape (W5), the expected modes of failure are: bond failure between the core layers or fiber crushing of the sinusoidal strips. Fig. 8 shows the failure mode of the proposed panel considered in the analysis. The failure that occurred in the panel is due to shear failure of bond between the FRP layers. A complete bond fail-

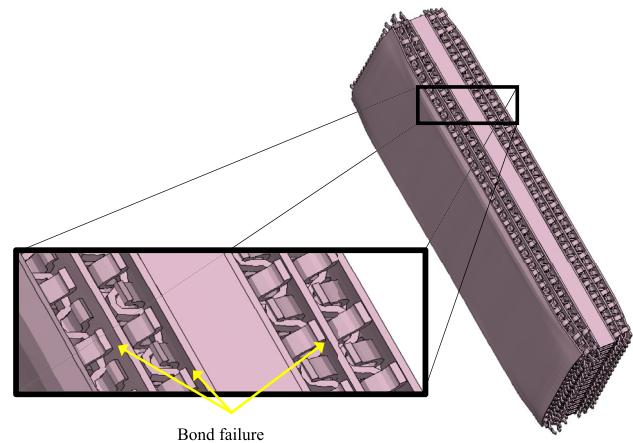


Fig. 8. Failure pattern of the proposed panel W5.

ure has occurred between few nodes of the sinusoidal strips and the flat layers, where it occurs in the edges nodes at the maximum shear.

#### 4. Parametric study

Parametric analysis has been carried out on WV2-1 layers to better understand the performance of the proposed FRP panel against blast loads. During the study, the effect of changing parameters on energy dissipated by the panel, the maximum deflection of the panel, the maximum chord rotation, and the energy-to-chord rotation ratio ( $E/\theta$ ) have been studied.  $E/\theta$  is defined as the total energy dissipated by the panel relative to the panel's maximum chord rotation. The higher value of  $E/\theta$  ratio is an indication for the panel's capability of absorbing a higher amount of energy with less deformations and less amount of damage. Fig. 9 shows schematics of elevation and cross section of WV2-1 strips, where  $t$  is the thickness of sinusoidal and flat layers,  $h$  is the height of sinusoidal layer,  $L$  represents a single sinusoidal wave length, and  $W$  is the width of one strip. It is worth mentioning that W5 has the same sinusoidal and flat layers' dimensions and amount of material—as the thick experimental panels. Accordingly, all results obtained from the other analyzed panels and the amount of used materials are compared with W5.

##### 4.1. Effect of length, width and height

Table 1 illustrates the effect of changing the layers' height ( $h$ ), wave length ( $L$ ), and the strip width ( $W$ ) on the panel's performance. Accordingly, Fig. 10 shows the time history of the central point deflection of the FRP panels with the changed parameters. In the study, nine panels including W5 have been studied. The three different heights ( $h$ ) considered in this study are 50, 30, and 110 mm. In order to maintain the total thickness of the TL and BL constant equals to 110 mm, the change in height is always associated with a change in the number of layers. The increase/decrease in the material weight (% Mass) – as a result of the dimensions' change – is illustrated in the table. The “No. of layers” column represents the total number of layers in both TL and BL. As listed in the table, the decrease in the height leads to better performance, as the energy dissipation increases by up to 25%, and panels' peak deflection decreases by up to 13.4%. Moreover, the decrease in the wave length slightly enhances the performance of the panels. Comparing W6 with W5, W9 with W8, and W12 with W11, the energy dissipation increases by 2.7%, 2.9%, and 6.9%, respectively. However, the panels' peak deflection decreases by 1.5%, 3.3%, and 7.3%, respectively. The comparison between these

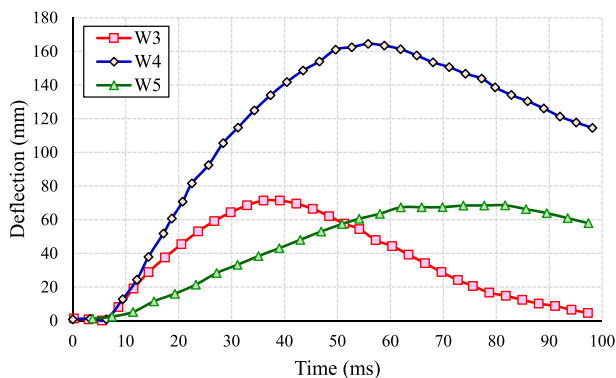


Fig. 7. Time history of central point deflection for the proposed panel.

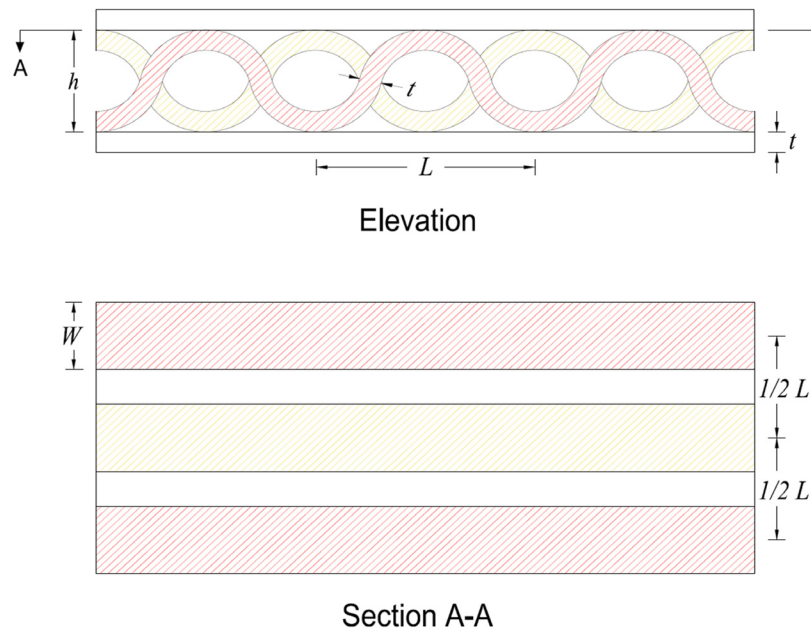


Fig. 9. Woven core sandwich panel schematic.

**Table 1**  
Effect of length, width, and height variations.

| Panel | $h$ (mm) | $L$ (mm) | $W$ (mm) | $t$ (mm) | No. of layers | % Mass | ED (J) | $\Delta_{\max}$ (mm) | $\theta_{\max}$ (°) | E/ $\theta$ | % E/ $\theta$ |
|-------|----------|----------|----------|----------|---------------|--------|--------|----------------------|---------------------|-------------|---------------|
| W5    | 50       | 100      | 33       | 10       | 4             | –      | 256    | 67                   | 2.95                | 86.8        | –             |
| W6    |          | 80       | 24       |          |               | +6.4   | 263    | 66                   | 2.91                | 90.4        | +4.1          |
| W7    |          | 120      | 40       |          |               | –6.6   | 249    | 69                   | 3.04                | 81.9        | –5.6          |
| W8    | 30       | 100      | 33       |          | 6             | +42.8  | 311    | 60                   | 2.64                | 117.8       | +34.8         |
| W9    |          | 80       | 24       |          |               | +44.2  | 320    | 58                   | 2.56                | 125.0       | +44.0         |
| W10   |          | 120      | 40       |          |               | +39.7  | 299    | 62                   | 2.73                | 109.5       | +26.1         |
| W11   | 110      | 100      | 33       |          | 2             | –37.3  | 203    | 96                   | 4.23                | 48.0        | –44.7         |
| W12   |          | 80       | 24       |          |               | –27.0  | 217    | 89                   | 3.92                | 55.4        | –36.2         |
| W13   |          | 120      | 40       |          |               | –47.5  | 184    | 103                  | 4.54                | 40.5        | –53.3         |

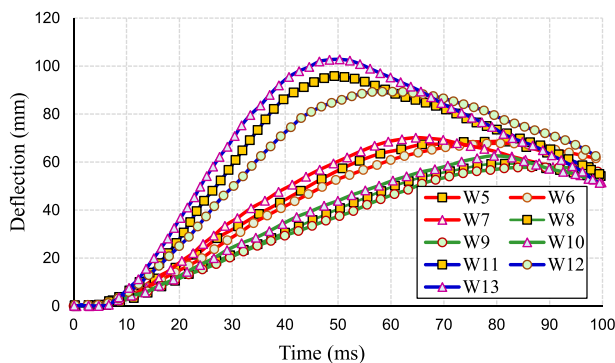


Fig. 10. Central point deflection time histories with changed parameters.

panels is only for guidance as the nine analyzed panels have different weights of material.

#### 4.2. Effect of thickness

The effect of changing layers' thickness ( $t$ ) on the panel's performance is illustrated in Table 2. Fig. 11 shows the time history of the central point deflection of W5 and W8 with different thickness. W5 and W8 panels are analyzed under four different thickness values: 10, 9, 8, and 7 mm. From the analyses, it is found that the decrease

in thickness of simulated panels has no effect on energy dissipation. Upon changing each of the panel's thickness, a maximum of 0.8% variation is obtained. On the other hand, changing thickness significantly affects the panels' peak deflection, where a difference of up to 19.4% is obtained. Moreover, when comparing the material weight used in the simulated panels (% Mass) with the change in energy-to-chord rotation ratio (% E/ $\theta$ ), the analyses show an interesting behavior of the panels. For instance, upon decreasing the material weight of W5 by 27.8%, the energy-to-chord rotation ratio decreases to 16.6% only. Regarding W8, the energy-to-chord rotation ratio is reduced to 13.7% upon decreasing the material weight by 28.2%. Additionally, when comparing the structural behavior of W5 and W8 (with  $t = 7$  mm), the energy-to-chord rotation ratio of the latter panel is increased by 17.1%; although both panels almost have the same material weight. Therefore, decreasing the thickness enhances the panels' performance. This is due to the failure in the bond between the FRP layers that has occurred in the simulated panels. Therefore, it could be said that the structural behavior is not affected with the decrease in the thickness of used panels the same way as much as it is affected by the number of bonds contacts and number of layers.

#### 4.3. Constant weight

Table 3 and Fig. 12 illustrate the effect of changing the dimensions of sinusoidal and flat layers on the panel's performance while

**Table 2**  
Effect of thickness variations.

| Panel | <i>h</i> (mm) | <i>L</i> (mm) | <i>W</i> (mm) | <i>t</i> (mm) | No. of layers | % Mass | ED (J) | $\Delta_{\max}$ (mm) | $\theta_{\max}$ (°) | E/ $\theta$ | % E/ $\theta$ |
|-------|---------------|---------------|---------------|---------------|---------------|--------|--------|----------------------|---------------------|-------------|---------------|
| W5    | 50            | 100           | 33            | 10            | 4             | –      | 256    | 67                   | 2.95                | 86.8        | –             |
|       |               |               |               | 9             |               | –8.8   | 257    | 72                   | 3.17                | 81.1        | –6.6          |
|       |               |               |               | 8             |               | –18.2  | 254    | 76                   | 3.35                | 75.8        | –12.7         |
|       |               |               |               | 7             |               | –27.8  | 255    | 80                   | 3.52                | 72.4        | –16.6         |
| W8    | 30            | 100           | 33            | 10            | 6             | +42.8  | 311    | 60                   | 2.64                | 117.8       | +35.7         |
|       |               |               |               | 9             |               | +29.8  | 309    | 64                   | 2.82                | 109.6       | +26.3         |
|       |               |               |               | 8             |               | +16.3  | 310    | 66                   | 2.91                | 106.5       | +22.7         |
|       |               |               |               | 7             |               | +2.5   | 309    | 69                   | 3.04                | 101.6       | +17.1         |

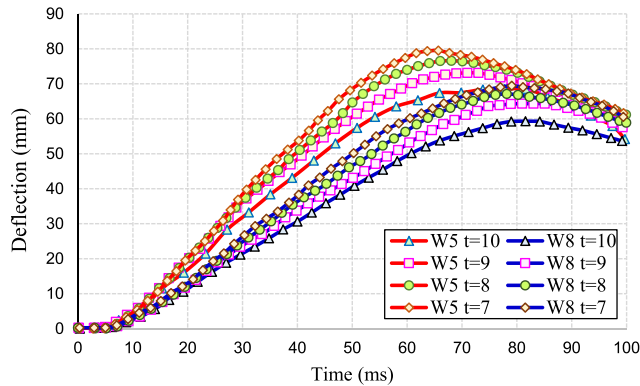


**Fig. 11.** Central point deflection time histories of W5 and W8 with different thickness.

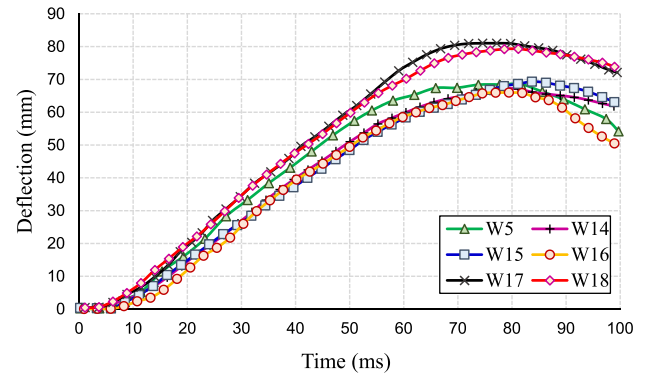


**Fig. 12.** Central point deflection time histories of panels with constant weight.

keeping the weight of material constant. Six panels including W5 have been studied. As shown in the table, three different heights (*h*) have been used for each two panels. The heights used are 50, 30, and 110 mm, respectively. As for the wave lengths (*L*), 100 and 80 mm are used across the three different wave heights mentioned. This means that each two waves of the same height are once tested using a 100 mm wave length and once using an 80 mm wave length. In order to maintain the same material weight, the strip width (*W*) and layers' thickness (*t*) are changeable. The panels that have been tested with 30 mm height (W15 and W16) have resulted in a superior performance compared to panel W5. Increasing the number of layers while decreasing the layers' thickness (*t*) in W15 has increased the energy dissipation by 20.3% and the panels' peak deflection by 2.9%. Relatively, the energy-to-chord rotation ratio increases by 16.7%. On the other hand, in W16, the energy dissipation has increased by 24.2% and the panels' peak deflection has decreased by 1.5%. Accordingly, the energy-to-chord rotation ratio has increased by 25.9%. This is attributed to the decrease in layers' heights that has increased the number of layers and, by default, the number of bonds contacts for W15 and W16. Also, the decrease in wave length (*L*) has resulted in increasing the number of the bonds contacts when comparing W16 with W15. Therefore, W16 shows better results than W15 and all other panels.

**Table 3**  
Effect of changing sinusoidal dimensions with constant weight.

| Panel | <i>h</i> (mm) | <i>L</i> (mm) | <i>W</i> (mm) | <i>t</i> (mm) | No. of layers | ED (J) | $\Delta_{\max}$ (mm) | $\theta_{\max}$ (°) | E/ $\theta$ | % E/ $\theta$ |
|-------|---------------|---------------|---------------|---------------|---------------|--------|----------------------|---------------------|-------------|---------------|
| W5    | 50            | 100           | 33            | 10            | 4             | 256    | 67                   | 2.95                | 86.8        | –             |
| W14   |               | 80            | 23            | 10            |               | 261    | 66                   | 2.91                | 89.7        | +3.3          |
| W15   | 30            | 100           | 33            | 6.8           | 6             | 308    | 69                   | 3.04                | 101.3       | +16.7         |
| W16   |               | 80            | 23            | 6.8           |               | 318    | 66                   | 2.91                | 109.3       | +25.9         |
| W17   | 110           | 100           | 36            | 15            | 2             | 192    | 81                   | 3.57                | 53.8        | –38.0         |
| W18   |               | 80            | 25            | 13.8          |               | 220    | 79                   | 3.48                | 63.2        | –27.2         |

#### 4.4. Effect of wave peak length

**Fig. 13** shows schematics of WV2-1 strips with wave peak length  $\geq 0$ . Wave peak length represented by (b) is changed to investigate its effect on the panel's performance. W5, W15, and W16 panels with the same material weight are analyzed under different wave peak length values. For W5, seven panels are studied where the wave peak length has been increased by 5 mm increments ranging in length from 0 to 30 mm; whereas for W15, five panels are studied where the wave peak length has been increased by 5 mm increments ranging in length from 0 to 20 mm. Finally, for W16, seven panels are studied where the wave peak length has been increased by 2.5 mm increments ranging in length from 0 to 15 mm. As the maximum value of wave peak length that can be reached is controlled by keeping strip layers contactless – strips are jointed only with flat layers – it is understood that the maximum peak wave length varies for each of the three studied panels. This means that maximum peak wave length for W5, W15, and W16 is 30, 20, and 15 mm, respectively.

**Fig. 14** demonstrates the effect of changing wave peak length on the energy-to-chord rotation ratio for W5, W15, and W16 panels. From the figure, it is shown that on increasing the wave peak length, the energy-to-chord rotation ratio increases until it reaches the peak value then decreases gradually. For the three studied panels, reaching the peak wave length differs from one panel to

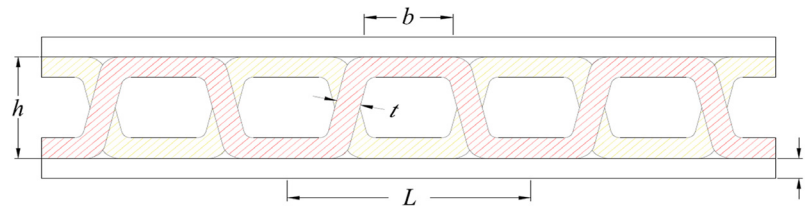


Fig. 13. Schematic of a woven core sandwich panel with wave peak length  $\geq 0$ .

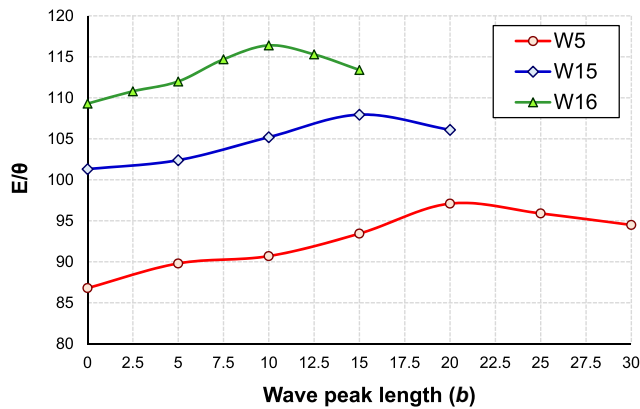


Fig. 14. Effect of peak length variations.

another. For W5, the maximum energy-to-chord rotation ratio is reached at wave peak length of 20 mm. Comparing the increase in  $E/\theta$  of changing the wave peak length from 0 to 20 mm, the  $E/\theta$  increases by 11.9%. As for W15, the maximum energy-to-chord rotation ratio is at wave peak length of 15 mm. Comparing the increase in  $E/\theta$  of changing the wave peak length from 0 to 15 mm, the  $E/\theta$  increases by 6.5%. Finally for W16, the maximum energy-to-chord rotation ratio is at wave peak length of 10 mm. Comparing the increase in  $E/\theta$  of changing the wave peak length from 0 to 10 mm, the  $E/\theta$  increases by 6.6%. This is attributed to the bond failure between FRP layers in simulated panels. As a result, the initial increase in the wave peak length increases bonding area which in return increases the panels' performance. However, the excessive increase in the wave peak length allows the

angle of diagonal ribs forming the strips to be more vertical which results in a stiffer panel and hence reduces its energy dissipation capabilities and its  $E/\theta$  ratio. A new comparison is conducted after obtaining the best results from the above mentioned analyses. The comparison is between W5 (with  $b = 0$ ) which has the same sinusoidal and flat layers' dimensions as the experimental panels and W16 (with  $b = 10$  mm) which has obtained the best results. As a result, the  $E/\theta$  has increased by 34.3%.

From the parametric study, it can be said that increasing the contact points results in better performance up to a certain level when strips reaches high stiffness value. Once a high stiffness value is reached, the panel's energy dissipation capabilities are reduced and hence its performance decreases as well. Therefore, it is recommended to have optimized panels that get the highest energy dissipation with reasonable strength. Moreover, woven shapes are advantageous for being formed of woven strips which can be conveniently distributed at unequal spacing along the panel based

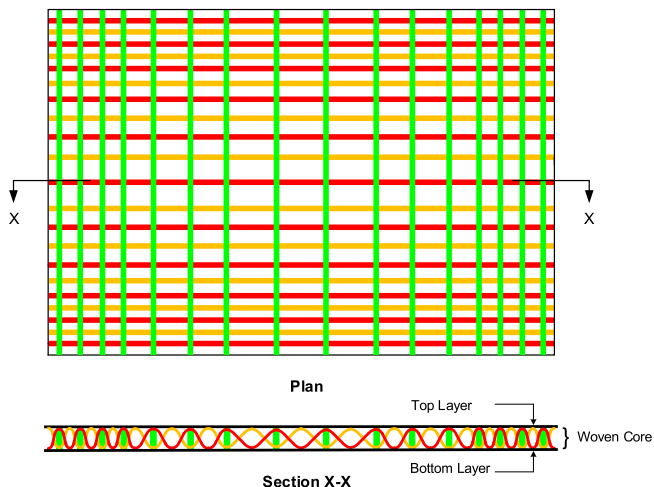


Fig. 15. Schematic of possible distribution of strips to optimize effectiveness of woven panels.

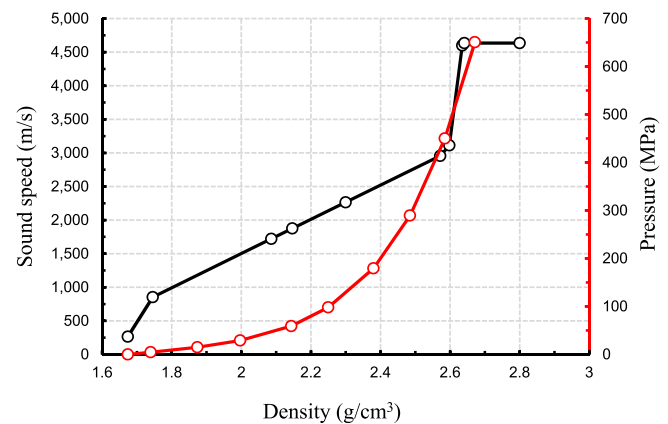


Fig. 16. Compaction of sand, adapted from Laine and Sandvik [36].

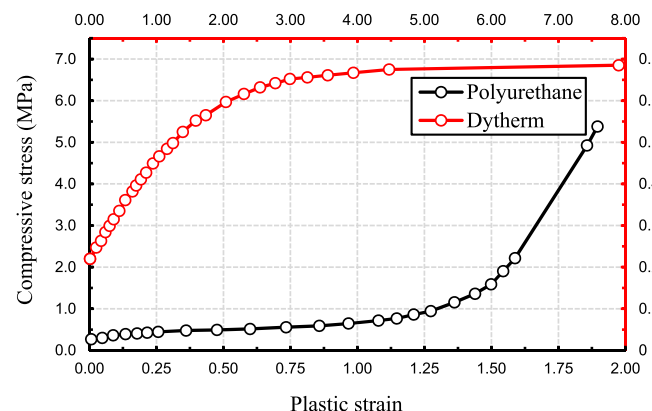


Fig. 17. Compaction of polyurethane and dytherm foams, adapted from Goel et al. [37].

on the observed failure that occurred in the panels that have equally-spaced woven strips. Since a shear failure has occurred at the maximum shear location at the edges of the panel, the optimized panels can increase the bond contact at the edges as schematically shown in Fig. 15. Increasing contact points at the edges results in changing the shape of the corrugated wave which leads to a stiffer area.

## 5. Filling material

Thick experimental panels (W3 and W4) and all of the proposed FRP panel are filled with sand. In this study, the mechanical properties of sand material used have been defined according to Laine and Sandvik [36]. The mechanical properties of the sand are

**Table 4**  
Mechanical properties of polyurethane and dytherm foam.

| Mechanical properties       | Polyurethane foam | Dytherm foam |
|-----------------------------|-------------------|--------------|
| Density, kg/m <sup>3</sup>  | 60                | 100          |
| Young's modulus, (MPa)      | 7.5               | 3.0          |
| Shear modulus, (MPa)        | 6.2               | 4.3          |
| Compressive strength, (MPa) | 0.20              | 0.22         |
| Tensile strength, (MPa)     | 0.02              | 0.02         |

defined as the granular material model. This material model is based on defining the compaction and the compaction wave of a porous material, where an equation of state “Compaction” is used. For the sand, density depends on both the longitudinal and shear wave velocities. The bulk sound speed is obtained from the longitudinal and shear wave velocities to define the elastic loading/unloading compaction curve, whereas the plastic compaction curve is defined by density as a function of pressure. The failure model parameter used for the sand is Hydro Tensile. Fig. 16 shows the compaction curves for sand. In the current study, W3, W4, W5, W15, and W16 are studied once without filling material and another time while using foam as a filling material. Two types of foam are considered; polyurethane and dytherm foam. The material properties and compaction curves for the considered foams are defined according to Goel et al. [37]. Fig. 17 shows the compaction curves for the polyurethane and dytherm foam and Table 4 lists the mechanical properties for the two considered foam types. The failure model parameter used for the foams is principle stress.

Fig. 18 represents the time history of central point deflection for W3, W4, W5, W15, and W16 with different filling materials; sand, no filling, polyurethane foam and dytherm foam. Table 5 illustrates the effect of changing the filling material on panel's performance. Table 6 represents a comparison between the original panels – using sand as a filling – and the other panels with different filling

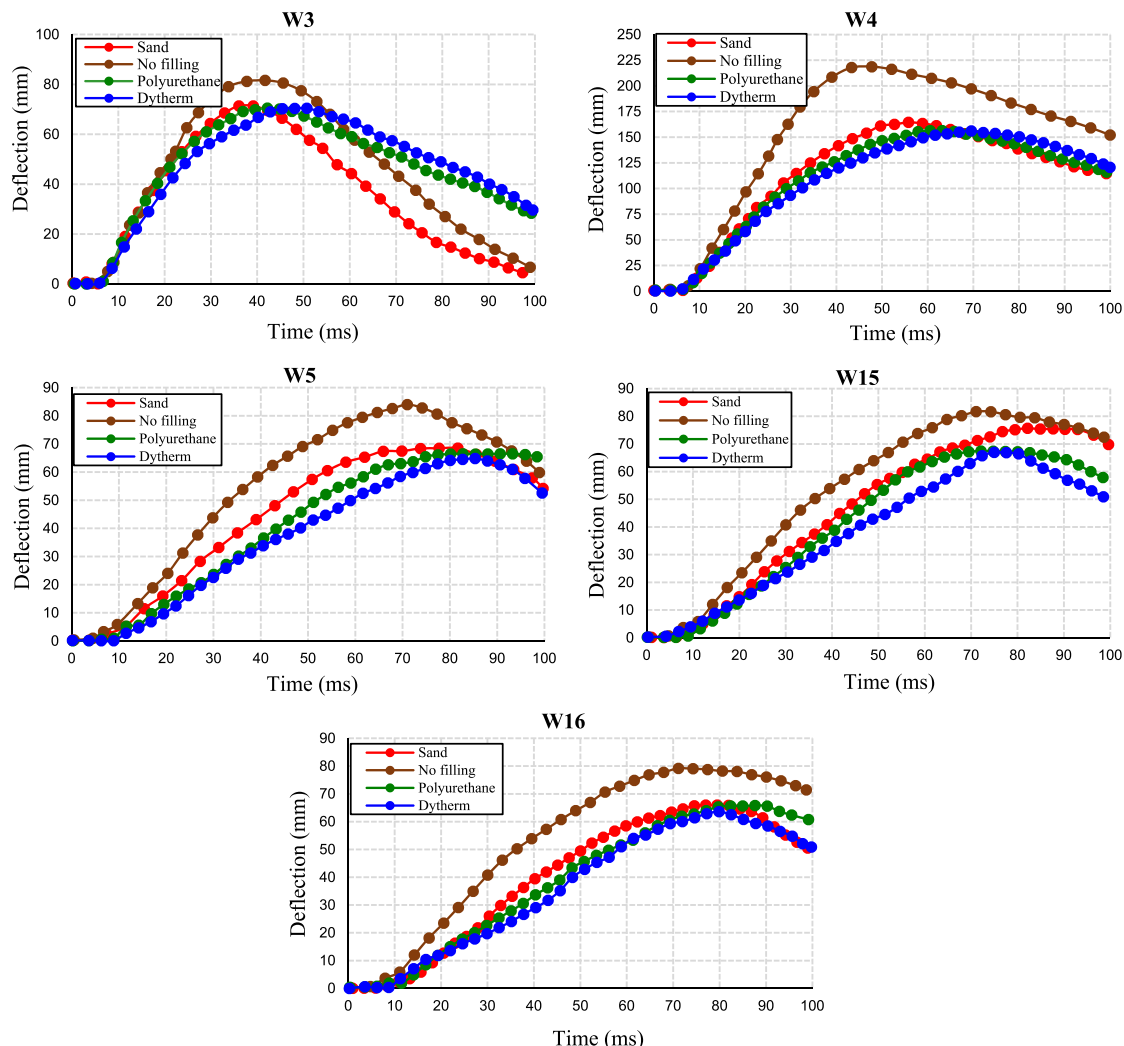


**Fig. 18.** Time history of the central point deflection for different filling materials.

**Table 5**  
Effect of filling materials on panel deformations and energy dissipation.

| Panel | With sand |                      |             | Without sand |                      |             | Polyurethane |                      |             | Dytherm |                      |             |
|-------|-----------|----------------------|-------------|--------------|----------------------|-------------|--------------|----------------------|-------------|---------|----------------------|-------------|
|       | ED (J)    | $\Delta_{\max}$ (mm) | E/ $\theta$ | ED (J)       | $\Delta_{\max}$ (mm) | E/ $\theta$ | ED (J)       | $\Delta_{\max}$ (mm) | E/ $\theta$ | ED (J)  | $\Delta_{\max}$ (mm) | E/ $\theta$ |
| W3    | 121       | 72                   | 38.1        | 103          | 82                   | 28.5        | 140          | 70                   | 45.2        | 142     | 70                   | 45.8        |
| W4    | 268       | 163                  | 37.3        | 205          | 219                  | 21.2        | 299          | 157                  | 43.3        | 307     | 156                  | 44.6        |
| W5    | 256       | 67                   | 86.8        | 228          | 84                   | 61.6        | 287          | 66                   | 98.6        | 291     | 65                   | 101.6       |
| W15   | 308       | 69                   | 101.3       | 266          | 82                   | 73.6        | 324          | 68                   | 108.1       | 330     | 67                   | 111.8       |
| W16   | 318       | 66                   | 109.3       | 282          | 79                   | 81.0        | 335          | 66                   | 115.1       | 339     | 64                   | 120.2       |

**Table 6**  
Comparison between panels of different filling materials.

| Panel | Without sand |                     |                 | Polyurethane |                     |                 | Dytherm |                     |                 |
|-------|--------------|---------------------|-----------------|--------------|---------------------|-----------------|---------|---------------------|-----------------|
|       | ED (%)       | $\Delta_{\max}$ (%) | E/ $\theta$ (%) | ED (%)       | $\Delta_{\max}$ (%) | E/ $\theta$ (%) | ED (%)  | $\Delta_{\max}$ (%) | E/ $\theta$ (%) |
| W3    | −14.8        | 13.9                | −25.2           | 15.7         | −2.8                | 18.6            | 17.4    | −2.8                | 20.2            |
| W4    | −23.5        | 34.4                | −43.2           | 11.6         | −3.7                | 13.7            | 14.6    | −4.3                | 19.6            |
| W5    | −10.9        | 25.4                | −29.0           | 12.1         | −1.5                | 13.6            | 13.7    | −3.0                | 17.0            |
| W15   | −13.6        | 18.8                | −27.3           | 5.2          | −1.4                | 6.7             | 7.1     | −2.9                | 10.4            |
| W16   | −11.3        | 19.7                | −25.9           | 5.3          | 0                   | 5.3             | 6.6     | −3.0                | 10.0            |

materials. Such comparison shows a percentage of difference in panel's deformations, energy dissipation, and E/ $\theta$  ratio. From the figure and tables, it is found that using filling material leads to having a stiffer panel that reduces panel's maximum deformation. Energy absorption increases by up to 49.7% and panels' deformation decreases by up to 28.8%. Comparing panels with no filling materials and others with sand, deformation increases by up to 25.4%, whereas energy absorption decreases by up to 23.5%. As a result, E/ $\theta$  ratio decreases by up to 43.2%. On the other hand, upon using polyurethane foam, the panels' maximum deflection decreases by up to 3.7%, while energy absorption increases by up to 15.7% in comparison with using sand material. Accordingly, E/ $\theta$  ratio increases by up to 18.6%. Moreover, on using dytherm foam, the panels' maximum deflection decreases by up to 4.3%, while the energy absorption increases by up to 17.4% in comparison with using sand. Therefore, this results in increasing the E/ $\theta$  ratio by up to 20.2%. Based on the results, using foam materials significantly enhances the panel's energy dissipation and causes minor enhancement in the deformation. This can be attributed to the fact that the main weakness of FRP panels is the debonding. Since the strength of the adhesion is lower than the strength of FRP layers, therefore the adhesion of FRP panels always fails first upon being subjected to either compression or bending. This resulted in a minor difference on using different filling materials and panels' peak deflection increases on using dytherm foam by up to 4.3% and 2.7% compared to using sand and polyurethane foam, respectively. On the other hand, the energy dissipation increases when using dytherm foam by up to 17.3% and 3% compared to using sand and polyurethane foam, respectively. Finally, the usage of FRP panels with filling materials provides a damping environment which reduces the maximum displacement. Therefore, using filling materials enhances the behavior of FRP sandwich panels under blast loading.

## 6. Conclusions

Effectiveness of new FRP honeycomb sandwich panels in blast load resistance has been investigated. Throughout this study, a proposed FRP panel with different inner core configurations has been analyzed. The panels' behavior is evaluated using a nonlinear explicit finite element simulation. The numerical model has been validated using experimental field tests conducted on four FRP honeycomb panels filled with sand and subjected to blast effects.

Numerical results have shown good agreement with experimental measurements. The proposed panel has led to a superior performance under blast effects as it increases energy dissipation by 111% and reduces level of deformation by 7%.

Parametric studies have been carried out to determine the effect of various parameters: thickness of layers, height of sinusoidal layer, length of sinusoidal wave, width of strip, and length of wave peak. Performance of the simulated panels are evaluated in terms of panel's peak deflection, energy dissipation, and energy-to-chord rotation ratio (E/ $\theta$ ). The following results have been observed:

- Changing one of the parameters from h, L, W, and t while keeping other parameters constant have resulted in changing the material weight which makes it difficult to compare results of different panels.
- Having the same material weight, then decreasing wave length increases bonds contacts, while decreasing layers' heights increases number of layers. Resultantly, the performance of analyzed panel is enhanced by up to 24.2% increase in energy dissipation and 1.5% decrease in panels' peak deflection.
- Changing wave peak length while keeping the material weight constant improve the performance of analyzed panel by up to 11.9% in energy-to-chord rotation due to the increase in the bonding area.
- Changing wave peak length and other parameters (h, L, W, and t) while keeping the material weight constant increase the energy-to-chord rotation ratio by 34.3%. To conclude, W16 (with b = 10 mm) performs the best among all other panels.
- Increasing the contact points results in better performance up to a certain level when strips reaches high stiffness value. Once a high stiffness value is reached, the panel's energy dissipation capabilities are reduced and hence its performance decreases as well.

The effect of changing filling material on panel's performance against blast loads has been investigated. It is found that using filling material provides a damping environment which reduces panels' deflection by up to 28.8% and increases panel's energy absorption by up to 49.7%. Among all the used filling materials in this study, dytherm foam has shown the best performance where it enhances the E/ $\theta$  ratio by up to 20.2% in comparison to using sand and 4.4% in comparison to using polyurethane foam.

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