

Numerical Simulation of FRP Sandwich Panels under Blast Effects

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Abstract: Mitigation of blast effects caused by accidental explosions is one of the major challenges in structural engineering. Fiber-reinforced polymer (FRP) sandwich panels offer promising systems for blast mitigation applications due to their considerable energy absorption compared to other materials with similar density. The FRP sandwich panels can have different inner core configurations that can be filled with other materials whenever needed. This paper numerically evaluates the effectiveness of new FRP honeycomb sandwich panels in resisting blast loads. A numerical model has been created using nonlinear explicit finite element simulation. Then, the model has been validated using the experimental field tests in the literature. Twelve FRP panels with different inner core configurations have been proposed to enhance the panels' performance by reducing their peak deformation and increasing their energy dissipation. The paper also investigates the effect of filling the FRP sandwich panels with sand on the panels' blast resistance. The analyses have shown that the FRP panels utilizing the new core configurations are able to dissipate more than twice the energy compared to the experimental panels with even less deformations. It has been found that using sand as a filling material provides a damping medium that enhances the panels' behavior under blast effect. DOI: [10.1061/\(ASCE\)CF.1943-5509.0000934](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000934). © 2016 American Society of Civil Engineers.

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Introduction

Blast mitigation of structures has become an active area of research for governmental, industrial, and military organizations. In several fields, such as cement production, coal mining and petrochemical fields, the consequences of accidental explosions should be carefully considered. For example, in the petrochemical field, human-caused accidents that occur in an industrial facility can trigger explosions that are accompanied by other phenomena such as fire and impacts caused by explosion-borne missiles (Baker et al. 1983). Accidental explosions can generate blast waves that threaten the structure's integrity. These structures are not usually designed to resist explosive actions, and hence they may be at great risk (Bulson 1997). Moreover, security has become a major concern for vital building facilities. Therefore, many facilities place blast-resistant checkpoints at the entrances or around the facility to control access. At higher levels of threat, the traditional way of reaching a higher protection level is to increase the standoff distance by providing temporary checkpoints. Occupants of these temporary checkpoints will be at a great risk, as these checkpoints are not usually designed against blast effects. Lightweight sandwich panels are one of the solutions to provide temporary checkpoints that can be designed to resist blast loads while being moveable and easy to assemble. Moveable structures with such specifications can be also beneficial

for temporary high-importance facilities such as barracks and hospitals (Hoemann 2007). In addition, these temporary structures can be used in hazardous industrial fields that are vulnerable to blast.

The lightweight prefabricated moveable structures can provide a robust, durable, and reliable replacement of the traditional sandbag bunkers used for temporary checkpoints. Sandwich panels are being used to manufacture lightweight moveable structures (Vinson 2001). Sandwich panels are usually made of lightweight material. They typically consist of outer skins with a low-density core in between (Davies 1993). Fiber-reinforced polymer (FRP) composites have a great potential in manufacturing prefabricated panels that can be used for moveable structures. The high strength-to-weight ratio, resistance to corrosion, and ease of handling and fabrication are the basic advantages of FRP. Steeves and Fleck (2004) reported that a significant reduction in the weight of sandwich panels was achieved using glass FRP (GFRP) skins and PVC or polyurethane cores. They also reported that the core material stiffness is the main factor controlling the sandwich panel's behavior.

Several studies have been conducted to examine the behavior of sandwich panels under static and blast loads. Jacob et al. (2002) summarized the effect of changing the FRP characteristics and their influence on the energy absorption of FRP sandwich panels. They indicated that the energy absorption increased when FRP tubes with fibers of less density, higher strain capacity, or higher interlaminar fracture toughness were used. Chen and Davalos (2003) reported that the delamination of the inner core from outer skins is the typical failure mode for FRP sandwich panels. Xue and Hutchinson (2004) investigated numerically the behavior of metal sandwich panels compared to solid plates made of the same material and having the same weight under impulsive/blast loading. They concluded that a well-designed sandwich panel can resist more blast effect compared to a solid plate. Bahei-El-Din et al. (2006) studied FRP sandwich panels under impulsive/blast loading and they proposed new designed panels. The failure mode of the panels was a permanent crushing of the foam core and an instant skin delamination. Zhou et al. (2007) examined the effect of

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changing the skin thickness and core density on the energy absorption of honeycomb sandwich panels. They concluded that the bigger skin thickness would lead to a significant increase of the initial threshold, ultimate load, and panel's energy absorption capacity. However, the increase in the core density led to a minor enhancement in the panel's ultimate load and the energy absorption capacity. Hoemann (2007) experimentally investigated the behavior of FRP sandwich panels under blast load and fragmentation. Four wall panels of different thicknesses and inner core configurations were tested after being filled with sand. Wang et al. (2009) experimentally studied sandwich panels with two different core configurations under blast loads. The results showed that using a more flexible core as a contact surface with the blast loading leads to a better performance. Arora et al. (2012) examined the blast resistance of GFRP sandwich panels with different core thicknesses. They found that the panel stiffness increased significantly when thicker cores were used, and that resulted in a major influence on the panels' resistance to blast effects. On the other hand, Wadley (2006) indicated that changing the core configuration has significantly influenced the behavior of sandwich panels. This raised the importance of examining different inner core configurations of the sandwich panels with different thicknesses. Other recent studies were conducted to investigate the performance of sandwich panels under blast loads, e.g., Su and McConnell (2011), LeBlanc and Shukla (2011), Goel et al. (2013), Langdon et al. (2012), and Arora et al. (2014). They concluded that the material density, tensile strength, the sandwich panels' delamination, core compression and fiber fracture are the main factors that influence the energy absorption capabilities of the panels.

Kujala and Klanac (2005) reported that introducing a filling material to the sandwich panels improved the panels' behavior. In this regard, Børvik et al. (2008) examined aluminum sandwich panels that were used in protecting a 6.0-m (20-ft) ISO container. They reported that the panel's ballistic and blast load resistance increased when a granular material was used as a filling material. Zhang et al. (2013), Yan et al. (2014), and Yazici et al. (2014)

studied the effect of using foam as a filling material on sandwich panels. They concluded that foam-filled cores can significantly increase the compressive strength of the panels and reduce the panels' deformations under static and blast loads.

The objective of this study is to numerically evaluate the effectiveness of FRP sandwich panels with existing and new inner core configurations in resisting blast loads. The finite element model has been validated using experimental tests available in the literature. The proposed inner core configurations of the FRP panels have been compared to the ones used in the experiments. The paper also investigates the effect of introducing a filling material to the FRP sandwich panels on their blast behavior.

Finite Element Analysis and Material Modeling

The finite element (FE) model that has been used in the current study is created using a dynamic nonlinear explicit software ANSYS *AUTODYN*. The software is capable of analyzing structural elements that are subjected to impacts or short-duration high-pressure loading, while considering the material nonlinearity and large deformations. The FE model was validated using the field experiments conducted by Hoemann (2007). The field experiments were designed based on a certain threat level of TNT located at 10.7 m from the test panels. As shown in Fig. 1, the center of the explosive charge was placed at 1.8 m above the ground level.

Fig. 2 shows the FE model of the FRP sandwich panels. The model consists of the explosive charge (TNT), the FRP sandwich panel (filled with sand if applicable), and the air domain. In the model, the TNT charge is located at the corner of the FRP panel to simulate the field tests.

In the FE simulation, FRP sandwich panels have been defined as eight-node solid hexahedron Lagrangian elements. In a Lagrangian analysis, the mesh elements would deform while no material movement between two elements would occur, i.e. the material within the element will remain inside it without any flow out of the

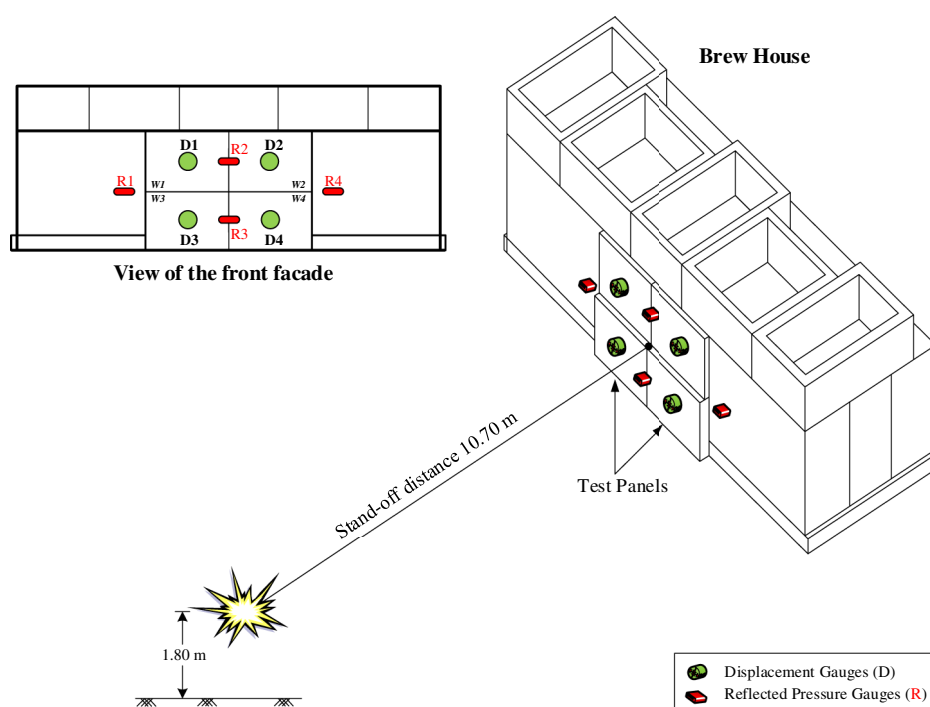


Fig. 1. Field test schematic (adapted from Hoemann 2007)

element. Lagrangian technique has the potential to be efficient and accurate for complex material models. The Lagrange method is best suited for modeling solid elements like structures (Zukas 2004). In this study, sand filling has been modeled as smooth particle hydrodynamics (SPH) objects; SPH is a gridless technique that neither leads to grid tangling in case of large deformation problems nor requires the use of an unphysical erosion algorithm (Hayhurst et al. 1996).

The air domain is modeled as Euler-flux corrected transport (Euler-FCT) subgrid that has been generated as a box with a length of 12 m in x -direction, a height of 1.8 m in y -direction and a width of 2.6 m in z -direction. Eulerian analysis involves the material movement between the mesh elements contrary to the Lagrangian analysis. The Euler-FCT processor is designed mainly to solve gas dynamics problems and in particular for blast simulations. In the model, flowout boundary conditions of the air domain have been applied along the box boundaries except at the bottom face, which represents the ground surface.

The explosion is simulated using the remap capability in *AUTODYN*, where the output of a one-dimensional (1D) high-resolution initial detonation is remapped as initial conditions for the subsequent calculation stages. The remapping is performed in three main steps:

1. Modeling of the 1D detonation and the initial expansion of TNT using a wedge model.
2. Remapping the results of the 1D analysis into a two-dimensional (2D) numerical model and then analyzing the model using a 2D code.
3. Remapping the results of the 2D analysis into a three-dimensional (3D) numerical model and then analyzing the model using a 3D code.

The aforementioned remapping steps are to be performed before any interaction with the ground or the FRP panel occurs.

Modeling the blast load using the remapping method enables the simulation of reflection and diffraction of the blast wave. This can represent the mutual interaction between the structure and the blast wave, which cannot be ignored when the structural displacement is large under the blast effect. Moreover, using the 1D analysis helps calculating the initial pressure distribution with a high accuracy and minimum processing time. This can be achieved by using a fine mesh for the initial detonation wedge, which is feasible compared to modeling the whole 3D domain using the fine mesh size. Wedge element sizes of 15, 10, 5, 3, 2, 1, 0.5, 0.25, 0.125, and 0.0625 mm have been examined to perform a mesh sensitivity analysis of air pressure measured at a distance of 1.8 m from the detonation point, which is the minimum distance before hitting any reflection surface as shown in Fig. 2. Fig. 3 shows the relationship between the wedge element size and the peak pressure. As shown in the figure, the element size of 0.25 mm showed a high level of accuracy, and hence was selected in the current study.

For the 3D air domain with dimensions of $12 \times 1.8 \times 2.6$ m, elements with aspect ratio of 1.0 and sizes of 50, 45, 40, 35, 30, 25, 20, and 15 mm were investigated. Fig. 4 shows the relationship between the air domain element size and the peak pressure measured at distance of 10.7 m as shown in Fig. 2. As shown in Fig. 4, the element size of 30 mm showed an acceptable level of accuracy (an error of less than 1.5%), and hence it was selected in the current study.

Hinged boundary conditions are applied to the two vertical sides of the FRP panel, while the top and bottom lines are free. In the field tests, each vertical side of the four tested panels was restrained by clamping anchorages along the edges. The four panels were clamped to the two side walls of the brew house and to the vertical interior column that is located in the center. In the numerical model,

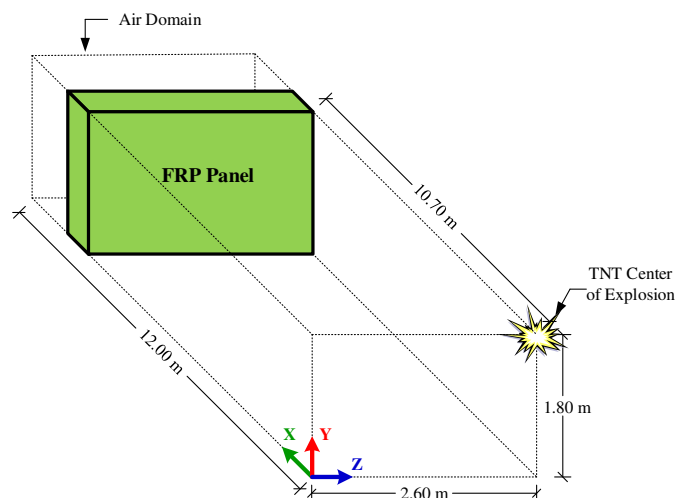


Fig. 2. Schematic of the finite element model

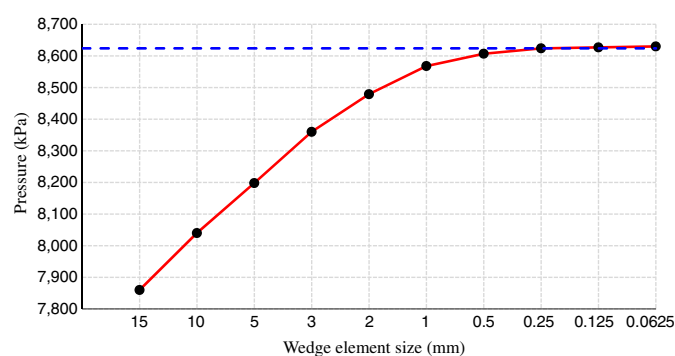


Fig. 3. Incident pressure for different wedge element sizes

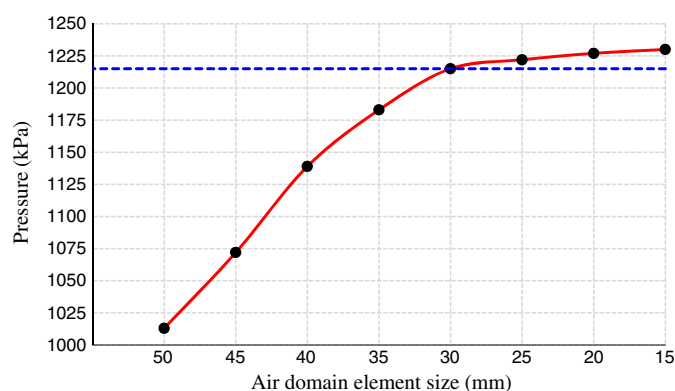


Fig. 4. Reflected pressure for different air domain element sizes

the two vertical sides of each panel were assumed to be hinged along the whole height.

The FRP panels are defined as Lagrangian elements while the air domain has been simulated using Euler-FCT elements. The Lagrangian and Eulerian elements exchange impulses at their interfaces and both solvers must be coupled to simulate the interaction between the structure and the air domain. In the coupling procedure, the mass, energy, momentum and forces are transferred from the Eulerian mesh to the Lagrangian one and vice versa. The

interaction has been defined as fully coupled where Lagrange elements interact dynamically with Euler elements (*AUTODYN*). This type of interaction is important especially when deflections have occurred, because the movement of the geometric constraint provided by the Lagrangian mesh influences the pressure values (Yun and Park 2013).

For the purpose of material modeling using *AUTODYN*, the parameters of the material's equation of state (EOS) must be defined first. Then the strength and failure models are defined for each material. For the TNT, the Jones-Wilkins-Lee (JWL) EOS has been used. The strength model parameter is defined as a hydro (i.e., no strength), while no failure mode has been defined. For the air, the ideal gas EOS has been used. The strength model parameter is defined as a hydro (i.e., no strength), while no failure mode has been defined. Regarding the sand material, the compaction EOS has been used, where the elastic loading/unloading compaction curve has been obtained from the density-dependent bulk sound speed. The strength model parameter used for the sand material is the granular strength model, while the failure model parameter used is the hydro tensile. The mechanical properties of sand material used in this study has been defined according to Laine and Sandvik (2001). For the FRP material, the orthotropic EOS has been used. The strength model parameter used is the orthotropic yield, while the orthotropic softening failure model parameter has been used. In this study, the FRP composite material has an ultimate tensile strength of 460 MPa and a modulus of elasticity of 21 GPa.

FRP Core Geometry

Five different configurations of the FRP panel inner core are considered in this study. Three configurations are in the literature and two other configurations have been newly proposed. The effectiveness of each configuration is investigated using a dynamic nonlinear explicit FE model. The numerical model simulates the dynamic response of the FRP sandwich panel when subjected to an impact resulting from an explosion.

Fig. 5 shows the five FRP panel inner core configurations considered in the analyses. Configurations (a), (b), and (c) are the ones tested by Hoemann (2007). In these configurations, the standard sinusoidal honeycomb core layers are placed in different orientations. Configuration (a) represents the parallel weak (PW) axis, configuration (b) is a "turned" right-angle weak (TRW) axis, and configuration (c) is the right-angle weak (RW) axis. Configurations (d) WV2-1 and (e) WV2-2 are proposed by the authors of this study and they consist of strips cut from the same sinusoidal honeycomb and are interlaced at a right angle forming the woven shape. Configuration WV2-1 consists of two sinusoidal honeycomb strips in the longitudinal direction and one transverse sinusoidal strip attached at every other peak of the longitudinal strips. For WV2-2, a transverse strip is provided at every peak of the longitudinal strips as shown in the figure. It is worth mentioning that the woven shape WV2-1 has been designed so that the amount of FRP material used would be the same amount used for PW, TRW, or RW shapes. While for the woven shape WV2-2, 33% more FRP material is used compared to the other shapes.

For each of the five configurations, every two sinusoidal honeycomb layers are bonded with a flat layer of similar material in between forming the core, where each of the two honeycomb layers are placed symmetrically about the flat layer as shown in the figure. Then the core is sandwiched between two FRP outer layers to form the honeycomb sandwich panels.

Numerical Model Validation and Applications

The numerical model is validated using the experimental results of the field tests conducted at Tyndall Air Force Base, Florida, by Hoemann (2007). Four FRP sandwich panels are constructed and tested under blast effects. Table 1 shows the dimensions of the tested FRP panels and their inner core configurations. As was shown in Fig. 2, four pressure gauges were installed. Table 2 provides a summary of the pressure gauge locations and their main readings during the experiment.

In the numerical model, two types of gauges are used: fixed gauges and moving gauges. Fixed gauges are attached to their coordinates and they do not move throughout the simulation, while the moving ones move with the element during the simulation. Fixed gauges are suitable to capture the pressure readings of the model, while moving gauges are used to capture the deflection readings. Several pressure gauges have been assigned to track the change in pressure along the air domain. In order to capture pressure readings, the air domain is simulated with 12 m length as shown in Fig. 2, such that fixed gauges can be assigned to track pressure in front of and behind the modeled panels. Fig. 6 shows the pressure time history of the numerical pressure gauge located at the wall panel center [x, y, z] = (10.7, 0.9, 1.3) m plotted with the three pressure gauge readings of the field test. The peak value of the numerical pressure is 1,215 kPa, which is close to the average value of the three test gauge peak pressures.

Experimental and Numerical Deflections

Figs. 7(a–d) show the experimental and numerical deflection time histories of the four panels considered (W1–W4). Davalos et al. (2001), Alagusundaramoorthy et al. (2006), and Ji et al. (2010) stated that deflection is the primary factor that controls the design of FRP panels. Particularly, the deflection of the back layer, which is the last shield that protects the occupants from blast. In the numerical model, the panel's deflection has been determined using a moving gauge at the center point of the back layer similar to the field tests. Table 3 shows the experimental and numerical peak deflection of the center point of the panel's back layer. The figures and the table show that the numerical model is able to predict the behavior of the tested panels under blast effects with a reasonable level of accuracy. The maximum deviation between the experimental and numerical peak deflections of the FRP panels is 18% as shown in the table. The figures show that the numerical model is able to efficiently track the panels' behavior with time for all panels except for panel W3. For this panel, the discrepancy between the numerical and experimental deflection time histories is noticed when the panel started the rebound phase. This can be attributed to the fact that during the experimental test of W3, the panel suffered an early rebound compared to other wall panels with a complete failure of the clamping anchorage joints. This major change in the panel's boundary conditions was not considered in the numerical model, where the boundary conditions are assumed to remain the same during the analysis.

Failure Modes

Fig. 8 shows the failure modes of the four panels considered in the analysis. Similar to the experimental observations, the failure of the test panels has occurred due to the shear failure of bond between the FRP layers. For panel W1, the model is able to simulate the complete bond failure and the separation occurred between the core and the outer layers as shown in the figure. For panel W3, a partial bond failure between the front layer and the core is noticed. On the other hand, for panels W2 and W4, a complete bond failure and a

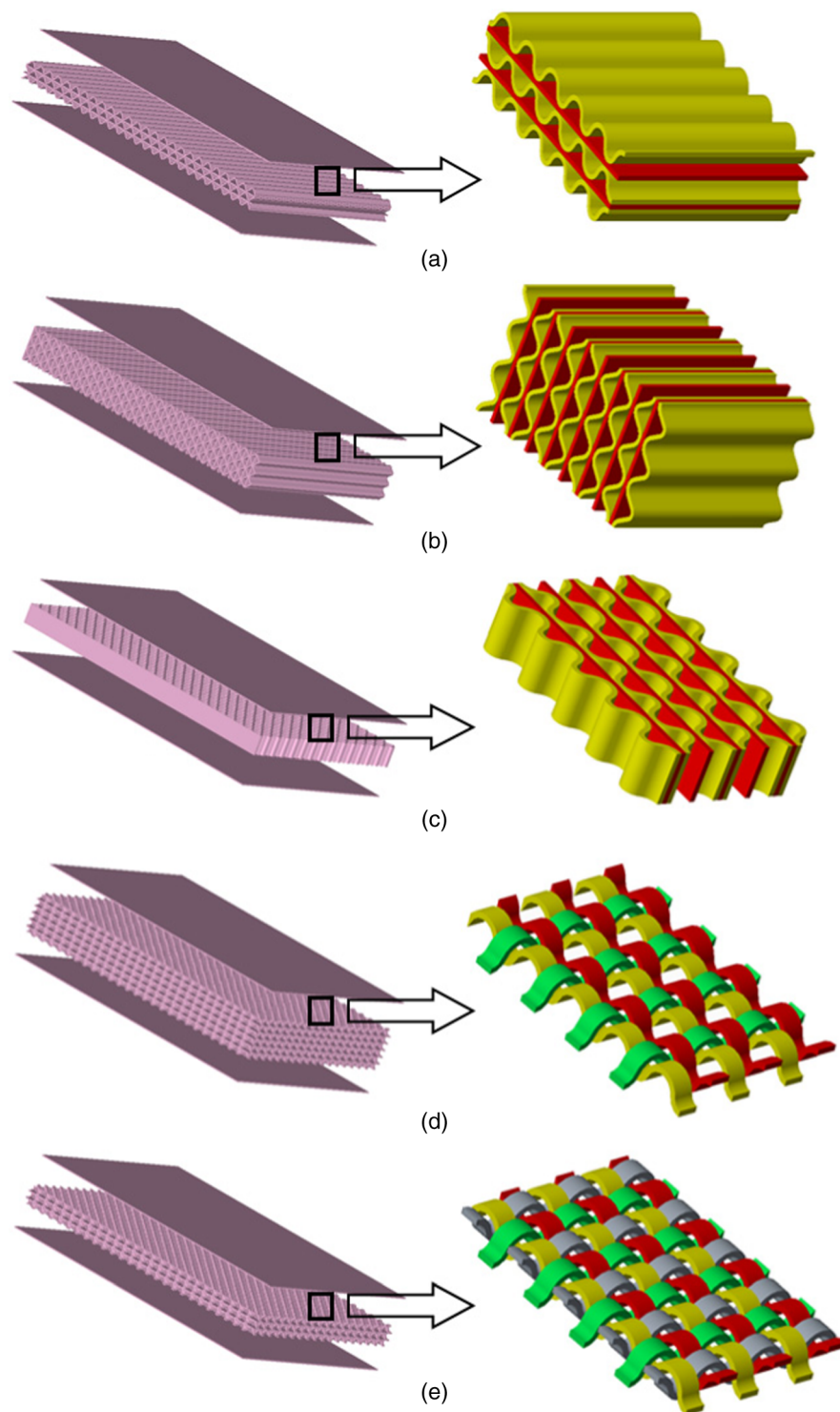


Fig. 5. Inner core configurations of the FRP sandwich panels

Table 1. Description of the FRP Panels Tested by Hoemann (2007)

Panel name	Length (m)	Width (m)	Height (mm)	Core configuration	
				Number of layers	Core shape
W1	2.60	1.80	190	1	TRW
W2	2.60	1.80	190	3	PW
W3	2.60	1.80	360	1	TRW
W4	2.60	1.80	360	6	PW

Table 2. Summary of the Blast Pressure and Impulse of the Experimental Tests (Data from Hoemann 2007)

Gauge name	Location	Elevation (m)	Peak pressure (kPa)	Impulse (kPa ms)
R1	Left side of the Brew House	2.13	1,076	2,061
R2	Center of the Brew House	2.74	1,224	2,434
R3	Center of the Brew House	0.91	Defective gauge	
R4	Right side of the Brew House	2.13	1,465	2,420

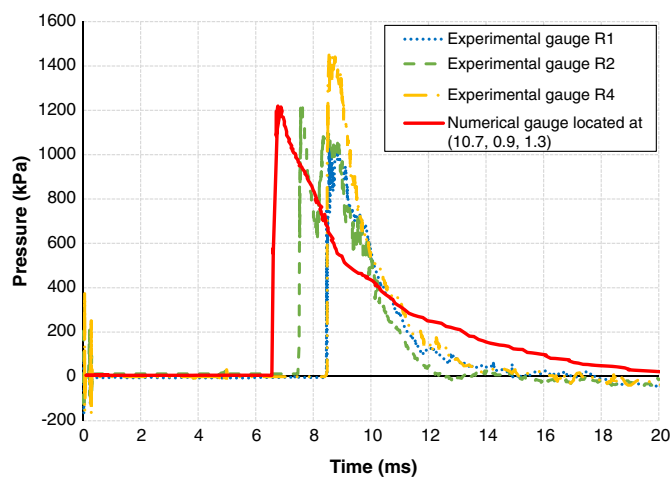


Fig. 6. Experimental (data from Hoemann 2007) and numerical pressure time histories

separation has occurred between the sinusoidal layers and the flat layers similar to what was observed during the experiment. By comparing the numerical findings with the experimental observations, it can be concluded that the Lagrangian mesh was able to capture the level of damage that occurred as well as the final failure pattern for each panel.

Energy Dissipation

As shown in Fig. 9, the energy dissipated by each component of the FRP panel is obtained numerically. The figure illustrates the contribution of the front layer, the inner core, and the back layer in the energy dissipated by the panel as well as their percentages relative to the total energy.

Table 3. Experimental (Data from Hoemann 2007) and Numerical Peak Deflections

Panel	$\Delta_{\max-\text{exp}}$ (mm)	$\Delta_{\max-\text{Num}}$ (mm)	% difference
W1	259	227	12
W2	269	262	3
W3	61	72	18
W4	190	163	14

From the figure, it can be noticed that the contribution of the back layer of W3 in the energy dissipation is considerable (even more than that of the front layer). This is attributed to the fact that W3 has experienced a minor damage, which enables all the panel components to contribute to the energy dissipation. On the other hand, the other panels have suffered a major level of damage, which does not allow force and energy transfer from the core to the back layer.

The energy-to-deflection ratios (E/Δ) of the analyzed panels have been calculated as 0.88, 0.85, 1.68, and 1.64 for W1, W2, W3, and W4, respectively. E/Δ ratio is defined as the total energy dissipated by the panel relative to the panel's maximum deflection at the center point. The higher value of E/Δ ratio indicates that the panel would be able to absorb a higher amount of energy with less deformations and less amount of damage. Although W3 has shown the least amount of energy absorption between all panels, this panel has the highest E/Δ ratio (which represents a smaller deflection). Therefore, to evaluate the performance of the FRP panels when subjected to blast loads, both deflection and E/Δ ratio should be considered.

Effect of Sand Filling on the Behavior of FRP Sandwich Panels

Figs. 10(a–d) show the numerical center point deflection time histories of the four test panels (W1–W4) with or without sand filling.

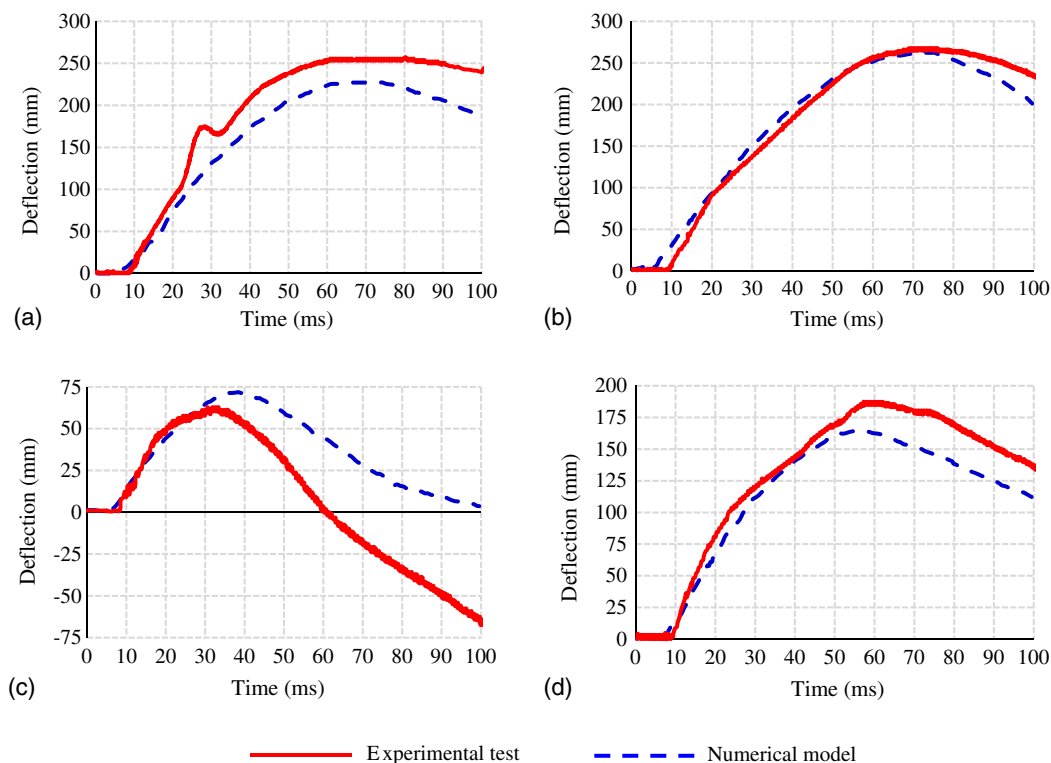


Fig. 7. Experimental and numerical deflection time histories for (a) W1; (b) W2; (c) W3; (d) W4

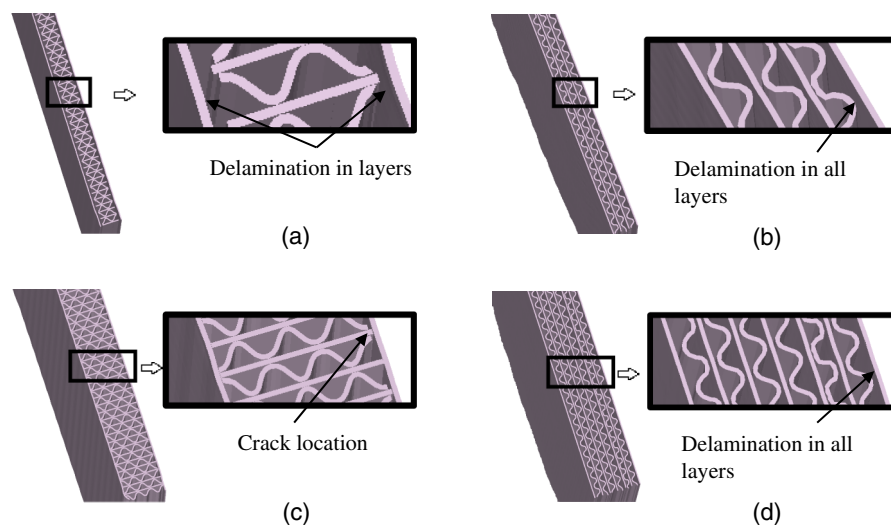


Fig. 8. Failure patterns of the simulated panels: (a) W1; (b) W2; (c) W3; (d) W4

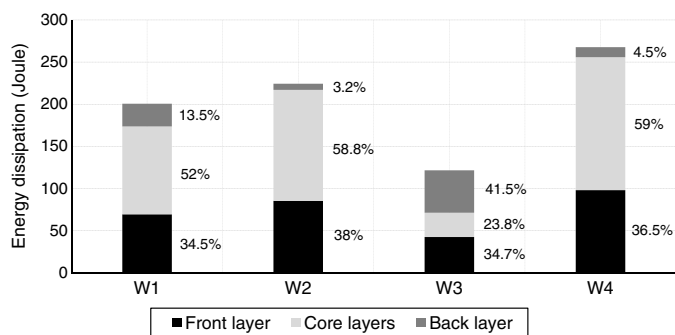


Fig. 9. Distribution of energy dissipated between the panel components

Table 4 illustrates the effect of sand filling on the energy dissipated by the panel, the maximum deflection of the panel, and the E/Δ ratio. From the figures and the table, it can be seen that sand filling has led to a stiffer panel through the reduction of the panel's maximum deformation. Adding sand to the FRP panels reduces the panels' maximum deflection by up to 26% and increases the E/Δ ratio by up to 76%. It is also noticed that adding sand to panel W3 does not result in a significant enhancement in the panel's behavior compared to other panels due to its high initial stiffness. Adding sand to the other panels provides a higher shear resistance that helps delaying the shear failure of bond between the FRP layers, and thus increases the energy absorption of the panels. Based on the results, it can be stated that filling the FRP panels with sand material provides a damping environment that enhances the behavior of FRP sandwich panels under blast loading. Moreover, the feasibility of using sand on site and its cost efficiency are also two advantages of using it as a filling material.

Proposed Core Configurations of the FRP Sandwich Panels

Table 5 shows the description of the proposed FRP panels and their inner core configurations. Twelve panels with different inner core configurations have been proposed and analyzed. The table shows

the panels' total thickness, the number of core layers, and the core shape used. The proposed panels have dimensions of 1.8×2.6 m similar to the experimental panels and they are categorized into three main groups. The first group includes three *thin panels* with a total thickness of 190 mm utilizing the core shapes RW, WV2-1, and WV2-2 [Figs. 5(c–e)]. The second group includes five *thick panels* with a total thickness of 360 mm utilizing different combinations of core shapes PW and RW [Figs. 5(a and c)]. The third group includes four thick panels that consist of different combinations of core shapes RW, WV2-1, and WV2-2. For each group, the panels have been subjected to the blast effect simulating the experimental field test. The proposed configurations aim to enhance the behavior of the FRP panel when subjected to blast loading through the increase of energy dissipated by the panel. It is also intended to reduce the panel's peak deflection, which can represent the panel's level of damage (Kalny and Peterman 2005).

Analysis Results

The following section presents the results of the explicit nonlinear dynamic analyses of the FRP panels with different core configurations when subjected to blast loading. Twelve FRP sandwich panels have been simulated and are classified into three main groups. The first group included thin panels that are 190 mm thick, whereas the second and the third groups included thick panels that are 360 mm thick. The numerical modeling of the experimental test panels have shown that, for thin panels, panel W1 had a higher energy-to-deflection ratio (E/Δ) than W2. Therefore, the behavior of the proposed FRP thin panels (Group 1) is compared to that of W1. Similarly, the behavior of the proposed thick panels (Groups 2 and 3) is compared to that of W3.

Numerical Results of Group 1

Fig. 11 shows the time history of the central point deflection of the FRP panels of Group 1 along with the simulated test panels W1 and W2. Table 6 shows the energy dissipated by the panels, the panels' peak deflections, and the energy-to-deflection ratios. From the figure and the table, it can be seen that the performance of panel W5 (with RW axis core configuration) is similar to W1 (TRW axis core configuration) with no enhancement in the behavior. However,

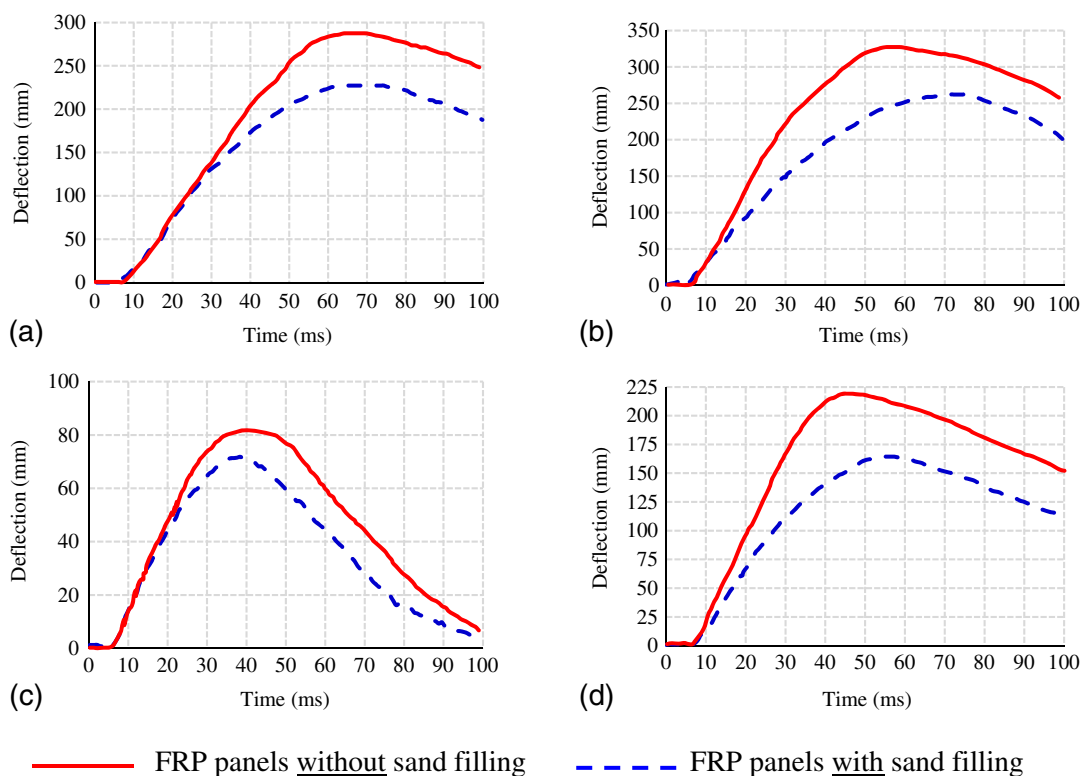


Fig. 10. Numerical deflection time histories of (a) W1; (b) W2; (c) W3; (d) W4

Table 4. Effect of Sand Filling on the Panel Deformations and Energy Dissipation

Panel	Without sand			With sand			% difference		
	Energy dissipation (J)	$\Delta_{\max}$ (mm)	E/Δ	Energy dissipation (J)	$\Delta_{\max}$ (mm)	E/Δ	Energy dissipation	$\Delta_{\max}$	E/Δ
W1	164	287	0.57	200	227	0.88	22	−21	54
W2	180	328	0.55	224	262	0.85	24	−20	55
W3	103	82	1.25	121	72	1.68	17	−12	34
W4	205	219	0.93	268	163	1.64	31	−26	76

the woven shapes represented by W6 and W7 have shown an enhancement in the energy-to-deflection ratio by almost 24% compared to W1 (considering that W7 uses 33% more FRP material). This minor enhancement can be attributed to the failure mode of the simulated panels of this group, which is a complete bond failure between the FRP layers. This high level of damage indicates that the small thickness of these panels is insufficient to resist the blast level considered in this study. For panel W5, a complete bond failure and a separation occurred between the core and the outer layers. Similarly, for panels W6 and W7, a complete bond failure and separation occurred between the sinusoidal strips and the flat layers.

Numerical Results of Group 2

Fig. 12 and Table 7 illustrate the analysis results for the second group along with the simulated test panels W3 and W4. It has been found that the behavior of panel W8 (with RW axis core configuration) is similar to that of the test panel W3 (TRW axis core configuration) which has been noticed earlier for Group 1. For the other core configurations, panels W11 and W12 have shown the highest values of E/Δ ratio within the group with an enhancement of up to 70% compared to W3. These panels have dissipated up to

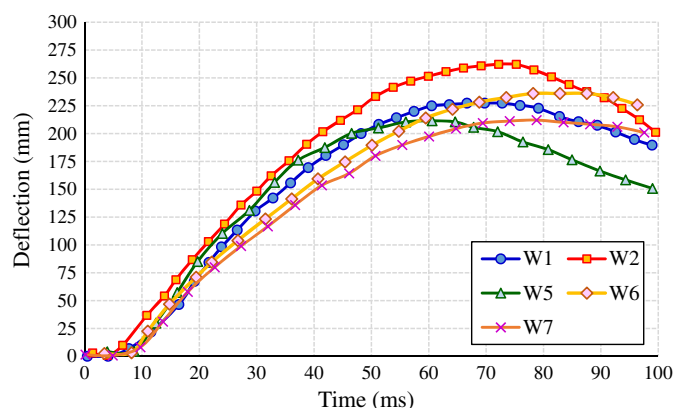
125% more energy compared to W3 accompanied with an increase in the panel's deflection by up to 31%. For panel W8, a partial bond failure between the front layer and the core was noticed at the panel edges at the maximum shear locations. For other panels of this group, the panels exhibited a partial bond failure within the layers of the weak PW axis core.

Numerical Results of Group 3

Fig. 13 and Table 8 illustrate the analysis results of the third group along with the simulated test panels W3 and W4. The results indicate that a significant enhancement in the behavior of the FRP panels is reached when the woven shapes WV2-1 and WV2-2 are used. Panel W13 with the shape WV2-1 is able to dissipate 113% more energy compared to W3 with just a 5% more deflection. Combining the woven shape WV2-1 and the RW axis (in W15 and W16) has resulted in a superior performance compared to the test panel W3. These panels are able to dissipate 111% more energy compared to W3 with even less deformations. Although using the woven shape WV2-2 (panel W14) has resulted in the highest energy-to-deflection ratio (which represents the best behavior among all panels), this core configuration uses about 33% more FRP material compared to other configurations. In addition, the

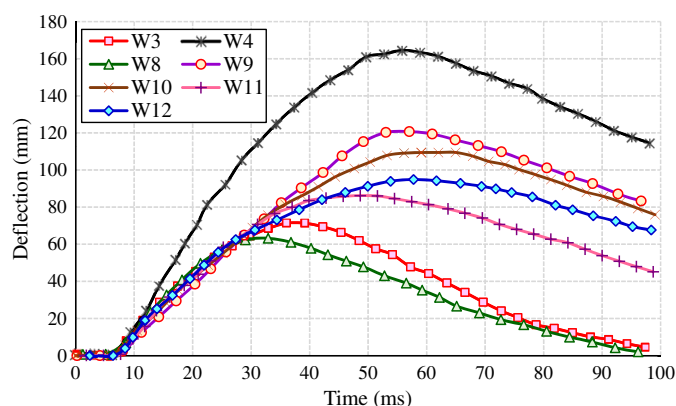
Table 5. Description of the Proposed FRP Panels and Their Core Configurations

Group number	Panel name	Total thickness (mm)	Core configuration		
			Number of layers	Core shape	Thickness (mm)
1	W5	190	1	RW	$\frac{1}{2} T^a$
	W6	190	3	WV2-1	$\frac{1}{2} T$
	W7	190	3	WV2-2	$\frac{1}{2} T$
2	W8	360	1	RW	T
	W9	360	1	RW ^b	$\frac{1}{2} T$
	W10	360	3	PW	$\frac{1}{2} T$
			3	PW ^b	$\frac{1}{2} T$
	W11	360	1	RW	$\frac{1}{2} T$
			1	RW ^b	$\frac{1}{3} T$
			2	PW	$\frac{1}{3} T$
			1	RW	$\frac{1}{3} T$
	W12	360	2	PW ^b	$\frac{1}{3} T$
			1	RW	$\frac{1}{3} T$
			2	PW	$\frac{1}{3} T$
3	W13	360	6	WV2-1	T
	W14	360	6	WV2-2	T
	W15	360	1	RW ^b	$\frac{1}{3} T$
			2	WV2-1	$\frac{1}{3} T$
			1	RW	$\frac{1}{3} T$
	W16	360	2	WV2-1 ^b	$\frac{1}{3} T$
			1	RW	$\frac{1}{3} T$
			2	WV2-1	$\frac{1}{3} T$

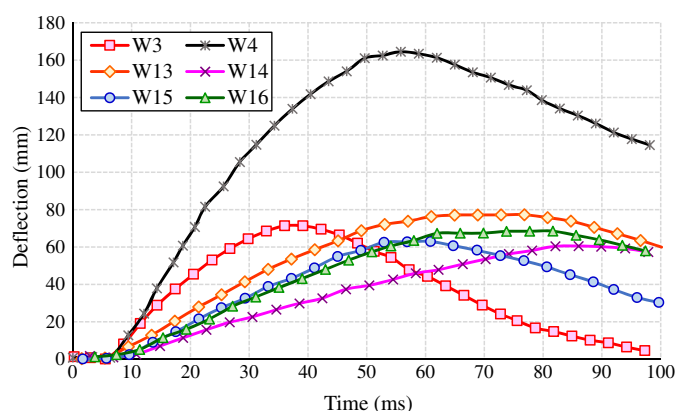
^a $T = 340$ mm.^bThe first layer subjected to the blast wave.**Fig. 11.** Central point deflection time histories of Group 1**Table 6.** Panel Peak Deflection and Energy Dissipation for Group 1

Panel	Energy dissipation (J)	$\Delta_{\max}$ (mm)	E/Δ	% E/Δ
W1	200	227	0.88	—
W5	182	210	0.87	—1
W6	258	236	1.09	24
W7	298	209	1.43	63

difficulty associated with the manufacturing of this shape makes the woven shape WV2-1 more practical and economical to use. Therefore, W16 is considered to have the best performance among the thick panels (Groups 2 and 3) with the most effective utilization of the FRP material. Panels of this group exhibited a bond failure between few nodes of the sinusoidal strips and the flat layers, especially in the nodes at the panel edges.

**Fig. 12.** Central point deflection time histories of Group 2**Table 7.** Panel Peak Deflection and Energy Dissipation for Group 2

Panel	Energy dissipation (J)	$\Delta_{\max}$ (mm)	E/Δ	% E/Δ
W3	121	72	1.68	—
W8	105	61	1.72	2
W9	257	121	2.12	25
W10	248	109	2.27	34
W11	236	86	2.74	62
W12	273	95	2.87	70

**Fig. 13.** Central point deflection time histories of Group 3**Table 8.** Panel Peak Deflection and Energy Dissipation for Group 3

Panel	Energy dissipation (J)	$\Delta_{\max}$ (mm)	E/Δ	% E/Δ
W3	121	72	1.68	—
W13	258	76	3.39	102
W14	298	60	4.97	196
W15	217	62	3.5	108
W16	256	67	3.8	126

Conclusions

The effectiveness of new FRP honeycomb sandwich panels in the blast load resistance was investigated. Twelve FRP panels with different inner core configurations and two different thicknesses have been analyzed. The panels' behavior is evaluated using a nonlinear explicit finite element simulation. The numerical model has been

validated using the experimental field tests conducted on four FRP honeycomb panels filled with sand when subjected to blast effects. The numerical model is able to predict the failure pattern of the test panels as well as their peak deflections with a maximum deviation of 18%. The study also investigates the effect of filling the FRP panel with sand on the panel's blast resistance. It is found that filling the panels with sand material provides a damping environment, which reduces the panels' deflection by up to 26% and increases the energy-to-deflection ratio by up to 76%.

The performance of the twelve proposed panels are evaluated in terms of the panel's failure mode, peak deflection, energy dissipation, and energy-to-deflection ratio (E/Δ). The numerical model showed a minor enhancement in the panels' behavior when the proposed configurations were applied to the thin panels. This is attributed to the fact that the proposed inner core configurations did not change the failure mode of thin panels, which was a complete bond failure. However, when the proposed configurations were applied to the thick panels, the following was observed:

- The combination of RW axis and the PW axis shapes (presented by W9–W12) has shown a major enhancement in the panels' energy dissipation by up to 125% with an increase in the panels' deflection by only 31%.
- The woven shape WV2-1 has dissipated almost twice the energy at the same level of deformation.
- The combination of RW axis and the woven shape WV2-1 has led to a superior performance under blast effects. This combination dissipates up to twice the energy at a reduced level of deformation.
- Despite the effectiveness of the woven shape WV2-2 in dissipating the blast energy at a reduced level of deformation, this configuration utilizes 33% more FRP material compared to the other configurations. Moreover, the complexity of manufacturing this shape will make it less economical and practical compared to other proposed configurations.

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