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FIBER REINFORCED POLYMER (FRP) PANELS FOR BLAST AND FRAGMENTATION MITIGATION

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Panels comprised of honeycomb fiber reinforced polymer (FRP) laminations were evaluated to examine their utility as prefabricated fighting positions. The panels were tested for both their blast, and fragmentation mitigation ability. Static resistance functions were developed using a combination of analytical and laboratory procedures in order to obtain the panels response, the response was implemented into a single-degree of freedom (SDOF) dynamic analysis. Engineered analytical prediction models showed that the panels' response in live explosive blast testing could be predicted. Sand-filled wall panels were subjected to blast and fragmentation loadings in full-scale experiments, but experimental and analytical evaluation indicated that further refinement of the panels design would be recommended.

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Fiber Reinforced Polymer (FRP) Panels for Blast and Fragmentation Mitigation

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ABSTRACT

Panels comprised of honeycomb fiber reinforced polymer (FRP) laminations were evaluated to examine their utility as prefabricated fighting positions. The panels were tested for both their blast, and fragmentation mitigation ability. Static resistance functions were developed using a combination of analytical and laboratory procedures in order to obtain the panels response, the response was implemented into a single-degree of freedom (SDOF) dynamic analysis. Engineered analytical prediction models showed that the panels' response in explosive blast testing could be predicted. Sand-filled wall panels were subjected to blast and fragmentation loadings in full-scale experiments, but experimental and analytical evaluation indicated that further refinement of the panels design would be recommended.

INTRODUCTION

Security of facilities, domestic or international, is of high importance to the owner. Problems arise when increasing to security to a facility; the increase would obstruct its ability for business, or give an impression of aggression to the public. Traditional checkpoints along the perimeter or entrances of facilities are used to control or limit access. But the problem is variability in the need of these checkpoints for different threats. If the threat level is high, a larger standoff or cleared distance around the structure might be desired from main structures in facility. But the increased standoff does not influence the danger to the occupants of the checkpoint. Likewise, the lower threat levels may reduce the need for maintaining any standoff all together. So the now the problem facing engineers is the need to protect occupants of these checkpoints and still have variability for threat levels; one solution would be a maneuverable structure. The structure would need to provide protection from blast and fragmentation, while still having the ability of being relatively mobile. This would reduce the need for hardened checkpoints. In addition, larger maneuverable structures could be built by linking components forming barracks, temporary hospitals, and command posts throughout all branches of service.

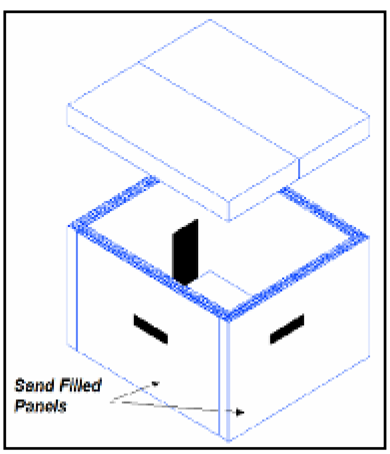

Figure 1 – Maneuverable Structure Concept

The design of the maneuverable structure must be evaluated to determine its material efficiency, cost, and performance. Such structures need to be able to resist a variety of blast and fragmentation threats. Due to this, fiber-reinforced polymer (FRP) composites were thought to be ideal candidates for maneuverable structures with previous research showing them to have high-strength-to-weight ratio. Fiber-reinforced polymer panels have advantages of being relatively flexible, which act as an absorption mechanism from imparted blast loads. Additionally, by filling the FRP panels with native granular materials to achieve the fragmentation protection, the panels receive a benefit of increased inertial resistance. Figure 1 shows a general schematic of the concept of a maneuverable FRP structure; where the honeycomb core is open upward facing for the placement of sand into the cells of the wall. This paper will present the study of the FRP materials as wall panels for these proposed structures.

The objective of this study was to analytically and experimentally evaluate FRP honeycomb composite panels for use as temporary structures subjected to blast and fragmentation loading. Preliminary research on the processes of fabrication and construction of the FRP composites was performed. Including a review of existing testing of similar panels used in other applications.

Static laboratory experiments were conducted to establish the section properties of the panels. In addition, physical observations on failure modes of internal variations of the panels honeycomb core were noted. Laboratory results were incorporated into dynamic models to quantify the FRP panels' response under blast loads. The predicted responses are then used in designing the appropriate experiment by varying charge weight and standoff distance. Additionally, an experiment demonstrating the panels' resistance to fragmentation penetration was performed to simulate a near-miss mortar attack. Research was sponsored by the Air Force Research Laboratory (AFRL), Airbase Technologies Division, Force Protection Branch, Engineering Mechanics and Explosive Effects Research Group at Tyndall Air Force Base, FL.

PANEL FABRICATION

The honeycomb panels used in this testing were fabricated using hand lay-up techniques, which are considered the simplest and most widely used. The evaluation included five different panel inner core designs. These cores were produced by varying the orientation of standard sinusoidal honeycomb core layers. Of the five variations, four were initially evaluated in laboratory testing. The five orientations are shown in Figure 2: (a) the parallel strong axis, (b) parallel weak axis, (c) right-angle strong axis, (d) right-angle weak axis, and (e) a "turned" right-angle weak axis, of which no panels were tested in the laboratory. The honeycomb core design consists of an FRP chopped strand mat formed into a sinusoidal wave, bonded with one flat face piece of similar makeup and thickness, creating a core layer. Core layers are connected together to form a honeycomb core. Face pieces are formed on a flat mold using hand lay-up also, though the fibers are an oriented mesh. The fully cured honeycomb core is bonded or pressed into the wet face pieces, to form a honeycomb panel section.

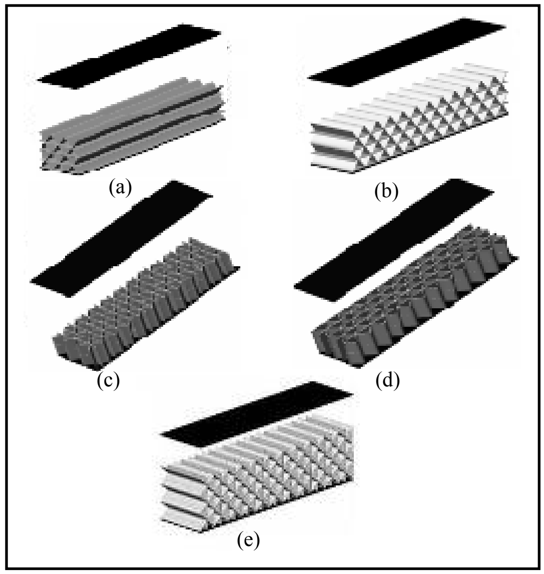

Figure 2 – Panel Inner Core Orientations

Depending on the orientation of the core honeycomb sections, different strengths and properties can be attained. The properties were used in the analytical models for predicting the dynamic response. The laboratory testing consisted initially of small-scale honeycomb FRP panels. In addition, laboratory testing allowed for physical observations of the internal bonds between core layers or faces that drove the overall behavior of the panel. The observations were beneficial in selecting the suitable core orientation appropriate for the proposed application. A procedure was formulated for extrapolating laboratory resistance functions into a full-scale resistance function for the panel dynamic model. Listed in Table 1 are the specimens' names and descriptions used for field evaluation discussed later in this paper. Note only two of the five orientations will be evaluated in full-scale experiments.

Field Panel Name – Dynamic Test	Panel Description	
	Core Orientation	Dimensions
W1 – Wall Panel Test	Right-Angle Weak Axis Turned	Height 7.5″, Width 71″, and Length 102″, 0.375″ structural outer surface + 6.75″ height inner core
W2 – Wall Panel Test	Parallel Weak Axis	Height 7.5″, Width 71″, and Length 102″, 0.375″ structural outer surface + three layers of 2.25″ height inner core
W3 – Wall Panel Test	Right-Angle Weak Axis Turned	Height 14.25″, Width 71″, and Length 102″, 0.375″ structural outer surface +13.5″ height inner core
W4 – Wall Panel Test	Parallel Weak Axis	Height 14.25″, Width 71″, and Length 102″, 0.375″ structural outer surface + six layers of 2.25″ height inner core
F3 – Wall Fragmentation Test	Parallel Weak Axis	Similar to W2
F4 – Wall Fragmentation Test	Parallel Weak Axis	Similar to W4
F5 – Wall Fragmentation Test	Right-Angle Weak Axis Turned	Similar to W3
F6 – Wall Fragmentation Test	Right-Angle Weak Axis Turned	Similar to W1

Table 1 – Description of Field Evaluated Samples

LABORATORY TESTING

Laboratory testing consisted of a 4-point bending configuration as seen in Figure 3. The testing results indicated that the parallel orientations, both strong and weak axis, performed well for providing continued resistance beyond their peak load capacity. This was due to their continuous horizontal shear failures between core layers at bonded interfaces. Once the center core layer had failed, the load redistributed and continued to provide resistance, but never regained full strength, until the horizontal shear in the outer surfaces likewise failed. In the right-angle configurations, the panels exhibited higher peak resistances and larger deflection responses at their peaks. But the right-panels lacked any sufficient redistribution mechanisms after the peak resistance was reached (Figure 4). No edge wraps were present along the laboratory-tested right-angle panels that might have provided additional confinement. The edge wrapping was where additional lay-ups were applied to the edges that clamp the thicker face layers together to achieve higher strength (Kaley et al., 2004).

Figure 3 – Four Point Bending of Small-Scale Samples

From the laboratory observations, an appropriate panel orientation for a side wall application was selected. In designing walls it is desirable to have a plastic response to absorb the energy from the blast. The absorption reduces the dynamic reactions into the connections and supporting structure. Whereas in a roof application, the panel would need to carry dead loads and be able to elastically respond to the imparted blast.

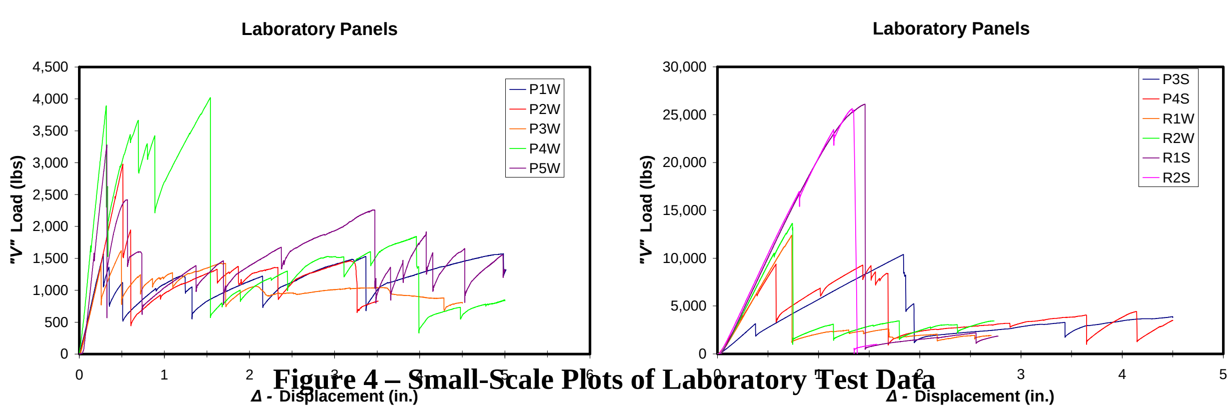

Figure 4 – Small-Scale Plots of Laboratory Test Data

ANALYTICAL PREDICTIONS

An idealized resistance function, a pressure vs. deflection curve, can be formulated for the parallel weak axis panels. Engineering judgment was used, and properties collected, during the laboratory testing. First the appropriate correlations between the lab and field panels must be developed. It is important to recognize that this procedure, outlined below, uses the delamination caused by the horizontal shear as the controlling failure mode, which was based on experimental observations.

Therefore, the pressure vs. deflection (static resistance function, p vs. Δ) is derived recognizing that the horizontal shear controls the failure mode. The following equation is the representation of the pressure vs. deflection relationship for the elastic region of the panel:

$$\Delta = \left(\frac{5L^4 b}{384 E_e I} \right) p$$

The equation is used to form the idealized resistance functions for full-scale wall panels using the parallel weak axis orientation (Figure 5). The post-peak behavior of the resistance function is an empirical representation of observations from the laboratory testing.

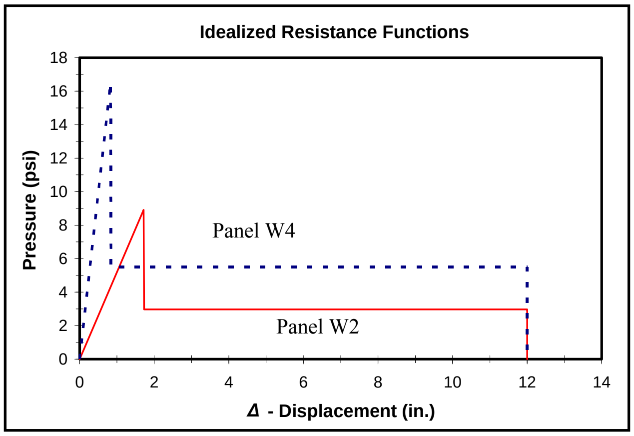

Figure 5 – Wall Panel Analytical Resistances

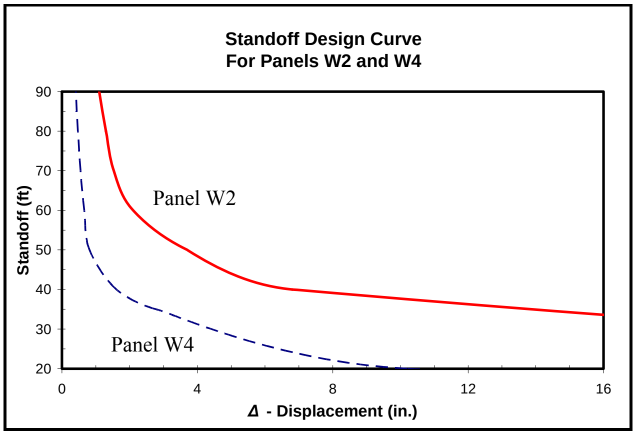

Figure 6 – Wall Panel Test Design Curve

The resistance functions developed for the wall were incorporated into a single-degree of freedom (SDOF) dynamic model to predict the displacement at any time step during the blast event. The SDOF models were used to predict the maximum displacement of the panel subjected to blast loads resulting from variable standoff distances. The standoff distance ranged between 20 and 90 feet, and the resulting displacements were plotted in Figure 6 for Panels W2 and W4.

FIELD EXPERIMENTS

The analytical prediction models developed are verified experimentally using live explosives on the honeycomb FRP wall panels. Since it is expected that such FRP panels would have to mitigate fragmentation threats in addition to blast, the internal cells formed by the core layers were filled with sand. This will also enhance their blast mitigation abilities due to the additional mass providing inertial resistance. Each panel was secured to the reaction structure by clamping plates along the edges of the panel. Also, ½-inch steel plate spacers were provided between the top and lower panels to reduce friction between panels. In addition, spacers were placed between the lower panels and ground surface. See Figure 7 for a setup overview.

Figure 7 – Wall Panel Experiment

Using the design chart of Figure 6, a vertical line was drawn at 12 inches of deflection, of which the corresponding lower-bound standoff for wall Panel W2 becomes 35 ft. Mid-span deflection of all four panels was recorded during testing, as well as the external reflected pressure and free-field pressure readings. Post-test observations indicate that Panels

W2 and W4 failed due to horizontal shear capacity being exceeded, as expected.

The wall panels were ultimately controlled by their bonded interfaces, as was seen in the laboratory testing. The internal cores and faces delaminated due to the horizontal shear in the panel. None of the panels had core configurations that were optimized for this application. Ideally, an optimization would produce thinner core sections by improving the bonded interface. If the bonds were sufficient compared to the FRP material itself, damage would be expected in the form of crushing or ripping apart of the FRP. The crushing and ripping would utilize the FRP material in absorbing the blast effects. The result would be a thinner and lighter panel serving the same purpose. The dynamic model comparison for Panel W2 was about 10% conservative in predicting the response, whereas the model for Panel W4 was an underestimate of its actual deflection. Error in Panel 4W can be attributed to the extrapolation of the idealized resistance function. When multiple core layers are stacked, the predicted post-peak resistance becomes increasing random. This is due to the variability of the bonded interfaces.

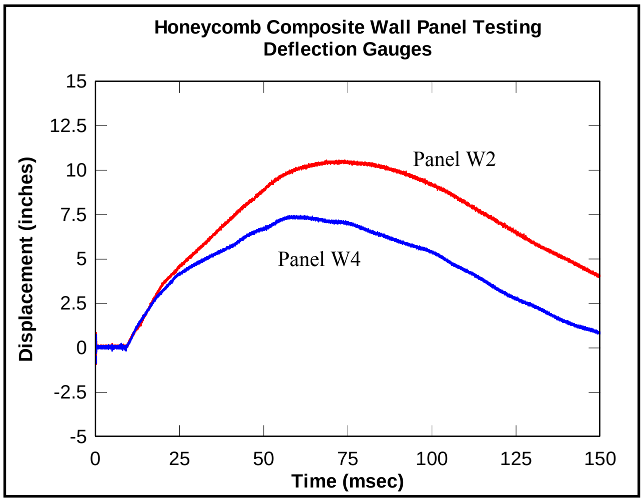

Figure 8 – Wall Panel Response

The honeycomb FRP panels were also evaluated using a near-miss simulated mortar attack. Four FRP wall panels were used in this test; they are F3, F4, F5, and F6 described in Table 1. In addition, two PVC wall panels, which are stay-in-place concrete forms that have 0.125 inch PVC surfaces, were also placed in the arena. It is assumed that the PVC forms provide no additional fragmentation resistance to their system. These two PVC panels were used for baseline comparisons. It was predicted that the FRP core would provide additional resistance to penetration due to the honeycomb cores' cells confining the sand, whereas the PVC samples do not provide such confinement, and thus the resistance will be provided by the sand only (Figure 9).

The mortar was placed at a set standoff distance from the face of each panel in the arena. The mortar, seen in Figure 10, was positioned pointing upward with its base elevated 40 inches from the ground surface.

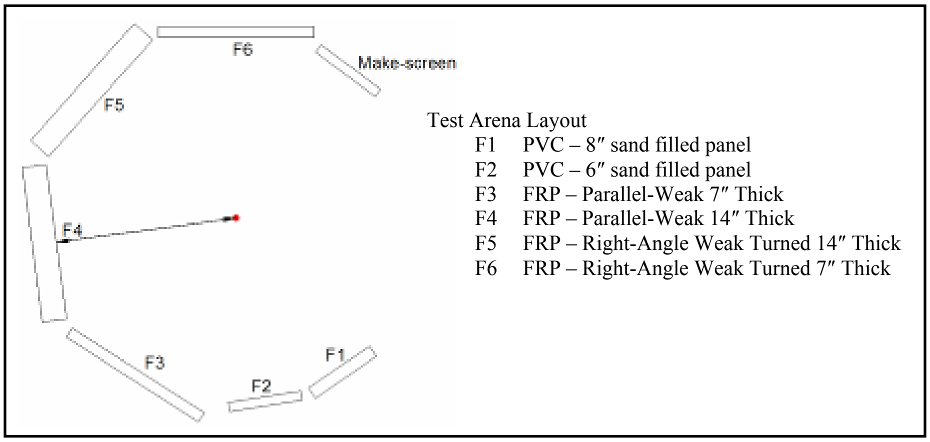

Figure 9 – Wall Panel Experiment for Fragmentation Setup

Figure 10 - Pre-detonation

The standoff-elevation combination was selected so that the majority of the fragments would hit the panels at their mid-height. The fragmentation pattern was as desired with a high percentage of hits in the center of the panels, as seen in Figure 11.

The honeycomb FRP wall panels used for this series of testing achieved the goal of stopping all the fragments. One draw back of using FRP was that once the panels were struck with fragments, they had large amounts of fiber debris that filled the air and spread into the surrounding vicinity. The breathing hazard associated with the FRP panels post-attack should be evaluated to identify an allowable exposure limit for airborne FRP material.

Figure 11 - Post-detonation

Again, the theory behind the honeycomb cores is the benefit of cores confinement to the sand fill of the panels, increasing their resistance to fragmentation. As the fragment passes through the faces of the panel, the fragment has to shear through the sand as it penetrates. Observations after the detonation showed evidence that the parallel weak axis panels delaminated between layers, ideally absorbing additional momentum from the fragment Figure 12a compared to 12b.

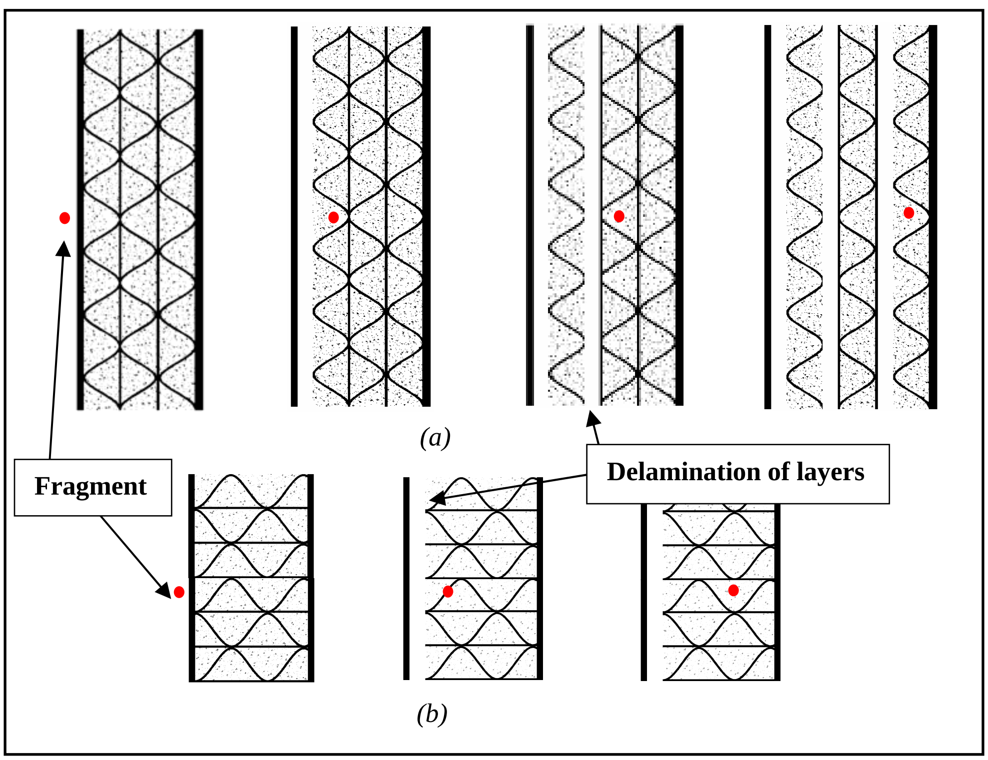

Figure 12 – Penetration Theory

CONCLUSIONS

These honeycomb fiber-reinforced polymers (FRP) panels were evaluated to study their feasibility as maneuverable structures, which could provide protection from both blast and fragmentation. The panels were tested in the laboratory. In addition, full-scale field experiments were designed for comparison of models and demonstrate proof of concept. Field experiments were designed to simulate real world applications and threats.

The primary static evaluation in the laboratory provided a method of characterizing the FRP material for behavior and mechanical properties. From the laboratory evaluation it was seen that the panel construction influenced their overall behavior due to insufficient bonding at interfaces. This information was then used in developing analytical predictions for recommending design of field experiments. The four panels were placed in front of a reaction structure and were submitted to a blast event. Their dynamic response and pressure vs. time histories were recorded. The overall performances of the panels were controlled by horizontal shear forces that developed internally in the panel. In other words, the bonded interfaces of the inner cores failed, leaving the panels with very small residual resistances in absorbing the blast loads. Therefore, it is believed that these FRP panels do not meet the optimum performance in blast mitigation as wall panels. Additional research is still needed to optimize these FRP panels design specifically for use as blast walls in temporary structures.

Similar wall panels were subjected to fragmentation from the detonation of a nearby munition. No complete penetrations were observed in the panels, but physical observations after detonation were made suggesting that the honeycomb cores confined the sand as expected, which provided the needed energy dissipation necessary for fragmentation protection. Though the overall hazard of loose fibers and panels debris in the surrounding air was not measured, it was duly noted to be a consideration for a health risk. Therefore, it is the recommendation of this paper that the honeycomb FRP panels be further researched to achieve a more desirable level of overall efficiency. If greater attention was paid in the fabrication process to secure better bonded interfaces, for the weaker axis configurations which could reduce or eliminate the horizontal shear failures, recommendations for the wall application might be considered as a potential component to temporary structures.

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