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Advancing Timber for the Future Built Environment

BLAST TEST OF A MASS TIMBER FAÇADE FOR DIPLOMATIC FACILITIES

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ABSTRACT: The U.S. Department of State (DOS) Bureau of Overseas Buildings Operations (OBO), in collaboration with DOS' Bureau of Diplomatic Security (DS), initiated a multi-phase applied research effort to assess the feasibility of incorporating mass timber (MT) into U.S. diplomatic facilities. As diplomatic facilities have stringent blast, ballistic, and forced entry resistance requirements, a primary objective of this effort was to demonstrate that mass timber systems can meet these requirements while still complying with the operations and logistics considerations inherent with DOS facilities. As a capstone to this effort, a full-scale two-story mock-up of a mass timber façade comprised of cross-laminated timber (CLT) panels, a ribbon window, a punched window, and a door was constructed at Tyndall Air Force Base. This mock-up was exposed to a large blast load to demonstrate its blast resistance and ability to maintain its forced entry and ballistic resistance envelope following a blast event. The results of this test indicated that the mock-up façade did indeed accomplish this objective. While the CLT panels exhibited various levels of rupture, they were shown capable of resisting the applied blast load without generating hazardous debris on the protected side of the façade. Furthermore, the self-drilling screw connections tying the panels, windows, and door elements together performed well, which serves to validate the analytical methods utilized to design the test article and its connections. The successful demonstration of this mock-up highlights the ability of CLT systems to effectively resist significant blast loads.

KEYWORDS: cross-laminated timber, blast, ballistic, forced entry, façade

1 – INTRODUCTION

A mock-up of a mass timber façade involving CLT panels was exposed to a large blast load as a capstone test for a multi-year applied research effort. The façade was designed to comply with the U.S. diplomatic facilities' architectural, structural, security, operations and maintenance, and procurement logistics requirements. This paper describes the test objectives, the constituent parts of the test article and how they were designed, the instrumentation used to quantify the response of the test article, and the overall results of the blast test performed.

2 – BACKGROUND

DOS buildings must meet blast and forced entry/ ballistic resistance (FE/BR) design requirements to mitigate the hazardous effects associated with violent acts or threats. Historically, OBO has used conventional reinforced concrete for its reliability in meeting these unique security requirements. However, the use of reinforced concrete comes with limitations including a reliance on local skilled labor and challenges with construction logistics at remote locations. The emergence of MT, and its attendant advantages including overall schedule reduction, quality control enhancement, and cost benefit potential, provides a responsible building material alternative to owners and architects developing such buildings.

3 – PROJECT DESCRIPTION

A multi-phase applied research effort was initiated to investigate incorporating mass timber into U.S. diplomatic facilities. The effort consisted of a Phase I scoping effort that focused on assessing the feasibility of incorporating

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mass timber into diplomatic facilities and a Phase II testing effort that focused on demonstrating that mass timber could effectively comply with the blast, ballistic, forced entry, and progressive collapse requirements for DOS construction. As a capstone to these individual Phase II testing efforts, a single blast test of a full-scale mock-up of a typical DOS façade complete with FE/BR protective elements was performed. This test was collaboratively overseen and funded by OBO and DS.

The purpose of this test was threefold: (1) to demonstrate CLT system-level response for large blast loads, (2) to demonstrate the blast resistance of typical structural details that might be used on a mass timber facade in a DOS facility, and (3) to evaluate the ability of the forced entry/ballistic resistant (FE/BR) envelope to maintain effectiveness following a blast event.

4 – EXPERIMENTAL SETUP

A two-story test article comprised of CLT panels filled the open end of the Full-Bay Airblast Test Structure (FATS) shown in Figure 1. The open end of the FATS measures approximately 30 feet wide by 24 feet high.

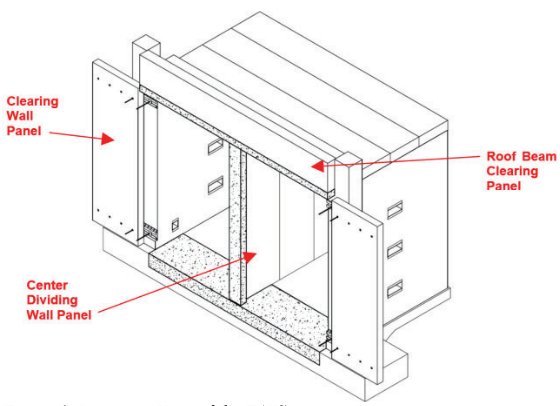

Figure 1. Isometric View of the FATS.

A pre-test photograph of the two-story mock-up test article from the exterior is shown in Figure 2. The test article consisted of non-load bearing 9-ply CLT wall panels, a 7-ply CLT elevated floor panel, a 9-ply roof panel, FE/BR cladding on the exterior face of the first story, a FE/BR ribbon window, a FE/BR punched window, and a FE/BR single-leaf door.

4.1 CLT PANELS

All CLT panels directly exposed to blast overpressure (i.e., the wall and roof panels) were Grade V3M7 9-alt panels manufactured by SmartLam. The Grade V3M7 panels consisted of No. 2 Southern Pine lumber in both the major and minor strength directions. The elevated floor panel that laterally supported the wall panels inside the FATS was a V3M7 7-alt panel manufactured by SmartLam. The Allowable Stress Design (ASD) strength and stiffness properties for these panel layups were obtained from APA Product Report PR-L327 (dated 30 November 2023). These CLT panels, along with their associated connection elements, were designed using the output from single degree-of-freedom dynamic analyses conducted using the Bio-Composite Blast Load Analysis Software Tool (BCBLAST) [1].

Figure 2. Pre-Test Photograph of Mock-Up Test Article.

4.2 FE/BR CLADDING

The FE/BR cladding consisted of 0.1875-inch thick steel plates backed by 0.625-inch thick Type X gypsum sheathing applied to the exterior (attack) face of the CLT wall panels. This cladding combination was shown to satisfy the FE/BR requirements defined in SD-STD-01.01, Revision H, via testing performed as part of the Phase II effort [2]. To facilitate installation, the steel plate dimensions were limited to 4 feet by 8 feet. In keeping with the results documented in Ref. [2], no plate or weld was provided to cover the seams separating adjacent plates.

4.3 FE/BR WINDOW PRODUCT

Two types of windows were included in the test article: (1) a punched window on the first level having a rough opening of 4.79 feet wide by 3.63 feet high and (2) a ribbon window on the second level having a rough opening of 13.1 feet wide by 4.79 feet high. Four identical FE/BR windows were aligned to form the ribbon window. A ribbon window was included in the test article to demonstrate the ability of CLT façades with large openings to resist blast loading. All FE/BR window products used were manufactured by Norshield Security Products (DOS Model No. GWV-15R-NOR-11). The window layup was an insulated glazing unit that consisted of a 0.79-inch attack side lite, a 0.54-inch air gap, and a 1.26-inch protected side lite. The total thickness and weight of the window layup was 2.59 inches and 19.6 psf, respectively.

4.4 FE/BR DOOR PRODUCT

A FE/BR door was mounted in a 3.43-foot wide by 8.10-foot high rough opening in the test article's first-level wall. The FE/BR door product was manufactured by Norshield Security Products (DOS Model No. GDT-15R-NOR-05[r]).

4.5 CONNECTION DETAILS

A primary purpose of performing the mock-up test was to demonstrate the blast resistance of typical structural details that might be used on a MT facade in a DOS building. Due

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to their importance, the elevated floor, roof, splice, and rough opening reinforcement details are briefly discussed and shown here.

Elevated Floor and Roof

The elevated floor detail is shown in Figure 3a. The distance from the top of floor slab to the underside of the elevated floor panel is 14 feet and the distance from the top of elevated floor topping to the underside of the roof panel is 9.03 feet. The defining characteristic of this detail is the lack of a mechanical connection between the first-level CLT wall panels, the second-level CLT wall panels, and the CLT elevated floor panel. Instead, the second-level CLT wall panel bears on the first-level CLT wall panel, and both wall panels are restrained laterally by tie-rods at 12 inches on center. This lack of mechanical connections was driven by the structural engineer’s desire for the wall panels to be non-load bearing (i.e., not resist gravity load deriving from the elevated floor) and have minimal in-plane stiffness for lateral (e.g., seismic) force resisting system detailing considerations.

The roof detail is very similar to the elevated floor detail except that the CLT wall panel is continuous where the roof panel ties into the wall panel. This CLT wall panel forms a 4.54 foot tall parapet for the façade.

Splice

The three details used to splice adjacent exterior CLT wall panels are illustrated in Figure 3b through Figure 3d.

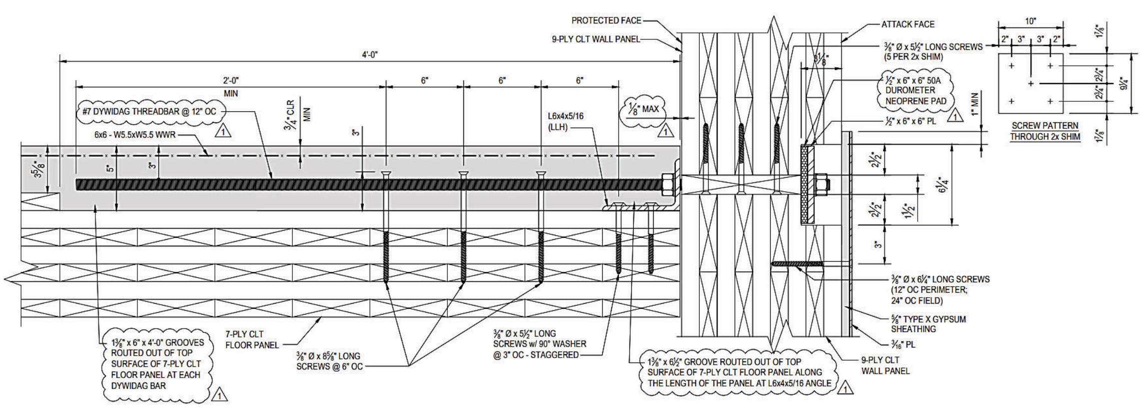
- Figure 3b utilizes a WT8x25 to tie adjacent CLT wall panels together. Two different screw spacings were used to tie the WT’s flange to the CLT panel: (1) a constant spacing of 8 inches as shown in Figure 3b and (2) a larger typical spacing of 10 inches but with additional screws placed in line with the top and bottom of the adjacent punched window. The result of this detailing decision is that the total number of screws in the WT flange were equal. The web screws in these details were positioned in such a way as to provide a symmetric arrangement relative to the punched window on the first level of the test article.
- Figure 3c utilizes a plate instead of a WT shape to tie adjacent CLT panels together. This detailing decision was made to minimize the required CLT panel edge routing. This detail is very similar to a detail tested in the component-level testing [3] except that the spacing of the screws in the mock-up test article was increased to 4 inches from 3 inches.
- Figure 3d was used at the jambs of the ribbon window on the second level. A slightly larger WT shape (i.e., WT8x33.5 versus WT8x25) was used to strengthen the jamb section further. At the ribbon window, half of the WT flange was cut out to make the vertical edge of the ribbon window’s rough opening.

The spacings of the screws securing the steel reinforcement to the exterior CLT wall panels were derived using the simplified design rules described in Ref. [3], namely:

- An effective jamb width of 25% of the jamb length was used, provided the panel’s geometry allowed for such a jamb width. The effective jamb width was assumed to span across the steel reinforcement (i.e., the steel reinforcement was assumed to remain engaged for the blast test).
- The ultimate resistance of the angles framing out the windows and/or door was used to derive the force demand on screws connecting the steel reinforcement to the CLT panels (i.e., see Section 4.4.2 of Ref. [3]).

Rough Opening

The typical rough opening reinforcement detail is shown in Figure 3e. This detail is identical to the rough opening reinforcement detail included in the component-level blast testing [3].



(a) Elevated floor detail (elevated roof detail is similar).

Figure 3. Key Connection Details Employed in the Mock-Up Test Article.

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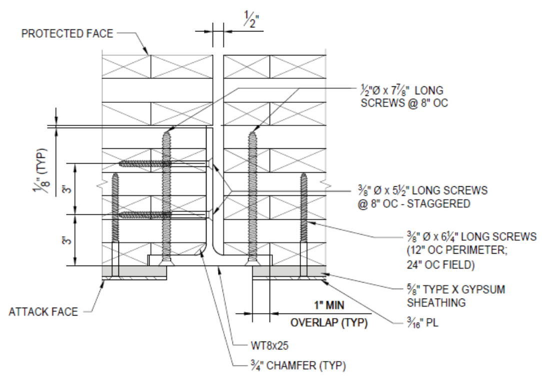
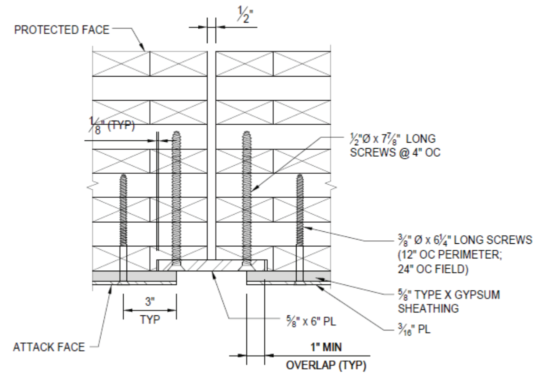
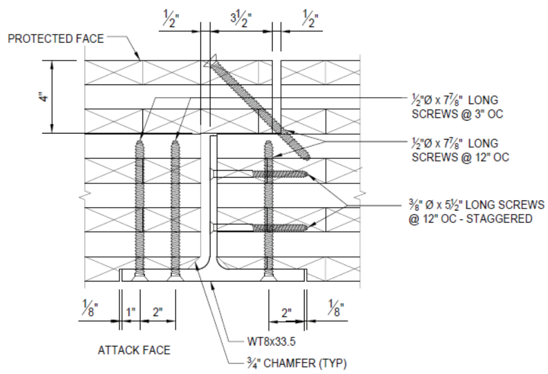


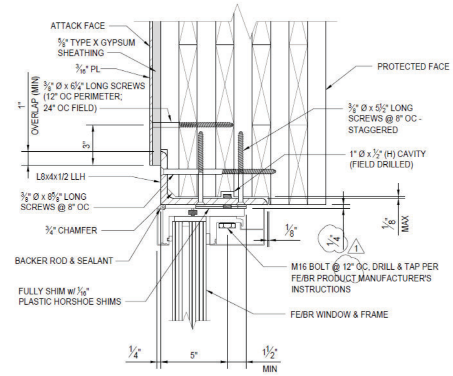
(b) WT-reinforced splice detail adjacent to punched window and door.



(c) Plate-reinforced splice detail.



(d) WT-reinforced splice detail adjacent to ribbon window.



(e) Typical rough opening reinforcement detail.

Figure 3. Key Connection Details Employed in the Mock-Up Test Article. (Cont'd)

4.6 INSTRUMENTATION

Reflected pressure (RP) gauge, displacement gauge (DG), and load cell (LC) instrumentation were used to document the response of the test article; a key plan indicating the locations of the RP, DG, and LG instrumentation employed on the front face of the test article is included in Figure 4.

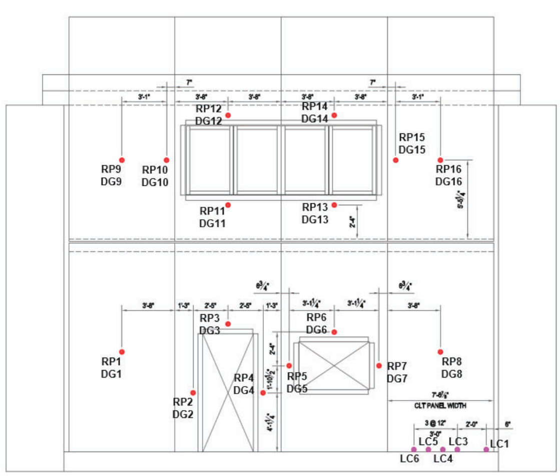


Figure 4. Instrumentation Key Plan on Front Face of Test Article.

- Eighteen reflected pressure gauges were used to measure the blast pressures applied the surface of the test article; sixteen were mounted to the front wall and the remaining two were mounted to the CLT roof panel.
- Seventeen displacement gauges were used to measure the out-of-plane displacement of the CLT panels; sixteen were mounted to the front wall and one was mounted to the CLT roof panel.
- Five load cells were equally spaced along the bottom edge of CLT panel P1B (i.e., see Figure 4 for a key plan in elevation) in order to measure the out-of-plane force applied by the CLT panel to the support angle at the foundation. Figure 5 illustrates how the load cell was integrated into the ground level connection detail.

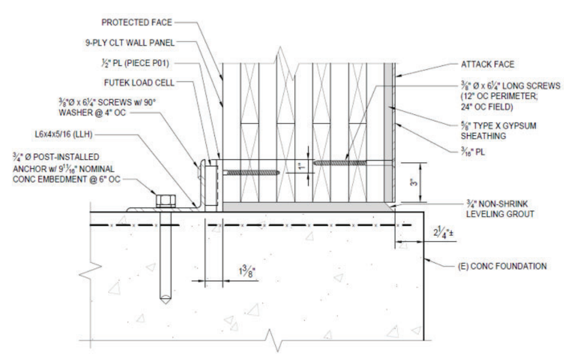


Figure 5. Detail Showing Integration of Load Cell into Typical Wall Panel Support Detail at Ground Level.

5 – RESULTS

5.1 OBSERVATIONS

A post-test photograph of the exterior of the mock-up test article is shown in Figure 6. Observable damage included cracking of the FE/BR glazing in the door and windows, the FE/BR door opening due to a failure of the door's latching mechanism, bulging of the FE/BR cladding in the vicinity of the punched window, and charring of the CLT panels at the second level. No screw failures were observed in any of the splice, rough opening reinforcement, or FE/BR cladding attachment details apart from the partial withdrawal of a screw from the sill angle of the ribbon window.

Figure 6. Post-Test Photograph of Exterior Wall Surface.

Damage to the interior surface of the test article is described using the key shown in Figure 7. Post-test photographs of the interior surfaces of the mock-up test article are included in Figure 8. In general, the damage observed in the CLT panels was concentrated at panel midspan (i.e., for the "P" surfaces in Figure 7) or at the top of the window or door (i.e., for "J" surfaces in Figure 7). The damage ranged from Superficial to Heavy, as defined in PDC-TR 06-08 [4].

Figure 7. Key for Describing Damage to Interior Surface of Mock-Up Test Article.

(a) Ground floor on side of punched window.

(b) Ground floor on side of door.

(c) Second floor.

Figure 8. Post-Test Photographs of Interior Wall Surface.

The rupture locations tended to concentrate around finger joints (Figure 9a) or in the vicinity of lumber abnormalities such as knots (Figure 9b) or sloped grain (Figure 9c). In one instance (i.e., in Jamb J3), one of the boards completely delaminated from the panel (Figure 9d). However, based on the high-speed video footage, it appears that this board completely delaminated in late time and fell straight to the ground (rather than being propelled into the room). It is interesting to note that the rupture did not always concentrate in the finger joints or lumber

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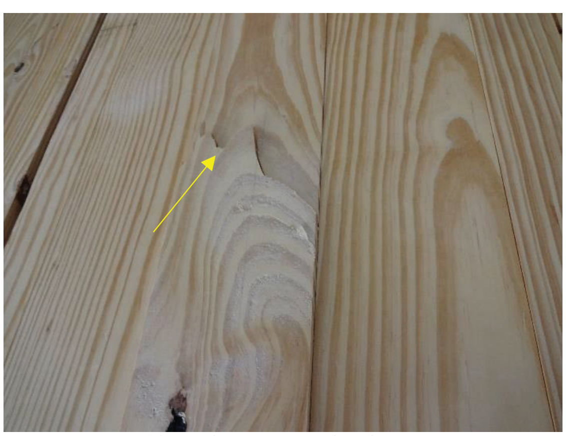
abnormalities, as there were several locations where the rupture line was near, but not at, the finger joint or an observable abnormality (Figure 9e). While there was damage observed in all of the CLT wall panels at the first floor, no damage was observed in the second floor CLT wall panels or the CLT roof panel. The observed damage in each test article panel as well as an assigned damage level according to the damage level definitions in PDC-TR 06-08 [4] are given in Table 1.

(a) Panel rupture near a finger joint.

(b) Panel rupture near a knot.



(c) Panel rupture near sloped grain.

Figure 9. Close-in Post-Test Photographs of Interior Wall Surface.

(d) Board delamination in Jamb J3.

(e) Rupture near, but not at, finger joint..

Figure 9. Close-in Post-Test Photographs of Interior Wall Surface. (Cont'd)

Table 1: Qualitative Damage Summary

Component	Observations	Damage Level
Panel P1A	Minimal rupture near midspan	Moderate Damage
Panel P1B	Minimal rupture near midspan	Moderate Damage
Panel P2A	No signs of rupture	Superficial Damage
Panel P2B	No signs of rupture	Superficial Damage
Jamb J1	Minimal rupture near top of door frame	Moderate Damage
Jamb J2	Moderate cracking near top of window frame	Heavy Damage
Jamb J3	Significant rupture near top of window; board disengaged (and fell straight to floor)	Heavy Damage
Jamb J4	No signs of rupture	Superficial Damage
Roof Panel	No signs of rupture	Superficial Damage

In general, most of the test article's connections were intact and undamaged following the blast test. There was only one case where complete tension rupture of a fastener occurred – at the bottom boundary angle on the left side of the door (as viewed from the interior) a single screw exhibited a tensile rupture failure and was missing at the end of the test (Figure 10a). On the other side of the door opening, partial withdrawal of several screws in the vertical leg of the foundation angle occurred (Figure 10b). Other partial connection failures included the partial withdrawal of several screws connecting the angle framing out the door opening to the CLT panel (Figure 10c), and several bolt bearing failures at the bolts connecting the door frame to the angle framing out the door opening (Figure 10d). Finally, the screws securing the 7-ply CLT elevated floor panel to the reaction structure and interior CLT partition wall exhibited significant shear deformation and withdrawal (Figure 10e). This failure type was observed at all four angles supporting the 7-ply CLT panel (i.e., two angles at both the reaction structure and the CLT interior partition). Despite this localized damage to connections, all self-drilling screws (with the one exception in Figure 10a) remained engaged and were not able to be pulled out of the parent CLT panel.

(a) Screw tensile rupture location.

(b) Partial screw withdrawal near door frame.

Figure 10. Post-Test Photographs of Damage to Connections.

(c) Partial screw withdrawal at door frame angle.

(d) Bolt bearing at door frame.

(e) Combined shear / withdrawal screw failures.

Figure 10. Post-Test Photographs of Damage to Connections. (Cont'd)

5.2 RECORDED DATA

Figure 11 plots the RP data on the surface of the test article. (Note that since the RP7 curve is such a clear outlier, the RP7 data is not used to derive the average (AVG) curve shown in Figure 11a. Also, the RP9 gauge malfunctioned, which is not shown in Figure 11b.) Table 2 summarizes the RP data on the exterior surface of the mock-up test article.

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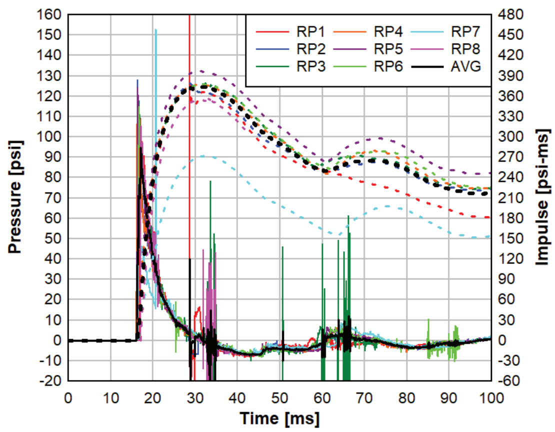
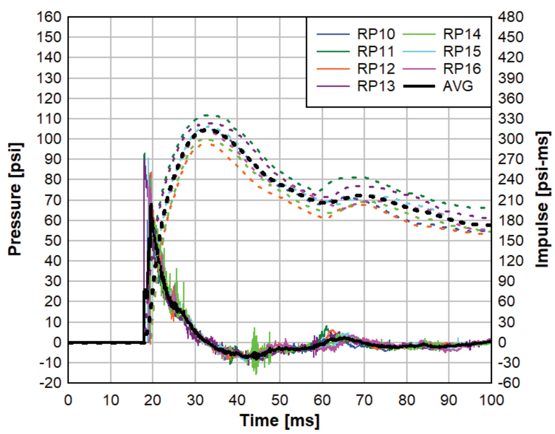
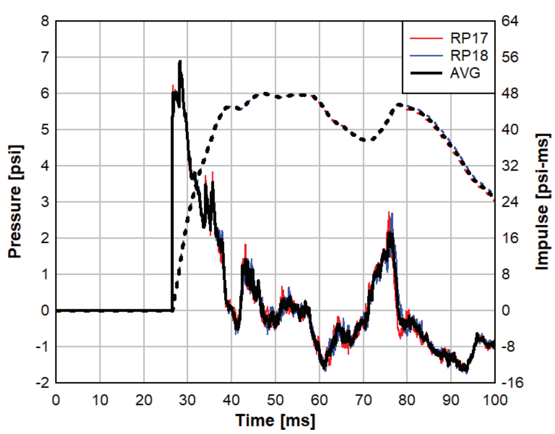


(a) First level.



(b) Second level.



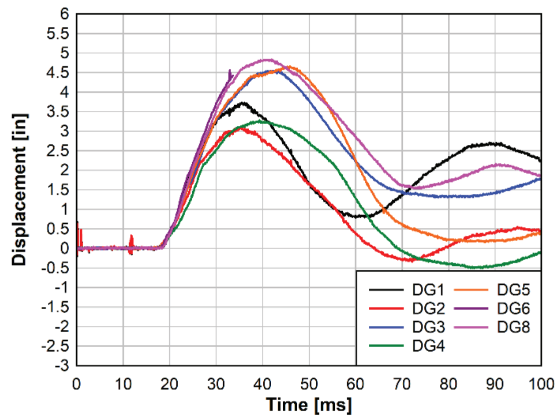
(c) Roof.

Figure 11. Reflected Pressure Data.

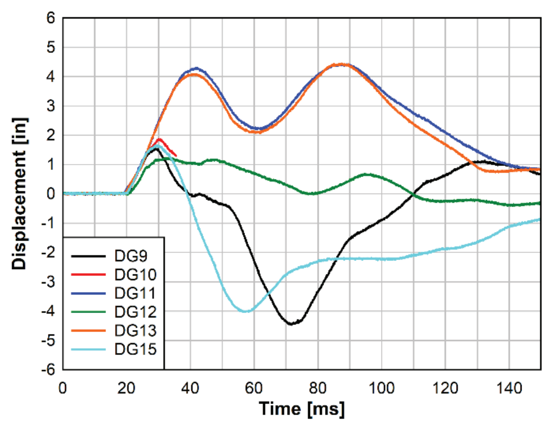
Table 2: Reflected Pressure Data (Average Curve) Summary

Location	Time of Arrival [ms]	Peak Positive Phase Pressure [psi]	Peak Positive Phase Impulse [psi-ms]
First Level	16.53	115.9	377.8
Second Level	18.72	86.76	314.0
Roof	26.45	6.91	48.08

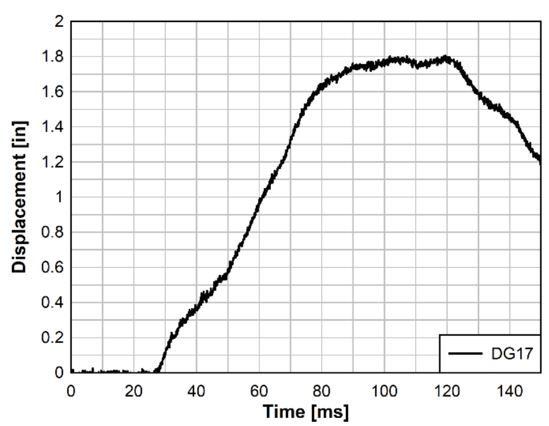
The displacement gauge data measured during the mock-up blast test are plotted in Figure 12. Peak values are summarized in Table 3. Several displacement gauges either reported no data or malfunctioned early on; the data from these gauges (i.e., DG7, DG14, and DG16) are not included in the plots in Figure 12 or in Table 3.



(a) First level.



(b) Second level.



(c) Roof.

Figure 12. Displacement Data.

Table 3: Displacement Data Summary

Location	Gauge No.	Peak Displacement (1) [in]
First Level	1	3.72
	2	3.11
	3	4.54
	4	3.28
	5	4.66
	8	4.83
Second Level	9	1.53 (4.47)
	10	1.86
	11	4.30
	12	1.21
	13	4.09
	15	1.65 (4.03)
Roof	17	1.81

(1) The value shown is derived from the first peak. Where a number is given in parentheses, this indicates a notable rebound response occurred, and the number in parentheses is the peak displacement in rebound.

The load cell data measured during the mock-up blast test is plotted in Figure 13 and summarized in Table 4. The average (AVG) curve in Figure 13 does not include the LC6 outlier. The LC3 gauge malfunctioned early on and is not included in Figure 13.

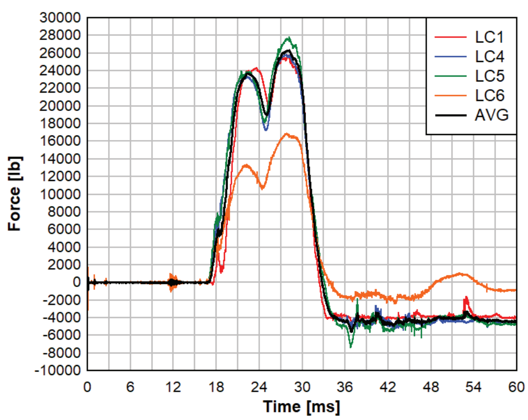


Figure 13. Load Cell Data.

Table 4: Load Cell Data Summary

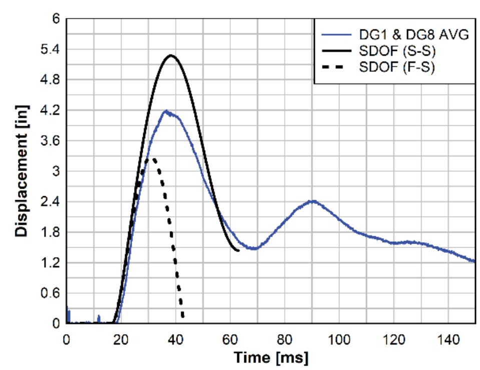
Gauge No.	Peak Force [lb]
1	25,772
4	25,880
5	27,865
6	16,912

5.3 ANALYTICAL MODEL COMPARISON

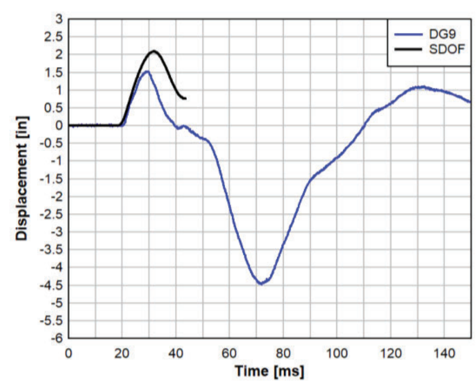
A series of single degree-of-freedom (SDOF) dynamic analyses were performed using the average pressure history curves measured during the mock-up blast test shown in Figure 11. The SDOF dynamic analysis parameters used are shown in Table 5. The following assumptions were employed in these analyses:

- The parameters used to construct the resistance function (i.e., elastic resistance, r_e, ultimate resistance, r_u, elastic stiffness, k_e, and elastic-plastic stiffness, k_{ep}) are computed using the methodology documented in PDC-TR 18-02 [5] for CLT panels (BCBLAST [1] was used to perform these SDOF analyses).
- CLT panel weight is derived assuming a specific gravity of 0.55. A moisture content of 12% is assumed for all analyses.
- The mass, m, shown in Table 5 is the component's self-weight plus any supported weight, w_{sup}.
- Viscous damping is applied. The fraction of critical damping is assumed to be 2%.
- Two boundary condition idealizations were assumed for Panel P1 due to the partial fixity of the CLT panel at the top boundary condition (i.e., see Figure 3a).

Figure 14 shows plots comparing the dynamic analysis results with the test data shown in Figure 12 and Table 5 summarizes the peak displacement for the SDOF analysis cases and corresponding test data. In most cases, the peak SDOF displacement exceeds the peak test displacement by at least 20% (with the exception of the F-S case for Panel P1). Comparing the S-S and F-S curves in Figure 14a indicates at least some of this discrepancy can be attributed to the idealized boundary conditions assumed.



(a) Panel P1.



(b) Panel P2.

Figure 14. Displacement Comparisons.

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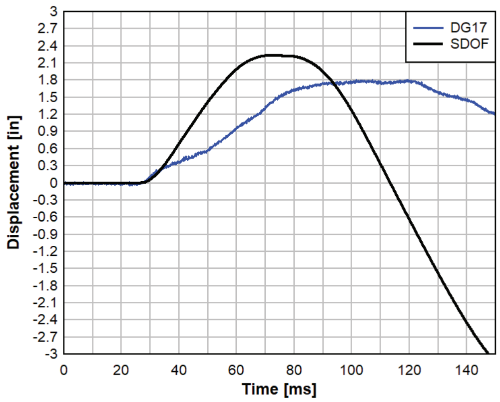

(c) Roof.

Figure 14. Displacement Comparisons. (Cont'd)

The computed dynamic reactions from the Panel P1 SDOF calculations are plotted against the average load cell data curve shown in Figure 13. (The LC data is divided by 12 inches (i.e., the load cell spacing) to obtain a pound-per-inch measurement.) It is interesting to note that the peak force from the LC data for gauges LC1, LC4, and LC5 is larger than the peak dynamic reaction for the S-S idealization (i.e., black solid line in Figure 15) but smaller than that for the F-S idealization (i.e., black dashed line in Figure 15). This pattern is consistent with the displacement result comparison shown in Figure 14a, and further supports the as-tested boundary condition at the top of Panel P1 being somewhere between the pinned and fixed idealizations.

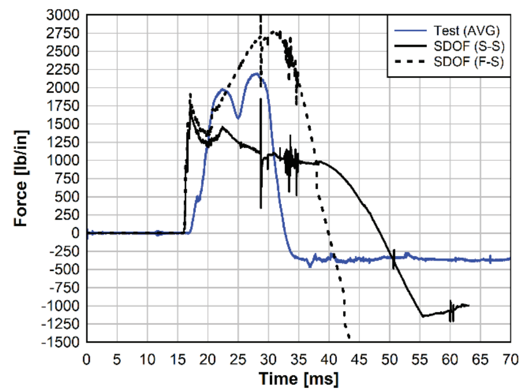

Figure 15. Displacement Comparisons.

Table 5: SDOF Analysis Comparison Result Summary

Comp. ID (Gauge ID) (1)	BC (2)	L [ft]	w_{sup} [psf]	m [psi-ms^2/in]	r_e [psi]	k_e [psi/in]	r_u [psi]	k_{ep} [psi/in]	Peak Displacement [in]			Peak Force [lb/in]		
									Test (4)	*Calc.*	*% Diff.*	*Test*	*Calc.*	*% Diff.*
Panel P1 (DG1 & DG8 AVG)	S-S	14	10.4	900.3	-	10.70	16.32	-	4.28	5.27	23%	2,195	1,846	-16%
	F-S				16.32	18.86	20.24	10.70		3.27	-31%		2,805	28%
Panel P2 (DG9) (3)	F-S	10.2	0	713.2	-	47.30	27.71	-	1.53	2.09	37%	-		
Roof (DG17)	S-S	30	0	713.2	-	0.64	3.55	-	1.81	2.23	23%			

(1) As defined in Figure 7.
(2) Boundary condition: S-S = simple-simple, F-S = fixed-simple.
(3) Panel P2 is predicted to exhibit a rolling shear failure prior to reaching its elastic ultimate resistance, r_e, in flexure, and thus does not have a trilinear resistance function even though it has a F-S boundary condition.
(4) The peak displacements shown are those associated with the inbound component response. In some cases, the rebound displacements exceed those shown in this table.

6 – CONCLUSIONS

The mock-up blast test demonstrates that the details developed as part of this effort, as well as the analysis procedures used to design the test article and its connections, are appropriate for the intense blast loading requirements associated with diplomatic facilities. Not only did the CLT panels respond well when exposed to this blast loading, but the relative ease through which ductile connection details can be designed for mass timber structures was demonstrated. The next step is to utilize this test and the other component-level tests conducted as part of the Phase II effort to inform a pilot project involving mass timber elements in diplomatic facilities.

7 – REFERENCES

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