FINAL REPORT

Shelter and Component Testing

OFDA transitional shelters: materials, techniques and structures

May 25, 2012

Project Number: WOW12-2012-02

SUBMITTED TO
Latin American and Caribbean Center
Disaster Risk Reduction Program
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Addendum to

FINAL REPORT

Shelter and Component Testing

OFDA transitional shelters: materials, techniques and structures (Supplementary Test)

May 29, 2012

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SUBMITTED TO
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1. Introduction

This report is a supplement to the final report for project number WOW12-2012-02. During the experimental tests performed for this project with the Wall of Wind (WoW), a base platform failure occurred with T-Shelter 2 at the highest wind speeds. The scope of work of the experiments did not consider the performance of the platform base (foundations) of the transitional shelter (T-Shelter) model under wind-induced loads. It was anticipated that the platform would be able to sustain the forces but at 95 mph the wood members on the platform weakened and fractured causing the T-Shelter model to disconnect from its foundation. This is not expected to be a typical failure of the T-Shelters and therefore it cannot be concluded that the materials and/or construction techniques would be able to sustain wind speeds of 95 mph. It was recommended to repeat the test with an identical model but with a reinforced base platform.

The objective of these experiments is to test the resistance of a strengthened T-Shelter model (T-Shelter 3) with identical characteristics and dimensions to that in T-Shelter 2, but with a reinforced base platform. For the model to be tested, the WoW will generate wind speeds of 85 mph, 95 mph, 100 and 110 mph for angles of attack of 0°, 45° and 90°. The tests were recorded on video.

2. Methodology

The tests followed the same methodology as that implemented during the full-scale model tests performed during project WOW12-2012-02. T-Shelter 3 was tested with 12-fan WoW (Figure 1).

Figure 1 – Testing equipment: Twelve-fan Wall of Wind

T-Shelter 3 was built with the standard shelter construction practices and materials identical to those used in the previous test of T-Shelter 2. Methods used in construction of T-Shelter 2 and 3 are bound to applicable guidelines for field deployment of T-Shelters and not to requirements of U.S. building codes. Table 2 describes the shelter model construction materials and details.

In this iteration, the T-Shelter model was built on a reinforced wooden platform that allowed it to be bolted to the turntable anchor locations. The number of wood members for the wooden platform was doubled compared to T-Shelter 2 and metal straps connected the foundation to the shelter superstructure. Also the corners of the bottom plate of the frame where bolted down into the platform. The 6 degree of freedom (6-DOF) load cells were not installed given that in the previous study the maximum capacity of the sensors was almost reached at 95 mph. There is a 5-in difference in height between T-Shelter2 and T- Shelter3 due to the removal of the 6-DOF sensors from the base. This variance in height is considered negligible.

Figure 2 - Base platform and load cell for T-Shelter tests. Arrows point out the difference: with and without 6-DOF load cells

The following changes or additions were done to the T-shelter model as requested by OFDA (see Figure 3):

- Window on a non-gable end wall with a stop molding (built of 2-in x 4-in lumber) around the window frame.
- Provide continuous door stop molding all around the door opening and reinforce the hinge connections.
- Additional lateral bracing on non-gable end walls. A diagonal x-brace spanning the length of the walls was installed on both non-gable end walls.

Figure 3 - T-Shelter model improvements for T-Shelter 3 testing

For each 3-minute test the 12-fan WoW produced a uniform sustained wind speed, with an initial speed of 85 mph. During testing of T-Shelter 2, it was observed that wind speeds lower than 85 mph didn't affect the integrity of the structure. Damage initiated at 85 mph, with the door detaching from hinges. Consequently, an initial test speed of 85 mph was chosen for T-Shelter 3's tests.

The initial wind speed of 85 mph was increased following the steps described on Table 1 while no structural failure of the T-shelter was observed. The model was rotated through 3 angles of attack (0, 45 and 90 degrees). At the higher speeds and the 45° angle of attack, the turntable wasn't able to hold the model steady due to the imbalanced resulting forces caused by the asymmetry of the structure. This angle of attack was omitted from the 100 mph and 110 mph tests.

Table 1 - Wind speeds and angles of attack for T-Shelter model tests

Model / Wind Speed	55 mph			65 mph			75 mph			85 mph			95 mph			100 mph			110 mph		
	Degrees																				
T-Shelter 1	0	45	90	0	45	90	0	45	90	-	-	-	-	-	-	-	-	-	-	-	-
T-Shelter 2	-	-	-	0	45	90	0	45	90	0	-	90	-	-	90	-	-	-	-	-	-
T-Shelter 3	-	-	-	-	-	-	-	-	-	0	45	90	0	45	90	0	-	90	0	-	90

The tests were recorded from multiple angles with the highest resolution the cameras would allow (720p and 1080p, depending on the camera) for the duration of the wind resistance test.

Table 2 - T-Shelter models specifications (shaded cells denote changes from previous model)

Structural Element		T-Shelter 2	T-Shelter 3
Walls	Lumber	2-in x 4-in	2-in x 4-in
	Fasteners	3 ¼-in common nail	3 ¼-in common nail
	Bracing	2-in x 4-in diagonals on X pattern on corners	2-in x 4-in diagonals on X pattern on corners and 2-in x 4-in and diagonals on long span walls
	Spacing	2-ft center-center	2-ft center-center
	Cladding	USAID/OFDA plastic fasteners: with 1 ¼-in roofing nails and tin cap discs at 12-in spacing, edges folded 3 times	USAID/OFDA plastic fasteners: with 1 ¼-in roofing nails and tin cap discs at 12-in spacing, edges folded 3 times
Roof	Type	5:12 (22.6°) Gable	5:12 (22.6°) Gable
	Structure	Trusses: 2-in x 4-in 2-in x 4-in purlins 5/8-in plywood gusset plates	Trusses: 2-in x 4-in 2-in x 4-in purlins 5/8-in plywood gusset plates
	Fasteners	3 ¼-in common nails	3 ¼-in common nails
	Hurricane straps	1-in metal strap fastened with 1¼-in roofing nails	1-in metal strap fastened with 1¼-in roofing nails
	Roof cladding	26-ga CGI	26-ga CGI
	Cladding fasteners	1 ¾-in ring shank neo roofing nail	1 ¾-in ring shank neo roofing nail
	Ridge cap	26-ga sheet metal	Manufactured ridge cap
	Overhang	1-ft all around	1-ft all around
Door		1 door centered on gable end wall	1 door centered on gable end wall with 2-in x 4-in door stop
Window		None	1 window on none-gable end wall with 2-in x 4-in stop

T-Shelter in Port-au-Prince, Haiti	T-Shelter 2	T-Shelter 3
		
		
		

3. Results

At the initial test speed (85 mph) it was observed that the T-Shelter structure was strong enough to be able to sustain the wind forces. No damage was noted on the framing or cladding. It is noteworthy to mention two effects on the T-Shelter as a result of the wind angle of incidence and the framing characteristics. At 0° there are sufficient uplift forces generated to cause a noticeable deformation on the leading edge purlin. A gap between the top chord of the truss and the purlin can be seen at one of the corners. The connections made with smooth shank nails were not adequate to prevent the nails from being pulled out under the uplift forces. The hurricane straps were shown to be effective to secure the purlins down to the trusses (Figure 4).

Figure 4 - Windward purlin deformation from uplift forces at 85 mph and 0° angle of attack

The deformation of the plastic sheeting suggested that when the wind had a 90° angle of attack, the flow separated near the leading edges and reattached further downwind. This is shown on Figure 5: bloated plastic surfaces at the windward side (suction) and plastic being pushed against the frame on the back (pressure). The roof also seemed to be susceptible to this effect, particularly with the long unsupported spans of roof structure. The edge purlins can be seen deforming by the action of the wind-induced forces.

It is important to consider that this model only had 3 roof trusses providing clear spacing of 7-ft between trusses. The spacing of the rafters was sub-optimal. The length of unsupported roof span was chosen for this structure to provide a comparable test with T-Shelter 1 and T-Shelter 2 in previous tests.

The goal was to prove that a stronger roof structure with the same spacing as T-Shelter 1 (weak construction T-Shelter from previous experiments) should be able to withstand hurricane force winds. Even with its stronger construction, large unsupported spans allow for greater deformations and flexibility. The vulnerability can be decreased by adding more trusses and reducing the clear spacing by half.

At 45° angle of attack there are no noticeable effects on T-Shelter 3. The turntable is not able to hold the model in place and can be seen slowly rotating clockwise showing that is torsional force produced by the flow around the asymmetric structure.

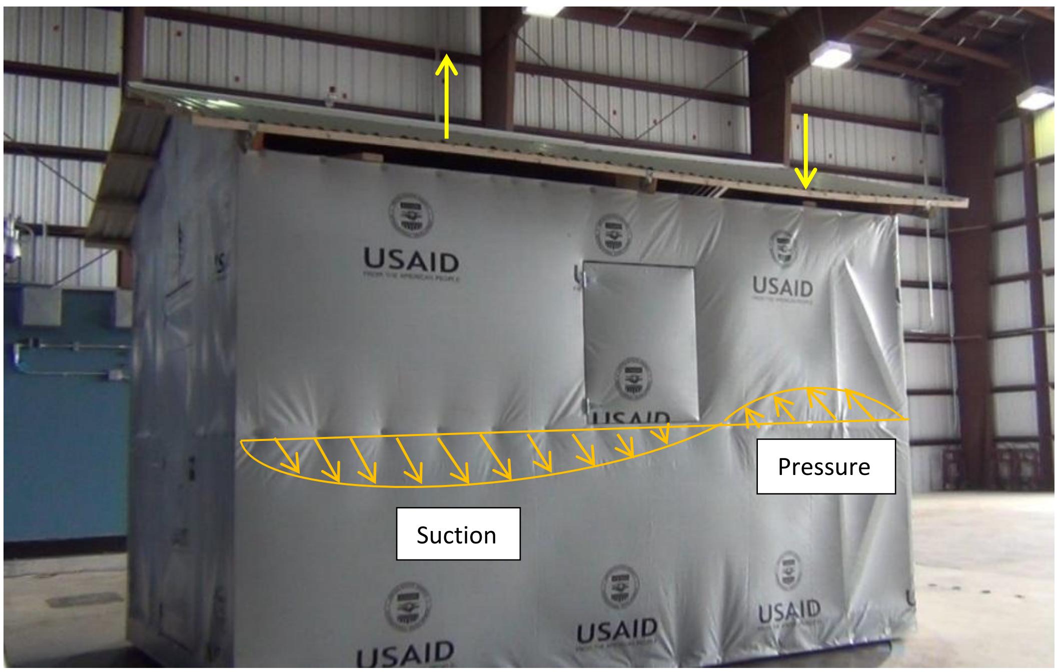

Figure 5 - T-Shelter 3 test at 85 mph and 90° angle of attack

Furthermore, the increase in speed from 85 mph to 95 mph did not produce noticeable damage on the outside of the shelter. The additional lateral bracing seemed to be effective to transfer the forces and reduce the deflection at 90° angle of attack. The reinforced door hinges and door stop are believed to have provided additional support and strengthened the door system. No damage to the door was observed. While inspecting the inside of the shelter it was observed that the door stop did transfer the loads from the door to the frame. The bottom section of the door stop was partially pulled out from its attachment (Figure 6). This was a consequence of a construction flaw, where the nails were driven into the gap between the bottom plate and the platform.

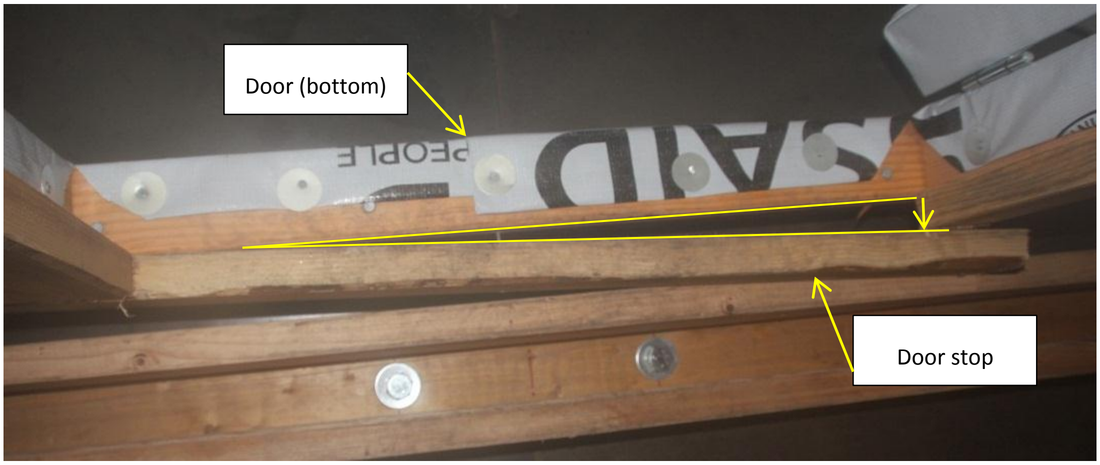

Figure 6 - Bottom door stop pulled-out

With the wind speed increased to 100 mph, sections of the OFDA plastic sheeting were pushed harder into the sharp edges of the tin caps. It is presumed that either the internal pressure build-up from air leaking through the shelter openings or the aerodynamic forces (suction) created on the wall surfaces, or a combination of both, caused the tin caps to start cutting through the plastic (Figure 7). It demonstrated that tin caps transfer the concentrated loads from the nail head to a bigger area on the plastic, but it's sharp edges can cut through it under repetitive loading. It is believed that a material with blunt edges (i.e. wood battens) might be a better option to enhance the durability of the USAID/OFDA plastic during repetitive loading and provide a surface to distribute the forces.

Figure 7 - Plastic puncture by tin cap discs

T-Shelter 3 was able to withstand up to 110 mph at a 90° angle of attack (wind into the gable end). At this angle of attack T-Shelter 2 (same strong construction) platform failed at 95 mph in the previous tests. In the case of testing T-Shelter 3, there was no door failure and therefore no wind penetrating directly into the inside of the shelter through the door location. Also it was observed that the structure was less susceptible to failure due to racking of the frame. It is believed that it is a result of the additional lateral bracing installed in this test specimen. The wall capacity to transfer the forces and pressures can be increased by providing a more rigid form of sheeting to the walls. Replacing the OFDA plastic with a rigid membrane, such as an adequately sized plywood board fastened to the frame, will let the wall act as a diaphragm and help carry in-plane shear. The choice of using OFDA plastic sheeting on all three T-Shelter tests was intended to allow comparable tests among models.

The frame on T-Shelter 3 failed at 110 mph and an angle of attack of 0°. It is believed that the failure mechanism is as follows:

1. The wind acted on the long wall that had an opening (window). The framing had vertical studs discontinued because of the window opening. A jack stud (Figure 8) was provided under the window sill but no cripple stud (shorter stud in window/door header) over the header. The spacing between studs was increased from 24-in on center to 32-in on center at the window opening.
2. While reviewing the video it can be observed that there was a sudden deformation of the wall in its mid-section (close to 1 min into the test). The window section of the wall buckled inwards but dids not detach from the rest of the frame (Figure 9). Until this moment the structure was still standing and the damage could have been repaired.

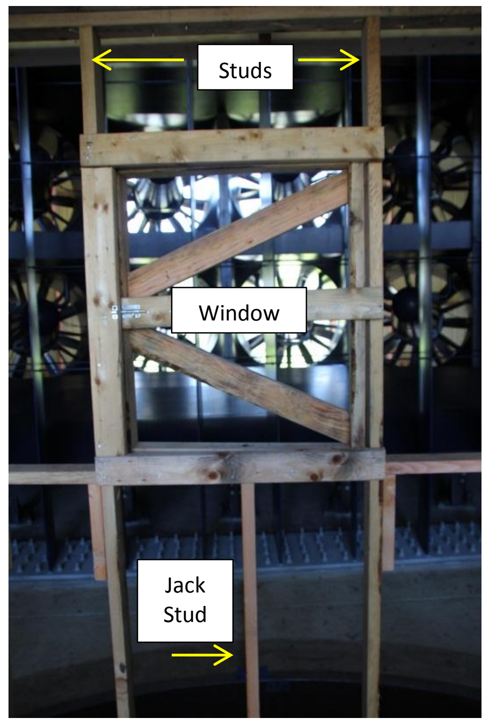

Figure 8 - Window framing

3. An inspection of the damaged wall after the test found that none of the studs around the window section fractured. Therefore, it is assumed that the wind-induced forces on the wall slowly pulled the nails out of the wood members that connected the studs to the top and bottom plates. There was no evidence of the nails failing from shear.
4. After the windward wall collapsed, it provided no support for the middle roof truss.
5. The roof system was now supported by two trusses on each corresponding gable-end wall creating an unsupported span of 14-ft.

6. One of the hurricane straps that connected one of the gable-end trusses sheared and at that moment the roof system completely disconnected from the shelter's walls.
7. With no structural members supporting the mid-span wall section and the roof diaphragm gone, the walls collapsed under the wind loads.

Figure 9 - Windward wall deformation at 0° angle of attack and 110 mph

Figure 11 shows the images of T-Shelter 3 failure step by step.

Considering the presumed failure mechanism, several key recommendations or modifications to T-Shelter construction should be considered:

- Adequate reinforcement at framing discontinuities must be provided to ensure the structure's ability to transfer the loads uninterruptedly to the foundation and distribute them along the structure. Door and window openings are discontinuities on the frame system that may become a weak point of the structure because of high stress concentrations on the discontinued frame members. Required elements to be included on the framing of door and window openings include: header, top cripples, and trimmer and jack studs (see Figure 10).

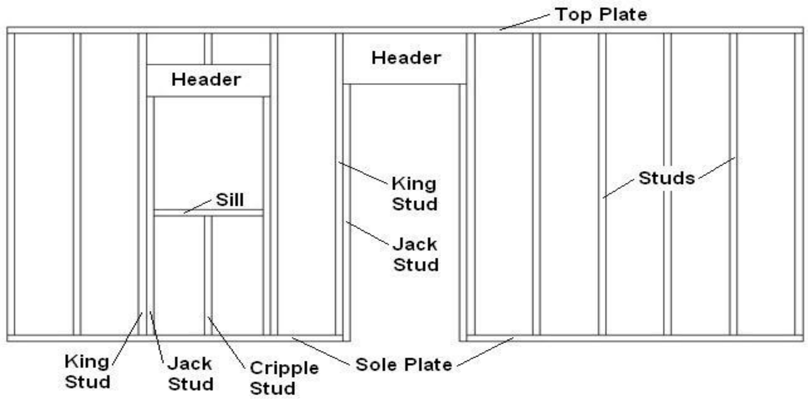

Figure 10 - Wood construction window and door framing details

- Use of smooth shank nails should be discouraged. Ring shank nails were used for T-Shelter 3 only to fasten cladding to the frame. For these tests it was specified that framing should be done using 12D common nail. There is a big improvement in the pull-out resistance of ring-shank nails compared to smooth shank nails. The use of ring-shank nails is recommended for framing construction.
- To make the structures less vulnerable to failure under high wind conditions, a factor of safety should be incorporated into the different construction techniques. It was observed that there is no redundancy in the structural elements of the shelter. Once one of the members is weakened and fails the rest of the structure is compromised and most likely to collapse. By adding redundant elements, in case the roof fails, an internal or partition wall can help distribute the windward wall forces.

The test's goal was to determine the ultimate wind speed the T-shelter would be able to withstand before one of its components or the whole system failed. The tests did not consider the effects of fatigue or cyclic loading in which the duration of the test would be considerably longer. Components and structures that fail during cyclic loads will do so at a lower force than the ultimate strength force. Ultimate strength of materials and/or construction techniques is representative of low probability of occurrence events with a high return period. Failure due to cyclic loads and fatigue will most likely occur with events of high probability of occurrence.

Appendix B includes tables explaining the relationship between the Saffir-Simpson Hurricane Scale (1-min wind speed average over water) to building code basic speeds (3-sec gust average over open terrain). The following table compares the WoW 3-second gust speeds at which failure of the models occurred with the 3-second gust relation with the Saffir-Simpson Hurricane Scale.

Table 3 - Comparison of WoW 3-second gust wind speed with Saffir-Simpson Hurricane Scale

WoW Nominal Wind Speed (mph)	WoW Average measured wind speed (mph)	WoW 3-sec gust* (mph)	Saffir-Simpson equivalent 3-sec gust** (mph)	Saffir-Simpson Hurricane Scale
75	77	80	79-102	1
95	98	103	103-118	2
110	111	116	103-118	2

*At test structure's eave height = 9-ft
**At 33-ft above ground

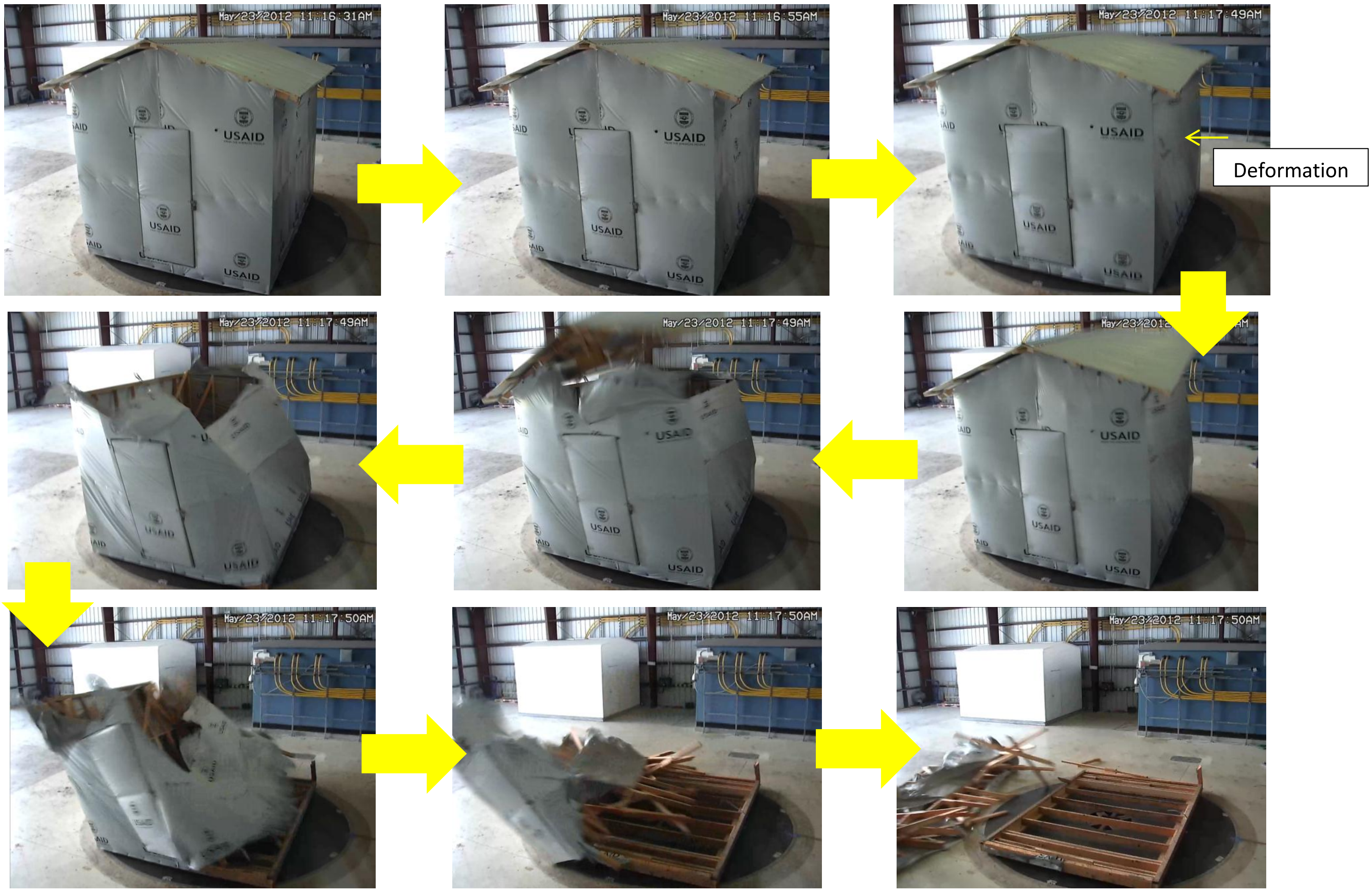

Figure 11 - Shelter 3 failure

4. T-Shelter material cost comparison

As a comparative measure, Table 4 shows the costs of materials for T-Shelter 1 and 2 (and 3). The cost of materials is based on the wholesale price at hardware and lumber suppliers in the Miami, FL area and do not include cost of freight or local and State taxes. All prices are given is US dollars. The price of 32 gauge CGI roofing sheets on T-Shelter 1 was estimated, since this material is not available for the US market. The sheets used in the construction of T-Shelter 1 were imported from Haiti but are manufactured by a US company in Jacksonville, FL.

It can be seen that the cost of the stronger shelter is almost double the cost of the weaker shelter. The increase in price (approximately 12%) between T-shelter 2 and 3 is due to the additional lateral bracing and reinforced window and doors.

Table 4 - T-Shelter material cost comparison

T-Shelter 1

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
1x4x8	40	ea	1.9	$77.60
1x4x10	14	ea	4.2	$58.10
1x6x8	6	ea	7.5	$44.76
2x2x8	18	ea	3.0	$53.46
				$233.92
FASTENERS				
4D common nail	5	lb	4.2	$21.20
5D electro galv roofing nail	5	lb	2.1	$10.47
				$31.67
ROOFING				
26x60 32Ga CGI*	10	ea	15.0	$150.00
26 Ga sheet metal	18	lf	1.4	$24.30
*cost not known, estimated				
				$24.30
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	3	ea	5.0	$14.91
Hurricane ties	48	ea	0.6	$28.32
Door hardware	0	ea		$0.00
				$43.23
TOTAL COST				**$333.12**

T-Shelter 2

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
2x4x8	70	ea	2.7	$190.40
2x4x10	11	ea	4.2	$46.09
2x4x14	14	ea	5.9	$82.18
19/32 plywood	1	ea	31.0	$30.97
				$349.64
FASTENERS				
12D Hot Galv Common nail	30	lb	1.4	$42.98
5D HG Ring Shank Neo	3	lb	4.2	$12.72
#11 Galvanized roofing nail	5	lb	10.5	$10.47
6D common nail	1	lb	3.5	$3.47
				$69.64
ROOFING				
26x60 26Ga CGI	10	ea	20.0	$199.80
26 Ga sheet metal	18	lf	1.4	$24.30
				$224.10
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	3	ea	5.0	$14.91
1-in Metal strap	50	ft	0.2	$10.00
Door hardware	1	ea	4.2	$4.24
				$29.15
TOTAL COST				**$672.53**

T-Shelter 3

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
2x4x8	80	ea	2.7	$217.60
2x4x10	11	ea	4.2	$46.09
2x4x14	20	ea	5.9	$117.40
19/32 plywood	1	ea	31.0	$30.97
				$412.06
FASTENERS				
12D Hot Galv Common nail	30	lb	1.4	$42.98
5D HG Ring Shank Neo	3	lb	4.2	$12.72
#11 Galvanized roofing nail	5	lb	10.5	$10.47
6D common nail	1	lb	3.5	$3.47
				$69.64
ROOFING				
26x60 26Ga CGI	10	ea	20.0	$199.80
10-ft Ridge cap	2	ea	11.3	$22.56
				$222.36
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	5	ea	5.0	$24.85
1-in Metal strap	50	ft	0.2	$10.00
Door hardware	4	ea	4.2	$16.96
				$51.81
TOTAL COST				**$755.87**

Appendix A- Fasteners

Appendix B – Relation between Saffir-Simpson Hurricane Scale and design wind speeds

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust in ASCE7-10:

TABLE C6-2 APPROXIMATE RELATIONSHIP BETWEEN WIND SPEEDS IN ASCE 7 10 AND SAFFIR/SIMPSON HURRICANE SCALE

Saffir/Simpson Hurricane Category	Sustained Wind Speed Over Water[a]		Gust Wind Speed Over Water[b]		Gust Wind Speed Over Land[c]	
	Mph	(m/s)	mph	(m/s)	mph	(m/s)
1	74–95	33–43	87-111	39-50	81-105	36-47
2	96–110	44–49	112-129	51-58	106-121	48-54
3	111–130	50–58	130-152	59-68	122-143	55-64
4	131–155	59–69	153-181	69-81	144-171	65-76
5	> 155	> 69	>181	>81.0	>171	>76

[a]1-minute average wind speed at 33 ft (10 m) above open water

[b]3-second gust wind speed at 33 ft (10 m) above open water

[c] 3-second gust wind speed at 33 ft (10 m) above open ground in Exposure Category C. This column has the same basis (averaging time, height, and exposure) as the basic wind speed from Fig. 6-1.

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust according to Simiu, Vickery, Kareem (2007)

Saffir-Simpson Hurricane Category	Sustained Wind Speed Over Water (mph) (1-min avg)	Gust Wind Speed Over Land Exposure Category C (mph) (3-sec avg)
1	74-95	79-102
2	96-110	103-118
3	111-130	119-139
4	131-155	140-166
5	>155	>166

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1. Introduction

The Wall of Wind (WoW) facility at Florida International University (FIU) was retained by the Latin America and Caribbean Center at FIU through its Disaster Risk Reduction Program (LACC-DRR) to provide wind resistance test services on full-scale transitional shelters (T-shelters). The T-shelters are used by the United States Agency for International Development through the Office of U.S. Foreign Disaster Assistance (USAID/OFDA) to provide expeditious and appropriate covered living space to shelter displaced populations in disaster stricken areas.

The objective was to test different T-shelter construction practices observed on the field at the WoW, with incremental wind loads, to identify good construction practices that will provide adequate resistance under severe windstorm conditions of up to category 1 storm on the Saffir-Simpson Hurricane Scale (74-95 mph). The primary consideration for the tests was the maximum wind speed that each of the component configurations and eventually the full T-Shelter models will be able to resist.

The full-scale model tests were executed at the 12-fan WoW, while component tests were done with the 2-fan electric system and a servo hydraulic testing machine at FIU's Civil Engineering Titan America Structures and Construction Testing Laboratory.

2. Methodology

The tests were executed in two phases: 1) component tests and 2) full-scale T-shelter model tests. A field visit by FIU-WoW engineers with OFDA staff to Port-au-Prince, Haiti allowed identifying several construction techniques on different models of T-shelters of interest for test purposes. There is no standardized T-shelter design and each organization setting these structures has the freedom to submit their own design. Therefore each organization may have used different lumber, member configuration, fasteners, hurricane strapping, roof cladding, etc. It is important to identify which of these material and/or technique combinations perform satisfactorily under wind-induced forces to establish guidelines for the organizations to follow. The construction techniques and different materials were grouped according to the structure's section. Test specimens and protocols were determined to be able to study the resistance of each of the components to wind induced loads or their static load equivalent. The components that showed the greatest strength were selected to be incorporated on a model of a full-scale T-shelter to be tested with the 12-fan WoW. A second model that incorporates construction practices and/or materials with poor wind resistance identified during component testing was also evaluated.

The following equipment was used to execute the tests: 1) 2-fan electric system, 2) servohydraullic testing machine 3) air-cannon and 4) the 12-fan WoW. Figure 1 shows the equipment used for the tests described in this report.

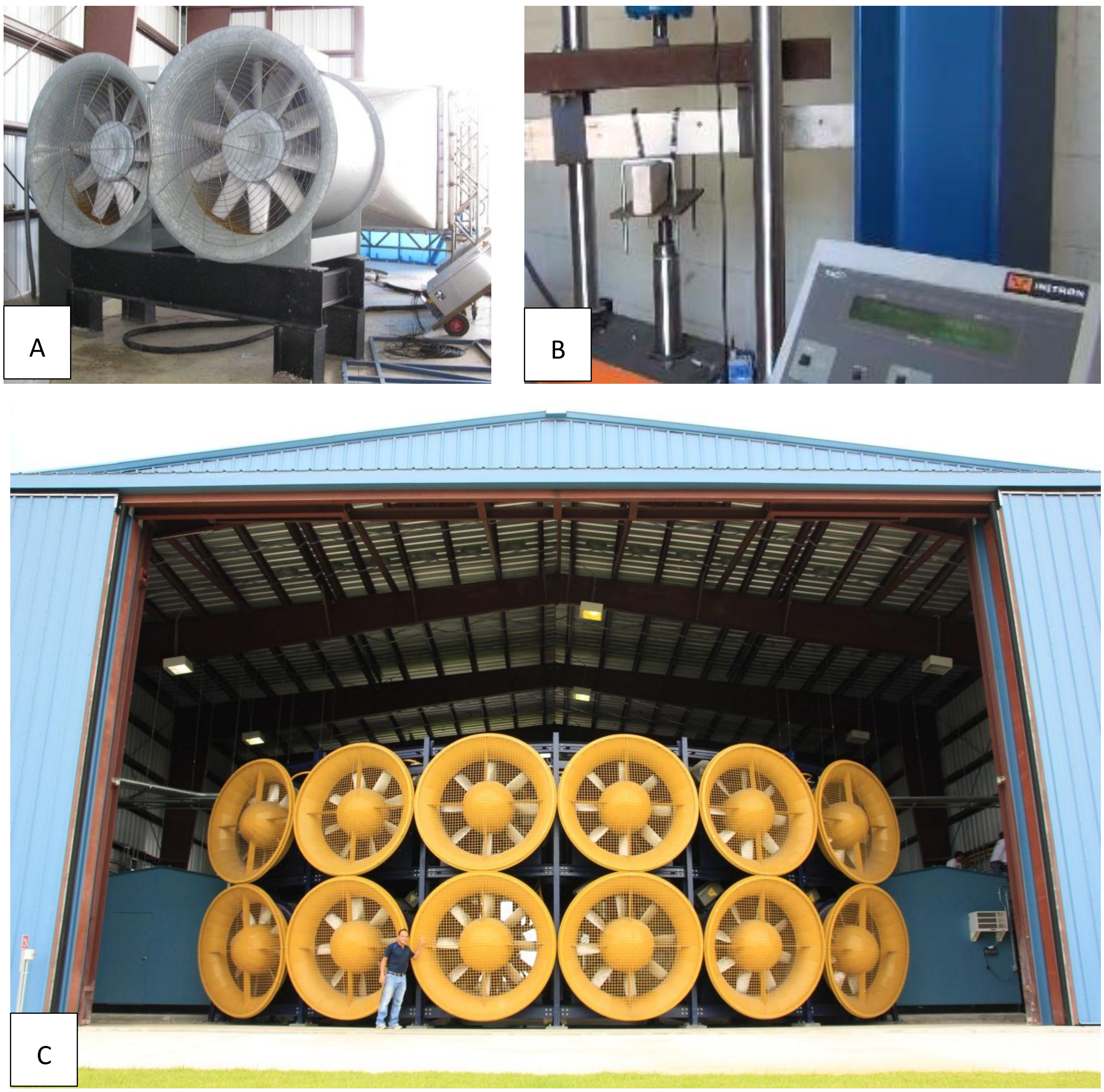


Figure 1 – Testing equipment: (A) Two-fan electric, (B) Servo-hydraulic testing machine, (C) Twelve-fan Wall of Wind

3. Component Testing

All of the component tests involving wind loading were performed with the 2-fan electric system and following the incremental wind speeds and durations given in the following table:

Table 1 - Wind speed increments and durations for component testing

Wind Speed (mph)	Duration (secs)
10	15
20	15
30	15
40	15
50	60
60	60
70	60
80	60

3.1. Plastic sheeting as wall cladding

The performance of plastic sheeting was evaluated on a test specimen fitted with different types of plastic and subjecting it to increasing wind speeds. The tests were documented with video cameras at different angles and a visual inspection of the plastic at the end of the test was used to determine the condition of the plastic.

All of the tests were done setting up the test specimens 5-ft away from the exit of the 2-fan electric system and at an angle of attack of 30 degrees. A preliminary test had an angle of attack of 0 degrees.

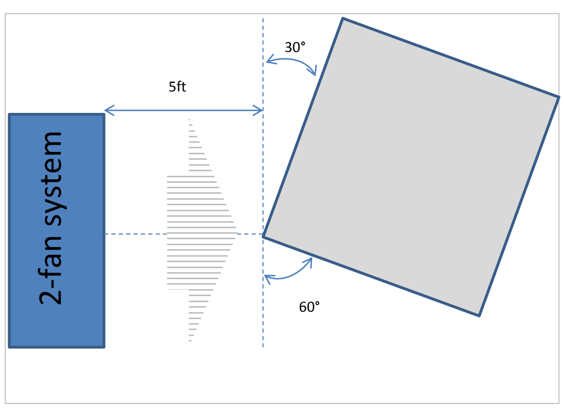


Figure 2 – Specimen for plastic as wall cladding experimental setup

3.1.1. OFDA plastic and blue tarpaulin comparison

The test model consisted of a corner section of T-Shelter composed by two perpendicularly-intersecting wooden frame walls. The frame was built using the following specifications:

1. 2-in x 4-in kiln dried SPF (spruce-pine-fir) lumber
2. panels 8-ft tall x 8-ft wide
3. stud spacing 24-in on-center
4. one wall will have one 34-in x 82-in door opening with fabricated door
5. fasteners: 12d nails (Appendix A)

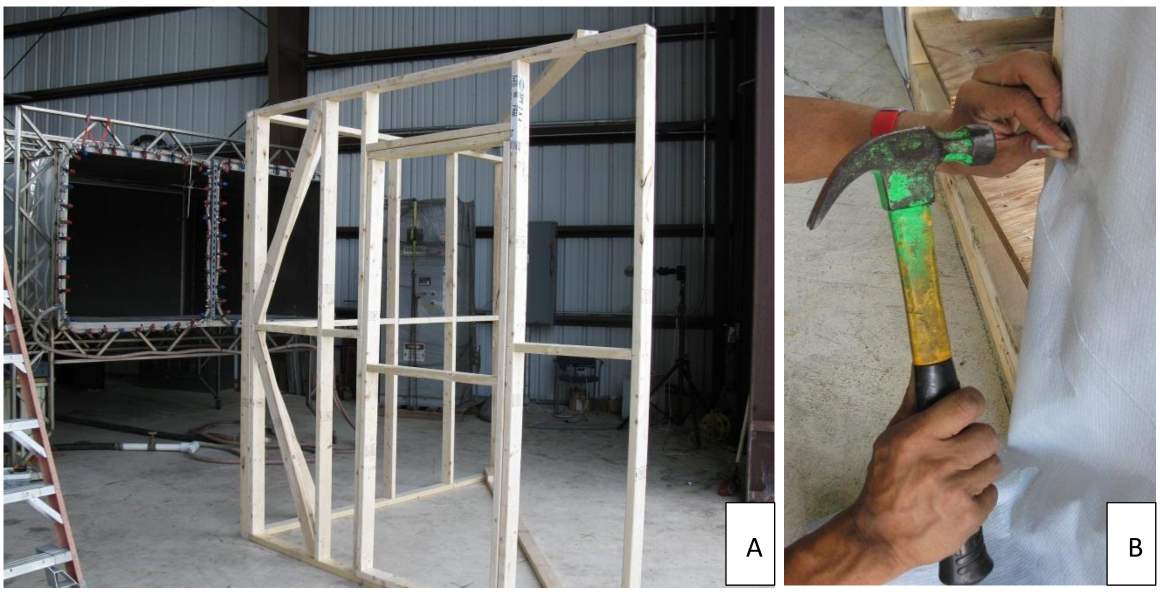


Figure 3 – (A) Shelter corner section frame and (B) sample plastic attachment

Both types of plastic sheeting were attached with 1 ¼-in hot dipped galvanized roofing nails (Appendix A), 1 $^{5}/_{8}$-in tin cap discs as washers and folding the edges of the sheeting (top, bottom and around openings) three times to provide added strength.

The model was first covered with commercially available blue tarpaulin sheeting (5.1 mil thick) then with OFDA plastic. Each of the test specimens were set up 5-ft away from the exit of the 2-fan electric system and at an angle of attack of 30 degrees. Wind was generated with this system with 10 mph speed increments according to Table 1. The tests were documented on video and the wind speed, at which damage or failure occurred, if any, was noted.

Two demonstrational tests were performed: resistance of OFDA plastic and blue tarpaulin to impact of various objects shot by an air cannon while producing 50 mph winds on the specimen, and the effects of wind on OFDA plastic partially attached to the wall. These tests were intended for demonstration purposes only and to be documented on video and do not quantity the physical properties or strength of the materials or its installation.

3.1.2. OFDA plastic attachment methods

The test model consisted of 4 wooden-frame wall panels in a box configuration with OFDA plastic as wall cladding. The wooden frame was built using the following specifications:

1. 2-in x 4-in kiln dried SPF lumber
2. wall panels 8-ft tall x 8-ft wide
3. fasteners: 12d nails (Appendix A)
4. one wall will have one 34-in x 82-in door opening with fabricated door

Stud spacing was varied between iterations: 16-in, 24-in and 48-in on-center to provide different unsupported spans of plastic sheeting. All of these tests were done by attaching the OFDA plastic with 1¼-in hot dipped galvanized roofing nails and tin cap discs at 12-in spacing.

OFDA plastic sheeting was attached with 1 ¼-in hot dipped galvanized roofing nails (Appendix A) at approximately every 12-in spacing and the different test iterations included these attachment methods: 1) roofing nails only, 2) roofing nails with plastic folded on edges 3 times and tin cap discs, 3) roofing nails with batten boards made of strips of bamboo around the door opening and roofing nails with metal bottle caps as washers.

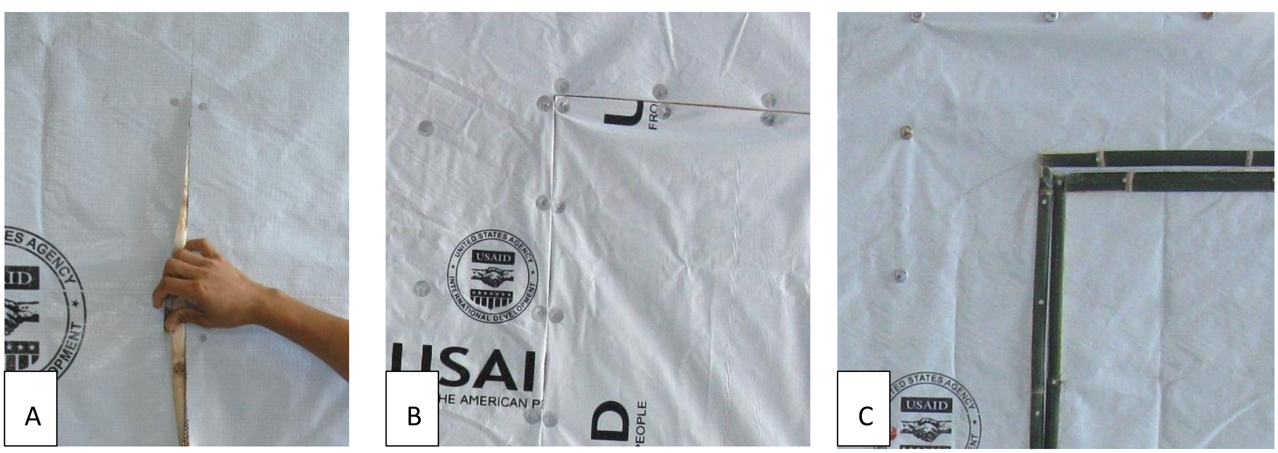


Figure 4 – Plastic attachment: (A) bare nails, (B) roofing nails and tin caps and (C) nails with bottle caps and bamboo battens

The test specimen was set up 5-ft away from the exit of the 2-fan electric system and at an angle of attack of 30 degrees. Wind was generated with this system with 10 mph speed increments according to Table 1. The tests were documented on video and the wind speed, at which damage or failure occurred, if any, was noted. The test is set as pass/fail, where failure was determined by visual inspection of damage to the materials (i.e. puncture of the wall cladding) or partial/total detachment of the wall cladding system.

3.1.3. Plastic sheeting as wall cladding test results

The plastic sheeting as wall cladding tests were not conclusive in determining an overall best performing fastening method. After generating winds of up to 80 mph for a period of 1 min, neither the blue tarpaulin material nor USAID/OFDA plastic presented visible damage.

The puncture resistance of the plastic sheeting where fasteners were placed was enhanced by adding washers to help distribute the load of the nail on the plastic surface. The different types of fixtures considered included tin cap discs and non-traditional materials like bamboo battens and metals bottle caps. The test could not determine an evident advantage among the different materials used as long as they helped distribute the load. Cyclic loading to induce fatigue on the plastic sheeting might give further information as to what is the best performing attachment method.

Folding the edges of the plastic seemed to improve the strength to tension on the plastic around the nails. The durability of the plastic should be prolonged by folding the cut edges since it prevents the material from fraying when exposed to wind and weather.

USAID/OFDA plastic will stay attached to the T-Shelter frame under conditions of wind up to 80 mph, but will not provide any resistance to impact from flying debris or security against theft since the plastic can be easily cut and/or penetrated. The wind resistance of the T-Shelter will be mostly dictated by the strength of the frame supporting the cladding and not by the plastic itself. The clear spacing between the lumber members of the structure won't significantly affect the resistance of the plastic but will allow a larger deformation of the plastic. When compared to the structural stability of the framing, the flexible plastic does not determine the rigidity of the T-Shelter and will only transmit some of the tension forces. Furthermore it is not an effective diaphragm to distribute wind loads to the structural members. At low wind speeds the USAID/OFDA plastic should have enough capacity to resist wind induced pressures on its surface up to category 1 hurricane (16 psf for 80 mph; worst case is approximately 26 psf for a 3-sec gust over open terrain of 102 mph, corresponding to 95 mph 1-min average over water as in the Saffir-Simpson scale).

3.2. Roof cladding

An 8-ft wide monoslope roof section was built out of 2-in x 4-in SPF lumber for this test. The framing of the roof section had the following specifications:

1. 3:12 roof slope (14 degrees)
2. 2-in x 4-in SPF purlins spaced at 2-ft on center
3. frame fasteners: 12d nails (Appendix A)
4. 1-ft overhang on 2 sides
5. OFDA plastic covering one end wall

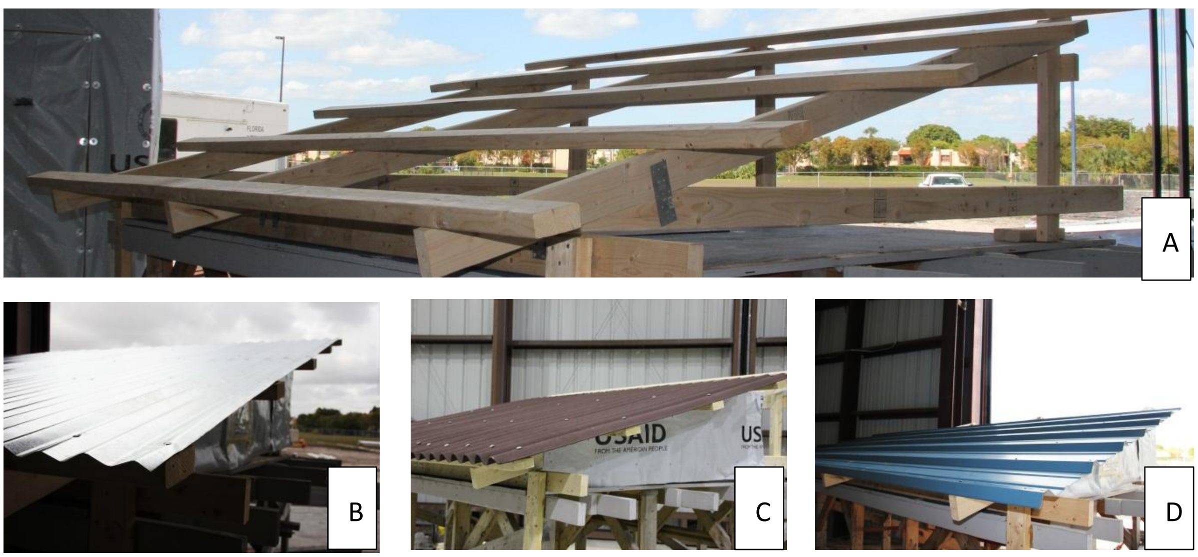


Figure 5 – (A) Roof framing, (B) 32-gauge CGI roofing, (C) cellulose-bitumen roofing and (D) Structural PBR roofing

The roof cladding tests were divided into two categories: 1) effect of fastening technique on different cladding materials under wind load and 2) wind resistance of gable end or edge sheeting with different fastening techniques. On both categories of testing, three roofing materials were considered: corrugated galvanized iron (CGI) sheets of 32 gauge, CGI sheets 26 gauge and corrugated bitumen saturated cellulose fiber sheets (CBCF) (3mm thick). Additionally, 24 gauge purlin bearing rib (PBR) structural panels were installed transversally on the roof section without purlins and its performance under applied wind load visually evaluated.

Figure 7 – Roof gable end with additional fascia board and with free purlin ends

To study the resistance of the sheeting attachment of the gable end or edge sheets two conditions were considered: 1) gable end and roof edge nailed into purlins only and 2) gable end and roof edge nailed into additional fascia board along the edge (Figure 7). The test specimen was located 5-ft away from the exit of the 2-fan electric system and at two different angles of attack: 0 and 90 degrees. Wind was generated with 10 mph speed increments according to Table 1. The tests were documented on video and the wind speed at which damage or failure occurred, if any, was recorded. Tests were evaluated as pass/fail, where failure was determined by visual inspection of damage to the materials (i.e. fasteners punch through roof cladding) or partial or complete detachment of the roof cladding system.

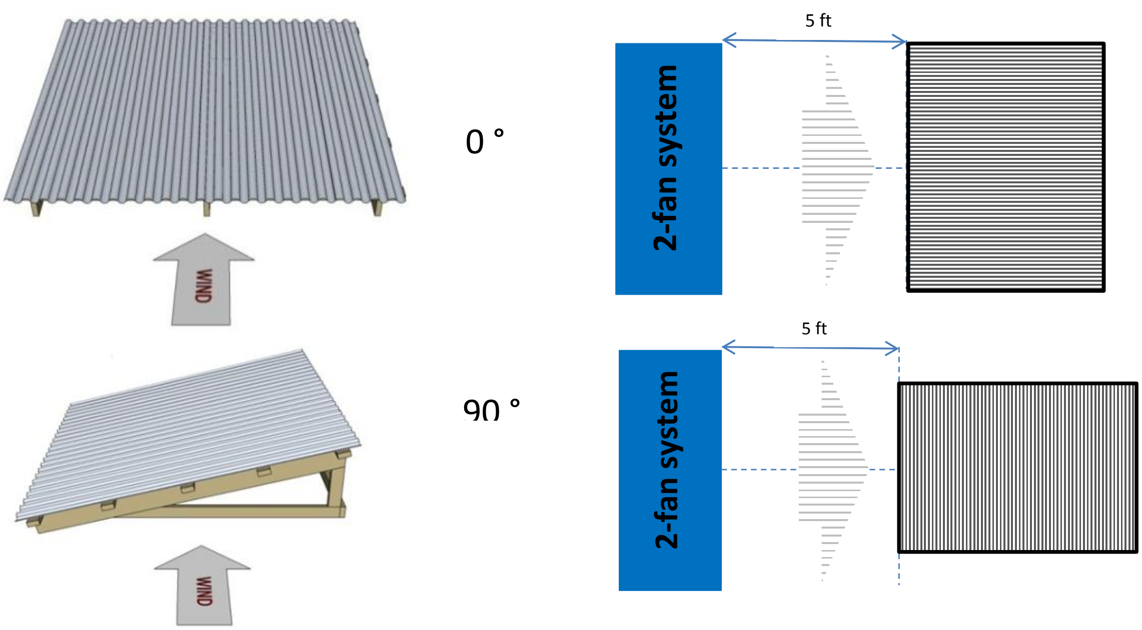


Figure 6 – Experimental setup for roof cladding tests

3.2.1 Roof cladding test results

The performance of nontraditional roofing practices was investigated by evaluating the effectiveness of different roofing elements: cladding materials and fasteners. Light roofing materials have a lower capacity to take concentrated loads and therefore showed less ability to resist puncture at the points where the material was penetrated by fasteners. The loads were highly concentrated around the head of the nail and it was able to punch through the thin roofing sheet. This type of failure was observed on the test with wind perpendicular to the gable end wall, where the solid wall forces the flow to separate abruptly and a stronger uplift force was perceived. The damage happened specifically where no additional fascia board was provided along the edge of the roof. The number of nails on the gable end edge was restricted by the purlin ends available to nail down the sheet (4 purlins); therefore the forces were highly concentrated at these points. The nail heads were able to punch through the 32-gauge CGI sheet along the border at a wind speed of 70 mph (Figure 8).

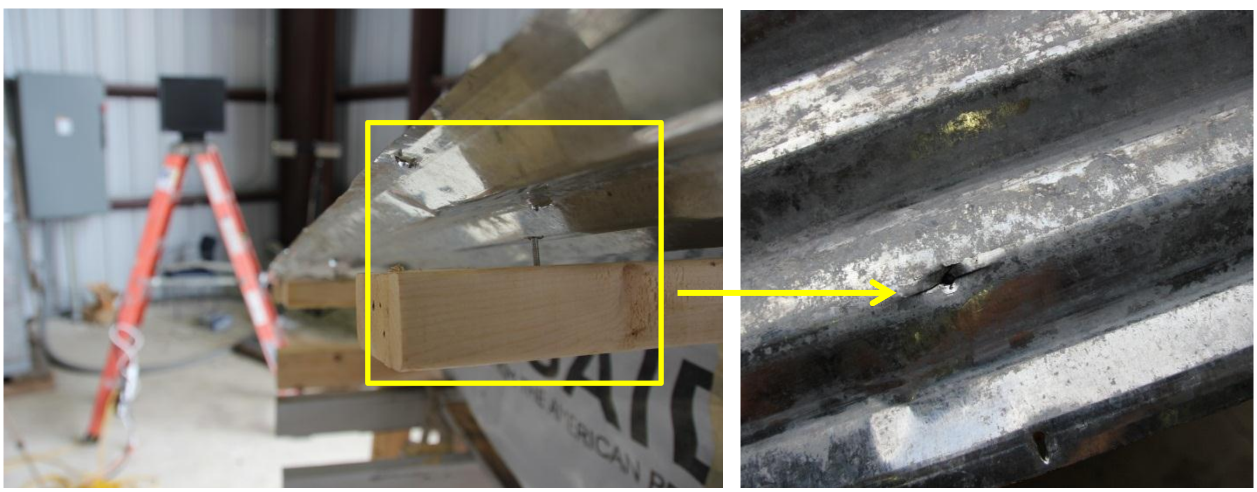


Figure 8 – Nails punctured the 32-gauge CGI roofing sheet on gable end at 70 mph wind speed

A similar failure was also observed with the corrugated bitumen saturated cellulose fiber sheets (CBCF) and 1 ¾-in roofing nails. In this case, the failure occurred at the gable end of the roof as well but translated to the rest of the fasteners producing a whole roof system failure. The roof breakdown happened at a speed of 70 mph, but some of the nails can be seen pulled out of the wood at 50 mph and 60 mph. The CBCF sheets can be seen bulging around the gable end edge due to insufficient fasteners along the border of the sheet and the flexibility of the material. All of the CBCF sheets were blown off the roof section at 70 mph. Some of the nails perforated the cellulose sheet while some were pulled out of the wood purlin and stayed connected to the CBCF sheet. These show two types of weaknesses: CBCF sheet not strong enough to take concentrated stresses from the uplift around the nail head and smooth shank roofing nails have low pull-out strength (see Figure 9).

The addition of bottle caps as washers to the 2-in roofing nail did not improve the performance of the roof system. The smooth nail shank together with the 1 ¼-in corrugation height and 2-in roofing nail did not provide a secure fastening method for the cellulose-bitumen panel. The nail heads did not puncture the panel but were pulled out of the purlin while staying attached to the bottle cap and roof panel (Figure 11).

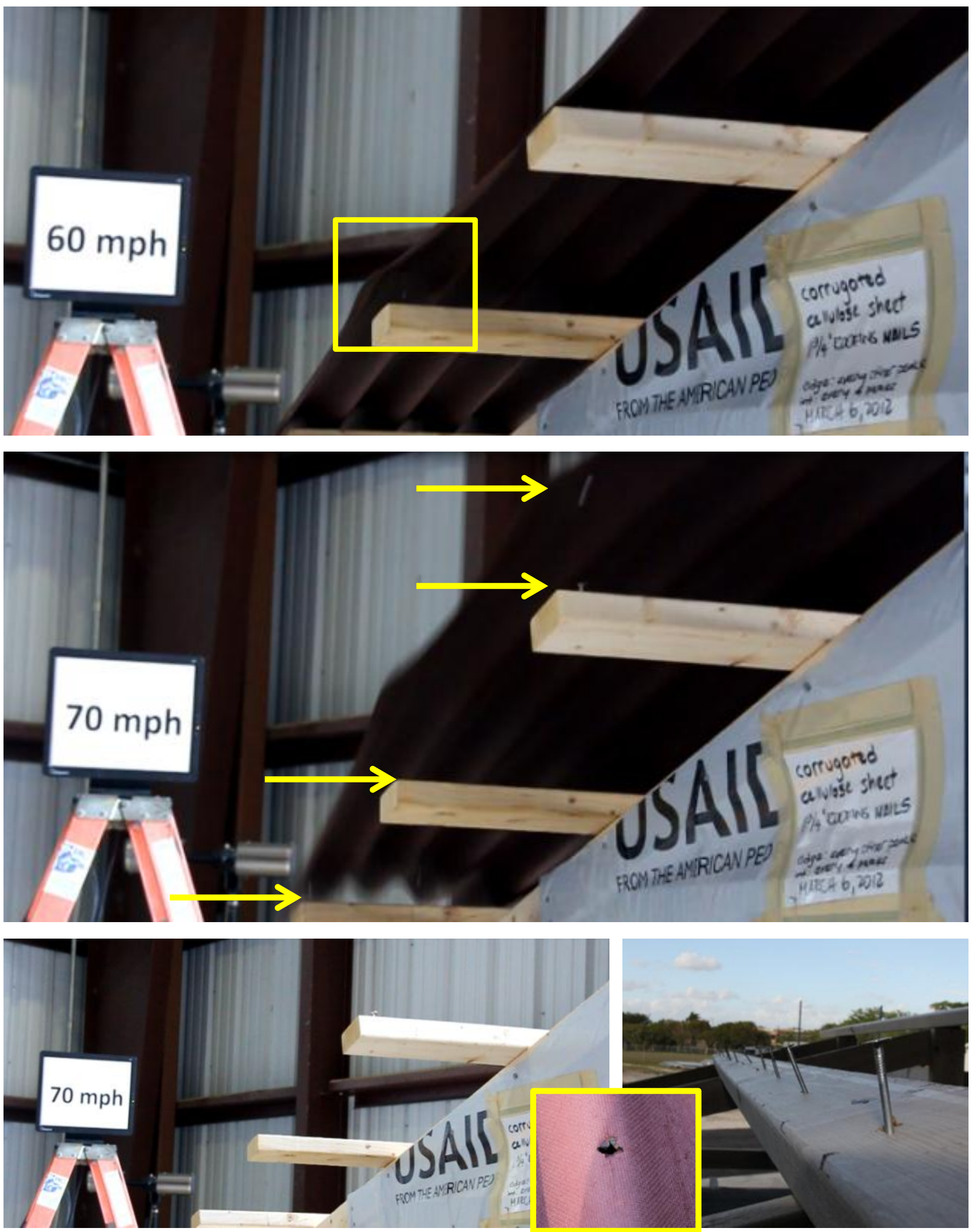


Figure 9 – Failure of cellulose-bitumen sheet by fastener puncture of the roofing material

Figure 11 - CBFB sheet detached from roof supporting structure, seen here with roofing nails and bottle caps still attached

In both cases where the roof cladding became partially or totally detached from the purlins, a simple change to the structure and fastening method secured the cladding. A fascia board was nailed to the purlin free ends on the gable end. This additional board allowed fastening the sheets of roof cladding with a shorter spacing between fasteners: every 12-in instead of every 24-in. Retesting the retrofitted setup confirmed that none of the sheets where punctured and that all the cladding stayed attached to the roof structure (Figure 10).

Figure 10 – Additional fascia board on purlin ends to provide additional fasteners on roof gable end

Furthermore, it was determined that using roofing nails with ring shanks increased the resistance to uplift of the roof system. Ring shank nails hold firmly in wood when compared to smooth shank nails.

Tests with smooth shank roofing nails showed some of the nails being pulled out of the purlin while the cladding fastened with the ring shank NEO roofing nail always held firmly in place.

A supplementary test not part of the original scope of work proved that 24-gauge purlin bearing rib (PBR) structural panels installed longitudinally on the roof rafters is an effective method of providing roof cladding (Figure 12). The test considered ring shank NEO roofing nails only. The purlins or battens were removed from the rafters and the sheets were directly nailed. It was observed that the ribs on the sheets provide enough structural rigidity to the roof system to sustain winds of up to 80 mph at angles of attack of 0 and 90 degrees.

Figure 12 – 24-gauge PBR structural panel with no purlins or battens between rafters

3. 3. T-Shelter footings

Three different type of footings were considered: 1) 4-in x 4-in timber embedded in cast-in-place concrete, 2) 4-in x 4-in timber with nails for traction embedded in cast-in-place concrete, and 3) pre-cast reinforced pier with anchor strap (Figure 13). The 4-in x 4-in timbers were 5.5-ft long and were embedded 2.5-ft in the concrete. The free end of the footings were connected to a load cell with a steel cable and then connected to a hydraulic jack (Figure 14). A vertical tensile force was applied to the foundation/load cell system with the hydraulic jack at a rate of approximately 20lb/sec. The goal was to determine the load at which the footing would be pulled out of its foundation.

The free end of the timber was connected to the steel wire rope to apply the tensile force. The precast pier was tested pulling the pier directly. The connection (metal strap) between the precast concrete pier and the superstructure is considered the weak point of the footing, therefore including this connection on the test will not be representative of the pull-out strength of the footing.

The ground was excavated to provide holes 2.5-ft deep for all footings. For the 4-in x 4-in timber holes were excavated with an auger to form circular holes with a diameter of 10-in and 2.5-ft deep. For the precast concrete pier a 2-ft x 2-f t x 2.5-ft hole was dug with a backhoe. The 40-in tall precast concrete pier was buried 30-in on the ground with 10-in protruding out of the ground.

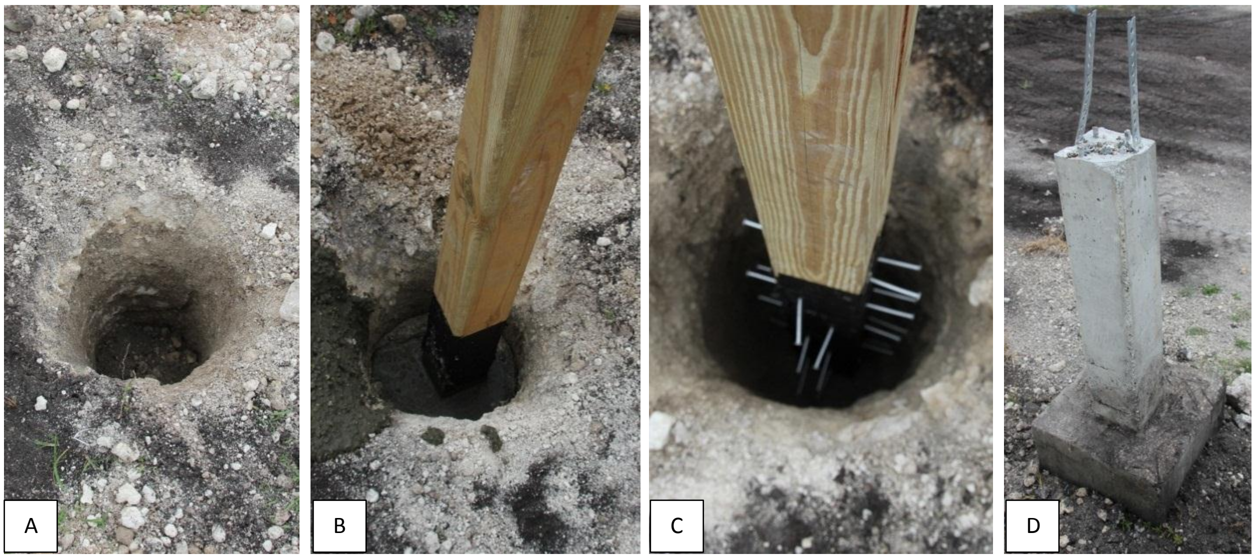


Figure 13 – (A) Auger-perforated hole, (B) 4-inx-4in timber embedded in concrete, (C) 4-inx4-in timber with nails embedded in concrete and (D) precast concrete pier

The limitations of this test were: load capacity of the load cell (10000 lbs.), capacity of the hydraulic jack (2 tons or 4000 lbs.), the strength of the wire rope and the soil conditions typical of Miami-Dade County. Most of the soils in the area are known as calcareous soils: marl and rocky/gravelly soils which derive from the Miami limestone surface rock. Given the type of soil found here it was decided to use a

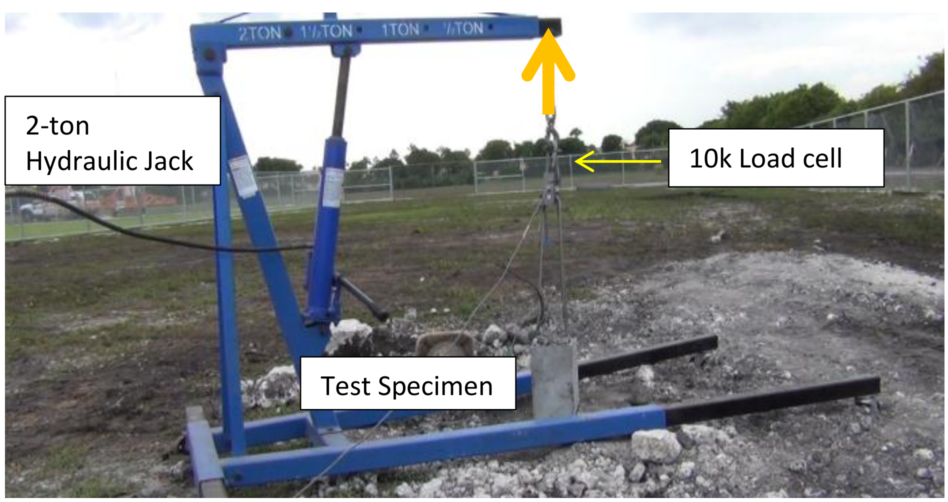


Figure 14 - Experimental setup for footing tests

form of mechanical excavation to dig the holes to set the footings. The soil type tested is not intended to be representative of the soil conditions of areas where T-Shelters are installed, but serve as a comparative measure of the resistance of the different footing systems under these particular conditions.

3.3.1. T-Shelter footings test results

The three different shelter footing methods considered were tested to determine the tension force (representing the wind induced uplift force transmitted by the structure to the foundation) required to pull out the foundation out of the ground.

Figure 15 – Pull-out test of footings with hydraulic jack. Left: 4x4 embedded in concrete, right: precast concrete pier

The experimental data shows (Figure 16) that the precast concrete pier required the lowest amount of force to pull the footing out of the ground. It is evident that the characteristics of the ground surrounding the excavated hole affected the performance of the precast concrete pier. The effective preconsolidation ratio of the rock (gravelly soil) achieved by manually compacting the backfill is less than that achieved by mechanical compaction or in an undisturbed and cohesive soil. The ultimate tension load the precast concrete pier held is 1712 lbs...

With the concrete-embedded 4x4's and 4x4's with nails, the pull out forces measured were substantially larger. The steel wire rope connection between the hydraulic jack, load cell and specimen was the weak link of the setup. The 3/8-in steel cable snapped in one case and the clamp and thimble (wire rope connection) fractured in the second. The ultimate load recorded while pulling the cast-in-place foundations are 3089 lbs. and 2904 lbs. for the 4x4 with nails and 4x4 embedded in concrete, respectively. These forces represent the highest force achieved before the cable broke and not the ultimate strength of the footing. The footings did not visibly move, even at the highest tension load.

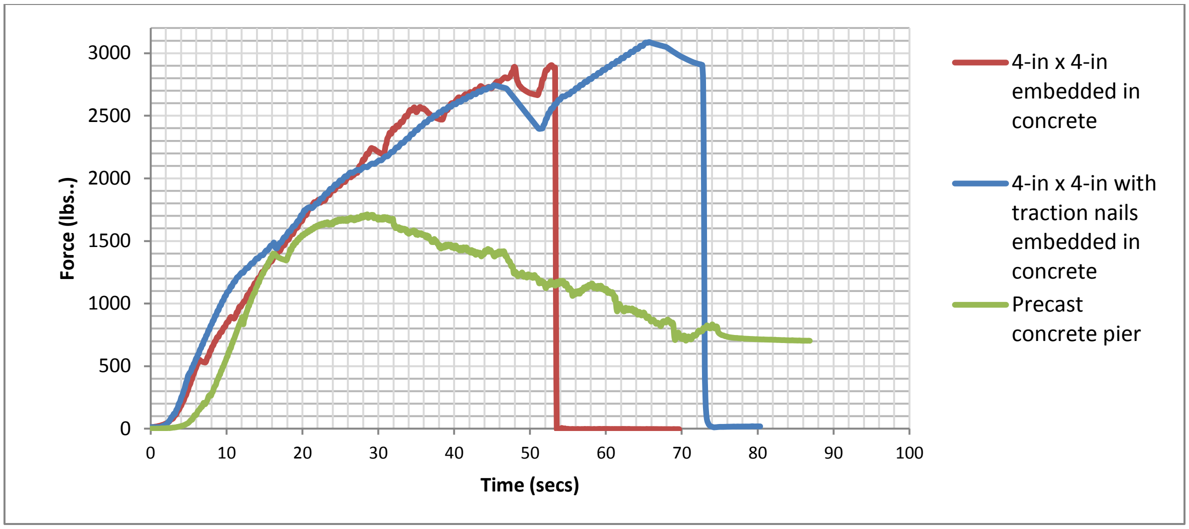


Figure 16 - Ultimate tension strength of footings

The cast-in-place footing will be effective to transfer compression forces to the ground but will depend on the friction between the concrete and the ground and the soil properties (effective stress friction angle). Rock (as that found in the Miami Limestone formation) will provide good traction characteristics on drilled shaft direct pour foundations.

3.4. Hurricane strapping

Three different hurricane strapping techniques were chosen to investigate the strength of the connection against wind-induced uplift. The techniques consisted of metal connections between the wood members to increase the tensile resistance of the fasteners between members and of the wood itself. Metal strap (1/2-in wide, recycled from shipping straps), 24-gauge steel wire and engineered hurricane ties were considered for this test. In addition to the different strapping techniques, the impact of lumber dimensions in the connecting members was determined by varying them among tests. A total of 6 different combinations and 2 specimens per combination were tested. Table 2 and Figure 17 show the different combinations considered for this component test.

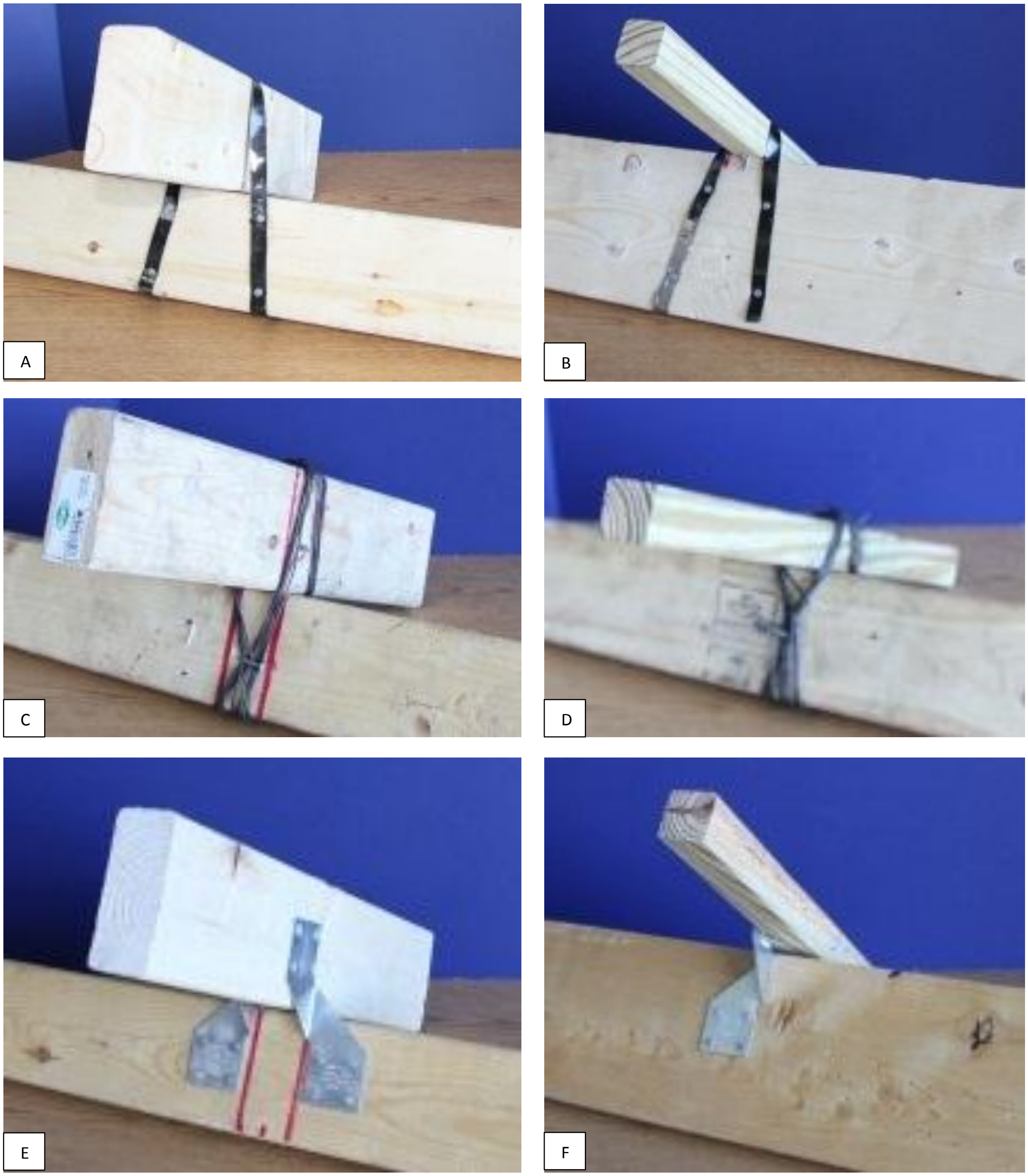


Figure 17 – Hurricane strapping techniques: (A) metal straps on 2-inx4-in, (B) metal strap on 2-inx2-in and 1-inx6-in, (C) metal wire on 2-inx4-in, (D) metal wire on 2-inx2-in and 2-inx4-in, (E) engineered tie on 2-inx4-in and (F) engineered tie on 2-inx2-in and 1-inx6-in

Table 2 - Hurricane strapping test combinations

Specimen	Connection	Rafter lumber	Purlin lumber	Fasteners
1	Metal strap	2-in x 4-in	2-in x 4-in	1½-in common nail
2	Metal strap	2-in x 4-in	2-in x 4-in	1½-in common nail
3	Metal strap	1-in x 6-in	2-in x 2-in	1½-in common nail
4	Metal strap	1-in x 6-in	2-in x 2-in	1½-in common nail
5	Steel wire	2-in x 4-in	2-in x 4-in	1½-in common nail
6	Steel wire	2-in x 4-in	2-in x 4-in	1½-in common nail
7	Steel wire	2-in x 4-in	2-in x 2-in	1½-in common nail
8	Steel wire	2-in x 4-in	2-in x 2-in	1½-in common nail
9	Engineered tie	2-in x 4-in	2-in x 4-in	N10 nail
10	Engineered tie	2-in x 4-in	2-in x 4-in	N10 nail
11	Engineered tie	1-in x 6-in	2-in x 2-in	N10 nail
12	Engineered tie	1-in x 6-in	2-in x 2-in	N10 nail

The test determined the force at which the connection would yield. A servohydraullic testing machine was used to apply a tensile force to the wooden members forming the connection until an inflection point on the load curve was identified. This point marked the ultimate tension load that the connection was able to withstand.

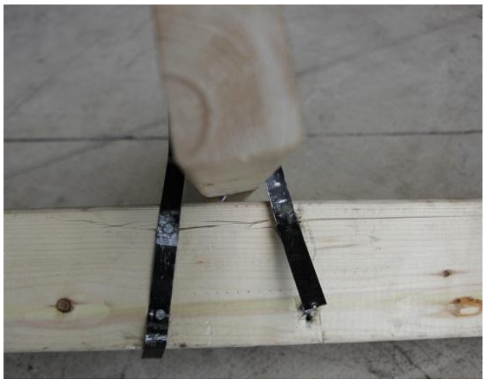
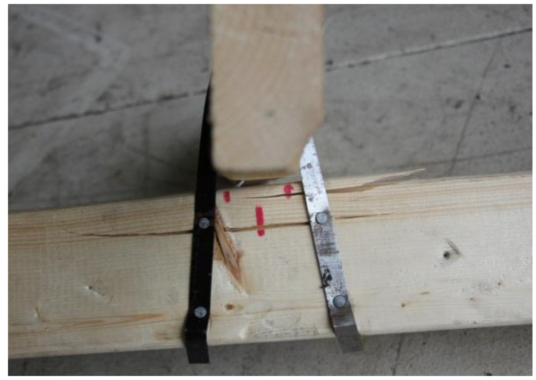
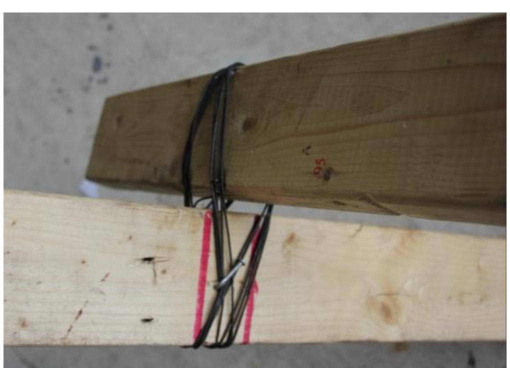
3.4.1 Hurricane strapping test results

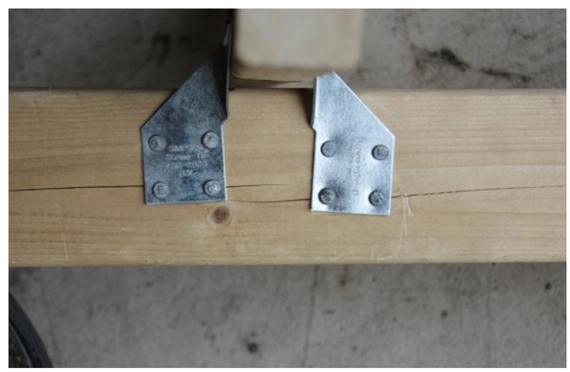
The different strapping methods yielded resistance to tension forces from as low as 462 lbs. up to 3000 lb. The highest resistance was achieved by a nontraditional technique: steel wire wrapped around the 2x4 members 8 times. This technique does not penetrate the lumber with nails and weaken the member. The engineered hurricane ties and the metal strap do penetrate the wood members, predetermining a fracture point in the wood. The steel wire connection was able to reach 3014 lbs. of tension before some of the wires started breaking causing it to lose the capacity to take any additional force.

Most of the connection techniques done between 2x4 lumbers were able to reach loads close to 2000 lbs. before failing. The lumber would split at the points were a nail was driven into the wood before the connection material or fasteners failed. Weaker lumber members broke before any other components of the connection. It was evident that the 2x2's made the connection weaker, where none of the connections were able to take more than 1400 lbs... Most of these systems failed at loads less than 1000 lbs.., except the ones with the wrapped steel wire. It is believed that the steel wire distributes the load around the slenderer lumber and also does not weaken it with multiple nails penetrations.

Even though the steel wire provided the best tension resistance, its performance depends on the number of wraps around the lumber and the method used to secure the loose ends. This factor will vary depending on the quality of the installation and the number of wire strands securing the connection. It will be contingent to the consistency of the wire wrap and its tightness around the lumber. This technique showed the biggest deformation presenting a big gap between the members before the wire started to break. This deformation may allow the members to slide within the connection if additional forces are present before the strapping can be fixed. Table 3 shows the ultimate strength in pounds achieved by each of the connections and the type of failure observed on the different hurricane strapping connections.

Table 3 – Hurricane strapping test results and observed failure

	Observed failure	
Metal strap	Specimen 1 Ultimate load: 1722 lbs. 	Specimen 2 Ultimate load: 1806 lbs. 
	Specimen 3 Ultimate load: 904 lbs. 	Specimen 4 Ultimate load: 912 lbs. 
Steel wire	Specimen 5 Ultimate load: 2608 lbs. 	Specimen 6 Ultimate load: 3014 lbs. 

	Observed failure	
Steel wire	Specimen 7 Ultimate load: 1484 lbs. 	Specimen 8 Ultimate load: 1121 lbs. 
Engineered tie	Specimen 9 Ultimate load: 1999 lbs. 	Specimen 10 Ultimate load: 1561 lbs. 
	Specimen 11 Ultimate load: 462 lbs. 	Specimen 12 Ultimate load: 1027 lbs. 

The preferred method to strap the roof to be included in the full scale T-shelter model test is the metal strap. Even though the engineered tie provides good resistance to tension loads, the size and pattern of the nails create a fracture plane on the lumber. Also it requires the installer to follow the correct instructions and application guidelines. Otherwise connections might be ineffective due to incorrectly sized lumber members and fasteners that might cause a connection or component failure.

The metal strap does not provide a predetermined nailing pattern and does not require a highly technical knowledge to install it. It also gives flexibility as to the installation location and number of fasteners to use. Also it was preferred over the steel wire because it is made of galvanized metal (corrosion resistant) and did not allow displacement of the members at the connection.

3.5. Wall bracing

Timber wall construction requires proper bracing to be able to resist lateral loads induced by wind on the structure and avoid failure from racking of the frame. Two types of braces were subject of this performance comparison study: 1) diagonal corner wood braces and 2) metal strap diagonal bracing in X pattern (Figure 18).

Figure 18 – Wall bracing techniques: corner diagonal wood braces (left) and metal strap diagonal X brace

To compare the performance of both types of braces, wall panels were braced with each technique and wind was applied to the wall panel at an increasing rate as described on Table 1. Simultaneously, a string potentiometer was installed at the top of the wall panel 2-ft away from the corner to measure the deflection of the panel at this point and compare to the deformation of the wall panel with the different wall braces.

3.5.1. Wall bracing test results

Both metal strap and wood braces performed well in avoiding big deformations on the wall panels when submitted to wind induced horizontal (shear) loads. The metal strap X brace did allowed deformation approximately 0.6-in greater than with the wood braces. During the wind loading one of the metal X braces became loose when the fasteners were pulled out of the wood. This can be seen in Figure 19 where the incremental deformation measured between 60 to 70 mph was substantially bigger than the with the other speed increments. The displacement measured is approximately 1.30-in, when with the other speed increments the displacement ranged between 0.02 and 0.2-in.

The metal strap is more convenient in terms of ease of installation, but its strength will depend on the fasteners used (ring shank vs. smooth shank, length of fastener). In the case tested, ring shank nails 1 ¾-in long were used and still some of them pull out of the wood members. For the metal straps to be effective they must be used in an X pattern so that they can transmit tension loads regardless of the wind direction. The wood braces are solid and will work well in compression and tension. Its tensile strength will depend mainly on the fastener and connection quality. Wood braces require more work and time to install them but become an integral part of the framing. Both types of bracing performed well in the tests but the fasteners on the metal straps may pull out of the wood.

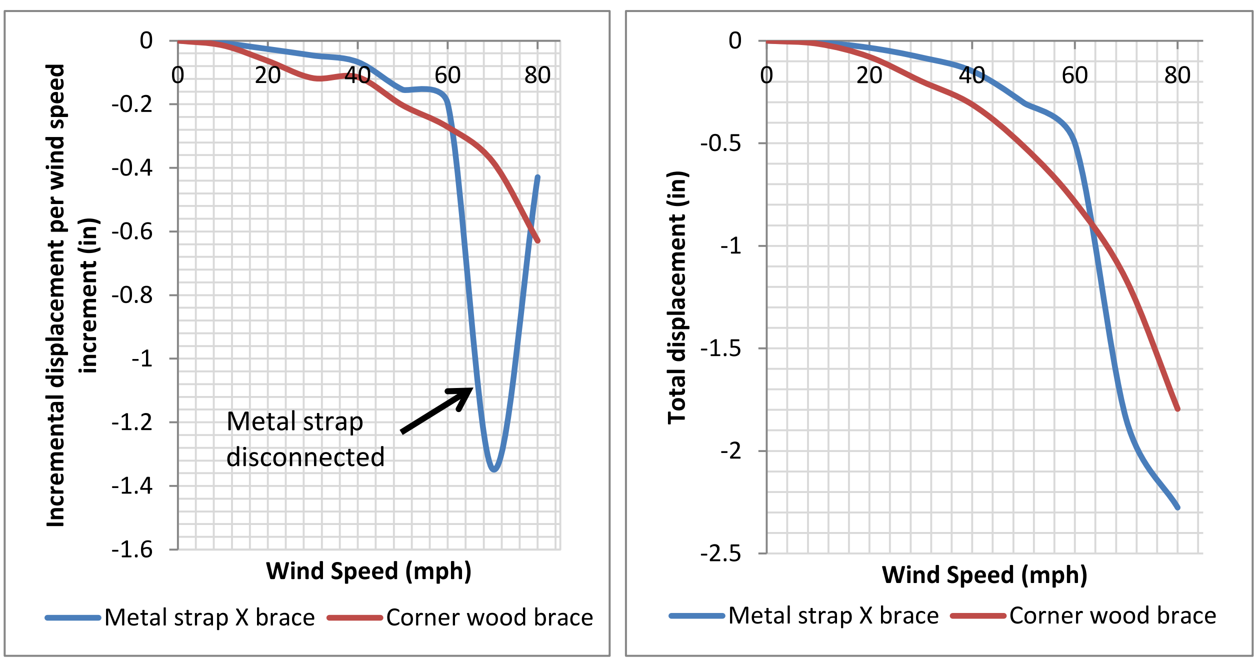


Figure 19 - Wall bracing deformation under wind loads

4. Full-scale T-shelter model

The individual component test results and observations from the field visit to Haiti were instrumental in identifying several key construction techniques to be in the full-scale T-shelter model tests. To fulfill the scope of work of this project, two T-Shelter models were built: one that included all the weak materials/poor construction techniques (T-Shelter 1) and a second model with good performing practices and materials (T-Shelter 2). Methods used in construction of T-Shelter 2 are limited to the applicable guidelines for field deployment of T-Shelters and not to requirements of U.S. building codes. Table 5 describes the shelter model construction materials and details.

Given the limitations of putting concrete foundations on the turntable without raising the structure in the wind field or exposing the footings to unrealistic wind loads, neither of the models considered the performance of the foundations as part of the test. Instead, forces were measured on the corners of the model to estimate the magnitude of the loads transmitted to the foundations. Both T-shelter models were built on top of a wooden platform that would allow them to be picked up and moved with a forklift, as well as being attached to the force sensors on the turntable (Figure 20).

Figure 20 - Base platform and load cell for T-Shelter tests

For each 3-minute test the 12-fan WoW produced a uniform sustained wind speed, with an initial speed of 55 mph. This speed was chosen based on observations from the series of component tests where it was noticed that wind speeds of 50 mph or lower did not affect the integrity of the T-Shelter components. The wind speed was increased by 10-mph increments up to speeds characteristic of category 1 hurricanes on the Saffir-Simpson scale or until structural failure of the T-shelter was observed. The model was rotated through 3 angles of attack (0, 45 and 90 degrees) at each wind speed before going to the next increment (Table 4). It was decided that T-Shelter 2 would not be tested at the lower wind speed since failure of the model was not expected at low speeds.

Table 4 - Wind speeds and angles of attack for T-Shelter model tests

Model \ Wind speed	55 mph			65 mph			75 mph			85 mph			95 mph		
	Degrees														
T-Shelter 1	0	45	90	0	45	90	0	45	90	-	-	-	-	-	-
T-Shelter 2	-	-	-	0	45	90	0	45	90	0	-	90	-	-	90

The tests were recorded from multiple angles with the highest resolution the cameras would allow (720p and 1080p, depending on the camera) for the duration of the wind resistance test (See Figure 21 for locations). Data was recorded from the force sensors for 180-seconds at a sampling rate of 100 Hz. Additionally a pre- and post- test baseline was recorded with each set of data.

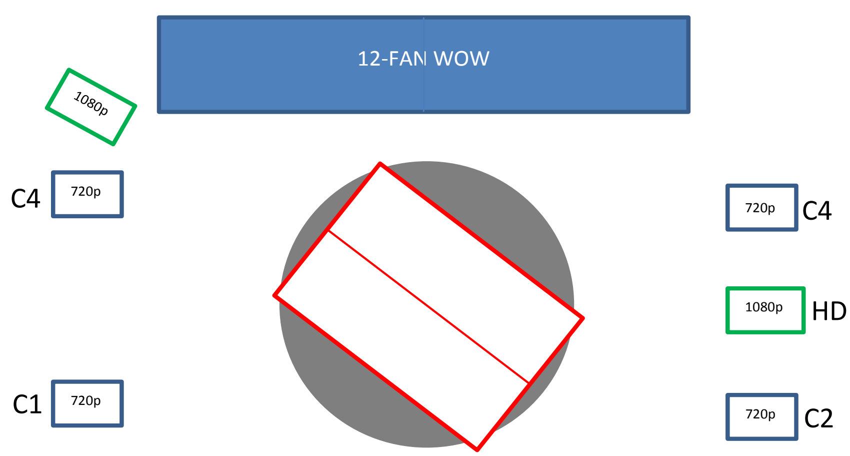


Figure 21 - High definition camera locations; T-Shelter shown at 45 degree angle of attack

Table 5 - T-Shelter models specifications

Structural Element		T-Shelter 1	T-Shelter 2
Walls	Lumber	1-in x 4-in	2-in x 4-in
	Fasteners	1 ½-in common nail	3 ¼-in common nail
	Bracing	1-in x 4-in diagonals on walls to corners	2-in x 4-in diagonals on X pattern on corners
	Spacing	7-ft center-center (long span) 5-ft center-center (short span)	2-ft center-center
	Cladding	USAID/OFDA plastic fasteners: 1 ¼-in roofing nails at 12-in spacing, edges folded 3 times	USAID/OFDA plastic fasteners: with 1 ¼-in roofing nails and tin cap discs at 12-in spacing, edges folded 3 times
Roof	Type	5:12 (22.6°) Gable	5:12 (22.6°) Gable
	Structure	Stick roof frame: 1-in x 6-in rafters 2-in x 2-in purlins	Trusses: 2-in x 4-in 2-in x 4-in purlins 5/8-in plywood gusset plates
	Structure fasteners	1 ½-in common nails	3 ¼-in common nails
	Hurricane straps	Engineered ties fastened with 1½-in common nail	1-in metal strap fastened with 1¼-in roofing nails
	Roof cladding	32-gauge CGI	26-gauge CGI
	Cladding fasteners	1 ¾-in galvanized roofing nail	1 ¾-in ring shank neo roofing nail
	Ridge cap	26-gauge sheet metal	26-gauge sheet metal
	Overhang	1-ft all around	1-ft all around
Door		1 door on gable end wall corner	1 door centered on gable end wall

Location	Shelter in Port-au-Prince, Haiti	Model at FIU: Miami, FL
T-Shelter 1		
		
		
		

Location	Shelter in Port-au-Prince, Haiti	Model at FIU: Miami, FL
		
T-Shelter 2		
		

4.1. Full-scale T-shelter model test results

The goal of this series of tests was to determine the wind speed at which the whole T-Shelter or its components would fail, and to determine the "weakest link" failure point of the structure.

Wind resistance of T-shelter construction techniques was evaluated by testing with the WoW two T-Shelter models built for these tests. T-Shelter 1 (weaker materials/poor construction techniques) and T-Shelter 2 (stronger materials/better construction techniques) both had the exact same dimensions and shape. The two structures were subjected to identical tests of uniform wind flows produced by the 12-fan Wall of Wind.

For each test, the wind speed was held constant for 3 minutes to determine the wind speed the structure would be hold before failure happened. The wind tests do not consider the effects of structural fatigue over time or that of cyclic loading in which the duration of the test would be considerably longer. It should be noted that cyclic loading can cause structures to fail at a lower force than those achieved in these tests. Failure due to cyclic loads and structural fatigue will most likely occur with events that have a high probability of occurrence.

The corners of the T-Shelter models were instrumented with load cells under the structure to measure the magnitude of forces transmitted to the foundation by the wind forces on the shelter. The magnitude of the uplift forces recorded during these tests is not a true representation of aerodynamic effects of wind around T-shelters during hurricane conditions. The size and position of the T-shelter model in respect with the WoW's wind field is suitable for failure study tests (destructive) but not conducive for aerodynamic studies were the blockage ratio between the wind field and the model should be kept at a minimum.

The objective of the load cell measurements is to obtain data to better understand load transfer paths within the structures; this data also allows comparison of the ability of both types of T-shelter frames to transfer wind forces down to the foundation and/or anchoring system. Table 6 shows a summary of the average forces measured with the load cells for the different cases. The measured load data should only be used for each individual T-shelter structure during testing (increase/decrease within structure during the test) and to compare the two T-shelters to each other. Nothing further should be extrapolated from the load force data.

Load force data allows comparison of the ability of both types of T-shelter frames to transfer the wind load forces down to the foundation. The load cell data showed that as wind speed increased, T-Shelter 1 had a decrease in the ability to transmit forces down to the windward corners rather than the expected increase. This anomaly shows that as the structure began to fail, the detached horizontal and diagonal bracing members did not allow the loads to be transferred, thereby restricting the load distribution paths available in the structure. In comparison with T-Shelter 1, the better constructed T-Shelter 2 is more efficient in transferring the loads down to the foundation; this is clearly shown in the load cell sensor data. The greater rigidity of the T-Shelter 2 structure allowed it to provide a path for the stresses to reach the footings without high deformation of the structural members. T-Shelter 1's weak and flexible frame showed much larger deformations under the same wind load forces.

Table 6 - Wind induced forces at the base corners of T-shelter models

Model	Angle of attack	Wind Speed (mph)	Windward forces (lbs.)		Leeward forces (lbs.)	
			Corner1	Corner2	Corner3	Corner4
T-Shelter 1	0	55	-191	-111	425	490
		65	-245	-168	606	722
		75	-533	-73	954	783
	90	55	-218	-298	329	403
		65	-317	-474	396	551
		75	-80	-192	261	452
T-Shelter 2	0	65	-352	-357	553	712
		75	-525	-491	818	974
		85	-717	-589	1096	1179
	90	65	-390	-282	623	486
		75	-457	-512	789	707
		85	-536	-532	1066	1028

Appendix C includes tables explaining the relationship between the Saffir-Simpson Hurricane Scale (1-min wind speed average over water) to building code basic speeds (3-sec gust average over open terrain). The following table compares the WoW 3-second gust speeds at which failure of the models occurred with the 3-second gust relation with the Saffir-Simpson Hurricane Scale.

Table 7 - Comparison of WoW 3-second gust wind speed with Saffir-Simpson Hurricane Scale

WoW Nominal Wind Speed (mph)	WoW Average measured wind speed (mph)	WoW 3-sec gust* (mph)	Saffir-Simpson equivalent 3-sec gust** (mph)	Saffir-Simpson Hurricane Scale
75	77	80	79-102	1
95	98	103	103-118	2

*At test structure's eave height = 9-ft
**At 33-ft above ground

4.1.1. T-Shelter 1 – weak construction

During testing of T-Shelter 1, it was observed that the shelter was able to hold the forces produced by 55 mph winds at all 3 angles of attack (0°, 45°, 90°). The frame showed flexibility, allowing the roof cladding to oscillate up and down indicating that the purlin and rafter lumber dimensions do not provide rigidity to the roof structure.

When the wind speed was increased to 65 mph and at 0°, one of the 1-in x 4-in making up a vertical member on the gable end detached (Figure 22). At 45° one of the horizontal members on the long windward face became loose from its supports and was hanging from the plastic sheeting. The plastic on the T-shelter walls can be seen bulging from the air infiltrating into the model but no perforations were seen even though only nails (no washers) were used to attach the plastic.

Figure 22 – T-Shelter 1 test at 65 mph and 0° and 90°; some of the wood boards part of the framing detached

It was observed that at 75 mph and 0° the amplitude of the vibrations on the roof was larger and the plastic sheeting also swelled more from the air permeating through the gaps. The structure did not suffer any new damages at this wind speed and angle of attack.

When the shelter was rotated to 45°, horizontal members running on the top of the leeward wall became detached from the vertical members (Figure 23). The shelter's framing was substantially weakened on the longitudinal direction. Now the loads are redistributed along the roof purlins (2-in x 2-in), the diagonal bracing, bottom and mid-height horizontal members (1-in x 4-in) and roof sheeting acting as a diaphragm. Until this moment the structure was damaged but still standing. It could be repaired to bring it back to original conditions.

The most common failure was nails being pulled out of the wood members (Figure 24). All elements of the structure were assembled from smaller pieces of lumber to produce a larger element. The attributes of this type of construction had substantial repercussions on the integrity of the framing once fasteners disconnected. Even though the nails were driven 1 ¼-in into the wood, two factors contributed to the low resistance of the connections: 1) smooth shank nails and 2) lumber being only ¾-

Figure 23 - Test at 75 mph and 45°; horizontal members detaching from framing

in thick (1-in x 4-in nominal is ¾-in x 3 ½-in) do not provide enough material for the nail to grab. Once the manufactured structure elements came apart, their load bearing capacity considerably decreased and the integrity of the T-Shelter model compromised. For example, vertical studs shown on Figure 24 were built of three 1-in x 4-in elements connected together to form a 2 1/4-in stud with a ¾-in gap in the middle. After the connection fails only one 1-in x 4-in took all the loads.

Figure 24 - Nail pull-out failure on shelter framing at 75 mph

When T-Shelter 1 was tested at 75 mph and 90°, the detached horizontal members had already weakened the frame. These members added strength to the shelter on the along-wind direction at this angle of attack. The roof purlins and cladding were able to distribute the load among the vertical structural members and held the walls together. Without horizontal braces, the walls had no ability to sustain the wind induced loads without lateral bracing and simple supports at the base. When the roof structure connection failed at one of the windward corners, the shelter lost the ability to withstand the wind loads and collapsed (See Figure 25). The walls, at this point, were comprised of weakened vertical studs and the number of horizontal members and diagonal bracing between the vertical studs was greatly reduced. Also, the large span between vertical studs allowed for greater flexibility of the structure and considerable deflections that might have contributed to the smooth shank nails pulling out of their connections. The resistance of the shelter could be easily and cost-effectively improved by increasing the lumber size and providing stronger connections made with ring shank nails. Also this framing system with multiple nailed connections is weaker than solid lumber elements. A substantial improvement can be achieved by modifying the construction method to minimize the number of nailed connections and strengthen the connections between structural components.

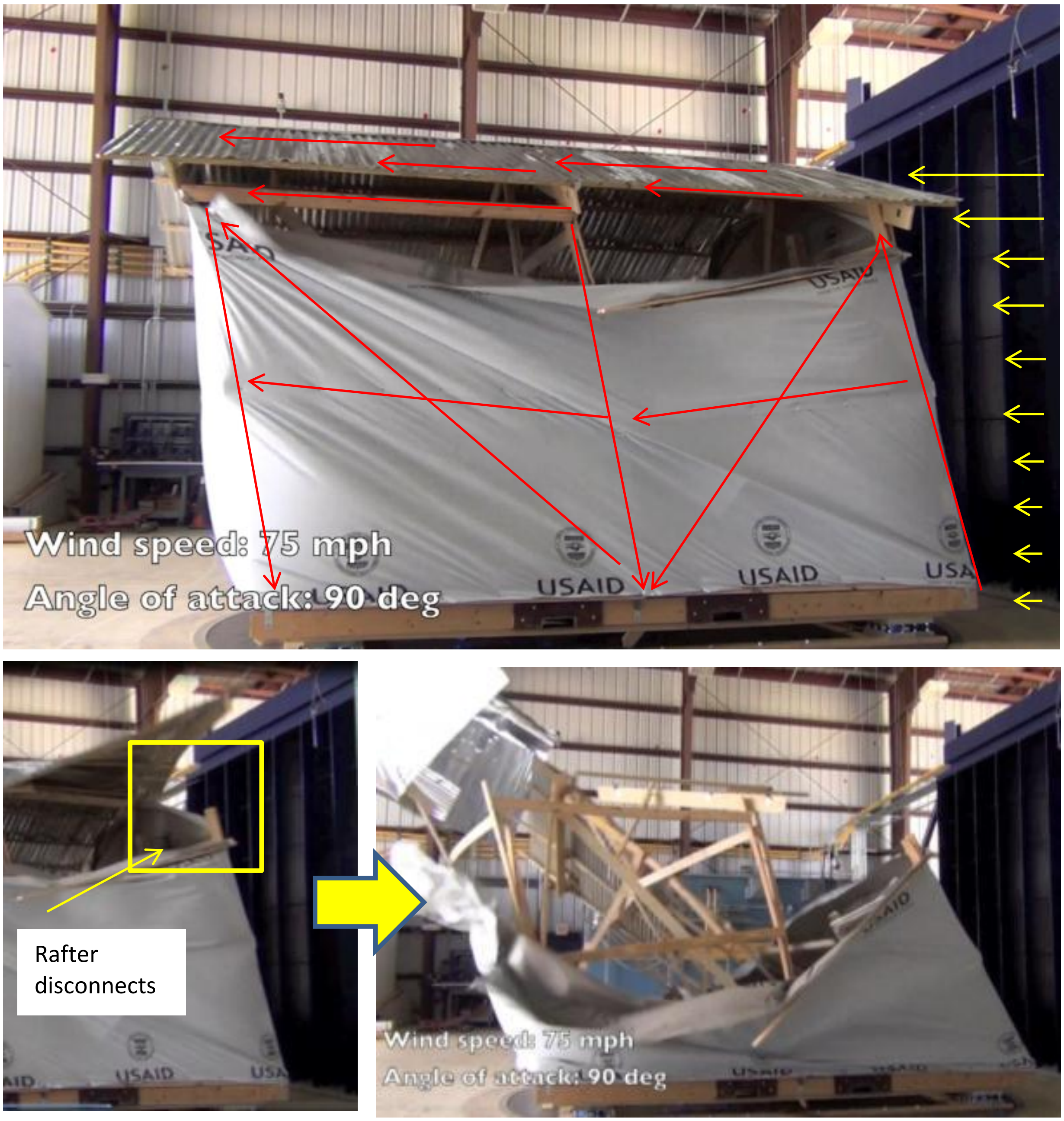


Figure 25 - Redistributed load path on T-Shelter 1 model

4.1.2. T-Shelter 2 – stronger construction

T-Shelter 2 incorporates stronger wood members, connections and construction practices. The lateral bracing was only provided as wood members in an "X" configuration at the corners only. It was easily observed that the shelter appeared to be sturdier under winds as compared to T-Shelter 1. At the lower speeds, it was noticed that the T-Shelter structure was not vibrating as much T-Shelter 1. The reinforced framing is more rigid and capable of transmitting the forces to the foundation without substantial vibrations or deformations. The cycle of wind speeds and angles of attack started at 65 mph and 0 degrees. Throughout the different combinations it was observed that no damage or considerable displacement was produced on the structure.

At 75 mph and 90 degrees a slight inclination of the shelter can be seen suggesting racking due to insufficient lateral bracing. High frequency vibrations can be seen on the roof purlins. This effect is produced by the longer than normal unsupported span between trusses. The shelter was built this way to prove that a stronger roof structure (a 2-in x 4-in truss vs. a 1-in x 6-in stick built rafter and joist frame) will provide sufficient strength with the same clear spacing. By providing two more trusses and reducing the clear spacing from 7-ft to 3.5-ft the robustness of the roof can be greatly increased.

Figure 26 - T-Shelter 2 load distribution path at 85 mph

Also at this speed and angle of attack the door is pushed in by the wind exposing the internal walls to positive pressures. The plastic sheeting is perforated by some of the tin cap discs when the plastic was pushed against them due to the increase in internal pressure. After the test was completed a provisional door stop made of a 1-in x 4-in member, 2-ft long was nailed to the door frame with the intent of providing additional support to the door edge opposing the hinged edge.

When the model was tested at 85 mph winds and 90 degrees the door was pushed out of its hinged support and broke the provisional door stop that had been added (Figure 27). The door opening was then uncovered, allowing the wind directly into the inside of the shelter. Despite that, the shelter was able to remain standing through the 85 mph test's duration.

Figure 27 - T-Shelter 2 door failure at 85 mph and 90 degrees. Red arrows show OFDA plastic perforated by tin caps

The following combination consisted of 95 mph winds at 90 degrees angle of attack. This case allowed the wind into the shelter through the door opening. The plastic sheeting walls were pressurized from the inside. The shelter's framing deformed backward under the wind pressure. The internal pressure of the T-Shelter increases due to the high speed winds. The ventilation openings between the walls and the roof were insufficient to relieve the additional pressure which increased the forces seen by the structure. The roof experienced an increased uplift from internal pressure that pushed the roof upward. The shelter's walls transferred uplift forces from the roof to the platform which suffered from increasing tension on the wood fibers.

Cracks due to tension stresses (Figure 28) slowly formed at the windward edge of the base platform at the locations where the lumber was pierced by fasteners. The wood platform finally gave way to the tensile forces and provided insufficient support for the T-Shelter, causing it to be blown off the platform by the wind (Figure 29).

Figure 28 - Tension cracks on T-shelter base platform's windward edge

This failure (Figure 29) is not considered a breakdown of the T-Shelter structure. Until that moment the T-Shelter was able to satisfactorily withstand the wind forces, with the exception of the door system. The damaged door did not affect the resistance of the shelter up to 85 mph but compromised the safety of the contents of the shelter and made it susceptible to wind coming inside the building through the door opening. It is highly unlikely for a shelter structure to fail in a similar mechanism if adequate footings and foundation-to-wall connections are provided. The T-Shelter adequately withstood wind speeds up to 85 mph. It is recommended to improve the robustness of the door system to prevent a door failure. Even though the door had hinges that let it swing outwards, the wind force was enough to push the door inwards detaching it from the hinges. Additional support should be provided to prevent it.

It is recommended that a reinforced base platform be provided to satisfactorily test the performance of the T-Shelter structure beyond wind speeds of 85 mph. By securing the shelter to a strengthened base, a failure at the foundation level is not likely to happen and the strength of the materials and construction of the shelter's superstructure will determine the ultimately wind speed it will be able to withstand.

Figure 29 - Platform base failure due to increased uplift tension on wood members

Appendix A- Fasteners


1 ¾” Electro Galvanized Roofing

Appendix B – Material Specifications

<u>All-purpose tarp</u>
Thickness: 5.1 mil
Length: 16-ft
Width: 12-ft

<u>Purlin Bearing Rib (PBR) Structural Panel</u>
Width: 36-in
Rib spacing: 12-in on center
Rib height: 1 ¼-in
Panel attachment: exposed fastening system
Gauge: 24
Finish: Smooth
Coating: Galvalume Plus

<u>Corrugated Galvanized Iron Panel</u>
Width: 25.75-in
Length: 96-in
Profile: E3
Gauge: 28
Finish: corrugated
Coating: electro galvanized

<u>Onduline classic roofing sheet</u>
Length: 6.5-ft
Width: 3-ft
Thickness: 3 mm
Corrugation width: 95 mm
Corrugation height: 38 mm

Appendix C – Relation between Saffir-Simpson Hurricane Scale and design wind speeds

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust in ASCE7-10:

TABLE C6-2 APPROXIMATE RELATIONSHIP BETWEEN WIND SPEEDS IN ASCE 7 10 AND SAFFIR/SIMPSON HURRICANE SCALE

Saffir/Simpson Hurricane Category	Sustained Wind Speed Over Water[a]		Gust Wind Speed Over Water[b]		Gust Wind Speed Over Land[c]	
	Mph	(m/s)	mph	(m/s)	mph	(m/s)
1	74–95	33–43	87-111	39-50	81-105	36-47
2	96–110	44–49	112-129	51-58	106-121	48-54
3	111–130	50–58	130-152	59-68	122-143	55-64
4	131–155	59–69	153-181	69-81	144-171	65-76
5	> 155	> 69	>181	>81.0	>171	>76

[a]1-minute average wind speed at 33 ft (10 m) above open water

[b]3-second gust wind speed at 33 ft (10 m) above open water

[c] 3-second gust wind speed at 33 ft (10 m) above open ground in Exposure Category C. This column has the same basis (averaging time, height, and exposure) as the basic wind speed from Fig. 6-1.

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust according to Simiu, Vickery, Kareem (2007)

Saffir-Simpson Hurricane Category	Sustained Wind Speed Over Water (mph) (1-min avg)	Gust Wind Speed Over Land Exposure Category C (mph) (3-sec avg)
1	74-95	79-102
2	96-110	103-118
3	111-130	119-139
4	131-155	140-166
5	>155	>166

Addendum to

FINAL REPORT

Shelter and Component Testing

OFDA transitional shelters: materials, techniques and structures (Supplementary Test)

May 29, 2012

Project Number: WOW12-2012-02-A

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1. Introduction

This report is a supplement to the final report for project number WOW12-2012-02. During the experimental tests performed for this project with the Wall of Wind (WoW), a base platform failure occurred with T-Shelter 2 at the highest wind speeds. The scope of work of the experiments did not consider the performance of the platform base (foundations) of the transitional shelter (T-Shelter) model under wind-induced loads. It was anticipated that the platform would be able to sustain the forces but at 95 mph the wood members on the platform weakened and fractured causing the T-Shelter model to disconnect from its foundation. This is not expected to be a typical failure of the T-Shelters and therefore it cannot be concluded that the materials and/or construction techniques would be able to sustain wind speeds of 95 mph. It was recommended to repeat the test with an identical model but with a reinforced base platform.

The objective of these experiments is to test the resistance of a strengthened T-Shelter model (T-Shelter 3) with identical characteristics and dimensions to that in T-Shelter 2, but with a reinforced base platform. For the model to be tested, the WoW will generate wind speeds of 85 mph, 95 mph, 100 and 110 mph for angles of attack of 0°, 45° and 90°. The tests were recorded on video.

2. Methodology

The tests followed the same methodology as that implemented during the full-scale model tests performed during project WOW12-2012-02. T-Shelter 3 was tested with 12-fan WoW (Figure 1).

Figure 1 – Testing equipment: Twelve-fan Wall of Wind

T-Shelter 3 was built with the standard shelter construction practices and materials identical to those used in the previous test of T-Shelter 2. Methods used in construction of T-Shelter 2 and 3 are bound to applicable guidelines for field deployment of T-Shelters and not to requirements of U.S. building codes. Table 2 describes the shelter model construction materials and details.

In this iteration, the T-Shelter model was built on a reinforced wooden platform that allowed it to be bolted to the turntable anchor locations. The number of wood members for the wooden platform was doubled compared to T-Shelter 2 and metal straps connected the foundation to the shelter superstructure. Also the corners of the bottom plate of the frame where bolted down into the platform. The 6 degree of freedom (6-DOF) load cells were not installed given that in the previous study the maximum capacity of the sensors was almost reached at 95 mph. There is a 5-in difference in height between T-Shelter2 and T- Shelter3 due to the removal of the 6-DOF sensors from the base. This variance in height is considered negligible.

Figure 2 - Base platform and load cell for T-Shelter tests. Arrows point out the difference: with and without 6-DOF load cells

The following changes or additions were done to the T-shelter model as requested by OFDA (see Figure 3):

- Window on a non-gable end wall with a stop molding (built of 2-in x 4-in lumber) around the window frame.
- Provide continuous door stop molding all around the door opening and reinforce the hinge connections.
- Additional lateral bracing on non-gable end walls. A diagonal x-brace spanning the length of the walls was installed on both non-gable end walls.

Figure 3 - T-Shelter model improvements for T-Shelter 3 testing

For each 3-minute test the 12-fan WoW produced a uniform sustained wind speed, with an initial speed of 85 mph. During testing of T-Shelter 2, it was observed that wind speeds lower than 85 mph didn't affect the integrity of the structure. Damage initiated at 85 mph, with the door detaching from hinges. Consequently, an initial test speed of 85 mph was chosen for T-Shelter 3's tests.

The initial wind speed of 85 mph was increased following the steps described on Table 1 while no structural failure of the T-shelter was observed. The model was rotated through 3 angles of attack (0, 45 and 90 degrees). At the higher speeds and the 45° angle of attack, the turntable wasn't able to hold the model steady due to the imbalanced resulting forces caused by the asymmetry of the structure. This angle of attack was omitted from the 100 mph and 110 mph tests.

Table 1 - Wind speeds and angles of attack for T-Shelter model tests

Model / Wind Speed	55 mph			65 mph			75 mph			85 mph			95 mph			100 mph			110 mph		
	Degrees																				
T-Shelter 1	0	45	90	0	45	90	0	45	90	-	-	-	-	-	-	-	-	-	-	-	-
T-Shelter 2	-	-	-	0	45	90	0	45	90	0	-	90	-	-	90	-	-	-	-	-	-
T-Shelter 3	-	-	-	-	-	-	-	-	-	0	45	90	0	45	90	0	-	90	0	-	90

The tests were recorded from multiple angles with the highest resolution the cameras would allow (720p and 1080p, depending on the camera) for the duration of the wind resistance test.

Table 2 - T-Shelter models specifications (shaded cells denote changes from previous model)

Structural Element		T-Shelter 2	T-Shelter 3
Walls	Lumber	2-in x 4-in	2-in x 4-in
	Fasteners	3 ¼-in common nail	3 ¼-in common nail
	Bracing	2-in x 4-in diagonals on X pattern on corners	2-in x 4-in diagonals on X pattern on corners and 2-in x 4-in and diagonals on long span walls
	Spacing	2-ft center-center	2-ft center-center
	Cladding	USAID/OFDA plastic fasteners: with 1 ¼-in roofing nails and tin cap discs at 12-in spacing, edges folded 3 times	USAID/OFDA plastic fasteners: with 1 ¼-in roofing nails and tin cap discs at 12-in spacing, edges folded 3 times
Roof	Type	5:12 (22.6°) Gable	5:12 (22.6°) Gable
	Structure	Trusses: 2-in x 4-in 2-in x 4-in purlins 5/8-in plywood gusset plates	Trusses: 2-in x 4-in 2-in x 4-in purlins 5/8-in plywood gusset plates
	Fasteners	3 ¼-in common nails	3 ¼-in common nails
	Hurricane straps	1-in metal strap fastened with 1¼-in roofing nails	1-in metal strap fastened with 1¼-in roofing nails
	Roof cladding	26-ga CGI	26-ga CGI
	Cladding fasteners	1 ¾-in ring shank neo roofing nail	1 ¾-in ring shank neo roofing nail
	Ridge cap	26-ga sheet metal	Manufactured ridge cap
	Overhang	1-ft all around	1-ft all around
Door		1 door centered on gable end wall	1 door centered on gable end wall with 2-in x 4-in door stop
Window		None	1 window on none-gable end wall with 2-in x 4-in stop

T-Shelter in Port-au-Prince, Haiti	T-Shelter 2	T-Shelter 3
		
		
		

3. Results

At the initial test speed (85 mph) it was observed that the T-Shelter structure was strong enough to be able to sustain the wind forces. No damage was noted on the framing or cladding. It is noteworthy to mention two effects on the T-Shelter as a result of the wind angle of incidence and the framing characteristics. At 0° there are sufficient uplift forces generated to cause a noticeable deformation on the leading edge purlin. A gap between the top chord of the truss and the purlin can be seen at one of the corners. The connections made with smooth shank nails were not adequate to prevent the nails from being pulled out under the uplift forces. The hurricane straps were shown to be effective to secure the purlins down to the trusses (Figure 4).

Figure 4 - Windward purlin deformation from uplift forces at 85 mph and 0° angle of attack

The deformation of the plastic sheeting suggested that when the wind had a 90° angle of attack, the flow separated near the leading edges and reattached further downwind. This is shown on Figure 5: bloated plastic surfaces at the windward side (suction) and plastic being pushed against the frame on the back (pressure). The roof also seemed to be susceptible to this effect, particularly with the long unsupported spans of roof structure. The edge purlins can be seen deforming by the action of the wind-induced forces.

It is important to consider that this model only had 3 roof trusses providing clear spacing of 7-ft between trusses. The spacing of the rafters was sub-optimal. The length of unsupported roof span was chosen for this structure to provide a comparable test with T-Shelter 1 and T-Shelter 2 in previous tests.

The goal was to prove that a stronger roof structure with the same spacing as T-Shelter 1 (weak construction T-Shelter from previous experiments) should be able to withstand hurricane force winds. Even with its stronger construction, large unsupported spans allow for greater deformations and flexibility. The vulnerability can be decreased by adding more trusses and reducing the clear spacing by half.

At 45° angle of attack there are no noticeable effects on T-Shelter 3. The turntable is not able to hold the model in place and can be seen slowly rotating clockwise showing that is torsional force produced by the flow around the asymmetric structure.

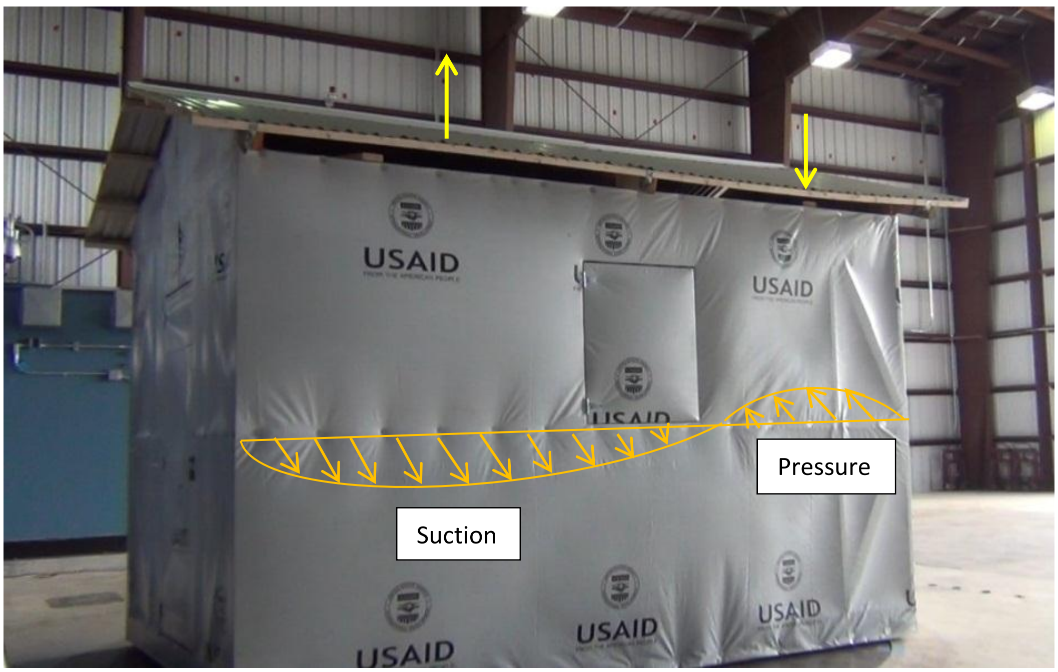


Figure 5 - T-Shelter 3 test at 85 mph and 90° angle of attack

Furthermore, the increase in speed from 85 mph to 95 mph did not produce noticeable damage on the outside of the shelter. The additional lateral bracing seemed to be effective to transfer the forces and reduce the deflection at 90° angle of attack. The reinforced door hinges and door stop are believed to have provided additional support and strengthened the door system. No damage to the door was observed. While inspecting the inside of the shelter it was observed that the door stop did transfer the loads from the door to the frame. The bottom section of the door stop was partially pulled out from its attachment (Figure 6). This was a consequence of a construction flaw, where the nails were driven into the gap between the bottom plate and the platform.

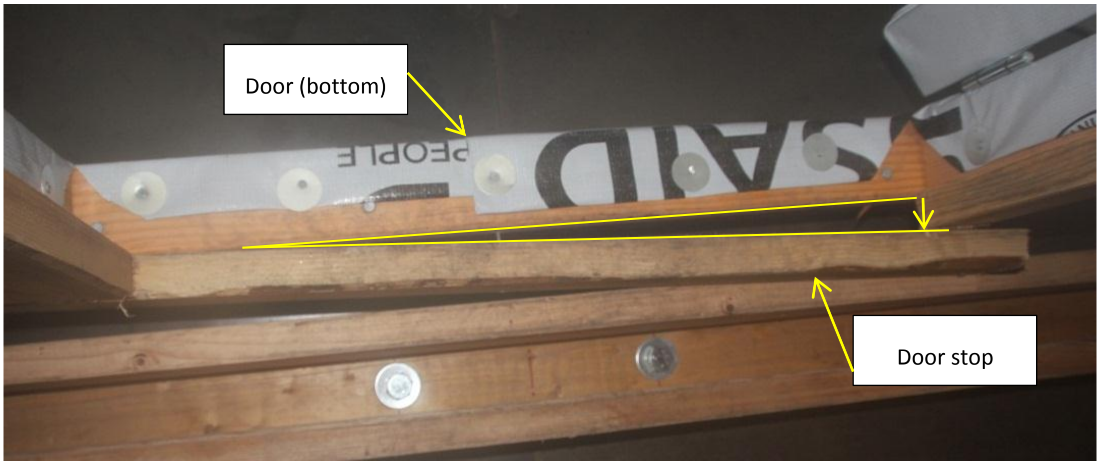


Figure 6 - Bottom door stop pulled-out

With the wind speed increased to 100 mph, sections of the OFDA plastic sheeting were pushed harder into the sharp edges of the tin caps. It is presumed that either the internal pressure build-up from air leaking through the shelter openings or the aerodynamic forces (suction) created on the wall surfaces, or a combination of both, caused the tin caps to start cutting through the plastic (Figure 7). It demonstrated that tin caps transfer the concentrated loads from the nail head to a bigger area on the plastic, but it's sharp edges can cut through it under repetitive loading. It is believed that a material with blunt edges (i.e. wood battens) might be a better option to enhance the durability of the USAID/OFDA plastic during repetitive loading and provide a surface to distribute the forces.

Figure 7 - Plastic puncture by tin cap discs

T-Shelter 3 was able to withstand up to 110 mph at a 90° angle of attack (wind into the gable end). At this angle of attack T-Shelter 2 (same strong construction) platform failed at 95 mph in the previous tests. In the case of testing T-Shelter 3, there was no door failure and therefore no wind penetrating directly into the inside of the shelter through the door location. Also it was observed that the structure was less susceptible to failure due to racking of the frame. It is believed that it is a result of the additional lateral bracing installed in this test specimen. The wall capacity to transfer the forces and pressures can be increased by providing a more rigid form of sheeting to the walls. Replacing the OFDA plastic with a rigid membrane, such as an adequately sized plywood board fastened to the frame, will let the wall act as a diaphragm and help carry in-plane shear. The choice of using OFDA plastic sheeting on all three T-Shelter tests was intended to allow comparable tests among models.

The frame on T-Shelter 3 failed at 110 mph and an angle of attack of 0°. It is believed that the failure mechanism is as follows:

1. The wind acted on the long wall that had an opening (window). The framing had vertical studs discontinued because of the window opening. A jack stud (Figure 8) was provided under the window sill but no cripple stud (shorter stud in window/door header) over the header. The spacing between studs was increased from 24-in on center to 32-in on center at the window opening.
2. While reviewing the video it can be observed that there was a sudden deformation of the wall in its mid-section (close to 1 min into the test). The window section of the wall buckled inwards but dids not detach from the rest of the frame (Figure 9). Until this moment the structure was still standing and the damage could have been repaired.

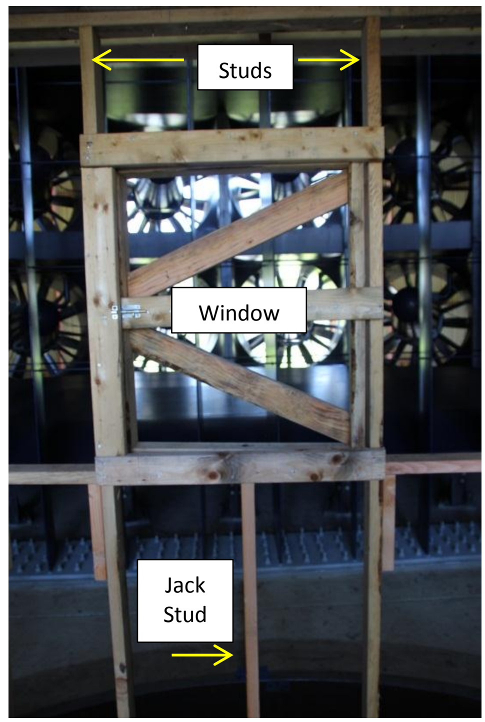


Figure 8 - Window framing

3. An inspection of the damaged wall after the test found that none of the studs around the window section fractured. Therefore, it is assumed that the wind-induced forces on the wall slowly pulled the nails out of the wood members that connected the studs to the top and bottom plates. There was no evidence of the nails failing from shear.
4. After the windward wall collapsed, it provided no support for the middle roof truss.
5. The roof system was now supported by two trusses on each corresponding gable-end wall creating an unsupported span of 14-ft.

6. One of the hurricane straps that connected one of the gable-end trusses sheared and at that moment the roof system completely disconnected from the shelter's walls.
7. With no structural members supporting the mid-span wall section and the roof diaphragm gone, the walls collapsed under the wind loads.

Figure 9 - Windward wall deformation at 0° angle of attack and 110 mph

Figure 11 shows the images of T-Shelter 3 failure step by step.

Considering the presumed failure mechanism, several key recommendations or modifications to T-Shelter construction should be considered:

- Adequate reinforcement at framing discontinuities must be provided to ensure the structure's ability to transfer the loads uninterruptedly to the foundation and distribute them along the structure. Door and window openings are discontinuities on the frame system that may become a weak point of the structure because of high stress concentrations on the discontinued frame members. Required elements to be included on the framing of door and window openings include: header, top cripples, and trimmer and jack studs (see Figure 10).

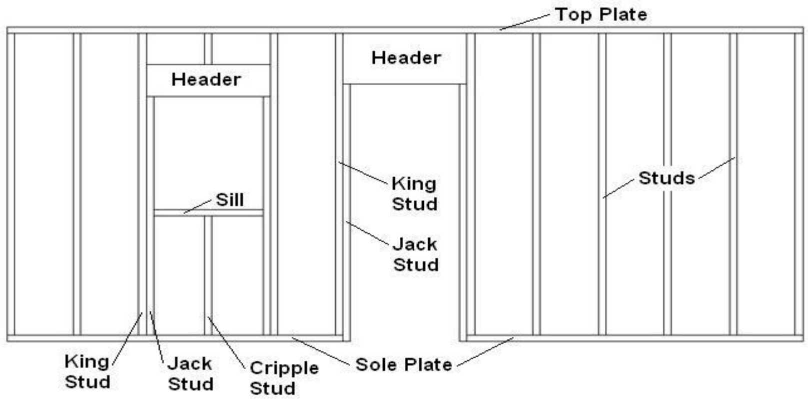


Figure 10 - Wood construction window and door framing details

- Use of smooth shank nails should be discouraged. Ring shank nails were used for T-Shelter 3 only to fasten cladding to the frame. For these tests it was specified that framing should be done using 12D common nail. There is a big improvement in the pull-out resistance of ring-shank nails compared to smooth shank nails. The use of ring-shank nails is recommended for framing construction.
- To make the structures less vulnerable to failure under high wind conditions, a factor of safety should be incorporated into the different construction techniques. It was observed that there is no redundancy in the structural elements of the shelter. Once one of the members is weakened and fails the rest of the structure is compromised and most likely to collapse. By adding redundant elements, in case the roof fails, an internal or partition wall can help distribute the windward wall forces.

The test's goal was to determine the ultimate wind speed the T-shelter would be able to withstand before one of its components or the whole system failed. The tests did not consider the effects of fatigue or cyclic loading in which the duration of the test would be considerably longer. Components and structures that fail during cyclic loads will do so at a lower force than the ultimate strength force. Ultimate strength of materials and/or construction techniques is representative of low probability of occurrence events with a high return period. Failure due to cyclic loads and fatigue will most likely occur with events of high probability of occurrence.

Appendix B includes tables explaining the relationship between the Saffir-Simpson Hurricane Scale (1-min wind speed average over water) to building code basic speeds (3-sec gust average over open terrain). The following table compares the WoW 3-second gust speeds at which failure of the models occurred with the 3-second gust relation with the Saffir-Simpson Hurricane Scale.

Table 3 - Comparison of WoW 3-second gust wind speed with Saffir-Simpson Hurricane Scale

WoW Nominal Wind Speed (mph)	WoW Average measured wind speed (mph)	WoW 3-sec gust* (mph)	Saffir-Simpson equivalent 3-sec gust** (mph)	Saffir-Simpson Hurricane Scale
75	77	80	79-102	1
95	98	103	103-118	2
110	111	116	103-118	2

*At test structure's eave height = 9-ft
**At 33-ft above ground

Figure 11 - Shelter 3 failure

4. T-Shelter material cost comparison

As a comparative measure, Table 4 shows the costs of materials for T-Shelter 1 and 2 (and 3). The cost of materials is based on the wholesale price at hardware and lumber suppliers in the Miami, FL area and do not include cost of freight or local and State taxes. All prices are given is US dollars. The price of 32 gauge CGI roofing sheets on T-Shelter 1 was estimated, since this material is not available for the US market. The sheets used in the construction of T-Shelter 1 were imported from Haiti but are manufactured by a US company in Jacksonville, FL.

It can be seen that the cost of the stronger shelter is almost double the cost of the weaker shelter. The increase in price (approximately 12%) between T-shelter 2 and 3 is due to the additional lateral bracing and reinforced window and doors.

Table 4 - T-Shelter material cost comparison

T-Shelter 1

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
1x4x8	40	ea	1.9	$77.60
1x4x10	14	ea	4.2	$58.10
1x6x8	6	ea	7.5	$44.76
2x2x8	18	ea	3.0	$53.46
				$233.92
FASTENERS				
4D common nail	5	lb	4.2	$21.20
5D electro galv roofing nail	5	lb	2.1	$10.47
				$31.67
ROOFING				
26x60 32Ga CGI*	10	ea	15.0	$150.00
26 Ga sheet metal	18	lf	1.4	$24.30
*cost not known, estimated				
				$24.30
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	3	ea	5.0	$14.91
Hurricane ties	48	ea	0.6	$28.32
Door hardware	0	ea		$0.00
				$43.23
TOTAL COST				**$333.12**

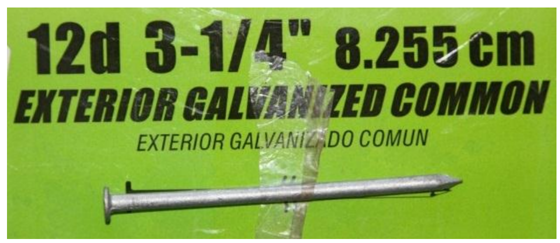
T-Shelter 2

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
2x4x8	70	ea	2.7	$190.40
2x4x10	11	ea	4.2	$46.09
2x4x14	14	ea	5.9	$82.18
19/32 plywood	1	ea	31.0	$30.97
				$349.64
FASTENERS				
12D Hot Galv Common nail	30	lb	1.4	$42.98
5D HG Ring Shank Neo	3	lb	4.2	$12.72
#11 Galvanized roofing nail	5	lb	10.5	$10.47
6D common nail	1	lb	3.5	$3.47
				$69.64
ROOFING				
26x60 26Ga CGI	10	ea	20.0	$199.80
26 Ga sheet metal	18	lf	1.4	$24.30
				$224.10
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	3	ea	5.0	$14.91
1-in Metal strap	50	ft	0.2	$10.00
Door hardware	1	ea	4.2	$4.24
				$29.15
TOTAL COST				**$672.53**

T-Shelter 3

Material	Qty	Unit	Unit Cost	Cost
LUMBER				
2x4x8	80	ea	2.7	$217.60
2x4x10	11	ea	4.2	$46.09
2x4x14	20	ea	5.9	$117.40
19/32 plywood	1	ea	31.0	$30.97
				$412.06
FASTENERS				
12D Hot Galv Common nail	30	lb	1.4	$42.98
5D HG Ring Shank Neo	3	lb	4.2	$12.72
#11 Galvanized roofing nail	5	lb	10.5	$10.47
6D common nail	1	lb	3.5	$3.47
				$69.64
ROOFING				
26x60 26Ga CGI	10	ea	20.0	$199.80
10-ft Ridge cap	2	ea	11.3	$22.56
				$222.36
WALL SHEETING				
USAID Plastic	50	ft		
ACCESSORIES				
6-in Door hinges	5	ea	5.0	$24.85
1-in Metal strap	50	ft	0.2	$10.00
Door hardware	4	ea	4.2	$16.96
				$51.81
TOTAL COST				**$755.87**

Appendix A- Fasteners



Appendix B – Relation between Saffir-Simpson Hurricane Scale and design wind speeds

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust in ASCE7-10:

TABLE C6-2 APPROXIMATE RELATIONSHIP BETWEEN WIND SPEEDS IN ASCE 7 10 AND SAFFIR/SIMPSON HURRICANE SCALE

Saffir/Simpson Hurricane Category	Sustained Wind Speed Over Water[a]		Gust Wind Speed Over Water[b]		Gust Wind Speed Over Land[c]	
	Mph	(m/s)	mph	(m/s)	mph	(m/s)
1	74–95	33–43	87-111	39-50	81-105	36-47
2	96–110	44–49	112-129	51-58	106-121	48-54
3	111–130	50–58	130-152	59-68	122-143	55-64
4	131–155	59–69	153-181	69-81	144-171	65-76
5	> 155	> 69	>181	>81.0	>171	>76

[a]1-minute average wind speed at 33 ft (10 m) above open water

[b]3-second gust wind speed at 33 ft (10 m) above open water

[c] 3-second gust wind speed at 33 ft (10 m) above open ground in Exposure Category C. This column has the same basis (averaging time, height, and exposure) as the basic wind speed from Fig. 6-1.

Relation between Saffir-Simpson Hurricane Scale and 3-sec gust according to Simiu, Vickery, Kareem (2007)

Saffir-Simpson Hurricane Category	Sustained Wind Speed Over Water (mph) (1-min avg)	Gust Wind Speed Over Land Exposure Category C (mph) (3-sec avg)
1	74-95	79-102
2	96-110	103-118
3	111-130	119-139
4	131-155	140-166
5	>155	>166