Addendum to

FINAL REPORT

Shelter and Component Testing

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

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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.

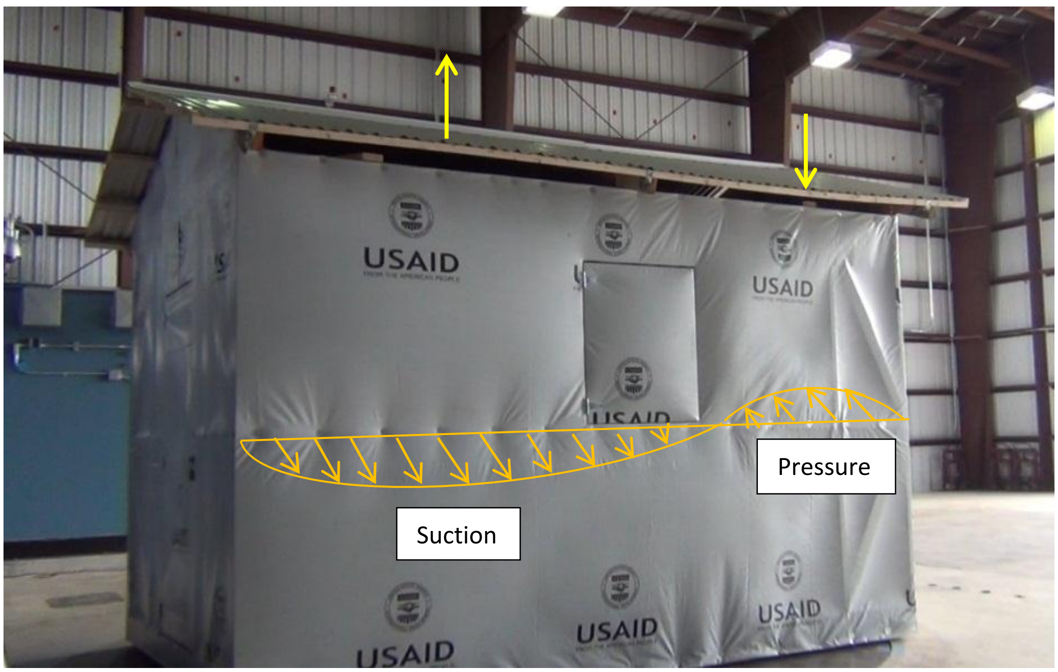

Figure 5 - T-Shelter 3 test at 85 mph and 90° angle of attack

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.

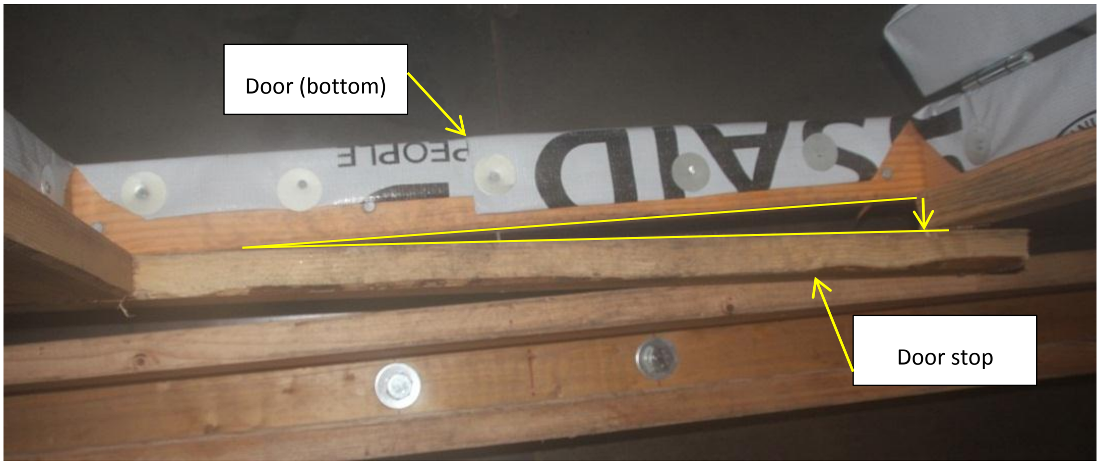

Figure 6 - Bottom door stop pulled-out

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.

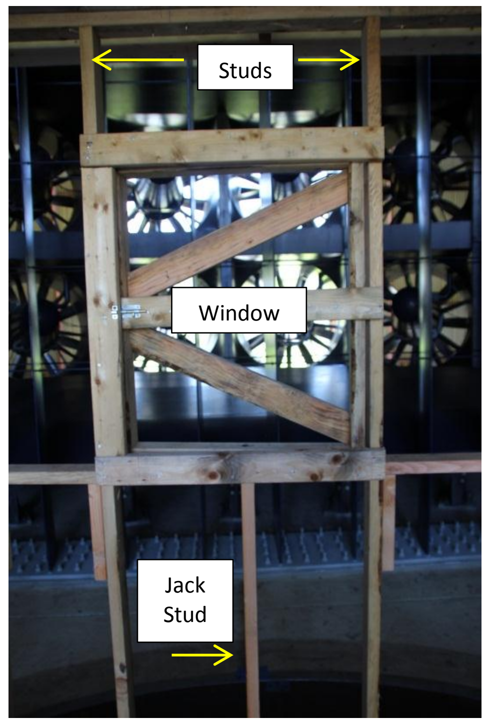

Figure 8 - Window framing

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).

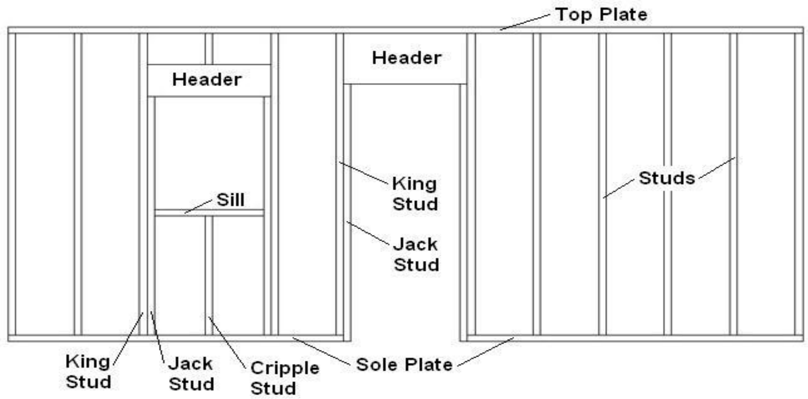

Figure 10 - Wood construction window and door framing details

- 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

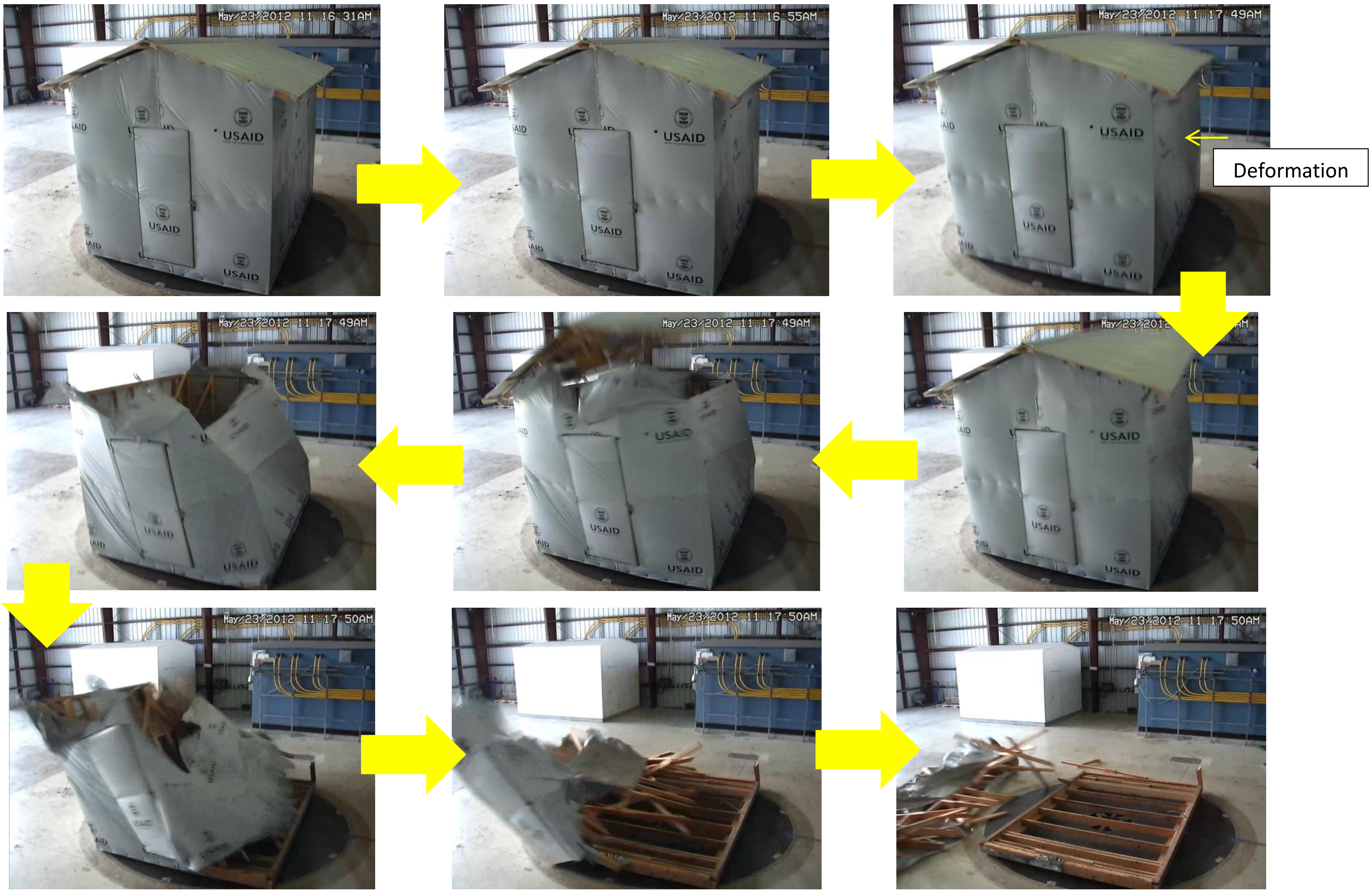

Figure 11 - Shelter 3 failure

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