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Development of a Ready-to-Assemble Tornado Shelter from Cross-Laminated Timber (CLT)

Impact and Wind Pressure Testing

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Forest Service
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Abstract

The development and use of tornado shelters have helped reduce loss of human life associated with extreme weather events. Currently, the majority of shelters are built from either steel or concrete. The development of the cross-laminated timber (CLT) industry in the United States has provided an ideal wood product to resist the debris impact and high wind forces associated with tornados. This report overviews the design and development of a residential tornado shelter constructed from CLT. This design was impact- and wind-pressure-tested according to the core requirements of the International Code Council Standard for the Design and Construction of Storm Shelters. Results indicate that a residential tornado shelter constructed of four-ply CLT walls, a three-ply roof, and a four-ply door can safely resist the impact of a 15-lb wooden missile traveling at 100-mi/h (mph)—the most severe impact test included in the ICC/NSSA-500 standard. Lateral load and uplift load testing indicated that the four-ply shelter can resist the applied pressure caused by a 250-mph wind, as calculated from wind load design criteria. More testing would be required to verify the performance of a CLT shelter intended for commercial or institutional applications.

Keywords: tornado, impact testing, cross-laminated timber, safe room

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Contents

English unit	Conversion factor	SI unit
inch (in.)	2.54×10^{1}	millimeter (mm)
foot (ft)	3.048×10^{-1}	meter (m)
mile (mi)	1.609347	kilometer (km)
pound, mass (lb)	4.535924×10^{-1}	kilogram (kg)
pound per square foot (lbf ft^{-2})	4.788026×10^{1}	pascal (Pa)
square foot (ft^2)	9.2903×10^{-2}	square meter (m^2)

Nominal lumber size (in.)	Standard lumber size (mm)
2 by 4	38 by 89
2 by 8	38 by 184

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Impact and Wind Pressure Testing

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Introduction

A tornado shelter is a reinforced structure specifically designed to meet the criteria of International Code Council Standard for the Design and Construction of Storm Shelters (ICC/NSSA 2014) and provides protection in extreme weather events, including tornadoes and hurricanes. If a tornado shelter is designed according to ICC/NSSA-500, occupants should have a very high probability of being protected from injury or death.

The recent growth of the cross-laminated timber (CLT) industry in North America has made available manufactured wood panels that are seemingly ideal for tornado shelters. The development of a tornado shelter from CLT that is easy to ship, ready to assemble, and quick to fabricate on site would not only increase the level of safety for the general population but also increase market opportunity for these wood products.

This study was initiated to determine if a shelter constructed from CLT could meet the impact and wind pressure requirements of the ICC/NSSA-500 standard for a residential tornado shelter. Results of impact and wind pressure testing performed to verify the tornado resistance of the developed CLT tornado shelter are presented here. Two sizes of safe shelters—8- by 8-ft and 5- by 5-ft—were constructed of both three-ply and four-ply CLT panels and were evaluated. The fact that the shelters evaluated were constructed of five full-sized panels, each of which can weight over 1000 lb, make these designs best suited for building that can accommodate lifting equipment.

Wood Tornado Shelter Design and Construction

DR Johnson, a CLT manufacturer in Riddle, Oregon, USA, provided panels for testing. Shelters constructed of both three-ply (4-1/8-in. thick) and four-ply (5-1/2-in. thick) CLT panels were evaluated. Although four-ply panels are not as common in the marketplace as three-ply or five-ply panels, previous impact testing of wood panels of different wood product types suggested that a panel of about 5 to 6 in. in thickness should perform well. Three-ply and four-ply panels were chosen for testing with the assumption that if four-ply worked, certainly five-ply would also resist the loads applied.

The laminations in each panel were 1- 3/8 in. thick and alternated direction orthogonally. Therefore, four-ply panels were constructed with the first and third and second and fourth laminations, respectively, parallel, but oriented 90° to each other. The panels were manufactured from Douglas Fir as a V1 grade.

Two sizes of tornado shelters constructed from each thickness of panel were evaluated. The first was a shelter 8 by 8 ft in plan (exterior dimensions) with a height of 8 ft (Fig. 1). This larger shelter, similar in size to that described in Falk and Bridwell (2018) is large enough for other uses (such as bathroom, utility shelter, sauna) when not needed in an emergency. The second shelter evaluated was 5.5 by 5.5 ft in plan (exterior dimensions) with a height of 7.67 ft (Fig. 2). Per FEMA recommendations of 5 ft^2 per person, the larger shelter will accommodate nine people and the smaller shelter five people.

Figure 1—8- by 8-ft CLT tornado shelter.

Figure 2—5- by 5-ft CLT tornado shelter.

The CLT panels were provided prefabricated and cut to size. Once at the Forest Products Laboratory (FPL), the panels were connected together with custom-made 14 gauge sheet steel angles. These 4- by 4-in. angles were attached at each inside shelter corner with 3/8- by 3-in. lag bolts (predrilled, 8 in. on center (o.c)). This panel connector system allowed the butting of CLT panels without field modification (Fig. 3). This connection system allowed for rapid construction. Each shelter was assembled by two people using only an overhead crane and hand tools in less than 4 hours.

Another important component of a tornado shelter is the entry door. Similar to the overall shelter itself, the door must be designed and constructed to withstand the wind and impact forces produced by a tornado. In this study, the impact resistance of an outswing door overlaying a standard 36- by 80-in. opening was evaluated. This door was similar in operation to the door described in Falk and Bridwell (2018).

As shown in Figure 4a, the door was hung with three 5/8-in. gate hinges, similar to those that might be found on a livestock gate (293BC and 294BC, National Hardware LLC, Pinedale, California, USA). These hinges were chosen because of their low cost and adjustability in hanging an overlaid door as well as the fact that they had performed well when used on the tornado shelter door described in Falk and Bridwell (2018). The door was latched from the inside using three cane bolts (Fig. 4b) (Product 5000-242, Snug Cottage Hardware Inc., Marysville, Michigan, USA). The ability of this hardware to withstand the suction forces of tornado-force wind pressures was previously evaluated by Falk et al. (2018).

Figure 3—Sheet steel angles for connecting CLT panels.

Securing the tornado shelter to the foundation is another important aspect of tornado shelter design. The hold-down connector, the anchors securing the hold-down connector, and the concrete foundation each must have adequate structural strength to resist the wind forces produced by a tornado. The hold-down connector utilized in the CLT safe shelters described here is a simple 13-in. long, 2-in. wide, 1/4-in. thick A36 steel bar bent in an "L" shape to allow attachment to a concrete floor (Fig. 5).

Each hold-down is attached to the tornado shelter using five 3/8- by3-in. long lag bolts, and each hold-down has a 3/4-in.-diameter through hole on the shorter leg for anchoring to the foundation. For the 8- by 8-ft shelter, 12 hold-downs were used, three on each wall. One hold-down was placed approximately at the center of each wall

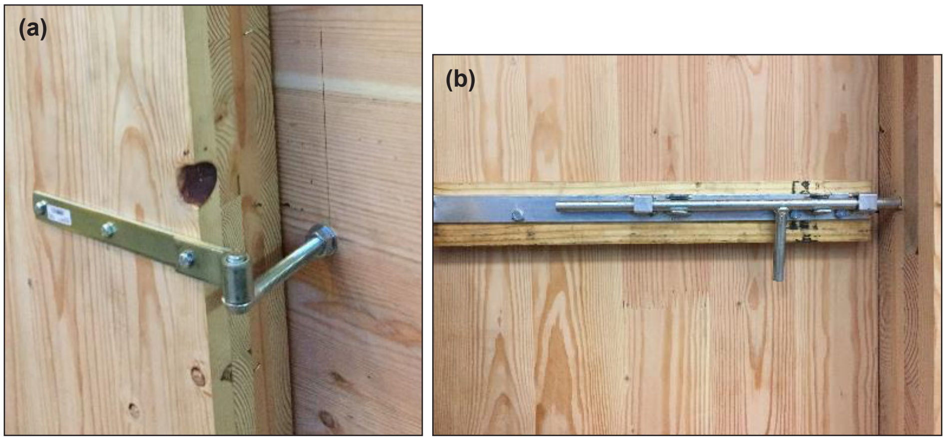

Figure 4—(a) Door hinge, (b) door latch.

Figure 5—Shelter hold-down.

panel and the other two approximately 12 in. from each wall corner. On the wall panel with the door, the middle hold-down was secured 12 in. in towards the door from the hold-down on the opposite side of the panel from the door hinges. For the 5.5- by 5.5-ft shelter, eight hold-downs were used, two on each wall placed about 12 in. from each wall corner, except in the case of the door panel, where they were placed 6 in. from each wall corner.

The concrete foundation that the tornado shelter sits atop must have enough thickness, reinforcement, and surface area to resist anchor bolt pullout, foundation sliding, and shelter overturning. These design considerations are addressed in FEMA P-320 (FEMA 2014), FEMA P-361, and ICC/NSSA-500.

Performance Criteria for Tornado Safe Shelters

The performance criteria for a residential tornado shelter has been standardized in ICC/NSSA-500. This standard presents occupancy requirements, impact testing, wind pressure testing, ventilation, and other performance criteria for these structures. This report is limited to impact and wind pressure testing of a residential tornado shelter and its components.

Table 1—Missile testing criteria[a]

Test	Missile	Missile size (lb)	Missile speed (mph)
Basic hurricane	2 by 4 wood stud	9	34
Hurricane enhanced–A	2 by 4 wood stud	15	50
Hurricane enhanced–B	2 by 4 wood stud	15	60
Tornado	2 by 4 wood stud	15	100
Hurricane shelter	2 by 4 wood stud	9	0.4 × wind zone speed

[a]NIST/TTU (2006).

Impact Criteria

According to ICC/NSSA-500, large missile impact testing is an accepted way of assessing the strength performance of assemblies and materials used in severe weather shelter design. The range of tests is given in Table 1. The tornado test imparts the most energy and thus can be considered the most severe.

In these tests, the walls of the tornado shelter are subjected to the impact of a 2×4 lumber stud (actual 1.5 by 3.5 in.) weighing between 14.75 and 15.25 lb. Density and moisture content of the missiles are required to ensure that a missile 13 to 14 ft in length satisfies the weight requirement. Missiles are also to be selected such that no knots appear within 12 in. of the leading edge and the missile has less than 0.5 in. of bow or warp when measured at any point along its length.

For a tornado test on a vertical wall, the missile must impact the target at a velocity of 100 mi/h (mph). Roof panels are impacted with the same size of missile, however the impact speed is 67 mph (see table 305.1.1 of ICC/NSSA (2014)). Target areas of particular interest are wall–wall intersections, wall–roof intersections, and areas around the sides and top of the door. These are typically vulnerable regions that rely on connections for performance.

ICC/NSSA-500 also requires that a paper witness screen of taut 70-lb kraft paper be erected no more than 5 in. behind the interior surface of the wall being tested. Any perforation of the screen by debris or a deforming wall is considered a failed test.

A successful impact test requires that the wall meet three basic criteria: (1) permanent wall deflection less than 3 in., (2) no perforation of the witness screen, and (3) no perforation of the interior surface of the wall by the missile.

Similar tests were performed on a tornado shelter constructed from commodity wood products and are detailed by Falk et al. (2018).

Wind Pressure Criteria

In addition to requiring resistance against the impact loads generated by wind-blown debris, ICC/NSSA-500 requires that a tornado shelter must be able to withstand high wind forces. Lateral wind pressure tests and wind suction uplift tests were performed to verify that the various components of the shelter (wall, roof, and door) remain intact under wind pressure loads and that the shelter hold-downs are able to adequately transfer wind pressure loads to the foundation.

Design wind pressures are to be calculated using ASCE/SEI 7-10 (ASCE 2013), section 6, method 2. As indicated by Falk and Shrestha (2016), the calculated lateral pressure from a 250-mph wind on the face of an 8- by 8-ft tornado shelter is 167 lb/ft^2. Similarly, the calculated suction (or uplift) pressure is 224 lb/ft^2.

Test Methods and Data Collection

Impact Testing

The impact and wind pressure tests were conducted at the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wisconsin, USA. For the impact tests, the shelter was anchored to the floor of the test laboratory using the hold-down anchors described earlier. These anchors were secured using 5/8-in.-diameter Grade 5 bolts to W12x120 steel beams that were clamped to the floor of the test laboratory (Fig. 1).

A 36- by 36-in. frame for the paper witness screen was constructed from 2×4 studs. After stapling a piece of 70-lb kraft paper taut against the studs, the frame was placed on a steel stanchion. For each test, the stanchion was placed 5 in. behind the interior of the target wall or door. Figure 6 shows the witness screen used for the impact tests.

Not all the missiles used in this study satisfied all the ICC/NSSA-500 criteria. Sourcing 13-ft-long 2×4s that were straight enough to physically load into the cannon barrel and safely fire was problematic. Although each missile used in this study met the temperature storage requirements, weighed at least 15.0 lb, and satisfied the knot distance requirement, some missiles were slightly shorter than required. Overall, tests performed in this study used missiles that averaged 12.75 ft in length and 15.25 lb in weight. We believe this discrepancy in length is insignificant because missile mass is the factor that determines impact force, not missile length. The trailing edge of each missile was affixed with a Delrin sabot weighing 0.4 lb.

Figure 6—Witness screen erected inside the shelter.

Figure 7—Debris impact cannon.

Impact testing was performed using a modified Mega Launcher II (referred to as a “cannon”) built by Spudtech, LLC (New London, Minnesota, USA) (Fig. 7). The cannon used compressed air to propel each missile. The pressure of the compressed air was adjusted to control the speed of the missile via an external control apparatus.

Figure 8—Panel wind pressure test setup.

Missile speed was computed with the use of two photoelectric sensors (FS2-65, Keyence Corp., Osaka, Japan) spaced at 12 in. inside the muzzle of the cannon. As the missile was launched past the sensors, signals from the sensors were conditioned in a programmable counter (P6000A, Newport Corp., Irving, California, USA) that output time-of-flight between the sensors. Velocity was computed by dividing the sensor spacing by the time-of-flight.

Wind Pressure Testing

Panel Test Method

An airbag (custom made by MatJack, Indianapolis Industrial Products, Inc., Indianapolis, Indiana, USA) was sandwiched between the panel and the floor of the test laboratory to simulate a uniformly applied wind load (Fig. 8). Pressurized air was delivered to the bag through a regulator (Model QBX, Proportion-Air, Inc., McCordsville, Indiana, USA). The regulator was controlled through proportional feedback using LabVIEW software (National Instruments Corp., Austin, Texas, USA). Deflection was measured on the top face in the geometric center of the panel using a cable-extension position transducer (Celesco PT101, 2 in. full-scale (Celesco Transducer Products, Inc., Chatsworth, California, USA)). Deflection data were captured using LabVIEW software at a frequency of 1 Hz.

Shelter Lateral Load Test Method

Similar to the impact tests, the full-size shelter was secured to the strong floor of the test laboratory through a series of steel beams, which in this case were placed adjacent to a reinforced concrete strong wall (Fig 9). The same airbag described earlier was sandwiched between the tornado shelter and the strong wall to simulate a uniformly applied wind load to the side of the shelter (Fig. 10). The lateral wind pressure load was applied using the same regulator, software, and procedure as outlined for the pressure test on the panel.

Figure 9—Tornado shelter tied down to strong floor.

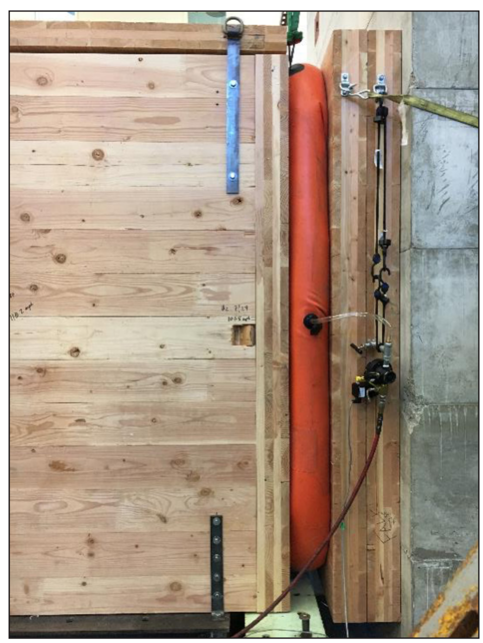

Figure 10—Airbag between tornado shelter and strong wall.

Figure 11—Uplift loading on CLT tornado shelter roof.

Using the same setup as described by Falk et al. (2018), the two upper corners of the shelter on the opposite side from airbag were fitted with position transducers (Celesco PT101, 2 in. full-scale (Celesco Transducer Products, Inc., Chatsworth, California, USA)). Deflection data were continuously acquired throughout the loading sequence using MTS 793 software at a rate of 1 Hz.

Shelter Uplift Test Method

A Miller Series HV2 hydraulic actuator (Miller Fluid Power Corporation, Des Plaines, Illinois, USA) was set up inside the tornado shelter, and two 78-in.-long W6x15 steel cross beams spaced at 30 in. (Fig. 11) were used to apply an uplift load to simulate the wind suction forces experienced by the CLT tornado shelter roof (three-ply). Deflection of the shelter was measured using a position transducer (Celesco PT101, 2 in. full-scale) attached to the geometric center on the external face of the roof. MTS 793 software controlled the actuator during the test and also acquired the load and deflection data at a rate of 1 Hz.

Results and Discussion

Impact Testing

Panel/Door Testing

Three-Ply Wall Panel

Before building and testing a full-size shelter, an 8- by 8-ft three-ply CLT wall panel was impact tested to determine if a three-ply panel could resist the impact loads. The first test was performed at the geometric center of the panel (P1, App. A). The panel failed the test because a piece of debris punched a small hole in the witness screen.

Figure 12—Single impact test to three-ply 5- by 5-ft shelter.

Three-Ply Roof Panel

According to ICC-500 (ICE/NSSA 2014), roof panels are required to withstand a missile speed of at least 67 mph. An 8- by 8-ft roof panel was impact tested twice (P2, P3, App. A), once at the geometric center and once near the panel edge. The roof panel survived tests with missile speeds well in excess of the requirement (84 mph and 78 mph, respectively).

Three-Ply Door

Next, a three-ply CLT door overlaying a standard 36- by 80-in. opening was impact tested. The door was hung on an 8- by 8-ft panel and was tested under the same conditions as if it had been hung on a shelter. As indicated in Appendix B, the door was impacted near the upper latch (D1), near the hinge (D2), and at the geometric center of the door (D3). The door passed all three tests with little damage and no debris.

Shelter Testing

Three-Ply 5- by 5-ft Shelter

The three-ply panel failure mentioned above suggested that an 8- by 8-ft shelter constructed of three-ply panels would not perform well, but we speculated that a three-ply shelter of smaller size might pass the impact test. Therefore, a 5- by 5-ft (interior dimension) three-ply shelter was built and subjected to impact. Figure 12 shows the results of

Figure 13—Interior damage to three-ply 5- by 5-ft shelter.

Figure 14—Tearing of witness paper.

the single impact test that was performed on this shelter. As shown in Figures 12 to 14 and Appendix D, the three-ply panel deflected more than 3 in. and debris pierced the witness screen. The shelter therefore failed the test. This test and the three-ply panel test described above suggest that a three-ply panel was too thin to resist the most severe impact forces dictated by the standard.

Four-Ply 8- by 8-ft Shelter

Because of the failure of the three-ply panel and the three-ply 5- by 5-ft shelter, an 8- by 8-ft shelter constructed of four-ply CLT was tested. Figures 15 and 16 indicate the locations of impact on the full-size shelter.

Although four-ply panels are not as common in the marketplace as three-ply or five-ply panels, previous impact testing of wood panels of different wood product types suggested that a panel of about 5 to 6 in. in thickness should perform well (Falk et al. 2015). Four-ply CLT was chosen to test with the assumption that if four-ply worked, certainly five-ply would also work.

Impact tests R1 to R5 were performed in sequence on the same shelter wall. As indicated in Appendix C, impact test R1 was intended to evaluate the resistance of the wall panel by targeting the geometric center of the panel. Tests R2 and R3 were positioned to concentrate forces at the wall–wall interface. Impact tests R4 and R5 were positioned to evaluate the wall–wall–roof and wall–roof interface, respectively. In all cases, the four-ply wall resisted the impacts with little or no damage.

Four-Ply 5- by 5-ft Shelter

Because the three-ply 5- by 5-ft shelter did not pass the impact test, a four-ply shelter (three-ply roof) of the same interior dimensions was constructed and tested. Results are tabulated in Appendix D.

Figure 15—Impact locations on wall panel of four-ply 8- by 8-ft shelter.

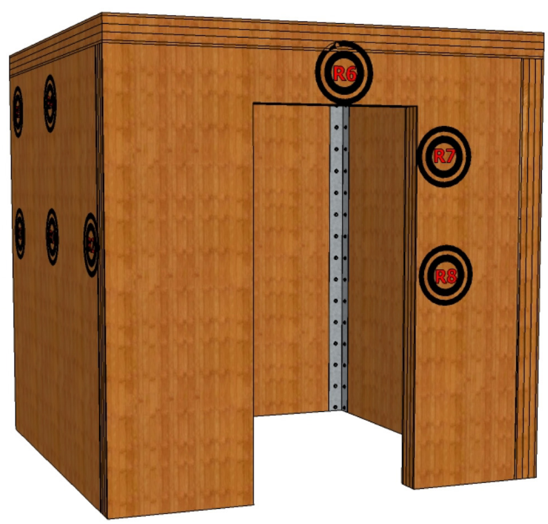

Figure 16—Impact locations on 8- by 8-ft shelter around door. (Door not shown for clarity.)

Figure 17—Impact locations on 5- by 5-ft shelter on wall panel.

Figure 18—Impact locations on 5- by 5-ft shelter around door. (Door not shown for clarity.)

Wall panel—Impact tests S1 to S6 were performed in sequence on the same shelter wall. As indicated in Figure 17 and Appendix D, impact test S1 was intended to evaluate the resistance of the wall panel by targeting the geometric center of the panel. Tests S2 and S3 were aimed to concentrate forces at the wall–wall interface at the mid-height of the wall panel. Impact tests S4 to S6 were aimed to evaluate the wall–wall–roof and wall–roof interface. In all cases, the four-ply wall resisted the impact with little or no damage and passed the test.

Door panel—Impact tests S7 to S9 were performed on the wall panel containing the door opening. These tests were directed near the door edge and indicated if the perimeter of the opening could withstand the applied impact forces. As indicated in Figure 18 and Appendix D, three tests were performed. In test S7, the missile was directed adjacent to the door between the door top and the roof panel. Tests S8 and S9 were directed between the upper and lower door hinges, respectively. In all tests, the door panel resisted the impact with no significant damage nor debris and passed the test.

Four-Ply Door

Although the three-ply door passed the impact test, the fact that the three-ply panel and three-ply 5- by 5-ft shelter failed prompted testing of a four-ply door. As indicated in Appendix E, three tests were performed (DD1 to DD3). The four-ply door withstood the impact with no debris, excessive deflection, nor damage to the door interior and passed the test.

Wind Pressure Tests

In addition to resisting the impact loads generated by windblown debris, a tornado shelter must be able to withstand the high wind forces from tornados. ASCE/SEI 7-10 (ASCE 2013) is used to calculate wind pressure loads.

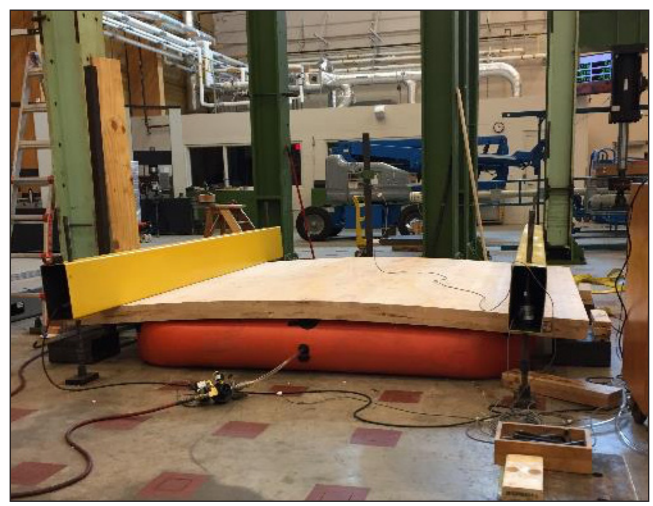

Figure 19—Three-ply panel at 1.8× design load.

Panel Tests

Prior to constructing the shelters, wind pressure testing of a three-ply CLT panel was performed. As indicated by Falk and Shrestha (2016), the calculated wind pressure on an 8- by 8-ft shelter is 167 lb/ft^2 (250-mph wind). An airbag (described earlier) was sandwiched between the panel and the strong floor to simulate a uniformly applied wind load (Fig. 17). The panel was loaded to 1.8× design, or 300 lb/ft^2. Though the panel deflected over 3 in., there was no damage, distress, or permanent deflection (Fig 19). No wind pressure tests were performed on a four-ply panel because the three-ply panel adequately resisted the factored design loads.

Full-Size Shelter Tests

Lateral wind pressure tests and wind suction uplift tests were also performed on the constructed four-ply shelter to evaluate the ability of the various components of the shelter (wall, roof) to remain intact under wind pressure loads and to evaluate the ability of the shelter tie downs to adequately transfer wind pressure loads to the foundation. The full-size shelter was secured to the strong floor of the test laboratory through a series of steel beams adjacent to a reinforced concrete strong wall (Fig 9). As described earlier, an airbag was used to induce the simulated wind load (Fig. 10). The lateral wind load pressure derived from ASCE 7 was calculated to be 167 lb/ft^2 (Falk and Shrestha 2016).

Two tests were performed, the first with the shelter oriented such that the door was opposite the airbag and the second with the door 90° to the side in contact with airbag. Air pressure was incrementally increased in the airbag, and over approximately 2 min the load was increased to a maximum of 2.3× design, or 395 lb/ft^2. Using the same setup and taking the same deflection measurements as described by Falk et al. (2018), two upper corners of the shelter (opposite side from airbag) were fitted with deflection measuring gauges (Celesco PT101, 2 in. full-scale (Celesco Transducer Products, Inc., Chatsworth, California, USA)), and deflection was continuously measured throughout the loading sequence using MTS 793 software. For the first test, measured deflections for the upper two corners of the shelter are designated as S1 and S2. For the second test, the deflections of the upper corners are S3 and S4, respectively.

Figures 20 and 21 show deflection as a function of applied wind pressure for the two tests. Figure 21 shows the deflection of the shelter with the door opening opposite

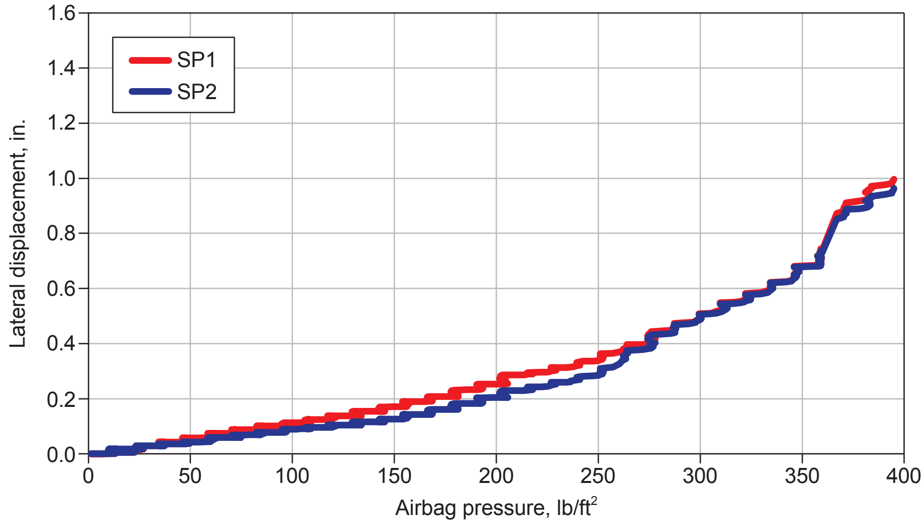

Figure 20—Test 1: displacement as a function of wind pressure.

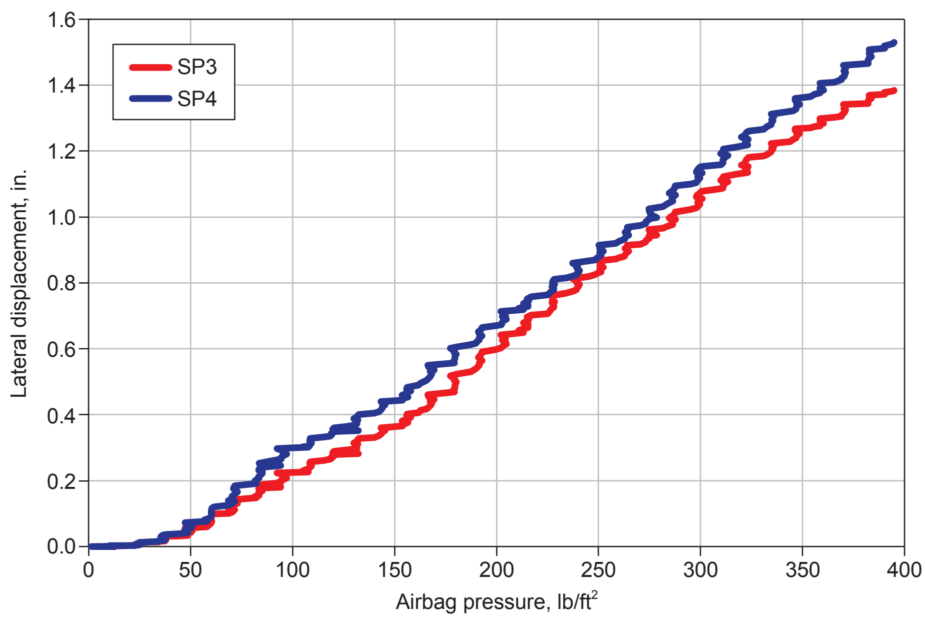

Figure 21—Test 2: displacement as a function of wind pressure.

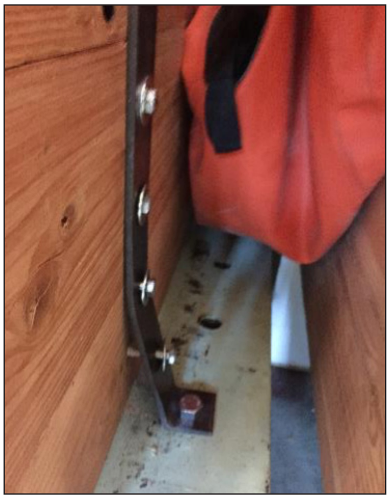

Figure 22—Pullout of lag bolt at 2.3× design wind load.

the airbag. Note that the shelter deflected symmetrically (deflection S1 is about equal to deflection S2) and reached a maximum of about 1.0 in. at 2.3× design. For test 2, deflection magnitude is greater than for Test 1 (1.5 in. at 2.3× design). Also, the deflections were slightly different, with the deflection of the door opening side greater than the side without the door (S4 > S3). This suggests that the door opening has an effect on overall stiffness of the shelter. This result is consistent with similar tests performed by Falk et al. (2018).

In both tests, the shelter walls and roof showed no damage or distress at 2.3× design. Some bending of the tie-downs and pullout of a lag bolt from the tie-downs on the load side did occur (Fig 22). The authors feel that this localized distress is not worrisome because significant capacity remained (four of five bolts still carrying load) at 2.3× the design load. Note that ICC/NSSA-500 does not specify lateral deflection limits for tornado shelters.

Roof Uplift

Two roof uplift tests were performed on the four-ply 8- by 8-ft shelter. During the first test, load was applied at a rate of about 240 lb/s such that the total uplift force reached 1.0× design load (14,300 lb) after one minute. The load was released at the same rate. Maximum deflection of the geometric center of the roof at 1.0× design load was 1.38 in. (Fig 23). Permanent deflection after the load was fully released was 0.54 in., a result of bending in the sheet metal angles connecting the roof to the walls of the shelter.

During the second test, uplift force was applied at the same rate up until the shelter reached 1.0× design load. The test was then manually paused for inspection for 10 s. After inspection, loading resumed at the same rate until the 1.2× design level was reached (17,200 lb). The test was manually paused again for a further 90 s of inspection before proceeding at the same load rate to 1.5× design load, 21,500 lb. The shelter was unloaded over the course of 60 s at a rate of 360 lb/s. Figure 24 is a plot of uplift force measured against roof displacement for the second test.

Including permanent deformation from the first test, the maximum deflection of the geometric center of the roof at 1.5× design load was 2.19 in. Permanent deformation after the second test totaled 1.22 in., also including the permanent deformation from the first test (Fig. 25). In spite of this deflection, the lag bolts continued to resist the applied loads and the roof remained attached to the wall panels. No deflection criteria are given in the ICC-500 standard and the authors feel that the deflection was not excessive.

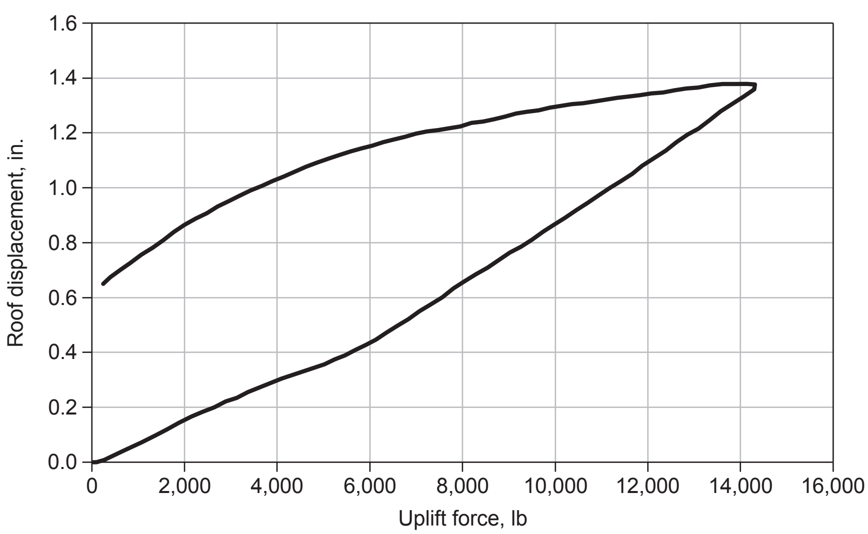

Figure 23—Plot of shelter displacement as a function of uplift force for 1× design load.

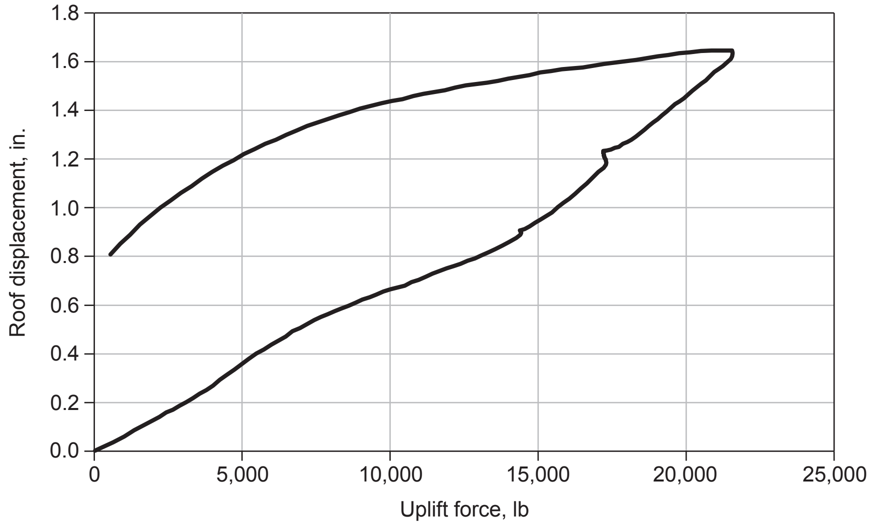

Figure 24—Plot of shelter displacement as a function of uplift force for 1.5× design load.

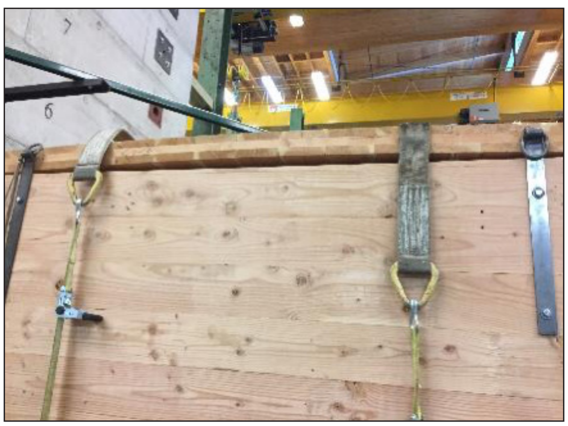

Figure 25—Deflection due to uplift loading on the shelter roof.

Conclusions

Tornado shelters constructed from CLT panels were successfully impact and wind pressure tested. Testing indicates that a CLT tornado shelter constructed of four-ply walls can safely withstand the most severe impact test included in the ICC/NSSA-500 standard. A three-ply roof withstood the lower speed impact requirement (67 mph). An overlaid four-ply door also safely resisted a 100 mph missile impact. Although some slight damage occurred, lateral load and uplift load testing indicated that the four-ply shelter can resist at least 1.5× the calculated wind pressure for a 250-mph wind derived from wind load design criteria (ASCE 2013).

All CLT panels tested in this study were pre-fabricated and full-size (that is, up to 8- by 8-ft with no joints or splices). Results from both the impact and wind pressure tests may be different for shelters constructed of panels that are not full-size and that contain splices or joints.

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Appendix A—Impact Test Results on a Three-Ply Panel

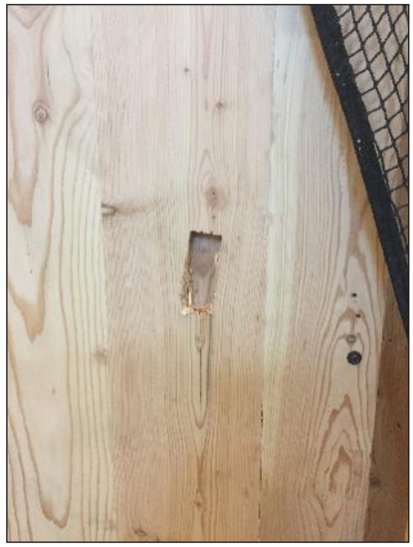
Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
P1	3-ply wall	106.7	1.9	1.6	N	Sliver of debris perforated witness screen	N	Impact at geometric center of panel

Left to right: Back side of panel, sliver of debris, hole in witness screen.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
P2	3-ply roof	85.9	1.0	<0.5	N	Slight cracking of back side of panel	Y	Impact at geometric center of roof panel; target speed 67 mph

Left to right: Impact at front of roof panel, slight cracking at back of panel.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
P3	3-ply roof	78.0	1.0	0.5	N	Slight cracking of back side of panel	Y	Impact 6 in. from edge of roof panel; target speed 67 mph



Impact at front of roof panel.

Appendix B—Impact Test Results on a Three-Ply CLT Door

Test no.	Door panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
D1	3-ply	103.4	2.0	<0.5	N	None to back side of door	Y	Shot to upper door latch; latch operable after impact

Front of door penetration.

Test no.	Door panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
D2	3-ply	104.4	0.8	<0.5	N	None to back side of door	Y	Shot to hinge; door operable after impact

Front of door penetration.

Test no.	Door panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
D3	3-ply	103.2	1.6	<0.5	N	Slight cracking of wood behind impact	Y	Shot to geometric center of door halfway between door latches; door operable after impact

Left to right: Front of door penetration, slight cracking of back of door.

Appendix C—Impact Test Results on a Four-Ply CLT Shelter (8 ft by 8 ft)

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R1	4-ply	110.2	1.8	<0.5	N	NA	Y	Impact at geometric center of panel

Left to right: Front of panel penetration, close-up of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R2	4-ply	107.8	1.5	<0.5	N	NA	Y	Impact at wall–wall connection (weak side)

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R3	4-ply	102.5	2.5	<0.5	N	NA	Y	Impact at wall–wall connection (strong side)

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R4	4-ply	105.1	1.5	<0.5	N	NA	Y	Impact at roof–wall intersection at top center of shelter

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R5	4-ply	102.0	1.5	<0.5	N	NA	Y	Impact at roof–wall intersection at top left of shelter

Photo not available

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R6	4-ply	114.0	0.8	<0.5	N	NA	Y	Impact at center of wall panel above door

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R7	4-ply	106.4	1.4	<0.5	N	NA	Y	Impact on panel at door edge between upper hinges

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
R8	4-ply	102.2	0.5	<0.5	N	NA	Y	Impact on panel at door edge between door latches

Front of panel penetration.

Appendix D—Impact Test Results on a Four-Ply CLT Shelter (5 ft by 5 ft)

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S1	4-ply	103.9	1.5	<0.5	N	NA	Y	Impact to center of wall panel

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S2	4-ply	101.6	1.0	<0.5	N	NA	Y	Impact at strong side of wall–wall connection

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S3	4-ply	101.1	1.1	<0.5	N	NA	Y	Impact at weak side of wall–wall connection; slight bending of sheet metal angle

Left to right: Front of panel penetration, slight bending of steel angle.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S4	4-ply	103.4	1.5	<0.5	N	NA	Y	Impact at strong side wall–roof intersection at top of wall

Right impact in photo.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S5	4-ply	103.3	1.5	<0.5	N	NA	Y	Impact at wall–roof panel intersection at center of wall panel

Middle impact in photo.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S6	4-ply	103.2	1.5	<0.5	N	NA	Y	Impact at weak side of wall–roof intersection at top of shelter

Left impact in photo.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S7	4-ply	99.7	0.8	<0.5	N	NA	Y	Impact at weak side wall panel next to door opening; speed was slightly below 100 mph, but test was deemed acceptable

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S8	4-ply	103.4	1.5	<0.5	N	NA	Y	Impact at strong side wall panel next to door opening near top hinge

Front of panel penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
S9	4-ply	102.4	1.3	<0.5	N	NA	Y	Impact at weak side wall panel next to door opening opposite middle hinge

Lower impact next to door in photo.

Appendix E—Impact Test Results on a Four-Ply CLT Door

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
DD1	4-ply	102.7	1.5	<0.5	N	NA	Y	Impact at upper center of door

Front of door penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
DD2	4-ply	Not recorded	1.3	<0.5	N	NA	Y	Impact near upper hinge


Front of door penetration.

Test no.	Panel construction	Missile speed (mph)	Front penetration (in.)	Permanent deflection (in.)	Panel/door perforated (Y/N)	Observed damage	Passed test (Y/N)	Additional notes
DD3	4-ply	102.5	1.5	<0.5	N	NA	Y	Impact at geometric center of door

Front of door penetration.