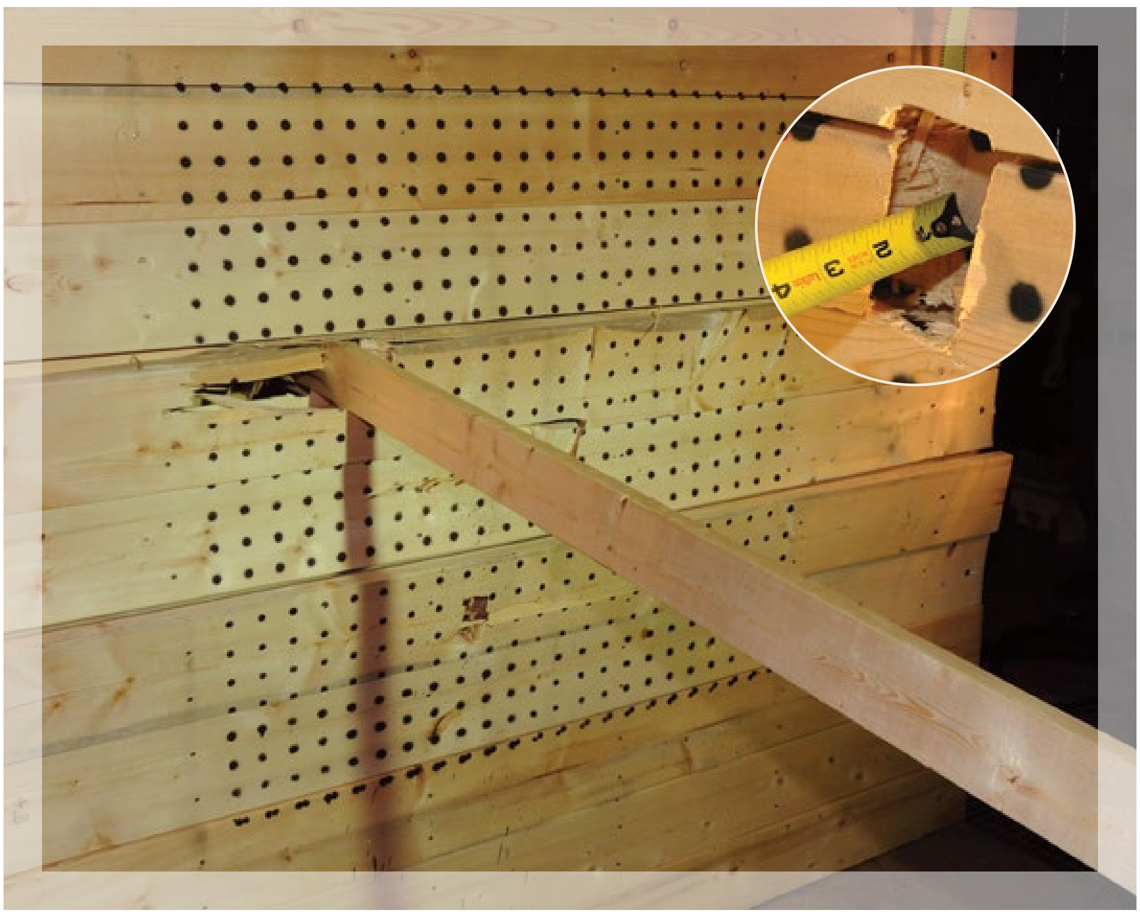
United States Department of Agriculture

Residential Tornado Safe Rooms from Commodity Wood Products

Wall Development and Impact Testing

Robert H. Falk
James J. Bridwell
John C. Hermanson



Forest Service | Forest Products Laboratory | Research Paper FPL–RP–681 | October 2015

Abstract

In the United States, tornadoes cause significant damage and result in many injuries and deaths. Although the development and use of tornado safe rooms and shelters have helped reduce the human toll associated with these events, the cost of these structures is often too high for many that could benefit from their use. The development of a residential tornado safe room constructed from commodity wood building products, buildable by a local contractor or do-it-yourselfer, and adaptable to existing homes could lower the cost of these structures and result in more widespread use. In this study, impact tests were performed on a series of 8-ft by 8-ft wood wall sections according to the standard test criteria of ICC-500. Results indicate that a nailed and glued wall section constructed of three layers of 2 × 8 lumber and sheathed with 23/32-in. CDX plywood can consistently pass the impact test. Included in the test results are the effects of wall construction, sheathing and lumber type, and added adhesive on impact performance.

Keywords: tornado, tornado shelter, wood, impact testing, walls

Contents

Conversion table

English unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
miles per hour (mph)	1.609	kilometers per hour (kph)
pound (lb)	0.4535	kilogram (kg)
pounds force (lbf)	4.448	newton (N)

October 2015

Falk, Robert H.; Bridwell, James J.; Hermanson, John C. 2015. Residential tornado safe rooms from commodity wood products: wall development and impact testing. Research Paper FPL-RP-681. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 15 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Residential Tornado Safe Rooms from Commodity Wood Products

Wall Development and Impact Testing

Robert H. Falk, Research General Engineer
James J. Bridwell, General Engineer
John C. Hermanson, Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

Introduction

A significant portion of the United States is susceptible to the dangerous winds of tornadoes (Fig. 1). Every year, these events cause injury, death, and billions of dollars of property damage (FEMA 2014). Improved weather forecasting, increased lead-in times for tornado warning, and the development of reinforced safe rooms has helped reduce the human toll from these events.

The principal aspect of a tornado safe room is that it must be able to withstand the loads generated by the high winds of a tornado (FEMA 2015). Tornado severity is categorized by the Enhanced Fujita Scale (EF Scale) and an EF-5 tornado is considered the most severe (wind speed greater than 200 mph).

In addition to high wind loading, the tornado safe room must also withstand the impact of the windblown debris (identified as missiles) associated with these events (NIST/TTU 2006). According to the ICC-500 (International Code Council Standard for the Design and Construction of Storm Shelters), large missile impact testing is an accepted way of assessing the performance of assemblies and materials used in safe room design (ICC/NSSA 2014). In these tests, the safe room is subjected to the impact of a 2 × 4 lumber stud weighing from 9 to 15 lb traveling at a speed of 34 to 100 mph. The range of standard tests is given in Table 1. The tornado test (highlighted yellow) imparts the most energy and thus can be considered the most severe.

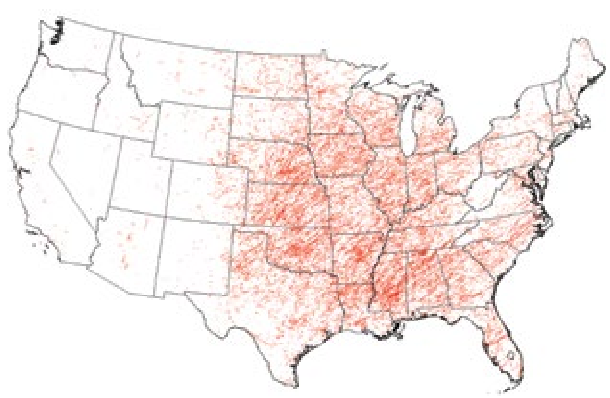


Figure 1—Tornado activity in the United States from 1950–2013 (Source: Storm Prediction Center 2014).

Table 1—Missile testing criteria (NIST/TTU 2006)

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

According to the ICC-500, paneled or framed walls are to be impacted in the center of the roof or wall section, at interface joints, or other locations of weakness. A successful impact test requires the wall meets three basic criteria. The performance criteria for impact testing places limits on the permanent wall deflection (3-in. max), the creation of significant debris, and any penetration of the missile into the room.

Objectives and Scope

The primary objectives in developing a safe room from commodity wood products were to use materials that are commonly available at local building material outlets, buildable by an advanced do-it-yourselfer (DIYer) or local contractor, and easily retrofitted into an existing home. Because commodity lumber is commonly sold in 8-ft lengths and wood sheathing materials are 4-ft by 8-ft, the walls tested were designed to represent walls from a safe room 8-ft by 8-ft in plan with a height of up to 8 ft. This size makes this space suitable for other uses (e.g., bathroom, sauna) during non-event periods and still accessible and useable when a wind event occurs.

The walls evaluated in this study were designed such that the components can be built on-site for new or existing construction, making it feasible to construct all or part of the safe room in a basement or other suitable area over a properly designed concrete slab.

Two basic wall designs were investigated in this study. The following provides an overview of the two basic designs. The Appendix provides more specific details.

Stacked 2 × 4 Wall

The first wall type investigated was constructed by stacking and nailing 2 × 4s (stud grade, SPF species) into a solid slab of wood. This slab was then covered with oriented strandboard (OSB) sheathing on the exterior faces (Fig. 2). To fasten each 2 × 4 layer, 16d smooth shank round head nails, 3 in. long, were nailed vertically using a pneumatic framing nailer in the nailing pattern shown in Figure 3. The sheathing was nailed to the stacked 2 × 4s as shown in Figure 4 using 16d, 2-3/8-in.-long nails. These were also driven with a framing nailer.

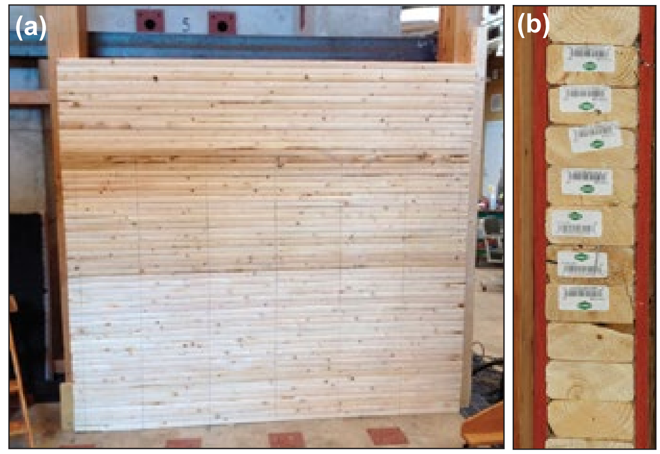


Figure 2—Stacked 2 × 4 wall design. (a) Stacked and nailed 2 × 4s prior to attachment of wood sheathing. (b) Side view of wall before testing.

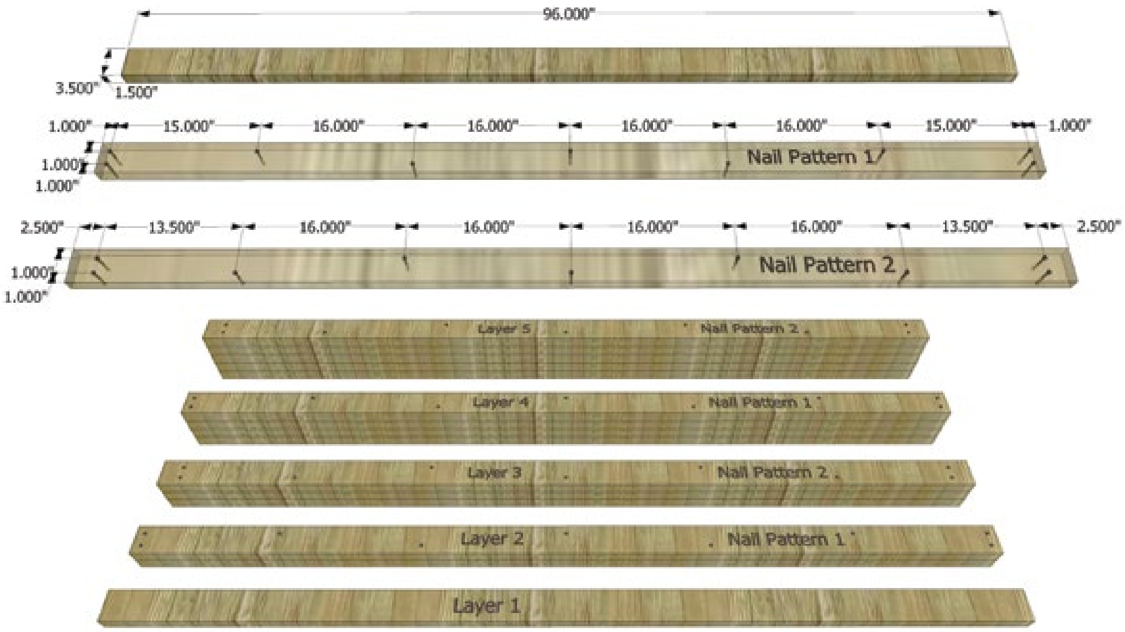


Figure 3—Repetitive nailing pattern for stacked 2 × 4 wall.

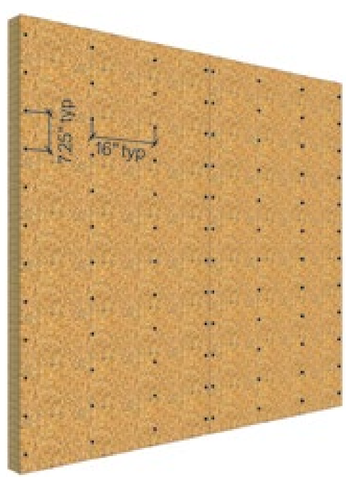


Figure 4—Sheathing nailing pattern for stacked 2 × 4 walls.

Nail Laminated 2 × 8 Wall

The second wall type evaluated was a wall constructed of nail laminated 2 × 8s (Fig. 5). Three 2 × 8s (No. 2 grade, SPF species) were nailed together (16d smooth shank nails, round head, 3 in. long) to form a beam with a tongue and groove configuration (Fig. 6a). The beams are then stacked and interlocked to create a wall (Fig. 6b). For most wall configurations, OSB or plywood sheathing was then nailed (or nailed and glued) to one or both faces of the wall (Fig 7). To nail the sheathing, 16d smooth shank nails, round head, 2-3/8 in. long, were used.

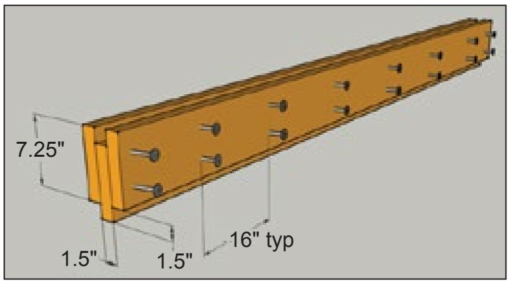


Figure 5—Nail laminated 2 × 8 wall beam.

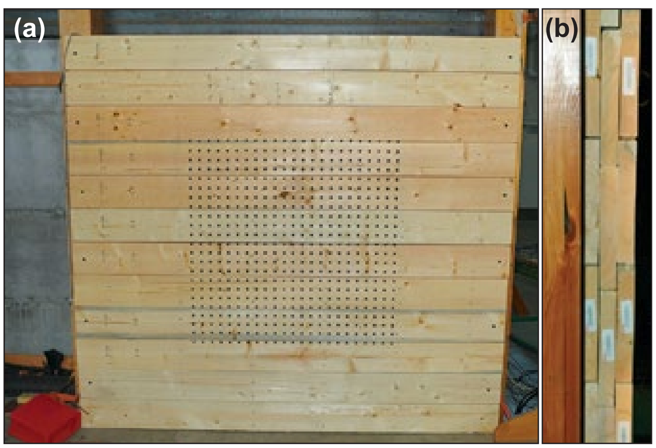


Figure 6—Nail laminated 2 × 8 wall design. (a) 2 × 8 wall prior to attachment of wood sheathing. (b) Side view of wall before application of sheathing.

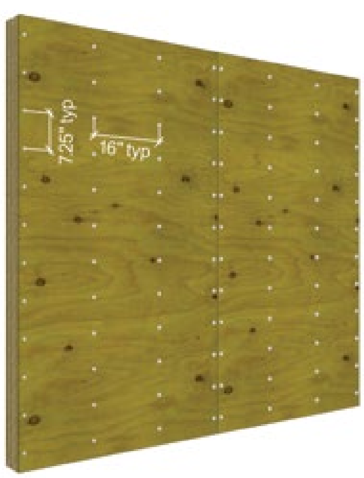


Figure 7—Sheathing nailing pattern for nail laminated 2 × 8 wall design.

Variables Evaluated

This study was intended to be an initial evaluation of the impact resistance and constructability of a wood safe room wall option and not a rigorous statistical evaluation of a wide set of variables or performance evaluation of a completed safe room design. That said, in addition to the two types of wall designs investigated, several variables, including sheathing type, sheathing placement, and use of adhesive, were investigated. Two types of sheathing were used: 1/2-in. OSB and 23/32-in. flooring grade plywood (CDX grade). Depending on the wall, sheathing was (1) not used, (2) nailed to the back side of the wall, or (3) nailed to both sides of the wall. A series of tests was also performed on the nail laminated 2 × 8 wall design investigating the effect of using a commonly available construction adhesive, Liquid Nails (PPG Architectural Coatings, Cranberry Township, Pennsylvania). The adhesive was placed (1) between the plywood and the 2 × 8s (Fig. 8), and/or (2) between the 2 × 8 beams (Fig. 9), and/or (3) between the 2 × 8 layers of the beams (Fig. 10). Table 2 summarizes the variables investigated.

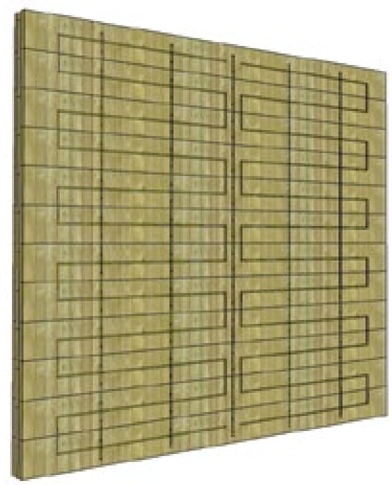


Figure 8—Adhesive placement between plywood and 2 × 8s in nail laminated wall.

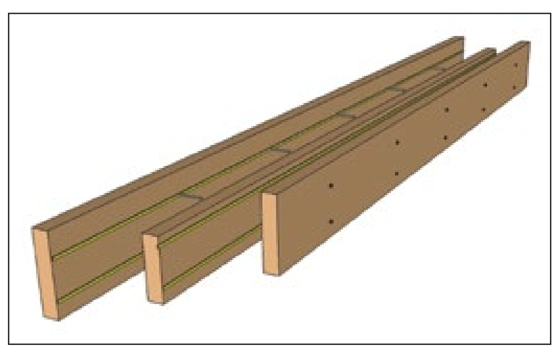


Figure 9—Adhesive placement between 2 × 8s in nail laminated wall.

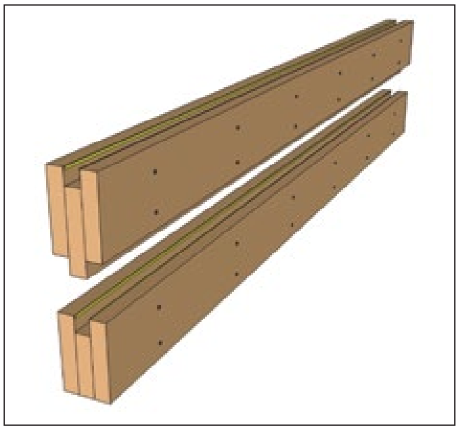


Figure 10—Adhesive placement between 2 × 8 beams in nail laminated wall.

Figure 11—Test cannon and 2 × 4 missiles.

Test Setup and Data Collection

The impact tests were performed at the Forest Products Laboratory using a missile cannon (Fig. 11) built by Spudtech, LLC (New London, Minnesota). The cannon used compressed air to propel the missile, and the pressure of the compressed air could be adjusted to control the speed of the missile. Missile speed was measured using a photoelectric timing device.

Each missile was a surface dry (moisture content between 16% and 19%) southern pine stud, selected such that no knots appeared within 12 in. of the leading edge. The trailing edge of each missile was affixed with a plastic sabot to facilitate launching.

The ends of the walls were supported by heavy wooden beams, which were themselves attached to a steel framework bolted to a massive concrete strong wall. Each wall was tested over a 7-ft 3-in. clear span, which represented the actual span of the wall in an 8-ft by 8-ft safe room.

Sensotec Model 41 load cells (10,000-lb capacity) (Sensotec, Jabbeke, Belgium) installed between each wooden support beam and the steel framework measured

Table 2—Variables investigated

Wall ID	Wall construction	Sheathing type	Sheathing placement	Adhesive[b] placement
1	2 × 4 stacked	1/2-in. OSB	Both sides	None
2	2 × 8 beams	None	None	None
3	2 × 8 beams	1/2-in. OSB	Back side only[a]	None
4	2 × 8 beams	1/2-in. OSB	Back side only[a]	None
5	2 × 8 beams	23/32-in. subfloor grade plywood	Both sides	None
6	2 × 8 beams	23/32-in. subfloor grade plywood	Both sides	Only on plywood
7	2 × 8 beams	23/32-in. subfloor grade plywood	Both sides	Between 2 × 8s and on plywood
8	2 × 8 beams	23/32-in. subfloor grade plywood	Both sides	Between 2 × 8s on plywood and between beams

[a]Back side indicates wall face away from missile impact.
[b]Liquid Nails Heavy Duty Construction Adhesive, LN-901/LNP-901 (www.liquidnails.com).

Figure 12—One of four load cells used to monitor force of impact.

Figure 13—Two of four displacement transducers used to monitor wall displacement.

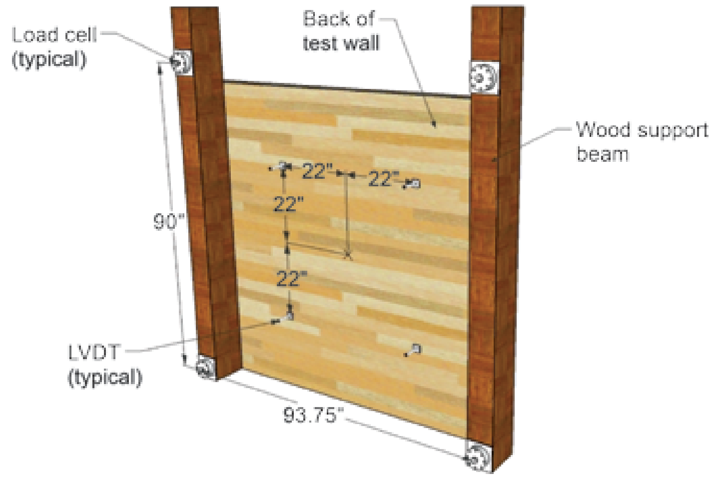


Figure 14—Location of load cells and displacement transducers (LVDTs).

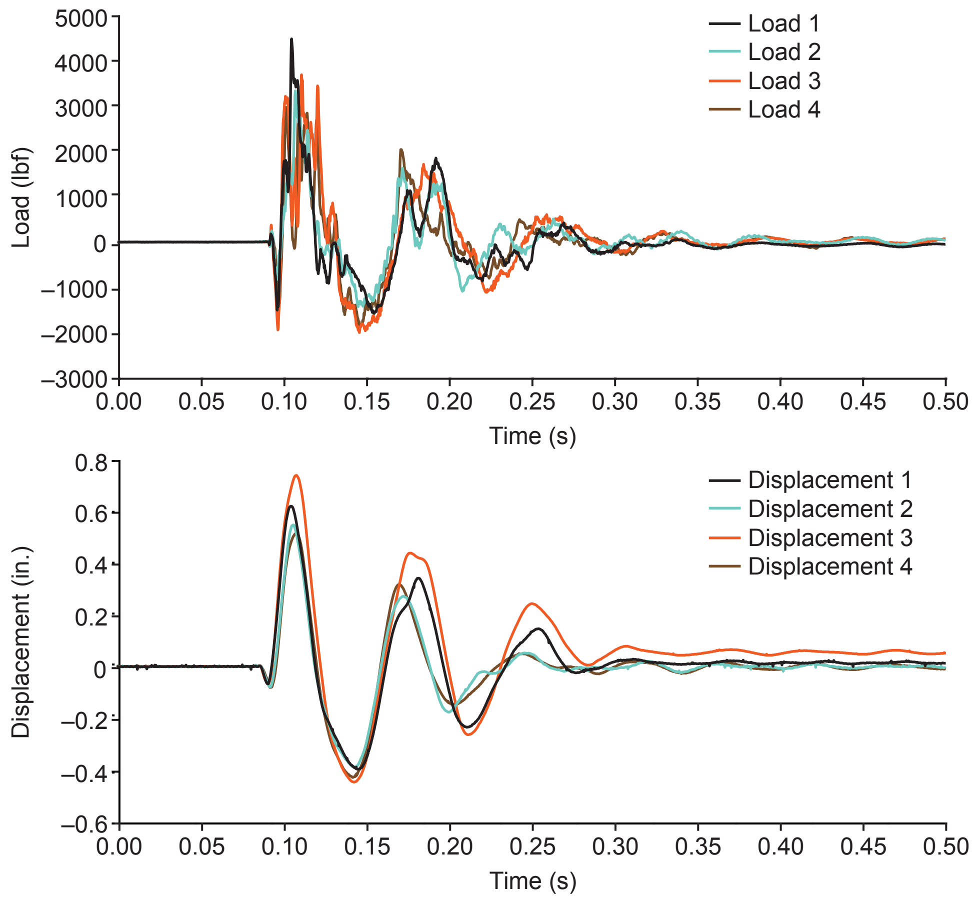


Figure 15—Load (top) and displacement (bottom) data from typical impact test.

the impact force transmitted to each corner of the impacted wall (Fig. 12). Four TRANS-TEK Model 0244, ±1.00 in. displacement transducers (TRANS-TEK, Inc., Ellington, Connecticut) were also connected to the back side of each wall to record the deflection of the wall during impact (Fig. 13). Location of these devices is shown in Figure 14.

Data from the load and displacement devices were captured using National Instrument NI-9205 and NI-9401 input modules (National Instruments Corporation, Austin, Texas) connected to an NI cDAQ-9172 chassis. LabVIEW software (National Instruments Corporation) was used to collect these data at 7,000 Hz, with recording triggered as the missile passed by the timing system in the barrel. Dynamic load versus time and displacement versus time plots from an impact test are shown in Figure 15. These data are being collected for use in ongoing studies to create design models for wood walls subject to impact.

Figure 16—High-speed camera setup.

Two high-speed Vision Research V710 cameras (Vision Research, Wayne, New Jersey) were used to capture the dynamic out-of-plane displacement response of the wall for each test. Using Phantom Camera Control software (Vision Research), the cameras were triggered to start coincidently with the LabVIEW data collection and recorded the movement of a 23 × 23 array of 0.5-in.-diameter black dots painted 2 in. on center (Figs. 6a and 16). These high-speed videos were recorded at a resolution of 800 × 800 and speed of 7,000 frames per second. The out-of-plane displacement of the walls was determined using the mesh-free random grid method (Iliopoulos et al. 2012).

In addition to notes about wall construction, observational data were also collected after each test and included the missile speed, type, and extent of damage, maximum permanent wall deflection, and amount and size of debris generated. These data are provided in the Appendix for all wall tests. Walls were tested more than once if they did not fail the test after the first impact. For all wall tests, the first shot was aimed at the geometric center of the wall. For most walls, subsequent shots were aimed 12 in. away from the first shot (either left, right, above, or below). Shot location information is given in the Appendix.

Results

The Appendix provides details of all test results; Table 3 provides a general summary.

As indicated in the photographs of the Appendix, Wall 1 showed little resistance to the impact and the 2 × 4 easily pierced the wall in all three tests. Wall 2 failed the test because the permanent wall deformation was 3 in., the maximum allowed by the test standard. No significant debris was generated.

The first impact test of Wall 3 (Wall Test 3a) resulted in a permanent deflection of 0.5 in. and no significant debris; however, a second shot on the same wall (Wall Test 3b) resulted in the 2 × 4 piercing the wall and a large permanent deflection. Unlike Wall 3, Wall 4 failed on the first shot (8.9 in. of deflection) because of a failure of the sheathing.

The first shot on Wall 5 (Wall Test 5a) resulted in 1.5 in. of permanent deflection and no debris was generated. A second shot (Wall Test 5b) also resulted in 1.5 in. of deflection; however, two small pieces of plywood veneer were dislodged and the test deemed a failure.

As indicated in the Appendix, Wall 6 was impacted four times and the first three impacts resulted in permanent wall deformation less than 2 in. and only slight cracking of the plywood. The fourth shot resulted in failure because the permanent deflection was 3.1 in., slightly greater than allowed. No debris was generated in this series of tests.

Wall 7 was constructed the same as Wall 5; however, construction adhesive was added between the 2 × 8s making up the wall beams as well as between the plywood sheathing and the 2 × 8 beams (see Figs. 10, 11). This wall was shot four times, and the first three impacts resulted in permanent wall deformation less than 1.5 in. and only slight cracking of the plywood. The fourth shot resulted in failure with a permanent deflection of 3.9 in. No debris was generated in this series of tests.

The final series of impact tests were performed on Wall 8. Also constructed the same as Wall 5, this wall included construction adhesive between the 2 × 8s making up the wall beams, between the 2 × 8 wall beams, and between the plywood sheathing and the 2 × 8 beams (see Figs. 9–11). This wall was shot six times. The first four impacts resulted in permanent wall deformation less than 2 in. and only slight cracking of the back side plywood face. The fifth shot resulted in a permanent deflection of 2.6 in. and the sixth shot resulted in failure with a permanent deflection of 5.9 in. No debris was generated in this series of tests, although the last test resulted in the separation of the plywood from the 2 × 8s in the area of impact.

Discussion

Resisting dynamic loads, such as wind, earthquake, or impact, can be achieved by either building a structure so stiff and massive that the loads have little effect on the structure or by building a structure that can dampen and dissipate the applied loads. Wood and wood construction are lower in mass compared with other building materials, such as steel or concrete, but have good damping characteristics and can dissipate load through deformation of and slippage between wood components, crushing of the wood, and deformation of fasteners. These characteristics were used in the design of the wood walls evaluated here.

Table 3—Summary of test results

Wall ID	Wall construction	Sheathing type	Sheathing placement	Adhesive placement	Passed test (Y/N)	Reason for failure
1	2 × 4 stacked	OSB	Both sides	None	N	Wall pierced by missile
2	2 × 8 beams	None	None	None	N	Deformation
3	2 × 8 beams	OSB	Back side only[a]	None	Y	
4	2 × 8 beams	OSB	Back side only[a]	None	N	Deformation
5	2 × 8 beams	Ply	Both sides	None	Y	
6	2 × 8 beams	Ply	Both sides	Only on plywood	Y[a]	
7	2 × 8 beams	Ply	Both sides	Between 2 × 8s and on plywood	Y[b]	
8	2 × 8 beams	Ply	Both sides	Between 2 × 8s, on plywood, and between beams	Y[c]	

[a]Wall 6 withstood three impacts before failing.
[b]Wall 7 withstood three impacts before failing.
[c]Wall 8 withstood five impacts before failing.

The dissipative characteristics described above are evident if one compares the missile impact performance of the stacked 2 × 4 wall design with the nail laminated 2 × 8 wall design. The stacked 2 × 4 design did not result in effective transfer of the impact energy from one 2 × 4 to the next, nor into and across the sheathing. The relatively high stiffness of this wall combined with the lack of energy transfer resulted in the punch-through of the missile witnessed in the tests. In contrast, the nail-laminated 2 × 8 wall design was much more effective in dampening and transferring the energy of impact. The layering of the 2 × 8s with the face of the lumber perpendicular to the impact load tended to flex, dissipating energy through bending and through the yielding of the nails and adhesive.

The performance criteria for impact testing places limits on permanent wall deflection, creation of debris, and penetration of the missile into the room. While permanent deflection can often be minimized by increasing the thickness of the wall cross section, the wall may still fail because of the generation of wood debris. These and previous unpublished testing (Murphy 2013, personal communication) indicate that the addition of sheathing material, especially on the inside of the wall (or room), is effective in reducing the amount of debris generated. As indicated in the test results of the Appendix, plywood is an effective sheathing material for impact resistance. The OSB was less effective and tends to fail more locally as compared with plywood, likely because of the small flake size used in its manufacture (relative to the size of the panel).

The results also indicate that the addition of construction adhesive is effective in stiffening and tying together the components of the wall as well as reducing the amount of debris. This is indicated in the performance of Walls 6–8.

Future Testing

Research is ongoing to evaluate the lateral wind load and impact performance of an 8-ft by 8-ft safe room constructed with the nail laminated beam design discussed above. Construction methods and cost estimates for construction are also being evaluated and will be published in a subsequent report.

Conclusions

Several conclusions can be reached regarding the impact tests performed in this study:

- The nail laminated 2 × 8 wall design presented in this study can effectively resist the standardized impact loads required for residential tornado safe rooms.
- The stacked 2 × 4 wall design presented in this study cannot effectively resist the standardized impact loads and is not recommended for use in safe rooms.
- Though not evaluated here, the use of a 2 × 6, 2 × 8, or 2 × 10 stacked wall configuration may better resist impact loads.
- The use of construction adhesive is effective in enhancing the impact performance of the nail laminated 2 × 8 wall design presented here.

Acknowledgments

The authors acknowledge the generous support of the Engineering Mechanics and Remote Sensing Laboratory at the Forest Products Laboratory. The technical support of Dave Simpson, Marc Joyal, and Sara Fishwild in testing and data collection was invaluable. Thanks also to Dr. Joseph Murphy (retired FPL scientist) whose previous impact cannon development work and safe room research paved the way for this study.

References

FEMA. 2014. Taking shelter from the storm: building a safe room for your home or small business. FEMA P-320, fourth edition.

FEMA. 2015. Safe rooms for tornadoes and hurricanes: guidance for community and residential safe rooms. FEMA P-361. Available at http://www.fema.gov/media-library/assets/documents/3140.

Iliopoulos, A.P.; Michopoulos, J.G.; Andrianopoulos, N.P. 2012. Performance analysis of the mesh-free random grid method for full-field synthetic strain measurements. Strain. 48(1): 1–15. doi: 10.1111/j.1475-1305.2010.00786.x

ICC/NSSA. 2014. ICC/NSSA Standard for the Design and Construction of Storm Shelters (ICC 500). Available at http://shop.iccsafe.org/standards/icc-standards. Lubbock, Texas: International Code Council/National Storm Shelter Association.

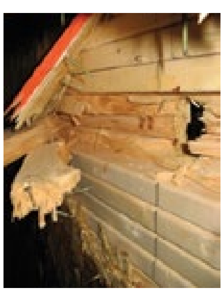
Murphy, J. 2013. Joseph Murphy, Retired FPL Research Scientist. October 2013, personal communication.

NIST/TTU. 2006. Debris impact resistance of building assemblies. A compilation of testing performed by the Wind Science and Engineering Research Center Texas Tech University and Florida A&M University, Florida State University, and University of Florida. Summary report submitted to National Institute of Science and technology (N.I.S.T.). August 2006.

Storm Prediction Center. 2014. NOAA National Weather Service. http://www.spc.noaa.gov/gis/svrgis/

Appendix—Wall Test Results

Note: All missiles targeted the geometric center of the wall panel unless otherwise noted.

<table>
<tr><th>Wall ID</th><th>Wall construction</th><th>Missile speed (mph)</th><th>Front penetration (in.)</th><th>Permanent wall deflection (in.)</th><th>Wall perforated (Y/N)</th><th>Observed damage</th><th>Passed test? (Y/N)</th><th>Additional notes</th></tr>
<tr><td>1a</td><td>Stacked 2 × 4s. Nailed 16 in. on center (oc). Sheathing both sides with 1/2-in. OSB.</td><td>97.8</td><td>–</td><td>–</td><td>Y</td><td>Missile completely pierced wall. Significant debris.</td><td>N</td><td>First shot on Wall 1. Impact 0 in. right, 3 in. below center.</td></tr>
<tr><td></td><td colspan="8">
Left to right: Wall before test, wall construction, impact damage to front of wall, impact damage to back of wall.</td></tr>
<tr><td>1b</td><td>Stacked 2 × 4s. Nailed 16 in. oc. Sheathed both sides with 1/2 in. OSB.</td><td>102.2</td><td>–</td><td>–</td><td>Y</td><td>Missile completely pierced wall. Significant debris.</td><td>N</td><td>Second shot on Wall 1. Impact 18 in. left, 10 in. above center.</td></tr>
<tr><td></td><td colspan="8">
Left to right: Impact damage to front of wall, impact damage to back of wall.</td></tr>
<tr><td>1c</td><td>Stacked 2 × 4s. Nailed 16-in. oc. Sheathed both sides with 1/2-in. OSB.</td><td>103.0</td><td>–</td><td>–</td><td>Y</td><td>Missile completely pierced wall. Significant debris.</td><td>N</td><td>Third shot on Wall 1. Impact 16 in. left, 13 in. below center.</td></tr>
<tr><td></td><td colspan="8">
Impact damage to back of wall.</td></tr>
</table>

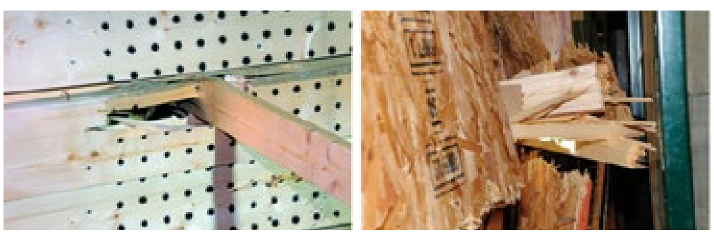
Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
2	Interlocking 3-ply sections of 2 × 8. No sheathing.	99.4	1.6	3.0	N	Wall displacement maximum allowable. No significant debris.	N	Impact at seam between 2 × 8 layers.

Left to right: Wall before test, impact damage to front of wall, impact damage to back of wall, side view of wall damage.

3a	Interlocking 3-ply sections of 2 × 8. 1/2-in. OSB sheathing nailed to back side.	97.0	1.5	0.5	N	Cracking of OSB on back side. No significant debris.	Y	Similar to Wall 2 with added 1/2-in. OSB. Impact 3 in. right, 0 in. below center.

Left to right: Wall before test, impact damage to front of wall, impact damage to back of wall.

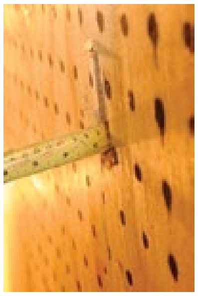
3b	Interlocking 3-ply sections of 2 × 8. 1/2-in. OSB sheathing nailed to back side.	100.5	2.8	4.1	Y	Missile pierced wall. Significant debris. Severe cracking of OSB.	N	Second shot on Wall 3. Impact 1 in. left, 0 in. below center.

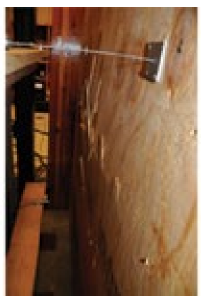
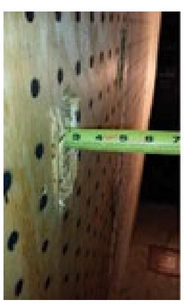


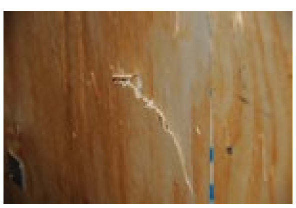
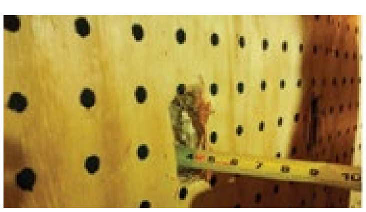
Left to right: Impact damage to front of wall, impact damage to back of wall.

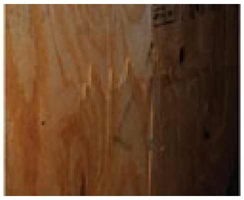
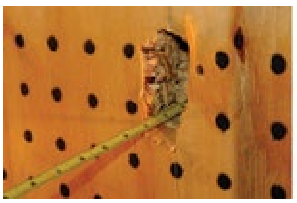
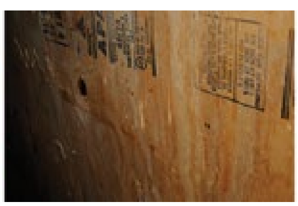
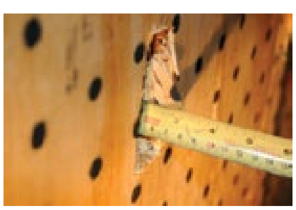
4	Interlocking 3-ply sections of 2 × 8. 1/2-in. OSB sheathing nailed to back side.	97.0	1.8	8.9	N	8.9-in. defect is from a section of delaminated OSB. Lumber deflection is closer to 1.5 in.	N	Same as Wall 3.

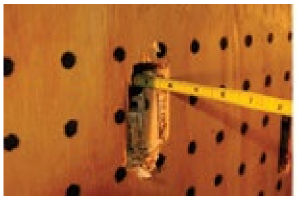
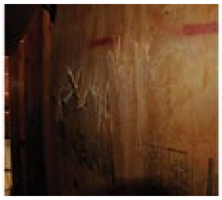
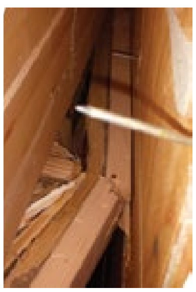
Left to right: Wall before test, impact damage to front of wall, impact damage to back of wall.

Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
5a	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. No adhesive.	101.7	2.0	0.5	N	Some permanent deformation and light cracking of plywood on back side of wall. No debris.	Y	First shot on Wall 5. Impact 0.5 in. right, 0 in. below center.
	 Impact damage to front of wall.							
5b	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. No adhesive.	102.6	2.5	1.5	N	Two pieces of plywood veneer, about 4 in. in length, dislodged from rear of panel.	N	Second shot on Wall 5. Impact 0.5 in. right, 12 in. above center.
	 Left to right: Wall before test, impact damage to back of wall.							
6a	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied to plywood only.	104.5	2.0	0.5	N	Some permanent deformation and light cracking of plywood on back side of wall. No debris.	Y	First shot on Wall 6. Impact 2 in. left, 1 in. above center.
	 Left to right: Wall before test, impact damage to front of wall, impact damage to back of wall.							

Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
6b	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied to plywood only.	103.5	2.1	1.8	N	Some permanent deformation and cracking of plywood on back side of wall. No debris.	Y	Second shot on Wall 6. Impact 0 in. right, 12 in. above center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
6c	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied to plywood only.	104.2	2.0	1.9	N	Some permanent deformation and more severe cracking of plywood on back side of wall. No debris.	Y	Third shot on Wall 6. Impact 1 in. right, 12 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
6d	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied to plywood only.	103.9	3.0	3.1	N	Excessive permanent deformation and splitting of plywood on back side of wall. No debris.	N	Fourth shot on Wall 6. Impact 13 in. left, 1 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							

Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
7a	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies and on the plywood.	102.0	2.4	1.4	N	Minor cracking of plywood.	Y	First shot on Wall 7. Impact 1 in. left, 0.5 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
7b	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies and on the plywood.	102.3	1.9	1.5	N	Minor cracking of plywood.	Y	Second shot on Wall 7. Impact 2 in. left, 12 in. above center.
	 Impact damage to front of wall.							
7c	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies and on the plywood.	101.2	2.3	1.5	N	Minor cracking of plywood.	Y	Third shot on Wall 7. Impact 1 in. right, 13 in. below center.
	 Impact damage to back of wall.							
7d	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies and on the plywood.	101.1	4.3	3.9	N	Excessive permanent deformation and splitting of plywood on back side of wall. No debris.	N	Fourth shot on Wall 7. Impact 13 in. left, 0 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							

Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
8a	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, 2 × 8 sections, and between plywood and 2 × 8 sections.	101.0	2.1	0.6	N	Minor cracking of plywood.	Y	First shot on Wall 8. Impact 1 in. right, 2 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
8b	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, 2 × 8 sections, and between plywood and 2 × 8 sections.	104.6	3.0	1.6	N	Minor cracking of plywood.	Y	Second shot on Wall 8. Impact 0 in. right, 11 in. above center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
8c	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, 2 × 8 sections, and between plywood and 2 × 8 sections.	103.1	2.0	1.8	N	Minor cracking of plywood.	Y	Third shot on Wall 8. Impact 1.5 in. left, 14 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
8d	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, between 2 × 8 sections, and on plywood.	103.1	2.5	1.9	N	Minor cracking of plywood.	Y	Fourth shot on Wall 8. Impact 13 in. left, 0 in. above center.
	 Impact damage to front of wall.							

Wall ID	Wall construction	Missile speed (mph)	Front penetration (in.)	Permanent wall deflection (in.)	Wall perforated (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
8e	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, between 2 × 8 sections, and on plywood.	104.5	3.5	2.6	N	Minor cracking of plywood.	Y	Fifth shot on Wall 8. Impact 13 in. left, 10 in. below center.
	  Left to right: Impact damage to front of wall, impact damage to back of wall.							
8f	Interlocking 3-ply sections of 2 × 8. 23/32-in. plywood sheathing both sides. Adhesive applied between 2 × 8 plies, between 2 × 8 sections, and on plywood.	104.3	5.3	5.9	N	Missile perforated the 2 × 8 plies, though not the plywood. Back side plywood was separated from the 2 × 8s in area of impact.	N	Sixth shot on Wall 8. Impact 12 in. left, 11 in. above center.
	 Impact damage to back of wall.							