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Development of a Tornado Safe Room Door from Wood Products

Door Design and Impact Testing

Robert H. Falk
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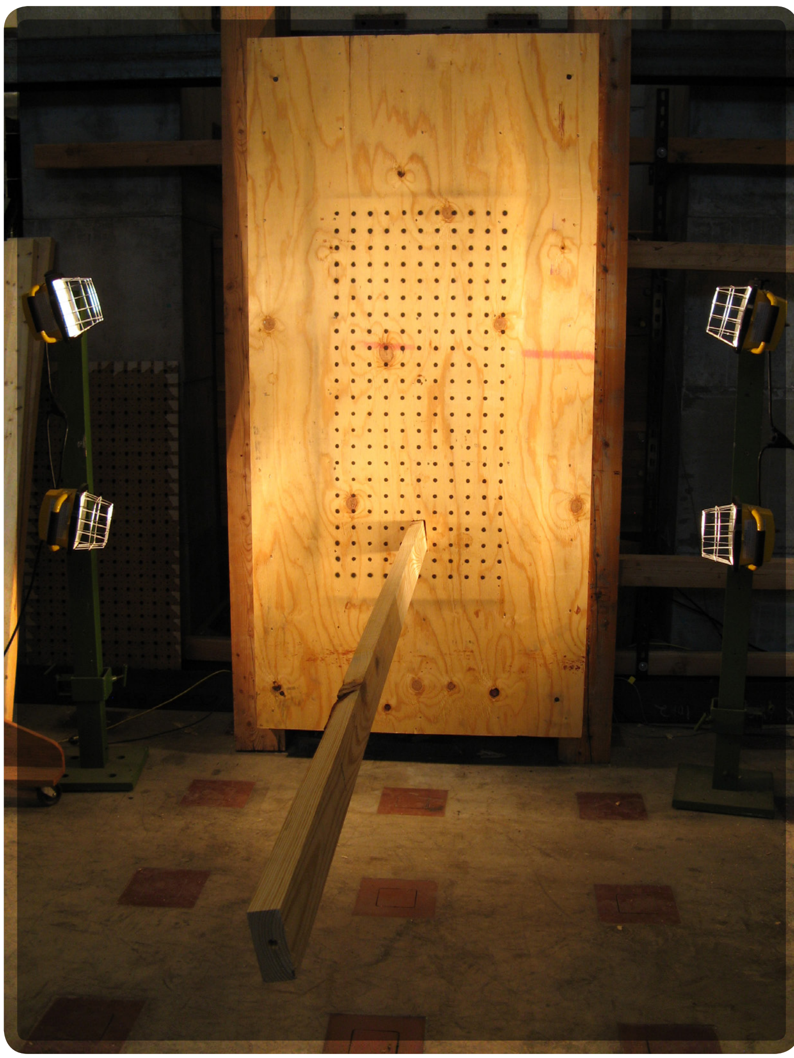

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Abstract

In this study, a tornado safe room door built from wood products and steel sheeting was developed and impact-tested according to tornado safe room standards. Results indicate that an door constructed from as few as two sheets of 23/32-in. (18.26-mm) construction-grade plywood and overlaid with 18-gauge (0.05-in.- (1.27-mm-) thick) steel can pass the required impact test.

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

Contents

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Door Design and Impact Testing

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Introduction

An important component of a tornado safe room is the entry door, and like the safe room itself, it must be designed and constructed to withstand the wind and impact forces produced by the tornado. Although many safe room doors exist in the marketplace, they are usually constructed solely of steel. This study was conducted to determine if a tornado safe room door could be produced from wood and other commodity building products. This study is an extension of research to develop a tornado safe room from commonly available wood building products (Falk and others 2015).

Materials and Methods

Standardized Testing of Safe Room Doors

Like the safe room itself, a safe room door must withstand the loads generated by both high winds from tornados and impact of windblown debris. Large missile impact testing is used to assess the performance of these assemblies and the materials used in safe room design (ICC/NSSA 2014). In these tests, the safe room door was subjected to the impact of a nominal 2- by 4-in. (standard 38- by 89-mm) lumber stud weighing 15 lb (6.8 kg) traveling at a speed of 100 mph (160 km/h). For a door to meet the requirements of the previously mentioned standard, impact testing is required at several locations (that is, within 6 in. (140 mm) of an interface hinge joint, an upper latch point, and center primary latches or operators). The door must also be tested for its ability to resist positive and negative pressure forces produced by the high winds of the tornado.

Door Design

Tornado safe room doors are typically constructed of steel and, much like conventional home entry doors, are inset in the door frame, hinged on one side, and fitted with a lockset on the other. This allows the door to be swung either inward or outward. An inset tornado storm door relies on the lockset and addition deadbolts to resist the forces generated by debris impact and the tornado wind loads (both pressure and suction).

Experts have not come to a clear consensus if a tornado door should swing inwards or outwards. The Federal Emergency Management Administration (FEMA) states: "*A common misconception about safe room doors is that they must swing in a particular direction – inward or outward. According to ICC-500, the pressure testing on a door must be conducted away from the door stop, meaning that the door is pressure-tested in the weakest condition regardless of being in-swinging or out-swinging. Additionally, a door must undergo the missile impact resistance testing in the configuration that will be used for installation. Beyond code requirements, both inward- and outward-swinging doors have benefits. For example, inward-swinging doors are less likely to be blocked by debris, while outward-swinging doors provide more space within the safe room. In some states or communities, the applicable building code may require that doors swing in a particular direction. For information on code requirements for your jurisdiction, contact a local building official or licensed design professional in your area.*" (FEMA 2015).

In this study, an overlaid outward-swinging door was evaluated. This configuration was chosen because the impact forces may be more effectively transferred into the safe room wall through the overlaid door edges rather than through deadbolts, which must resist the greatly concentrated forces of impact.

Three wood products were evaluated as potential wood door materials. Laminated strand lumber (LSL), laminated veneer lumber (LVL), and plywood were used as core materials for the doors. Initial tests evaluated the impact resistance of the wood product itself. Subsequent tests evaluated the impact performance with an added steel skin (14, 18, and 22 gauge) (0.07, 0.05, and 0.03 in. (1.8, 1.27, and 0.76 mm) thick) fastened to the faces of the door with either nails or bolts.

Test Setup, Data Collection, and Test Parameters

The impact tests were performed at the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wisconsin, using a missile cannon built by Spudtech, LLC (spudtech.com, 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. Each missile was a surface dry (moisture content between 16% and 19%) Southern Pine stud, selected such that no knots appeared within 12 in. (286 mm) of the leading edge. The trailing edge of each missile was affixed with a plastic sabot to facilitate launching. Details of this test cannon can be found in Falk and others (2015).

Each door was tested across a 36-in. (0.91-m) clear span, which represented the actual span of the door in a safe room designed for the American Disabilities Act (ADA) compliance. The door was supported in the same test frame used to test the wall sections described in Falk and others (2015). Similar to the wall testing, load and deflection of the door were recorded in real time.

Both high-speed and normal-speed videos were recorded for each test. High-speed video was recorded using two high-speed cameras (Phantom V710, Vision Research, Wayne, New Jersey). These high-speed videos were recorded at a resolution of 800 × 800 and speed of 7,000 frames per second.

Each door was impacted at the geometric center of the door. Observational data were also collected after each test and included the missile speed, type and extent of damage, and amount and size of debris generated. These data are provided in the Appendix for all door tests.

ICC/NSSA (2014) requires the impact testing of doors near hinges and latches (chapter 8, section 804.9.6). Because the focus of this study was to develop a workable wood-based tornado safe room door, specific testing of hinges and latches were not performed here. Latch and hinge impact resistance (as well as door pressure testing) is ongoing.

Door Construction

Each door was 42 by 86 in. (1.07 by 2.08 m), which provided an overlap on the sides and top of the door opening. Some doors were constructed from wood only (plywood, LVL, or LSL), although most included a sheet of hot-rolled steel (22, 18, or 14 gauge) attached to the front face (impact side) or both faces of the door. Nails or bolts, and in some cases, construction adhesive, were used to secure the layers together. For door configurations thicker than about 2.5 in. (63.5 mm) and faced with the thinner gauges of steel (18 and 22), a pneumatic nail gun and 16d wood framing nails were used to fasten the layers together. For doors thinner than this, 1/4-in. (6.35-mm) bolts were used to secure the layers together. Figures 1 and 2 show the layered construction of the tested doors, and Figures 3 and 4 indicate the fastener spacing used for all doors tested.

Results

The Appendix provides details of all test results, whereas Table 1 provides a general summary. The first four impact tests were performed on wood products with no steel sheeting reinforcement (Doors 1–4). Door 1 was 1-3/4-in.- (44.5-mm-) thick LSL. The door was pierced by the missile and failed the test. To test if added plywood would improve impact resistance, 23/32-in. (18.26-mm) plywood was nailed to each face (Door 2). Again, the missile pierced the wood door. As indicated in Table 1 and the Appendix, both LVL and plywood (four layers) doors also failed the test, with the missile piercing the door in both cases.

As indicated in Table 1, the addition of sheets of 18-gauge hot-rolled steel to the faces of the wood door core dramatically improved impact performance. When sheathed with steel, the LSL, LVL, and plywood doors (Doors 5–8) passed the test and did not excessively deform nor create debris.

To investigate if steel might be used on only one side of the door, four sheets of 23/32-in. (18.26-mm) plywood were nailed together with a sheet of 18-gauge steel only on the front (impact) side (Door 9). As indicated in Table 1, the door failed the test because large splinters of wood protruding more than 3 in. (76.2 mm) from the back of the door were produced (minimal flying debris was created, however).

To investigate if thinner steel might be used, four sheets of 23/32-in. (18.26-mm) plywood were nailed together with a sheet of 22-gauge steel on the front and back (Door 10). This door also passed the test but had slightly more deformation (1.4 in. (35.56 mm)) than Door 9. No further door tests were conducted with 22-gauge steel because the cost savings of this thinner steel were not significant enough to warrant using it.

Significant cost savings could be realized, however, if sheets of plywood sheathing could be eliminated from the core of the door. For this reason, tests were conducted using successively fewer sheets of plywood (Doors 11, 12, and 13). Because these doors were too thin to be nailed with commonly available 16d nails, 1/4-in. (6.35-mm) bolts were used to fasten the sheathing layers together.

As indicated in Table 1, doors with four, three, and two layers of plywood (but still retaining 18-gauge steel on both sides) passed the test. However, Door 13, with two layers of plywood, resulted in rather large (but acceptable) permanent deformation (2.1 in. (53 mm)). Using two sheets of plywood and 14-gauge steel (Door 14) significantly decreased the deformation (0.9 in. (22.86 mm)) but at the cost of thicker (and more expensive) steel sheeting.

As indicated in the Appendix, all doors (with the exception of Doors 1–4 and 6) were impacted twice and passed the test in each case. Door 9 failed the first test but passed the second.

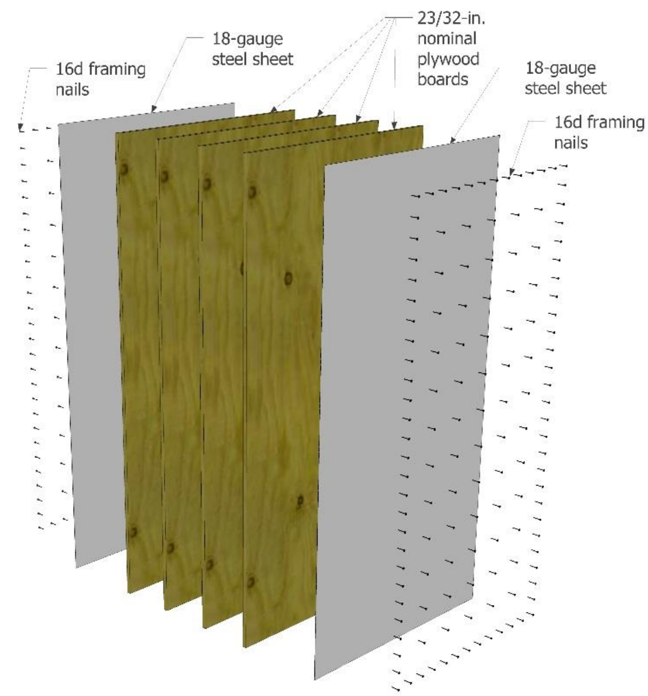

Figure 1—Layered construction of nailed door (1 in. = 25.4 mm).

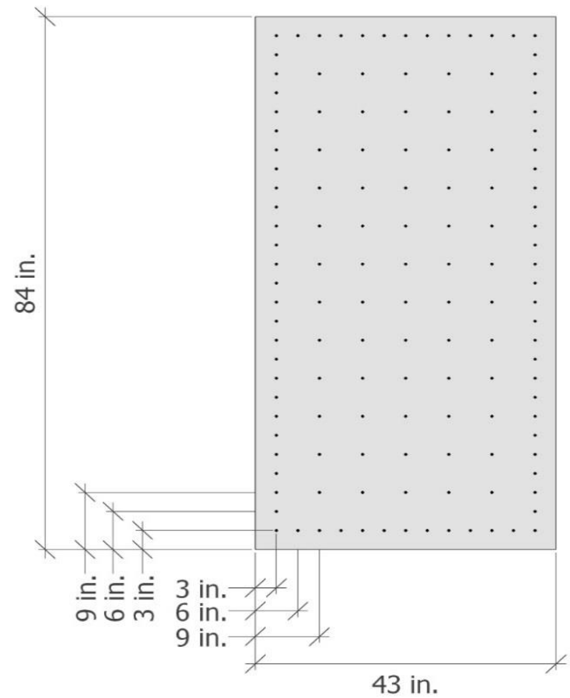

Figure 3—Fastener pattern for nailed door (1 in. = 25.4 mm).

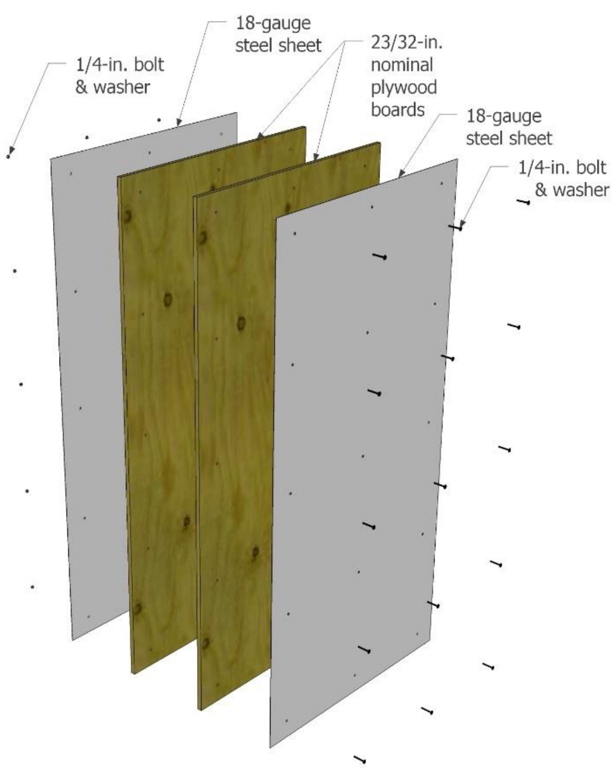

Figure 2—Layered construction of bolted door (1 in. = 25.4 mm).

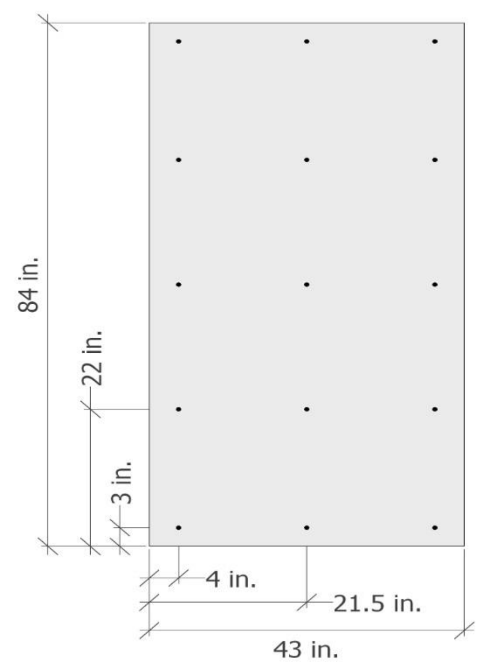

Figure 4—Fastener pattern for bolted door (1 in. = 25.4 mm).

Table 1. Summary of test results[a]

Door number	Door core construction	Wood sheathing type	Steel sheet placement[b]	Adhesive placement	Passed test (Y/N)	Further information
1	1-3/4-in. LSL	-	-	-	N	Wall pierced by missile
2	1-3/4-in. LSL	23/32-in. plywood, both sides	-	Between plywood and LSL	N	Wall pierced by missile
3	Two sheets of 1-1/4-in. LVL glued and nailed	-	-	Between LVL layers	N	Wall pierced by missile
4	Four sheets of 23/32-in. plywood, nailed	-	-	-	N	Wall pierced by missile
5	1-3/4-in. LSL	-	18-gauge steel, both sides	-	Y	Permanent deformation 2.3 in.
6	Two sheets of 1-1/4-in. LVL, center layer of 3/4-in. plywood, glued and nailed	-	18-gauge steel, both sides	Between LVL and sheet metal layers	Y	Permanent deformation 0.6 in.
7	Two sheets of 1-1/4-in. LVL nailed	-	18-gauge steel, both sides	-	Y	Permanent deformation 0.6 in.
8	Four sheets of 23/32-in. plywood, nailed	-	18-gauge steel, both sides	-	Y	Permanent deformation 1.4 in.
9	Four sheets of 23/32-in. plywood, nailed	-	18-gauge steel, front side only	-	N	Large splinters of plywood extended more than 3 in. from back of wall. Minimal debris created.
10	Four sheets of 23/32-in. plywood, nailed	-	22-gauge steel, both sides	-	Y	Permanent deformation 1.4 in.
11	Four sheets of 23/32-in. plywood, bolted	-	18-gauge steel, both sides	-	Y	Permanent deformation 1.2 in.
12	Three sheets of 23/32-in. plywood, bolted	-	18-gauge steel, both sides	-	Y	Permanent deformation 0.9 in.
13	Two sheets of 23/32-in. plywood, bolted	-	18-gauge steel, both sides	-	Y	Permanent deformation 2.1 in.
14	Two sheets of 23/32-in. plywood, bolted	-	14-gauge steel, both sides	-	Y	Permanent deformation 0.9 in.

[a]1 in. = 25.4 mm; LSL, laminated strand lumber; LVL, laminated veneer lumber.
[b]14, 18, and 22 gauge = 0.07, 0.05, and 0.03 in. (1.8, 1.27, and 0.76 mm) thick.

Discussion

At the thicknesses tested, a tornado safe room door constructed of wood cannot withstand a standard impact missile without the addition of steel sheeting applied to the door faces. A thicker wood door without steel might pass the test. However, the thickness required would probably be impractical from a construction, usage, and cost standpoint.

The necessity for steel sheeting is affected by both door thickness and span. The 6-in.- (0.15-m-) thick wood walls tested in Falk and others (2015) survived the impact tests without steel sheeting not only because the walls were thicker but also because the longer span of the walls allowed for more deflection (and acceleration of mass), which helped dissipate the impact energy.

A door is thinner and has a shorter span, therefore requiring reinforcement to prevent punch-through and to allow the impact force to be distributed into the wood core. A door or wall subjected to impact must resist the dynamic energy of the missile and its tendency to punch through while distributing and dissipating the high forces through deflection, mass acceleration, and damping.

A door is stiff relative to a wall (mostly because of its shorter span) and as a result, the missile has a tendency to punch through because the forces cannot be effectively transferred from the impact area into adjacent areas. Steel sheeting has enough stiffness to prevent punch-through and allows the forces caused by impact to be transferred into the wood core.

Conclusions

Several conclusions can be drawn from the results of this study:

1. A tornado safe room door can be constructed of wood but requires steel sheeting on both faces.

2. Steel sheeting of at least 18 gauge in thickness is recommended for door faces.

3. Laminated veneer lumber (LVL), laminated strand lumber (LSL), and plywood all perform well as door core materials as long as steel sheeting is applied to the door faces.

4. Although as few as two sheets of plywood can be used in a tornado safe room door, three sheets are recommended (with applied 18-gauge steel on both faces).

5. Nails or bolts work well to tie the steel door faces to the wood core. No adhesive is required.

Acknowledgments

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Appendix—Door Test Results

Definitions and unit conversions for this Appendix are as follows:

LSL, laminated strand lumber

LVL, laminated veneer lumber

1 in. = 25.4 mm

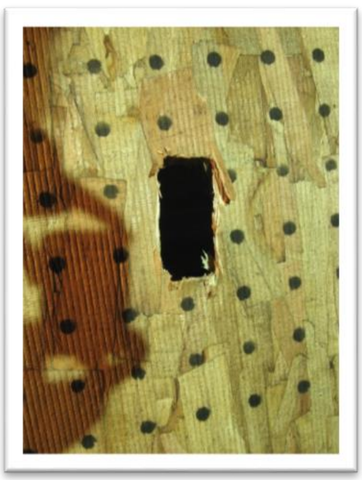
1 mph = 1.61 km/h

14 gauge = 0.07 in. (1.8 mm) thick

18 gauge = 0.05 in. (1.27 mm) thick

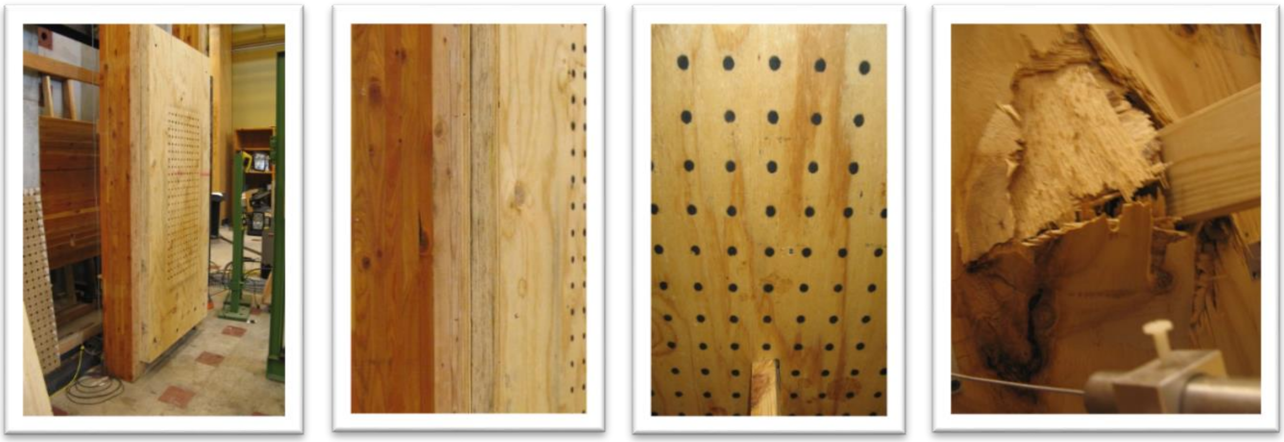
22 gauge = 0.03 in. (0.76 mm) thick

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
1	1-3/4-in. LSL	103.5	Full	-	Y	Wall pierced by missile	N	3-in. bearing on vertical edges, horizontal edges free



L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
2	1-3/4-in. LSL, 23/32-in. plywood both sides	102.3	Full	-	Y	Wall pierced by missile	N	3-in. bearing on vertical edges, horizontal edges free



L to R: Door prior to test, edge detail of door, missile embedded in front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
3	Two sheets of 1-1/4-in. LVL glued and nailed	104.4	Full	-	Y	Wall pierced by missile	N	3-in. bearing on vertical edges, horizontal edges free

L to R: Front of door after impact, damage to back of door.

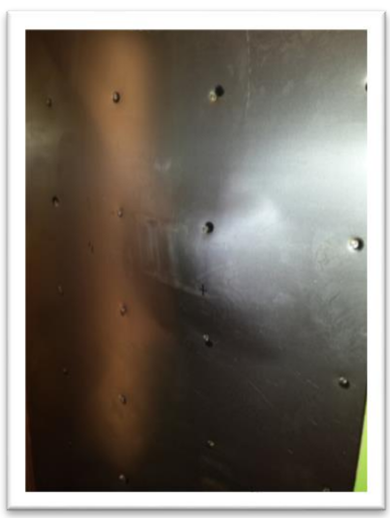
Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
4	Four sheets of 23/32-in. plywood, nailed	102.0	Full	-	Y	Wall pierced by missile	N	3-in. bearing on vertical edges, horizontal edges free




L to R: Door prior to test, edge detail of door, missile embedded in front of door, impact damage to back of door.

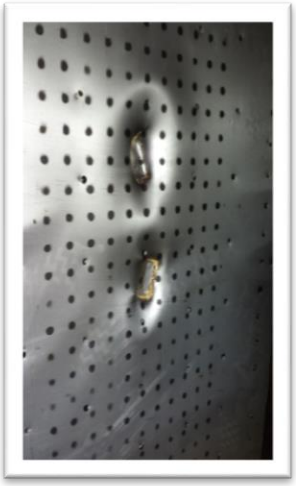
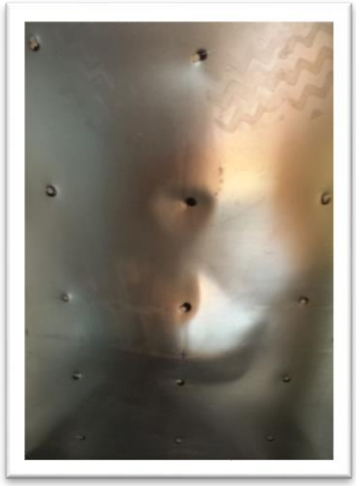
Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
5a	3-1/2-in. LSL with 18-gauge steel sheeting nailed both sides	102.2	2.6	2.3	Y	Front steel sheet torn at impact location	Y	Rear steel sheet intact





L to R: Door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
5b	3-1/2-in. LSL with 18-gauge steel sheeting nailed both sides	102.5	3.6	2.5	N	Front steel sheet torn at impact location	Y	Second shot on door 5, rear steel sheet intact

L to R: Door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
6	Two 1-1/4-in. LVL panels with one sheet 23/32-in. plywood between, 18-gauge steel sheeting nailed both sides	101.5	0.8	0.6	N	Front steel sheet torn at impact location	Y	Rear steel sheet intact



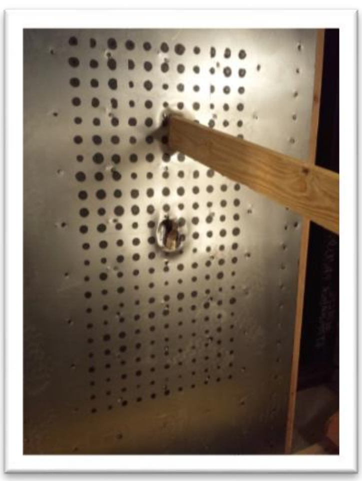
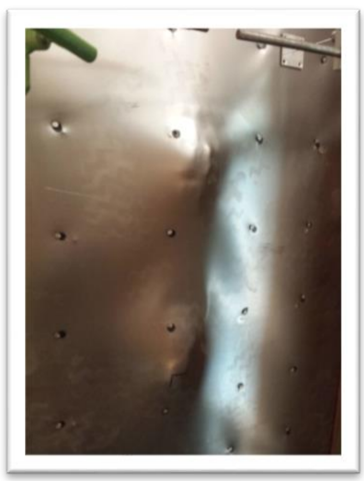
L to R: Door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
7a	Two 1-1/4-in. LVL panels with 18-gauge steel sheeting nailed both sides	101.1	0.5	0.6	N	Front steel sheet torn at impact location	Y	Rear steel sheet intact



L to R: Door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
7b	Two 1-1/4-in. LVL panels with 18-gauge steel sheeting nailed both sides	102.1	1.0	1.2	N	Front steel sheet torn	Y	Second shot on door 7, rear steel sheet intact

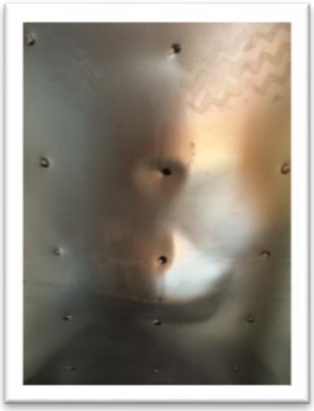




L to R: Door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
8a	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting nailed to both sides	102.3	1.0	1.4	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Rear steel sheet intact

L to R: Front of door prior to impact, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
8b	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting nailed to both sides	102.2	1.3	1.4	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Second shot on door 10, rear steel sheet intact



L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
9a	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting nailed to front face only	102.0	Full	-	Y	Missile pierced steel sheet	N	Large splinters of plywood extended more than 3 in. from back of wall, minimal debris created




L to R: Front of door prior to test, back of door prior to test, missile embedded in front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
9b	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting nailed to front face	101.2	N	<3 in.	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Second shot to door 8, shot 10 in. above previous impact location, no plywood splintering or debris created


L to R: Impact damage to front of door (top dent is second shot), impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
10a	Four sheets of 23/32-in. plywood, 22-gauge steel sheeting nailed to both sides	105.6	2.5	1.4	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Rear steel sheet intact



L to R: Front of door prior to impact, impact damage to front of door, impact damage to back of door.

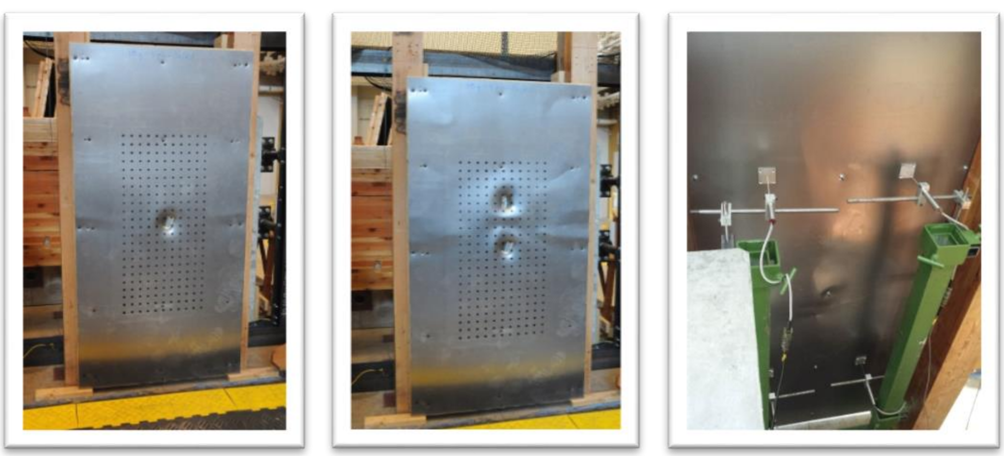
Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
10b	Four sheets of 23/32-in. plywood, 22-gauge steel sheeting nailed to both sides	102.3	-	1.5	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Second shot on door 9, rear steel sheet intact


L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
11a	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	101.5	1.8	1.2	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Rear steel sheet intact

L to R: Front of door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
11b	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	101.8	1.5	1.3	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Second shot on door 11, rear steel sheet intact



L to R: Front of door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
12a	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	100.8	0.8	0.9	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Rear steel sheet intact



L to R: Front of door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
12b	Four sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	101.3	1.8	1.3	N	Steel sheet on front face torn, some steel sheet buckling at location of impact	Y	Second shot on door 12, rear steel sheet intact


L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
13a	Two sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	102.1	2.0	2.1	N	Steel sheet on front face dented	Y	

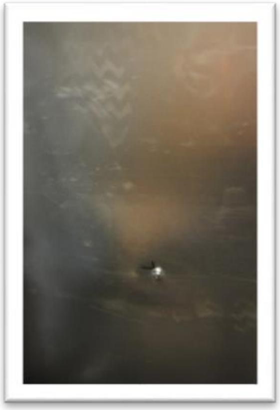


L to R: Front of door prior to test, impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
13b	Two sheets of 23/32-in. plywood, 18-gauge steel sheeting bolted to both sides	101.3	1.6	2.4	N	Steel sheet on front face dented	Y	Steel sheet buckled but intact


L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
14a	Two sheets of 23/32-in. plywood, 14-gauge steel sheeting bolted to both sides	102.7	1.0	0.9	N	Steel sheet on front face dented	Y	Missile shattered on impact

L to R: Impact damage to front of door, impact damage to back of door.

Door number	Door construction	Missile speed (mph)	Front penetration (in.)	Permanent door deflection (in.)	Door perforated? (Y/N)	Observed damage	Passed test? (Y/N)	Additional notes
14b	Two sheets of 23/32-in. plywood, 14-gauge steel sheeting bolted to both sides	101.9	0.9	0.5	N	Steel sheet on front face dented	Y	Missile shattered on impact. Permanent door deflection was a localized measurement in the area of the second shot.


L to R: Impact damage to front of door, impact damage to back of door.