A summary report on

Debris Impact Testing at Texas Tech University

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Table of Contents

Forward

Overview iii
Facility Development iii
Definitions iv

Section A - 15 lbf, 2×4 Board missiles

A1 Reinforced Concrete Slabs 1
A2 Reinforced Concrete Walls Constructed using Insulating Concrete Forms (ICF) 2
A3 Reinforced Concrete Masonry Unit (CMU) Walls 3
A4 Reinforced Brick Cavity Walls with Concrete Infill 5
A5 Stud Walls with Concrete Block Infill 5
A6 Stud Walls with Concrete Infill 7
A7 Stud Walls with Plywood 8
A8 Stud Walls with Plywood and Steel Plate 10
A9 Stud Walls with Plywood and Expanded Metal 12
A10 Stud Walls with Inserts between Studs 12
A11 Stud Walls with Infill and Siding Materials 13
A12 Stud Walls with Polystyrene Infill 15
A13 Stud Walls with Corrugated Infill Materials 15
A14 Brick Veneer Walls 15
A15 Doors 16

Section B - 2×4 Board missiles of various weights

B1 Reinforced Concrete Masonry Unit (CMU) Walls 17
B2 Reinforced Concrete Slabs 19
B3 Brick Veneer Walls 19
B4 Plywood layers 19
B5 OSB layers 19

Table of Contents

Section C - 10 ft. length, 3 inch diameter PVC pipe missiles
C1 Reinforced Concrete Masonry Unit (CMU) Walls 20

Section D - EMT Conduit missiles
D1 Reinforced Concrete Masonry Unit (CMU) Walls 20
D2 Reinforced Brick Cavity Walls with Concrete Infill 20
D3 Stud Walls with Plywood and Steel Plate 20

Section E - 3 inch diameter Steel Pipe (Schedule 40) missiles
E1 Reinforced Concrete Slabs 21
E2 Reinforced Concrete Masonry Units (CMU) 22
E3 Reinforced Brick Cavity Walls with Concrete Infill 22

Section F - 15 lbf, 3 inch diameter Pressure-treated Fence Post missiles
F1 Stud Walls with Plywood and Steel Plate 22

Section G - 15 lbf, 2×6 Board missiles
G1 Stud Walls with Plywood and Steel Plate 22

Section H - 22.5 lbf, 2×6 Board missiles
H1 Stud Walls with Plywood and Steel Plate 23

Section I - Clay Brick missiles
I1 Stud Walls with Plywood and Steel Plate 23

Section J - 2×4 Board missile Drop tests (65 mph)
J1 Wall Sections 24
J2 Doors 24

References

A summary report on

Debris Impact Testing at Texas Tech University

Overview

Since the early 1970's, Texas Tech University has been deeply involved in wind engineering research conducted through the Institute for Disaster Research and the Wind Engineering Research Center. One very important aspect of the wind engineering research is the effect of wind-generated debris on structures. In violent wind storms and tornadoes, windborne debris causes considerable damage to buildings and poses a threat to life, even to building occupants. Texas Tech University has lead in this field of research. Hundreds of tests have been conducted in the Debris Impact Test Facility. Test results on products that are not proprietary are reported herein. Testing was divided into sections based on missile types and subsections based on target configurations. The data is presented in a tabular format to facilitate comparison of missile type, weight, speed, momentum, energy, and description of damage for the various types of targets.

While this report is not complete in terms of considering all types of debris or all types of impacted surfaces, it is considered a significant contribution to a database for resistance by the most commonly used shelter components to windborne debris. This report is presented with the expectation that it will be useful in future wind engineering research and in product development.

Facility Development

Facilities were developed with funds from: the State of Texas, the Federal Emergency Management Agency (FEMA), Texas Tech University, companies involved in product development, and others. Funding for upgrading launch facilities and relocating the main facility to Reese Technology Center was provided, in part, by the National Institute for Standards and Technology (NIST) and Texas Tech.

This facility includes a pneumatic cannon that can accelerate a 15-lb (6.8-kg), nominal 2 x 4-in. (actual 1.5 x 3.5

in. or 3.8 x 8.9 cm) timber plank from rest to a speed of 150 mi/hr (67 m/s). The cannon can also project a 75-lb (34 kg), 3-in. (7.6 cm) diameter Schedule 40 steel pipe at speeds up to 75 mi/hr (34 m/s). Other types of simulated debris, or "missiles," include: nominal 2 x 6-in. (actual 1.5 x 5.5 in. or 3.8 x 14 cm) timber planks, fence posts, bricks, PVC pipe, and steel conduit.

Different types of building components, or targets, are tested in this facility including: concrete masonry unit (CMU) wall sections, reinforced concrete slabs, plywood and metal combinations, doors, and others.

A brochure titled *Debris Impact Testing—Wind Science and Engineering, Texas Tech University* more fully describes the facility.

Definitions

Failure is defined as behavior that might cause injury to occupants of a shelter using the component. Perforation by the missile, scabbing of target material that would create debris or large deformations of the target would constitute *failure*.

In this report, *repercussed* denotes that the missile was repelled or failed to inflict sufficient damage to the target to endanger a person on the non-impact side.

The *threshold speed*, usually given as a range of speeds, is the speed, above which, perforation or failure was shown to occur or would likely occur.

Perforation implies that the missile passed through the barrier so that it could be seen from the non-impact (back) side.

Penetration implies that the missile made an indention or embedded itself in the target but did not perforate the target.

Missile Momentum (p) is calculated as:

$$p = m \cdot v = \frac{w}{g} \cdot v \qquad (1)$$

where w is the weight of the missile in pounds-force (lbf), g is the acceleration of gravity (32.2 ft/s^2), and v is the speed of the missile in feet per second (ft/s). Thus, the units for Missile Momentum are pounds-force times seconds (lbf-s).

Missile Energy (T) is calculated as:

$$T = \tfrac{1}{2} \cdot m \cdot v^2 = \tfrac{1}{2} \cdot \frac{w}{g} \cdot v^2 \qquad (2)$$

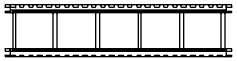
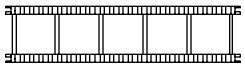
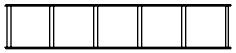
where w is the weight of the missile in pounds-force, g is the acceleration of gravity (32.2 ft/s^2), and v is the speed of the missile in feet per second (ft/s). Thus, the units for Missile Energy are feet times pounds-force (ft-lbf).

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A1 - Reinforced Concrete Slabs								
2 in. thick pea-gravel concrete with #4 rebar reinforcement 12 in. o.c. each way.		2 × 4 Board	15	< 26.0	< 18	< 339	The missile repercussed. (1 shot)	S & C (2001) P.T.
		2 × 4 Board		26.0 - 30.0	18 - 20	339 - 451	Threshold was observed. (2 shots)	
		2 × 4 Board		> 30.0	> 20	> 451	The missiles perforated the barrier. (7shots)	
3 in. thick pea-gravel concrete with #4 rebar reinforcement 12 in. o.c. each way.		2 × 4 Board	15	< 102.0	< 70	< 5213	The missiles repercussed. (4 shots)	S & C (2001) P.T.
		2 × 4 Board		102.0 - 106.0	70 - 72	5213 - 5630	Threshold was observed. (3 shots)	
		2 × 4 Board		> 106.0	> 72	> 5630	The missile perforated the barrier. (1 shot)	
4 in. thick pea-gravel concrete with #4 rebar reinforcement12 in. o.c. each way.		2 × 4 Board	15	104.0 - 162.0	71 - 111	5419 - 13149	The missiles repercussed. (5 shots)	S & C (2001) P.T.
6 in. thick pea-gravel concrete with #4 rebar reinforcement 12 in. o.c. vertically.		2 × 4 Board	15	102.4	70	5254	No cracking, front face spalling, or back face scabbing was observed.	K & C (1997)
6 in. thick pea-gravel concrete with #4 rebar reinforcement 24 in. o.c. vertically.		2 × 4 Board	15	102.4	70	5254	No cracking, front face spalling, or back face scabbing was observed.	K & C (1997)

Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A2 - Reinforced Concrete Walls Constructed using Insulating Concrete Forms (ICF)								
6 in. thick GREENBLOCK ICF (Exterior finish consists of vinyl siding attached to ICF fastening strips.)		2 × 4 Board	15	103.8 - 119.9	71 - 82	5398 - 7203	No cracking, front face spalling, or back face scabbing of the concrete core was observed. The missile penetrated the vinyl siding and the Green block form.	K & C (1997)
6 in. thick BLUE MAXX ICF (Interior finish consists of 5/8 in gypsum board attached directly to ICF fastening strips. Exterior finish consists of 3 in. brick veneer attached to ICF fastening strips with brick ties 12 in o.c.)		2 × 4 Board	15	99.0	68	4911	No cracking, front face scabbing, or back face spalling of the concrete core was observed. The missile penetrated the brick veneer, cracking it from the point of impact to the top of the sample. The Blue Mix ICF was indented but the missile never made direct contact with the concrete core.	K & C (1997)
4 in. thick LITE FORM ICF (Interior finish consists of 5/8 in gypsum board attached directly to ICF fastening strips. Exterior finish consists of vinyl siding attached to ICF fastening strips.)		2 × 4 Board	15	96.7	66	4685	No cracking, front face scabbing, or back face spalling of the concrete core was observed. The missile penetrated the vinyl siding and the Late Form ICF form. The missile made contact with the concrete core.	K & C (1997)
6 in. thick POLYSTEEL (WAFFLE) ICF (Exterior finish consists of 1/4 in thick Exterior Insulation Finish System (EIFS) applied directly to ICF.)		2 × 4 Board	15	100.2 - 103.8	68 - 71	5030 - 5398	No cracking, front face scabbing, or back face spalling of the concrete core was observed. The missile penetrated the EIFS siding and the Polyester ICF. The missile made contact with the concrete core. The missile hit the target at the side of the thicker column.	K & C (1997)

Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A3 - Reinforced Concrete Masonry Unit (CMU) Walls								
8 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	> 100.0	> 68	> 5010	The target was impacted over thirty times with the design missile. This was done for demonstration purposes only the first (verification) test was conducted as part of G&O contract.	Carter (1998)
8 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	116.0	79	6742	Wall remained intact; no stress cracks in block nor joints could be found. Missile splintered on impact.	TTU (1990)
8 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	121.0	83	7336	Minor surface indention (1/8").	White (1986)
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	101.6 - 106.7	69 - 73	5172 - 5704	No visible damage was observed. 1/8 to 3/16 in. indentation on impact side.	Carter (1998)
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	98.5 - 103.4	67 - 71	4861 - 5357	The missile impacted the target at a mortar joint. The target was cracked from the point of impact to the top of the target both in the front and in back. The mortar spalled out of the joint on the back of the target.	Carter (1998)
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	92.4 - 97.0	63 - 66	4278 - 4714	The missile impacted the target at a mortar joint. The cracking of the wall was extended into the base. A new crack appeared in the next joint 8 in. away and extended to the top of the target. The missile perforated the target and spilled the concrete fill out of the back of the target.	Carter (1998)

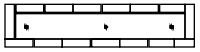
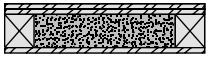
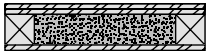
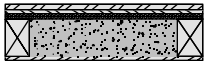
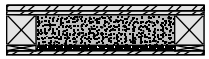
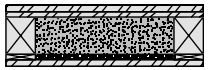
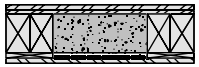
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A3 - Reinforced Concrete Masonry Unit (CMU) Walls								
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	NA	NA	NA	No penetration of the target occurred. The target was cracked from the point of impact to the top of the target.	Carter (1998)
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	106.1 - 111.3	72 - 76	5640 - 6207	The target was impacted at a vertical mortar joint. There was a 1/16 in. indentation on the impact face but no visible damage to either side of the target.	Carter (1998)
6 in. CMU reinforced with concrete and #4 rebar in every cell; truss type horizontal reinforcement was placed every 16 in.		2 × 4 Board	15	101.8 - 106.9	70 - 73	5192 - 5726	The target was impacted at a vertical mortar joint. There was a 1/16 in. indentation on the impact face. The joint spalled slightly on the non-impact side of the target. A small crack was detected at the impact point terminating at the top of the target.	Carter (1998)
6 in. CMU reinforced with concrete and #4 rebar in every cell; 8-gage truss horizontal reinforcement every other course		2 × 4 Board	15	< 130.0	< 89	< 8467	The missiles repercussed.	S & C (2001) P.T.
				130.0 - 137.0	89 - 94	8467 - 9404	Threshold was observed. (2 shots)	
				> 137.0	> 0	> 0	The missiles perforated the barrier. (2 shots)	

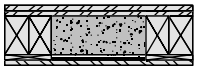
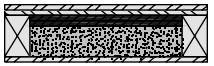
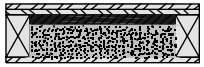
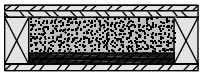
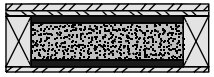
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A4 - Reinforced Brick Cavity Walls with Concrete Infill								
Brick cavity wall reinforced with #4 rebar every 12 in. and concrete infill.		2 × 4 Board	15	> 100.0	> 68	> 5010	The target has been proven successful in previous tests.	Carter (1998)
A5 - Stud Walls with Concrete Block Infill								
4x4 stud wall, containing 4 in. concrete block, and one layer of 3/8 in. CD grade plywood on the impact and two layers ¾ in. CD grade plywood non-impact faces.		2 × 4 Board	15	110.1 - 115.7	75 - 79	6074 - 6707	There was no missile penetration.	K & C (1998)
4x4 stud wall, containing 4 in. concrete block, and one layer of 3/8 in. CD grade plywood on the impact and two layers ¾ in. CD grade plywood non-impact faces.		2 × 4 Board	15	103.8 - 109.0	71 - 74	5398 - 5953	The missile impacted the interface between the block and the 4x4 stud perforating the target 3 ft.	K & C (1998)
4in. concrete block in a 2X4in. stud wall with two layers of ¾ in CD grade plywood.		2 × 4 Board	15	103.9 - 109.1	71 - 75	5409 - 5964	The missile impacted the stud and perforated the target 18 in.	Carter (1998)
4 in. concrete block in a 2x4 in. stud wall with two layers of ¾ in. CD grade plywood one the non-impact side, one layer of plywood on the impact side, and 14 ga. ½ in. expanded metal.		2 × 4 Board	15	101.6 - 106.7	69 - 73	5172 - 5704	¾ in. of penetration. No evident damage to the non-impact side.	Carter (1998)
4 in. concrete block in a 2x4 in. stud wall with two layers of ¾ in. CD grade plywood one the non-impact side, one layer of plywood on the impact side, and 14 ga. ½ in. expanded metal.		2 × 4 Board	15	101.0 - 106.1	69 - 72	5111 - 5640	The missile impacted the stud and sheared it in two. The non-impact side showed no damage.	Carter (1998)
4x4 stud wall with 1x4's on the studs, containing 4 in. concrete block, gypsum board infill, and one layer of ¾ in. CD grade plywood on the impact face and two layers on the non-impact face.		2 × 4 Board	15	101.4 - 106.5	69 - 73	5152 - 5683	Missile penetrated the target, but did not perforate when impacted at the interface between the block and the 4x4 stud.	K & C (1998)
4x4 stud wall with 1x4's on the studs, containing 4 in. concrete block, gypsum board infill, and one layer of ¾ in. CD grade plywood on the impact face and two layers on non-impact face.		2 × 4 Board	15	105.9 - 111.2	72 - 76	5619 - 6196	The missile impacted the stud and ½ in. of deflection occurred on the non-impact face.	K & C (1998)
Double studded 2x4 wall with furring. Two layers of ¾ in. CD grade plywood on the non-impact face, one layer on the impact face, and a layer of 3/8 in. gyp. board. The wall is filled with 4 in. concrete block.		2 × 4 Board	15	103.0	70	5315	The missile impacted ½ in. on the stud and ½ in. on the concrete block infill. There was ½ in. of deformation on the non-impact side.	K & C (1998)

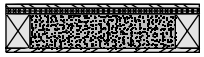
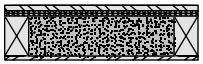
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A5 - Stud Walls with Concrete Block Infill								
Double studded 2x4 wall with furring. Two layers of ¾ in. CD grade plywood on the non-impact face, one layer on the impact face, and a layer of 3/8 in. gyp. board. The wall is filled with 4 in. concrete block.		2 × 4 Board	15	100.7	69	5081	The missile impacted next to the stud. There was ½ in. of deformation and cracking on the non-impact side.	K & C (1998)
Double studded 2x4 wall with furring. Two layers of ¾ in. CD grade plywood on the non-impact face, one layer on the impact face, and a layer of 3/8 in. gyp. board. The wall is filled with 4 in. concrete block place vertically in the cell.		2 × 4 Board	15	101.9	70	5203	The missile perforated the target 3 in.	K & C (1998)
4 in. concrete block in a 2X6 in. wall with 1 ½ in. of polystyrene between block and one layer of ¾ in. CD grade plywood		2 × 4 Board	15	81.0 - 85.1	55 - 58	3287 - 3629	The missile penetrated the target. The non-impact plywood was punched out in the area of impact.	Carter (1998)
4 in. concrete block in a 2x6 in. wall with 1 ½ in. of polystyrene between block and two layers of ¾ in. CD grade plywood.		2 × 4 Board	15	106.0 - 111.3	72 - 76	5630 - 6207	The missile penetrated the target. There was no damage to the back side of the target.	Carter (1998)
4 in. concrete block in a 2x6 in. stud wall with 1 ½ in. of polystyrene between the block and the impact face of ¾ in. CD grade plywood. There is also two layers of plywood on the non-impact face.		2 × 4 Board	15	100.7 - 105.4	69 - 72	5081 - 5566	The missile penetrated the target but did not perforate it. The back face plywood pulled from the studs and the studs were torn in half. There was catastrophic damage to the structure.	Carter (1998)
4 in. concrete block in a 2x6 in. wall with 1 ½ in. of polystyrene on each side of the block, one layer of ¾ in. CD grade plywood on the impact side, and two layers on the non-impact face.		2 × 4 Board	15	99.0 - 104.0	68 - 71	4911 - 5419	The missile penetrated the target but did not perforate it. The back face plywood pulled from the studs and the studs were torn in half. There was catastrophic damage to the structure.	Carter (1998)

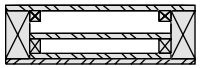
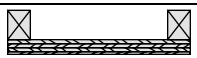
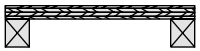
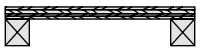
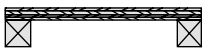
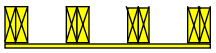
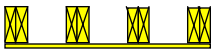
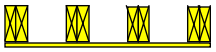
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A6 - Stud Walls with Concrete Infill								
Stud wall with CD grade plywood, 14 ga. ½ in. expanded metal, and concrete infill.		2 × 4 Board	15	101.0 - 106.1	69 - 72	5111 - 5640	The missile impacted 1 ½ in. to the left of a stud. No damage was visible on the back of the target.	Carter (1998)
Stud wall with CD grade plywood, 14 ga. ½ in. expanded metal, and concrete infill.		2 × 4 Board	15	100.4 - 105.4	69 - 72	5051 - 5566	The missile impacted 1 in. to the right of a stud. No damage was visible on the back of the target.	Carter (1998)
Stud wall with CD grade plywood, 14 ga. ½ in. expanded metal, and concrete infill.		2 × 4 Board	15	100.0 - 105.0	68 - 72	5010 - 5524	The missile impacted 4 in. to the left of a stud. No damage was visible on the back of the target.	Carter (1998)
Stud wall filled with concrete with no plywood and 14 ga. ½ in. expanded metal on the non-impact face.		2 × 4 Board	15	102.6 - 107.7	70 - 74	5274 - 5812	The missile made partial contact with the stud. The concrete was cracked around the impact area.	Carter (1998)
Stud wall filled with concrete with no plywood and 14 ga. ½ in. expanded metal on the non-impact face.		2 × 4 Board	15	102.1 - 107.2	70 - 73	5223 - 5758	The missile made partial contact with the stud. The concrete was severely damaged and a 4 in. deflection on the back of the target was observed.	Carter (1998)
Stud wall filled with concrete with no plywood and 14 ga. ½ in. expanded metal on the non-impact face.		2 × 4 Board	15	102.0 - 107.1	70 - 73	5213 - 5747	The missile impacted the concrete. No visible damage was observed.	Carter (1998)
Stud wall filled with concrete with no plywood and 14 ga. ½ in. expanded metal on the non-impact face.		2 × 4 Board	15	99.5 - 104.5	68 - 71	4960 - 5471	The missile hit the stud fully. There was 3 in. of deflection to the back of the target but no perforation.	Carter (1998)

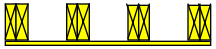
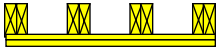
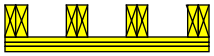
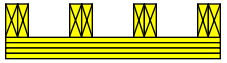
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A7 - Stud Walls with Plywood								
2x8 in. stud wall with ¾ in. CD grade plywood inserts.		2 × 4 Board	15	101.3 - 106.4	69 - 73	5141 - 5672	The full length of the missile perforated the target.	Carter (1998)
4 layers of ¾ in. CD grade plywood.		2 × 4 Board	15	96.0 - 100.8	66 - 69	4618 - 5091	The missile perforated the target 4 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood.		2 × 4 Board	15	93.0 - 97.7	64 - 67	4333 - 4783	The missile perforated the target 2 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood.		2 × 4 Board	15	85.4 - 89.7	58 - 61	3654 - 4031	The missile perforated the target 2 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood.		2 × 4 Board	15	86.7 - 91.0	59 - 62	3766 - 4149	The missile perforated the target 1 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood glued together and attached to the frame with screws.		2 × 4 Board	15	82.0 - 86.1	56 - 59	3369 - 3714	The missile perforated the target 3 ft.	Carter (1998)
4 layers of ¾ in. BC grade plywood glued together and attached to the frame with screws.		2 × 4 Board	15	98.2 - 103.1	67 - 70	4832 - 5326	The missile perforated the target 7 ft.	Carter (1998)
4 layers of ¾ in. BC grade plywood glued together and attached to the frame with screws.		2 × 4 Board	15	86.3 - 90.6	59 - 62	3732 - 4113	The missile perforated the target 3 ft.	Carter (1998)
4 layers of ¾ in. BC grade plywood glued together and attached to the frame with screws.		2 × 4 Board	15	78.9 - 82.8	54 - 57	3119 - 3435	The missile perforated the target 1 ft.	Carter (1998)
1 layer of 1/2 inch Plywood		2 × 4 Board	15	52.0	36	1355	The missile perforated the target.	Bailey (1984)
1 layer of 1/2 inch Plywood with Masonite Siding		2 × 4 Board	15	52.0	36	1355	The missile perforated the target.	Bailey (1984)
1 layer of 3/4 inch Plywood		2 × 4 Board	15	53.0	36	1407	The missile perforated the target.	Bailey (1984)

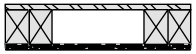
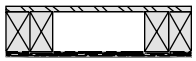
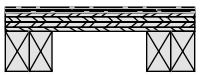
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A7 - Stud Walls with Plywood								
1 layer of ¾ in. plywood mounted with 3 in. #8 wood deck screws spaced 6 in on center to the double stud 4X4 ft. frame.		2 × 4 Board	15	< 29.0	< 20	< 421	The missiles repercussed. (4 shots)	S & C (2001) P.T.
				29.0 - 31.0	20 - 21	421 - 481	Threshold was observed. (1 shot)	
				> 31.0	> 21	> 481	The missiles perforated the barrier. (3 shots)	
2 layer of ¾ in. plywood mounted with 3 in. #8 wood deck screws spaced 6 in on center to the double stud 4X4 ft. frame.		2 × 4 Board	15	< 41.0	< 28	< 842	The missile repercussed. (1 shot)	S & C (2001) P.T.
				41.0 - 44.0	28 - 30	842 - 970	Threshold was observed. (1 shot)	
				> 44.0	> 30	> 970	The missiles perforated the barrier. (4 shots)	
3 layer of ¾ in. plywood mounted with 3 in. #8 wood deck screws spaced 6 in on center to the double stud 4X4 ft. frame.		2 × 4 Board	15	< 59.0	< 40	< 1744	The missiles repercussed. (2 shots)	S & C (2001) P.T.
				59.0 - 61.0	40 - 42	1744 - 1864	Threshold was observed. (1 shot)	
				> 61.0	> 42	> 1864	The missiles perforated the barrier. (4 shots)	
4 layer of ¾ in. plywood mounted with 3 in. #8 wood deck screws spaced 6 in on center to the double stud 4X4 ft. frame. All plywood layers are rotated 90 degrees from the previous layer.		2 × 4 Board	15	< 71.0	< 49	< 2526	The missiles repercussed.	S & C (2001) P.T.
				71.0 - 74.0	49 - 51	2526 - 2744	Threshold was observed. (4 shots)	
				> 74.0	> 51	> 2744	The missiles perforated the barrier. (3 shots)	

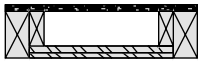
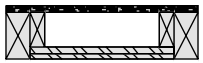
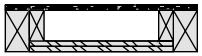
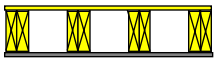
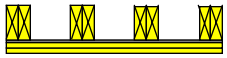
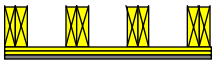
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A8 - Stud Walls with Plywood and Steel Plate								
Double 2x4 stud wall with one layer of 12 ga. steel on the impact side and one layer of ¾ in. CD grade plywood on the non-impact side.		2 × 4 Board	15	NA	NA	NA	The missile impacted near the stud and was deflected.	K & C (1998)
Double 2x4 stud wall with one layer of 12 ga. steel on the impact side and one layer of ¾ in. CD grade plywood on the non-impact side.		2 × 4 Board	15	NA	NA	NA	The missile impacted the stud and was deflected, there was some damage to the non-impact face.	K & C (1998)
Double 2x4 stud wall with one layer of 12 ga. steel on the impact side and one layer of ¾ in. CD grade plywood on the non-impact side.		2 × 4 Board	15	105.2	72	5545	The missile impacted next to the stud and was destroyed.	K & C (1998)
Double 2x4 stud wall with one layer of 12 ga. steel on the impact side and one layer of ¾ in. CD grade plywood on the non-impact side.		2 × 4 Board	15	103.6	71	5378	The missile impacted next to the stud and was destroyed.	K & C (1998)
2x8 stud wall with two layers of ¾ in. plywood and one layer of 14 ga. steel.		2 × 4 Board	15	100.9	69	5101	The missile impacted the stud and broke it, but did not perforate the target.	Carter (1998)
Double stud wall with 4 layers of ¾ in. CD grade plywood and 14 ga. steel on the back face of the target.		2 × 4 Board	15	99.0 - 107.0	68 - 73	4911 - 5736	1 in. of deformation on the back face of the steel but no perforation.	Carter (1998)
Double stud wall with 4 layers of ¾ in. CD grade plywood and 14 ga. steel on the back face of the target.		2 × 4 Board	15	101.5 - 106.6	69 - 73	5162 - 5694	The target was impacted next to a stud. Several heads of screws were popped off the back of the target. The steel had 1 in. of deformation. No perforation.	Carter (1998)
Double stud wall with 4 layers of ¾ in. CD grade plywood and 14 ga. steel on the back face of the target.		2 × 4 Board	15	99.9 - 104.9	68 - 72	5000 - 5513	The target was impacted on the stud line. The stud was cut in two. No deformation was observed on the back side. No perforation.	Carter (1998)
Stud wall with 2 layers of ¾ in. CD grade plywood with 16 ga. metal on non-impact side.		2 × 4 Board	15	100.7 - 105.7	69 - 72	5081 - 5598	1 in. deformation of 16 Ga. metal on non-impact side of target. No perforation.	Carter (1998)
Stud wall with 2 layers of ¾ in. CD grade plywood with 16 ga. metal on non-impact side.		2 × 4 Board	15	99.7 - 104.7	68 - 72	4980 - 5492	Wood screws pulled out of studs and 16 Ga. metal had 3 ½ in. of deformation. No perforation.	Carter (1998)
Stud wall with 2 layers of ¾ in. CD grade plywood with 16 ga. metal on non-impact side.		2 × 4 Board	15	100.1 - 105.1	68 - 72	5020 - 5534	Wood screws pulled through metal and 1 in. of deformation of 16 Ga. Metal. No perforation.	Carter (1998)
Stud wall with 3 layers of ¾ in. CD grade plywood inserts with 14 ga. metal on the non-impact side.		2 × 4 Board	15	100.7 - 105.7	69 - 72	5081 - 5598	The first insert of plywood failed in shear while the interior two failed in bending. The studs started to be torn in half and there was 3 in. of deformation in the steel.	Carter (1998)

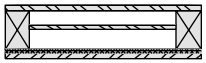
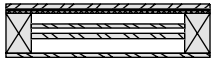
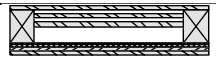
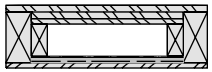
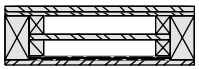
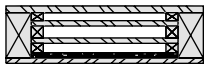
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A8 - Stud Walls with Plywood and Steel Plate								
2 layers of ¾ in. CD grade plywood with 14 ga. steel on the non-impact side, and gypsum board on both the impact and non-impact faces.		2 × 4 Board	15	92.6 - 97.2	63 - 66	4296 - 4734	4 in. of deformation on the non-impact side. The wood screws were pulled from the studs and the studs were torn in half. The inserts were sheared through with no bending action.	Carter (1998)
2 layers of ¾ in. CD grade plywood with 14 ga. steel on the non-impact side, and gypsum board on both the impact and non-impact faces.		2 × 4 Board	15	99.6 - 104.6	68 - 71	4970 - 5482	4 in. of deformation on the non-impact side. The wood screws were pulled from the studs and the studs were torn in half. The inserts were sheared through with no bending action.	Carter (1998)
2 layers of ¾ in. CD grade plywood with 14 ga. steel on the non-impact side, and gypsum board on both the impact and non-impact faces.		2 × 4 Board	15	103.2 - 108.4	71 - 74	5336 - 5887	The metal screws were pulled from the studs 6 in.	Carter (1998)
1 layer of 12 ga. steel that was hot rolled A569 Grade 33 on impact side of the double stud frame; a layer of ¾ in. plywood on the non-impact side		2 × 4 Board	15	< 145.0	< 99	< 10534	The missiles repercussed. (3 shots)	S & C (2001) P.T.
				145.0 - 148.0	99 - 101	10534 - 10975	Threshold was observed. (4shots)	
				> 148.0	> 101	> 10975	The missiles perforated the barrier. (3 shots)	
2 layers of ¾ in. plywood, one layer of 14 ga. steel.		2 × 4 Board	15	< 130.0	< 89	< 8467	The missile repercussed. (1 shot)	S & C (2001) P.T.
				130.0 - 133.0	89 - 91	8467 - 8863	Threshold was observed. (3 shots)	
				> 133.0	> 91	> 8863	The missiles perforated the barrier. (4 shots)	
2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 × 4 Board	15	112.8 - 117.8	77 - 80	6375 - 6953	The missile ricochets at 15°, 12.5° and at 11.25° and perforated at any angle lower than 10°. Repeat shots were fired at 12.5°, 10° and 0° resulting in confirmed conclusions that the critical angle lay within 11° and 13°. Although the missile does not perforate the target, permanent deflection and some structural damage were recorded.	C & S (2001) C.A.

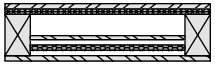
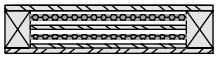
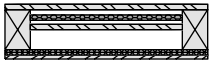
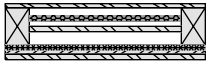
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A9 - Stud Walls with Plywood and Expanded Metal								
3 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the impact side.		2 × 4 Board	15	103.8 - 109.0	71 - 74	5398 - 5953	The missile perforated the target 12 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the non-impact side.		2 × 4 Board	15	99.2 - 104.2	68 - 71	4931 - 5440	The missile perforated the target 7 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the non-impact side.		2 × 4 Board	15	102.7 - 107.8	70 - 74	5285 - 5822	The missile perforated the target 3 ft.	Carter (1998)
3 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the non-impact side.		2 × 4 Board	15	100.9 - 105.9	69 - 72	5101 - 5619	The full length of the missile perforated the target.	Carter (1998)
5 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the impact side.		2 × 4 Board	15	NA	NA	NA	The missile perforated the target 3 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the impact side.		2 × 4 Board	15	98.7 - 103.6	67 - 71	4881 - 5378	The missile perforated the target 10 ft.	Carter (1998)
A10 - Stud Walls with Inserts between Studs								
4 layers of ¾ in. plywood with 14 Ga. steel insert with spacers between inserts and the back face of the target.		2 × 4 Board	15	104.2 - 109.4	71 - 75	5440 - 5997	The missile penetrated the target 1 ½ - 2 in. There was a crack in the plywood on the back face caused bending, but total separation did not occur.	Carter (1998)
14 ga. steel insert with spacers between all the inserts and the back face has two layers of ¾ in CD grade plywood.		2 × 4 Board	15	103.0 - 110.0	70 - 75	5315 - 6063	The missile penetrated the target 1 ½ - 2 in. There was a crack in the plywood on the back face caused by bending, but total separation did not occur.	Carter (1998)
4 layers of ¾ in. CD grade plywood with 14 ga. steel insert and spacers between all inserts.		2 × 4 Board	15	99.6 - 104.6	68 - 71	4970 - 5482	All plywood inserts failed in bending. The top third of the inserts were shot out the non-impact side of the target.	Carter (1998)

Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A11 - Stud Walls with Infill and Siding Materials								
3 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the non-impact side and bead-board infill.		2 × 4 Board	15	90.8 - 95.3	62 - 65	4131 - 4550	The full length of the missile perforated the target.	Carter (1998)
4 layers of ¾ in. CD grade plywood with two layers of energy absorbing bead board as inserts.		2 × 4 Board	15	102.2 - 107.3	70 - 73	5233 - 5769	The missile perforated the target 7 ft.	Carter (1998)
3 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the impact side and bead-board infill.		2 × 4 Board	15	104.8 - 110.0	72 - 75	5503 - 6063	The full length of the missile perforated the target.	Carter (1998)
4 layers of ¾ in. CD grade plywood with 14 ga. ½ in. expanded metal on the impact side and bead-board infill.		2 × 4 Board	15	103.3 - 108.5	71 - 74	5346 - 5898	The missile perforated the target 3 ft.	Carter (1998)
Masonite siding wall; 7/16 in. masonite siding (rough finish) on the front face and 1/2 in. gypsum wallboard on the back face.		2 × 4 Board	15	54.0	37	1461	The missile perforated the target.	Bailey (1984)
Insulation Board / Masonite siding wall;1/2 in. insulating board and 7/16 in. masonite siding (rough finish) on the front face and 1/2 in. gypsum wallboard on the back face.		2 × 4 Board	15	54.0	37	1461	The missile perforated the target.	Bailey (1984)
5/8 in gypsum board attached directly to steel studs 16 in o.c.; 3 1/2 in fiberglass batt insulation; Vinyl siding over 3/4 in plywood sheathing on exterior face		2 × 4 Board	15	103.5	71	5367	The missile completely perforated the target; little or no damage to the missile	K & C (1997)
Plywood / Masonite siding wall; 1/2-in. plywood sheeting and 7/16-in. masonite siding (rough finish) in the front face and 1/2-in. gypsum wallboard in the back face.		2 × 4 Board	15	52.0	36	1355	The missile perforated the target.	Bailey (1984)

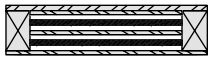
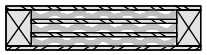
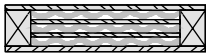
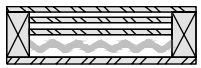
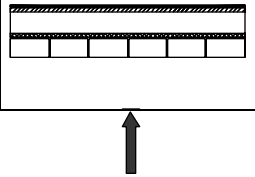
Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

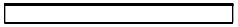
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A11 - Stud Walls with Infill and Siding Materials								
Plywood wall; 1/2-in. plywood sheeting on the front face and 1/2-in. gypsum wallboard on the back face.		2 × 4 Board	15	52.0	36	1355	The missile perforated the target.	Bailey (1984)
Plywood wall; 3/4-in. plywood sheeting on the front face and 1/2-in. gypsum wallboard on the back face.		2 × 4 Board	15	53.0	36	1407	The missile perforated the target.	Bailey (1984)
Stucco wall; 1/2-in. plywood sheeting topped by 3 course stucco exterior on the front face and 1/2-in. gypsum wallboard on the back face.		2 × 4 Board	15	53.0	36	1407	The missile perforated the target.	Bailey (1984)
Lapboard siding wall; 3/4-in. plain lapboard siding on the front face and 1/2-in. gypsum wallboard on the back face.		2 × 4 Board	15	53.0	36	1407	The missile perforated the target.	Bailey (1984)
Insulation Board / Lapboard siding wall; 1/2-in. insulation board and 3/4-in. plain lapboard siding on the front face and 1/2-in. gypsum wallboard on the back face.		2 × 4 Board	15	52.0	36	1355	The missile perforated the target.	Bailey (1984)

Missile Direction

Section A - 15 lbf, 2 × 4 Board missiles

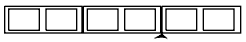
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A12 - Stud Walls with Polystyrene Infill								
4 layers of ¾ in. CD grade plywood with two layers of energy absorbing polystyrene as inserts.		2 × 4 Board	15	100.4 - 105.4	69 - 72	5051 - 5566	The missile penetrated the target but did not perforate it. The back of the target had 6 in. of deformation and the back layer of plywood was pulled from the frame.	Carter (1998)
4 layers of ¾ in. CD grade plywood with two layers of energy absorbing polystyrene as inserts.		2 × 4 Board	15	104.1 - 109.3	71 - 75	5430 - 5986	The missile perforated the target 4 ft.	Carter (1998)
4 layers of ¾ in. CD grade plywood with two layers of energy absorbing polystyrene as inserts.		2 × 4 Board	15	> 100.0	> 68	> 5010	The full length of the missile perforated the target.	Carter (1998)
A13 - Stud Walls with Corrugated Infill Materials								
3 layers of corrugated tin with four layers of ¾ in. CD grade plywood.		2 × 4 Board	15	104.1 - 109.3	71 - 75	5430 - 5986	The missile perforated the target 8 ft.	Carter (1998)
3 layers of corrugated tin with four layers of ¾ in. CD grade plywood.		2 × 4 Board	15	100.9 - 105.9	69 - 72	5101 - 5619	The missile perforated the target 7 ft.	Carter (1998)
1 layer of corrugated tin with four layers of ¾ in. CD grade plywood.		2 × 4 Board	15	104.8 - 110.0	72 - 75	5503 - 6063	The missile perforated the target 7 ft. The missile also broke the interior layers of plywood and pushed the pieces and the corrugated tin out the back of the target.	Carter (1998)
A14 - Brick Veneer Walls								
Brick veneer wall. (Interior finish consists of 5/8-in. gypsum board attached directly to the wood studs. 3 1/2-in. fiberglass batt insulation was placed between 2x4 studs. Exterior finish consists of 3/4-in. plywood sheeting attached to the studs with a 3-in. brick veneer.)		2 × 4 Board	15	69.4	47	2413	The missile perforated completely through the brick veneer, exterior and interior sheeting. The brick veneer was cracked horizontally and vertically from the point of impact.	K & C (1997)

Section A - 15 lbf, 2 × 4 Board missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
A15 - Doors								
Curries 14 ga. Steel door with 20 ga. Metal ribs. The door was installed and tested as a swing out door. (Sargent mortise lock with deadbolt function)		2 × 4 Board	15	82.0 - 106.6	56 - 73	3368 - 5690	The door withstood several impacts at the midpoint of the door next to the hardware and at the upper and lower corners next to the hinges and on the lock side respectively.	K & C (1998)
Republic 14 ga. Door with a polystyrene infill. The door was mounted and tested as a swing in door. (Yale mortise lock set with dead bolt function)		2 × 4 Board	15	81.3	56	3312	The door failed the impact test due to hardware failure. When modified with three slide dead bolt locks, mounted opposite the hinges, the door is successful.	K & C (1998)
Republic 20 ga. Door, a honeycomb infill, with a 14 ga. Steel plate mounted on the non-impact side. The door was mounted and tested as a swing in door. (Standard heavy duty lock with three 1/2 inch slide bolts mounted opposite the hinges)		2 × 4 Board	15	103.9	71	5407	There was a local failure of the hardware, but the redundancies in the hardware held the door in place. The missile penetrated the impact skin, but did not perforate the non-impact side or the 14 ga. Steel plate. There was permanent deformation.	K & C (1998)
Republic 20 ga. Door, a honeycomb infill, with a 14 ga. Steel plate mounted on the impact side. The door was mounted and tested as a swing in door. (Standard heavy duty lock with three 1/2 inch slide bolts mounted opposite the hinges)		2 × 4 Board	15	104.1	71	5429	The missile did not penetrate the door, but it caused permanent deformation in the internal door frame. (The door buckled around the standard lock set.)	K & C (1998)
Hollow core door (wooden door).		2 × 4 Board	15	54.0	37	1461	The missile perforated the target.	
Solid-core door (particle board fill).		2 × 4 Board	15	53.0	36	1407	The missile perforated the target.	

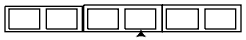
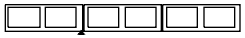
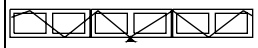
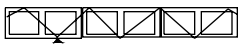
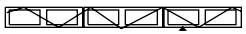
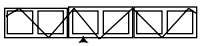
Missile Direction

Section B - 2×4 Board missiles of various weights

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
B1 - Reinforced Concrete Masonry Unit (CMU) walls								
8 in. CMU reinforced with #4 rebar at 24 in. on center cells with rebar filled with grout.		2 × 4 Board	13.75	92.0	58	3887	45 degree impact angle, No damage was observed. The impact point was at the joint between cells.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 24-in. on center cells with rebar filled with grout.		2 × 4 Board	11.5	116.0	61	5169	45 degree impact angle, No damage was observed. The impact point was at the joint between cells.	TTU (1990)
8 in. CMU with no reinforcement.		2 × 4 Board	13	60.0	36	1563	The missile perforated the barrier. The impact point was at the center of the cell.	White (1986)
8 in. CMU with no reinforcement.		2 × 4 Board	11	131.0	66	6305	The missile perforated the barrier. The impact point was at the joint between cells.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 16 in. on center cells with rebar filled with grout.		2 × 4 Board	11	135.0	68	6696	No penetration of the target occurred. One big crack was observed. The impact point was at the joint between cells.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 16 in. on center cells with rebar filled with grout.		2 × 4 Board	11.25	104.0	53	4064	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 16 in. on center cells with rebar filled with grout.		2 × 4 Board	11	49.0	25	882	No damage was observed. The impact point was at the center of the cell where the rebar and the grout are located.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 16 in. on center cells with rebar filled with grout.		2 × 4 Board	12	120.0	66	5772	No damage was observed. The impact point was at the center of the cell where the rebar and the grout are located.	TTU (1990)
8 in. CMU reinforced with grout filled in every cell.		2 × 4 Board	12.5	98.0	56	4010	No damage was observed. The impact point was at the joint between cells.	TTU (1990)
8 in. CMU with no reinforcement.		2 × 4 Board	13.75	71.0	44	2315	The missile perforated the barrier. The impact point was at the center of the cell; the missile had pointed end.	TTU (1990)
8 in. CMU with no reinforcement.		2 × 4 Board	13.75	100.0	63	4593	The missile perforated the barrier. The impact point was at the joint between the CMU's; the missile had pointed end.	TTU (1990)

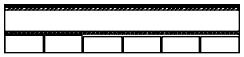
Missile Direction

Section B - 2×4 Board missiles of various weights

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
B1 - Reinforced Concrete Masonry Unit (CMU) Walls								
8 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	12.5	104.0	59	4516	The missile perforated the barrier. The impact point was at the joint between the cells.	TTU (1990)
8 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	12.5	89.0	51	3307	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)
12 in. CMU with no reinforcement.		2 × 4 Board	11.75	120.0	64	5652	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)
12 in. CMU with no reinforcement.		2 × 4 Board	12	85.0	46	2896	The missile perforated the barrier. The impact point was at the joint between the CMU's.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	11.75	125.0	67	6132	No penetration of the target occurred. Small cracks were observed. The impact point was at the joint between cells.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	11.75	124.0	66	6035	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	12.75	86.0	50	3150	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	12	76.0	42	2315	The missile penetrated the barrier by 2.5 in. The impact point was at the center of the cell, the missile had pointed end.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	12.25	72.0	40	2121	The missile perforated the barrier. The impact point was at the center of the cell, the missile had pointed end.	TTU (1990)
12 in. CMU with steel trusses in horizontal joints.		2 × 4 Board	13	85.0	50	3137	The missile perforated the barrier. The impact point was at the center of the cell.	TTU (1990)

Missile Direction

Section B - 2×4 Board missiles of various weights

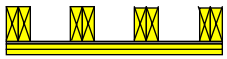
	Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
B2 - Reinforced Concrete Slabs									
	4 in. thick reinforced concrete; #3 rebar at 6 inch o.c. each way in the middle of the slab		2 × 4 Board	13.5	121.0	74	6602	No damage; the missile was reduced to splinters	TTU (1989)
	4 in. thick reinforced concrete; #3 rebar at 6 inch o.c. each way in the middle of the slab		2 × 4 Board	14	147.0	94	10105	Hairline cracks on the back face; missile was reduced to splinters	TTU (1989)
	4 in. thick concrete - NO Reinforcement		2 × 4 Board	14.25	122.0	79	7085	No penetration, 0.24 in vertical crack propagated through the panel	TTU (1989)
	6 in. thick reinforced concrete; #3 rebar at 6 inch o.c. each way in the middle of the slab		2 × 4 Board	13.75	140.0	88	9002	No damage; the missile was reduced to splinters	TTU (1989)
B3 - Brick Veneer Walls									
	Brick veneer wall with 1/2-in. insulation board and 1/2-in. gypsum wallboard.		2 × 4 Board	12.5	120.0	68	6012	The missile penetrated the target and the brick veneer crushed into small pieces. The backside wallboard remained intact.	Bailey (1984)
B4 - Plywood layers									
	1 layer of 3/4 inch Plywood		2 × 4 Board	14	48.4 - 54.2	31 - 35	1095 - 1374	Interior deformation - Total Failure	Robbins (1995)
	2 layers of 3/4 inch Plywood		2 × 4 Board	14	63.0 - 66.9	40 - 43	1856 - 2093	Interior deformation - Total Failure	Robbins (1995)
	3 layers of 3/4 inch Plywood		2 × 4 Board	14	76.6 - 84.5	49 - 54	2744 - 3339	Interior deformation - Total Failure	Robbins (1995)
	4 layers of 3/4 inch Plywood		2 × 4 Board	14	110.2 - 120.8	70 - 77	5679 - 6824	Interior deformation - Total Failure	Robbins (1995)
B5 - OSB layers									
	1 layer of 3/4 inch OSB		2 × 4 Board	14	NA	NA	NA	No lower bound could be established	Robbins (1995)
	2 layers of 3/4 inch OSB		2 × 4 Board	14	NA	NA	NA	No lower bound could be established	Robbins (1995)
	3 layers of 3/4 inch OSB		2 × 4 Board	14	62.3 - 67.4	40 - 43	1815 - 2124	Interior deformation - Total Failure	Robbins (1995)
	4 layers of 3/4 inch OSB		2 × 4 Board	14	74.3 - 90.9	47 - 58	2582 - 3864	Interior deformation - Total Failure	Robbins (1995)

Missile Direction

Section C - 10 ft. length, 3 in. diameter PVC pipe missiles

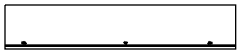
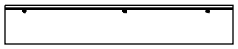
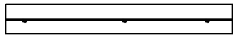
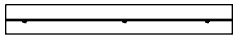
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
C1 - Reinforced Concrete Masonry Unit (CMU) Walls								
8 in. CMU reinforced with #4 rebar at 24-in. on center cells with rebar filled with grout.		10 ft Length, 3 in PVC	14.25	92.0	60	4029	No Damage was observed. The impact point was at the center of the cell where the grout and the rebar are located.	TTU (1990)
8 in. CMU reinforced with #4 rebar at 24-in. on center cells with rebar filled with grout.		10 ft Length, 3 in PVC	14	93.0	59	4045	No Damage was observed. The impact point was at the center of the cell where the grout and the rebar are located.	TTU (1990)
8 in. CMU reinforced with grout filled in every cell.		10 ft Length, 3 in PVC	14.25	102.0	66	4952	No penetration of the target occurred. Small cracks were observed. The impact point was at the joint between cells.	TTU (1990)

Section D - EMT Conduit missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
D1 - Reinforced Concrete Masonry Unit (CMU) Walls								
8 in. CMU reinforced with #4 rebar at 24-in. on center cells with rebar filled with grout.		EMT Conduit	14.75	67.0	45	2212	The missile penetrated the target. The impact point was at the center of the cell where the grout and the rebar are located.	TTU (1990)
D2 - Reinforced Brick Cavity Walls with Concrete Infill								
Brick wall with concrete interior wall and #4 rebar reinforcement.		10 ft; 1 in. EMT Conduit	7.45	116.9 - 190.0	40 - 64	3401 - 8983	Missile failed with very little damage to the target.	C & S (2001) I.W.
D3 - Stud Walls with Plywood and Steel Plate								
2 layers of ¾-in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		10 ft Length; 1 in. diameter EMT Conduit	7.45	< 48.0	< 16	< 573	The missiles repercussed.	C & S (2001) I.W.
				48.0 - 50.0	16 - 17	573 - 622	Threshold was observed.	
				> 50.0	> 17	> 622	The missiles perforated the barrier. (The impacts resulted in a hole punching effect.) (5 shots)	

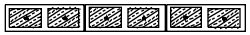
Missile Direction

Section E - 3 in. diameter Steel Pipe (Schedule 40) missiles

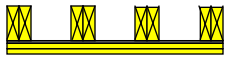
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
E1 - Reinforced Concrete Slabs								
6-in. slab with # 3' s 9 in. o.c. each way, 1.5-in. from the front face.		3 inch Steel Pipe	73	36.0	120	3160	The missile penetrated the target by 0.25 in. Radial cracks with a 0.19 in. maximum width propagated through slab.	Nevins (1993)
6-in. slab with # 4' s 12 in. o.c. each way, 1.5-in. from the back face.		3 inch Steel Pipe	73.25	37.0	123	3350	The missile penetrated the target by 0.38 in. Radial cracks with a 0.06 in. maximum width propagated through slab.	Nevins (1993)
6-in. slab with # 3' s 6 in. o.c. each way, 1.5-in. from the back face.		3 inch Steel Pipe	73	38.0	126	3521	The missile penetrated the target by 0.38 in. Radial cracks with a 0.06 in. maximum width propagated through slab.	Nevins (1993)
8-in. slab with # 4' s 9 in. o.c. each way, placed in the middle of the slab.		3 inch Steel Pipe	72.5	44.0	145	4688	The missile penetrated the target by 0.38 in. Radial cracks with a 0.06 in. maximum width propagated through slab.	Nevins (1993)
8 in. slab with # 4' s 12 in. o.c. each way, placed in the middle of the slab.		3 inch Steel Pipe	79.5	44.0	159	5141	The missile penetrated the target by 0.63 in. Radial cracks with a 0.06 in. maximum width propagated through slab.	Nevins (1993)
8 in. slab with # 3' s 12 in. o.c. each way, placed 1.5 in. from each face.		3 inch Steel Pipe	79.5	50.0	181	6639	The missile penetrated the target by 0.69 in. Radial cracks with a 0.09 in. maximum width propagated through 3/4 of slab width.	Nevins (1993)
9 in. slab with # 4' s 12 in o.c. each way, placed 1.5 in. from each face.		3 inch Steel Pipe	79	50.0	180	6597	The missile penetrated the target by 0.44 in. Hairline radial cracks propagated through half the slab thickness.	Nevins (1993)
9 in. slab with # 4' s 12 in. o.c. each way, placed 1.5 in. from each face.		3 inch Steel Pipe	76.5	78.0	272	15546	The missile penetrated the target by 1.5 in. Radial cracks propagated with scabbing, scab fragments had dimensions of 1.0 in x 0.5 in.	Nevins (1993)
10 in. slab with # 4' s 12 in. o.c. each way, placed 1.5 in. from each face.		3 inch Steel Pipe	73.5	74.0	248	13444	The missile penetrated the target by 0.81 in. Radial cracks with hairline width, cracks did not propagate through slab.	Nevins (1993)

Missile Direction

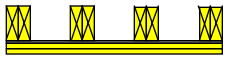
Section E - 3 in. diameter Steel Pipe (Schedule 40) missiles

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
E2 - Reinforced Concrete Masonry Unit (CMU) Walls								
8 in. grouted CMU wall with # 4 bars 8 in. o. c. and horizontal ties 16 in. o.c., single brick wythe on front face.		3 inch Steel Pipe	77	50.0	175	6430	The missile penetrated the target by 2.13 in. Vertical cracks with a 0.38 in. maximum width propagated through wall.	Nevins (1993)
8 in. grouted CMU wall with # 4 bars 8 in. o. c. and horizontal ties 16 in. o.c.		3 inch Steel Pipe	77.5	51.0	180	6733	The missile perforated the target. Pieces of scabbing weighing between 7 and 14 lbs. were found.	Nevins (1993)
12 in. grouted CMU wall with # 4 bars 12 in. o. c. and horizontal ties 16 in. o.c.		3 inch Steel Pipe	73.5	59.0	198	8546	The missile penetrated the target by 1.38 in. Threshold of scabbing reached.	Nevins (1993)
E3 - Reinforced Brick Cavity Walls with Concrete Infill								
9.5 in. brick cavity wall (grouted) with # 4 bars 8 in. o.c. and horizontal ties 16 in. o.c.		3 inch Steel Pipe	79	50.0	180	6597	The missile penetrated the target by 1.13 in. Vertical cracks with a 0.25 in. maximum width propagated through wall.	Nevins (1993)

Section F - 15 lbf, 3 inch diameter Pressure-treated Fence Post missiles

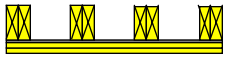
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
F1 - Stud Walls with Plywood and Steel Plate								
2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		3 in Pretreated. Fence Post	15	< 133.0	< 91	< 8863	The missiles repercussed. (5 shots)	C & S (2001) I.W.
				133.0 - 136.0	91 - 93	8863 - 9267	Threshold was observed. (3 shots)	
				> 136.0	> 93	> 9267	The missiles perforated the barrier. (1 shot)	

Section G - 15 lbf, 2×6 Board missiles

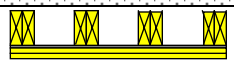
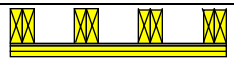
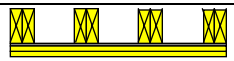
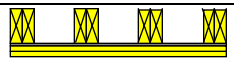
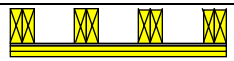
Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
G1 - Stud Walls with Plywood and Steel Plate								
2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 × 6 Board	15	< 165.0	< 113	< 13641	The missiles repercussed. (5 shots)	C & S (2001) I.W.
				NA	NA	NA	The speed necessary to perforate the target is beyond the capacity of the canon. Testing the missile configuration at higher speeds was abandoned.	


Missile Direction

Section H - 22.5 lbf, 2×6 Board missiles

	Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
H1 - Stud Walls with Plywood and Steel Plate									
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 × 6 Board	22.5	< 165.0	< 169	< 20461	The missiles repercussed. (5 shots)	C & S (2001) I.W.
					NA	NA	NA	The speed necessary to perforate the target is beyond the capacity of the canon. Testing the missile configuration at higher speeds was abandoned.	

Section I - Clay Brick missiles

	Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
I1 - Stud Walls with Plywood and Steel Plate									
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 5/8 in × 3 in × 8 5/8 in Clay Brick	4.05	131.9	24	2354	Missile impacted and rebounded. Penetrated target 1/2 inch causing very slight deflection in steel of non-impact side.	C & S (2001) I.W.
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 5/8 in × 3 in × 8 5/8 in Clay Brick	4.05	225.9	42	6903	Missile reduced to powder; penetration 1 inch and permanent deflection in steel of 1/2 inch	C & S (2001) I.W.
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 5/8 in × 3 in × 8 5/8 in Clay Brick	4.05	231.4	43	7244	Missile penetrated 1.75 inch then turned into powder. Deflected steel on non-impact side of 1 inch. Cracked outside stud.	C & S (2001) I.W.
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 5/8 in × 3 in × 8 5/8 in Clay Brick	4.05	232.6	43	7319	Missile perforated target causing 3.5 inch petaling and deflection to non-impact side. Brick remained lodged in the target.	C & S (2001) I.W.
	2 layers of ¾ in. plywood, one layer of 14 ga. steel and the 4x4 ft, double stud frame.		2 5/8 in × 3 in × 8 5/8 in Clay Brick	4.05	270.3	50	9884	Missile penetrated 2.5 inch causing 1.5 in deflection in steel on non-impact side. Both studs cracked. Brick disintegrated.	C & S (2001) I.W.

Missile Direction

Section J - 2×4 Board missile Drop tests (65 mph)

Target Name	Target Description	Missile Description	Missile Weight (lbf)	Missile Speed (MPH)	Missile Momentum (lbf-s)	Missile Energy (ft-lbf)	Damage Description	Reference
J1 - Wall sections								
3/4 inch plywood	NA	2 × 4 Board	15.8	65.0	47	481	Missile passed through	Thompson (1973)
Expanded metal (1/4 inch) over 3/4 inch plywood	NA	2 × 4 Board	46.3	65.0	137	1411	Missile passed through	Thompson (1973)
3/4 inch plywood over expanded metal	NA	2 × 4 Board	86.9	65.0	257	2650	Plywood was penetrated, several wires broken	Thompson (1973)
3/4 inch plywood-lightweight concrete - 3/4 inch plywood	NA	2 × 4 Board	86.9	65.0	257	2650	Plywood was penetrated, concrete broke in cone shaped hole, bottom plywood cracked	Thompson (1973)
3/4 inch plywood - expanded metal - lightweight concrete - 3/4 inch concrete	NA	2 × 4 Board	185.1	65.0	548	5645	Plywood was penetrated, several wires broken, concrete broke in cone shaped hole, bottom plywood had 1 inch deep bulge	Thompson (1973)
3/4 inch plywood - lightweight concrete - expanded metal - 3/4 inch plywood	NA	2 × 4 Board	185.1	65.0	548	5645	Plywood was penetrated, concrete broke in cone shaped hole, 3 inch deep bulge in wire, bottom plywood cracked	Thompson (1973)
Concrete block beam filled with lightweight concrete	NA	2 × 4 Board	92.5	65.0	274	2822	Block beam destroyed	Thompson (1973)
Concrete block beam filled with lightweight concrete with #3 rebar in each cavity	NA	2 × 4 Board	185.1	65.0	548	5645	No penetration or cracks	Thompson (1973)
Preformed, steel reinforced masonry wall panel, about 4 inch thick	NA	2 × 4 Board	185.1	65.0	548	5645	No penetration, one horizontal mortar joint cracked, allowing about 1 inch lateral deformation in 4 ft span, impacted brick did not crack, missile shattered	Thompson (1973)
1 3/4 inch solid wood	NA	2 × 4 Board	74.0	65.0	219	2258	Wall section destroyed	Thompson (1973)
J2 - Doors								
Solid (filled) door	NA	2 × 4 Board	86.9	65.0	257	2650	Missile passed through	Thompson (1973)
16 gage steel over hollow-core door	NA	2 × 4 Board	86.9	65.0	257	2650	Metal deformed, door destroyed	Thompson (1973)
Expanded metal over filled door	NA	2 × 4 Board	74.0	65.0	219	2258	Missile passed through	Thompson (1973)
Filled door over expanded metal	NA	2 × 4 Board	74.0	65.0	219	2258	Missile passed through door, large deformation in wire	Thompson (1973)
Hollow core door over 16-gage steel	NA	2 × 4 Board	74.0	65.0	219	2258	Door destroyed, large deformations in metal	Thompson (1973)
14 gage steel over 1 1/2 inch solid wood door	NA	2 × 4 Board	175.8	65.0	521	5362	Large deflection of metal door cracked	Thompson (1973)

Missile Direction

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