THE EFFECTS OF WINDBORNE DEBRIS ON SAFEROOM WALL PANELS AND FENESTRATION SYSTEMS

Stephen T. Peters

and

Ian N. Robertson

UNIVERSITY OF HAWAII
COLLEGE OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Research Report UHM/CEE/12-10

February 2012

ABSTRACT

Twenty-three different saferoom wall panels and six different fenestration assemblies were tested for hurricane debris impact resistance. The American Society for Testing and Materials (ASTM) E 1886-05 and ASTM E 1996-09 specifications provided requirements for the test procedures and analysis criteria. The focus of the research was to establish an economic pre-qualified list of assemblies for inclusion in the Hawaii State Building Code. The saferoom test specimens consisted of 4ft by 8ft and 4ft by 4ft wall panels framed using either wood or cold formed steel studs at 16in and 24in on center. The fenestration assemblies consisted of polyvinyl chloride (PVC) louver windows and aluminum diamond mesh protection screens of varying sizes. Each test specimen was shot with a projectile missile that corresponded with the protection requirement. The windborne debris missiles were fired by a pressurized-air cannon built and operated by the University of Hawaii at Manoa and Hawaii State Civil Defense.

It was found that the type and spacing of stud used in the construction of the saferoom panels generally did not affect the performance of the system. The cladding material combinations that proved most effective in debris impact resistance were 22gauge sheet metal, Hardie Board lap siding over 5/8in plywood, and 3/4in plywood. The PVC louver window panels passed the small missile test, but did not pass the level C large missile test. The aluminum diamond mesh screens passed the level C large missile test. The maximum dynamic deflection of the small and large window screens was 5in and 4.6in. The combination of aluminum diamond mesh screen and PVC louver window panels could potentially meet the level D large missile test though more testing would be required to verify this performance.

TABLE OF CONTENTS

TABLE OF FIGURES

1 INTRODUCTION

1.1 Background

The Hawaiian archipelago islands, located in the central Pacific Ocean, are in the direct path of many tropical storms. There have been a total of 38 tropical cyclones, either tropical storms or hurricanes, that have affected Hawaii since 1949. The most recent devastating storm, Iniki, struck the islands in September 1992 causing $2 billion in damage and claiming 6 lives. Kauai experienced the fastest wind gusts, measuring approximately 120MPH sustained speeds at landfall, which classified it as a Category 3 hurricane based on the Saffir-Simpson Scale. Many of the residential houses in Kauai had their windows shattered due to the magnitude of windborne debris in the air. This allowed internal pressurization to develop inside the houses and in turn created enough uplift to tear roofs from their rafters. This disastrous event not only proved to be costly but exposed families inside to the harmful elements.

Typical windborne debris objects found in these tropical cyclones are large missile objects such as loose timber and tree limbs, and small missile objects such as gravel and roof ballast. The large missile objects may only travel at a fraction of the wind speed but are still capable of penetrating residential walls of homes and breaking through window fenestrations. Since many commercial buildings are finished with rock ballast on the top of their roof, these tropical storms have been known to lift the stones during an event and propel them against the glass face of other buildings causing a brittle shattering failure.

Each county in the state of Hawaii currently has adopted their own version of the International Building Code (IBC) and International Residential Code (IRC). On April 16th, 2010 the State of Hawaii adopted a state building code which required all counties to subsequently implement the 2006 IBC (ICC 2006) with optional state amendments (Table 1-1). The counties were given two years to implement the state code, at which time it would be automatically mandated.

Table 1-1: Current and Future County Code Adoption

County	Adopted	Under Additional Consideration
Honolulu	2006 IBC and 2003 IRC	2006 IRC
Hawaii	2006 IBC	
Maui	2006 IBC	2006 IRC
Kauai	2006 IBC and 2003 IRC	2006 IBC and IRC
State of Hawaii	2006 IBC	2009 IBC and 2009 IRC

The 2003 IBC, which was the most recent code for Honolulu City and County, required the implementation of window protection systems up to 60ft in all category IV buildings as well as some category III and II buildings. An alternative to this requirement is the option to leave windows unprotected and design the building as a partially enclosed structure subjected to internal pressurizations typical during a Category 3 hurricane. This can help to decrease the damage done to an individual's property; however, it is still not safe for residents to shelter in place. They would still need to evacuate to a designated shelter. Honolulu City and County has adopted the 2006 IBC as of April 16th 2012. This new code, along with Hawaii State amendments, has more refined allowances for the windborne debris requirements based on the building risk category (Table 1-2).

Table 1-2: 2006 IBC with State Amendments Windborne Debris Requirements

Risk Category	Description	Windborne Debris for Portion of Building ≤ 60ft. Required? Note: Large Missile for ≤ 30ft Small Missile for > 30ft.
I	Buildings and Other Structures that Represent a Low Hazard to Human Life in the Event of Failure, Such as: + Agricultural Facilities + Temporary Structures + Minor Storage Facilities	Not Required
II	All Buildings and Structures Not in Categories I, II, or IV	+ Not Required if it is Structurally Designed for Internal Pressure + Residential Safe Room req'd by State Building Code for R-3 Buildings (Single and Two-Family Dwellings, Adult Care Facilities for Five or Fewer Persons, Child Care Facilities for Five or Fewer Persons, and Congegrate Living Facilities with 16 or Fewer Persons)
III	Buildings and other structures that represent a Substantial Hazard to Human Life in the Event of Failure + Buildings whose Primary Occunpancy is Public Assembly with an Occupant Load Greater than 300 Persons + Elementary and Secondary Education Facilities with an Occupant load Greater than 250 Persons + College and University Facilities with an Occupant Load Greater than 500 Persons + Health Care Facilities with an Occupant Load of 50 or more Resident Patients, but not Having Surgery or Emergency Treatment Facilities + Any Other Public Building with an Occupant Load Greater than 5,000	Glazing Protection Required for: a. Covered Structures whose Primary Occupancy is Public Assembly with an Occupant Load Greater than 300 b. Health Care Facilities with an Occupant Load of 50 or more Resident Patients, but not having Surgery or Emergency Treatment Facilities. c. Any other Public Building with an Occupant Load Greater than 5,000
IV	Essential Facilities Including: + Health Care Facilities with Surgery or Emergency Room Facilities + Fire, Rescue, Police, and Ambulance Buildings + Designated Emergency Shelters + Emergency Operations Centers and Communications Centers + Power-Generation Station Buildings + Buildings with Highly Toxic Materials + Aviation Control Towers + Water Storage/Pump Stations	Glazing Protection Required for all Category IV Buildings and Structures

By providing opening protection systems, such as hurricane screens and impact resistant glazing panels, Hawaii can reduce the risk of homeowner property loss and overall cost of damage to government structures. The current material cost of providing opening protection for a 2000 square foot regular family home not exceeding 400 square feet total glazed area is estimated at $10,000. This includes the use of 5/16in thick impact resistive heat strengthened laminated glass with 0.090in polyvinyl butyral (PVB) interlayer covering all fenestrations (SEAOH, 2012). Provided the residence is otherwise structurally sound for hurricane resistance, this will allow residents to "shelter in place" and not seek refuge elsewhere.

The implementation of safe rooms in residential homes places an emphasis on protecting human lives. The state of Hawaii does have designated evacuation shelters provided for the general public; however, there is a shortage of space and providing protection for the entire population is infeasible. Therefore, by temporarily providing an enhanced protection area in individual's residential homes this will increase the level of safety provided to the general public in the event of a tropical storm. Each safe room must be fully enclosed within a dwelling or within an accessory structure to a residence. It must be designed and constructed as a self sufficient structural system capable of carrying the full superimposed dead load of the building. In addition, it must also simultaneously resist lateral and uplift wind pressures imposed by the hurricane.

1.2 Objective

The Hawaii State Legislature, through State Civil Defense, provided funding to fabricate a windborne debris cannon. This equipment was designed, constructed, and operated by the Civil Engineering Department at the University of Hawaii at Manoa with oversight from State Civil Defense.

Additional funding provided by the Department of Business, Economic Development & Tourism (DBEDT) Office of Planning Hawaii Coastal Zone Management Program and under coordination of Martin and Chock, was provided to test typical wall framing systems for use in safe room construction. Local timber and steel framing industries fabricated and donated various wall panel assemblies for testing. These panels are consistent with typical framing assemblies found in current Hawaiian residential construction projects. Each panel was subjected to large missile impact forces corresponding to those found in a Category 3 hurricane. The results from the testing will be used to develop a pre-qualified list of acceptable safe room designs used by county building officials in compliance with the Hawaii State Building Code (IBC 2006). Each panel was tested in accordance with the procedures outlined in the American Society for Testing and Materials (ASTM) E 1886-05 and ASTM E 1996-09.

The initial cannon design was intended to conduct only large missile testing of safe room assemblies. In order to also perform a small missile test, as defined in the ASTM E 1996-09, of fenestrations and window protection systems, the equipment was modified to accommodate this test procedure. The design, analysis, and fabrication of this system were undertaken by the University of Hawaii research team and calibrated for regular test operation.

The cannon has also been used for education purposes and outreach to the public, legislators, media, local engineers, and military personnel. In this aspect, it has served as a demonstrative tool for raising awareness of the need for shelters and improvement to local building codes.

2 LITERATURE REVIEW

2.1 Overview

The American Society for Testing and Materials (ASTM) has established a test method to help determine the performance of exterior windows, curtain walls, doors, and impact protective systems impacted by missiles. This provides guidance in establishing an appropriate missile propulsion device and test chamber as well as official testing procedures and failure analysis. All related material may be found in the ASTM E 1886-05 and ASTM E 1996-09 specifications.

The Wind Science and Engineering Research Center at Texas Tech University has been conducting similar testing since 1973 and has compiled all of their findings in their latest summary report (Texas Tech University, 2003). Much of their testing has been directed toward debris velocities found in Category 5 hurricanes and tornados. In order to keep the University of Hawaii's Category 3 hurricane testing results comparable with those previously conducted; some standard definitions need to be established.

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.

Repurcussed denotes that the missile was repelled or failed to inflict sufficient damage to the target to endanger a person on the non-impact side.

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:

$$p = m \times v = \frac{w}{g} \times v$$

Where w is the weight of the missile in pounds-force (lbf), g is the acceleration due to 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:

$$T = \frac{1}{2} \times m \times v^2 = \frac{1}{2} \times \frac{w}{g} \times v^2$$

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).

3 TEST SETUP AND CALIBRATION

3.1 General Equipment Overview

The wind cannon test system is comprised of a 25ft long cannon oriented orthogonally to a steel test frame which is surrounded by a polycarbonate protection barrier (Figure 3-1 and Figure 3-2).

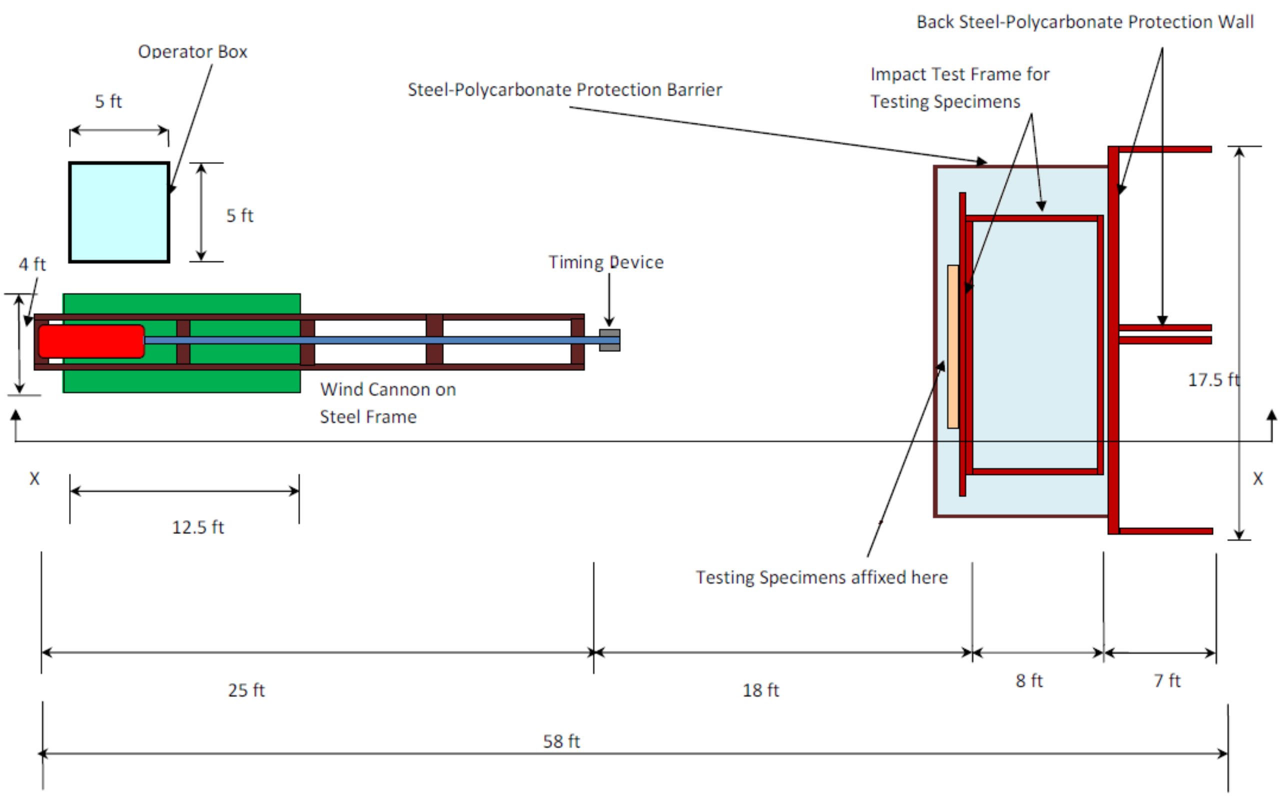

Figure 3-1: Wind Cannon System Plan View

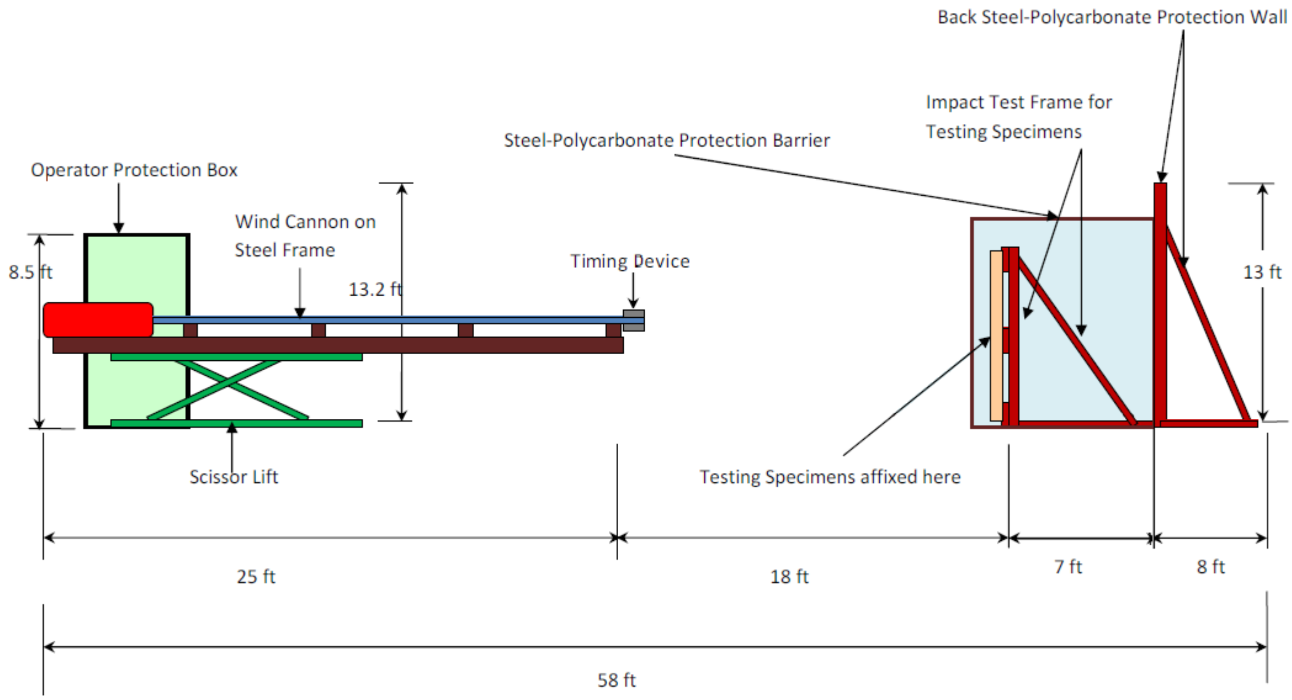

Figure 3-2: Wind Cannon System Profile View (Section X-X)

The wind cannon is pneumatically driven using compressed air which is stored in a 10gal tank at the rear of the cannon. The pressurized air is released via a Schaevitz butterfly valve into the 4in diameter 20ft long polyvinyl chloride (PVC) barrel. This is situated on top of a hydraulic scissor lift that allows the technician to adjust the height of the equipment. Both the butterfly valve and storage tank are supplied with pressurized air via a 25HP compressor. They are connected in series to a control box that allows the technician to operate the pneumatics manually (Figure 3-4). The test missile is loaded into the front of the cannon and physically pushed a fixed distance (10ft) to the rear. As the compressed air is released by the butterfly valve (Figure 3-5), the pressure behind the missile causes it to accelerate down the length of the barrel and out the front. A fiber optic timing device manufactured by Keyence Corp is installed on the muzzle of the cannon and records the leading edge velocity of the missile (Figure 3-6). A laser siting device, attached near the end of the muzzle, was used to pinpoint the exact impact location of the missile (Figure 3-7).

Figure 3-3: Wind Cannon System Isometric View

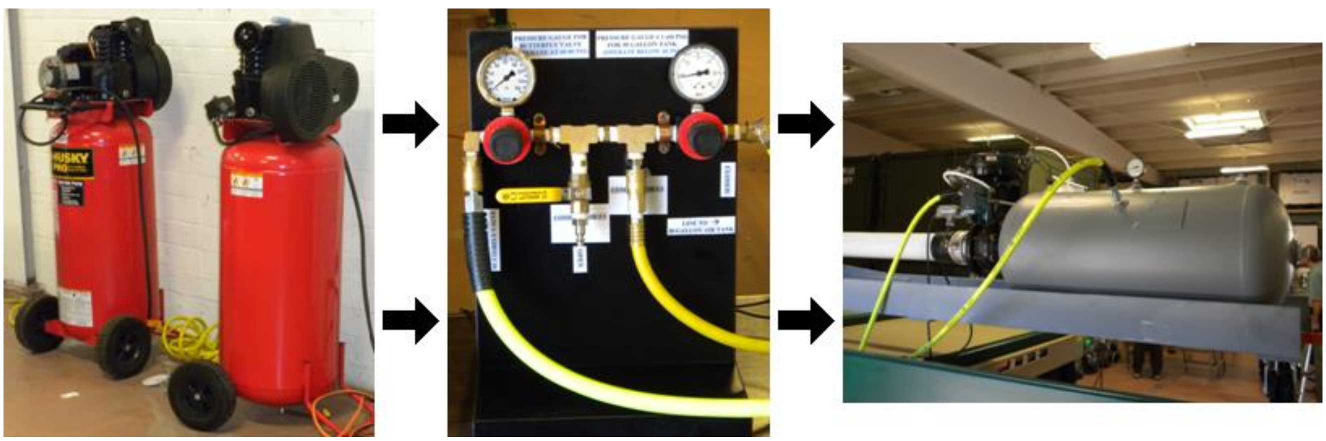

Figure 3-4: Compressor, Control Box, Butterfly Valve and Tank Setup

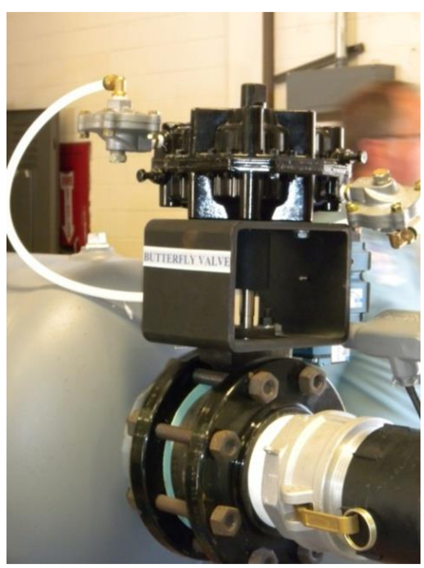

Figure 3-5: Butterfly Valve

Figure 3-6: Timing Device with Installed Fiber Optic Sensors

Figure 3-7: Laser Siting Device

The wall panel test specimens are mounted at the top and bottom to an inner adjustable steel frame (Figure 3-8). The stiffness of the frame does not allow the panel to deflect laterally at the top and bottom edges but does along the unbraced height. A steel-polycarbonate protection barrier and wall surround the inner frame to stop any missiles from penetrating through the rear. A steel-polycarbonate operator box was also constructed with the original intent that the technician could stand in it to protect himself from recoiling missiles (Figure 3-9). It was actually implemented to protect the expensive high speed cameras used during the testing.

Figure 3-8: Steel Test Frame Surrounded by Polycarbonate Protection Barrier

Figure 3-9: Operator Protection Box

Two MS75K and MS80K model high speed cameras, manufactured by Mega Speed Corp, were used to record the images of the frontside and backside impact locations (Figure 3-10). The videos were helpful in analyzing the results and were used for documentation purposes and presentation aids. They were also instrumental for calibrating the cannon by monitoring the missile velocity.

Figure 3-10: MS75K Mega Speed Camera

3.2 Large Missile Test

3.2.1 Test Missile Overview

The ASTM E 1996-09 states that Hawaii shall design for basic wind speeds based on Wind Zone 1 criteria. This requires enhanced protection (essential facilities) from level D missiles (Table 3-2) through all heights of the structure and basic protection from level C missiles below 9.1m (Table 3-1). The level D missile used for testing is an 8ft long lumber stud weighing 9.0lbs and traveling with a velocity of 15.25m/s (50ft/s). The level C missile used for testing is a 4ft long lumber stud weighing 4.5lbs and traveling with a velocity of 12.19m/s (40ft/s). Both missiles are fitted with a 1/4in thick 4in diameter plastic circular sabot on the trailing end (Figure 3-11 and Figure 3-12). This provides the released tank pressure with an area to exert a force on the missile and accelerate it down and out the barrel (Figure 3-13).

> **6.2.2.1** Wind Zone 1 – 110 mph (49 m/s) ≤ basic wind speed < 120 mph (54 m/s), and Hawaii

Table 3-1: ASTM E 1996-09 Description Levels

Level of Protection	Enhanced Protection (Essential Facilities)		Basic Protection		Unprotected	
Assembly Elevation	≤9.1 m (30 ft)	>9.1 m (30 ft)	≤9.1 m (30 ft)	>9.1 m (30 ft)	≤9.1 m (30 ft)	>9.1 m (30 ft)
Wind Zone 1	D	D	C	A	None	None
Wind Zone 2	D	D	C	A	None	None
Wind Zone 3	E	D	D	A	None	None
Wind Zone 4	E	D	D	A	None	None

Table 3-2: ASTM E 1996-09 Applicable Large Missiles

Missile Level	Missile	Impact Speed (m/s)
A	2 g (31 grains) ± 5% Steel Ball	39.62 (88.63 mph)
B	910 g ± 100 g (2.0 lb ± 0.25 lb) 2 x 4 in. 52.5 cm ± 100 mm (1 ft - 9 in. ± 4 in.) lumber	15.25 (34.11 mph)
C	2050 g ± 100 g (4.5 lb ± 0.25 lb) 2 x 4 in. 1.2 m ± 100 mm (4 ft ± 4 in.) lumber	12.19 (27.27 mph)
D	4100 g ± 100 g (9.0 lb ± 0.25 lb) 2 x 4 in. 2.4 m ± 100 mm (8 ft ± 4 in.) lumber	15.25 (34.11 mph)
E	4100 g ± 100 g (9.0 lb ± 0.25 lb) 2 x 4 in. 2.4 m ± 100 mm (8 ft ± 4 in.) lumber	24.38 (54.54 mph)

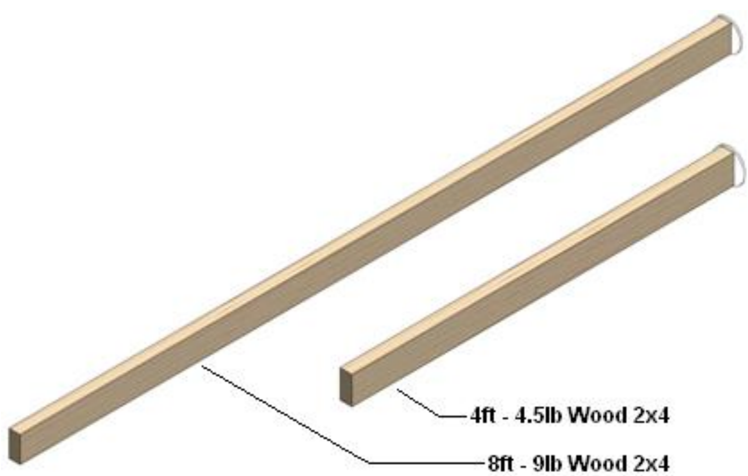

Figure 3-11: Large Missile Test Specimens

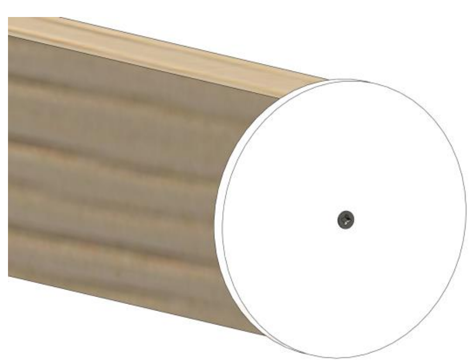

Figure 3-12: Plastic Sabot Fastened to Rear End of Large Missile

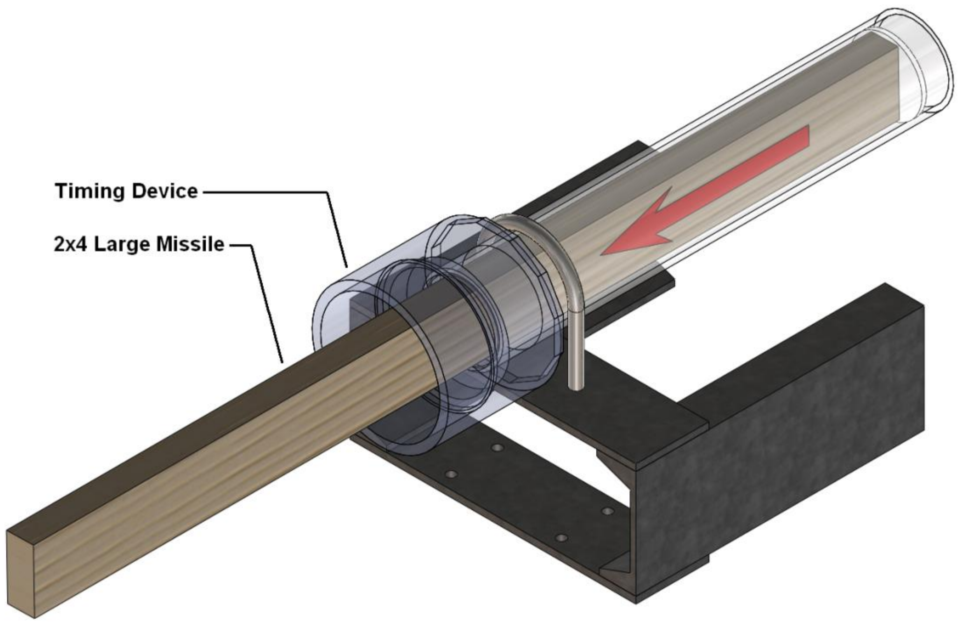

Figure 3-13: Large Missile System

Based on the weight and velocity requirements for the large missile, a range of ideal momentum and energy values were established (Table 3-3). Due to the variability in the test equipment many of the momentum and energy values fell outside the desired range. Most, however, were on the higher end which produced more conservative results.

Table 3-3: Large Missile Ideal Momentum and Energy Range

Large Missile Category	Impact Velocity (mph)	Weight (lbs)	Ideal Momentum (lbf-s)	Ideal Energy (ft-lbf)
C	27.27	4.5 ± 0.25	5.28 - 5.90	105.59 - 118.01
D	34.11	9 ± 0.25	13.59 - 14.36	339.67 - 359.08

3.2.2 Pretest Calibration

A program was written using Keyence Ladder Builder software to track the velocity of the missile leaving the muzzle of the cannon (Figure 3-14). Using two fiber optic sensors installed at the end of the cannon, the velocity of the missile was calculated at the leading edge and displayed on a Keyence KV-D20 Operator Interface Panel.

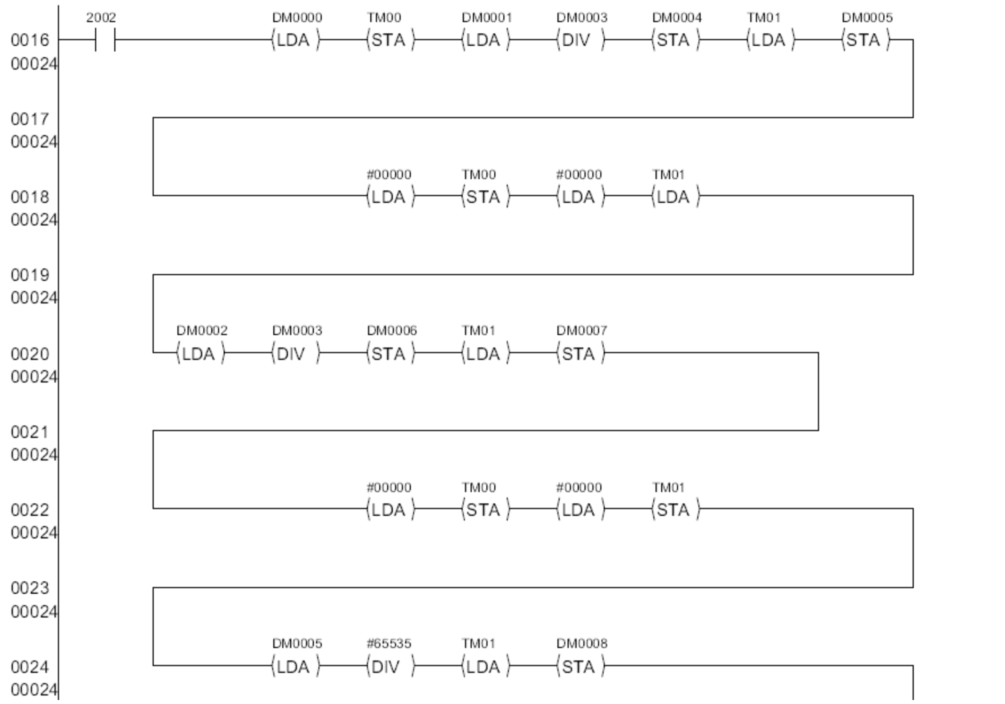

Figure 3-14: Muzzle Velocity Program Example

Since the timing device installed on the muzzle of the cannon was to be used in the calculation of the official velocity recordings, the precision of its readings needed to be verified. High speed Camera A was set to 5,000 frames-per-second (fps) and was used to calculate the exit velocity of a typical 8ft - 9lb large missile across a range of pressures and velocities. These results were compared to the digital recordings of the timing device and found to be accurate within an average of 1.47% (Figure 3-15). This was within the specified tolerance as defined by the ASTM E 1886-05, so the timing device was used for the official muzzle velocity readings.

> **"9.1** The speed measuring system shall be calibrated to an accuracy of ±2% of the elapsed time required to measure the speed of the specified missile…. The speed measuring system shall be calibrated by at least one of the following methods:
>
> **9.1.2** Photographically, using a high speed motion picture or video camera with a frame rate exceeding 500 fps and capable of producing a clear image and a device that allows single frame viewing." (ASTM E 1886-05)

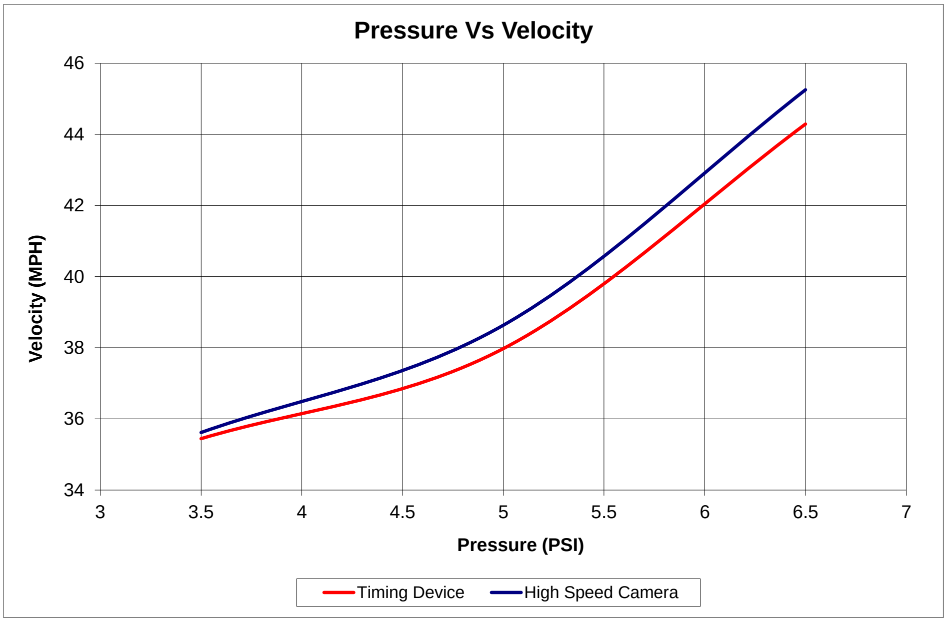

Figure 3-15: Muzzle Velocity from both Camera and Timing Device

Due to air drag as well as the variable wind force at the rear of the test missile, it was desirable to track how the velocity of the missile varied from the time it exited the muzzle to the time it impacted the test specimen. A series of trial shots had to be conducted for both the 8ft – 9lb and 4ft – 4.5lb test missile. The timing device was used to record the exit velocity while high speed Camera A was used to record the velocity as the missile passed the specimen plane. The camera was set to 5000fps and arranged orthogonally to the direction of the missile trajectory (Figure 3-16).

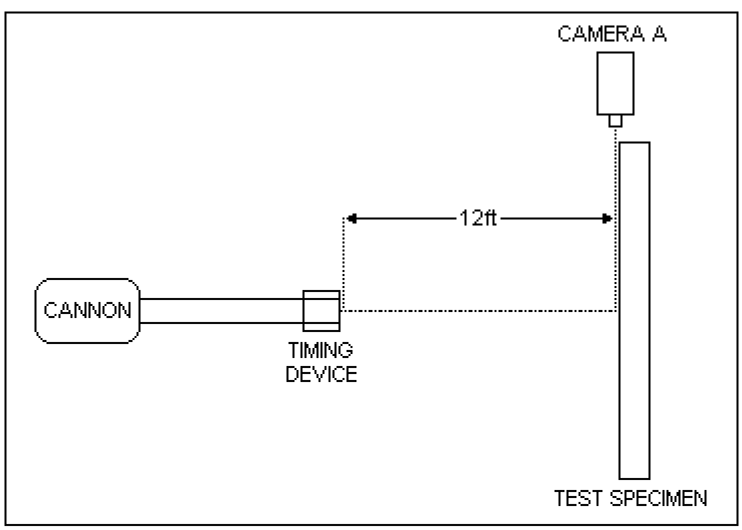

Figure 3-16: High Speed Camera Orientation for Calibration

As expected, the cannon pressure used to accelerate the missile directly affected the relationship between the muzzle velocity and impact velocity. For the 8ft – 9lb missile, the impact velocity was lower than the muzzle velocity until around 9.5psi (Figure 3-17). For the 4ft – 4.5lb missile, this intersecting point was closer to 7.4psi (Figure 3-18).

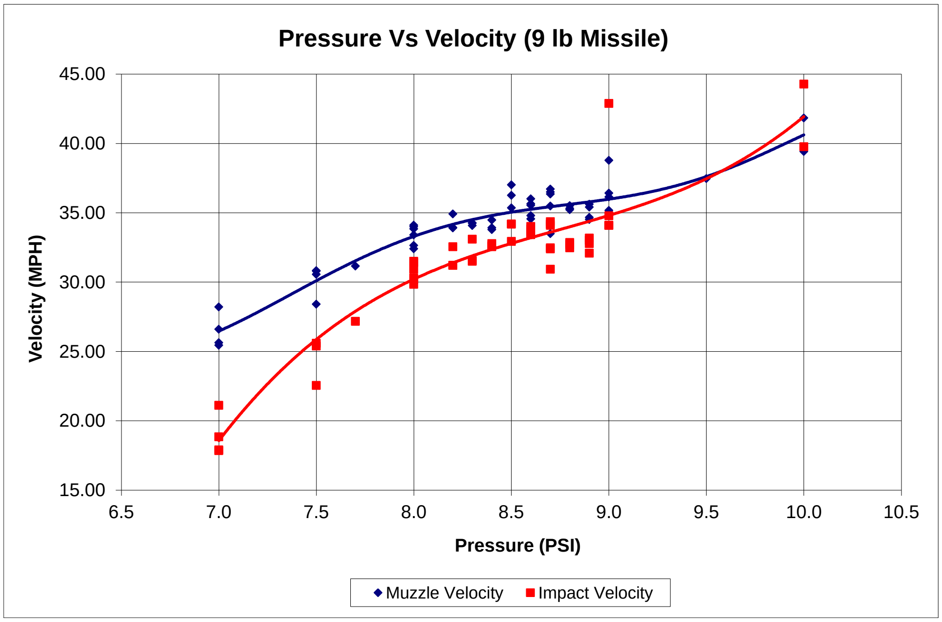

Figure 3-17: Pressure VS Velocity (8ft – 9lb)

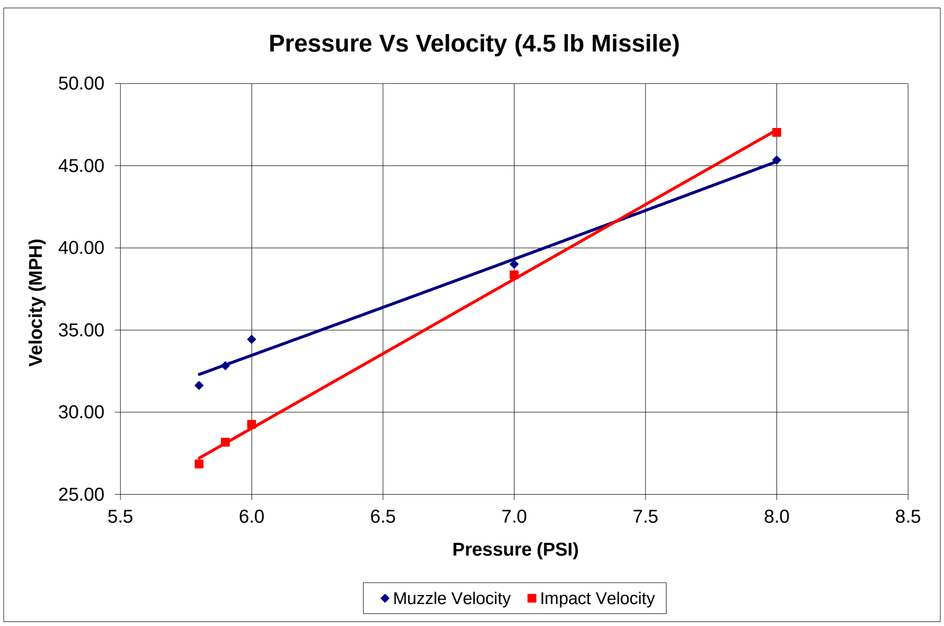

Figure 3-18: Pressure VS Velocity (4ft – 4.5lb)

To accurately calculate the official impact velocity of each test shot using only the reading from the timing device, a scatterplot of the two variables was created and a linear regression line equation was calculated (Figure 3-19 & Figure 3-20). The equation for the 8ft – 9lb missile is assumed to be accurate only for muzzle velocity readings between 26-41mph. The equation for the 4ft – 4.5lb missile is assumed to be accurate only for muzzle velocity readings between 32-45mph.

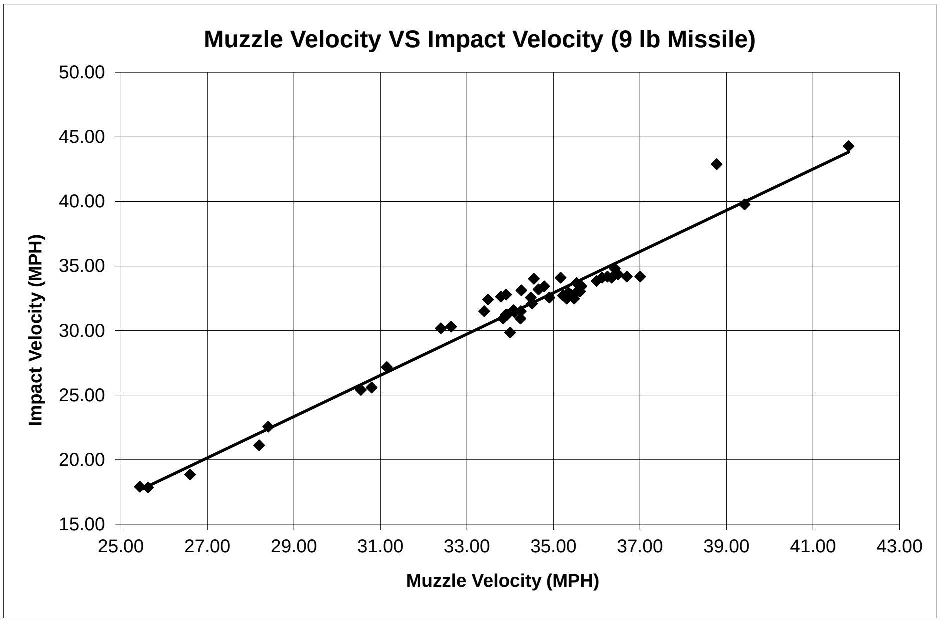

Figure 3-19: Muzzle Velocity VS Impact Velocity (8ft – 9lb)

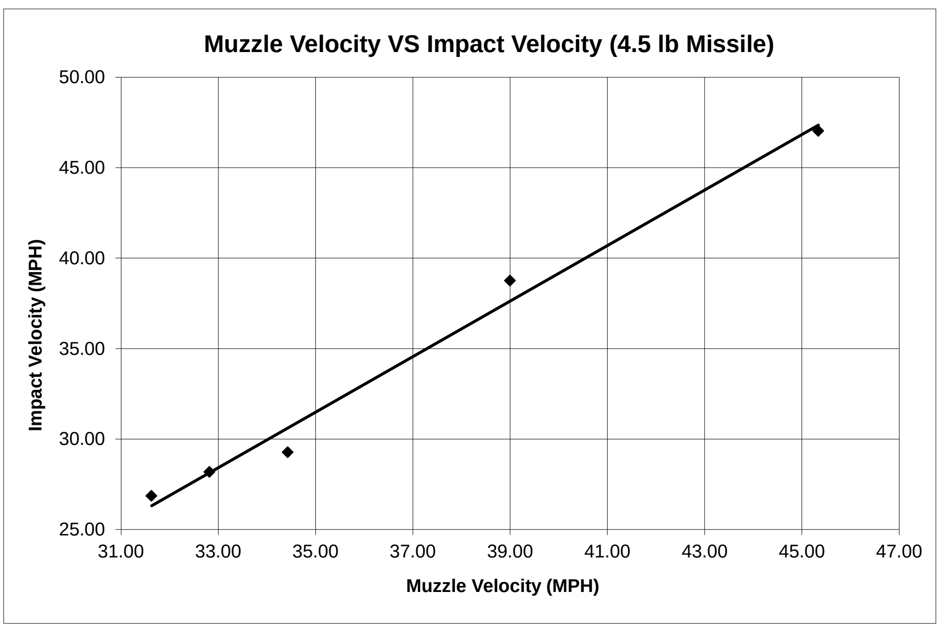

Figure 3-20: Muzzle Velocity VS Impact Velocity (4ft – 4.5lb)

Calibration was also performed at velocities between 41-100mph for the 8ft – 9lb large missile. These are not relevant to the tests performed in this study.

3.2.3 Test Procedure

Each large missile was required to strike the test specimen in a certain impact location based on the requirements of ASTM E 1996-09. Since it was believed that the impact damage from one test could affect the structural integrity of the specimen for another test, three identical panels were required for testing. It was originally planned that each panel would be shot with one missile before switching to a new undamaged panel for the next shot. Figure 3-21 shows the impact location for the large missile testing.

> "**5.3** *Location of Impact*
>
> **5.3.1.1** Impact one specimen with the center of the missile within a 65 mm (2 ½ in.) radius circle and with the center of the circle located at the center of each type of infill.
>
> **5.3.1.2** Impact a different specimen with the center of the missile within a 65 mm (2 ½ in.) radius circle and with the center of the circle located 150 mm (6 in.) from supporting members at a corner.
>
> **5.3.1.3** Impact the remaining specimen with the center of the missile within a 65 mm (2 ½ in.) radius circle and with the center of the circle located 150 mm (6 in.) from supporting members at a diagonally opposite corner." (ASTM E 1996-09)

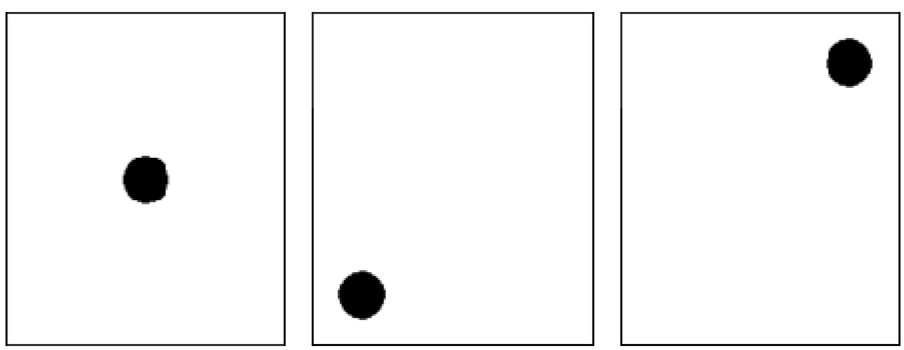

Figure 3-21: Large Missile Impact Locations

After conducting several trial runs, it was determined that the damage from the first shot did not affect the performance of the panel for the next shot. For this reason, one panel was tested in the lower and upper corners and a second panel was tested in the center. The third panel was saved in case any additional shots were needed.

The laser siting device (Figure 3-7) had to be calibrated in order to accurately propel the missile at the test specimen and strike the object within the required 2 ½ in radius. A trial run was conducted to accurately adjust the laser to the corresponding weight and speed of the test missile. The cannon could then be adjusted in the lateral and vertical direction to ensure proper missile impact location.

As defined by ASTM E 1886-05, the following set of test procedures are required for proper test operation;

> "**11.1.2** Missile Impact – Secure the specimen and mounting frame such that the missile will impact the exterior side of the specimen as installed.
>
> **11.1.5** Weigh each missile within 15 min prior to impact.
>
> **11.1.6** Load the missile into propulsion device.
>
> **11.1.7** Reset the speed measuring system.
>
> **11.1.8** Align the missile propulsion device such that the specified missile will impact the test specimen at the specified location.
>
> **11.2** Propel the missile at the specified impact speed and location."

If one of the three tests is deemed a failure, another test at that particular impact location shall be repeated on a new specimen. If the new test passes, then the panel is considered to pass. If not, the panel is a failure.

The two high speed cameras were used to capture images of the large missile impact on the front and back side of the specimen at 1000fps (Figure 3-22). High speed Camera A was positioned at a 45° angle on the front side of the specimen while Camera B was arranged at a 30° angle on the back side. There was also a third Camera, C, recording a 30fps color video. Ample lighting was required to ensure clear video images, especially for the high frame rate cameras. Following each test, a digital camera was used to photograph the resulting damage.

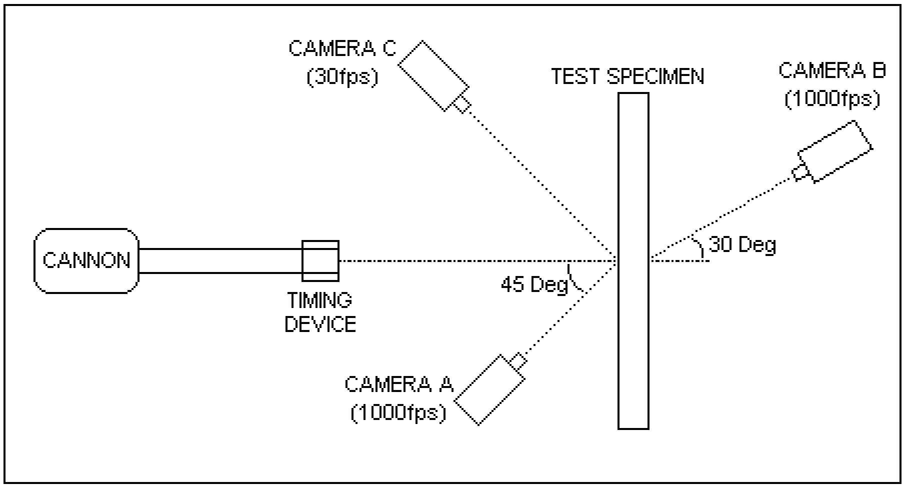

Figure 3-22: Large Missile Test Camera Orientation

3.3 Small Missile Test

3.3.1 Test Missile Overview

Based on the ASTM E 1996-09 requirement that Hawaii design for wind speeds consistent with Wind Zone 1 criteria, basic protection from level A missiles above 9.1m must be provided (Table 3-1). The level A missile used for testing consists of 10 steel balls weighing 2g each traveling with a velocity of 39.62m/s (130f/s) (Table 3-4 and Figure 3-23).

Table 3-4: Applicable Small Missiles

Missile Level	Missile	Impact Speed (m/s)
A	2 g (31 grains) ± 5% Steel Ball	39.62 (88.63 mph)
B	910 g ± 100 g (2.0 lb ± 0.25 lb) 2 x 4 in. 52.5 cm ± 100 mm (1 ft - 9 in. ± 4 in.) lumber	15.25 (34.11 mph)
C	2050 g ± 100 g (4.5 lb ± 0.25 lb) 2 x 4 in. 1.2 m ± 100 mm (4 ft ± 4 in.) lumber	12.19 (27.27 mph)
D	4100 g ± 100 g (9.0 lb ± 0.25 lb) 2 x 4 in. 2.4 m ± 100 mm (8 ft ± 4 in.) lumber	15.25 (34.11 mph)
E	4100 g ± 100 g (9.0 lb ± 0.25 lb) 2 x 4 in. 2.4 m ± 100 mm (8 ft ± 4 in.) lumber	24.38 (54.54 mph)

A container and end trap were custom designed and built to fire the small steel balls from the muzzle of the cannon. The 1.5ft long 3.875in diameter tubular container was built out of an ultra-high-molecular-weight polyethylene (UHMW) material (Figure 3-24). This particular material was chosen due to its lightweight properties and high yield strength. The end trap was constructed out of a series of welded steel plates to form a stiff

U-shaped system capable of absorbing impact forces. The concept behind the system is that the small missiles would be placed in the canister with a tissue paper cover over the open end to keep the balls in place until firing. The canister is loaded into the barrel 10ft from the open end. The released pressure accelerates the container down the barrel and out the muzzle of the cannon. As the container exits the timing device it impacts the end trap and propels the small missile balls through the tissue paper and towards the test specimen. (Figure 3-25). The end trap was designed to rotate out of the line of fire so that the cannon could still be used for large missile projectiles. After several modifications to the system, the final design was decided upon and implemented as the official small missile test system.

Figure 3-23: Small Missile Steel Balls

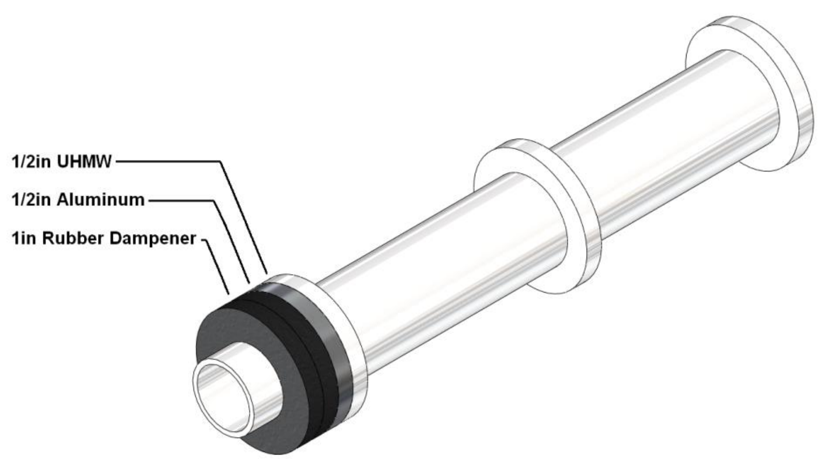

Figure 3-24: Small Missile UHM Canister

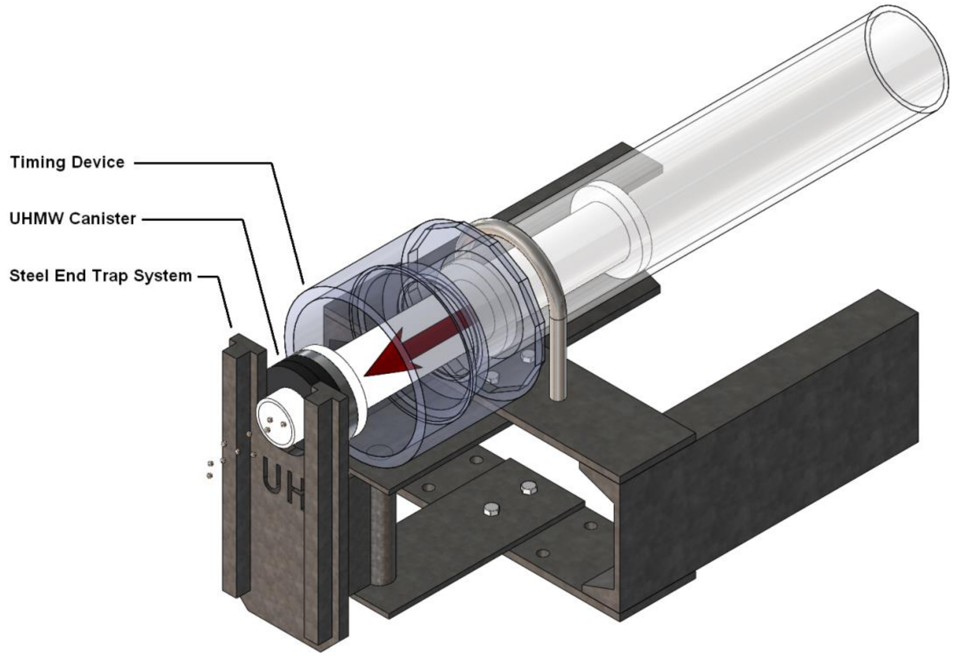

Figure 3-25: Small Missile Test System

3.3.2 Pretest Calibration

ASTM E 1886-05 requires that the small missile test be conducted at a distance no less than 1.80m. However, in order for all 10 of the small missile shots to strike the target within the required 10in radius, the test specimen had to be located closer to the muzzle of the cannon. This distance was adjusted until all 10 balls consistently struck within a 10in radius circle. This resulted in a muzzle to target distance of 3ft. This action was approved by specifying authorities.

> "**11.1.3** Locate the end of the propulsion device from which the missile will exit at a minimum distance from the specimen equal to 1.5 times the length of the missile. This distance shall be no less than 1.80m." (ASTM E 1886-05)

Because the steel test frame was stationary, it could not be moved to accommodate this distance. A smaller wooden frame was constructed so that the fenestrations and window protection systems could be mounted and moved into the desired location for testing (Figure 3-26).

Figure 3-26: Mini Frame for Small Missile Test

Before official tests were run with the small missile system, it was calibrated at the desired 88.63mph. Due to the manner in which the UHMW canister broke the plane of the fiber optic sensors, the timing device was not able to measure the velocity of the small missiles. To accurately measure the muzzle velocity, a high speed camera was set to record at 5000fps and oriented orthogonal to the midflight path. After running a series of test shots, and taking the average velocity of each ball per test, the target pressure of 7.6psi was determined to be the ideal setting (Figure 3-27). It was determined that the velocity of the steel balls did not significantly decrease from the muzzle to the point of impact, so the midflight velocity was taken as the official speed.

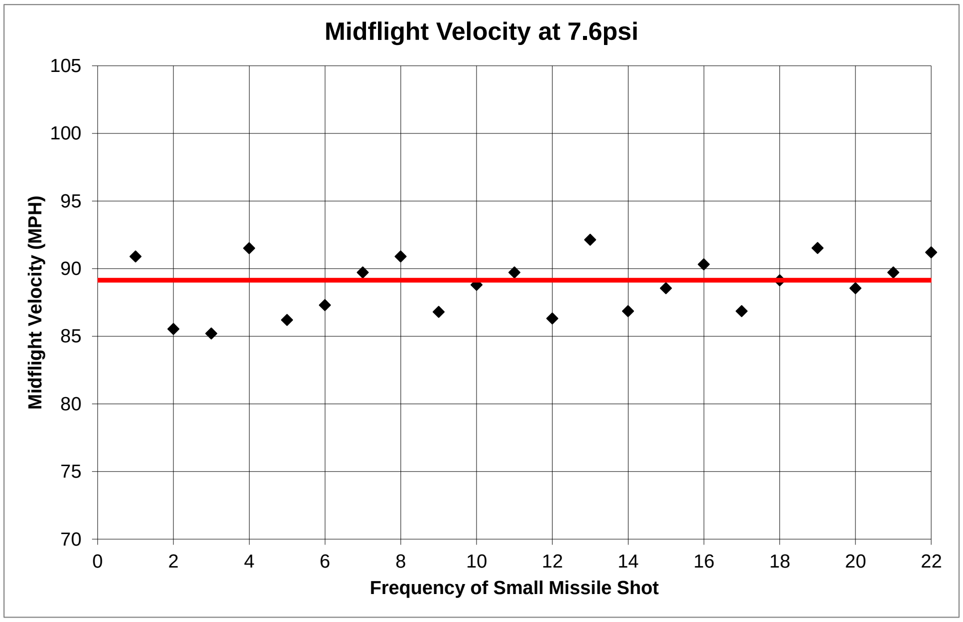

Figure 3-27: Velocity of Small Missile

3.3.3 Test Procedure

Each small missile was required to strike the test specimen in a certain impact location based on the requirements of ASTM E 1996-09. Each specimen was to be tested with a series of 3 shots (of 10 balls each) in the lower corner, upper corner, and center. Figure 3-28 shows the impact location for the small missile testing.

> "**5.3.4** *Small Missile Test* – Impact each impact protective system specimen and each fenestration assembly infill type three times with ten steel balls each as shown in Figure 3-28.
>
> **5.3.4.1** Each impact location shall receive distributed impacts simultaneously from ten steel balls.
>
> **5.3.4.2** The corner impact locations shall be entirely within a 250 mm (10 in) radius circle having its center located at 275 mm (11 in) from the edges.
>
> **5.3.4.4** The center impact location shall be entirely within a 250 mm (10 in) radius circle having its center located at the horizontal and vertical centerline of the infill." (ASTM E 1996-09)

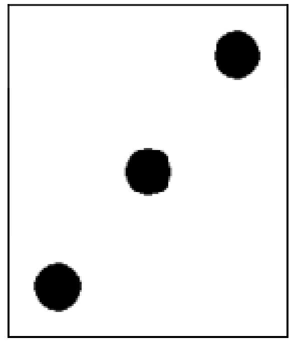

Figure 3-28: Small Missile Impact Locations

The laser siting device (Figure 3-7) had to be calibrated in order to accurately aim the small missile balls at the test specimen and strike the object within the required 10in radius. A trial run was conducted to adjust the laser to the corresponding speed of the test missile. The cannon could then be adjusted in the lateral and vertical direction to ensure proper missile impact location.

As defined by ASTM E 1886-05, the following set of test procedures are required for proper test operation;

> "**11.1.2** Missile Impact – Secure the specimen and mounting frame such that the missile will impact the exterior side of the specimen as installed.
>
> **11.1.6** Load the missile into propulsion device.
>
> **11.1.8** Align the missile propulsion device such that the specified missile will impact the test specimen at the specified location.
>
> **11.2** Propel the missile at the specified impact speed and location."

The two high speed cameras were used to capture images of the small missile impact on the front side of the specimen at 1000fps (Figure 3-28). High speed Camera A was positioned at a 45° angle on the front side of the specimen while Camera B was positioned orthogonally to the missile's flight path at the muzzle location. There was also a third Camera, C, recording a 30fps color video of the shot. Ample lighting was required to ensure clear video images, especially for the high frame rate cameras. Following each test, a digital camera was used to photograph the resulting damage.

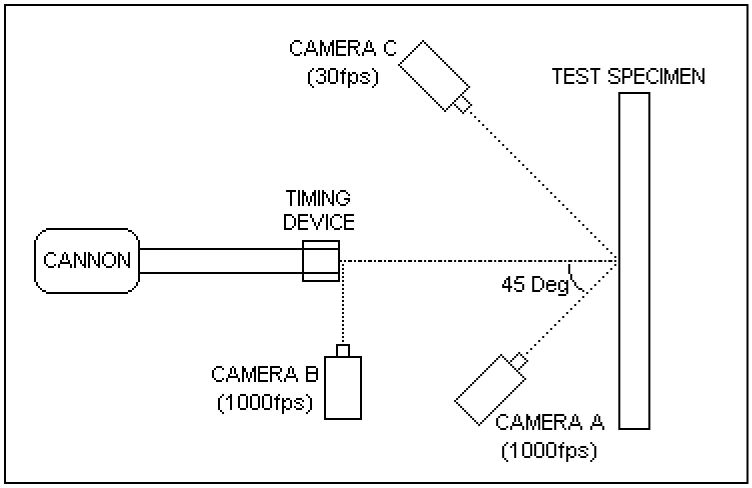

Figure 3-29: Camera Orientation

4 RESULTS

4.1 Overview

The intent of the safe room wall testing was to establish economical pre-qualified wall systems, both exterior and interior, for use in construction of safe rooms to withstand wind-borne debris impacts for essential facilities during a Category 3 hurricane. This involved testing each specimen type with a level D missile in the lower, center, and upper corner.

The safe room wall panels tested were framed using both wood and cold formed steel studs at both 16 and 24 inches on center. Both types of framing are popular in Hawaii. The exterior and interior layers fastened to the studs were selected by the local manufacturers with input from Gary Chock, PE. These consisted of typical materials used in new home construction throughout Hawaii. Since each safe room may be situated in different locations in a home, a variety of interior and exterior wall systems were tested. The test specimens were constructed and donated by Hawaii Lumber Products Association (HLPA), Hawaii Steel Framing Alliance (HSFA), Cemco Steel, and Sunrise Construction.

The intent of the window fenestration testing was to determine whether different vinyl louver systems could be considered for basic protection of facilities against wind-borne debris in a Category 3 hurricane. The original proposal was to test each panel initially with the class A small missile test in the lower, center, and upper corner. If the specimen passed this test, it would then be subjected to the class C large missile test in the lower, center, and upper corner. The initial test of the medium size louver panel with the class A small missile showed minimal damage. It was determined that the two subsequent specimens would not be tested with the small missile test and automatically approved for basic protection above 9.1m.

The window fenestrations tested consisted of three vinyl jalousie panels mounted in a wood frame. All of the panels were constructed from extruded PVC slats measuring 4in wide by 3/4in thick. The slats were held in place by one piece aluminum pivot clips that were pinned to the aluminum window frames. A push bar and operator arm allowed the louver window to rotate from open to a closed and locked position. The aluminum frame was fastened to the outer wood frame with 1.25in long #10 wood screws. All jalousie panels were constructed by Aloha Visualite, Ltd and provided by Hawaii State Civil Defense.

The intent of the window protection testing was to determine whether different aluminum security screens could be considered for both basic and enhanced protection of facilities against wind-borne debris in a Category 3 hurricane. It is important that the window protection systems do not deflect far enough to strike the fenestration assemblies behind them during wind borne debris impact. During two of the test runs, the static and dynamic deflections of the protection screens were measured independently of the louvers. This was performed with a level C missile in the lower, center, and upper corner. A third specimen, assembled from both a protection screen and louver, was tested in the center with a level D missile.

The protection systems tested consisted of three security screens made of an extruded aluminum diamond mesh. The mesh was attached to an aluminum frame using 1/8in pop rivets. This assembly was fastened to a wood frame via lag screws and aluminum clips. All protection systems were constructed by Emtek Products, Inc and Ulrich Aluminum Company. Hawaii State Civil Defense organized their fabrication and provided the specimens for testing.

4.2 Analysis of Wall Systems

Twenty-three saferoom wall panels were tested using a class D large missile at the center position or two opposite corners. The missile impact was recorded on the front and rear side using two high speed cameras.

A wall panel is considered to fail if the impacting missile creates a tear in the interior face longer than 5in and wider than 1/16in. Air is not allowed to pass through this tear nor is a solid sphere with a 3in diameter. Similarly, the panel is considered a pass if the missile is repurcussed from the specimen without having perforated the interior face of the specimen. All pass/fail criteria are taken from the ASTM E 1996-09 specifications, as follows;

> "**7.1.1** Fenestration Assemblies and Non-Porous Impact Protective Systems:
>
> **7.1.1.1** The test specimen shall resist the large or small missile impacts, or both, with no tear formed longer than 130 mm (5 in.) and wider than 1 mm (1/16 in.) through which air can pass, or with no opening formed through which a 76 mm (3 in.) diameter solid sphere can freely pass when evaluated upon completion of missile impacts."

4.2.1 Panel O

This wall specimen served as the control sample for the HLPA 4'x8' panels as it represents typical residential exterior wall construction. The exploded view of the wall, and all similar figures, indicate the wall layers in the order in which they will be struck by the missile (Figure 4-1). The large missile perforated the lap siding, HomeWrap and drywall of Panel O with little resistance (Figure 4-2). Panel O is considered a failure based on all three tests (Table 4-1).

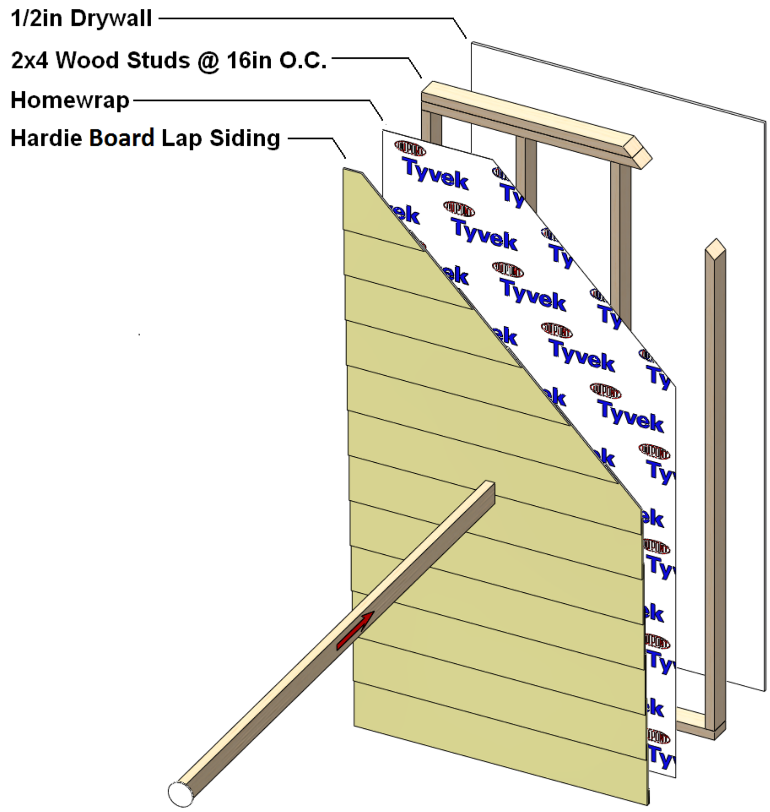

Figure 4-1: Panel O Exploded View

Figure 4-2: Panel O Typical Front (Left) and Rear (Right) Damage

Table 4-1: Panel O Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
O-1	Bottom Left	8.931	35.68	33.36	13.57	331.98	FAIL
O-1	Top Right	8.931	37.66	37.06	15.08	409.75	FAIL
O-2	Center	8.931	36.13	33.95	13.81	343.90	FAIL

4.2.2 Panel A

This specimen was a derivative of the previous panel O with a layer of StormWrap replacing the HomeWrap behind the lap siding (Figure 4-3). It was constructed with the expectation that it would provide better resistance to impact forces. It did not prove effective at preventing missile perforation (Figure 4-4). Panel A is considered a failure based on all three tests (Table 4-2).

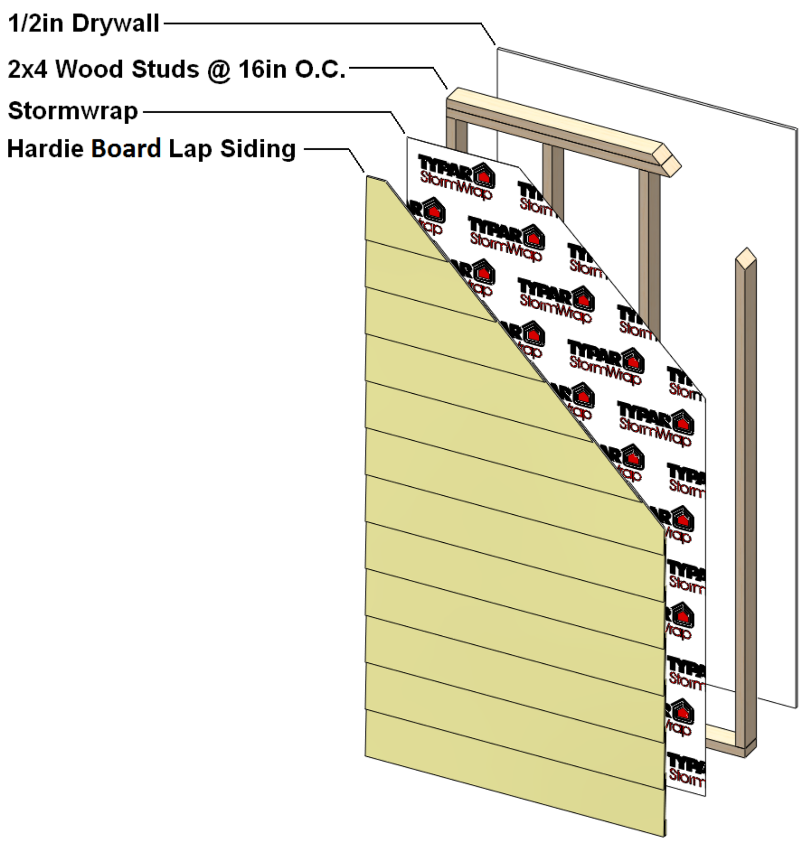

Figure 4-3: Panel A Exploded View

Figure 4-4: Panel A Typical Front (Left) and Rear (Right) Damage

Table 4-2: Panel A Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
A-3	Bottom Left	8.751	36.43	34.43	13.72	346.46	FAIL
A-3	Top Right	8.751	37.06	35.65	14.21	371.41	FAIL
A-2	Center	8.751	36.93	35.37	14.10	365.68	FAIL

4.2.3 Panel B

This specimen is based on Panel O but with the addition of a 1/2in plywood sheet behind the HomeWrap (Figure 4-5). For the first two tests, the missile perforated all layers of the panel (Figure 4-6). On the third test, the missile penetrated the interior cladding and caused a 5in long split in the drywall, but not wide enough to be considered a failure. However, since two of the three tests resulted in perforation, the specimen was considered a failure (Table 4-3).

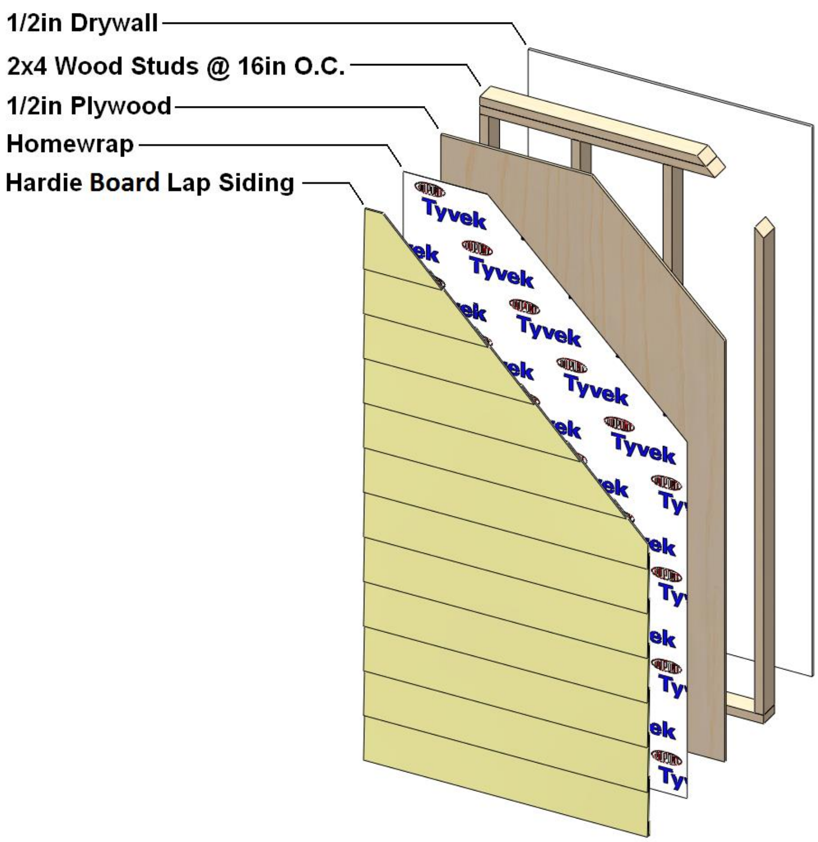

Figure 4-5: Panel B Exploded View

Figure 4-6: Panel B Front (Left) and Rear (Right) Damage for Bottom Left Test

Table 4-3: Panel B Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
B-1	Center	8.931	37.31	36.21	14.73	391.12	FAIL
B-2	Bottom Left	8.931	36.69	34.89	14.19	363.22	FAIL
B-2	Top Right	8.931	36.18	34.03	13.84	345.41	PASS

4.2.4 Panel C

This panel was identical to panel B but with a 5/8in plywood sheet replacing the 1/2in plywood (Figure 4-7). The first test caused a 10in long and 1in wide split in the drywall. This was considered a failed test, however, the remaining two tests were considered a pass as no damage was done to the interior drywall (Figure 4-8). A fourth test was implemented on a new panel to compare with the original failure. This final test was a pass, therefore, the panel was approved for class D large missile windborne debris impact resistance (Table 4-4).

Table 4-4: Panel C Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
C-1	Center	8.751	37.61	36.94	14.72	398.77	FAIL
C-2	Bottom Left	8.751	37.01	35.54	14.17	369.17	PASS
C-2	Top Right	8.751	38.12	38.26	15.25	427.91	PASS
C-3	Center	8.750	37.60	36.91	14.71	398.19	PASS

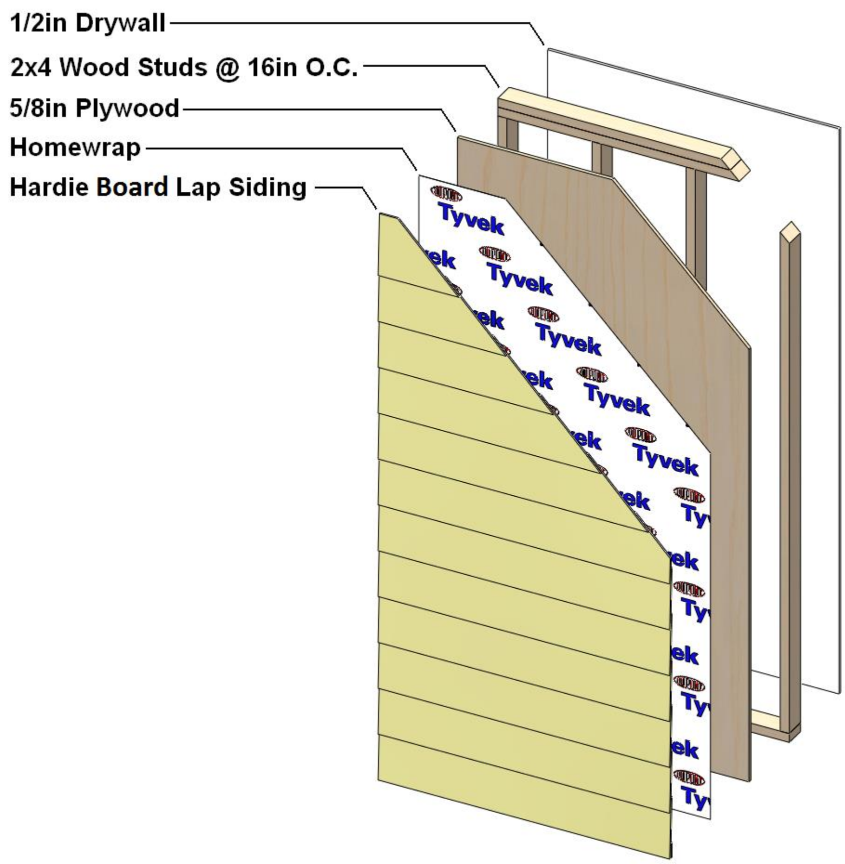

Figure 4-7: Panel C Exploded View

Figure 4-8: Panel C Front (Left) and Rear (Right) Damage for Three Passing Tests

4.2.5 Panel O'

This wall specimen served as the control sample for the cold formed steel (CFS) 4'x8' panels (Figure 4-9). The large missile perforated the T1-11 exterior plywood and the drywall with little resistance (Figure 4-10). Panel O' is considered a failure based on all three tests (Table 4-5).

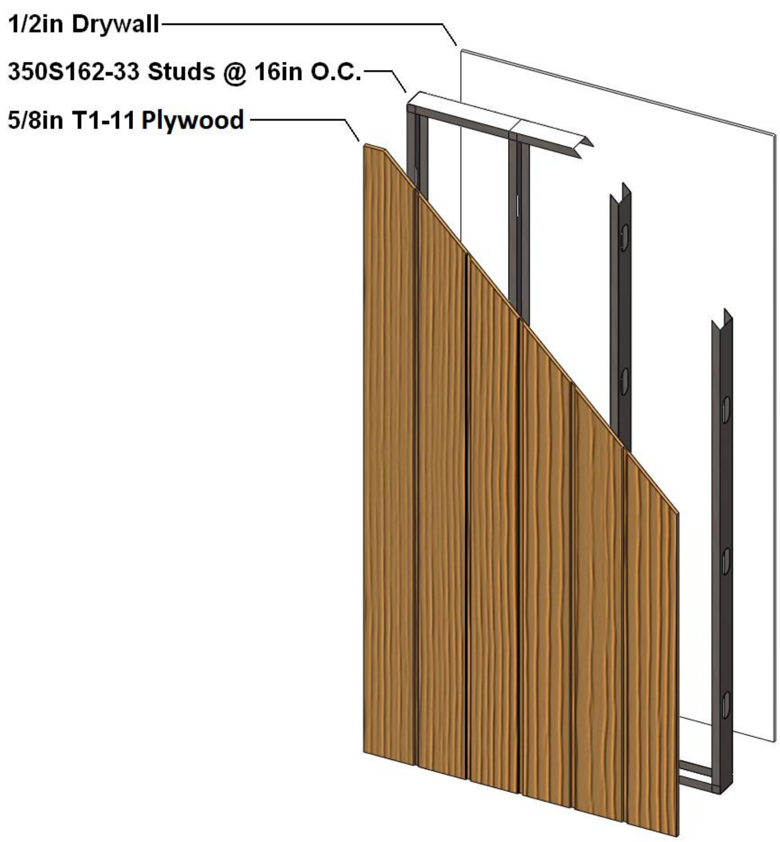

Figure 4-9: Panel O'

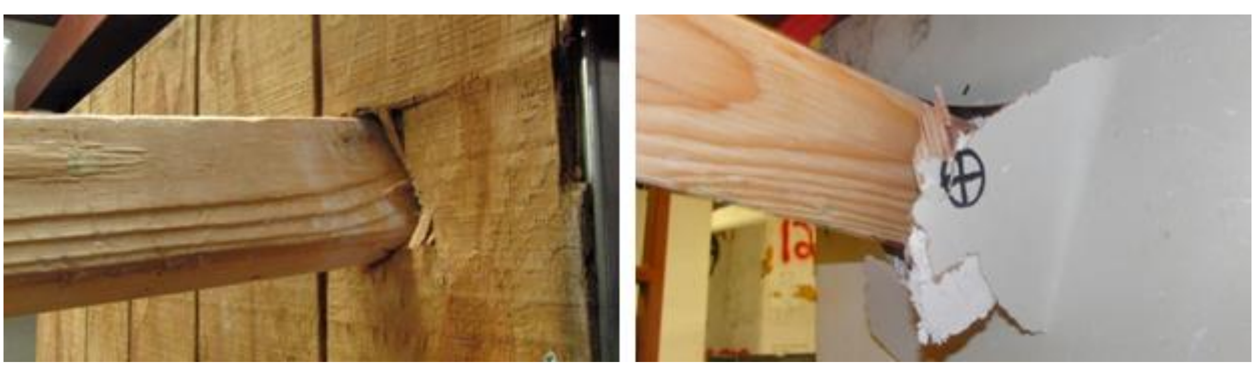

Figure 4-10: Panel O' Typical Front (Left) and Rear (Right) Damage

Table 4-5: Panel O' Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
O'-1	Center	8.750	36.91	35.33	14.08	364.79	FAIL
O'-2	Bottom Left	8.750	37.70	37.16	14.81	403.65	FAIL
O'-2	Top Right	8.750	38.00	37.94	15.12	420.76	FAIL

4.2.6 Panel G'

Panel G' consisted of exterior Hardie Board siding, a 22gauge sheet metal layer screwed to the exterior of CFS studs placed at 16in on center, and an interior drywall layer (Figure 4-11). The addition of the sheet metal panel behind the lap siding greatly improved the performance of the wall system. During corner strikes, the CFS studs buckled under the impact load but there was no damage to the drywall (Figure 4-12). All three test shots were regarded with passing results (Table 4-6).

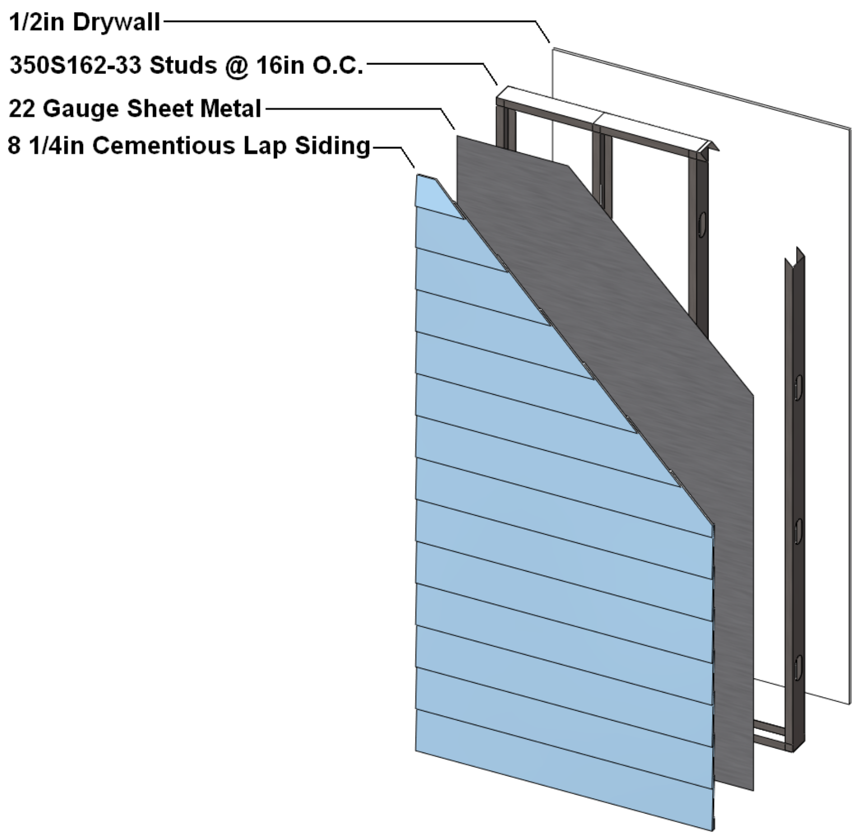

Figure 4-11: Panel G' Exploded View

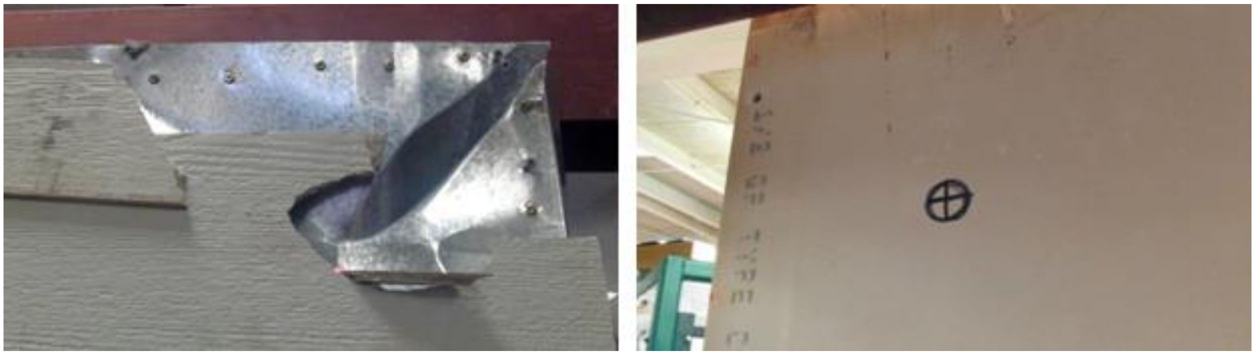

Figure 4-12: Panel G' Typical Front (Left) and Rear (Right) Damage

Table 4-6: Panel G' Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
G'-1	Top Right	8.750	37.34	36.28	14.46	384.68	PASS
G'-1	Bottom Left	8.750	37.51	36.69	14.62	393.40	PASS
G'-2	Center	8.750	36.64	34.80	13.87	353.95	PASS

4.2.7 Panel H

This specimen is similar to Panel G' but with CFS studs at 24in on center instead of 16in. The 22 gauge sheet metal was also fastened behind the studs with self-taping screws (Figure 4-13). All three shots caused the drywall to delaminate (Figure 4-14). However, the missile did repurcuss from the sheet metal without perforating it. There was no tear in this layer of the panel so the specimen was considered a pass (Table 4-7).

Table 4-7: Panel H Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
H-1	Bottom Left	8.750	35.82	33.53	13.36	328.59	PASS
H-1	Top Right	8.750	36.21	34.07	13.58	339.32	PASS
H-2	Center	8.750	37.35	36.30	14.47	385.18	PASS

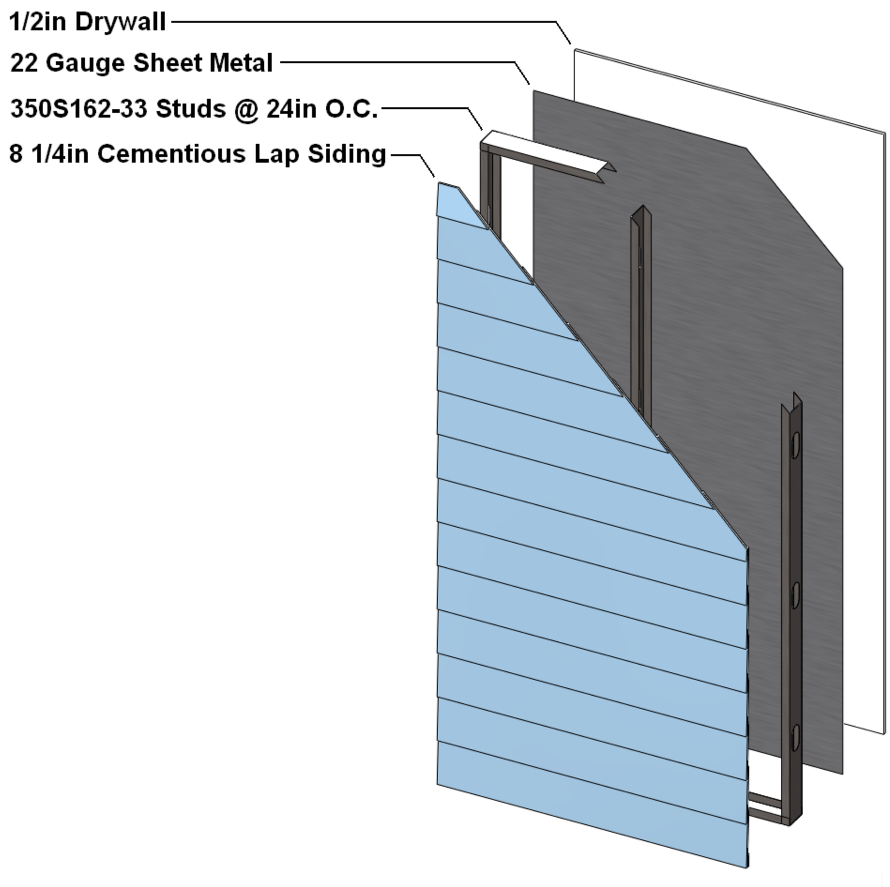

Figure 4-13: Panel H Exploded View

Figure 4-14: Panel H Typical Front (Left) and Rear (Right) Damage

4.2.8 Panel M-O

This wall specimen served as the control sample for the CFS 4'x4' panels (Figure 4-15). The large missile perforated the T1-11 plywood and drywall with little resistance (Figure 4-16). Panel M-O is considered a failure based on all three tests (Table 4-8).

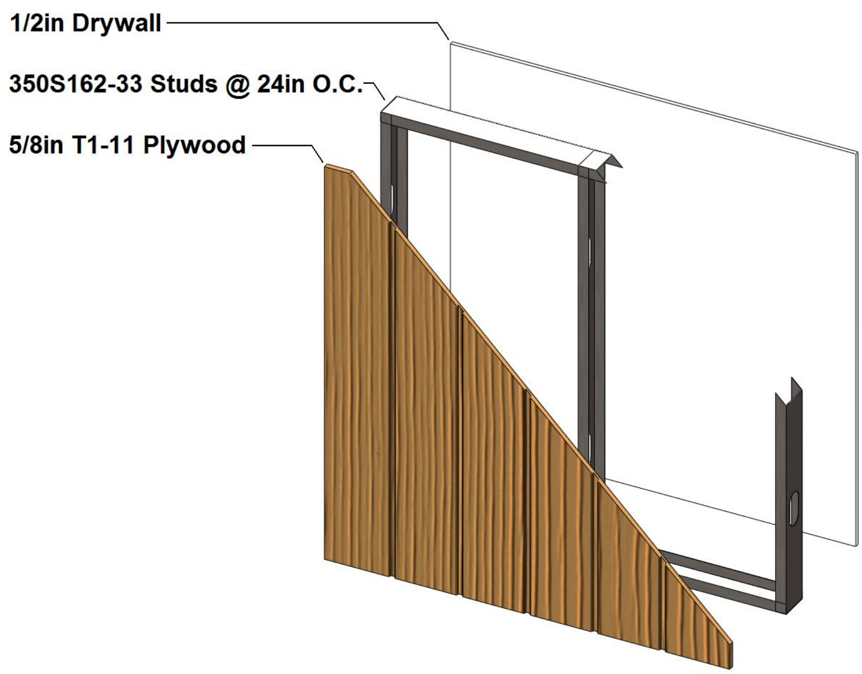

Figure 4-15: Panel Control M-O Exploded View

Figure 4-16: Panel Control M-O Typical Front (Left) and Rear (Right) Damage

Table 4-8: Panel M-O Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-O-1	Top Right	8.750	36.96	35.43	14.12	366.93	FAIL
M-O-2	Bottom Left	8.750	36.14	33.97	13.54	337.23	FAIL
M-O-2	Center	8.750	36.48	34.51	13.76	348.14	FAIL

4.2.9 Panel M-A

This specimen was a derivative of the previous panel M-O with CFS studs at 16in on center instead of 24in and the use of a 5/8in fiberboard to simulate T1-11 plywood (Figure 4-17). The missile perforated the fiberboard and drywall with little resistance (Figure 4-18). Panel M-A is considered a failure based on all three tests (Table 4-9).

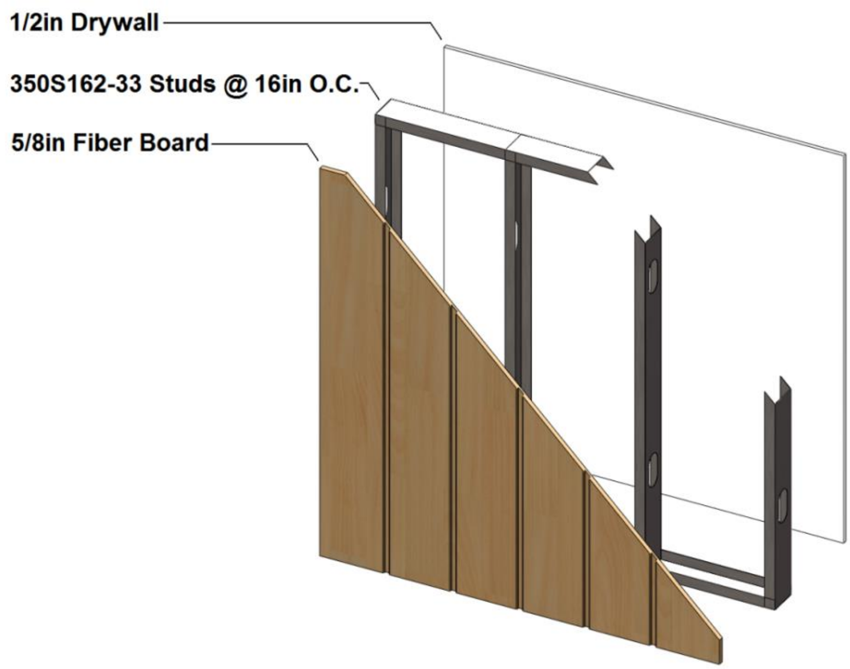

Figure 4-17: Panel M-A Exploded View

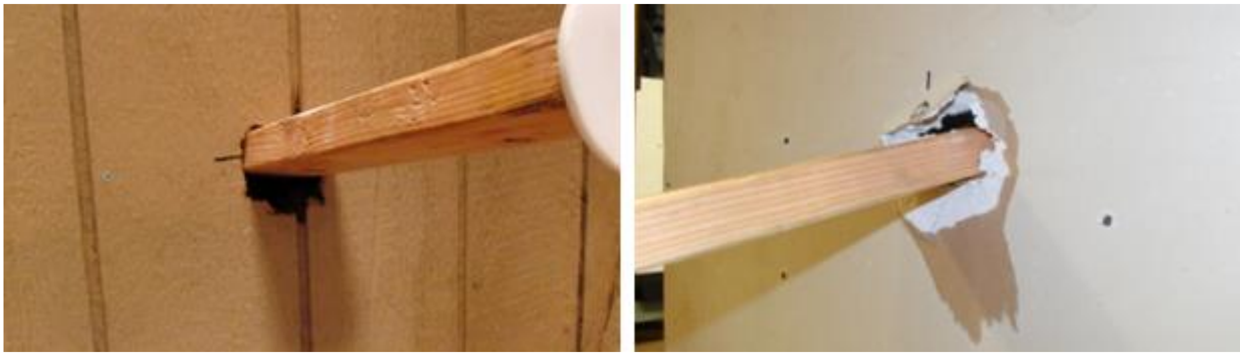

Figure 4-18: Panel M-A Typical Front (Left) and Rear (Right) Damage

Table 4-9: Panel M-A Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-A-1	Bottom Left	8.750	36.04	33.82	13.48	334.37	FAIL
M-A-1	Top Right	8.750	36.81	35.13	14.00	360.62	FAIL
M-A-2	Center	8.750	36.17	34.01	13.56	338.11	FAIL

4.2.10 Panel M-B

This panel was identical to panel M-A but with CFS studs placed at 24in on center instead of 16in (Figure 4-19). The rearrangement of the studs did not affect the performance of the wall panel. The large missile perforated the fiberboard and drywall with little resistance (Figure 4-20). Panel M-B is considered a failure based on all three tests (Table 4-10).

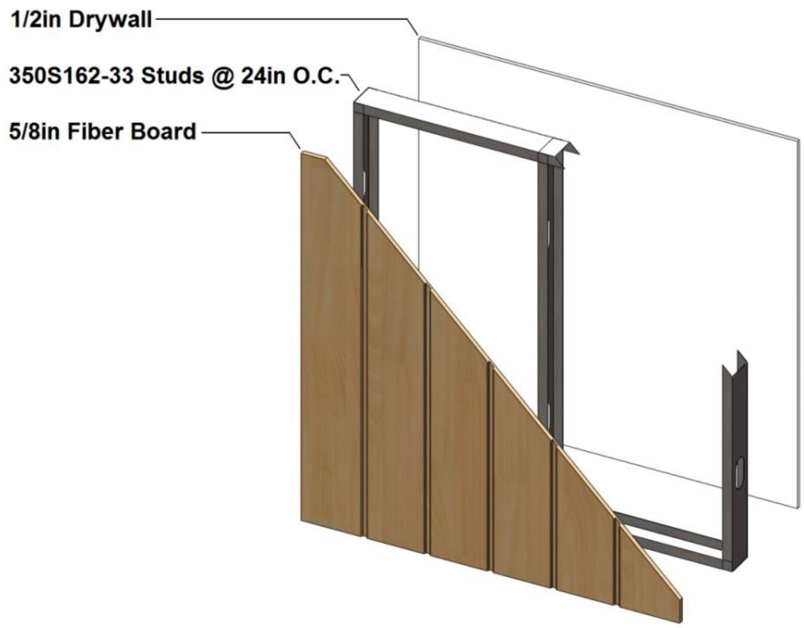

Figure 4-19: Panel M-B Exploded View

Figure 4-20: Panel M-B Typical Front (Left) and Rear (Right) Damage

Table 4-10: Panel M-B Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-B-1	Bottom Left	8.750	35.51	33.17	13.22	321.52	FAIL
M-B-1	Top Right	8.750	37.61	36.94	14.72	398.73	FAIL
M-B-2	Center	8.750	37.27	36.12	14.39	381.23	FAIL

4.2.11 Panel M-C

Panel M-C consisted of exterior 3/4in oriented strand board (OSB), CFS studs at 16in on center, and an interior 1/2in drywall (Figure 4-21). The OSB did absorb a substantial amount of the energy but not enough to keep the missile from perforating all the layers (Figure 4-22). Based on all three tests, Panel M-C is considered a failure (Table 4-11).

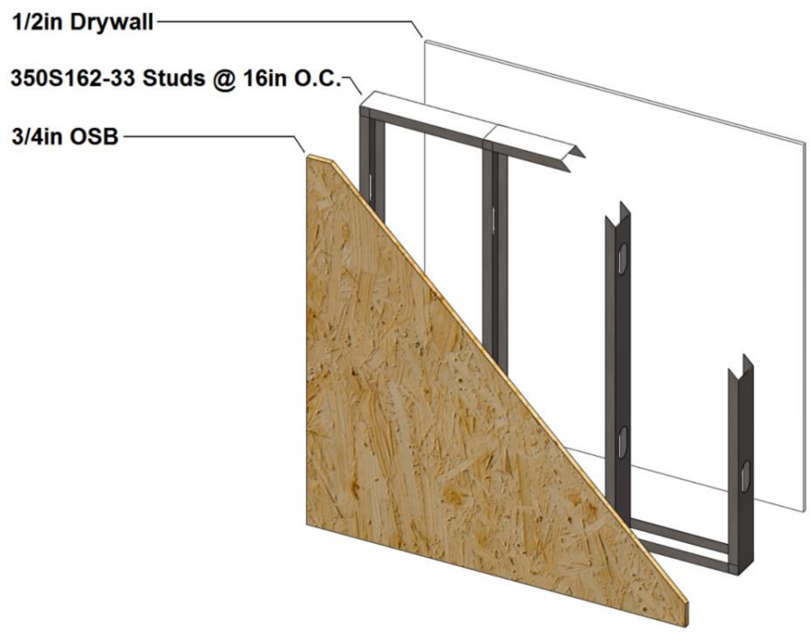

Figure 4-21: Panel M-C Exploded View

Figure 4-22: Panel M-C Typical Front (Left) and Rear (Right) Damage

Table 4-11: Panel M-C Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-C-1	Center	8.750	37.14	35.82	14.28	375.03	FAIL
M-C-2	Bottom Left	8.750	36.73	34.97	13.94	357.42	FAIL
M-C-2	Top Right	8.750	36.72	34.95	13.93	357.03	FAIL

4.2.12 Panel M-D

This panel was identical to panel M-C but with the CFS studs placed 24in on center instead of 16in (Figure 4-23). The first three test missiles repurcussed from the exterior OSB layer (Figure 4-24). These results were not expected since panel M-C failed all three shots. An additional five test shots were conducted to verify these results. Seven of the total eight missile impacts passed the testing criteria; therefore, panel M-D is approved for class D large missile windborne debris impact resistance (Table 4-12). However, because of the failure of similar OSB wall panels with studs at 16in on center in panel M-C, 3/4in OSB wall panels are not recommended for use in safe room construction.

Figure 4-23: Panel M-D Exploded View

Figure 4-24: Panel M-D Typical Front (Left) and Rear (Right) Damage

Table 4-12: Panel M-D Testing Summary

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-D-1	Top Right	8.750	36.42	34.41	13.71	346.08	PASS
M-D-1	Bottom Left	8.750	35.90	33.63	13.40	330.61	PASS
M-D-2	Center	8.750	37.23	36.02	14.36	379.29	PASS
M-D-2	Top Left	8.720	36.70	34.91	13.87	355.03	PASS
M-D-2	Center	8.720	36.63	34.78	13.81	352.37	PASS
M-D-2	Top Right	8.720	36.52	34.58	13.74	348.35	PASS
M-D-1	Center	8.720	37.31	36.21	14.38	381.88	FAIL
M-D-1	Top Left	8.720	37.12	35.78	14.21	372.82	PASS

4.2.13 Panel M-E

Panel M-E consisted of exterior lap siding, CFS studs at 24in on center, and 5/8in T1-11 plywood attached to the interior face with self taping screws (Figure 4-25). The flexibility of the T1-11 plywood and attaching hardware dissipated a substantial amount of the missile's energy. However, the panel was not strong enough to resist the missile from perforating the interior layer of the panel (Figure 4-26). Based on all three tests, Panel M-E is considered a failure (Table 4-13).

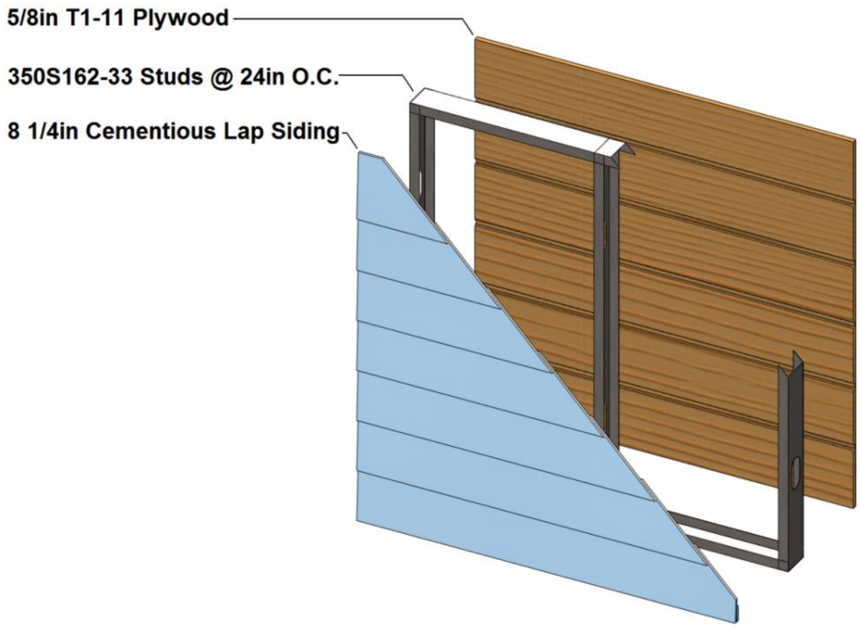

Figure 4-25: Panel M-E Exploded View

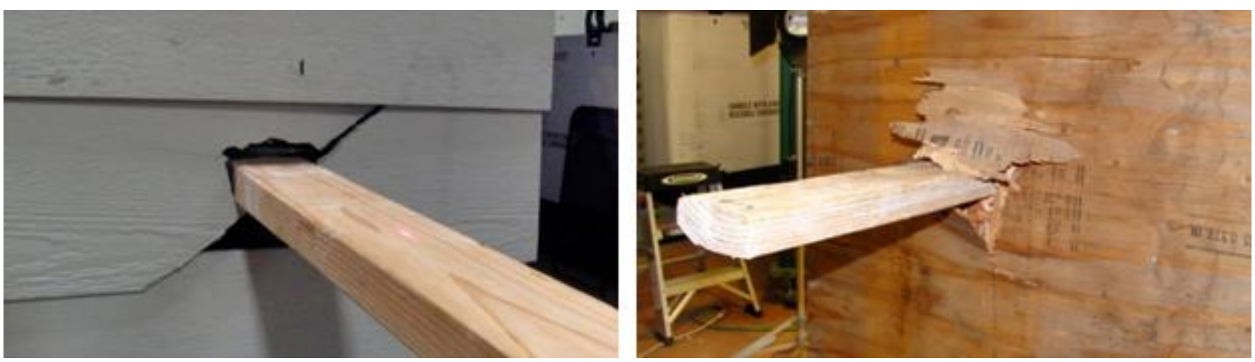

Figure 4-26: Panel M-E Typical Front (Left) and Rear (Right) Damage

Table 4-13: Panel M-E Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-E-1	Center	8.750	36.49	34.53	13.76	348.49	FAIL
M-E-2	Bottom Left	8.750	35.62	33.29	13.27	323.90	FAIL
M-E-2	Top Right	8.750	36.29	34.20	13.63	341.81	FAIL

4.2.14 Panel M-F

This specimen was a derivative of the previous panel M-E with a layer of 3/4in plywood replacing the 5/8in T1-11 plywood (Figure 4-27). The missile shots in the bottom left corner and center of the specimen produced visible damage to the plywood layer (Figure 4-28). However, the splits were not large enough to be considered a failure. The third shot in the top right corner penetrated the plywood with a 7in long and 1/16in deep split. Since two of the test shots were a pass, the entire specimen is approved for class D large missile windborne debris impact resistance (Table 4-14).

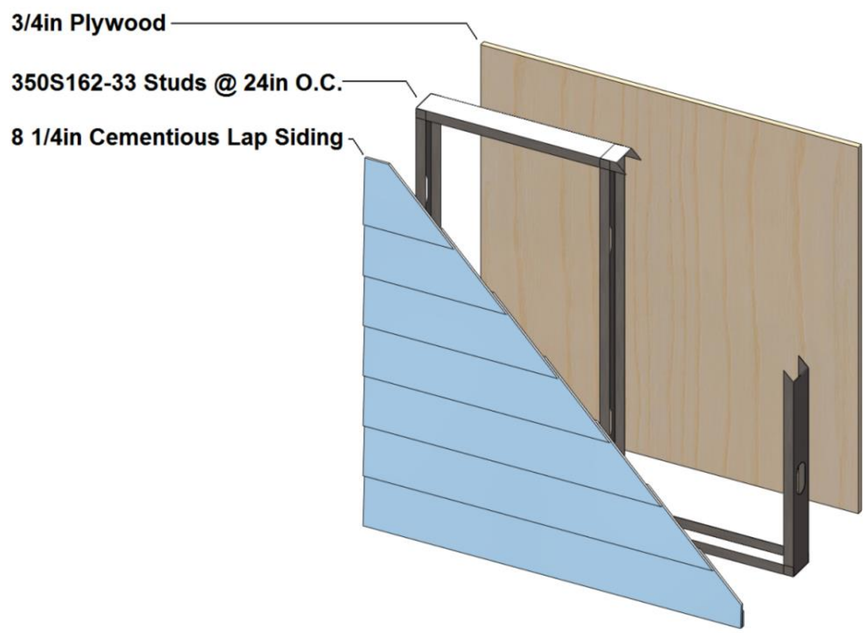

Figure 4-27: Panel M-F Exploded View

Figure 4-28: Panel M-F Front (Left) and Rear (Right) Damage for Bottom Left Test

Table 4-14: Panel M-F Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-F-1	Bottom Left	8.750	36.02	33.80	13.47	333.81	PASS
M-F-1	Top Right	8.750	37.17	35.89	14.30	376.44	FAIL
M-F-2	Center	8.750	36.90	35.31	14.07	364.36	PASS

4.2.15 Panel M-F'

Panel M-F' is the same as Panel M-F but tested from the opposite side. The first shot penetrated the exterior layer and split the plywood substantially (Figure 4-29). It did not, however, perforate to the lap siding on the interior face. The following three missiles were repurcussed from the exterior face. Based on all four test shots, panel M-F is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-15).

Figure 4-29: Panel M-F' Typical Front (Left) and Rear (Right) Damage

Table 4-15: Panel M-F' Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-F'-2	Bottom Left	8.720	37.67	37.09	14.73	400.62	PASS
M-F'-2	Top Right	8.720	36.90	35.31	14.02	363.11	PASS
M-F'-2	Center	8.720	37.49	36.64	14.55	391.00	PASS
M-F'-2	Top Left	8.720	37.07	35.67	14.17	370.54	PASS

4.2.16 Panel M-G

Panel M-G consisted of exterior lap siding, 22gauge sheet metal, CFS studs at 24in on center, and 1/2in drywall (Figure 4-30). The missile perforated the lap siding but was repurcussed by the sheet metal panel (Figure 4-31). Based on all three tests, panel M-G is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-16).

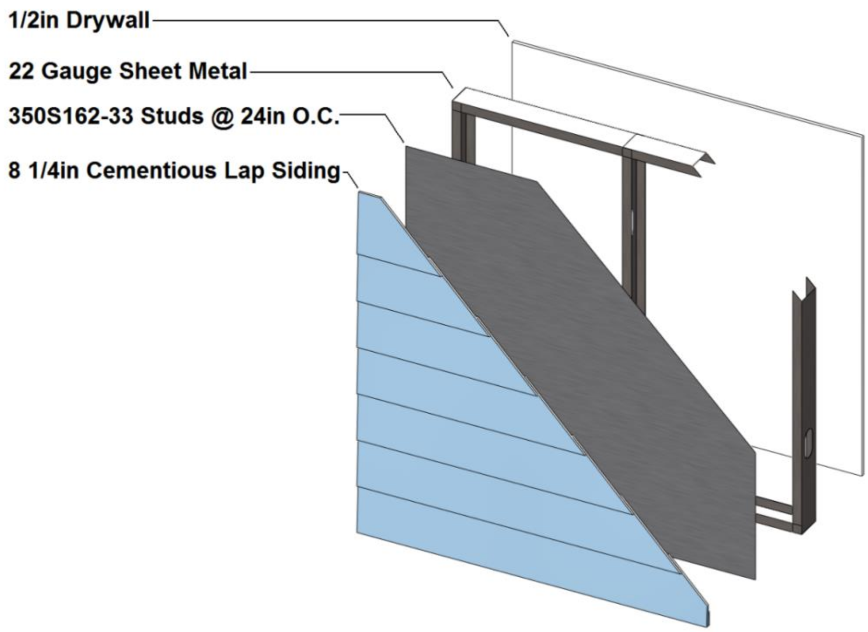

Figure 4-30: Panel M-G Exploded View

Figure 4-31: Panel M-G Typical Front (Left) and Rear (Right) Damage

Table 4-16: Panel M-G Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
M-G-1	Center	8.750	36.24	34.12	13.60	340.24	PASS
M-G-2	Top Right	8.750	36.39	34.36	13.69	345.07	PASS
M-G-2	Bottom Left	8.750	37.55	36.79	14.66	395.51	PASS

4.2.17 Panel 1

Panel 1 consisted of Hardie Board lap siding, HomeWrap, wood studs at 16in on center, and CEMCO SureBoard (Figure 4-32). The missile perforated the lap siding and HomeWrap but was repurcussed by the SureBoard panel (Figure 4-33). The split that was inflicted on the exterior face of the SureBoard was superficial since the interior layer was still intact. Based on all three tests, panel 1 is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-17). During the testing of panel 1, the nails on the interior face began to loosen and pop out of the SureBoard (Figure 4-33). It is recommended that screws be used on the interior face of the saferoom panels.

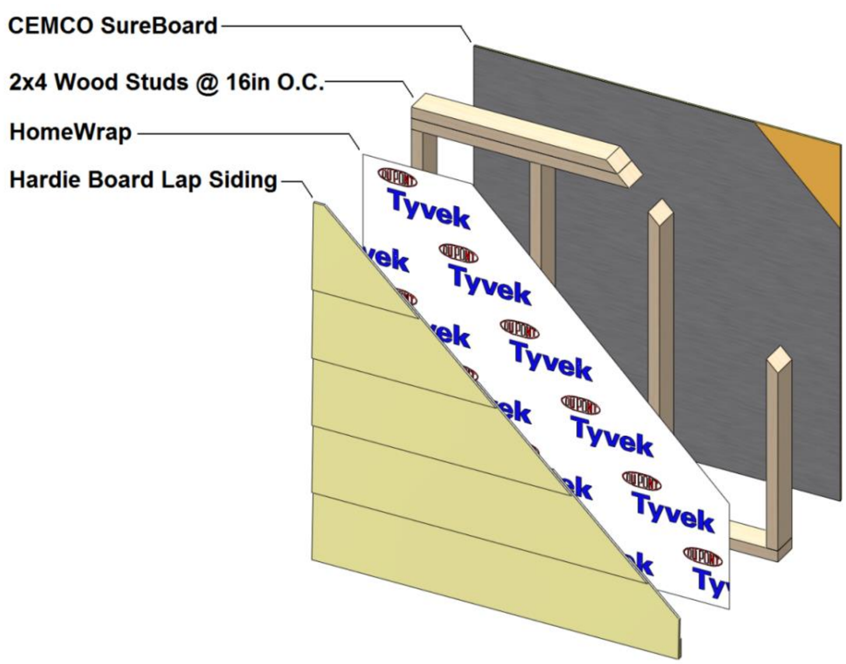

Figure 4-32: Panel 1 Exploded View

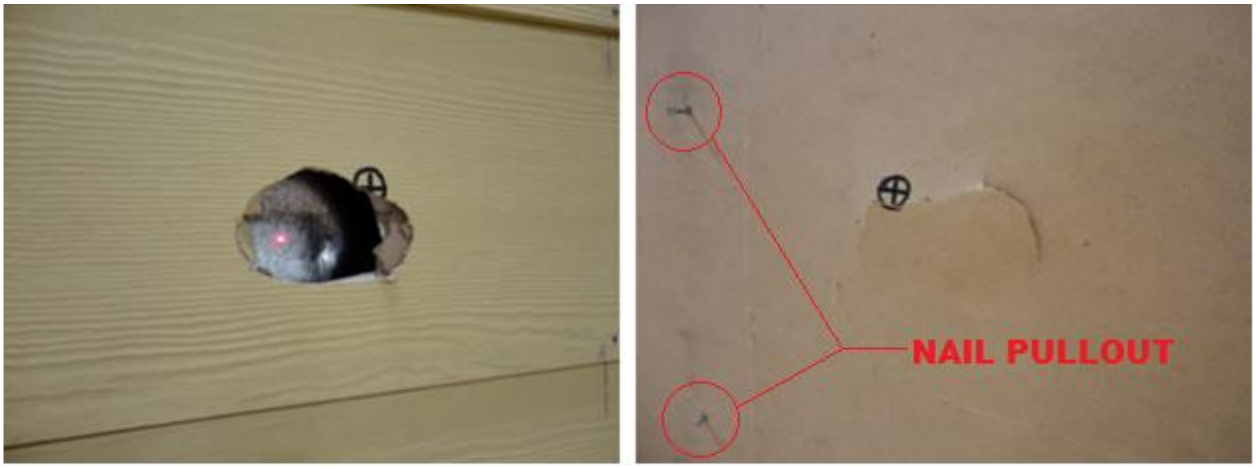

Figure 4-33: Panel 1 Typical Front (Left) and Rear (Right) Damage

Table 4-17: Panel 1 Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
1-1	Center	8.638	37.57	36.84	14.49	391.50	PASS
1-2	Bottom Left	8.638	35.94	33.69	13.25	327.41	PASS
1-2	Top Right	8.638	35.79	33.49	13.18	323.66	PASS

4.2.18 Panel 2

Panel 2 consisted of Hardie Board lap siding, wood studs at 16in on center, 22gauge sheet metal, and 1/2in drywall (Figure 4-34). The missile perforated the lap siding but was repurcussed by the sheet metal panel (Figure 4-35). The force of the missile caused the drywall on the interior face to delaminate. The sheet metal in front of the drywall was still structurally intact so the damage was only superficial. Based on all three tests, panel 2 is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-18).

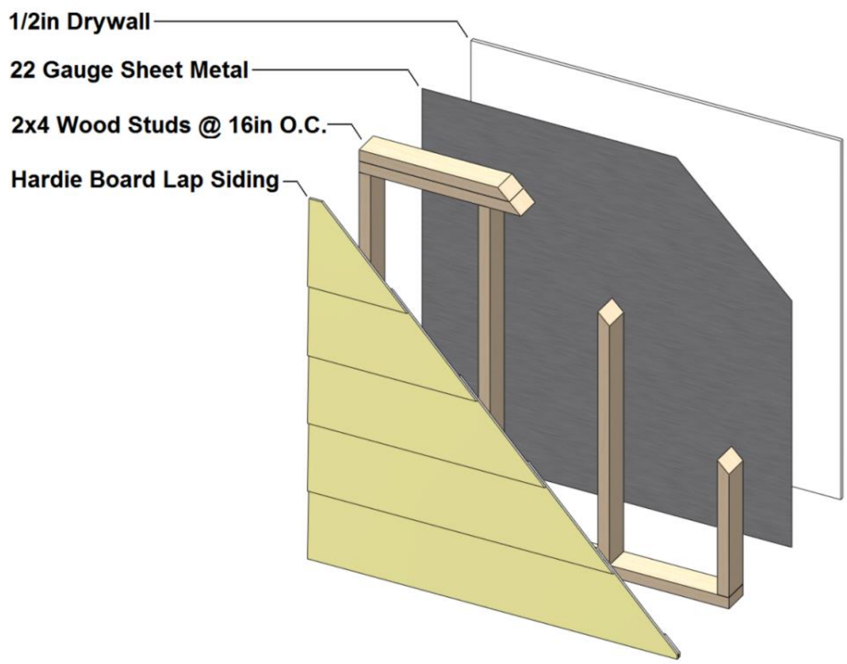

Figure 4-34: Panel 2 Exploded View

Figure 4-35: Panel 2 Typical Front (Left) and Rear (Right) Damage

Table 4-18: Panel 2 Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
2-1	Top Right	8.625	39.59	41.87	16.45	505.15	PASS
2-1	Bottom Left	8.625	39.62	41.93	16.47	506.54	PASS
2-2	Center	8.625	39.27	41.20	16.19	489.07	PASS

4.2.19 Panel 3

Panel 3 represented a true interior wall and consisted of 1/2in drywall, wood studs at 16in on center, 22gauge sheet metal, and 1/2in drywall (Figure 4-36). The missile perforated the exterior drywall but was repurcussed by the sheet metal panel (Figure 4-37). The force of the missile caused the drywall on the interior face to delaminate. The sheet metal in front of the drywall was still structurally intact so the damage was only superficial. Based on all three tests, panel 3 is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-19).

Table 4-19: Panel 3 Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
3-1	Center	8.625	38.50	39.28	15.43	444.45	PASS
3-2	Bottom Left	8.625	37.20	35.96	14.13	372.46	PASS
3-2	Top Right	8.625	37.42	36.47	14.33	383.17	PASS

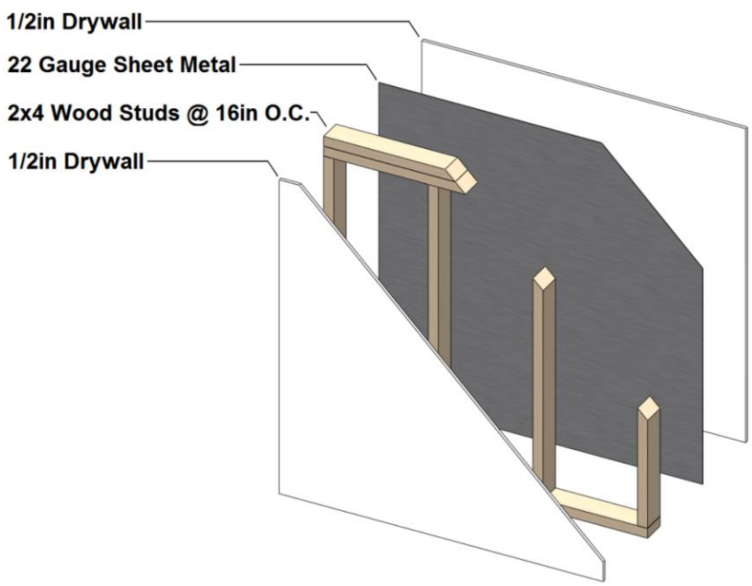

Figure 4-36: Panel 3 Exploded View

Figure 4-37: Panel 3 Typical Front (Left) and Rear (Right) Damage

4.2.20 Panel 3'

Panel 3' is the same as panel 3 but tested from the opposite side (Figure 4-38). All three shots were repurcussed by the exterior layer of sheet metal. There was no damage done to the interior drywall layer (Figure 4-39). Based on all three test shots, panel 3' is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-20).

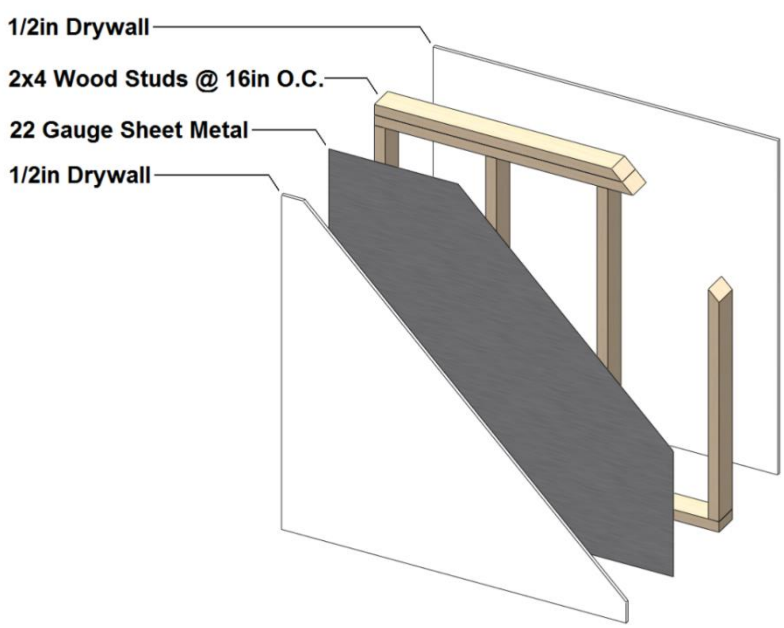

Figure 4-38: Panel 3' Exploded View

Figure 4-39: Panel 3' Typical Front (Left) and Rear (Right) Damage

Table 4-20: Panel 3' Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
3'-3	Bottom Left	8.638	37.84	37.52	14.76	406.22	PASS
3'-3	Center	8.638	36.99	35.50	13.96	363.51	PASS
3'-3	Top Right	8.638	38.26	38.64	15.20	430.67	PASS

4.2.21 Panel 4

Panel 4 consisted of CEMCO SureBoard, wood studs at 16in on center, and 1/2in drywall (Figure 4-40). All three missiles were repurcussed by the SureBoard on the exterior face. There was no damage done to the interior drywall (Figure 4-41). Based on all three tests, panel 4 is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-21).

Table 4-21: Panel 4 Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
4-1	Top Right	8.613	35.56	33.22	13.03	317.51	PASS
4-1	Bottom Left	8.613	36.21	34.07	13.37	333.99	PASS
4-2	Center	8.613	36.55	34.64	13.59	345.12	PASS

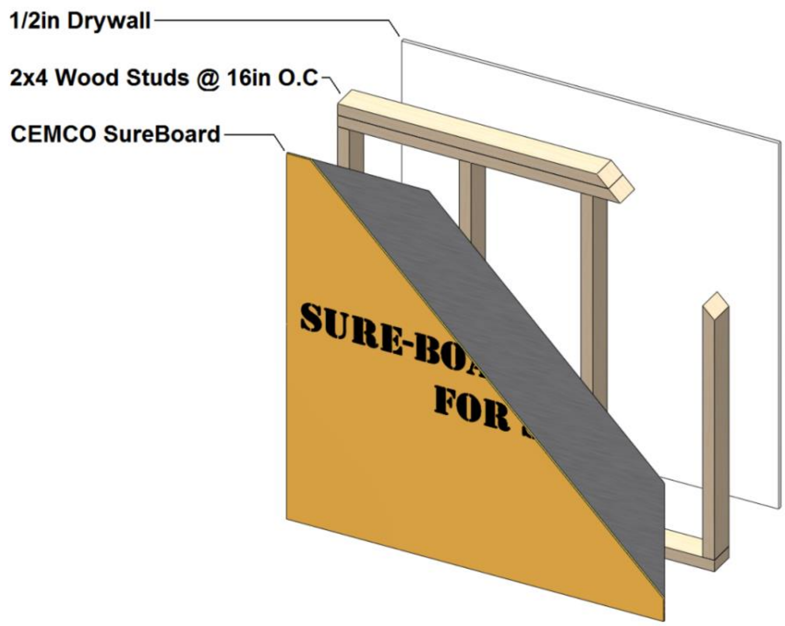

Figure 4-40: Panel 4 Exploded View

Figure 4-41: Panel 4 Typical Front (Left) and Rear (Right) Damage

4.2.22 Panel 4'

Panel 4' is the same as panel 4 but tested from the opposite side (Figure 4-42). All three missiles perforated the exterior drywall layer but were repurcussed by the interior SureBoard. The force of the missile created a split on the interior face of the SureBoard (Figure 4-43). The sheet metal was still structurally intact so the damage was only superficial. Based on all three tests, panel 4' is considered a pass and is approved for class D large missile windborne debris impact resistance (Table 4-22).

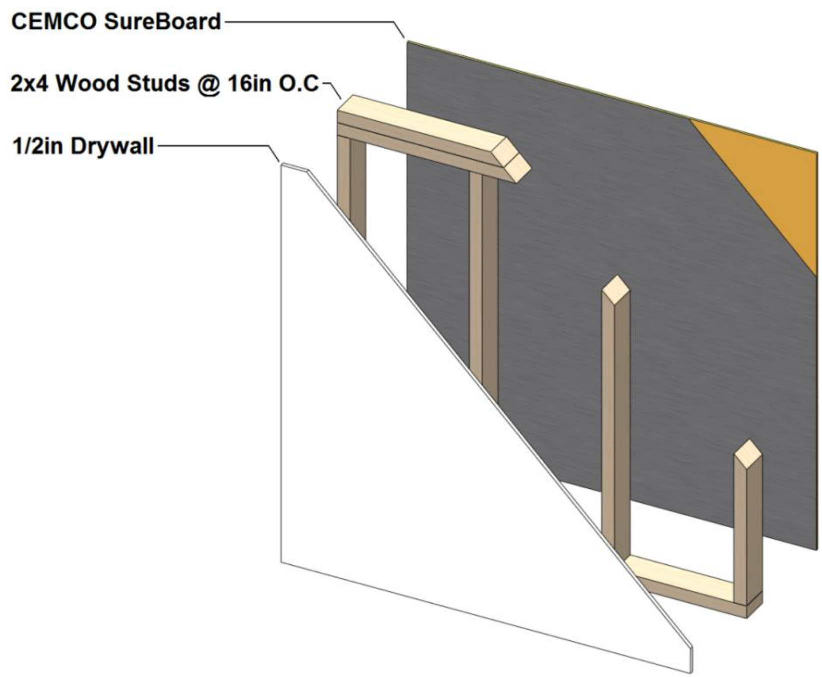

Figure 4-42: Panel 4' Exploded View

Figure 4-43: Panel 4' Typical Front (Left) and Rear (Right) Damage

Table 4-22: Panel 4' Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
4'-3	Top Right	8.650	36.84	35.19	13.86	357.72	PASS
4'-3	Bottom Left	8.650	36.30	34.21	13.48	338.22	PASS
4'-3	Center	8.650	36.57	34.67	13.66	347.34	PASS

4.2.23 Panel 5

Panel 5 consisted of 1/2in drywall, 5/8in plywood, wood studs at 16in on center, and 1/2in drywall (Figure 4-44). The specimen was tested twice, and both missiles perforated the exterior and interior layers (Figure 4-45). Based on both tests, Panel 5 is considered a failure (Table 4-23).

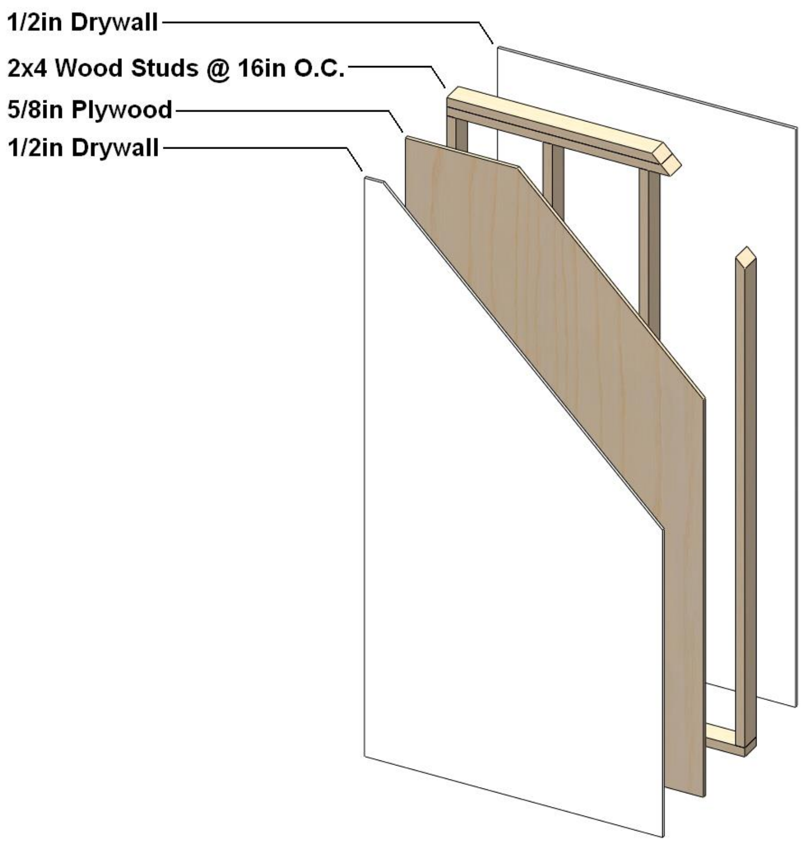

Figure 4-44: Panel 5 Exploded View

Figure 4-45: Panel 5 Typical Front (Left) and Rear (Right) Damage

Table 4-23: Panel 5 Testing Results

Test Panel	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
5-1	Bottom Left	8.750	36.88	35.27	14.06	363.52	FAIL
5-1	Center	8.750	36.62	34.76	13.85	353.20	FAIL

4.3 Wall Panel Summary

Based on the results from the individual wall panel tests, Table 4-24 was created as a summary overview of all the specimens.

Table 4-24: Wall Specimen Testing Summary

TEST PANEL	ASSEMBLY DESCRIPTION	RESULTS
O	Hardie Board Lap Siding / HomeWrap / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
A	Hardie Board Lap Siding / StormWrap / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
B	Hardie Board Lap Siding / HomeWrap / 1/2 inch Plywood / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
C	Hardie Board Lap Siding / HomeWrap / 5/8 inch Plywood / 2x4 Wood Studs @ 16 inches o.c / 1/2 inch Drywall	PASS
O'	5/8 inch T1-11 / 350S162-33 Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
G'	8 ¼ inch Cementious Lap Siding / 22 Gauge Sheet Metal / 350S162-33 Studs @ 16 inches O.C. / 1/2 inch Drywall	PASS
H	8 ¼ inch Cementious Lap Siding / 350S162-33 Studs @ 24 inches O.C. / 22 Gauge Sheet Metal / 1/2 inch Drywall	PASS
M-O	5/8 inch T1-11 / 350S162-33 Studs @ 24 inches O.C. / 1/2 inch Drywall	FAIL
M-A	5/8 inch Fiber Board / 350S162-33 Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
M-B	5/8 inch Fiber Board / 350S162-33 Studs @ 24 inches O.C. / 1/2 inch Drywall	FAIL
M-C	3/4 inch OSB / 350S162-33 Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL
M-D	3/4 inch OSB / 350S162-33 Studs @ 24 inches O.C. / 1/2 inch Drywall	PASS
M-E	8 ¼ inch Cementious Lap Siding / 350S162-33 Studs @ 24 inches O.C. / 5/8 inch T1-11	FAIL
M-F	8 ¼ inch Cementious Lap Siding / 350S162-33 Studs @ 24 inches O.C. / 3/4 inch Plywood	PASS
M-F'	3/4 inch Plywood / 350S162-33 Studs @ 24in O.C. / 8 ¼ inch Cementious Lap Siding	PASS
M-G	8 ¼ inch Cementious Lap Siding / 22 Gauge Sheet Metal / 350S162-33 Studs @ 24 inches O.C. / 1/2 inch Drywall	PASS
1	Hardie Board Lap Siding / HomeWrap / 2x4 Wood Studs @ 16 inches O.C. / Sureboard	PASS
2	Hardie Board Lap Siding / 2x4 Wood Studs @ 16 inches O.C. / 22 Gauge Sheet Metal / 1/2 inch Drywall	PASS
3	1/2 inch Drywall / 2x4 Wood Studs @ 16 inches O.C. / 22 Gauge Sheet Metal / 1/2 inch Drywall	PASS
3'	1/2 inch Drywall / 22 Gauge Sheet Metal / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	PASS
4	1/2 inch Drywall / 2x4 Wood Studs @ 16 inches O.C. / Sureboard	PASS
4'	Sureboard / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	PASS
5	1/2 inch Drywall / 5/8 inch Plywood / 2x4 Wood Studs @ 16 inches O.C. / 1/2 inch Drywall	FAIL

4.4 Analysis of Window Fenestrations

Three louver window fenestrations were tested against a class A small missile at the center position and two opposite corners. This was followed with a class C large missile at the same locations. The missile impact was recorded on the front and rear side using two high speed cameras.

A window fenestration is considered a failure if the impacting missile creates a tear in the interior face longer than 5in and wider than 1/16in. Air is not allowed to pass through this tear nor is a solid sphere with a 3in diameter. All fasteners must remain engaged throughout the testing process. Similarly, the window is considered a pass if the missile is repurcussed from the specimen without having perforated the interior face of the specimen. All pass/fail criteria are taken from the ASTM E 1996-09 specifications, which states:

> "**7.1.1** Fenestration Assemblies and Non-Porous Impact Protective Systems:
>
> **7.1.1.1** The test specimen shall resist the large or small missile impacts, or both, with no tear formed longer than 130 mm (5 in.) and wider than 1 mm (1/16 in.) through which air can pass, or with no opening formed through which a 76 mm (3 in.) diameter solid sphere can freely pass when evaluated upon completion of missile impacts."

During preliminary trial tests, it was determined that the original #8 screws securing the inner aluminum frame to the outer wood frame sheared off. This would not classify as a passing test, therefore, all securing screws were replaced with 1.25in long #10 wood screws prior to testing of all louvers reported here (Figure 4-46).

4.4.1 Small Louver Fenestration

This fenestration assembly was constructed of 6 vinyl blades attached to an aluminum frame measuring 36in wide by 22in high (Figure 4-47). The small missile shot did no apparent damage to the louvers. The 4ft – 4.5lb missile did significant damage to the aluminum clips that held the blades to the frame (Figure 4-48). Based on the two shots conducted, the openings between the deformed louvers would have allowed a 3in diameter sphere to pass through. A third test was not conducted since the damage to the assembly from the first two shots was so significant that it would have affected the outcome of the top right impact location. This specimen is deemed a failure and is not approved for class C large missile windborne debris clearance (Table 4-25).

Figure 4-46: Screw Replacement for Louver Assemblies (Upper #8 screw replaced by lower #10 wood screw)

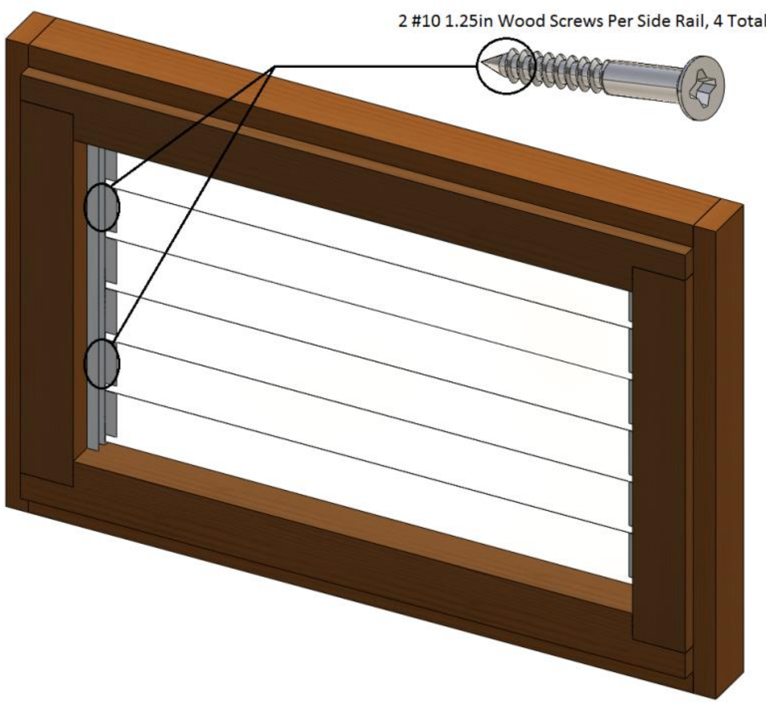

Figure 4-47: Small Louver Fenestration Assembly

Figure 4-48: Small Louver Typical Front (Left) and Rear (Right) Damage

Table 4-25: Small Louver Testing Results

Test Window	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
Small Louver	Center	4.45	33.63	28.52	5.78	120.90	FAIL
Small Louver	Bottom Left	4.45	33.95	28.91	5.86	124.23	FAIL

4.4.2 Medium Louver Fenestration

This fenestration assembly was constructed of 13 vinyl blades attached to an aluminum frame measuring 36in wide by 46in high (Figure 4-49). The small missile shot did no apparent damage to the louvers (Figure 4-50). The vinyl material was examined and there were no permanent marks left on the surface. Based on the three shots conducted for the class A small missile test, the panel is considered a pass (Table 4-26). The louvers behaved in a very elastic manner when tested in the center with the 4ft large missile. The projectile struck the target and recoiled back leaving very little inelastic damage to the specimen. The lower left and upper right shots, however, bent several of the aluminum clips and even broke one of the louvers. Since two of the three trials did significant damage, the specimen is considered a failure for the class C large missile test (Table 4-26).

Figure 4-49: Medium Louver Fenestration Assembly

Figure 4-50: Medium Louver Sustained No Damage from Small Missiles

Figure 4-51: Medium Louver Typical Front (Left) and Rear (Right) Damage from Large Missile

Table 4-26: Medium Louver Testing Results

Test Window	Impact Location	Missile Weight	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
Medium Louver	Bottom Left	10 x 2 grams	89.14	89.14	0.18	11.70	PASS
Medium Louver	Center	10 x 2 grams	89.14	89.14	0.18	11.70	PASS
Medium Louver	Top Right	10 x 2 grams	89.14	89.14	0.18	11.70	PASS
Medium Louver	Center	4.45 lb	32.79	27.67	5.61	113.80	PASS
Medium Louver	Top Right	4.45 lb	32.08	27.21	5.52	110.05	FAIL
Medium Louver	Bottom Left	4.45 lb	33.61	28.49	5.77	120.65	FAIL

4.4.3 Large Louver Fenestration

This fenestration assembly was constructed of 17 vinyl blades attached to an aluminum frame measuring 36in wide by 63in high (Figure 4-52). The small missile shot did no apparent damage to the louvers. The 4ft – 4.5lb missile was rejected at the center position as the flexible blades absorbed most of the energy. At the bottom left, there was inelastic damage done to the aluminum clips that held the vinyl louvers in place. At the top right, the missile broke through one of the panels (Figure 4-53). Since two of the three trials did significant damage, the specimen is considered a failure for the class C large missile test (Table 4-27).

Figure 4-52: Large Louver Fenestration Assembly

Figure 4-53: Large Louver Typical Front (Left) and Rear (Right) Damage

Table 4-27: Large Louver Testing Results

Test Window	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Results
Large Louver	Center	4.45	35.15	28.00	5.68	116.53	PASS
Large Louver	Bottom Left	4.45	33.26	28.21	5.72	118.29	FAIL
Large Louver	Top Right	4.45	33.18	28.03	5.68	116.78	FAIL

4.5 Window Fenestration Test Summary

Based on the results from the individual window fenestration tests, Table 4-28 was created as a summary overview of all the specimens. All PVC louvers were able to resist the small missile tests, however, none of the PVC louvers tested in this series was able to resist the class C large missile.

Table 4-28: Window Specimen Testing Summary

TEST PANEL	ASSEMBLY DESCRIPTION	SMALL MISSILE RESULTS	LARGE MISSILE RESULTS
Small Louver	6 - 902mm x 102mm Vinyl Blades / 902mm x 559mm Aluminum Frame	PASS	FAIL
Medium Louver	13 - 902mm x 102mm Vinyl Blades / 902mm x 1181mm Aluminum Frame	PASS	FAIL
Large Louver	17 x 902mm x 102mm Vinyl Blades / 902mm x 1600mm Aluminum Frame	PASS	FAIL

4.6 Testing Of Window Protection Systems

Two window protection systems were tested independently from the fenestration assemblies. They were shot with a class C large missile at the center position and two opposite corners. The maximum dynamic deflection and residual static deflection were recorded using a high speed camera. If the deflection was considered to be excessive due to a failure of the protection system, the specimen was considered a failure.

A dual system, that consisted of a window protection screen and vinyl jalousie panel was tested with a class D large missile at the center position. The maximum dynamic deflection and residual static deflection were recorded. All fasteners must remain engaged throughout the testing process. All pass/fail criteria are taken from the ASTM E 1996-09 specifications, which states;

"**5.5** For impact protective system specimens that are tested independently of the fenestration assemblies they are intended to protect, measure, and record both the maximum dynamic and the residual deflection following the impact test.... Measure all deflections to the nearest 2 mm (0.1 in).

7.1.2 Porous Impact Protective Systems Tested Independently of the Fenestration Assemblies They are Protecting:

7.1.2.1 There shall be no penetration of the innermost plane of the test specimen by the applicable missile(s) during the impact test(s).

7.1.2.2 Upon completion of the missile impact(s), there shall be no horizontally projected opening formed through which a 76 mm (3 in.) diameter solid sphere can pass."

For this particular test procedure, the high speed cameras were rearranged from their normal configuration to one that allowed the dynamic deflection to be captured on high speed film at 5000fps. High speed camera B was moved from the muzzle of the cannon to an orthogonal recording direction with the test specimen impact location (Figure 4-54).

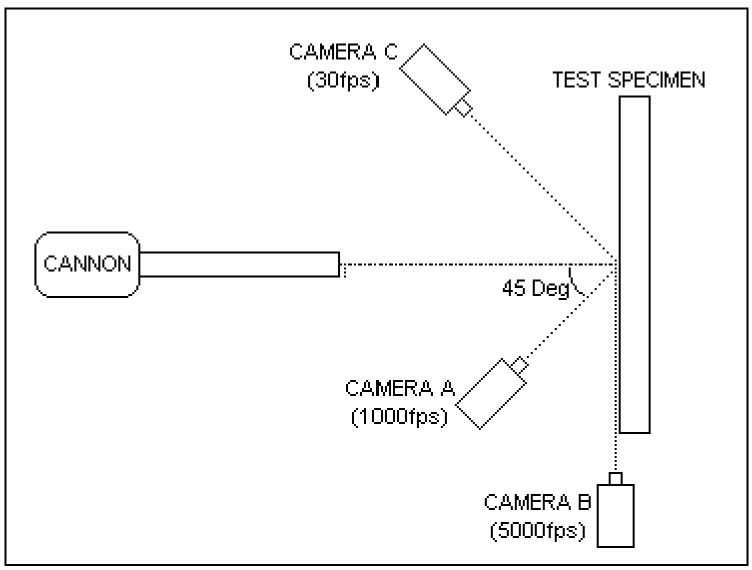

Figure 4-54: Window Protection Screen Testing Camera Orientation

4.6.1 Small Window Protection Screen

This small protection screen was made of an extruded aluminum mesh connected to an aluminum frame via pop rivets (Figure 4-55). The screen was installed in an opening measuring 36in wide by 22in high. This security screen and all subsequent security screens were fastened to the wood frame using 1in long #5 lag screws. For the center shot, the 4ft – 4.5lb missile deflected the screen 3.8in dynamically. At the bottom right, the screen deflected 5in. At the top left, the pop rivets that held the screen to the frame broke free which resulted in an excessive deflection (Figure 4-56). The test results can be seen in Table 4-29.

Had the three tests been performed on three separate specimens, it is predicted that all three tests would pass.

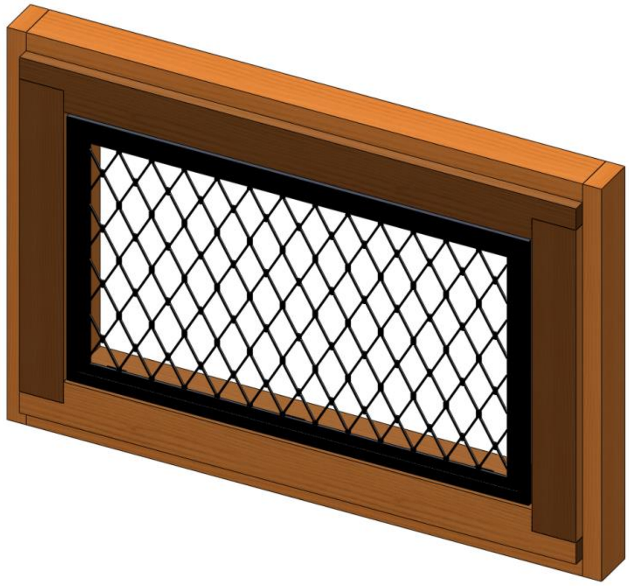

Figure 4-55: Small Window Protection Screen

Figure 4-56: Small Window Screen Typical Front (Left) and Rear (Right) Damage

Table 4-29: Small Screen Testing Results

Test Screen	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Deflection Static (in)	Deflection Dynamic (in)
Small Screen	Center	4.45	32.95	27.81	5.64	114.96	2.5	3.9
Small Screen	Bottom Right	4.45	34.45	29.60	6.00	130.23	3.6	5.0
Small Screen	Top Left	4.45	33.43	28.29	5.73	118.96	Excessive	Excessive

4.6.2 Large Window Protection Screen

This large protection screen was made of an extruded aluminum mesh connected to an aluminum frame via pop rivets (Figure 4-57). The screen was installed in an opening measuring 36in wide by 63in high. For the center shot, the 4ft missile deflected the screen 4.4in dynamically. At the bottom right, the screen deflected 4.6in. At the top left, the screen deflected 3.0in (Figure 4-58). The test results can be seen in Table 4-30.

Figure 4-57: Large Window Protection Screen

Figure 4-58: Large Window Screen Typical Front (Left) and Rear (Right) Damage

Table 4-30: Large Screen Testing Results

Test Screen	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Deflection Static (in)	Deflection Dynamic (in)
Large Screen	Center	4.45	34.03	29.01	5.88	125.09	2.1	4.4
Large Screen	Bottom Right	4.45	34.26	29.33	5.94	127.87	2.8	4.6
Large Screen	Top Left	4.45	33.01	27.87	5.65	115.45	2.3	3.0

4.6.3 Dual System

This system consisted of a protection screen installed in front of a PVC louver assembly (Figure 4-59). The medium size protection screen was made of an extruded aluminum mesh connected to an aluminum frame via pop rivets. The medium size fenestration assembly was constructed of 13 vinyl blades attached to an outer aluminum frame. The system was installed in an opening measuring 36in wide by 46in high. This assembly was subjected to a single center shot using a level D missile. For the center shot, the 8ft missile deflected the system 5.6in dynamically (Figure 4-60). The missile was repurcussed with no significant damage to the screen or louver elements. The test results can be seen in Table 4-31.

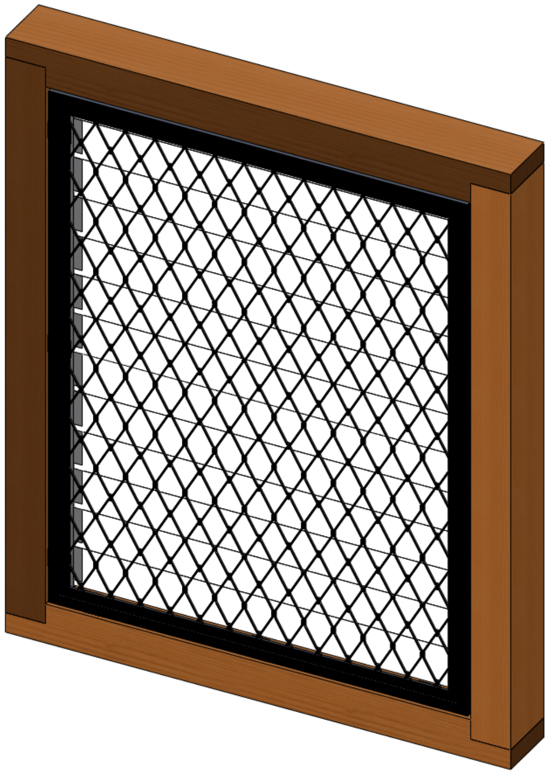

Figure 4-59: Dual System

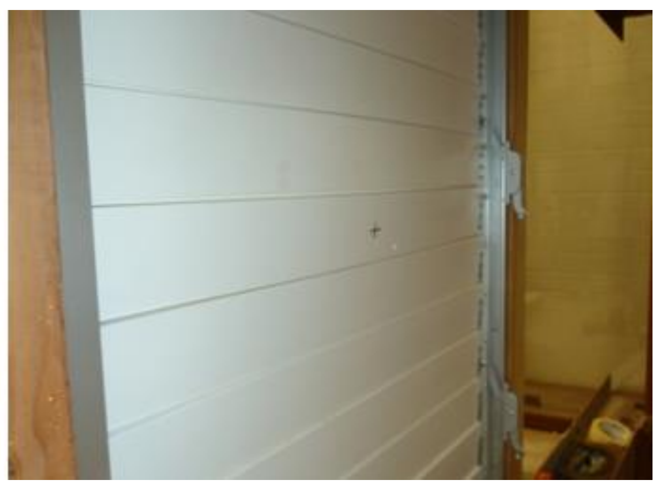

Figure 4-60: Dual System Typical Front (Left) and Rear (Right) After Test

Table 4-31: Dual System Testing Results

Test System	Impact Location	Missile Weight (lb)	Muzzle Velocity (mph)	Impact Velocity (mph)	Momentum (lbf-s)	Energy (ft-lbf)	Deflection Static (in)	Deflection Dynamic (in)
Dual System	Center	9.03	38.32	38.80	15.96	454.08	2.75	5.6

4.7 Window Protection Overview

Based on the results from the individual window protection screen tests, Table 4-32 was created as a summary overview of all the specimens.

Table 4-32: Window Protection System Testing Summary

TEST PANEL	ASSEMBLY DESCRIPTION	MAX STATIC DEFLECTION (in)	MAX DYNAMIC DEFLECTION (in)
Small Screen	902mm X 559mm Steel Window Screen	3.6	5.0
Large Screen	902mm X 1600mm Steel Window Screen	2.8	4.6
Medium Screen & Louver	902mm X 1181mm Steel Window Screen / 902mm x 1181mm Vinyl Louver Window	2.8	5.6

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

Different saferoom wall panel assemblies were tested for category 3 hurricane debris impact resistance. The test procedures and analysis criteria were established based on the ASTM E 1886-05 and ASTM E 1996-09 specifications. The specimens consisted of panels measuring 4ft by 8ft and 4ft by 4ft. They were constructed of both wood and cold formed steel studs, at 16in on center and 24in on center. A selection of interior and exterior cladding materials were used for each saferoom specimen, as they represent typical wall panels found in new home construction throughout Hawaii. All specimens were constructed and/or donated by Hawaii Lumber Products Association (HLPA), Hawaii Steel Framing Alliance (HSFA), Cemco Steel, and Sunrise Construction. Each panel was shot with a Class D 8ft ~ 9lb wood 2x4 in the lower corner, center, and upper corner at approximately 34mph. The results for all the tested wall panels are shown in Table 4-24.

There was no noticeable difference in the performance of the wood stud specimens versus the cold formed steel stud specimens. Therefore, it was concluded that the panel's behavior under impact loading was independent of the framing material.

Wall panels with studs spaced at 16in and 24in generally perform the same. Panels M-C and M-D were the exceptions to this conclusion. Both panels were constructed of 3/4in OSB, CFS studs, and 1/2in drywall. Panel M-C, that had 16in on center studs, was considered a failure. Panel M-D, that had 24in on center studs, was considered a pass. The greater flexibility of the OSB in Panel M-D dissipated more energy between the missile and test specimen. Based on the failure of Panel M-C, 3/4in OSB panels cannot be recommended for use in saferoom construction.

Among the 23 different saferoom wall panels tested, there were many material combinations that did not prove effective in resisting a Level D missile. 1/2in drywall, fiberboard, HomeWrap, and the cementious lap siding did little to slow the penetration of the missile through the wall panel. StormWrap also provided minimal resistance to the impact forces of the projectile. The 5/8in T1-11 plywood was not sufficient by itself in resisting the missile forces. There were certain cladding material combinations, however, found to perform with consistently positive results. The following is a list of those materials that passed the minimum qualifications for Category 3 windborne debris resistance regardless of the framing combination.

- 22 Gauge Sheet Metal (Independent or in a SureBoard Composite)
- Combination of Hardie Board Lap Siding over 5/8 inch Plywood
- 3/4 inch Plywood

Different fenestration assemblies were tested for category 3 hurricane debris impact resistance. The test procedures and analysis criteria were established based on the ASTM E 1886-05 and ASTM E 1996-09 specifications. The specimens consisted of vinyl louver windows and aluminum protection screens. The tested specimens were constructed for window openings measuring 36in by 22in, 36in by 46in, and 36in by 63in. These fenestration systems represent a particular window assembly currently used at schools around Hawaii. All specimens were constructed and/or donated by Aloha Visualite Ltd, Emtek Products Inc, Ulrich Aluminum Company, and Hawaii State Civil Defense. The jalousie windows were shot with Class A 10 x 2gram steel balls at the lower corner, center, and upper corner at approximately 89mph. This was followed with a Class C 4ft ~ 4.5lb wood 2x4 in the same locations at approximately 27mph. The aluminum protection screens were tested with the Class C missile in the lower corner, center, and upper corner. A protection screen and louver window assembly was tested in combination using a Class D 8ft ~ 9lb wood 2x4 in the center at approximately 34mph. The results for all the tested fenestration assemblies are shown in Table 4-28 and Table 4-32.

It was concluded that none of the louver window specimens meet the criteria to be considered for wind zone 1 basic protection of facilities by themselves. The protection screens do pass the requirements for basic protection but must still comply with specific offset requirements. The maximum dynamic deflection measured during the testing will help to ensure that the individual screens are installed a specified distance from the window behind. The following are the minimum requirements for this specification.

- 5.0 inch offset with 36in by 22in aluminum screens
- 4.6 inch offset with 36in by 63in aluminum screens

Based on the information gathered from the debris cannon testing, it is estimated that the material cost of building an 8ft x 12ft saferoom with plywood sheathing rather than drywall, plus an impact resistant window, and a solid wood door is $1,500 (SEAOH, 2012). Similarly, the material cost of providing 5/16in thick impact resistive heat strengthened laminated glass with 0.090in PVB interlayer for a 2,000 square foot regular home with rectangular windows is $10,000 (SEAOH, 2012). These estimates show the cost benefits of the Hawaii State Amendment for the 2006 IBC that allows for the option of saferoom construction.

5.2 Recommendations

It is recommended that if a 22gauge sheet metal panel is used in the construction of a saferoom, the contractor should place the material on the exterior face of the framing. Although the sheet metal is approved for installation on both sides, when utilized on the interior face, any impacting missile will cause the sheet metal to flex. This can cause superficial damage to any interior finishing of the wall and may prove disconcerting to any individuals sheltering inside.

If any of the above approved cladding materials are positioned on the interior face of the saferoom panel, they must be fastened with screws that are in accordance with typical construction hardware sizes and spacing. The use of nails on the interior face is not recommended since the impact force of the missile can cause these fasteners to loosen and pull out.

The hardware used to fasten the vinyl louver windows to the surrounding frame must be equivalent to a #10 wood screw. Prior tests showed that smaller diameter screws were not sufficient in resisting the shear stress imposed by the impact forces.

Additional testing is required to confirm that the combination of expanded aluminum screen and PVC louver is capable of resisting the class D large missile test. Only a single center impact test has been performed in this study, which is not sufficient to qualify this system for use in saferoom or shelter locations.

Additional testing should also be performed on other metal screen systems. Only one type of expanded aluminum security screen was tested in this study.

6 References

ASTM E 1886-05, 2005. “Test Method for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Missiles and Exposed to Cyclic Pressure Differentials”, American Society for Testing and Materials

ASTM E 1996-09, 2005. “Specification for Performance of Exterior Windows, Glazed Curtain Walls, Doors and Impact Protective Systems Impacted by Windborne Debris in Hurricanes”, American Society for Testing and Materials

ICC, 2006. “International Building Code – 2006”, International Code Council, January.

ICC, 2006a. “International Residential Code – 2006”, International Code Council, January.