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DESIGN, CONSTRUCTION, CALIBRATION AND APPLICATIONS OF AN APPARATUS WHICH CONDUCTS THE LARGE MISSILE IMPACT TEST

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Abstract

Prior to Hurricane Andrew (August 1992), the South Florida Building Code maintained provisions for the design of building openings based on wind pressure only. Hurricane Andrew provided evidence of other failure modes, including windborne debris and internal pressure. Following the hurricane, several changes were made to building codes in South Florida. One addition requires building openings to resist windborne debris. A missile impact test incorporated into recently accepted Dade and Broward Counties editions of the South Florida Building Code states a window, door, or external protection device shall resist a prescribed number of impacts from a nine pound 2x4 timber accelerated to 50 ft/sec. The design, construction and calibration of an apparatus to conduct this test, as well as its current applications are presented in this report.

INTRODUCTION

The report begins with a brief overview of recent developments in the building codes in South Florida as a result of Hurricane Andrew. It then details the large missile impact test incorporated in these new code provisions. Design criteria used in the development of the apparatus to conduct the missile impact test are stated along with descriptions of the general design and construction processes. Velocity versus pressure curves for the apparatus and external checks of the missile timing system are reported. Recommendations for improvements in accuracy and operating efficiency are made throughout, and a summary of the objectives accomplished is provided.

BACKGROUND

Hurricane Andrew has become the most researched storm in several years. Although meteorologists and engineers disagree on the exact wind speed generated by the storm, the storm contained winds of at least 110-125 MPH. [1] Many people considered the South Florida Building Code [2], at the time Hurricane Andrew roared into Dade County, completely adequate with its design wind speed of 120 MPH. This was the highest design wind speed in the nation. With the devastation well researched and documented [3], the design wind speed was proven not to be the only important feature of the building code and several deficiencies were highlighted.

The code contained no requirements for internal pressure, or impacts from windborne debris. Consequently, many buildings remained structurally sound (no members ruptured), but received severe damage on the interior of the building because the building envelope failed allowing wind and rain to enter. As the winds increased, they began to pick up surrounding materials and subjected the structures not only to intense pressures, but also to a barrage of windborne debris. These missiles included everything from 2x4s to trash cans. The most destruction resulted from roofing tiles and roof gravel. As the buildings were impacted by debris, windows, doors and shutter systems began to fail, creating internal pressure. This, effectively doubled the pressure on some other building components, and promoted further failures.

To avoid similar situations in the future, Dade and Broward counties in South Florida have taken two important steps. The first was adoption of ASCE 7-88 [4], the national standard for loads on buildings which contains provisions for internal pressure. The other major step was to adopt provisions requiring building openings to resist missile impacts, thus assuring the integrity of the building envelope.

In the new codes in Dade and Broward counties [5,6], a "large" missile impact test along with cyclic pressure loadings are used to determine if particular building products can be used in the lower thirty feet of a structure, where large windborne debris is prevalent. A "small" impact test is used to test building materials utilized above thirty feet. The codes maintain the following large missile specifications:

1. The large missile is to be a 2x4 piece of graded lumber.
2. It must be without knots within 12 in. of the impact end.
3. It is to maintain a weight of 9.0-9.5 lb including the sabot.[1]
4. It shall have a normal impact with a specimen.
5. It is to be accelerated to a speed of at least 50 ft/sec using an air cannon.

The codes also detail the test apparatus:

1. The cannon is to use compressed air to accelerate the missile.
2. It is to be comprised of a compressed air supply, pressure release valve, pressure gauge, barrel, supporting frame, and a timing system.
3. The barrel and frame are to facilitate the aiming of the missile at the desired locations.
4. The timing device is to measure the speed of the 2x4 after exiting the barrel using photoelectric sensors and an electronic clock operating at a frequency of no less than 10 kHz.

Three specimens are to be provided for testing. They are to receive a prescribed number of impacts in specified areas, and then subjected to cyclic pressure loadings. If two of the three specimens tested resist the large missile impacts and the cyclic pressure loadings without forming a crack longer than 5 in. or an opening more than 3 in. in diameter, the product has passed the code and may be certified. For example, a window is to receive two impacts from the 2x4 missile; one within a five in. radius circle located at the center of the specimen, and the other within a similar circle centered in a corner a distance of 6 in. from the supporting members. After the specimen is impacted twice, it is then subjected to cyclic pressure loadings.

DESIGN CRITERIA

At the time of design, specific criteria governing the cannon as stated above were not in place. Therefore, the design was based on a similar existing cannons, and ideas for further improvement. The following design criteria were established to facilitate fabrication of a properly functioning test apparatus:

1. The cannon must accelerate a 2x4 missile weighing 9.0-9.5 lb to the required velocity of 50 ft/sec, and accommodate possible increases in the required velocity due to future changes in building codes.
2. The apparatus must facilitate the aiming of the 2x4 missile to ensure the accurate impact of the missile against a test specimen; impact heights range from approximately 10 in. to 6 ft above the ground.
3. The cannon must be constructed within economic constraints.
4. The cannon must employ a device to accurately time the missile's velocity upon exit from the barrel.

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[1] A sabot is a plug attached to the trailing edge of the missile which conforms to the basic dimensions of the cannon barrel. It gives the compressed air a larger area to contact and accelerate the missile.

DESIGN AND CONSTRUCTION

Compressed air was chosen as the energy source to accelerate the missile to the required velocity. It was easy to acquire, provided for a safe acceleration within a barrel, and provided a simple means to adjust the resulting missile velocity by regulating the amount of pressure. Another option, a mechanical arm utilizing a spring system was considered, but concerns about the accuracy of the impact, safety, and timing instrument implementation deemed this option incompatible for the situation. Use of compressed air requires a storage tank of large enough volume to provide for proper acceleration of the missile. The necessary containment was estimated. In this calculation, a particular tank size and barrel configuration was assumed and the pressure required to accelerate the missile to the required velocity was found. The calculations were completed using the basic definition of pressure, the ideal gas law, and assuming a twenty percent decrease in available pressure for acceleration due to losses of the air around the sabot and through the pipes and valve. Other assumptions included the amount of friction and air drag present. The results indicated a tank volume of 30 gallons would provide the required air to yield 50 ft/sec with as little as 5 psi pressure.

To provide for possible increases in required missile velocity, variations in missile weights, and adaptations in the barrel configuration, a tank of 50 gallons or more was thought to be necessary. An out-of-service 60 gallon compressed air tank was available for no charge and promptly used. The tank contained two 2 in. diameter outlets on its face; this was in contrast to a single 4 in. diameter outlet considered in design calculations. However, with a 60 gallon tank and the low amount of pressure estimated to be required, the losses involved in the expansion from 2 in. outlets to a 4 in. barrel were relatively insubstantial. The use of the existing 2 in. holes also avoided the expense of creating a 4 in. outlet.

The barrel was chosen to be 4 in. diameter PVC pipe. Other considerations included a sizable rectangular barrel made from aluminum which would have provided a much larger sabot area for the compressed air to accelerate the projectile. This approach would have required a more extensive supporting frame, and a more complicated expansion from 2 in. outlets to a rectangular barrel. These requirements made this option impractical.

With the barrel selected, the transition from the 2 in. outlets to the 4 in. barrel was designed. It consisted of inserting two 2 in. male adapters into the outlets, which were then connected to 2 in. unions. The unions were connected to a 2x4 reducer, thus providing the necessary diameter. The reducers were connected to 90° bends which brought the two sides together into a 4 in. tee. The tee then exited into a female adapter connected to a 4 in. (quarter turn fully open) ball valve. The ball valve was connected to the barrel using a 4 in. steel nipple. This piping network is shown in Figure 1.

PVC schedule 40 pressure fittings were used at all locations with exception to the steel nipple. Schedule 40 PVC provides for pressure capabilities over 200 psi. The pressure fittings contributed a slightly deeper socket and gluing area, thus incorporating additional safety. The steel nipple was used to accommodate the moment present from the weight of the barrel. The 2 in. unions provided for construction ease and the ability to remove the piping from the tank.

The 4 in. (quarter turn fully open) ball valve was chosen in part due to the simplicity of operation. A 4 in. butterfly valve was also considered. The butterfly valve would have provided for a "quicker and cleaner" opening, yielding a better impulse of air. Along with the butterfly valve, a solenoid trigger system was considered; all of these components would increase the accuracy and efficiency of the system. Because of the relative ease of manually controlling a ball valve, these options were not chosen.

The compressed air tank was connected to shop air using a 1/2 in. stop valve. The line enters the tank through a pressure regulator which provides a means of controlling the pressure. A 30 psi pressure gauge was obtained with 0.5 psi increments for accuracy in reading the tank pressure. It was manufactured with a 0.5% error and was chosen to provide repeatable tank pressures. A relief valve set to approximately 20 psi was also included for safety.

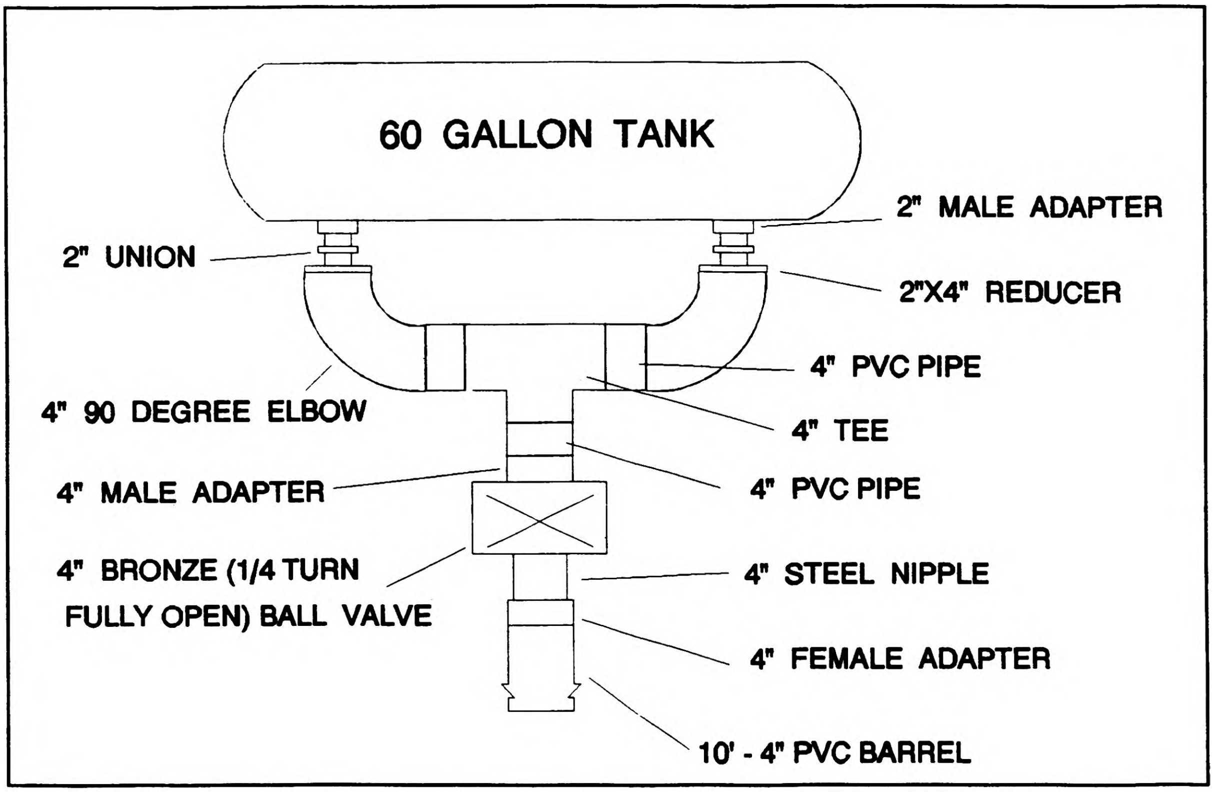

Figure 1. Piping Network

At this stage, the design of a frame was considered. The frame needed to support the vertical loads of the apparatus and the horizontal load due to the "kick"; it also must be maneuverable in all directions. The "kick" was estimated to be a maximum of approximately 300 lb, assuming a constant acceleration of a 9.5 lb missile in a 10 foot long barrel to a speed of 100 ft/sec. The value of 100 ft/sec was used as a worst case scenario. The vertical load was also very small; it was estimated to be less than 500 lb. In order to accomplish maneuverability, the frame was designed to allow the hand forklift already present in the research laboratory to raise and lower the apparatus.

The frame was designed and constructed of 3" steel channel. It supported the air tank and piping system up to the barrel. The majority of the weight was due to the air tank. However, the valve was estimated to weigh approximately 50 lb, and required support to avoid stresses in the PVC connections to the tank. The horizontal "kick" force is transferred to the frame through bolts connecting the air tank and a 4 in. U-bolt tightly fastened around the valve. The frame is raised 4 in. off the ground to allow the forklift to slide underneath. Four swivel casters were also provided to accommodate movement of the apparatus around the lab.

The timer consists of a two sensor array within a diffuser. The 4 in. PVC barrel exits into a 6"x4" reducer and then into the 6 in. diffuser made from PVC pipe as shown in Figure 2. The diffuser's basic function is to allow the compressed air to exit around the sabot and out through the slots provided to avoid acceleration of the missile during the timing process. The timer uses a two sensor array activated by the reoccurrence of light. The sensors are separated by a distance of one foot. As the trailing edge of the missile passes the upstream sensor, an electronic clock, operating at 100 kHz, is started. The missile continues to exit, passing the second sensor; this stops the electronic clock. The digital readout displays a number which corresponds to the electronic clock reading. The inverse of this number is multiplied by 100000 and the velocity of the missile in ft/sec is obtained.

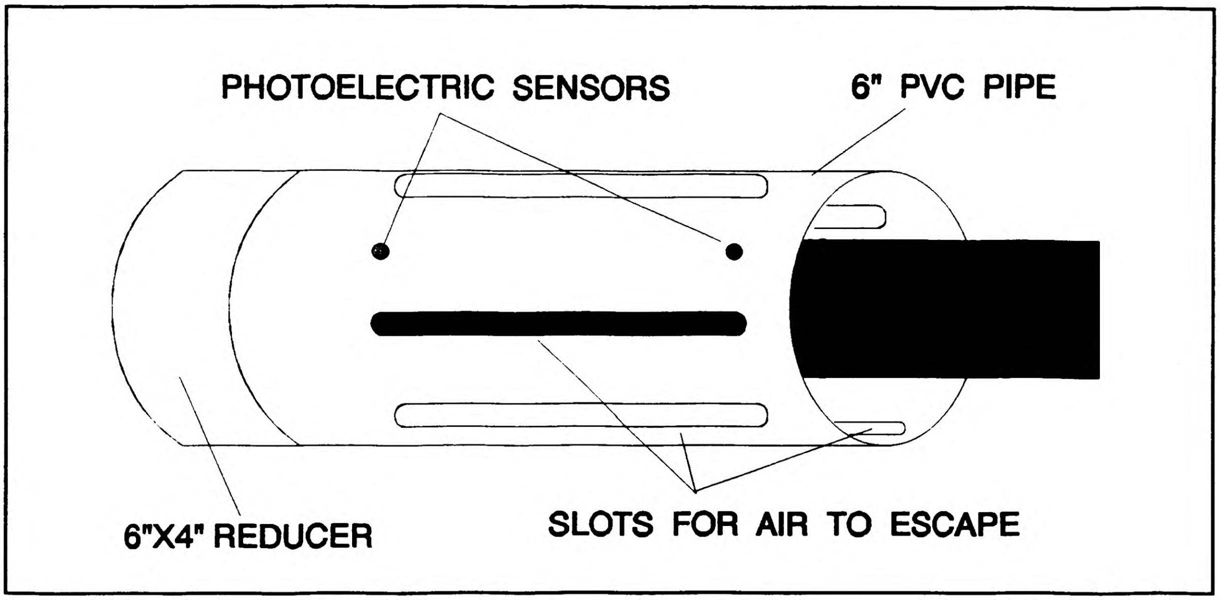

Figure 2. Timer/Diffuser

VELOCITY VERSUS PRESSURE CURVES

The results of the design and construction phase of the project produced an apparatus, as shown in Figure 3, which satisfied the design criteria. Continuing to ready the apparatus for research required the development of velocity versus pressure curves. This task was completed by firing the cannon more than 190 times over a range of pressures and recording the resulting velocities. Procedures and results follow.

Figure 3. Large Missile Impact Apparatus

A backstop, as shown in Figure 4, was constructed to absorb the missile impacts during the calibration process. It consisted of about 1.5 ft of compressed cardboard turned on a 90° angle. Under the vertical cardboard was a 1 in. horizontal layer of cardboard, and an oak wood skid. The backstop proved rather poor in its original form. The 2x4 traveled between the vertical cardboard, through a seam, and impacted the horizontal cardboard and the wood skid. Carpeting was later added to alleviate this problem. Although serving its purpose, the backstop deteriorated quickly.

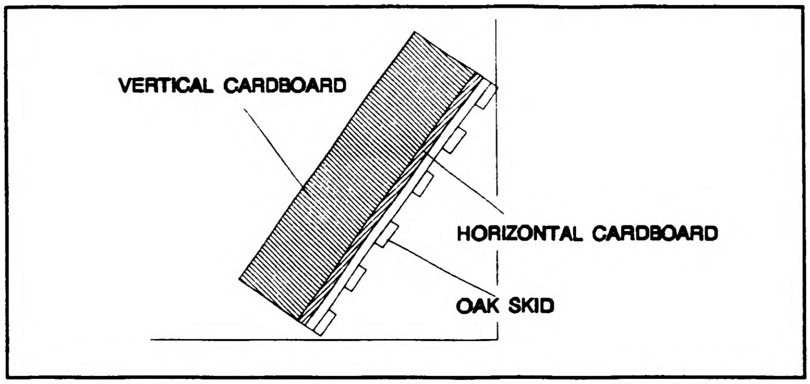

Figure 4. Backstop

The cannon was set-up, and aligned with the backstop. The timer was attached and the air tank was pressurized to a desired level. The cannon was fired, and the timer readout and pressure were recorded. A sample of the data collected is shown in graphical form in Figure 5. Several factors affected the velocity of the 2x4, these included:

1. Manual operation of the ball valve
2. Size and stability of the sabot
3. Weight of the missile
4. Condition of the barrel interior

The obvious variable was the manual operation of the ball valve. When the operator opened the valve as quickly as possible during each firing, the overall effect on the missile velocity was not substantially apparent. With the amount of data collected for individual sabot and 2x4 combinations, there was little deviation within the various sets of data. This result indicated that the effect of manual valve operation was insignificant. However, when the operator opened the valve "slower", deviation from the expected missile velocity became apparent. The valve would release part of the air before it was completely open. This reduced the remaining pressure in the tank without providing for substantial acceleration of the missile. When the valve finally reached the open position, the tank no longer had the required pressure to accelerate the missile to the expected velocity.

The size and stability of the sabot used proved to be a critical variable. Five different sabots were tested throughout 194 shots. They varied in composition from woods; namely plywood, oak and fir; and also included aluminum. Three different types of sabot attachment configurations were used ranging from a simple nail to supporting angles. A final configuration submerged the 2x4 into an aluminum sabot. All configurations are shown in Figure 6.

The plywood and fir sabots deteriorated quickly as they fell to the floor after the missile impacted the backstop. The plywood sabot developed chips along its edge making data repeatability unlikely. The fir sabot cracked after falling to the floor a few times. The oak sabots did not deteriorate in the same manner, but the attachment configuration to the 2x4 proved to be an important factor in the consistency of the results. When the sabots were connected with one common nail the stability of the sabot was deficient and the resulting data showed a wider deviation from the best fit line. When two small angles were used along with the nail, the results were more consistent. The oak sabots split after repeated impacts to the floor.

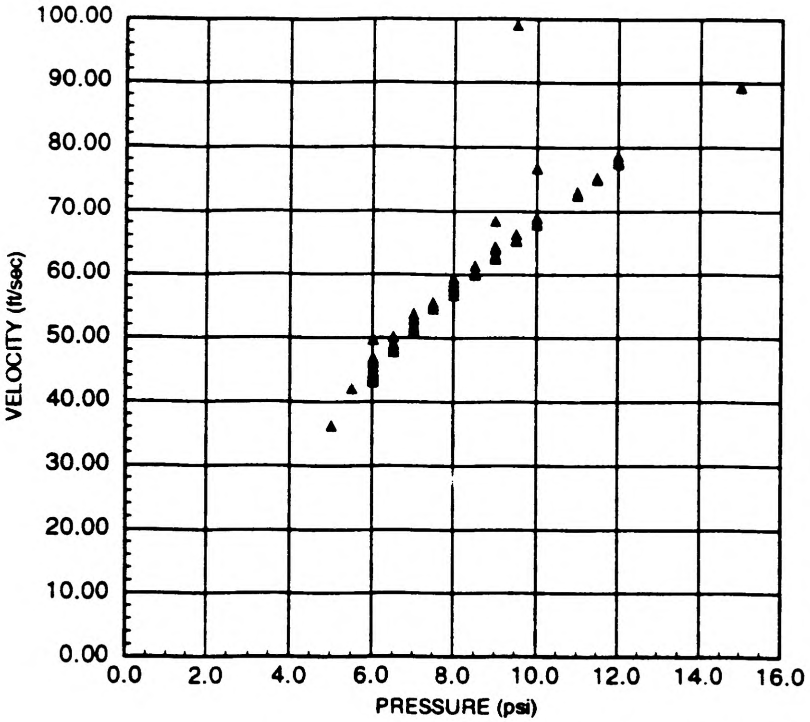

Figure 5. Velocity versus Pressure Curve-Aluminum Sabot

The final sabot was aluminum and the attachment configuration submerged the 2x4 into the sabot. As expected, the aluminum sabot held up superbly and did not loosen throughout the 102 shots performed with it. There was a high degree of consistency in the data as exhibited by a correlation coefficient of 0.95 for the logarithmic best fit line. However, a few shots developed a higher velocity than expected. The anticipated reason is because the sabot was milled to a slightly smaller diameter than the wooden sabots. This process reduced the amount of available contact area for the air. This effect was indicated in the overall data as the aluminum sabot yielded slightly lower velocities for all pressures than the larger wooden sabots. However, the difference in diameter also created enough room for the sabot to get "caught" in the downstream impulse of air and effectively "float", reducing the friction and increasing the velocity. This occurred about 3% of the time. The results are shown in Figure 5.

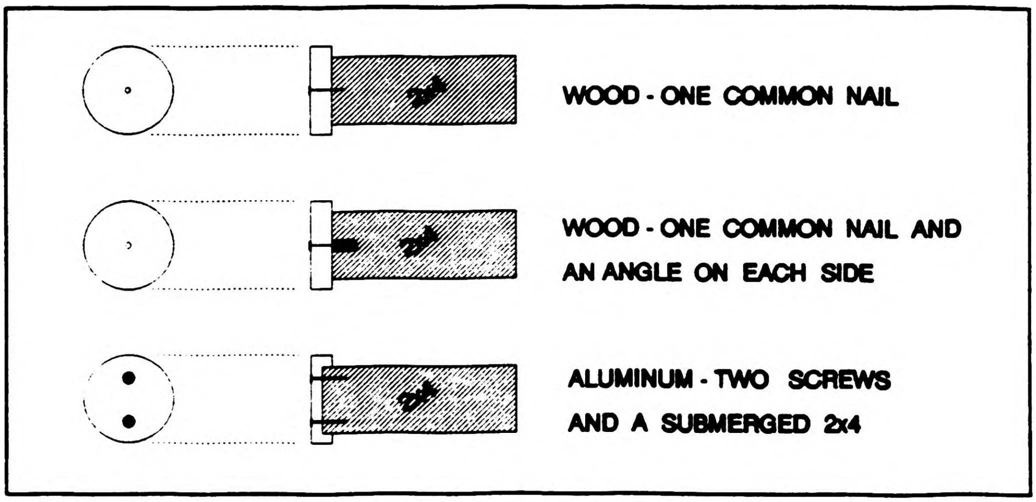

Figure 6. Sabot Attachment Configurations

The operator may choose the sabot type for a particular research project, and only a small amount of data is needed to obtain a velocity versus pressure curve for a desired pressure region. In the case of the codes implemented in South Florida the desired velocity of the 2x4 is 50 ft/sec and the required pressure is approximately 6.5 psi depending on the exact sabot used. Recommendations include an aluminum or plastic sabot with a secure attachment configuration and a diameter close to that of the barrel. A cushion placed on the floor will soften the sabot's fall.

The differing missile weights are also a variable. Again, the amount of deviation developed as a the result of a 0.5 lb change in the overall weight was not readily apparent. A final variable in the velocity versus pressure curve was the condition of the barrel. Throughout the 194 shots the same 4 in. PVC barrel was used; its condition deteriorated. The inside of the pipe became scratched, and its surface was no longer smooth. Although this obviously had some effect on the results, no systematic decline in the velocities for a given pressure were observed. Thus, the effect is minor and can be neglected for any research conducted without firing several hundred shots.

EXTERNAL ACCURACY CHECKS

The timer determines the velocity of the final foot of the missile as it exits the barrel. This procedure is important due to the magnitude of acceleration applied to the 2x4 while it is in the barrel. Two external checks on timer accuracy were performed. One was completed by dropping a short length of 2x4 through the timer from a known height and then comparing the timer reading and corresponding object velocity to that given by basic physics. This check was not without flaws. The object was dropped through a 4 in. PVC pipe to ensure proper entry into the timer, and during the descent the 2x4 grazed the sides of the PVC pipe providing friction and effectively slowing the object. This minor amount of contact was neglected and this process was used to calibrate the timer.

The second check completed on the timer utilized a video camera. The cannon was set up in its usual manner and the timer secured to the end of the barrel. The video camera was set up perpendicular to the end of the timer. A 1"x2" piece of wood approximately six feet long was obtained and lines were drawn on it at one foot increments. This piece of wood was attached to the outside of the timer and extended through mid-air. The set-up is shown in Figure 7.

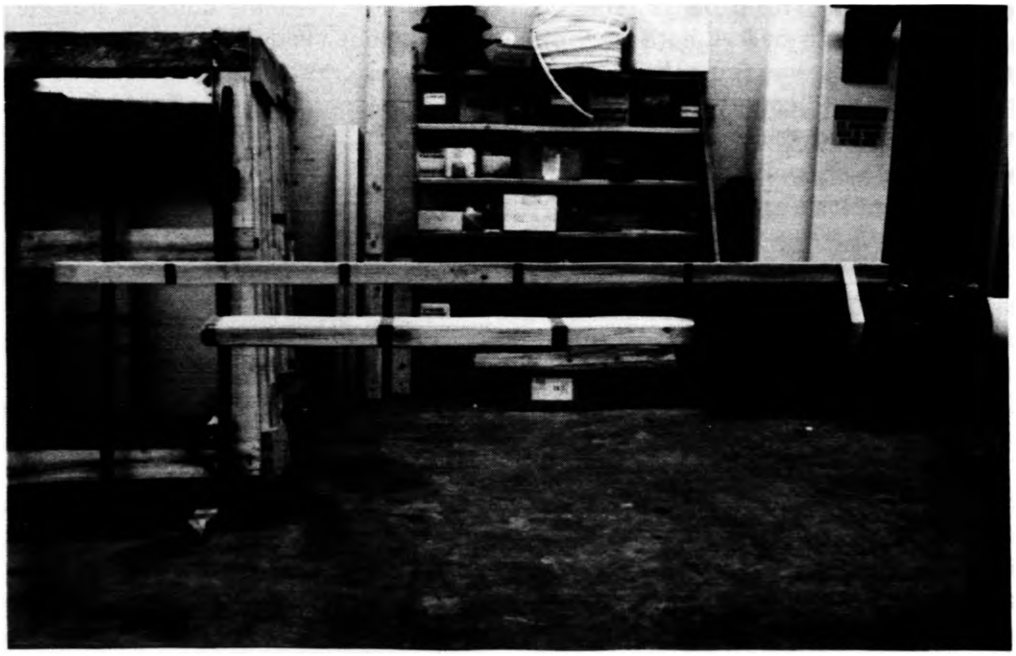

Figure 7. Calibration Set-up

The cannon was fired several times while the camera recorded each shot and the corresponding timer reading. The video tape was played back using a frame-by-frame VCR and the end of the missile was observed as it passed the markings on the piece of wood attached to the timer. With the knowledge of the exposure length for each frame of the tape being 0.0333 seconds (or 30 frames per second film speed) and the distance traveled in one frame observed, the approximate velocity of the missile was determined. This velocity was compared to the timer's velocity.

The results indicate the timer is adequate. In general when the trailing edge of the missile was easily viewed using the frame-by-frame VCR, the deviation between the timer velocity and the calculated velocity was less than 2 ft/sec. However, in several shots the approximate position of the trailing edge of the 2x4 was indeterminable. This was due to a "blurring" effect the missile created as it traveled during the exposure length.

CURRENT APPLICATIONS

The cannon is currently being used to provide research data for the American Plywood Association. Various grades, widths, and spans of plywood to be used as external protection devices, or shutters, are tested in accordance with the Dade and Broward counties editions of the South Florida Building Code. The plywood panels are attached to a wooden frame shown in Figure 8 using common 8d nails spaced 6 in. on center. The cannon is used to impact the panels in the center and 6 in. from each edge with a 9.0-9.5 lb 2x4 accelerated to a velocity of 50 ft/sec. Each impact is recorded using a video and still camera, and a written damage log is completed. The exact velocity, weight, and length of the missile are recorded. Penetration is noted, along with dynamic deflection, if applicable.

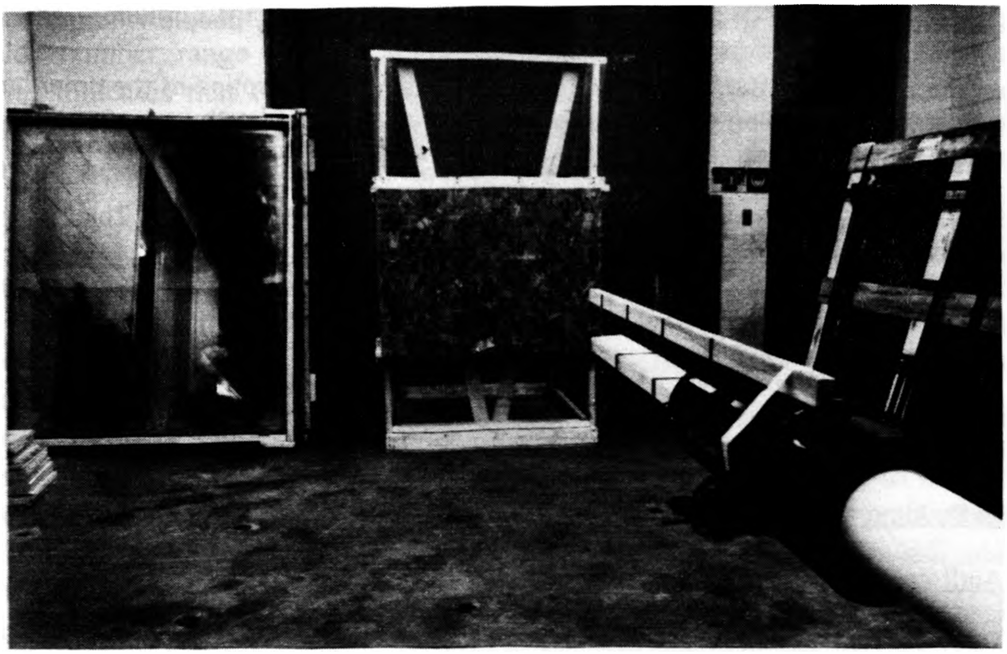

Figure 8. Plywood Backstop

With the first set of tests completed, 5/8 in. Douglas Fir plywood in a 4 foot width and a 4 foot span was able to withstand the center impact, but full penetration occurred when it was impacted in the corner. The 3/4 in. Douglas Fir plywood in a 4 foot width and 5 foot span was able to withstand the center impact, and also resisted the corner impact at times. To date, none of the panels of smaller thickness have been able to resist penetration.

The width and span are important parameters affecting the behavior of the panel. The same panels passing with large widths and spans have failed with shorter widths and spans. This indicates the ability of the panel to absorb the energy of the missile by deflection is critical.

SUMMARY

Building code changes implemented in South Florida require building openings to resist windborne debris, thus preserving the integrity of the building envelope and avoiding the development of internal pressure. Along with these changes, the challenge of product certification is created. One part of the certification process involves a "large" missile impact test which consists of accelerating a 2x4 missile to 50 ft/sec and impacting a test specimen in the appropriate locations.

To accomplish this task, a 60 gallon compressed air tank was acquired. Using existing 2 in. diameter outlets on its face, the tank discharges compressed air through a network of piping which exits through a 4 in. ball valve down a 4 in. PVC barrel. A sabot is used behind the 2x4 to facilitate the required acceleration. Many types of sabots may be used, but the size and stability of the sabot affect the discharge velocity of the missile. The operator should choose the sabot carefully and conduct several calibration shots before beginning a research project to obtain the pressure required to produce the desired velocity. The timer uses a two sensor array within a 6 in. PVC diffuser, and is triggered by the reoccurrence of light. This procedure has proven to effectively time the last foot of the missile as it exits the barrel. The cannon is currently being used to research the ability of different grades, widths and spans of plywood, used in shutter systems, to resist penetration.

Acknowledgements

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