U.S. Department of Housing and Urban Development
Office of Policy Development and Research

WIND-BORNE DEBRIS

IMPACT RESISTANCE OF RESIDENTIAL GLAZING

PATH (Partnership for Advancing Technology in Housing) is a new private/public effort to develop, demonstrate, and gain widespread market acceptance for the "Next Generation" of American housing. Through the use of new or innovative technologies, the goal of PATH is to improve the quality, durability, environmental efficiency, and affordability of tomorrow's homes.

PATH is managed and supported by the Department of Housing and Urban Development (HUD). In addition, all Federal Agencies that engage in housing research and technology development are PATH Partners, including the Departments of Energy and Commerce, as well as the Environmental Protection Agency (EPA) and the Federal Emergency Management Agency (FEMA). State and local governments and other participants from the public sector are also partners in PATH. Product manufacturers, home builders, insurance companies, and lenders represent private industry in the PATH Partnership.

To learn more about PATH, please contact:

PATH
PARTNERSHIP FOR ADVANCING TECHNOLOGY IN HOUSING

451 7th Street, SW
Washington, DC 20410
202-708-5873 (fax)
e-mail: pathnet@pathnet.org
website: www.pathnet.org

Visit PD&R's Web Site
www.huduser.org
to find this report and others sponsored by
HUD's Office of Policy Development and Research (PD&R).

Other services of HUD USER, PD&R's Research Information Service, include listservs; special interest, bimonthly publications (best practices, significant studies from other sources); access to public use databases; hotline 1-800-245-2691 for help accessing the information you need.

WIND-BORNE DEBRIS

IMPACT RESISTANCE OF RESIDENTIAL GLAZING

Prepared for

U.S. Department of Housing and Urban Development
Office of Policy Development and Research
Washington, DC

Cooperative Agreement H-21172CA

by

NAHB Research Center, Inc.
Upper Marlboro, Maryland

January 2002

Acknowledgments

This report was prepared by the NAHB Research Center under contract to the U.S. Department of Housing and Urban Development (HUD). The review and guidance provided by Dana Bres, William Freeborne, and Andrea Vrankar of HUD is appreciated. The following employees of the NAHB Research Center are acknowledged for their work on this project:

Jay Crandell, P.E., Technical Reviewer
Steve Graves, Technician
Lynda Marchman, Administrative Assistant
Denise McCoskery, Technician/Researcher
Brandy Rogers, Technician
Mark Wagner, Technician

ABOUT THE NAHB RESEARCH CENTER, INC.

The NAHB Research Center is a not-for-profit subsidiary of the National Association of Home Builders (NAHB). The NAHB has 200,000 members, including 50,000 builders who build more than 80 percent of new American homes. The NAHB Research Center conducts research, analysis, and demonstration programs in all areas relating to home building and carries out extensive programs of information dissemination and interchange among members of the industry and between the industry and the public.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

PAGE

LIST OF FIGURES

PAGE

1.0 INTRODUCTION

Since the disaster caused by Hurricane Andrew in 1992, protection of glazing (i.e., windows and doors on the exterior of homes and other buildings) from wind-borne debris damage has received much attention. The resulting impact on product standards and building regulations has affected the balance of affordability and performance of new homes in some hurricane-prone regions of the United States with uncertain costs and benefits. In part, this uncertainty is due to the lack of an objective calibration of performance criteria to historically accepted levels of risk. In general, historically accepted levels of risk are represented by the actual built environment and are not easily determined by supposition based on anecdotal observations and "expert" opinion. Data on the impact resistance of typical residential glazing materials (i.e., annealed glass) is needed to realistically analyze and benchmark an acceptable level of risk of glass breakage due to wind-borne debris. From such data, risk-consistent levels of performance (i.e., impact load criteria) can be objectively determined and applied to specify glass (or glass protection devices such as shutters) used in hazardous conditions, particularly when the benchmarked level of accepted risk is exceeded with typical glazing materials such as annealed glass.

The objective of this research was to provide needed data on the fragility (i.e., impact magnitude vs. glass breakage probability) of typical residential glass using field-observed and standardized missile types representing wind-borne debris. In this experimental study, representative sources of debris hazards, such as pieces of roof shingles and nominal 2 in. by 4 in. dimension lumber (hereafter referred to as a '2x4') were used to impact "standard" (i.e., non-impact resistant) glass, namely annealed glass. The test matrix included both 3/32-in. and 5/32-in. glass thickness tested at 1:1 and 2:1 aspect ratios (2 ft x 2 ft and 2 ft x 4 ft panels). Impact speed was varied as necessary to characterize fragility (i.e., glass breakage probability vs. impact magnitude). In addition, the response of annealed glass to multiple impacts was investigated. Representations of impact magnitude using kinetic energy and momentum are also compared with respect to the ability to predict glass behavior or fragility.

From this work, it is anticipated that wind-borne debris hazards and standardized performance criteria for wind-borne debris protection of glazing in residential buildings will be improved or at least better understood. In particular, this information is intended to improve hazard-modeling assumptions used to assess the risk of glass breakage in hurricane-prone environments of the United States. Ultimately, such research should lead to optimized solutions for wind-borne protection of window and door glazing in homes and other buildings.

2.0 BACKGROUND

2.1 WIND-BORNE DEBRIS HAZARD STUDIES

Recent studies have given some scientific insights into major factors governing wind-borne debris hazards in residential settings. For example, glass breakage in residential buildings during Hurricane Andrew was extensive [1]. Hurricane Andrew produced winds of up to 165 mph gust which are estimated to represent a 300-year return event in South Florida. On the other hand, glass breakage in Hurricane Opal was minimal with design level wind speeds (i.e., 50-year return period) of about 110 mph gust over much of the affected housing population [2]. Differences in wind magnitude and exposure were considered to be key factors distinguishing the outcome of these events.

In an effort to simulate wind debris risk, wind exposure and shielding were found to have a pronounced effect on relative reliability estimates [3]. In addition, roof shingles were found to be a dominant source of wind-borne debris in residential settings, not a wood 2x4 as used in standardized test methods and product acceptance criteria. Furthermore, the simulation procedure used some conservative assumptions to determine estimates of relative risk of window breakage. For example, a window break was considered to occur for any type or magnitude of debris impact which, in turn, increases subsequent debris generation and hazard to other simulated homes in a compounding fashion. Given a lack of data on the fragility (i.e., glass damage probability vs. impact magnitude) of typical glass and typical sources of debris in residential settings, such a conservative assumption was felt to be a prudent preliminary decision in the research.

2.2 Wind-borne Debris Impact Resistance

The most recent national model building codes have adopted ASTM E1996 [4] and ASTM E1886 [5] as the acceptance criteria for window and door protection systems (i.e., shutters) or impact resistant glass. These protective measures may be required (by local statues) in some hurricane-prone regions of the United States. Therefore, the consideration of wind-borne debris has become an important aspect of design for coastal regions of the country where buildings are subjected to severe wind events, such as hurricanes.

As a means of determining the impact resistance of a fenestration unit, the ASTM E1996 standard requires the use of 2x4 missiles for assembly heights of less than 30 ft. However, there has been little research regarding the breakage characteristics of plate glass when impacted by 2x4 missiles. Experimental evidence has focused mainly on glass damage caused by small steel balls [6,7,8,9,10,11,12]. The small steel balls are intended to represent small gravel projectiles commonly produced from commercial buildings with flat roof systems using gravels as ballast – an uncommon roof construction method in residential settings. More recently, tests have been conducted with impacts from 2x4 missiles on annealed glass [6,7,8,11], tempered glass [11], and laminated glass [9,10,12].

Other types of missiles that are more commonly generated in residential settings during major hurricanes include composition roof shingles [3]. Unfortunately, there is very little information regarding glass resistance to this common source of wind-borne debris. This situation is due in part to the difficulty of developing a repeatable test method for impacting fenestration units with missiles such as shingles. No studies were found in the literature that investigated roof shingle missiles or determined fragility curves that are necessary for rigorous risk analysis of glass performance in residential buildings. Fragility curves depict the probability of window (glass) breakage based on magnitude of impact and are crucial material property inputs to model risk.

2.3 Description of Annealed Glass

Annealed glass, the most common glazing material used in residential windows, is a ceramic material (typically soda-lime glass) formed by heating the constituents to fusion and then cooling the mixture to a rigid state in a controlled atmosphere [13]. The physical properties are similar to traditional ceramics in that glass is a brittle and relatively hard substance with low toughness and ductility [13]. Strength values of glass are based on theoretical bond strength, while practically it exhibits fracture at a much lower value. This difference is due to surface flaws that create local areas of stress concentration. There has been much analysis concerning the fracture mechanics of glass (a review of the subject can be found in a report by Brungs) [14].

2.4 IMPACT MECHANICS

Impacts or collisions are described by the "sudden, forceful coming together in direct contact of two bodies" [15]. Impacts, therefore, are usually associated with impulsive forces that are generally very large and short-lived in nature.

Impacts are classified into two types: elastic and inelastic (plastic). In extremely elastic collisions (as in atomic collisions that do not result in changes to atomic energy states), very little energy is lost due to deformation of the colliding bodies during impact and it can be generally ignored in analyzing the mechanics of such collisions. In extremely plastic collisions (as in a ball of soft putty impacting a steel plate), considerable energy is lost due to plastic material deformation. The lost energy is manifested in the production of heat internal to the deformed material and cannot be ignored in analyzing the mechanics of such collisions. In reality, there is a continuum of conditions ranging from elastic to very inelastic (plastic) types of collisions.

Three physical parameters are inextricably related to the outcome of an impact:

- material properties of the colliding bodies (i.e., hardness, brittleness, elasticity, and ductility);
- force imparted during the collision; and
- duration of contact.

Because of the force-time relationship during an impact is difficult to measure, the application of conservation laws are generally employed to predict the outcome of a collision. These laws require that energy and momentum are conserved (i.e., the total energy or momentum prior to collision equals the total afterwards). Regardless of the elasticity or plasticity of the colliding bodies, the total momentum and energy must be conserved. However, in the case of energy conservation, energy loss due to inelastic collisions resulting in the formation of heat energy must be considered. In the context of this study, the collision of a 2x4 missile and plate glass can be considered relatively elastic in comparison to the collision of an asphaltic composition shingle missile and plate glass. Thus, in the absence of accounting for material deformations and associated energy losses (i.e., transformation of some of the initial kinetic energy to heat energy), conservation of momentum could be expected to more consistently depict the outcome of collisions involving missiles of differing degrees of elasticity or plasticity.

3.0 REFERENCES

[1] NAHB Research Center, "Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki," report prepared for the U.S. Department of Housing and Urban Development, September 1993.

[2] NAHB Research Center, "Assessment of Damage to Homes Caused by Hurricane Opal," report prepared for the Florida State Home Builders Association, January 1996.

[3] Applied Research Associated, Inc., “Analysis of Hurricane Windborne Debris Impact Risk for Residential Structures: Part II,” prepared for State Farm Mutual Automobile Insurance Companies, January 1999.

[4] ASTM E1996, “Standard Specification for Performance of Exterior Windows, Glazed Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes,” American Society of Testing and Materials, West Conshohoken, PA.

[5] ASTM E1886, “Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials,” American Society of Testing and Materials, West Conshohoken, PA.

[6] Ball, A., McKenzie, H.W., "On the low velocity impact behaviour of glass plates," *Journal de physique*, IV, Vol. 4, No. 8, 1994, pp. c8-783-c8-788.

[7] Wilson, J.F., "Similitude Experiments on Projectile Induced Fracture of Monolithic Glass," *Int. J. Impact Engineering*, Vol. 18, No. 4, 1996, pp. 417-424.

[8] Wiederhorn, S.M., Lawn, B.R., "Strength Degradation of Glass Impacted with Sharp Particles: I, Annealed Surfaces," *Journal of the American Ceramic Society*, Vol. 63, No. 1-2, 1979, pp. 66-70.

[9] Behr, R.A., Kremer, P.A., "Performance of Laminated Glass Units Under Simulated Windborne Debris Impacts," *Journal of Architectural Engineering*, Vol. 2, No. 3, 1996, pp. 95-99.

[10] Pantelides, C.P., Horst, A.D., Minor, J.E., "Postbreakage Behavior of Heat Strengthened Laminated Glass Under Wind Effects," *Journal of Structural Engineering*, Vol. 119, No. 2, 1993, pp. 454-466.

[11] Harris, P.L., "The Effects of Thickness and Temper on the Resistance of Glass to Small Missile Impact," Texas Tech University, Institute for Disaster Research, *1978*.

[12] Beason, W.L., Masters' thesis, "Breakage Characteristics of Window Glass Subjected to Small Missile Impacts," Texas Tech University, Institute for Disaster Research, 1974.

[13] Smith, W.F., *Principles of Materials Science and Engineering - 2nd Edition*, 1990, McGraw-Hill.

[14] Brungs, M.P., "Fracture and Failure of Glass," *Materials Forum*, Vol. 19, 1995, pp. 227-239.

[15] *The New Encyclopaedia Britannica,* Vol. 3, Encyclopedia Britannica, Inc., Chicago, 1994.

4.0 EXPERIMENTAL PROGRAM

4.1 GENERAL TEST PLAN

To determine the damage characteristics of standard residential glazing, a study matrix of test parameters was initially developed (see Table 1). Low, medium, and high velocity levels for impacts were determined by preliminary testing to guide in the selection of impact levels that would bound high and low probabilities of glass breakage for each glass specimen size and thickness and each missile type. This initial phase of testing was done to ensure that, upon execution of the test plan, the data would yield a reasonable depiction of glass fragility curves (i.e., breakage probability verses impact magnitude).

TABLE 1
TEST PARAMETERS AND STUDY MATRIX

Glass Type	Annealed
Glass Thickness	3/32 in., 5/32 in.
Glass Size	2 ft x 2 ft, 2 ft x 4 ft
Missile Types	2x4, Roof Shingle
Impact Velocity	Low, Medium, High
Impact Location	Center of Specimen
Impact Vector	Perpendicular to Specimen Surface
Repetitions	5 Minimum

4.2 TEST EQUIPMENT AND MATERIALS

4.2.1 Test Facility

A 40 ft long x 8 ft wide x 8 ft high shipping container served as the wind debris lab (see Figure 1). The interior space of the container was conditioned to maintain a relatively stable temperature throughout the test program. Temperature stability was considered to be relatively important due to potential effects on the glass and missile material properties, particularly the stiffness of the shingle missiles.

To support the glass specimens and frames, a reaction wall (Figure 2) was constructed 94 in. high x 48 in. wide according to standard wood-frame construction practice using 2x4 Spruce-Pine-Fir stud and plate material. An opening was framed into the wall to accommodate the glass specimen test frames, which were bolted onto the wall. The bottom plate was held in place by a 4-in.-wide metal track fastened to the wood floor of the container and the top plate was held in place by a steel L-channel welded to the ceiling of the container.

Figure 1
Photograph of debris impact test lab showing air compressor, holding tank, air cannon, and reaction wall.

Figure 2
Reaction wall with 2 ft x 2 ft glass specimen frame (left) and 2 ft x 4 ft glass specimen frame with one side removed (right).

According to size, glass specimens were mounted into one of two test frames (2 ft x 2 ft and 2 ft x 4 ft) fabricated from 1 in. x 2 in. Poplar wood. Each frame consisted of two parts. One side of the wood frame was recessed and lined with 3/8-in.-wide x 3/16-in.-thick vinyl foam weather-strip gasket. The glass was placed against the weather-stripping and the other side of the wood frame, also lined with weather-stripping, was secured directly against the glass. A series of bolts and wing nuts held the wood frame together (see Figure 2). The entire test frame assembly was intended to represent the stiffness of actual window mountings in residential wood-frame construction. However, no attempt was made to quantify window frame and assembly stiffness in actual homes. Variations in stiffness and dampening in actual window mountings and potential effects on glass performance should be considered when interpreting the results of this study.

An electronic timing device with a sampling frequency of 100KHz was configured to receive start and stop pulses from two pair of through-beam photoelectric sensors. The distance between the sensors was divided by the time interval recorded by the device to determine the missile speed. The system operation was verified using the equations of motion and gravity (see Appendix A).

4.2.2 Test Specimens (Glass)

Two hundred pieces of annealed float glass were purchased from CARDINAL®DPG, Minneapolis, MN, and shipped to the Research Center. The glass arrived in November 2000 and was stored in the Research Center laboratory until testing began in May 2001. Specimens consisted of 2 ft by 2 ft and 2 ft by 4 ft glass panels at 3/32-in. and 5/32-in. thickness. Tables 2 and 3 summarize the geometry and thickness of the glass used in each series of tests, as well as the temperature conditions during testing.

TABLE 2
GLASS SIZE AND TESTING CONDITIONS FOR PENDULUM TESTS (2x4 MISSILES)

Specimen	Aspect Ratio (h x w)	Number of Specimens Tested	Average Glass Thickness (in) (COV)	Average Temperature (°F) (COV)
2' x 2' 3/32"	1:1	21	0.09163 (0.8%)	72.7 (1.7%)
2' x 2' 5/32"	1:1	18	0.15084 (0.5%)	71.8 (0.4%)
2' x 4' 3/32"	2:1	26	0.09241 (2.3%)	73.0 (1.2%)
2' x 4' 5/32"	2:1	16	0.152347 (0.8%)	70.8 (4.8%)

TABLE 3
GLASS SIZE AND TESTING CONDITIONS FOR AIR CANNON TESTS (SHINGLE MISSILE)

Specimen	Aspect Ratio (h x w)	Number of Specimens Tested	Average Glass Thickness (in) (COV)	Average Temperature (°F) (COV)
2' x 2', 3/32"	1:1	30	0.09191(0.6%)	72.3 (2.4%)
2' x 2', 5/32"	1:1	20	0.15190 (1.0%)	79.9 (4.4%)
2' x 4', 3/32"	2:1	17	0.09194 (0.4%)	71.5 (1.8%)
2' x 4', 5/32"	2:1	18	0.15138 (0.5%)	71.4 (1.7%)

4.2.3 Pendulum Apparatus and 2x4 Missile

A pendulum apparatus was constructed to propel a 2x4 missile at low speeds. The 2x4 missile used throughout the test program was a 3-ft-long Southern-Yellow-Pine 2x4 weighing 4.6 lbs (including the weight of rigidly attached hardware). Two elastic (bungee) cords were used to provide additional energy to the missile. The bungee cords were anchored to eyebolts installed on the floor near the reaction wall and hooked onto a L-shaped bolt on the missile, which allowed the elastic cords to disengage prior to impact (Figure 3). A rope and pulley system was used to pull the missile back, stretching the bungee cords into position. At the opposite end of the missile an eyebolt was installed to function as part of the trigger mechanism and a digital force gauge, installed in line between the missile and pulley, measured the tension force (Figure 4). The missile was suspended by 1/8 in. aircraft cable. The cable was run through two eyebolts on the missile and continued up to two eyebolts on the ceiling forming a V pattern, which held the missile centered on the plane of the specimen (Figure 5). The specimens were impacted within a 2-in. radius circle located at the center of each specimen.

Figure 3
Elastic cord attachment to the 2x4 missile.

Figure 4
Trigger system.

Figure 5
Pendulum system.

A relationship between force and speed was developed to eliminate the exposure of the speed measuring system to glass debris and to document uncertainty in impact velocity (Appendix B). Thus, the desired missile speed during testing was obtained by applying a calibrated draw-back force. By this method, missile impact speed was controlled to within an estimated two percent error.

4.2.4 Air-Cannon Apparatus and Shingle Missile

Three-tab composition roof shingles (manufactured by GAF – Royal Sovereign series) were cut into pieces approximately 2 in. wide x 6 in. long and bundled into packets of six (the number of pieces from a single tab). Duct tape was wrapped around one end of each packet to facilitate insertion into the sabot and ensure that the shingles would not break apart before hitting the target. A new packet of shingles was used for each impact and the weight of each packet was recorded. The average weight of the packets of shingles was 0.46 lbs with a coefficient of variation (COV) of 4 percent. The missile configuration was intended to provide for a worst case, direct impact from the edges of the several shingle pieces bundled together. This shingle missile configuration also prevented uncontrolled impact conditions associated with glancing blows, sideways impacts, or excessive shingle deformations (i.e., buckling) during impact that would result in a lower breakage probability. However, these avoided impact test conditions are probably more representative of random shingle impacts in actual hurricane wind conditions.

The sabot used with the shingle missile was a 4-in. diameter open cell foam packing material that was wrapped in cotton material (Figure 6). A second 4-in. diameter open cell foam sabot was left uncovered and a slot cut into the middle to hold the shingle packet in a horizontal firing position. These sabots were not considered to have a significant effect on the outcome of the test due to their light weight (~0.05 lbs each).

Compressed air was supplied to a 5-gal holding tank fitted with a pressure gauge. To fire the air cannon, an actuator valve released the air in the holding tank through a 1-1/2-in. hose into the barrel. The barrel was made from a 4-in. diameter PVC pipe cut to a 5-ft length. The PVC pipe was attached to a 3.5-in. x 5.5-in. x 5 ft piece of pressure treated timber to absorb the reaction and was secured on a steel shelving unit that allowed for both horizontal and vertical positioning of the cannon (Figure 7). The muzzle (exit point of the barrel) was positioned 6 ft from the target impact plane.

Figure 6
Sabots and shingle packet.

Figure 7
Shingle packet being loaded into the air cannon.

The photoelectric sensors were placed 12 in. apart at the exit point of the cannon and set to pulse as the leading edge of the shingle missile passed by each pair of detectors. Speed was determined by dividing the distance between the sensors by the recorded time interval. A relationship between air pressure and speed was developed to establish pressures associated with target missile velocities for the purpose of being able to select a target missile velocity according to the test plan (see Appendix C). However, the speed measuring system was left in place and the actual missile speed was recorded with each test. The specimens were impacted within a 4-in. radius circle located at the center of each specimen.

4.3 TEST PROCEDURES

Glass specimens were moved to the test lab at least 24 hours prior to testing to allow for temperature equilibration. Each piece of glass was assigned a unique identifying number and all test data for that specimen was recorded on a test data sheet. Recorded data included the test date, missile type, temperature, glass size, and measured thickness. The thickness of each glass specimen was measured in two places. Specimens were then secured in the test frame by consistently hand-tightening wing nuts on bolts holding the wood frame together. No attempt was made to quantify torque applied to the wing nuts or the resulting clamping force on the glass specimens.

In general, five to ten specimens were tested at each of three selected impact speeds for both missile types (shingle and 2x4). The result of the initial impact, including the nature of damage (if any) was recorded. If a break occurred, the next specimen was mounted and tested at the specified speed. If a break did not occur, the specimen was impacted up to four additional times at the same missile speed. For pendulum (2x4 missile) tests, the impact surface of the 2x4 was inspected after each impact for evidence of deterioration; no damage was observed throughout the testing due to the relatively low impact velocities used. For the air-cannon (shingle missile) tests, a new shingle missile “packet” was used for each impact.

The data of most interest in this study was the outcome (i.e., break or no break) from the first impact with both missile types investigated. Additional impacts were conducted on specimens that did not break upon the initial impact to gain some insight into the effects of multiple impacts and potential cumulative damage that may reduce glass resistance to subsequent impacts.

5.0 RESULTS

Two technical issues were investigated: (1) glass fragility in relation to a single impact from 2x4 and shingle missiles and (2) glass fragility in relationship to multiple impacts and potential cumulative damage effects. The test data presented in this section address these two areas of interest. A discussion of the results is provided in Section 6.0.

5.1 FRAGILITY (SINGLE IMPACT)

Principles of kinetic energy (i.e., $E = 1/2mv^2$, ft-lbs) and momentum (i.e., $P = mv$, lb-s) are often assumed to relate, and even normalize, the potential for glass breakage across glass configurations and missile types. Based on the discussion in Section 2.4, Impact Mechanics, the data in this section are presented in terms of the momentum (Figure 8). Summary data, including missile kinetic energy, are provided in Tables 4, 5, and 6 for the 2x4 missile and shingle missile tests. Additional discussion on the use of missile kinetic energy in comparison to momentum is provided later in Section 6.0.

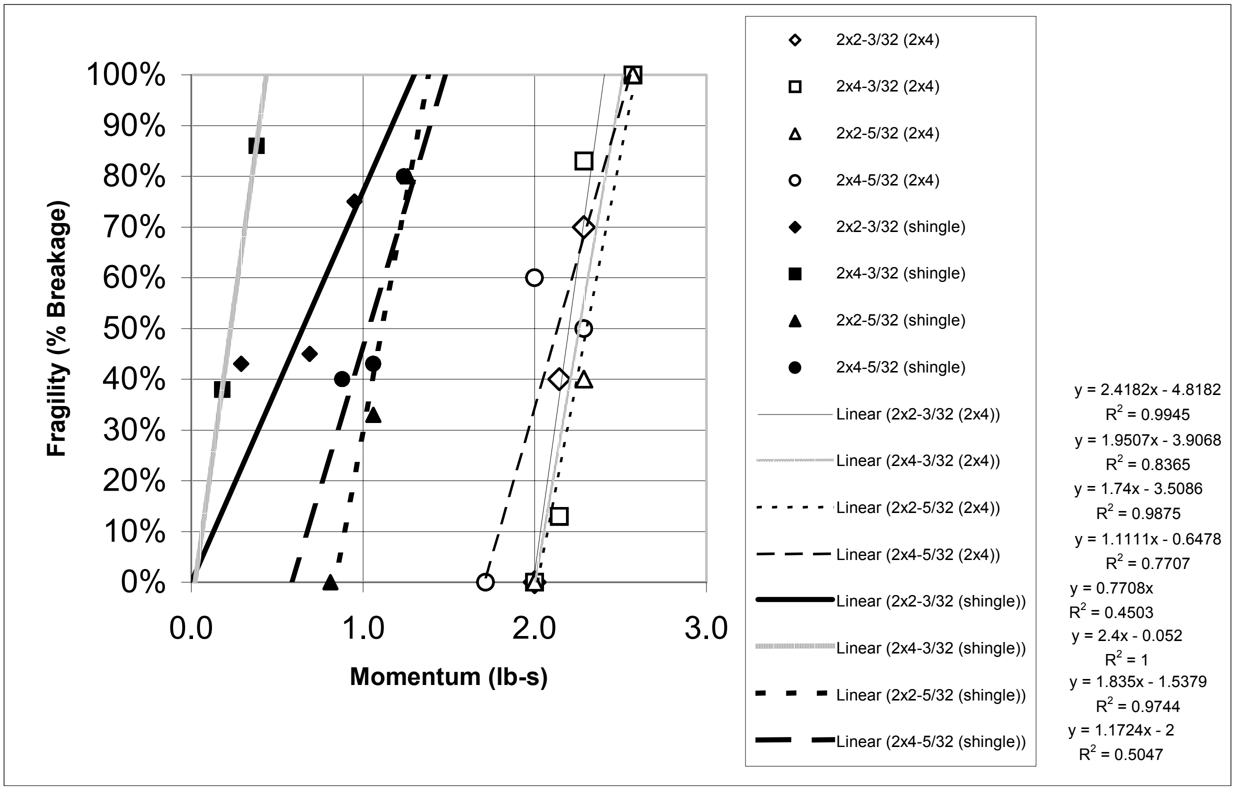


Figure 8
Fragility of annealed glass specimens based on impact momentum of 5 lb 2x4 missile (pendulum apparatus) and shingle missile (air cannon apparatus).

TABLE 4
SUMMARY OF 2X4 MISSILE FRAGILITY DATA

SPECIMEN	SAMPLE SIZE	WEIGHT	SPEED (ft/s)	MOMENTUM (lb-s)	ENERGY (ft-lbs)	PERCENT BREAKAGE (FRAGILITY)* N = NUMBER OF IMPACTS		
						n=1	n<=3	n<=5
2X2-3/32	5	4.6	14	2.0	28.0	0%	0%	0%
	5	4.6	15	2.1	32.1	40%	60%	80%
	10	4.6	16	2.3	36.6	70%	90%	100%
2X4-3/32	5	4.6	14	2.0	28.0	0%	0%	0%
	8	4.6	15	2.1	32.1	13%	38%	38%
	6	4.6	16	2.3	36.1	83%	100%	100%
	5	4.6	18	2.6	46.3	100%	100%	100%
2X2-5/32	6	4.6	14	2.0	28.0	0%	33%	50%
	5	4.6	16	2.3	36.6	40%	60%	80%
	5	4.6	18	2.6	46.3	100%	100%	100%
2X4-5/32	5	4.6	12	1.7	20.6	0%	0%	0%
	5	4.6	14	2.0	28.0	60%	60%	60%
	6	4.6	16	2.3	36.6	50%	100%	100%

*Percent breakage is a cumulative value based on total sample size within each glass size – missile speed category.
Note: 60% value for 2x4-5/32 and n=1 may be classified as 40% since the group contained the only sample that cracked (across bottom) rather than completely shattered (i.e., 'destroyed').

TABLE 5
SUMMARY OF SHINGLE MISSILE FRAGILITY DATA BASED ON MOMENTUM (SINGLE IMPACT ONLY)

SPECIMEN	SAMPLE SIZE	BINS OF MOMENTUM (lb-s)	AVERAGE MOMENTUM (lb-s)	% BREAKAGE (FRAGILITY)
2X2-3/32	7	0.22-0.52	0.29	43%
	11	0.53-0.82	0.69	45%
	12	0.83-1.11	0.95	75%
2X4-3/32*	8	0.14-0.23	0.18	38%
	7	0.33-0.41	0.38	86%
2X2-5/32	4	0.72-0.94	0.81	0%
	6	0.95-1.16	1.06	33%
	10	1.17-1.38	1.26	80%
2X4-5/32	5	0.85-0.99	0.88	40%
	7	1.00-1.14	1.06	43%
	5	1.15-1.28	1.24	80%

*Middle bin not included due to small sample size of one in bin.

TABLE 6
SUMMARY OF SHINGLE MISSILE FRAGILITY DATA BASED ON ENERGY (SINGLE IMPACT ONLY)

SPECIMEN	SAMPLE SIZE	BINS OF ENERGY (ft-lbs)	AVERAGE ENERGY (ft-lbs)	% BREAKAGE (FRAGILITY)
2X2-3/32	13	3.5-31.3	15.8	46%
	10	31.4-59.1	47.8	50%
	7	59.2-86.9	69.4	86%
2X4-3/32*	8	1.2-4.5	2.3	38%
	7	7.7-11.0	9.8	86%
2X2-5/32	5	36.1-69.3	51.4	0%
	8	69.4-102.5	86.9	50%
	7	102.6-135.8	117.3	86%
2X4-5/32	6	52.0-71.9	56.9	50%
	6	72.0-91.9	80.9	33%
	5	92.0-111.9	106.6	80%

*Middle bin not included due to small sample size of one in bin.

The data, as illustrated in Figure 8, support the following observations:

1. For shingle missiles, the impact momentum causing a 50 percent breakage probability ranges from 0.2 to 1.2 lb-s for all glass specimen configurations.
2. For the 2x4 missile, impact momentum causing a 50 percent breakage probability ranged from 2.3 to 2.5 lbs for all glass specimen configurations.
3. For the 2x4 missile, an impact threshold of about 1.8 to 2.0 lb-s was found, below which the probability of breakage is near zero; such a distinct threshold was not observed for the shingle missile data.
4. Due to the relatively tight grouping of the 2x4 missile fragility data (Figure 8), there is no clear distinction between glass thickness and size in terms of fragility.

5. Increased glass thickness consistently lowered the probability of breakage with the shingle missile.
6. For the shingle missile and a given glass thickness, there is a tendency for the smaller glass panel to exhibit greater impact resistance.

With the 2x4 missile, glass specimen failure, when it occurred, was catastrophic (Figure 9) in all but one case where the failure mode was a horizontal crack a few inches from the bottom edge of the specimen. With the shingle missile, glass failure (when it occurred) was usually catastrophic. However, in about 22 percent of the failed specimens, there was a measurable perforation at the impact point ranging from 4 in. to 13 in. in diameter (see Figure 10).

Figure 9
Glass failure (2x4 impact).

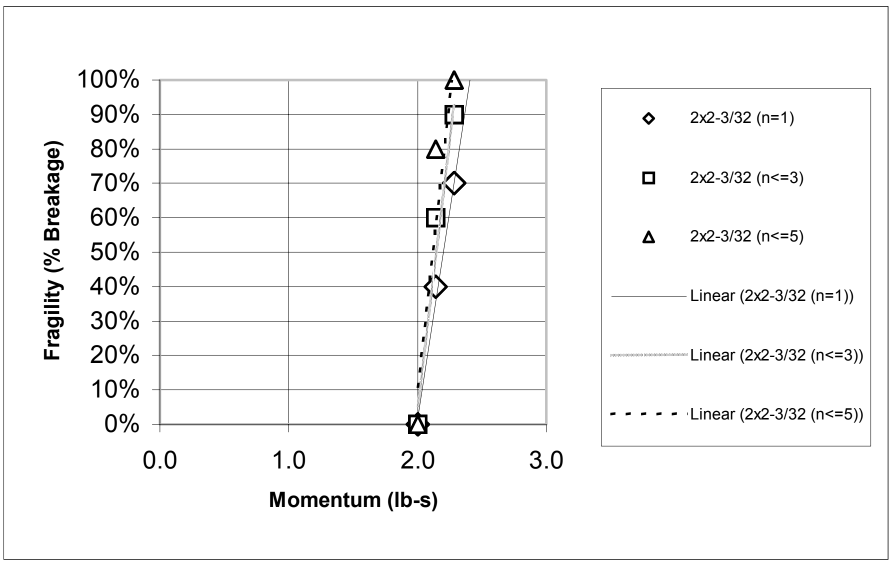
Figure 10
Glass failure (shingle impact).

5.2 FRAGILITY (MULTIPLE IMPACTS)

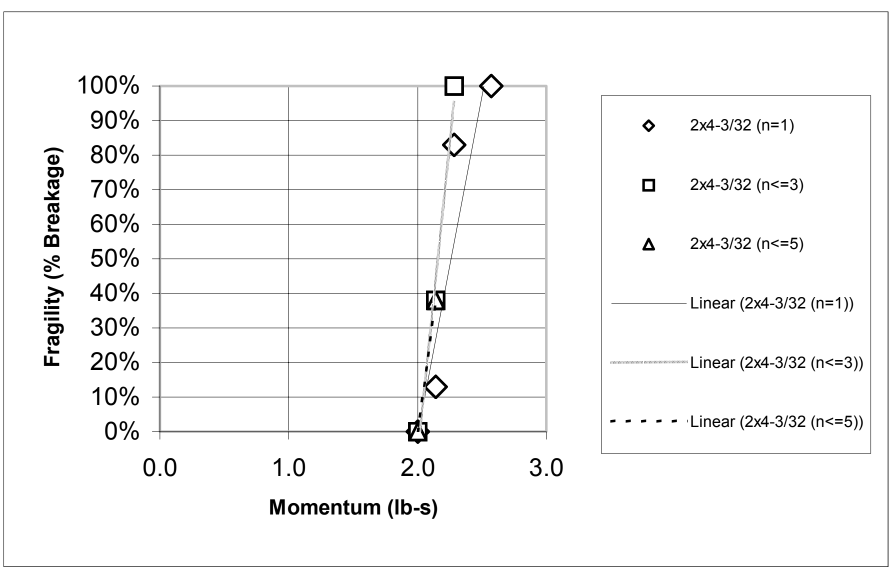
Fragility of the glass specimens, as affected by multiple impacts from the 2x4 missile at constant levels of momentum, are shown in Figure 11 (see Table 8 for data). The observed tendency for increased breakage of the sample of glass with increasing number of impacts is intuitive, but may be difficult to explain physically due to several possible counteracting effects. These effects include:

1. The reported fragility (percent breakage of sample) is based on a cumulative result (e.g., for 3 and fewer blows the percent breakage includes those specimens that broke at one, two, and three blows),
2. The surviving sample becomes more "selective" as specimens are removed from the sample due to breakage (i.e., the glass that did not break may have different characteristics due normal variability in the original sample), and
3. If each impact was assumed to be an independent trial and the initial (first impact) probability of failure was assumed to be constant, classical probability theory would predict greater amounts of breakage than observed for multiple impacts.

Based on the above confounding factors, a much larger sample is needed to better explain the observed trend. However, the data do indicate that the ability of glass to resist a given level of impact is reduced with increasing numbers of impacts. In general, this cumulative damage characteristic appears most evident for momentum levels some amount greater than the point at which near zero probability of failure occurs for a single impact (i.e., the x-axis intercept of the fragility curve). However, this trend is not always consistent as realized for 2x2-5/32 glass specimens. In summary, the effect of multiple blows at a given momentum seems to increase the slope of the fragility curve (in this case the linear trend line), but does not seem to consistently decrease the threshold momentum at which probability of breakage begins to increase rapidly with increasing momentum.



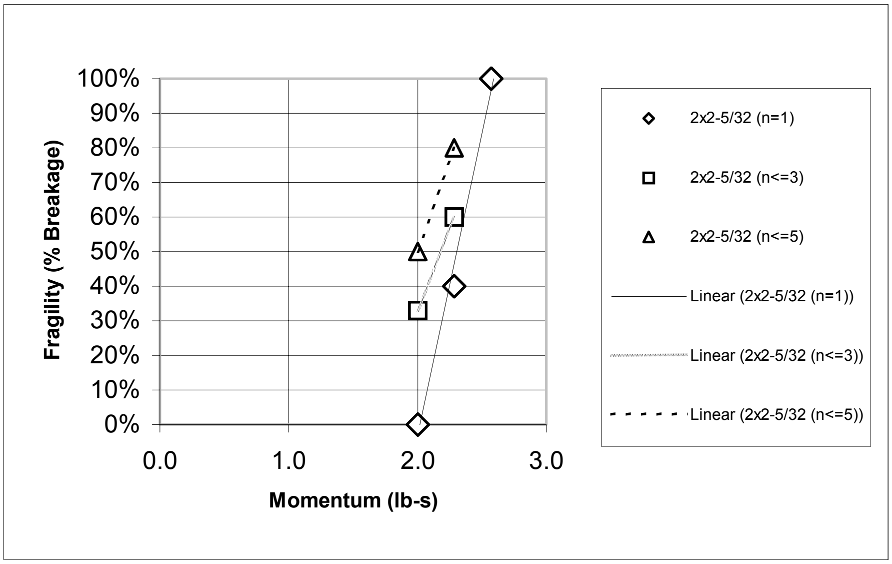
(a) 2x2 – 3/32 specimens



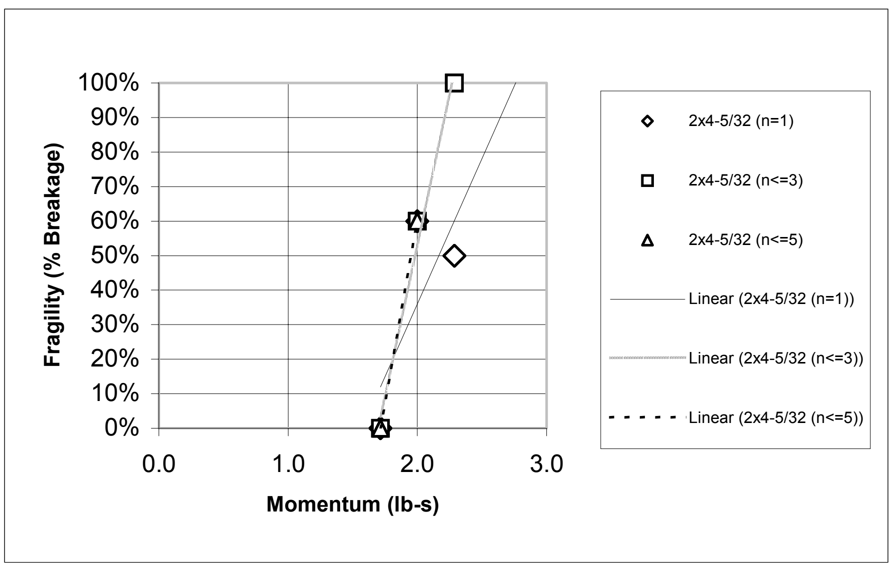
(b) 2x4 – 3/32 specimens

Figure 11

Effect of multiple 2x4 missile impacts on glass specimen fragility.



(c) 2x2 – 5/32 specimens



(d) 2x4 – 5/32 specimens
Figure 11
Effect of multiple 2x4 missile impacts on glass specimen fragility (continued).

6.0 DISCUSSION

2x4 Missile – The performance of most glass specimen types was remarkably similar (see Figure 8). However, the 2 ft x 4 ft – 5/32 in. glass specimens showed apparently anomalous results (i.e., lower probability of breakage for greater impact velocities within the range considered). Additional testing should conducted to verify this erratic behavior, which may be attributed to sampling error experienced in this particular study. Given the overall similarity in performance, fragility could be simply modeled by a single line for all of the glass specimens when considering a 2x4 or other similar missiles.

Shingle Missile – The glass specimen fragility for roof shingle impacts varied more across glass configurations than observed for the 2x4 missiles (Figure 8). Increased glass thickness had a noticeable effect on reducing the breakage probability for both glass sizes considered. Although secondary to glass thickness in importance, the smaller glass panel size also improved resistance to the shingle missile. These two factors should be considered in selecting a model for glass fragility due to impacts from roof shingles or other similar missiles.

Energy vs. Momentum – Fragility of the glass specimens as related to shingle missile kinetic energy varied much more widely than that found for the 2x4 missile (see Figure 12). This finding may be indicative of the importance of differences in the behavior of the shingle missile at differing velocities (i.e., impact energy or force pulse that is moderated through deformation of the missile). Differing dynamic response of the glass (and frame support) to the shingle missile at various velocities may also be a factor.

Using the basis of momentum, a definite distinction of missile types with respect to fragility was observed (see Figure 8). While the fragility of the specimens impacted by the shingle missile still varied more than those impacted by the 2x4 missile, it was considerably reduced which suggests that momentum is a more reliable index for a fragility model, particularly for missiles of varying types.

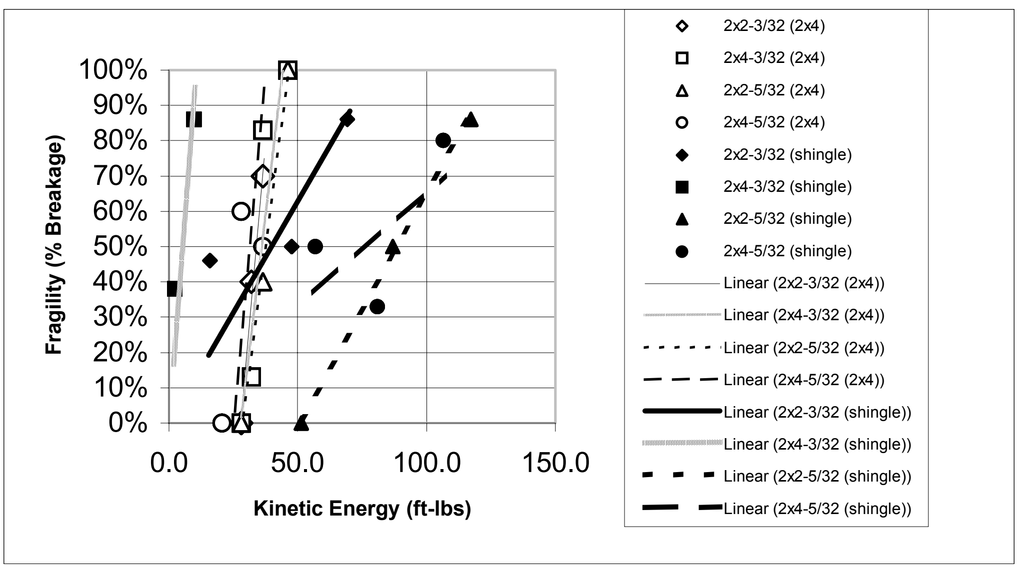


Figure 12
Fragility of annealed glass specimens based on impact energy of 5 lb 2x4 missile (pendulum apparatus) and shingle missile (air cannon apparatus).

7.0 CONCLUSIONS

1. Annealed glass, which is a common glazing material in residential windows and doors, was found to provide a non-negligible resistance to impacts from 2x4 and roof shingle missiles– sources of debris found in major hurricane events and used in risk modeling.

2. The study plan was able to reasonably document the fragility (breakage probability vs. impact magnitude) for four glass configurations and two missile types. In particular, a

plausible and reasonably repeatable method of impacting glass with a "packet" roof shingles was developed.

3. For the roof shingle missile, the impact momentum causing a 50 percent breakage probability ranged from 0.2 to 1.2 lb-s for all glass specimen configurations.

4. For the 2x4 missile, the impact momentum causing 50 percent breakage probability ranged from 2.3 to 2.5 lb-s for all glass specimen configurations; the range from essentially zero breakage probability to 100 percent breakage probability was about 1.8 to 2.7 lb-s.

5. The resistance of the glass specimens subjected to the roof shingle impact increased with increasing glass thickness and decreasing panel size; for the 2x4 missile, glass fragility was similar for all glass specimen configurations.

6. For the 2x4 missile, a trend of increasing fragility for multiple impacts at a given momentum was observed, which provides some insight into the nature of cumulative damage on annealed glass.

8.0 RECOMMENDATIONS

The results of this study should be used to improve risk modeling of wind-borne debris and to help define acceptable levels of glazing performance (i.e., target reliability) in residential buildings. Thus, in higher hazard conditions, target or acceptable reliabilities can be achieved through performance test criteria that are risk-consistent with the accepted use of annealed glass in areas of lesser hazard.

More testing should be conducted to better define fragility of annealed glass with respect to missile types, glass configuration, and frame stiffness. In particular, other realistic methods of projecting roof shingles (or pieces of roof shingles) should be investigated with respect to impact on fragility. Additional testing of actual windows should be conducted for the sake of confirmation of this data in view of existing building products.

APPENDIX A
VERIFICATION OF SPEED MEASURING SYSTEM

The photoelectric sensors were positioned vertically at a distance of one foot apart. An object was dropped through the sensors and the time to fall was recorded by an electronic timing device. This procedure was repeated 15 times (see table below) and the average time was compared to the theoretical time for an object to fall a distance of one foot using the equation of motion as solved below.

$$x - x_0 = v_0 t + \frac{1}{2} a t^2$$

where

x_0 = initial position (ft)
x = final position (ft)
v_0 = initial velocity = 0
t = time (s)
a = acceleration due to gravity (32.174 ft/s^2).

Eliminating $v_0 t$ and solving for t gives

$$t = \sqrt{2(x - x_0)/\ a}$$

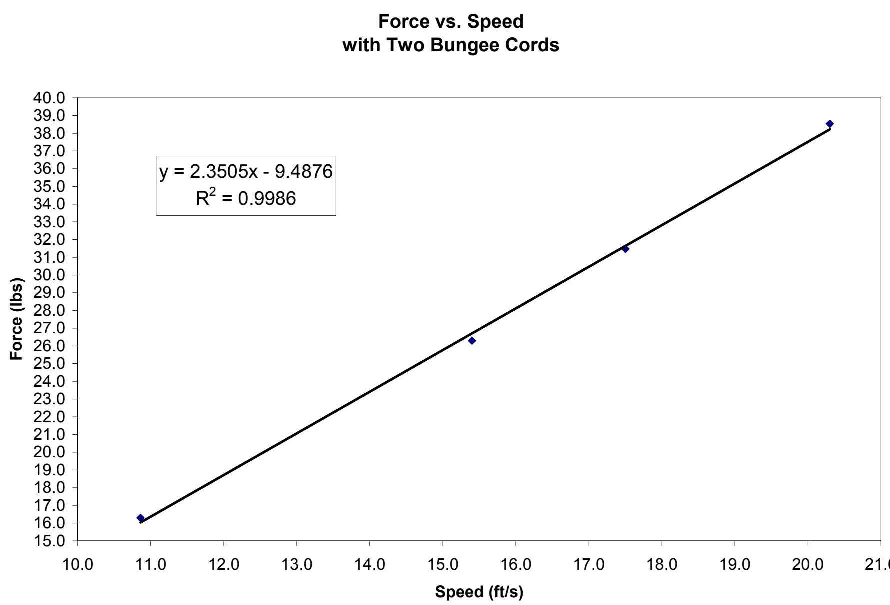
$$t = 0.2493\,\text{s}$$

TRIAL NUMBER	TIME (sec)
1	0.2509
2	0.2486
3	0.2506
4	0.2555
5	0.2448
6	0.2660
7	0.2538
8	0.2567
9	0.2473
10	0.2612
11	0.2556
12	0.2217
13	0.2278
14	0.2367
15	0.2217
Ave	0.2466
% Difference	1.1

APPENDIX B
CALIBRATION OF PENDULUM APPARATUS (2X4 MISSILE)

To allow for control of the 2x4 missile speed at impact, it was necessary to calibrate the pendulum apparatus. To achieve this calibration, a rope and pulley system was used to pull the missile and elastic cords up to a specified height. The force required to hold the missile in position was recorded and the missile was released. The time interval was recorded and the speed of the missile was determined using photoelectric sensors and a timing device. The photoelectric sensors where placed to either side of the glass specimen frame without a specimen in place. A trend line was fit to the data (as shown below) to allow the missile impact speed to be determined from the “draw-back” force reading taken prior to missile release. Thus, a target missile speed could be selected and obtained without using the photoelectric sensors and timing device during testing. The estimated total error in missile speed control is about ± 2 percent.

AVERAGE FORCE (lbs)	AVERAGE SPEED (ft/s)	AVERAGE SPEED COV (%)
16.3	10.9	1.0
26.3	15.4	0.8
31.5	17.5	0.7
38.5	20.3	1.0



APPENDIX C
CALIBRATION OF AIR CANNON APPARATUS (SHINGLE MISSILE)

The air cannon apparatus, using the shingle missile and sabot, was calibrated to provide a relationship between air pressure and missile speed (see table below). Actual shingle missile speeds for each trial (5 repetitions for each pressure setting) were recorded using the photoelectric sensors and a timing device. The relationship between shingle missile speed and air pressure released to the cannon was used to select a pressure to produce a desired velocity. Actual shingle missile velocity was measured by the photoelectric sensors and timing device during all tests due to the uncertainty in relying on pressure alone (i.e., COV a large as 19 percent for the lowest missile speed and air pressure).

AIR PRESSURE (psi)	AVG. MEASURED SHINGLE MISSILE SPEED (ft/s)	COEFFICIENT OF VARIATION (COV)
15	63	19%
20	74	5%
22.5	78	3%
25	85	8%
27.5	90	5%
30	97	2%