Designation: E997 – 15

Standard Test Method for Evaluating Glass Breakage Probability Under the Influence of Uniform Static Loads by Proof Load Testing[1]

This standard is issued under the fixed designation E997; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This proof load test method is a procedure to determine, with a 90 % confidence level, if the probability of breakage under design loads for a given population of glass specimens is less than a selected value. It is not intended to be a design standard for determining the load resistance of glass. Practice E1300 shall be used for this purpose.

1.2 This test method describes apparatus and procedures to select and apply a proof load to glass specimens, to determine the number of glass specimens to be tested, and to evaluate statistically the probability of breakage. This test method may be conducted using the standard test frame specified herein or a test frame of the user's design.

1.3 Proper use of this test method requires a knowledge of the principles of pressure measurement and an understanding of recommended glazing practices.

1.4 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E631 Terminology of Building Constructions

E1300 Practice for Determining Load Resistance of Glass in Buildings

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of general terms related to building construction used in this test method refer to Terminology E631.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *coefficient of variation, v*—ratio of the standard deviation of the breakage load to the mean breakage load.

3.2.2 *design load, n*—the specified uniform load and load duration.

3.2.3 *glass specimen, n*—the glass to be tested, for example, a single pane, an insulating glass unit, laminated glass, etc. (does not include test frame).

3.2.4 *glass specimen breakage, n*—the fracture or cracking of any glass component of a glass specimen.

3.2.5 *negative load, n*—an outward-acting load that results in the indoor side of a glass specimen being the high-pressure side.

3.2.6 *positive load, n*—an inward-acting load that results in the outdoor side of a glass specimen being the high-pressure side.

3.2.7 *probability of breakage, n*—the probability that a glass specimen will break when tested at a given load.

3.2.8 *proof load, n*—a uniform load at which glass specimens shall be tested.

3.2.9 *proof load factor, a, n*—the constant which, when multiplied by the design load, determines the proof load.

3.2.10 *specifying authority, n*—professional(s) responsible for determining and furnishing information required to perform the test.

4. Summary of Test Method

4.1 This test method consists of individually glazing glass specimens in a test frame that is mounted into or against one face of a test chamber and supplying air to, or exhausting air from, the test chamber so that each glass specimen is exposed to a proof load. Load-time records shall be kept for each glass specimen. Each glass specimen break shall be recorded.

4.2 After testing the required number of glass specimens, it is determined, with a 90 % confidence level, if the probability

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[1] This test method is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of E06.51 on Performance of Windows, Doors, Skylights and Curtain Walls.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

of breakage under design loads for the given population of glass specimens is less than a specified allowable probability of breakage.

5. Significance and Use

5.1 Glass specimens to be tested shall be mounted in a standard test frame with four sides supported, or in a test frame designed to represent specific glazing conditions.

5.2 Loads on glass in windows, curtain walls, and doors may vary greatly in magnitude, direction, and duration. Any design load (wind, snow, etc.) that can reasonably be applied to the test specimens or transformed into an equivalent uniform design load can be considered. Load transformation techniques are addressed in the literature (**1**, **2**, **3**).[3]

5.3 The strength of glass varies with many different factors including surface condition, load duration, geometry, relative humidity, and temperature (**4**). A thorough understanding of those strength variations is required to interpret results of this test method.

6. Apparatus

6.1 The description of apparatus is general in nature. Any equipment capable of performing the test procedure within the allowable tolerances is permitted.

6.2 *Major Components:*

6.2.1 *Test Frame,* in which glass specimens are mounted for testing. The test frame shall provide either standardized support conditions or specified support conditions. Specifications of standardized support conditions are presented in Annex A1.

6.2.2 *Test Chamber,* sealed, with an opening in which or against which the test frame is installed. At least one static pressure tap shall be provided to measure the test chamber pressure and shall be so located that the reading is minimally affected by the velocity of the air supply to or from the test chamber or any air movement. The air supply opening into the test chamber shall be arranged so that the air does not impinge directly on the glass specimen with any significant velocity. A means of access into the test chamber may be provided to facilitate adjustments and observations after the specimen has been installed.

6.2.3 *Air System,* a controllable blower, compressed air supply, exhaust system, reversible blower, or other device designed to apply the proof load to the glass specimen with required control.

6.2.4 *Pressure Measuring Apparatus,* to record continuous test chamber pressures within an accuracy of ±2 %.

6.2.5 *Temperature Measuring Apparatus,* to measure the ambient temperature within an accuracy of ±1°F (0.6°C).

6.2.6 *Relative Humidity Apparatus,* to measure the relative humidity within an accuracy of ±2 %.

7. Safety Precautions

7.1 Proper precautions shall be taken to protect observers in the event of glass breakage. At the pressures used in this test method, considerable energy and hazard are involved. In cases of breakage, the hazard to personnel is less with an exhaust system, as the specimen will tend to blow into rather than out of the test chamber. Personnel should not be permitted in such chambers during tests.

8. Sampling and Glass Specimens

8.1 Surface condition, cutting, fabrication, and packaging of the glass specimens shall be representative of the glass whose strength is to be evaluated.

8.2 All glass specimens shall be visually inspected for edge or surface irregularities prior to testing. All glass specimens with edge or surface irregularities not representative of the glass whose strength is to be evaluated shall not be tested.

8.3 Glass specimens shall be handled carefully at all times because the strength of glass is influenced by its surface and edge conditions.

9. Calibration

9.1 Pressure-measuring systems should be verified prior to testing. If calibration is required, the manufacturer's recommendations or good engineering practices shall be followed.

10. Required Information

10.1 The specifying authority shall provide the design load (positive or negative), the orientation of the glass specimen to the test chamber, the design load allowable probability of breakage for the glass specimens, and the coefficient of variation of the breakage loads typical of the glass specimens tested.

10.2 The specifying authority shall state whether the glass specimens shall be glazed in a standard test frame (see Annex A1) or in a test frame designed to simulate a specific glazing system. If the test frame is to simulate a specific glazing system, complete glazing details and support conditions shall be provided by the specifying authority.

11. Selection of Proof Load and Initial Sample Size

11.1 The glass specimens shall be tested with a proof load that is larger than the design load. The proof load is found by multiplying the design load by the proof load factor, *a*, as follows:

$$q_p = aq_d \tag{1}$$

where:

q_p = proof load,
a = proof load factor, and
q_d = design load.

11.1.1 If the glass specimens are to be tested in a standard test frame, the proof load factor, *a*, is found in Table 1 through Table 4, given the design load allowable probability of breakage and the appropriate coefficient of variation, ν. The proof load factor, *a*, is selected with due regard to the maximum capacity of the test apparatus. The tables indicate the initial sample size, n, of glass specimens to be tested. If the sample size entry in Table 1 through Table 4 is blank an alternate proof load factor shall be selected.

[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

TABLE 1 Required Zero Break Sample Size (ν = 0.10)

		Proof Load Factor, *a*	
		1.2	1.3
Design Load Probability of Breakage	0.010	10	
	0.009	11	
	0.008	12	
	0.007	13	
	0.006	14	
	0.005	16	
	0.004	19	
	0.003	23	
	0.002	31	
	0.001		14

TABLE 2 Required Zero Break Sample Size (ν = 0.15)

		Proof Load Factor, *a*			
		1.3	1.4	1.5	1.6
Design Load Probability of Breakage	0.010	14			
	0.009	16			
	0.008	17			
	0.007	19	10		
	0.006	22	11		
	0.005	25	13		
	0.004	31	15		
	0.003	39	19	10	
	0.002		26	13	
	0.001		47	23	13

11.2 Rationale to develop Table 1 through Table 4 is presented in Appendix X1.

12. Procedure

12.1 Measure and record the ambient temperature and the relative humidity.

12.2 Install glass specimens in the test frame in accordance with recommendations presented in Annex A1 for standard support conditions or as specified for a specific glazing system.

12.3 Apply one half of the proof load to the glass specimen and hold for 10 s. Reduce the test pressure to zero and vent the test chamber for a period from 3 to 5 min before the pressure-measuring apparatus is adjusted to zero.

12.4 If air leakage around the glass specimen is excessive, tape may be used to cover any cracks and joints through which leakage is occurring. However, tape shall not be used when there is a possibility that it will significantly restrict differential movement between the glass specimen and the test frame.

12.5 Apply the proof load to the glass specimen as quickly as possible, but no longer than 15 s. Maintain the proof load for the same duration as the specified design load, and then vent the test chamber. Continuous load-time records shall be kept for the duration of the loading.

12.6 If the glass specimen does not break, remove it from the test frame. Select a new glass specimen, and repeat procedures in 12.2 through 12.5. If the glass specimen does break, record the break and, if desired, determine from Table 5 through Table 8 (using the design load probability of failure, the appropriate coefficient of variation, and the selected proof load factor) the "one break" sample size, N_1. This sample size represents the total number of tests to be conducted with only one associated specimen break such that there is a 90 % confidence level that the actual probability of breakage at the design load is less than the allowable probability of breakage. If elected by the specifying authority or other appropriate party, testing may then continue in accordance with procedures in 12.2 through 12.5.

12.7 If, during the course of testing N_1 samples, a second break occurs, record the break and, if desired, determine from Table 9 through Table 12 (using the design load probability of failure, the appropriate coefficient of variation, and the selected proof load factor) the "two break" sample size, N_2. This sample size represents the total number of tests to be conducted with only two associated specimen breaks such that there is a 90 % confidence level that the actual probability of breakage at the design load is less than the allowable probability of breakage. If elected by the specifying authority or other appropriate party, testing may then continue in accordance with procedures in 12.2 through 12.5.

12.8 Inspect the test frame for permanent deformation or other failures of principal members. If failure of the standard test frame occurs, it shall be appropriately stiffened and strengthened and the test restarted. If failure occurs in a user specified test frame, the proof load shall be reduced or the test frame appropriately stiffened or strengthened and the test restarted.

12.9 Rationale used to develop Table 5 through Table 12 is presented in Appendix X1. Guidance for testing a sample of glass specimens with more than two breaks is not given in this test method, but may be determined using the principles described in Appendix X1.

13. Interpretation of Results

13.1 If no specimen breaks during the testing of the initial sample size, n, given in Table 1 through Table 4, there is a 90 % confidence level that the actual probability of breakage at the design load is less than the allowable probability of breakage.

13.2 If one specimen breaks during the testing of sample size, N_1, given in Table 5 through Table 8, there is a 90 % confidence level that the actual probability of breakage at the design load is less than the allowable probability of breakage.

13.3 If two specimens break during the testing of sample size, N_2, given in Table 9 through Table 12, there is a 90 % confidence level that the actual probability of breakage at the design load is less than the allowable probability of breakage.

14. Report

14.1 The report shall include the following information:

14.1.1 The date of the test, the date of the report, the ambient temperature, and the relative humidity.

14.1.2 Identification of the glass specimens (manufacturer, source of supply, dimensions both nominal and measured, manufacturer's designation, materials, and other pertinent information).

14.1.3 Detailed drawings of the glass specimens, test frame, and test chamber indicating orientation of the glass specimen to the test chamber. A complete description of pressure-measuring

TABLE 3 Required Zero Break Sample Size (ν = 0.20)

		Proof Load Factor, *a*							
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2
Design Load Probability of Breakage	0.010	14							
	0.009	15	10						
	0.008	17	11						
	0.007	19	12						
	0.006	22	14						
	0.005	26	17	11					
	0.004	32	21	14	10				
	0.003	43	28	18	13				
	0.002		42	27	19	13	10		
	0.001				38	26	19	14	10

TABLE 4 Required Zero Break Sample Size (ν = 0.25)

		Proof Load Factor, *a*															
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
Design Load Probability of Breakage	0.010	33	24	18	14	10											
	0.009	37	27	20	15	12											
	0.008	43	31	23	17	13	10										
	0.007	49	36	27	20	15	12										
	0.006		43	32	24	18	14	11									
	0.005			40	30	23	18	14	11								
	0.004				39	30	23	18	15	12							
	0.003					43	34	26	21	17	14	11					
	0.002							45	36	29	23	19	16	13	11		
	0.001												44	37	31	26	22

TABLE 5 Required One Break Sample Size (ν = 0.10)

		Proof Load Factor, *a*	
		1.2	1.3
Design Load Probability of Breakage	0.010	17	
	0.009	18	
	0.008	20	
	0.007	21	
	0.006	24	
	0.005	27	
	0.004	32	
	0.003	39	
	0.002	52	
	0.001		24

TABLE 6 Required One Break Sample Size (ν = 0.15)

		Proof Load Factor, *a*			
		1.3	1.4	1.5	1.6
Design Load Probability of Breakage	0.010	24			
	0.009	26			
	0.008	29			
	0.007	32	17		
	0.006	37	18		
	0.005	43	21		
	0.004	51	25		
	0.003	66	32	17	
	0.002		44	23	
	0.001		79	39	22

apparatus, and a statement that the test was conducted using a standard test frame or a test frame of the user's design.

14.1.4 Records of start/stop load times and pressure differences exerted across each glass specimen during the test with each specimen being properly identified.

14.1.5 Identification or description of any applicable specification.

14.1.6 A statement that the tests were conducted in accordance with this test method, or a full description of any deviations.

14.1.7 Interpretation of the test results.

15. Precision and Bias

15.1 Conclusions reached regarding the probability of breakage of the glass specimens tested are based upon statistical inference and assumptions regarding the coefficients of variation of the glass. As a result, there exists a probability that the conclusion reached is incorrect. A full discussion of assumptions made in development of the decision criteria is presented in Appendix X1.

16. Keywords

16.1 curtain walls; destructive testing; doors; exterior windows; glass performance; performance testing; structural performance; uniform static loads

TABLE 7 Required One Break Sample Size (ν = 0.20)

		Proof Load Factor, *a*							
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2
Design Load Probability of Breakage	0.010	23							
	0.009	25	17						
	0.008	28	19						
	0.007	32	21						
	0.006	37	24						
	0.005	44	28	20					
	0.004	55	35	24	17				
	0.003	73	47	31	22				
	0.002		70	46	31	22	16		
	0.001				65	44	31	23	17

TABLE 8 Required One Break Sample Size (ν = 0.25)

		Proof Load Factor, *a*															
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
Design Load Probability of Breakage	0.010	56	41	30	23	18											
	0.009	63	46	34	26	20											
	0.008	72	52	39	29	23	18										
	0.007	84	61	45	34	26	20										
	0.006		73	54	41	31	24	19									
	0.005			67	50	39	30	24	19								
	0.004				66	50	39	31	25	20							
	0.003					73	57	45	35	28	23	19					
	0.002							77	61	49	39	32	27	22	19		
	0.001												75	62	52	44	37

TABLE 9 Required Two Break Sample Size (ν = 0.10)

		Proof Load Factor, *a*	
		1.2	1.3
Design Load Probability of Breakage	0.010	24	
	0.009	25	
	0.008	27	
	0.007	30	
	0.006	33	
	0.005	38	
	0.004	43	
	0.003	53	
	0.002	71	
	0.001		33

TABLE 10 Required Two Break Sample Size (ν = 0.15)

		Proof Load Factor, *a*			
		1.3	1.4	1.5	1.6
Design Load Probability of Breakage	0.010	34			
	0.009	36			
	0.008	40			
	0.007	45	23		
	0.006	50	26		
	0.005	59	29		
	0.004	70	34		
	0.003	91	43	23	
	0.002		60	31	
	0.001		108	54	29

TABLE 11 Required Two Break Sample Size (ν = 0.20)

		Proof Load Factor, *a*							
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2
Design Load Probability of Breakage	0.010	32							
	0.009	35	23						
	0.008	39	26						
	0.007	44	29						
	0.006	51	33						
	0.005	60	39	27					
	0.004	75	48	33	23				
	0.003	100	64	43	29				
	0.002		97	64	44	30	22		
	0.001				89	61	44	32	24

TABLE 12 Required Two Break Sample Size (ν = 0.25)

		Proof Load Factor, *a*															
		1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
Design Load Probability of Breakage	0.010	77	56	42	32	24											
	0.009	86	63	46	36	28											
	0.008	98	71	53	40	31	24										
	0.007	115	83	62	47	36	28										
	0.006		100	74	56	43	33	27									
	0.005			91	69	53	41	33	26								
	0.004				91	69	54	43	34	28							
	0.003					100	77	61	49	39	32	26					
	0.002							104	83	67	54	44	37	31	26		
	0.001												103	85	71	60	50

ANNEX

(Mandatory Information)

A1. STANDARD GLASS TEST FRAME

A1.1 Introduction

A1.1.1 The standard test frame shall be designed to support a rectangular glass specimen in a vertical plane and expose it to the design load. The test frame consists of two primary systems, a structural support system and a glazing system. The structural support system shall be designed to resist applied loads with limited deflections and provide an interface between the test chamber and the glazing system. The glazing system shall be designed to limit lateral displacements of the glass specimen edges while minimizing rotational and in-plane restraints of the glass specimen edges. This annex presents pertinent details relating to the design and construction of a standard test frame.

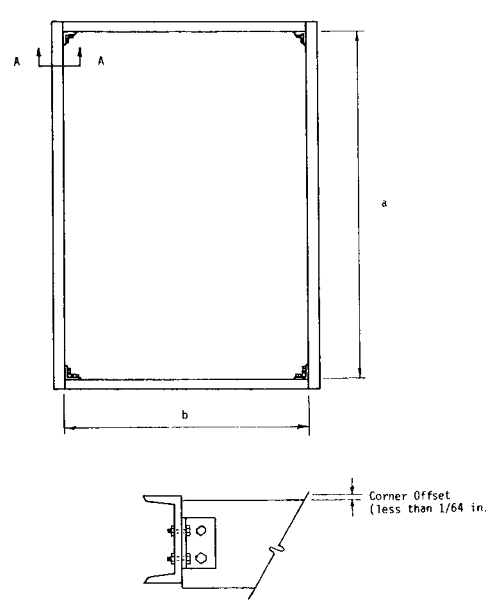

FIG. A1.1 Structural Support System

A1.2 Structural Support System

A1.2.1 The structural support system consists of four main structural members arranged as shown in Fig. A1.1. The inside rectangular dimensions, *a* and *b*, of the support system shall be found by subtracting 1 in. from the corresponding dimensions of the glass specimens. These dimensions shall be maintained within a tolerance ±1⁄16 in. (1.6 mm).

A1.2.2 The structural members shall be selected from available American Standard channels with flange widths greater than or equal to 1¾ in. (44 mm). The structural members shall be designed to withstand the appropriate proof load without permanent deformations. In addition, the structural members shall be designed to meet the following deflection criteria:

A1.2.2.1 The maximum out-of-plane deflection (referenced to glass specimen) of the structural members shall not exceed *L*/750 where *L* is the length of the shorter side of the glass specimen,

A1.2.2.2 The maximum rotation of the structural members shall not exceed 1°, and

A1.2.2.3 The maximum in-plane deflection (referenced to the glass specimen) of the structural members shall not exceed *L*/2000, where *L* is the length of the shorter side of the glass specimen.

A1.2.3 The corner connections of the support system shall be designed using angle braces and bolts to minimize racking or twisting during testing.

A1.2.4 In addition to the above criteria, the following fabrication tolerances shall be met:

A1.2.4.1 The maximum out-of-plane offset at the corners shall not exceed 1⁄64 in. (0.4 mm) (see Fig. A1.1),

A1.2.4.2 The maximum planar variation of the outside edges of the structural members shall not exceed 1⁄16 in. (1.6 mm),

A1.2.4.3 The maximum difference in the measured diagonals of the interior rectangular opening shall not exceed 1⁄8 in. (3.2 mm), and

A1.2.4.4 The depth of the structural members shall be sufficient to allow unimpaired out-of-plane displacements of the glass specimens during the test.

A1.2.5 Holes shall be provided as required in the flanges of the structural members for fasteners.

A1.3 Glazing System

A1.3.1 The glazing system, which attaches to the vertical structural support system, consists of the following major components (see Fig. A1.2, Fig. A1.3, and Fig. A1.4):

A1.3.1.1 Inside and outside glazing stops,

A1.3.1.2 Aluminum spacers,

A1.3.1.3 Inside and outside neoprene gaskets,

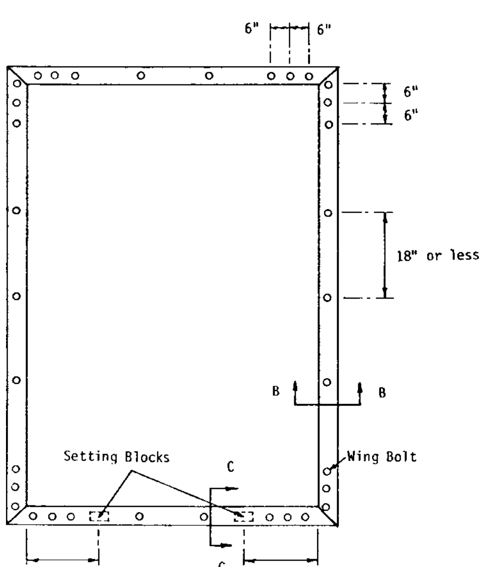

FIG. A1.2 Standard Glazing System

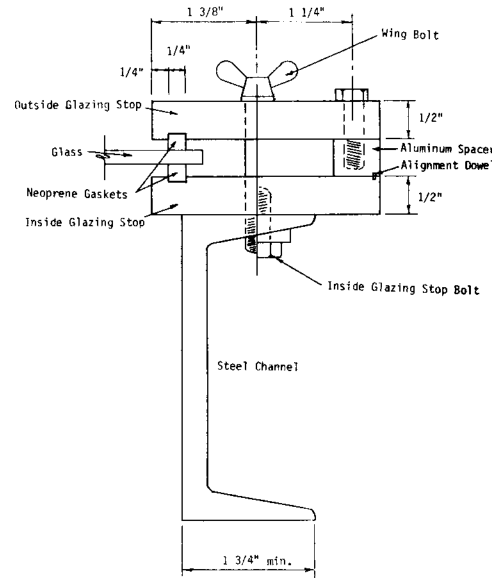

FIG. A1.3 Section *B-B* of Standard Glazing System

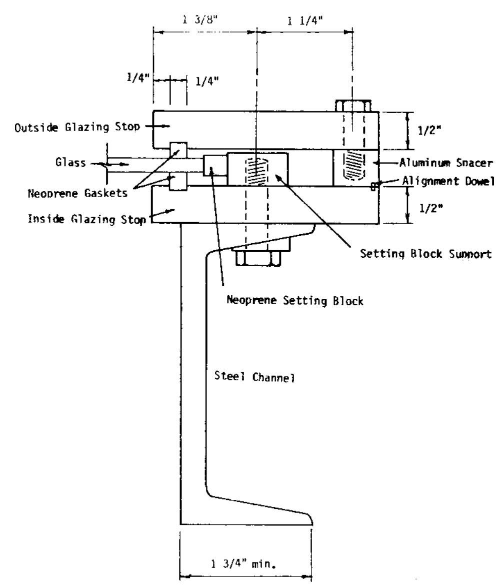

FIG. A1.4 Section *C-C* of Standard Glazing System

A1.3.1.4 Structural fasteners, and

A1.3.1.5 Neoprene setting blocks.

A1.3.2 The glass specimen rests on two neoprene setting blocks (85 ± 5 Shore A durometer) as shown in Fig. A1.4. The glass specimen is laterally supported around its perimeter with neoprene gaskets (65 ± 5 Shore A durometer). The glass specimen shall be centered within the glazing system to a tolerance of ±1⁄16 in. (1.6 mm). A minimal clamping force (4 to 10 lbf/in.) (700 to 1750 N/m) is applied to the edge of the glass specimen by loosely tightening the wing bolts that are spaced around the specimen perimeter.

A1.3.3 The glazing stops shall be fabricated using ½ by 3-in. (13 by 76-mm) aluminum bar stock (6061 T 6511) in sections no shorter than 24 in. (610 mm) or the smaller rectangular glass specimen dimension. A 1⁄8 by 3⁄8-in. (3.2 by 9.5-mm) rectangular slot shall be machined in the glazing stops as shown in Fig. A1.3. At each corner the glazing stops shall be mitered and fitted as shown in Fig. A1.2.

A1.3.4 The inside glazing stop shall be fastened to the top flange of the structural support members using ¼-in. (6.4-mm) diameter bolts. These bolts pass through a clear hole in the channel flange into a threaded hole in the inside glazing stop. These bolts shall not extend above the surface of the inside glazing stop. These bolts shall be spaced no further than 24 in. (610 mm) apart with no fewer than two bolts per glazing stop section.

A1.3.5 The outside glazing stop shall be secured to the support system using ⅜-in. (9.5-mm) diameter wing bolts. These bolts pass through the outside glazing stop through the inside glazing stop and into a threaded hole in the support channels. In the corner areas there shall be three wing bolts spaced at 6-in. (152-mm) intervals as shown in Fig. A1.2. Between these corner bolts, the bolts shall be spaced no further than 18 in. (457 mm) apart with a minimum of two bolts per glazing stop section.

A1.3.6 The rectangular aluminum spacers shall be fabricated using ¾-in. (19-mm) wide aluminum bar stock. The depth of the spacers shall be equal to the thickness of the glass plus ⅜ in. (9.5 mm). This dimension shall be maintained within a tolerance of ±1⁄32 in. (0.8 mm). The lengths of the spacers shall correspond to the lengths of matching outside glazing stop sections. In corner areas the spacers shall extend no further than 1 in. (25.4 mm) past the corner of the installed glass specimen. The spacers shall be fastened to the outside glazing stops using ¼-in. (6.4-mm) diameter bolts. These bolts pass through the outside glazing stop into a threaded hole in the spacer. These bolts shall be spaced no further than 24 in. (610 mm) apart with no fewer than 2 bolts per glazing stop section.

A1.3.7 Two neoprene (85 ± 5 Shore A durometer) setting blocks shall be centered at the quarter points of the glass specimen width as shown in Fig. A1.2. Appropriate supports, fastened through the inside glazing stop to the support channels, shall be provided. The required length of a setting block (in in. (in mm)) is found by multiplying the glass specimen area (square feet (square metres)) by 0.10. However, in no case shall the setting block length be less than 4 in. (102 mm). The width of the setting block shall be 1⁄16 in. (1.6 mm) greater than the specimen thickness so that continuous support across the thickness of the specimen is provided.

A1.3.8 The neoprene gaskets shall be fabricated using 5⁄16-in. (7.9 mm) thick neoprene (65 ± 5 Shore A durometer) to fit snugly into the glazing stop slots. These gaskets shall be placed so that continuous support of the glass specimen perimeter is achieved. The gaskets may be held in place using an appropriate glue or cement. However, the neoprene surface in contact with the glass specimen shall be kept free of all foreign materials.

A1.3.9 Silicone sealant or other appropriate material may be used to seal joints against leakage. However, under no circumstances is a sealant to contact the glass specimen.

APPENDIX

(Nonmandatory Information)

X1. STATISTICAL BASIS FOR TEST LOAD AND SAMPLE SIZE REQUIREMENTS

X1.1 The specified test loads and associated sample sizes were developed to determine whether or not the probability of breakage under design loads, for a given population of glass specimens, is less than a selected value; and to do so at a 90 % confidence level, using non-destructive (that is, proof load) testing on a small sample of the population.

X1.2 The approach adopted in development of this test method is to increase the probability of breakage of the glass specimens to be tested by exposing the specimens to a proof load whose magnitude is greater than the design load. By thus increasing the specimen probability of breakage, the number of specimens that must be tested to reach a statistically, defensible conclusion is greatly reduced.

X1.3 The number of glass specimens that must be tested depends upon the magnitude of the design probability of breakage, the ratio of the proof load to the design load, and the coefficient of variation of the glass specimen breakage loads. Information to determine the required number of specimens to be tested and the allowable number of specimen breaks is presented in Sections 11 and 12. Fundamental concepts of probability and statistics along with critical assumptions used to generate this information is presented in this appendix.

X1.4 The first assumption made in development of this test method is that the glass specimen breakage loads are normally distributed. The normal distribution is the best understood and most widely used continuous probability distribution function available. Further, the normal distribution has historically been used to represent glass specimen breakage loads.

X1.5 The standard normal probability density function, *f(z)*, is as follows:

$$f(z) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{z^2}{2}\right] \quad \text{(X1.1)}$$

$$z = \frac{q-\mu}{\sigma} \quad \text{(X1.2)}$$

where:

q = breakage load,
μ = mean breakage load, and
σ = breakage load standard deviation.

X1.5.1 The standard normal cumulative probability function, *F(z)*, is found by integrating the density function, Eq

X1.1, from negative infinity to a particular value of the standard variate, z_0, as follows:

$$F(z_0) = \int_{-\infty}^{z_0} \exp\left[-\frac{z^2}{2}\right] dz \qquad (X1.3)$$

X1.5.2 Eq X1.3 cannot be integrated directly, hence, values of the standard normal cumulative probability function must be found using numerical methods. Values of F(z) are available in numerous texts and handbooks.

X1.6 The ratio of the standard deviation of a distribution to the mean of the distribution (sometimes expressed as a percent) is called the coefficient of variation, ν, of the distribution. The relationship between the mean, standard deviation, and coefficient of variation is as follows:

$$\sigma = \nu\mu \qquad (X1.4)$$

X1.6.1 The coefficient of variation is particularly useful when addressing glass strength because its magnitude tends to be constant for a particular glass type (annealed, heat-strengthened, and tempered). Typical values of the coefficient of variation of different types of glass are presented in Table X1.1.

X1.7 If Eq X1.4 is substituted into Eq X1.2, the following relationship results:

$$z = \frac{q - \mu}{\nu\mu} \qquad (X1.5)$$

X1.7.1 Eq X1.5 can be rearranged, resulting in the following relationship:

$$q = \mu(\nu z + 1) \qquad (X1.6)$$

X1.7.2 Eq X1.5 and Eq X1.6 can be used in conjunction with tabulated values of the standard normal cumulative distribution to calculate the probability of breakage of a glass specimen exposed to a proof load given a design load and its associated probability of breakage. For example, consider a sample of annealed glass with a coefficient of variation of 0.25 and a design probability of breakage of 0.008. The value of the standard normal variate, *z*, corresponding to a probability of breakage of 0.008 is −2.41. Eq X1.6 can be used to express the magnitude of the design load, *q d*, in terms of the mean breakage load, μ, as follows:

$$q_d = \mu[(0.25)(-2.41)+(1.0)] = 0.40\mu \qquad (X1.7)$$

X1.7.3 If a proof load factor, *a*, of 2.0 is considered the proof load magnitude, q_p, will be 0.80μ. Eq X1.5 can then be used to determine the corresponding value of the standard normal variate as follows:

$$z = \frac{0.80\mu - \mu}{0.25\mu} = -0.80 \qquad (X1.8)$$

X1.7.4 Then the probability of a specimen break at the proof load, *p*, can be found to be 0.21 using tabulated values of the standard normal cumulative distribution. The probability of there being no break during a test (P_{NB}) is one minus the probability of breakage, or 1–0.21 = 0.79 in this example. The probability of doing *n* consecutive tests with no breaks is $(P_{NB})^n$. If n is selected so that $(P_{NB})^n$ is equal to 0.1, and n tests are conducted with no breaks, there is a 90 % confidence level that the actual probability of breakage is less than the allowable rate. In the example, 9.8 tests (that is, 10 tests) would need to be performed without sustaining a break in order to be 90 % confident the actual probability of failure was less than the allowable value of 0.008. If one or more breaks occur before *n* tests have been completed, there is not a 90 % confidence level that the population probability of failure is less than the assumed value. If only one break occurs during the *n* tests, there is about a 67 % confidence level that the actual probability of failure is less than the allowable value. In order to be 90 % confident, additional tests—up to a total of N_1 (which is 18 in this example)—would have to be conducted with no additional breaks. If two breaks occur before completing the *n* tests, there is only about a 41 % confidence level that the actual probability of failure is less than the allowable value. In order to have 90 % confidence with two breaks, a total of N_2 (which is 24 in this example) tests would have to be conducted with no additional breaks.

X1.8 The basic test plan is to select a sample of several glass specimens and to independently expose each specimen to the proof load, noting each break. There are two possible outcomes for each specimen. Either the specimen breaks or does not break. Further, if the glass specimens are reasonably similar, the probability that a particular specimen breaks when exposed to the proof load can be assumed to be constant. It is further assumed that the outcome for one specimen does not affect the outcome for another specimen. With these assumptions, the process can be modeled using the binomial distribution.

X1.9 If the probability of an event occurring in one trial is given by *p*, then the probability, *Pr*, of it occurring *r* times in *n* independent trials is the binomial distribution as follows:

$$Pr = \frac{n!}{r!(n-r)!}\, p^r(1-p)^{n-r} \qquad (X1.9)$$

X1.9.1 For r = 0, Eq X1.9 simplifies to Pr = $(1-p)^n$. For a 90 % confidence level, the probability of zero breaks should be 1–0.9 = 0.1. Setting Pr = 0.1 and solving for *n* gives: *n* = log(0.1)/log(1–*p*). So, for any selected *p*, it can be calculated how many tests, with no breaks, need to be conducted to have a 90 % confidence level that the actual *p* is less than or equal to the allowable *p*. While this calculation can be performed for any *p* (for example, 0.008 if that is the value of interest), low values of *p* require large numbers of tests (*n*). Using *p* = 0.008 would require 287 tests at the design load. To reduce the number tests, the proof load can be increased. At higher proof loads, the probability of breakage increases. So, if *p* = 0.008 at

TABLE X1.1 Typical Coefficients of Variation, ν, for Flat Glass

Glass Type	Typical Coefficient of Variation, ν[A]
Annealed	0.20–0.25
Heat strengthened	0.15
Tempered	0.10

[A] Glass manufacturers should be contacted for more specific information. These values may vary significantly.

the design load, p would be higher (and less tests required) for a higher test load. However, in order to determine p for a given load (other than the design load), the coefficient of variation (COV) of the population must be assumed using the values of COV for specific types of glass given in this test method. The procedure for calculating the probability of failure at the test load (p_{TL}) given a selected probability of failure at the design load (p) is as follows:

X1.9.1.1 Calculate the number of standard deviations (B) separating the average population strength (S) from the design load (DL):

$$B = \Phi^{-1}[1 - p] \quad (X1.10)$$

where:

Φ^{-1} = the inverse of the normal distribution function.

X1.9.1.2 The average strength (S) is then:

$$S = DL/(1 - COV \times B) \quad (X1.11)$$

X1.9.1.3 For a given test load (TL), calculate the number of standard deviations (C) separating TL from S:

$$C = (S - TL)/(COV \times S) \quad (X1.12)$$

X1.9.1.4 Now, the probability of failure given the test load (p_{TL}) can be calculated as follows:

$$P_{TL} = 1 - \Phi[C] \quad (X1.13)$$

where:

Φ = the normal distribution function.

X1.9.1.5 Building on the previous example for which p is 0.008 and COV = 0.25; and a selected test load of 2 × the design load:

$$B = \Phi^{-1}[1 - 0.008] = 2.41 \quad (X1.14)$$

$$S = DL/(1 - 0.25 \times 2.41) = 2.52 \times DL = 2.52\ DL$$

that is, average strength is 2.52 × the design load

$$C = (2.52\ DL - 2\ DL)/(0.25 \times 2.52\ DL) = 0.825$$

$$P_{TL} = 1 - \Phi[0.825] = 0.21$$

X1.9.1.6 Solving for n for this probability of failure gives:

$$n = \log(0.1)/\log(1 - 0.21) = 9.8 \text{ tests}$$

that is, 10 tests (X1.15)

X1.9.1.7 For a given p and COV, any value of TL can be selected and a corresponding n calculated. For practical reasons, the standard limits combinations of p, COV and TL to those that result in n values between 10 and about 50.

X1.10 If one break occurs during the testing, Eq X1.9 can be used to calculate the probability of getting exactly one break and the probability of getting exactly zero breaks. These two probabilities added together represent the probability of getting less than two breaks for the associated p. In each case, the corresponding value is about 0.33 (which means the probability of the actual failure rate being less than the assumed value is 1–0.33 = 0.67). To get this value to 0.9 (that is, to establish 90 % confidence), n must be increased as discussed above. The N_1 values were determined by increasing the number of tests until the cumulative probability of getting one or zero breaks equaled 0.1. A similar process was used to determine the N_2 values.

X1.11 Two examples of this method are presented below to aid the user.

X1.11.1 *Example 1:*

X1.11.1.1 The destructive test procedure shall be conducted to determine if the probability of breakage of a set of annealed glass specimens (ν = 0.20) is equal to or less than 8⁄1000 at a design load of 30 lbf/ft^2. The standard test frame shall be used.

X1.11.1.2 To determine the proper sample size, Table 3 is entered with a design load probability of breakage of 0.008 and a proof load factor is selected based upon the minimum sample size of 12. The proof load factor thus selected is 1.6. Therefore, 12 glass specimens are independently subjected to a proof load of 48 lbf/ft^2.

X1.11.1.3 If no specimens break, we can be 90 % confident the actual probability of failure given the design load is less than the assumed value of 0.008; if one breaks, we can be 67 % confident. To establish 90 % confidence, we would need to test a total of 19 specimens (that is, seven more) with no additional breaks. If we get another break in the seven additional tests, to establish a 90 % confidence level that the probability of breakage under the design load is less than 0.008, we would need to do a total of 26 tests (another seven) with no further breaks. If we get yet another break, it suggests we cannot be 90 % confident in the assumed conditions.

X1.11.2 *Example 2:*

X1.11.2.1 The destructive test procedure shall be conducted to determine if the probability of breakage of a set of annealed glass specimens (ν = 0.20) is equal to or less than 0.001 when exposed to a design load of 40 lbf/ft^2. The specimens shall be tested in a test frame representative of a particular glazing system.

X1.11.2.2 First the representative test frame is analyzed using engineering principles, and it is determined that the test frame can safely withstand a proof load of 80 lbf/ft^2.

X1.11.2.3 The value of the proof load factor, a, is then computed to be 2.0. Then Table 3 is entered with a proof load factor, a, of 2.0 and a design load probability of breakage of 0.001, and it is determined that 19 specimens should be exposed to a proof load of 80 lbf/ft^2 provided none break. The corresponding one break and two break numbers of tests (N_1 and N_2) are 31 and 44, respectively.

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