Uniform Pressure Load Resistance of Thin Boro-aluminosilicate Glass for use in Triple-Glazed Insulating Glass Units

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Abstract

Over the past several years, there has been an increase in the use of triple-glazed insulating glass (IG) units as opposed to the more well-researched double-glazed IG unit. This expanded use is driven primarily by the ever-increasing demand for more energy-efficient windows and an increase in energy costs. The addition of the third glass plate creates a second gas-space cavity that significantly increases the thermal performance of the triple-glazed IG unit over the double-glazed IG unit.

To reduce the use of raw glass material and overall unit weight of a triple-glazed IG unit, there is an interest in inserting a thin-borosilicate glass plate between two thicker glass plates. The primary purpose of the thin-borosilicate glass plate is to divide the gas-space cavity while the purpose of the outer glass plates is to carry the uniform pressure load. However, the thin-borosilicate glass plate will need to resist some smaller amount of the uniform pressure load.

Currently, there is little widely published information about the strength of thin-borosilicate glass to resist uniform pressure loads. As such, this paper presents the results of testing performed to determine the overall strength of thin-borosilicate glass for use later as plates in a triple-glazed IG unit. This was accomplished using controlled weak-axis, four-point bending testing on 0.5-mm thick borosilicate glass specimens that were subjected to two different loading rates. The primary outcome of this testing shows that the strength of the thin borosilicate glass is, at a minimum, analogous to the typical strength data measured for freshly-manufactured annealed soda-lime float glass and may be well suited for use as the third plate in a triple-glazed IG unit.

Keywords

Triple-Glaze, Borosilicate, Glass Strength, Thin Glass

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1. Introduction

Over the past several years, there has been an increase in the interest and use of triple-glazed insulating glass (IG) units as opposed to the more well-researched double-glazed IG unit. This expansion is driven primarily by the ever-increasing demand for more energy-efficient windows and an increase in energy costs. The primary advantage of the triple-glazed IG unit is that two gas space cavities can significantly decrease the flow of thermal energy through the IG unit as compared to the flow of thermal energy through the single gas-space cavity of the double-glazed IG unit. In addition, by incorporating two smaller gas-space cavities, as compared to a single larger gas-space cavity, the triple-glazed IG unit can be manufactured with the same or similar overall thickness as a common double-glazed IG unit. Thus, a significant increase in the thermal performance of windows can be realized by using triple-glazed IG units installed in window framing systems that are currently used for double-glazed IG units with little or no modifications. As such these window systems with triple-glazed IG units provide improved U-factors, environmental comfort, and their energy efficiencies can meet or exceed the current and likely future requirements from programs such as the United States and Canadian Energy Star and/or other building code requirements.

Only a thin piece of glass is required to properly divide the gas-space cavity of a triple-glazed IG unit. The use of thin glass helps to reduce the raw glass material required, the overall unit weight, and the overall thickness of the triple-glazed IG unit. It seems logical that the middle glass plate should be relatively thin as compared to the outer glass plates because the middle glass plate's primary purpose is simply to divide the gas-space cavity. Alternatively, the primary purpose of the outer glass plates is to carry the majority of the applied uniform pressure load.

Regardless, a thin middle glass plate (relative to the outer glass plates) will need to be able to resist some small percentage of the overall uniform pressure load that is applied to the window system. The stress distribution that develops in each glass plate of the triple-glazed IG unit is complex to calculate and depends on numerous factors such as the percentage of overall uniform pressure load that is distributed between each glass plate, glass plate thicknesses, overall window size, aspect ratio, spacer stiffness, frame stiffness, etc. This discussion is outside of the scope of this paper and is an excellent topic for future research.

To efficiently achieve a triple-glazed IG unit with a thin middle glass plate, there is an interest in inserting a thin boro-aluminosilicate glass plate between two thicker, soda-lime glass plates. The use of boro-aluminosilicate is of interest due to the current ability to produce it in thin sheets as compared to typical thicknesses readily available for soda-lime float glass. However, there is currently little widely published information about the strength of thin boro-aluminosilicate glass in resisting uniform pressure loads.

The purpose of this paper is to provide the results of testing that was performed to determine the overall strength of thin boro-aluminosilicate glass. These data are intended to be used later in the design of boro-aluminosilicate glass plates which will be incorporated into a triple-glazed IG unit with thicker, soda-lima float glass for the outer glass plates. The testing was accomplished using controlled weak-axis, four-point bending testing on 0.5-mm thick boro-aluminosilicate glass specimens that were subjected to two different loading rates. The primary outcome of this testing shows that the strength of the thin boro-aluminosilicate glass is, at a minimum, analogous to the typical strength measured for freshly-manufactured annealed soda-lime float glass and may well be suited for use as the middle glass plate in a triple-glazed IG unit.

2. Objective

The propose of this report is to present the results of testing conducted to evaluate the strength of 0.5-mm thick boro-aluminosilicate glass beams that were subjected to bending loads. This objective was accomplished by the writers by conducting a set of carefully controlled tests at Beason Brackin & Associates, LLC's test facility located in College Station, Texas. The research effort consisted of testing two sets of 0.5-mm thick boro-aluminosilicate glass beams. Both sets of beams were produced at the same time and provided by Corning. One set of the boro-aluminosilicate glass beams were subjected to a fast load rate and the other set was subjected to a slower load rate. This testing involved the use of weak-axis, four-point bending tests. The primary purpose of the testing, as mentioned above, was to determine the strength of the boro-aluminosilicate glass for use later as plates in a triple-glazed insulating glass unit to resist uniform pressure loads.

3. Glass Specimens

A total of 70 boro-aluminosilicate glass beams were received for testing. A total of 60 specimens were tested and the remaining 10 were used as exemplars and for preliminary "shake-out" tests. The width, length, and thickness were measured and recorded for each specimen prior to testing. In addition, each specimen was inspected for any existing damage, inclusions, defects, etc. prior to testing. The glass beams were nominally 1.5-inches wide by 6-inches long and the average thickness for the glass beams was 0.0197 inches.

These specimens were divided into two batches of 30 specimens. One batch was tested with a load rate that induced approximately 10,000 psi of bending stress per minute. The second batch was tested with a load rate that induced approximately 1,000,000 psi of bending stress per minute. These two independent loading rates were used to identify what, if any, affect static fatigue may have on the strength of the boro-aluminosilicate glass.

4. Test Procedure

The testing was performed using a weak-axis, four-point bending test facility. The weak-axis, four-point bending test machine setup is shown in Figure 1. Load is applied to the top of the glass beam through a symmetrically positioned loading beam. Load is symmetrically applied to the center of the upper side of the loading beam. The load applied to the glass specimen was measured using a calibrated load cell and data acquisition system with a 100-Hz sample rate. These data measured were stored as a test file for post-test processing.

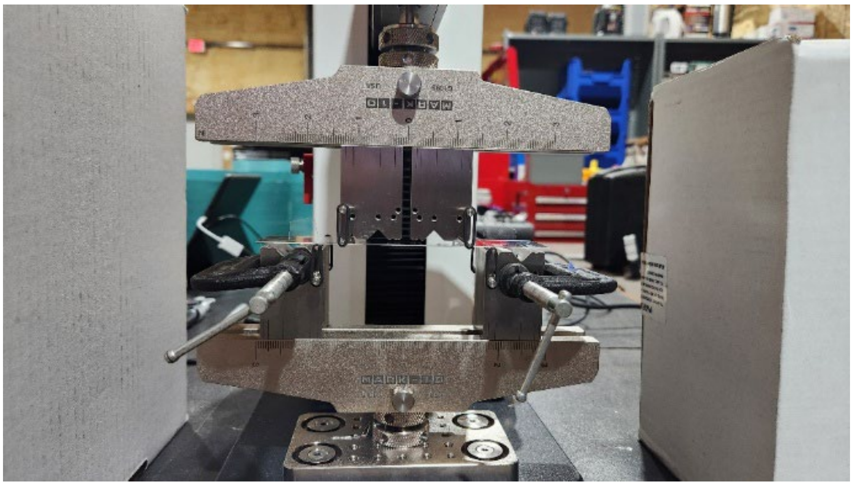

Fig. 1: Four-Point Bending Machine.

Figure 2 presents a schematic of the loading experienced by a typical glass beam during testing. With this arrangement, the central area of the glass beam is subjected to a constant moment and zero shear. The magnitude of the maximum tensile stress was calculated using principles of elementary mechanics and did not require any type of finite element (FE) analysis. As such, the stress in the glass beam can be calculated simply using Equation 1 where σ is the maximum tensile stress, P is the applied load, A is the offset as shown in Figure 1, W is the width of the glass beam, and T is the thickness of the glass beam.

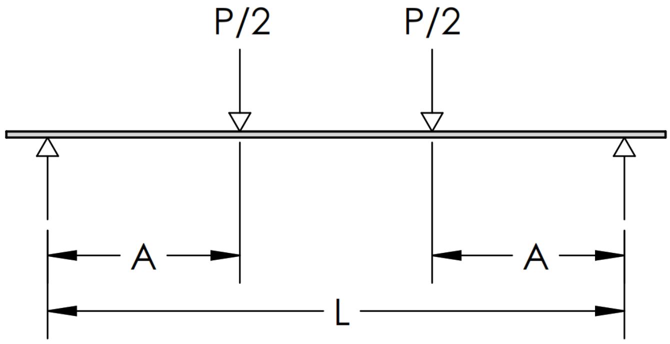

Fig. 2: Beam Load Schematic.

$$\sigma = \frac{3 \times P \times A}{W \times T^2} \quad (1)$$

Ultimately, the testing of each beam was accomplished using a modified ASTM C158 “Standard Test Methods for Strength of Glass by Flexure (Determination of Modulus of Rupture)” [ASTM C158, 2023] procedure, as follows:

1. Each specimen was labeled with a unique identifier.
2. Each specimen was carefully inspected.
3. Physical measurements were verified for each specimen.
4. Each beam specimen was carefully installed in the testing machine.
5. A controlled ramp loading was applied to each specimen (i.e. to achieve the target loading rate discussed previously).
6. The resulting load-time data, to the point of breakage, was recorded and stored for each specimen tested.
7. Each beam specimen was removed and reconstructed (when possible) for examination.
8. The load-time data were converted to constant duration failure stresses corresponding to durations of 3 seconds, 60 seconds, and 1 hour using industry accepted static fatigue correction procedures.

According to previous research[Wiederhorn and Bolz, 1970], borosilicate glass is less susceptible to static fatigue than soda-lime silicate glass. For the purposes of this report, these data were corrected for static fatigue using traditional design methods for glass subjected to uniform pressure loads. This approach provides a conservative design value for the time-corrected strength values for these glass specimens.

5. Test Results

When a glass beam is tested in bending, as was done in the current situation, the top surface of the beam is subjected to compressive stresses and the bottom surface of the glass is subjected to tensile stresses. It is well known that the strengths of the glass beams subjected to bending are controlled by surface tensile stresses. Thus, it is the characteristics of the bottom surface (tension surface) of the glass that control the strength of a beam installed in the testing machine.

Table 2 presents the 3-sec equivalent breakage stresses, the 60-sec equivalent breakage stresses, and the 1-hr equivalent breakage stresses for each specimen tested with a loading rate of 10,000 psi stress per minute. Table 3 presents the 3-sec equivalent breakage stresses, the 60-sec equivalent breakage stresses, and the 1-hr equivalent breakage stresses for each specimen tested with a loading rate of 1,000,000 psi stress per minute. Tables 2 and 3 also present the respective means, standard deviations, coefficients of variation, and allowable tensile stresses associated with a probability of breakage of 0.008.

Based on the writers' collective experiences, the strength data presented in Tables 1 and 2 are greater than would be expected for strength data associated with freshly-manufactured, soda-lime float glass. In addition, the estimated allowable tensile stresses associated with a probability of breakage of 0.008 were in excess of what would normally be required for annealed glass designs. The allowable stress associated with a 3-second duration loading is generally associated with allowable stresses used for wind loadings (i.e. uniform pressure loads). The approximate minimum allowable 3-second duration surface stress associated with a probability of breakage of 0.008 for annealed glass is 3,380 psi as presented in Appendix X6, Section 2 of ASTM E1300-16 (ASTM E1300, 2016) and 2,510 psi for ASTM E1300-24 (ASTM E1300, 2024).

Table 1: 0.5-mm Thick Boro-aluminosilicate Glass Beams, 10,000 psi stress per minute load rate.

Specimen	Equivalent Breakage Stress (psi)		
	3-Sec	60-Sec	1-Hr
1	18,962	15,724	12,174
2	18,307	15,181	11,754
3	20,027	16,607	12,858
4	16,220	13,450	10,413
5	20,190	16,743	12,963
6	20,600	17,082	13,226
7	17,561	14,563	11,275
8	17,680	14,662	11,351
9	18,450	15,300	11,845
10	17,556	14,558	11,271
11	19,152	15,882	12,296
12	20,115	16,680	12,914
13	19,155	15,885	12,298
14	19,976	16,565	12,825
15	19,984	16,572	12,830
16	19,060	15,805	12,237
17	17,553	14,556	11,270
18	17,097	14,178	10,977
19	14,891	12,348	9,560
20	19,104	15,842	12,265
21	20,027	16,608	12,858
22	19,889	16,493	12,769
23	19,359	16,053	12,429
24	18,875	15,652	12,118
25	17,351	14,388	11,140
26	18,695	15,503	12,002
27	16,213	13,445	10,409
28	20,320	16,850	13,046
29	18,559	15,390	11,915
30	17,541	14,546	11,262
Mean, psi	18,616	15,437	11,952
Standard Deviation, psi	1408	1167	904
Coefficient of Variation, %	7.56	7.56	7.56
Allowable Stress, psi, P_b = 0.008	15,223	12,624	9,774

Table 2: 0.5-mm Thick Boro-aluminosilicate Glass Beams, 1,000,000 psi stress per minute load rate.

Specimen	Equivalent Breakage Stress (psi)		
	3-Sec	60-Sec	1-Hr
1	18,390	15,250	11,807
2	17,736	14,708	11,387
3	17,122	14,198	10,993
4	17,402	14,431	11,173
5	16,743	13,884	10,749
6	17,263	14,315	11,083
7	17,313	14,357	11,116
8	15,992	13,262	10,267
9	17,356	14,392	11,143
10	16,903	14,017	10,852
11	17,576	14,575	11,284
12	16,863	13,984	10,826
13	15,914	13,197	10,217
14	17,502	14,514	11,237
15	17,731	14,704	11,384
16	14,675	12,169	9,422
17	17,840	14,794	11,454
18	17,925	14,864	11,508
19	17,993	14,920	11,552
20	16,865	13,985	10,828
21	18,720	15,523	12,019
22	18,238	15,124	11,709
23	17,931	14,869	11,512
24	16,728	13,871	10,740
25	18,080	14,993	11,608
26	18,287	15,164	11,741
27	15,233	12,632	9,780
28	17,454	14,474	11,206
29	17,597	14,592	11,298
30	16,856	13,978	10,822
Mean, psi	17,274	14,325	11,090
Standard Deviation, psi	910	755	584
Coefficient of Variation, %	5.27	5.27	5.27
Allowable Stress, psi, P_b = 0.008	15,081	12,506	9,682

6. Conclusions

There is a paucity of data with respect to the strength of boro-aluminosilicate glass to resist uniform pressure loads when used in triple-insulating glass units. As stated previously, the purpose of this report was to determine the strength of a specific 0.5-mm thick boro-aluminosilicate glass material that may be used in a triple-glazed IG unit as the middle glass plate. This was accomplished using weak-axis, four-point bend testing on a set of glass specimens subjected to two different loading rates. The primary outcome of this testing shows that the strength of the thin boro-aluminosilicate glass tested is at a minimum analogous to the typical strength data measured for annealed soda-lime float glass. The resulting strength data for this specific glass were presented herein. In summary, the approximate minimum allowable 3-second duration surface stress associated with a probability of breakage of 0.008 is 15,080 psi. As such, it is feasible to consider the use of thin boro-aluminosilicate glass as the middle glass plate in a triple-glazed IG unit window system.

7. Future Research

Future research is needed to fully determine the load resistance of thin boro-aluminosilicate glass plates used in full-scale triple-glazed IG units that are subjected to uniform pressure loads. This includes an understanding of the stress distribution that develops as a function of the load sharing and relative thicknesses of the three glass plates used in a triple-glazed IG unit. In addition, future research should include an understanding of thin boro-aluminosilicate glass resistance to typical thermal loads imposed on triple-glazed IG units.

Acknowledgements

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