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Evaluation of the Edge Strength of Architectural Glass

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EVALUATION OF THE EDGE STRENGTH OF ARCHITECTURAL GLASS

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ABSTRACT

A mechanical device to test the edge strength of glass was developed in a previous study and was to be modified for more accurate results in this study. The mechanical apparatus allows for a load to be applied and directed along one diagonal of a glass beam making the other diagonal the neutral axis. This allows only one edge to be in tension where the failure is desired.

This study evaluated the scored edge lines and the other edge lines of annealed glass which was cut by an experienced glass cutter with a steel scoring wheel, and a carbide scoring wheel. The failure loads were recorded for four test series of 30 samples each. The first two series were performed to determine the scored edge strength of the glass specimen. The third series tested the other edge of both the steel and carbide cut glass. Finally, one series of tests was administered to determine the combined effects of the scored edge line and the other edge line of carbide cut glass. The scored edge line was on the order of 50 percent weaker than the other edge line and the steel cut glass exhibited 25 percent less strength than the carbide cut glass.

INTRODUCTION

The edge strength of an architectural glass window is an important property in the design of glass. Care must be taken not to overlook the importance of thermal and mechanical loads which can cause failure or cracking at the glass edges. In the case of mechanical forces such as wind pressure, surface strength or edge strength can be deterministic of failure and in the case of thermal stresses, edge strength is always deterministic of failure [1]. Glass, from its chemical composition is a very stiff and brittle material, and like most brittle material tension is the predominant mode of failure. Glass strength is dependent on the glass surface exhibiting tensile stresses. Larger surfaces under tensile stresses increase the probability of premature failure according to the weakest-link theory. The larger the surface, the more flaws and weak spots which predetermine the initial failure locations. This sensitivity to surface conditions means that strength is not an intrinsic property of glass, and that the strength depends strongly on the history of treatment, handling of surface [2].

The handling of the surface and edges when cutting glass can determine how a glass lite will respond to loadings. Cutting a glass window to size requires a careful scoring of one surface followed by breaking the lite along the scored line (see Figure 1).

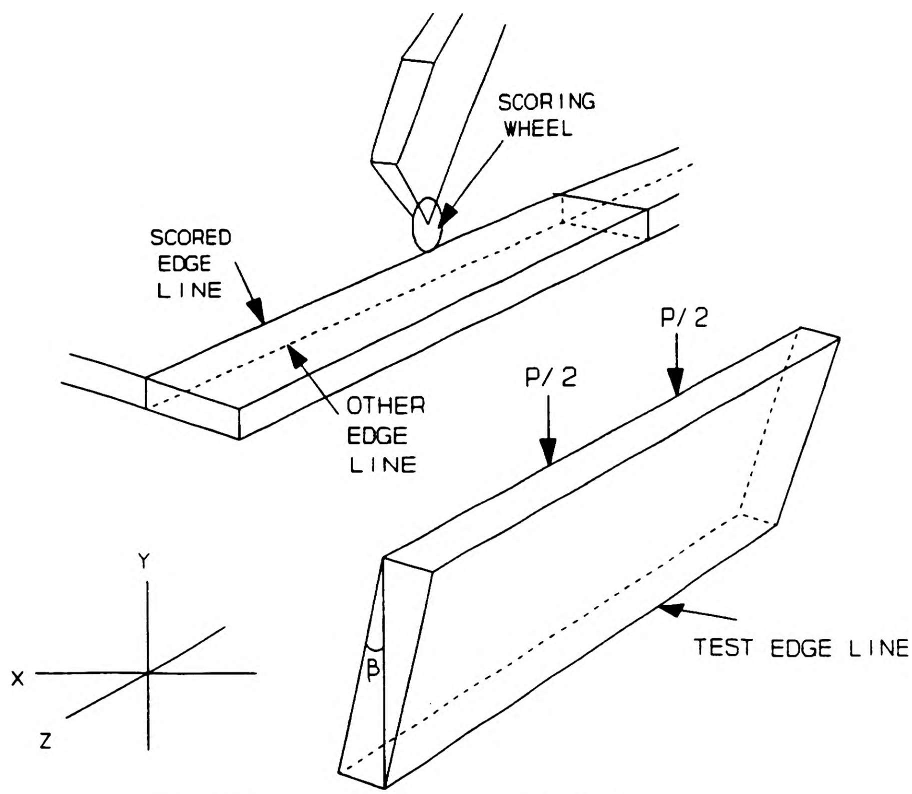

FIGURE 1. Edge Definitions

Scoring the glass when cutting damages the glass surface and induces flaws along that edge. A glass window will then have a weak scored edge and a relatively strong unscored edge called the "other edge."

This research focused on the evaluation of the edge strength of window glass. The test of both the scored edge line and the other edge line of annealed glass specimens constituted the experimental program of this investigation. The test was to model the thermal and mechanical edge stresses that are observed during the normal use of a glass unit. Thermal stresses are created by a temperature gradient generated by the interior of the glass being heated by the sun and the edges of the glass being kept cool by the frame of the window. If the temperature gradient is large enough, the expansion of the interior of the glass can force the outside edge into tension therefore inducing failure and cracking at the edges. In the case of mechanically induced stresses, the wind causes the window to deflect in or out putting the edges and one of the surfaces in tension. This tension, if large enough, can cause failure.

The following report identifies the research plan and theory, describes the testing apparatus, presents some preliminary results, identifies errors, and gives insight into the test. The report also includes some recommendations for future work.

RESEARCH PLAN

The research plan was to perform edge strength tests on glass lites for the scored edge and the other edge when cut with a steel wheel cutter and a carbide wheel cutter (see TABLE I).

TABLE I: Testing Outline

Test specimen size:	Beam of 6.00" span, 1.00" deep, and 0.125" wide
Type Of Glass:	Annealed glass
No. of Specimen Tested:	30 per series
Test Parameters:	*Type of Scoring Wheel, Steel vs. Carbide *Test Edge, Scored edge in tension while other edge exhibits nil stresses, other edge in tension while the scored edge exhibits nil stresses, and both edges in tension simultaneously
Series of Tests:	I. Steel Scoring Wheel - Scored Edge Line II. Carbide Scoring Wheel - Scored Edge Line III. Other Edge Line IV. Carbide Scoring Wheel - Combined Edge Line
Loading Rate:	100 lbs. per minute

Test Concept

This study incorporated the theory of unsymmetrical bending of rectangular beams [3]. The loads were applied along the diagonal of a rectangular glass specimen. This placed the edge line where the force was applied into compression and placed the opposite edge line in tension. This allowed the other diagonal of the rectangular cross section to become the neutral axis.

In order to provide pure bending in the test region, a four point loading was applied (i.e. two supports, and two applied loads). This test arrangement was chosen over the three point loading system, in order to test a larger area of the edge line.

Machine Description

The testing facility used in this project was based on a modification of an existing facility used in a previous study. The new facility consisted of the glass testing bed, the loading angle and ball bearing, a hydraulic cylinder and jack, a hydraulic control valve, a 2000 lb. load cell, a load conditioner, and an X-Y plotter. This system was the same as the previous system, however changes were made to the glass testing apparatus and to the way the loads were applied.

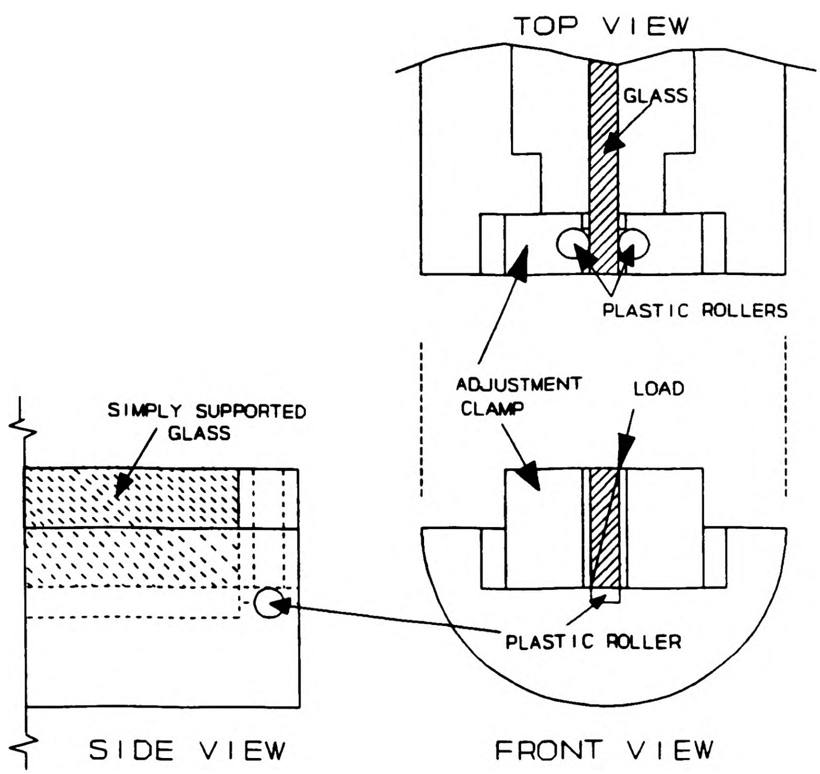

FIGURE 2. Glass Test Bed End Conditions (Three Views)

The loading angle, ball bearing, and loading bar arrangement were added to more accurately direct the load through the diagonal of the glass and to prevent some of the error that existed in the previous study.

The glass testing bed was the first piece of equipment to be evaluated and changed in order to better model the desired bending conditions. The first change that developed from the previous machine was that the entire depth of the glass was to be enclosed at the boundary conditions rather than being allowed to rest halfway into the cylinder of the test bed. The previous arrangement introduced additional bending stresses in the third direction due to the glass being cantilevered along its depth. The desired stress was to be introduced in the direction which was parallel to the edge of the glass which constitutes the Z-direction, however the cantilevered glass was introducing stress in the Y-direction which is along the depth of the cross section.

The second change dealt with the end conditions. The previous machine modeled the end conditions as fixed-fixed in one direction and pinned-pinned in the other direction. This arrangement complicated the stress distribution and placed both bottom edges in tension. Therefore, boundary conditions were created which would allow for both the X and Y-directions to be modeled as pinned connections. This was done by using Nylon 101 dowel rods in the ends to act as rollers (see Figure 2). The Nylon 101 was used since it did not cold flow like Teflon under the loading. The plastic also helped to distribute the loads in order to keep from having shear failure caused by point loads at the end conditions. With the end conditions modeled as pinned-pinned connections, the following two dimensional stress equation could be used to solve for the stress:

$$\sigma = \frac{M_x C_y}{I_x} + \frac{M_y C_x}{I_y} \tag{1}$$

where:

M_x = Moment about the X-axis created by the failure load component in the Y-direction due to the beta (ß) angle of the glass

M_y = Moment about the Y-axis created by the failure load

component in the X-direction due to the beta (ß) angle of the glass
I_x = Moment of inertia about the X-axis
I_y = Moment of inertia about the Y-axis
C_x, C_y = Distance from centroidal axis to point of stress observation

The moments about the X and Y-axis can be identified with the following equations:

$$M_x = \frac{P \cdot \cos(\beta) \cdot L}{6} \quad (2)$$

and:

$$M_y = \frac{P \cdot \sin(\beta) \cdot L}{6} \quad (3)$$

where:

P = Failure load
ß = Angle glass is rotated to direct vertical force through the diagonal of the glass beam
L = Beam span (5.5 inches)

The third change to the glass test bed made it easier to align the glass parallel with the Z-axis and to secure it in the machine (see Figure 2). End clamps were designed to adjust the end conditions from one side of the testing apparatus making the test preparation much easier and more accurate. Previously, shims were used to make the end connections fit correctly. The shims created problems in the alignment of the glass in the Z-direction.

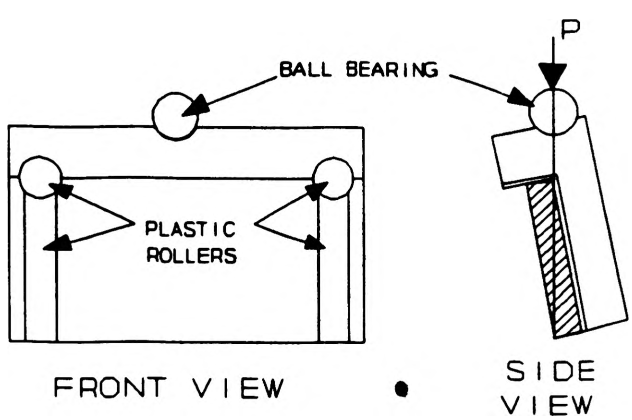

FIGURE 3. Loading Angle And Ball Bearing

Allowing the rollers to be adjusted from one side removed the risk of the glass not being aligned parallel with the Z-axis which could create unnecessary stresses.

After developing the glass testing device, the glass loading angle had to be developed. The mechanism had to apply a two point load, each located a third of the span from the support, which would provide the assumed perfect bending between the two loads (see Figure 3).

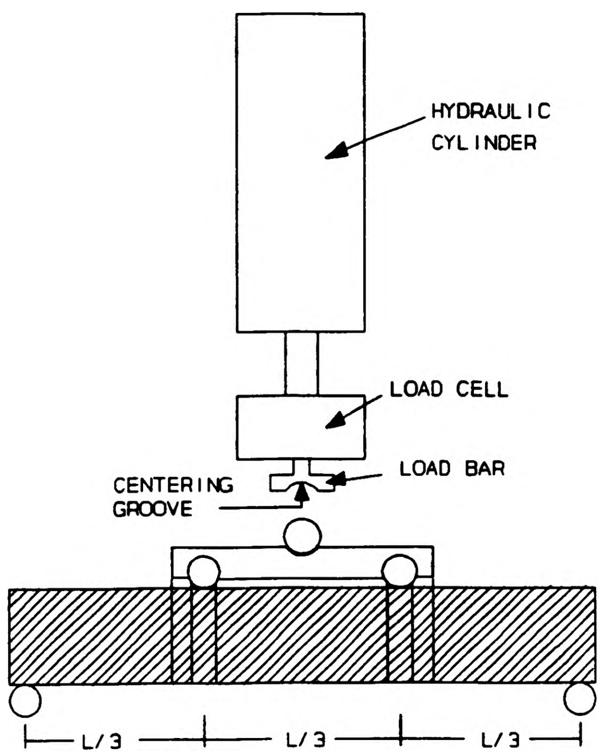

FIGURE 4. Loading Arrangement

The force was to be applied to the loading angle using the hydraulic cylinder and the load bar. The loading bar was designed with a groove for the ball bearing to adjust to the different angles created by different thicknesses of glass (see Figure 4). The groove in the load bar also assisted in centering the loading angle on the glass specimen, therefore, placing the forces a third of the span away from the supports. This decreased any errors associated with measuring the center as in the previous study.

Error Identification

Throughout the development of the testing apparatus, the objective was to create a machine which would decrease the amount of errors. The observed errors which could not be overcome were errors in the precision of the instrument, which were identified as errors in the angles, and errors in the bending moments.

The first errors were introduced by differences in the beta (ß) angles which are associated with the cutting and manufacturing of the glass. This introduced error since the beta (ß) angle for each specimen was different depending on the dimensions. Another error associated with the beta (ß) angle, was the error introduced by the loading angle being designed for glass of 0.125 inch by 1.00 inch. Each of the errors can be identified with the following equation:

$$e=\cos(\Delta\beta)+\frac{h^2-t^2}{2ht}\cdot\sin(\Delta\beta)-1 \qquad (4)$$

where:

e = Error
h = Height of glass specimen
t = Thickness of glass specimen
$\Delta\beta$ = Angle difference between the actual and the theoretical beta angle

This equation was developed to determine the error introduced in the failure stress by incorrect angles. For example this relationship gives an error in the stress of 2.289 percent for an angle difference of 00°20'00 (0.3333°) relative to the theoretical beta (ß) angle.

The errors in the angle also introduced a small amount of torsion into the glass. This torsion created some shear stress in the glass. The shear stress could be calculated by using relationships developed from torsion in reinforced concrete [4]. For an angle difference of 00°20'00" (0.3333°) relative to the theoretical angle and for a failure load of 125 lbs. the shear stress was calculated to be 77.25 psi.

There was also error introduced in the bending moments by the loading angle not being exactly centered between the supports. For example if the loading angle is off center by a difference of 0.1 inch the error in the moment is calculated to be 1.62 percent. This error as well as the angle errors could be considered insignificant if care was taken during the procedure.

Test Procedure

All of the glass specimen were placed in the testing device and were loaded through the loading angle and ball bearing. The load rate was kept constant at 100 lbs. per minute for all of the specimens. This load rate was applied manually using the hydraulic jack and by using an X-Y plotter with time on the X-axis and load on the Y-axis. When the specimen would fail the peak load could be determined from the plots, and could be read from the display of the load conditioner.

From the recorded failure loads, the bending moments were calculated using Equations 2 and 3. After finding the bending moments, the failure stresses were calculated using Equation 1.

Test Results

Failure loads and failure stresses for annealed glass specimens cut with a steel scoring wheel and a carbide scoring wheel were calculated using Equation 1 in conjunction with Equations 2 and 3. The average failure loads and failure stresses are reported in Tables II-V.

TABLE II. STEEL SCORING WHEEL - SCORED EDGE LINE

Average Failure Load:	114.5 lbs.
Standard Deviation for Load:	12.1 lbs.
Average Failure Stress:	10286 psi
Standard Deviation for Stress:	1117.8 psi
Coefficient of Variation for Load and Stress:	10.9 %

TABLE III. CARBIDE SCORING WHEEL - SCORED EDGE LINE

Average Failure Load:	154.3 lbs.
Standard Deviation for Load:	28.2 lbs.
Average Failure Stress:	13900 psi
Standard Deviation for Stress:	2553 psi
Coefficient of Variation for Load and Stress:	18.4 %

TABLE IV. STEEL AND CARBIDE SCORING WHEEL - OTHER EDGE LINE

Average Failure Load:	276.3 lbs.
Standard Deviation for Load:	62.9 lbs.
Average Failure Stress:	24858 psi
Standard Deviation for Stress:	5492.2 psi
Coefficient of Variation for Load and Stress:	22.1 %

TABLE V. CARBIDE SCORING WHEEL - COMBINED EDGE LINES

Average Failure Load:	224 lbs.
Standard Deviation for Load:	25.5 lbs.
Average Failure Stress:	9723 psi
Standard Deviation for Stress:	1054.6 psi
Coefficient of Variation for Load and Stress:	10.8 %

From the results, the scored edge line for the steel cut glass was 25 percent weaker than the scored edge line of the carbide cut glass. During the test, there was a noticeable difference in the glass edges cut with the steel wheel and the carbide wheel. The steel cut glass had rougher edges than the carbide cut glass. In comparing the results, the coefficient of variation for the steel scored edge line was less than that of the carbide cut glass. It is inherent that by introducing more edge flaws with the steel scoring wheel the probability of failure was increased and the strength was thereby decreased.

In comparing the scored edge line to the other edge line, the other edge line was 58 percent stronger for the steel cut glass and 44 percent stronger for the carbide cut glass. When the combined edge strength was tested, the break stress dropped to below the edge strength of the scored edge. This drop can be attributed to the increased area under tensile stresses increasing the probability of failure and decreasing the strength of the glass.

From the results it was noticed that the break stresses were significantly higher in comparison to most handbook values. Typical strength values for annealed glass are 8000 psi and 22 percent for the coefficient of variation [5]. Checks were made on the testing apparatus calibration and on the glass surface stresses to determine possible sources of error. To date, there is no explanation as to why the reported values are so much greater than the book values.

CONCLUSIONS AND RECOMMENDATIONS

This research focused on the determination of the edge strength of annealed glass cut with two different scoring tools. The research proved that the strength of glass edges is determined by the conditions of the edge after cutting. The research showed that the edge strength of the scored edge is approximately 50 percent of the other edge.

With the machine already designed, it is recommended that further research be done in the area of glass edge strength testing. Testing should be performed further on annealed glass to determine the reasons for the high failure stresses. When the reasons are determined, it is recommended that tests be performed on heat strengthened glass and fully tempered glass. There is much to be learned from the strength of glass in engineering design.

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