01 Apr 1991

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Recommended Citation

Sallee, Gregory P., "The Edge Strength of Annealed and Heat-Strengthened Glass" (1991). *Opportunities for Undergraduate Research Experience Program (OURE)*. 116.
https://scholarsmine.mst.edu/oure/116

THE EDGE STRENGTH OF ANNEALED AND HEAT-STRENGTHENED GLASS

Gregory P. Sallee

Pre-Testing Setup and Research

It was once stated that "a chain is only as strong as its weakest link." In the specific discipline of large commercial building design, this axiom takes no exception. Indeed, the required strength and stability of a structure can be obtained only if its individual components are sound.

It is for this reason, therefore, that engineers devote a great deal of their attention to the design of structural elements and to the strict control and inspection of plan interpretation and subsequent construction. Consider, for example, the analogous comparison of a modern skyscraper building to the human body. Undoubtedly, the framework is of primary importance, as it will determine how the structure will withstand physical loading. This framework takes the form of steel and concrete beams and columns in the skyscraper, and bones, tendons, ligaments and muscles in the human body. Also, the plumbing, electrical, and communication network systems are very instrumental in an operational building, just as circulatory and nervous systems are vital to the body's proper functioning. Yet, perhaps the most important element from a standpoint of serviceability and aesthetics is the protective barrier which lies between the structure's in-service functions and the harsh external environment. In the case of the human body, the skin serves this purpose well. Similarly, the "skin" of a skyscraper takes the form of glass windows.

Inarguably, the beauty of a building is a function of the condition of its glass covering. Furthermore, cracked or broken windows are not only distracting in appearance, but also fail to serve their primary purpose of weatherproofing and more importantly, thermal energy conservation. Moreover, in today's world of engineering economy and accompanying monetary significance, the need for properly designed glass units is of great importance and therefore, deserves much attention.

Sadly, up until now, very little research has been conducted in the field of glass window strength. The purpose of this research, therefore, is to explore the topic of glass window strength such that we might offer some conclusive evidence as to the probable in-situ performance of structural windows. Our intention is to examine the specific phenomenon of thermally- induced stress and its effect on glass strength. J. G. Croll explains the existence of this well-documented problem. "Whenever a structure is subjected to a varying temperature distribution, or where it is prevented from free expansion, stresses will be induced that are generally proportional to the difference in temperature from the unstressed state" (Croll, pp.181-182).

The importance of this research is clear in the case of the glass failure of the Merchants National Bank and Trust Company Building in Fargo, North Dakota. In the fall of 1964, the building began losing tinted, heat-absorbing panes due to thermally-induced stresses. Specifically, the glass in the sunlight was heated while portions of the panes in the shadow, or near the building's cool walls along the pane's edges, stayed relatively cold. The resulting uneven thermal expansion caused cracks. These cracks were significant enough to require replacement of the individual 10x14 feet panes which cost $1200 apiece (Ross, p. 274). Before the problem was diagnosed, hundreds of windows had to be removed, costing tens of thousands of dollars. Clearly, a better working knowledge of this problem could have saved the headaches resulting from this particular incident. Our experimentation should be of great help in an effort to obtain this working knowledge.

The initial steps in this research involved theorizing and some guesswork, just as in any new process. We began by narrowing the scope of our problem to avoid too many experimental variables. Since filed observations have shown that the window failures are governed by an initial cracking originating at the pane edges (i.e. a corner in the glass window cross section), we decided to focus our testing on this "weakest link". Hence, if we could experimentally analyze the average edge strength of a window, we could then determine the probable governing strength of the entire glass window.

Development of Testing Procedure

The primary difficulty we faced lay in the development of an accurate testing procedure that would lead us to good results. Although the ideal modeling and testing procedure would involve some type of thermal-loading, this could not guarantee us accurate information that would lead us to our specific goal of obtaining the edge strength; therefore, another alternative was developed. The design which we used involved a mechanical loading procedure that would maximize stresses at the targeted edge of the glass. The testing equipment consisted of glass samples, a hydraulic manually-operated load bar, an adjustible aluminum block, and load measuring devices.

First, the most important consideration in our experimental design lay in the development of a good loading procedure. From a practical standpoint, the procedure needed to be simple to limit possibilities of experimental error. This simplicity was found to be optimum in a third point bi-axial beam loading scheme. This type of loading would maximize a pure bending stress at the edge of a glass beam, and consequently, would allow us to determine the strength of the edge through simple mechanics of materials calculations.

The next step in building our testing procudure was to devleop the size and dimensions of our glass samples. The sample thickness of 2.5 mm was an already present property of the large glass panes from which our beams were cut. This dimension controlled the depth of the depth of the beam since a critical angle of loading, which is created by a depth/width ratio of 10:1, is necessary in order to develop the maximum loading stress at the edge. This is a result of the bi-axial bending theory found in advanced mechanics of materials. Also, we chose the length of our samples to be 150mm (approximately 6 in.) along with the depth of 25mm. The reason for these numbers lies in the fact that a ratio of length to width larger than this would result in warping problems whereas a smaller ratio would have accompanying shear difficulties in the loading.

After determining an appropriate sample size, we began considering exactly how we would categorize our tests. We opted to test both annealed glass and heat-strengthened glass in their respective subgroups of scored (cut) edge/ other (uncut) edge and air side edge/tin side edge so that we could create a comparative edge strength study.

Samples from the annealed glass sheets were easy to obtain through a simple steel roller scoring and manual breaking process. The heat-strengthened samples, however, could not be obtained in this manner. Instead, they were manufactured by utilizing the state-of-the-art water jet technology available in the Mining Engineering department at the University of Missouri-Rolla. The water jet was altered experimentally until it could successfully cut the glass to the size we had specified. At this point, the samples were polished at a local glass shop so that their testing quality rivaled that of in-situ glass windows. Enough samples of both annealed and heat-strengthened glass were cut so that we could obtain enough successful tests to satisfy our quest for the glass edge strength.

The next most important experimental consideration concerned the loading aparatus itself. We designed and fabricated a manually-operated hydraulic loading bar which could be lowered onto two small points on the adjacent edge of the edge to be tested. This would model the third-point, pure bending load scheme which we desired. Also, an adjustable aluminum support block was machined so that the glass beams could be rigidly placed under the loading bar with the intention of loading to edge failure. Finally, the magnitude and rate of the bar loading was monitored via stress/strain gages and experimental graphing of bar load versus time. Importantly, these monitoring procedures were used to determine the failure stress in the samples.

In short, our preparations were carefully researched and planned so that our experimentation would yield satisfactory results. From these results, we could determine if there are appreciable differences between the average edge strengths of annealed and heat-strengthened glass.

Testing

The majority of the glass testing took place during the summer months of 1990. The samples were all cut and effectively marked so that they could be re-examined for future analysis. Also, the testing aparatus was manufactured and calibrated to avoid unecessary errors. But, as is the case with any experimental process, some unanticipated difficulties and required changes were encountered during the testing.

One particular problem which needed to be addressed concerned the rate at which the samples should be loaded. This could only be examined through actual testing. Accordingly, many "test" samples were loaded at various rates so that we could determine the rate which would give us the most consistent and reasonable results. Rates of 50 lbs./min, 100 lbs./min, 200 lbs./min, and 250 lbs./min, and 300 lbs./min were all examined. After graphing and interpreting the data from each of these rates, it was determined that the loading rate of 100 lbs./min yielded the most consistent results for both annealed and heat-strengthened glass. Thus, this was the rate chosen for the sample testing.

The next problem we encountered was how to actually model the third point loading on the inclined beam. Our solution was to transfer the bar load directly to two very small square steel "shoes" which would be glued on the compression edge of the glass beam. These shoes were carefully machined to sit on the inclined sample so that their tops would be in contact with the horizontal load bar without creating an eccentricity in the beam. As a result, the distributed bar load could be transfered directly to the two points on the beam.

Other additions were also employed during the course of the testing. For example, plastic cushions were installed to prevent stress concentrations and resulting undesireable failures at the beam supports. Also, thin strips of tin and copper were inserted in the contact regions of the beam ends and the aluminum block support so that the uneven torsion and beam slippage could be avoided.

Notwithstanding the pre-planning and changes, some problems were encountered. This fact is clear when the low percentage of successful tests in the annealed samples is examined: only 26.2% of the tests were satisfactory for experimental consideration. These problems were seen as failures at points other than the theoretical location of maximum stress. Specifically, uneven loading due to machine misalignment, torsional stress, and shear stress concentrations caused failures to occur in undesireable places in the beam. However, all of these problems were diagnosed and successfully corrected so that we could obtain enough data to satisfy our requirements. In fact, we were able to achieve an 88.2% success rate in the second series of heat-strengthened glass tests once we corrected our experimental sources of error.

Furthermore, we were able to successfully test enough samples to be assured of a 95% confidence level in our our final edge strength statistical calculations.

Results and Analysis

The primary objective of this research was to determine the relationship among the six series of tests in regard to edge strength. We accomplished this goal by examining the samples through the application of the basics of statics and mechanics of materials.

First, the failure loads were recorded for 20 samples in each of the following test situations: annealed air side, annealed tin side, annealed scored edge, annealed other side edge, heat- strengthened air side, and heat-strengthened tin side. It should be noted that the air side is the side of the glass plate which is facing up during the manufacturing process. Conversely, the tin side faces downward during the manufacture process. The scored edge is the side which is cut with a steel wheel before breaking. The other edge is the side which is not cut before before breaking.

Next, the bending stresses about both the x and y axes were calculated using a modeling scheme developed from statics and mechanics of materials. The beam was analyzed as a simply supported beam in bending about its short axis, and a double-fixed end beam in bending about its long axis. The corresponding stresses were thus calculated and added linearly to give a maximum theoretical total stress at the edge.

In comparing the heat-strengthened tin side to the air side, there was only a 0.13% difference in failure stress. However, in the annealed glass air side/tin side, a difference of 8.6% was found. A comparison of annealed scored edge to other edge yielded a difference in failure stresses of 17%. The greatest percent difference, 34% was found to exist between the annealed and heat strengthened glass specimens. Therefore, we concluded that the heat strengthened samples would be more resistant than the annealed samples to thermally-stressed failures occuring at their edges. Also, the other edge would resist stress better than the scored edge on annealed glass.

Theoretically, these hypotheses seemed accurate. The only problem we faced after this statistical analysis was to account for failures occuring at places other than at the point of maximum theoretical stress. In fact, we observed many failure indications beginning at points along the long side of the sample cross section. This lead us to focus our attention to determining the cause of these unforeseen failures.

We examined the possibility of changes in the loading angle as the cause for stresses exceeding the desired maximum at the edge. However, calculations proved this effect was minimal and therefore was of no consequence in our experimental analysis.

Our second hypothesis was formed using the possibility of shear and torsion developing in the critical failure section of theoretical pure bending. A load differential at the two loading points could have caused both shear and torsion to devleop in the failure section. After extensive research and theoretical calculations, we found that only a 3% or less differential in loading between the two points could cause a maximum stress to occur at a point other than at the edge due to the combined loading of bending, shear, and torsional stresses. Our theory was proven correct after we attached strain gages to the two loading points of the beam and observed a difference that proved the 3% stress difference theory was correct.

One final portion of the experimentation process which has not yet been completed involves the correlation of our results with previous work. There has been a proposed theory which gives a direct relationship between failure stresses and glass fracture mirror radii. We are in the process of measuring, via microscope and micrometer, the radii of our sample fracture mirrors. If the stresses we calculate from the theory correspond with our experimental stresses, we can be much more confident that our results are good enough to give us the ability to suggest how to best utilize glass from the standpoint of edge strength in thermally adverse conditions. Moreover, our results thus far have certainly lead us very close to the completion of this goal.