Structural Performance of Laminated and Unlaminated Tempered Glass Under Monotonic Transverse Loading

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ABSTRACT

A total of thirty-six bending tests have been conducted on 1220x460mm sheets of glass, 9.5, 12.7 and 15.9 mm thick, using slow-rate monotonic loading. Twenty-four specimens were laminated on one side using either one or two 0.36mm thick polyester transparent laminates. The study showed that lamination has significantly changed the failure mode of glass from a catastrophic failure, where fragments of glass shatter in different directions, to one which is still brittle yet quite safer, as the fractured glass remain fully intact. The average gains in flexural strength, stiffness and strain energy, as a result of lamination, were 20, 10 and 34 percent, respectively, while the maximum gains were 36, 33 and 52 percent. Because of the wide scatter of data, no specific correlation between the amounts of gain and the ratio of laminate-to-glass thickness (reinforcement ratio) was observed. The load-deflection behaviour of both laminated and unlaminated glass was linear up to failure. No rupture or delamination of the laminates were observed

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1. INTRODUCTION

Glass is increasingly being used in the construction industry. Tempered glass, in particular, is increasingly used in overhead situations. Glass, which is quite a brittle material, is generally vulnerable to failure due to a number of reasons, such as excessive wind loading in hurricane situations, accumulation of snow in overhead roofing applications or due to terrorism and vandalism acts. An additional problem with broken tempered glass in overhead situations is that, when it breaks, it tends not to break into its constituent diced parts. It may rather fall in large clumps of diced glass. If clumps of such glass strike a person below, serious injury can result [1].

Tempered glass, sometimes referred to as toughened glass, is produced by heating ordinary annealed glass to just below its softening point, to about 650^{o}C, and then cooling it rapidly with blasts of air. This causes the surface of the glass to cool more rapidly than the inner core, which in turn causes the outer zones of the glass to be in under compressive stresses, while the inner core is under tensile stresses. These stresses are in a state of equilibrium and are generally of 70 MPa at least [2]. This prestressing effect results in increasing the bending strength of glass by four to five times, compared to ordinary glass. It also changes the failure mode of the glass [3], from shattering into few large and sharp pieces; to small pieces with a diameter less than 10mm and without sharp edges. However, as indicated earlier, clusters of the small broken pieces could be lumped, and when falling from a height, could induce severe injuries.

The term “laminated glass” or “sandwich glass” often refers to a two or more glass plies bonded together with an elastomeric interlayer such as polyvinyl butyral (PVB) to improve the post-breakage characteristics of the glass. This type of glass is usually prefabricated in this form before installation and commonly used in automotive vehicles windshields. In this paper, however, the term “laminated glass”, it is used within a different context to indicate a regular single sheet of tempered glass, which is retrofitted, while in service conditions or before installation, using a special polymeric transparent lamina attached to the external surface of the glass to enhance the performance and failure mode of glass. This simple technique is quite useful and economical, compared to sandwiched glass. While the structural performance and failure modes of standard tempered glass and sandwiched glass have been studied experimentally and numerically under transverse loading [4, 5 and 6], the behavior and failure mode of externally laminated tempered glass have not been studied. In this paper, tempered sheets of glass of different thickness have been externally laminated using transparent polyester laminate and tested in flexure. The study is focused on examining the effect of lamination on failure mode, flexural strength, stiffness, and strain energy, as compared to unlaminated glass.

2. EXPERIMENTAL PROGRAM

In this section, the transparent polymer laminate and the installation procedure are described. The test specimens, along with the test setup and procedure are also described.

2.1 Laminate Material and Installation

The laminate used in this study consists of three layers of polyester film, bonded together using acrylic pressure-sensitive adhesive. The cold-lamination process under high pressure provides high shock absorption performance and superior optics at the same time. The laminate has a total thickness, including adhesive, of 0.36 mm, a tensile strength of 193 MPa and a Young’s modulus of 3.8 GPa, determined in accordance with ASTM (D 882-75, 1004-76 and D 1938-67) [7, 8]. The laminate has a Visible Light Transmittance capacity of 92 percent, a Total Solar

Energy rejection of 17 percent and an Ultraviolet Light Transmittance of zero to 5 percent. The side of the laminate, which is bonded to glass, has a layer of acrylic pressure-sensitive adhesive, coated with a thin protective film. This film can easily be peeled off, prior to installation, in a similar fashion to wall paper. For retrofit application, the surface of ordinary glass is cleaned and dried, followed by installation of the laminate (or multiple laminates) under high pressure. For the glass replacement applications or new glass installation, the laminate is pre-installed on typical standard size annealed or tempered glass, using the same process, and shipped to the site. The peel strength of the laminate is 3.86 MPa.

2.2 Description of Test Specimens and Parameters

The experimental program included a total of 36 tests conducted on both unlaminated and laminated tempered glass specimens. Two different glass products, provided by two suppliers from the United States and Canada were used in this study and referred to, herein, as Glass A (provided by Virginia Glass) and Glass B (provided by Laurier Glass). All specimens consisted of 1220 x 460 mm sheets of glass with polished edges. Three different thicknesses were investigated in this study, namely 9.5, 12.7, and 15.9 mm. Table 1 provides summary of test specimens. Specimens A1 to A5 are of Glass A, whereas B1 to B7are of Glass B. Three identical specimens were tested for each parameter to provide reliable average values. Specimens A1, A4, B1, B4 and B7 were unlaminated control specimens. Specimens A2, A5, B2 and B5 were laminated with a single laminate applied to one face. Specimens A3, B3 and B6 were laminated using two laminates (0.72 mm thick), both applied to the same face. The laminates were applied to the entire surface area of glass. This scheme has resulted in a reinforcement ratio, defined as the ratio thickness of laminate to glass, ranging from 2.26 to 7.58 percent.

Specimens (A1, B4) and (A4, B7) will be compared to examine the effect of glass type (A and B) for the same thickness. Specimens (A1 to A3), (A4, A5), (B1 to B3), and (B4 to B6) will be compared to examine the effect of lamination, including the number of laminates, on the behaviour. Finally, specimens (A1, A4), and (B1, B4, B7) will be compared to examine the effect of thickness of glass on the behaviour.

2.3 Test Setup and Procedure

The experimental program described in this paper was intended to simulate lateral pressure applied gradually to glass at a slow rate, over a period of time. As such, all specimens were tested to failure under monotonic loading, using a four-point bending configuration as shown in Fig. 1. An MTS hydraulic actuator was used to apply the load using stroke control at a rate of 0.5 to 1.0 mm/minute. This setup is a modified version of the one used to determine the strength of glass in flexure (ASTM C 158-95) [9], mainly to accommodate full scale specimens in this case. The span between supports was 990 mm, while the distance between the loads was 330 mm. Steel rollers of 50 mm diameter were used at both loading and support points. Rubber pads, 12 mm thick, were placed between the steel rollers and surface of glass in order to avoid any stress concentrations. Deflections were measured using two electric potentiometers at mid span, at both sides, and also at the center of each support to account for the settlement resulting from the rubber pads. This configuration allows for measuring the net deflection.

3. TEST RESULTS AND FAILURE MODES

The load-deflection behaviours of the 15.9 mm, 12.7 mm and 9.5 mm thick specimens, both laminated and unlaminated, are shown in Fig. 3, Fig. 4 and Fig. 5 respectively. For each parameter, the behaviour of three identical specimens is presented. In general, the behaviour of the specimens is considered fairly linear. Fig. 6 (a, b, c and d) presents a comparison of the ultimate load, maximum deflection, stiffness, and strain energy of all test specimens, in order to assess the effects of type of glass, lamination, and thickness.

3.1 Effect of Type of Glass

Specimens A1 and B4 of Glass A and B respectively were both 12.7 mm thick and unlaminated. The ultimate load and stiffness of A1 was 35 and 33 percent higher than B4 respectively. Specimens A4 and B7 were both 15.9 mm thick and unlaminated. The ultimate load and stiffness of A4 was about 3 and 9 percent lower than B7 respectively. Therefore, the strength and stiffness ratios of types A and B glass do not appear to be consistent for all thicknesses. As will also be confirmed later, specimen B7 appears to have a higher strength and stiffness than expected.

3.2 Effect of Thickness of Glass

Specimens A1 and A4 of Glass A were 12.7 and 15.9 mm thick respectively. The ratios of strength and stiffness of A4 to A1 were 1.51 and 1.92, respectively. These ratios are in good agreement with thickness ratios [$(15.9:12.7)^2 = 1.57$] for strength and [$(15.9:12.7)^3 = 1.96$] for stiffness, based on basic mechanics. Specimens B1, B4, and B7 of Glass B were 9.5, 12.7 and 15.9 mm thick respectively. The ratios of strength and stiffness of B7 to B4 were 2.11 and 2.82 respectively, which are not in good agreement with thickness ratios [$(15.9:12.7)^2 = 1.57$] for strength and [$(15.9:12.7)^3 = 1.96$] for stiffness. The ratios of strength and stiffness of B4 to B1 were 1.81 and 2.23 respectively, which are in good agreement with thickness ratios [$(12.7:9.5)^2 = 1.79$] for strength and [$(12.7:9.5)^3 = 2.39$] for stiffness. These observations confirm that an inconsistency, perhaps related to quality control and tempering process, appears to be associated with specimens B7 (15.9 mm Glass B) and results in higher strength and stiffness than expected.

3.3 Effect of Lamination

Fig. 6 shows a comparison of all test specimens, both laminated and unlaminated, in terms of maximum load, deflection, stiffness and elastic strain energy. The stiffness is defined as the slope of the load-deflection curve in this case, whereas strain energy is defined as the area under the load-deflection curve. Fig. 7 shows a relation between the reinforcement ratio, represented as the ratio of thickness of laminate to that of glass, and the percentage increase in ultimate load, deflection, stiffness and the strain energy. While Fig. 6 and Fig. 7 show that gains in strength, stiffness, and strain energy, up to 36, 33, and 52 percent, respectively, were observed as a result of the lamination, Fig. 7 clearly shows a wide scatter of data, which makes it very difficult to establish a correlation between the reinforcement ratio and the gain in strength, stiffness, or strain energy. This could be attributed to the very brittle nature of glass and its sensitivity to any slight difference in quality control during the tempering process. Based on test results, however, the average gains in strength, stiffness and strain energy were 20, 10 and 34 percent, respectively. It is also clear from Fig. 6 that using two laminates doesn’t provide additional gains compared to one laminate. Perhaps the most pronounced advantage of lamination is its effect on failure mode as discussed in the following section.

3.4 Failure Modes

A distinct difference in failure mode between the laminated and unlaminated glass was observed for all range of thickness and for both Glass A and Glass B. Fig. 8(a) shows an unlaminated 15.9

mm Glass A, specimen A4, with high deflection, moments before failure. Fig. 8(b) shows the same specimen A4 and also specimen B7 immediately after failure. The unlaminated glass shatters violently once the modulus of rupture of glass is attained. Fig. 8(b) clearly reflects the very brittle and catastrophic nature of the failure. Fragments of glass were scattered and have travelled more than 6 meters away from the specimen. All unlaminated specimens failed in this manner. It is envisioned that serious injuries and panic would have definitely resulted, had a similar scenario been encountered in a real structure. Careful examination of the failure of both unlaminated Glass A and B shows that, while both were extremely brittle, Glass B shatters into smaller fragments compared to Glass A as shown in Fig. 8(b). This could be attributed to slight differences in the tempering processes of both types.

Fig. 8(c) shows the laminated glass after failure. Although the glass itself was completely fractured in every direction, throughout the entire surface, all pieces were contained together as one unit due to the presence of the laminate. All laminated specimens failed in this manner. Fig. 8(c) also shows that the specimen maintains the same deflected shape after failure. No signs of delamination between glass and laminates were observed, neither were there any sign of failure of the laminates themselves. This failure mode was distinctly different from that of unlaminated glass and was certainly quite safer and less catastrophic. Failed specimen was easily removed from the test setup as one unit. Similarly, in an actual structure, failed panels would have been easily removed and replaced.

4. SUMMARY AND CONCLUSIONS

This study included a total of 36 tests conducted on both unlaminated and laminated clear float tempered glass sheets of three different thicknesses (9.5, 12.7, and 15.9 mm). Monotonic loading was applied at a slow rate to simulate a rather gradual and sustained pressure over a short period of time. The lamination used involved either a one or two 0.36 mm thick polyester laminates attached to one side of the glass. Based on this study, the following conclusions are drawn:

1. The most distinct advantage of lamination is that it significantly changes the failure mode from a brittle and catastrophic failure, where small fragments of glass shatter in different directions, potentially causing serious injuries, to one which is still brittle yet quite safer as the fractured glass remain intact and can easily be removed and replaced.
2. The average gains in flexural strength, stiffness and strain energy as a result of lamination were 20, 10 and 34 percent respectively. Although gains as high as 36, 33 and 52 percent in strength, stiffness and strain energy were observed, the wide scatter of data made it difficult to establish a specific correlation between the reinforcement ratio (thickness of laminates-to-thickness of glass) and the gains. The scatter of data could be attributed to the very brittle nature of glass and its sensitivity to slight variations in tempering process, especially for different thicknesses, where the cooling rate across the thickness affects the level of residual stresses.
3. Adding a second laminate had an insignificant effect on strength, stiffness, strain energy, and failure mode.
4. The load-deflection behaviour of both laminated and unlaminated glass is linear up to failure.
5. No rupture or delamination of the laminates were observed.
6. The lamination process is quite suitable for both retrofit of glass in existing structures as well as for new structures, where pre-laminated glass can be installed in the field.

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