Investigations on the flexural performance of laminated glass

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Abstract. Laminated Glass, regarded as the safety glass, is widely used in modern architectural applications. The structural behaviour of this type of glass is highly complex owing to the presence of the interlayer. In such a case, classical theoretical formulations are of no use and it becomes necessary to employ specially formulated equations or numerical simulations to evaluate the performance of laminated glass. Present work consists of displacement-controlled four-point bending tests on laminated glass beams to study the load-deflection behaviour and fracture pattern of the samples. Numerical simulations of the test samples are carried out in ANSYS to achieve the maximum tensile stress and deflection values corresponding to the initial failure load. Three laminated glass performance models are used to analytically evaluate the values of failure stress for laminated glass.

1. Introduction

The present-day trends in modern architecture are aimed to abate the differences between the exterior and interior of the building. This has resulted in a persistent growth in the number of translucent surfaces. For architectural glazing applications, the use of Laminated Glass (LG) has become increasingly common owing to the ability to withstand collapse after failure, improved sound insulation, decreased transmission of ultraviolet light, and enhanced thermal insulation [1]. LG consists of two or more glass panes of equal or unequal thickness bonded together by means of one or more interlayer. The glass panes may be of the same type or different in heat treatment. PVB (Polyvinyl Butyral), EVA (Ethylene Vinyl Acetate), SG (SentriGlass) and resin are the commonly used interlayer materials and are usually less stiff than glass, in several orders of magnitude. Lamination improves the post-breakage behaviour, as after failure, glass fragments adhere to the interlayer lowering the risk of injury [2-4].

In the glazing industry, the Four-Point Bending Test (FPBT) is used as the standard test to study the structural behaviour of LG [5, 6]. An effective thickness approach is employed to capture many of the important variables that influence the highly complex behaviour of LG [7, 8]. Three simplified
analytical models are widely used to evaluate the structural performance of LG: fully monolithic, layered and equivalent monolithic performance models [1]. The fully monolithic model assumes that the structural behaviour of LG is analogous to that of a monolithic glass beam having thickness equal to the total thickness of LG and provides an upper boundary for LG performance. The layered model considers the structural behaviour of LG as similar to that of a system of separate monolithic glass beams stacked in layers and gives lower boundary for LG performance. The equivalent monolithic model gives a solution which lies in between the solutions given by the other two models.

The present paper deals with both experimental and numerical investigations conducted on LG beams. Three performance models are used to obtain the failure stress values and the results obtained are compared.

2. Test specimens and procedure
LG samples (see table 1) used for the present study consist of two identical toughened glass panes (4/5/6 mm thick) and 0.98 mm thick resin interlayer.

| Type of glass          | Length (mm) | Width (mm) | Thickness (mm) | Designation       |
|------------------------|-------------|------------|----------------|-------------------|
| Laminated Glass        | 700         | 100        | 8.98           | LG108, LG208, LG308 |
|                        |             |            | 10.98          | LG110, LG210, LG310 |
|                        |             |            | 12.98          | LG112, LG212, LG312 |

Displacement-controlled FPBT (at the rate of 0.1 mm/minute) is conducted on all the glass specimens in MATEST Loading Frame of capacity 50 kN (see figure 1). The loading rollers and the supporting rollers are maintained at a distance of 200 mm and 600 mm respectively. Rubber pads are placed at all the points of contact between the rollers and specimen to ensure even distribution of load. Load-deflection behaviour and failure pattern of the LG samples are noted.

(a) During loading  (b) After failure

Figure 1. Laminated glass sample in the FPBT jig
Numerical models are developed in the finite element analysis software ANSYS to get the values of maximum tensile stress and deflection corresponding to the initial failure load of each LG sample. SOLID 186 and CONTA 174 elements are used for modelling. The input data for the numerical models are given in table 2.

**Table 2.** Material properties of glass and interlayer [9]

| Particulars              | Glass  | Interlayer |
|--------------------------|--------|------------|
| Density (kg/m³)          | 2500   | 1100       |
| Modulus of elasticity (GPa) | 70     | 0.22       |
| Poisson’s ratio          | 0.23   | 0.495      |

Three LG performance models (Fully monolithic, Layered and Equivalent monolithic performance models) are used to obtain the failure stress values analytically by employing Equation (1) to Equation (3).

- **Fully monolithic performance model:**
  \[
  f_{tb} = \frac{6M}{b(2t_g + t_i)^2}
  \]  
  (1)

- **Layered performance model:**
  \[
  f_{tb} = \frac{3M}{bt_g^2}
  \]  
  (2)

- **Equivalent monolithic model:**
  \[
  f_{tb} = \frac{3M}{2bt_i^2}
  \]  
  (3)

Where \( f_{tb} \), \( M \), \( b \), \( t_g \), and \( t_i \) are failure stress, applied bending moment, width of the specimen, thickness of the glass pane, and thickness of the interlayer respectively.

**3. Results and discussion**

Details of the FPBT results are tabulated in table 3 and given in figure 2.

**Table 3.** FPBT results of laminated glass specimens

| Sl. No. | Designation | Initial failure load (N) | Deflection at initial failure load (mm) | Maximum residual load (N) | Maximum residual deflection (mm) |
|---------|-------------|--------------------------|----------------------------------------|---------------------------|----------------------------------|
| 1       | LG108       | 975                      | 23.336                                 | -                         | -                                |
| 2       | LG208       | 845                      | 19.950                                 | 209                       | 33.170                           |
| 3       | LG308       | 898                      | 21.250                                 | -                         | -                                |
| 4       | LG110       | 1640                     | 21.093                                 | -                         | -                                |
| 5       | LG210       | 1541                     | 19.703                                 | 480                       | 32.791                           |
| 6       | LG310       | 1555                     | 19.420                                 | 479                       | 32.720                           |
| 7       | LG112       | 2527                     | 19.494                                 | 798                       | 29.300                           |
| 8       | LG212       | 2453                     | 18.809                                 | 775                       | 28.206                           |
| 9       | LG312       | 2387                     | 18.458                                 | 774                       | 27.587                           |
Figure 2. Load-deflection behaviour of laminated glass specimens

The load-deflection graph shows that the samples LG108 and LG308 have no residual load-carrying capacity as the two glass panes in both the specimens failed simultaneously on reaching the initial fracture load of 975 N and 898 N respectively. The initial fracture of LG208 occurred at 845 N, then the load value dropped to 29 N (3.4% of initial failure load) and further increased to a value of 209 N. Finer cracks are generated in the load span region of bottom glass plate at the time of initial fracture. The top plate showed finer cracks in the mid-span region and wider cracks near the supports. Tearing of resin interlayer occurred during the fracture of LG308. Initial fracture of sample LG110 took place at load value of 1640 N with fracture origin of the bottom plate in the load span, near one loading roller. Top glass pane did not fail as the value of stop load set during the experiment was not sufficient to ensure total failure. So the value was increased from 50% to 90% for further tests. The bottom glass pane of LG210 failed at 1541 N, then the load value decreased to 209 N (13.5% of initial failure load) and again increased to 480 N. Fracture origin of the bottom plate is located below one of the loading rollers. Cracks spread throughout the two glass plates. Initial fracture of LG310 occurred at 1555 N, then the load value dropped to 192 N (12.3% of initial fracture load) and further showed an increase up to 479 N. Fracture pattern is similar to LG210. Fracture of lower glass pane took place at 2527 N, then the load value suddenly dropped to 408 N (16.1% of initial failure load) and further raised to 798 N for the sample LG112. Initial fracture of LG212 occurred at 2453 N, then the load value suddenly decreased to 402 N (16.3% of initial failure load) and further increased to 775 N. Bottom plate of LG312 fractured at 2387 N, then the load value suddenly dropped to 408 N (17.1% of initial failure load) and further increased to 774 N. The reduced structural contribution of lamination is attributed to its low stiffness. Since the drop in load value after the initial fracture is more than 80%, the quality of the interlayer should be improved to enhance a better load transfer mechanism. From
the load-deflection data obtained from the four-point bending tests of laminated glass specimens, the values of stiffness before the elastic limit, stiffness after the elastic limit, normalised stiffness, normalised load and normalised deflection are calculated using Equation (4) to Equation (8) and is shown in Table 4.

\[
\text{Stiffness before the elastic limit} = \text{Slope of load} - \text{deflection graph before elastic limit} \quad (4)
\]

\[
\text{Stiffness after the elastic limit} = \text{Slope of load} - \text{deflection graph after elastic limit} \quad (5)
\]

\[
\text{Normalised stiffness} = \frac{\text{Stiffness after the elastic limit}}{\text{Stiffness before the elastic limit}} \quad (6)
\]

\[
\text{Normalised load} = \frac{\text{Residual load}}{\text{Initial failure load}} \quad (7)
\]

\[
\text{Normalised deflection} = \frac{\text{Residual deflection}}{\text{Deflection at initial failure load}} \quad (8)
\]

| Sl. No. | Designation | Stiffness before the elastic limit (N/mm) | Stiffness after the elastic limit (N/mm) | Normalised stiffness | Normalised load | Normalised deflection |
|--------|-------------|------------------------------------------|------------------------------------------|---------------------|-----------------|----------------------|
| 1      | LG108       | 42.05                                    | -                                        | -                   | -               | -                    |
| 2      | LG208       | 42.74                                    | 11.38                                    | 0.27                | 0.25            | 1.66                 |
| 3      | LG308       | 42.64                                    | -                                        | -                   | -               | -                    |
| 4      | LG110       | 77.90                                    | -                                        | -                   | -               | -                    |
| 5      | LG210       | 78.34                                    | 20.54                                    | 0.26                | 0.31            | 1.66                 |
| 6      | LG310       | 80.38                                    | 20.85                                    | 0.26                | 0.31            | 1.68                 |
| 7      | LG112       | 129.60                                   | 36.50                                    | 0.28                | 0.32            | 1.50                 |
| 8      | LG212       | 130.20                                   | 36.79                                    | 0.28                | 0.32            | 1.50                 |
| 9      | LG312       | 129.10                                   | 37.18                                    | 0.29                | 0.32            | 1.49                 |

3.1. Effect of lamination

Glass specimens having effective thickness 8 mm showed 11% decrease in load at initial failure, 44% increase in deflection at initial failure, 38% decrease in stiffness before initial failure and 25% residual load-carrying capacity. Glass specimens having effective thickness 10 mm displayed 20% decrease in load at initial failure, 39% increase in deflection at initial failure, 43% decrease in stiffness before initial failure and 31% residual load-carrying capacity. Glass specimens having effective thickness 12 mm exhibited 32% decrease in load at initial failure, 22% increase in deflection at initial failure, 44% decrease in stiffness before initial failure and 32% residual load-carrying capacity. These inferences are made by comparing the results of LG samples with the FPBT results obtained by the same authors on toughened glass specimens having the same thickness. Thus, the initial failure load and stiffness showed a negative relationship with glass thickness contrary to residual load and deflection at initial failure load which displayed a positive relationship with thickness.

3.2. Failure pattern

As the laminated glass specimens were subjected to four-point bending, the bottom toughened glass failed first, followed by load transfer to the top toughened glass plate through the resin interlayer. The fracture origin of the bottom plates was within the loading span. Failure of bottom plate resulted in a sudden drop in the load value and then due to load transfer mechanism, the majority of specimens showed a further increase in load-carrying capacity until complete failure. All the fragments adhered to the resin interlayer even after complete failure (see figure 3). The fragment size of 12 mm samples
is lower than that of 10 mm samples. Among the samples, the glass plies of two samples (8.96 mm thick) showed a simultaneous fracture. This can be attributed to the low stiffness value of the interlayer.

![Fracture pattern](image)

**Figure 3.** Fracture pattern

3.3. **Numerical simulation results**
The sample simulation output is depicted in figure 4 and table 5 gives the numerical simulation results of LG beams.

![Sample simulation output](image)

(a) Maximum tensile stress at initial failure load

![Sample simulation output](image)

(b) Deflection at initial failure load

**Figure 4.** Sample simulation output
Table 5. Numerical simulation results of LG beams

| Sl. No. | Thickness of LG sample (mm) | Maximum tensile stress at initial failure load (MPa) | Maximum deflection at initial failure load (mm) |
|---------|----------------------------|---------------------------------------------------|-----------------------------------------------|
| 1       | 8.98                       | 82.74                                             | 10.92                                         |
| 2       | 8.98                       | 71.69                                             | 9.47                                          |
| 3       | 8.98                       | 76.19                                             | 10.06                                         |
| 4       | 10.98                      | 95.48                                             | 10.77                                         |
| 5       | 10.98                      | 89.71                                             | 10.11                                         |
| 6       | 10.98                      | 90.53                                             | 10.20                                         |
| 7       | 12.98                      | 108.10                                            | 10.82                                         |
| 8       | 12.98                      | 104.93                                            | 10.50                                         |
| 9       | 12.98                      | 102.11                                            | 10.22                                         |

The maximum tensile stress values got for the numerical models do not show much scatter in the data for each thickness. The maximum deflection values obtained for the numerical models showed significant deviation from the experimental results. Thus more refinement in modelling is required to get satisfactory results.

3.4. Laminated glass performance models

The failure stress values calculated for the three performance models are summarised in Table 6.

Table 6. Failure stress values for the LG performance models

| Particulars               | Failure stress (MPa) |
|---------------------------|----------------------|
|                           | 8.98 mm  | 10.98 mm  | 12.98 mm  |
| Fully monolithic performance model | 67.41     | 78.57     | 87.45     |
| Layered performance model  | 182.44    | 189.44    | 204.64    |
| Equivalent monolithic model | 91.22    | 94.72     | 102.32    |

The layered model gives the maximum failure stress values and fully monolithic model gives the minimum failure stress values for the LG samples. The performance of numerical models developed for 8.98 mm thick LG samples are in between the fully monolithic and equivalent monolithic performance models. The structural performances of 10.98 and 12.98 mm thick LG numerical models are very much close to the equivalent monolithic model.

4. Conclusion

The bending responses of two-ply LG beams with resin interlayer are studied by conducting displacement-controlled FPBT. Numerical models are developed in ANSYS and the results are compared with experimental and analytical values. Load-deflection behaviour showed a linear relationship up to the initial failure load. Lamination resulted in residual load carrying capacity and safe failure behaviour. Experimental results highlighted that the resin interlayer, whose elastic properties are much lower than PVB, does not significantly enhance the post-failure response. The structural performances of the numerical models are comparable to that of the laminated glass performance models. The maximum deviation in the failure stress values (obtained for numerical and equivalent monolithic models) is less than 6% for 10.98 mm and 12.98 mm thick specimens, whereas the highest variation for 8.98 mm thick samples is 22%. Thus the equivalent monolithic model showed better performance for LG samples having a higher thickness.
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