Evaluation of Behaviours of Laminated Glass

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Abstract. Visual appearance of building facades and other load bearing structures, which now are part of modern architecture, is the reason why it is important to investigate in more detail the reliability of laminated glass for civil structures. Laminated glass in particular has become one of the trendy materials, for example Apple© stores have both load carrying capacity and transparent appearance. Glass has high mechanical strength and relatively medium density, however, the risk of sudden brittle failure like concrete or other ceramics determine relatively high conservatism in design practice of glass structures. This should be changed as consumer requirements evolve calling for a safe and reliable design methodology and corresponding building standards. A design methodology for glass and glass laminates should be urgently developed and included as a chapter in Eurocode. This paper presents initial experimental investigation of behaviour of simple glass sheets and laminated glass samples in 4-point bending test. The aim of the current research is to investigate laminated glass characteristic values and to verify the obtained experimental results with finite element method for glass and EVA material in line with future European Structural Design of Glass Components code.

1. Introduction

Transparency of glass and apparent lightness of design of glass structures are the reasons why in the 21st century glass is one of the most widely used building materials. However, brittle behaviour without plastic deformation is the negative characteristic that largely restricts application of glass as a material to be used in the load bearing structures.

Initially, glass as a material is obtained in the liquid form then cooled to the rigid state without crystallizing. Raw materials for glass production are 75% silica (SiO₂), sodium oxide Na₂O from soda ash, lime CaO, and several minor additives. In the production process, all ingredients have been heated at the temperature higher than 1200°C [1]. When the molten mass cools, glass gradually passes from being a liquid to a solid without – as it is normally the case with molten products – forming a
regular symmetrical or periodic crystal lattice. Glass is isotropic, i.e. its properties do not depend on direction or orientation [2].

The modulus of elasticity of glass is typically assumed to be 70 GPa, only about a third of that of steel but five times greater than hardwood [3]. Under loading glass shows linear stiffness behaviour where relative strain to the stress is fully linear up to brittle fracture with relatively small scatter between different glass treatment technologies. On the contrary, strength characteristics may depend on glass treatment type. For example, as a reference bending strength of annealed glass is $f_{ck,\text{float}}=45 \text{ N/mm}^2$, heat strengthened glass $f_{ck,\text{heat strengthened glass}}=70 \text{ N/mm}^2$ and tempered glass $f_{ck,\text{thermally toughened glass}}=120 \text{ N/mm}^2$ [4/5].

Laminated glass is a glass unit that consists of at least two panes and one intermediate layer, whereby the panels are boned to the intermediate layer in the manufacturing process [6]. The materials used for the interlayers are polyvinylbutyral (PVB), cast–in-place resin (CIP), ethylene vinyl acetate (EVA) [3]. Full-surface bonding provides many opportunities to modify the mechanical and optical properties of glazing through the selection of the component layers, their sequence and thicknesses. Laminated safety glass remains as one piece when shattered and has an increased residual load-bearing capacity.

2. Materials and methods

2.1. Finite element method (FEM) – numerical solution

To determine the exact behaviour of glass at various loading stages and to verify the obtained test results, commercial finite element method engineering simulation software ANSYS 11.00 was used. In the current research two different models were examined – single glass sheet and laminated glass model, which consisted of three sheets of glass and ethylene vinyl acetate (EVA) film between.

For the annealed single glass sheet model in ANSYS code the 4-node SHELL 181 element has been used. It is a four-noded element with six degrees of freedom at each node: translations in the $x$, $y$, and $z$ directions, and rotations about the $x$, $y$, and $z$ axes [6]. Mechanical parameters, which have been defined for the calculation, were density $\rho=2500\text{ kg/m}^3$, Young Modulus $E=70 \text{ GPa}$ and Poisson’s ratio $\nu=0.23$ [7].

For the laminated glass model in ANSYS code alternative element has been selected to incorporate fully nonlinear behaviour of polymer film, thus nonlinear layered structural 9-node SHELL91 element has been selected. The mechanical properties of the tested glass specimens have been maintained, however, for (EVA) film stress and strain values obtained from test results and shown in figure 2 were used.

![Figure 1](image_url)

Figure 1. (a) Model geometry; (b) FE meshed structure; (c) deformed state.
2.2. Analytical stress analysis

Bending stress can also be calculated with conventional analytical formulas, which formerly established values by testing. Single glass sheets stress calculation was made according to LVS EN 1288-3:2001 [8].

\[
\sigma_{sb} = k \left( F_{\text{max}} \frac{3(L_s - L_b)}{2bh^2} + \sigma_{bG} \right)
\]

where \( b \) – width of the specimen; \( h \) – thickness of the specimen; \( L_s \) – distance between the center lines of the supporting rollers; \( L_b \) – distance between the centre lines of the bending rollers; \( y \) – central deflection of the specimen; \( k = k_s \) – dimensionless factor as function of \( y/h \) (to determine the stress at the middle of the span \( k=1 \)); \( \sigma_{sb} \) – bending strength; \( \sigma_{bG} \) – bending stress imposed by the self-weight of the specimen [8]. Bending stress imposed by the self-weight of the specimen is [8]:

\[
\sigma_{bG} = \frac{3\rho g L_p^2}{4h}.
\]

3. Materials and methods

3.1. Glass 4-point bending tests

Glass samples have been tested in 4-point bending according to LVS EN 1288-3:2001 [8] at Riga Technological University, Institute of Materials and Structures (IMS). For testing the INSTRON 8802 testing machine (figure 3) was exploited. Universal test machine allows conducting tests in tension, compression, bending and fatigue, both statically and dynamically load up to the 250 kN capacity. Glass panel samples of size \( L_p = 1100 \text{ mm} \pm 5 \text{ mm} \) long and \( b_p = 360 \text{ mm} \pm 5 \text{ mm} \) wide were cut from a
single glass plate with a thickness of 8, 10, 12 mm ($h_p$). These were industrially cut on cutting machines and finished by grinding and polishing as required by industry standard for the best quality glass product. The spam length between supports has been assumed to be constant of 1000 mm and distance between the loading points set 300 mm, as shown in figure 3.

Specimens were divides in two groups for tests: simple annealed glass sheets with polishing edges ((glass thickness) mm _AP_ (number)) and annealed laminated glass with two and three annealed glass sheets ((glass thickness)/EVA/(glass thickness)_number).

![Figure 3](image)

**Figure 3.** (a) Single glass sheet sample test (b) laminated glass sample in bending test set up (INSTRON 8802).

4. Results and discussion

During the tests it was observed that the annealed glass comparing with the tempered glass has slightly lower bending strength, however, that does not mean that it cannot be exploited as a load bearing structural material. If annealed glass is part of a laminated glass structure then material properties are sufficient for load bearing strength requirements and acceptable by deflection limitations.

Annealed glass samples have been tested with polished edges, which basically eliminates any possibility of micro cracks. Bending strength of this type of glass samples resulted in load-bearing capacity increment of 1.5 times higher than the same sample without polished edges. As shown in figure 4, the sample collapsed directly beneath loading space and shards are with sharp edges.
Comparing test and numerical results with ANSYS software (table 1), one should note that specimens failed in deflection state in between 1/50 to 1/70 relative to the span length. On the other hand, the ultimate stress state observed during the tests ranged from 40 to 60 MPa. The test results correlate with linear analysis of the numerical procedure.

**Table 1.** Bending tests results.

| Number of test | Failure load $F_{max}$ [N] | Deflection $u$ [mm] | Young’s Modulus $E$ [GPa] | Bending strength $\sigma_{lg}$ [MPa] | Bending strength (ANSYS) $\sigma_{A}$ [MPa] |
|----------------|----------------------------|--------------------|---------------------------|-------------------------------------|-------------------------------------|
| 8mm_AP_1       | 1188                       | 20.3               | 74.5                      | 56.43                               | 55.9                                |
| 8mm_AP_2       | 1137                       | 19.1               | 74.5                      | 54.11                               | 53.3                                |
| 10mm_AP_1      | 1 664                      | 13.4               | 73.8                      | 57.3                                | 57.8                                |
| 10mm_AP_2      | 1 497                      | 13.3               | 73.8                      | 51.7                                | 52.1                                |
| 10mm_AP_3      | 1 709                      | 15.0               | 73.8                      | 58.8                                | 59.4                                |
| 10mm_AP_4      | 2 031                      | 17.9               | 73.8                      | 66.5                                | 70.5                                |
| 10mm_AP_5      | 1 242                      | 11.0               | 73.8                      | 43.2                                | 43.1                                |
| 10mm_AP_6      | 1 609                      | 14.1               | 73.8                      | 55.5                                | 55.9                                |
| 12mm_AP_1      | 2935                       | 14.1               | 72.6                      | 60.9                                | 61.4                                |
| 12mm_AP_2      | 2904                       | 14.0               | 72.6                      | 60.3                                | 60.7                                |

The main aim of the laminated glass is to hold glass shards after initial brittle failure of outer plies. Permanent connection of two or more single pane glasses with sticky, elastic, highly tear-resistant foils (EVA) makes a multi-functional element from the glass, which can handle high static forces and constructive tasks in addition to its given transparency. The safety effect of the laminated safety glass is based on the extremely high tensile strength of the interlayer and its excellent adhesion to the adjacent glass surface [10]. In terms of mechanical stress such as shock, impact or influence from other forces breaking the glass, though, the fragments adhere to the interlayer so that the laminated safety glass will usually retain its stability under load [10]. The failure of a laminated glass sheet can be subdivided in five phases:
1. Elastic behavior of the glass plies/sheets.
2. The breakage of the first glass ply, however other plies are still intact; the interlayer is not damaged.
3. The breakage of the second glass ply; the interlayer stops behaving elastically.
4. The interlayer behaves plastically; the splinters are kept together by the interlayer.
5. The interlayer fails by reaching its failure strength or by cutting from the splinters [11].

Laminated glass test consisted of 4 series of samples (table 2). For finite element model, combination of two elements – shell and solid – was used. The same model was used by Sun et al. [12] for modelling the failure behaviour of windscreens. Solid element represents EVA interlayer, which use hyper elastic law.

| Number of test | Thickness $h_i$ [mm] | Failure load $F_{max}$ [N] | Deflection $u_f$ [mm] | Deflection (ANSYS) $u_A$ [mm] |
|----------------|----------------------|---------------------------|----------------------|---------------------------|
| 4/EVA/4-1      | 8.42                 | 1151                      | 18.3                 | 19.78                     |
| 4/EVA/4-2      | 8.39                 | 1245                      | 19.4                 | 21.33                     |
| 4/EVA/4-3      | 8.26                 | 1244                      | 19.1                 | 21.31                     |
| 4/EVA/4-4      | 8.31                 | 843                       | 13.1                 | 14.71                     |
| 4/EVA/4-5      | 8.27                 | 1446                      | 22.7                 | 24.64                     |
| 4/EVA/4-6      | 8.32                 | 1206                      | 19.1                 | 20.69                     |
| 4/EVA/4-7      | 8.31                 | 868                       | 13.5                 | 15.11                     |
| 4/EVA/4-8      | 8.41                 | 979                       | 15.3                 | 16.95                     |
| 5/EVA/5-1      | 10.39                | 1706                      | 14.2                 | 14.95                     |
| 5/EVA/5-2      | 10.35                | 2263                      | 18.6                 | 19.65                     |
| 5/EVA/5-3      | 10.41                | 1726                      | 14.4                 | 15.11                     |
| 5/EVA/5-4      | 10.37                | 1380                      | 11.4                 | 12.19                     |
| 5/EVA/5-5      | 10.42                | 1914                      | 15.8                 | 16.70                     |
| 5/EVA/5-6      | 10.36                | 1735                      | 14.4                 | 15.19                     |
| 5/EVA/5-7      | 10.31                | 1373                      | 11.3                 | 12.13                     |
| 5/EVA/5-8      | 10.35                | 1361                      | 11.1                 | 12.02                     |
| 6/EVA/6-1      | 12.38                | 2375                      | 11.7                 | 11.99                     |
| 6/EVA/6-2      | 12.36                | 3259                      | 16.2                 | 16.32                     |
| 6/EVA/6-3      | 12.36                | 2775                      | 13.3                 | 13.95                     |
| 6/EVA/6-4      | 12.45                | 2034                      | 9.9                  | 10.32                     |
| 6/EVA/6-5      | 12.38                | 1401                      | 6.8                  | 7.22                      |
| 6/EVA/6-6      | 12.55                | 1622                      | 8.0                  | 8.30                      |
| 6/EVA/6-7      | 12.53                | 2438                      | 11.9                 | 12.31                     |
| 4/EVA/4/EVA/4-1| 12.71                | 2076                      | 10.4                 | 9.98                      |
| 4/EVA/4/EVA/4-2| 12.81                | 2426                      | 12.1                 | 11.61                     |
| 4/EVA/4/EVA/4-3| 12.76                | 2730                      | 13.7                 | 13.02                     |
| 4/EVA/4/EVA/4-4| 12.76                | 2200                      | 11.2                 | 10.55                     |
| 4/EVA/4/EVA/4-5| 12.76                | 2473                      | 12.6                 | 11.83                     |
| 4/EVA/4/EVA/4-6| 12.82                | 2706                      | 13.7                 | 12.91                     |
| 4/EVA/4/EVA/4-7| 12.74                | 3235                      | 16.6                 | 15.37                     |
The observed physical behaviour confirmed that glass laminate in 4-point bending test is perfectly linear (figure 5, 6). Figures 5 and 6 show that all laminate sample deformation levels up to 1/65 of the span numerically around 15 mm, however, it should be noted that ultimate load was varying. Two ply 4 mm glass laminate breaks at 1.1 kN where 5 mm at 1.9 kN and 6 mm at 2.2 kN high load (figure 5). Three layer laminate has higher result and breaks at 2.5 kN (figure 6).

After testing and visual observation of the specimens, one can observed that for two layer laminate glass first breaks in the tension zone. However, for three ply laminate both two bottom layers break instantly and that means that for load bearing structures just two glass layers are designed.

![Figure 5. Experimental data for two layer samples (a) 4/EVA/4 laminate, (b) 5/EVA/5 laminate.](image)

![Figure 6. Experimental data for two and three layer samples (a) 6/EVA/6 laminate, (b) 4/EVA/4/EVA/4 laminate.](image)
5. Conclusions
In the present article it has been confirmed that the laminated glass has several advantages compared with the conventional glass sheets, for example, higher durability in bending and the interlayer insure that shards are kept together after the laminate collapse. A verification study confirmed that material properties implemented for nonlinear simulation of polymer films show good agreement with larger scale physical tests. One should note that different shell element types in commercial code ANSYS have been utilised for conventional glass sheet and laminate simulation. Test results confirmed that there is at least four times the safety margin if specimens are designed for bending according to deflection limit of 1/250 compared to the span length. More detailed evaluation is foreseen to estimate the reasons for relatively high strength value scatter.

6. References
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