Post-Failure Behavior of Point-Fixing Laminated Glass Plates under Out-of-Plane Uniform Pressure

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Abstract

This paper presents the results of an experimental and numerical investigation of the mechanical response of undamaged and damaged 2-ply laminated glass plates. Two types of glass plies, thermally toughened and heat-strengthened, coupled with SentryGlas (SG) were considered. Laminated glass plates supported with articulated point fixing bolt under out-of-plane uniform pressure were investigated under four different damage configurations: (i) undamaged; (ii) partially damaged, with the bottom ply broken; (iii) partially damaged, over-flipping the specimen of mode II; (iv) both two glass plies broken, which was applicable for LG plates made by heat-strengthened glass. In the above four modes, the top ply is always subjected to compression while the bottom one is in tension. The different responses of each configuration (different glass types and damage modes) were discussed and compared in this study. In addition, numerical models were adopted to reproduce the experimental results. The influence of the hitting location and glass types on the mechanical behavior of LG plates was analyzed. The results showed that the contribution of the broken glass ply could not be disregarded in the evaluation of the global stiffness of partially damaged LG plates and their bearing capacity.

Keywords

Laminated glass plates, Thermally toughened and heat-strengthened glass, Post-failure behavior, Point-fixing, Numerical modelling.

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1. Introduction

The development of the whole architectural history manifests the pursuit of aesthetics by a human being. Among all building materials, glass has always been a wonderful and magic material, which fascinates both designers and the collective imagination (Piscitelli 2018). However, due to the intrinsic brittleness of glass, the use of monolithic glass as a structural material can not meet the requirement proposed by the fail-safe approach. Therefore, laminated glass (LG), manufactured by bonding two or more glass layers with films of polymeric interlayers under specific temperatures and pressure, has been developed.

Laminated glass is widely employed for plates, subjected to out-of-plane loading are often employed for floors, roofs, balustrades, or façades (Wurm 2007). Several studies have been carried out to investigate the mechanical behavior of laminated glass plates (Foraboschi 2012; Galuppi et al. 2012; Castori et al. 2017; Vedrtnam et al. 2017; Biolzi et al. 2022a; Biolzi et al. 2022b;). However, they are only focused on the simply-supported boundary conditions and mid-span loading. The effect of the point-fixing condition on the mechanical behavior of LG plates can differ from that under simply-supported boundary conditions. High local stress occurs at the edge of drilled holes if LG plates supported by point-fixing. Previous researches have been carried out to investigate the stress distribution of point-fixing connections (Seel 2016; Beyer 2007;) and the in-plane behavior (Maniatis 2006). However, researches on the effect of point-fixing conditions and out-of-plane uniform pressure on the behavior of LG plates are missing. This has, to the best of the authors' knowledge, not been presented in literature before. Thus, this study is an attempt to overcome this gap by experimentally investigating the post-failure behavior of point-supported laminated glass plates under out-of-plane uniform pressure.

In this paper, the post-failure response of 2-ply point-supported LG plates under out-of-plane uniform pressure was experimentally investigated at different test configurations. Two types of glass plies, thermally toughened and heat-strengthened, coupled with SentryGlas (SG) were considered. The experimental findings were simulated and compared with finite element (FE) analyses. The present research indicates that the post-failure behavior of point-supported LG plates under out-of-plane uniform pressure is dependent on the glass types, and the hitting location. It is emphasized the importance of the post-failure behavior of the glass elements which is directly connected to interlayer, and glass types (Galuppi et al. 2020).

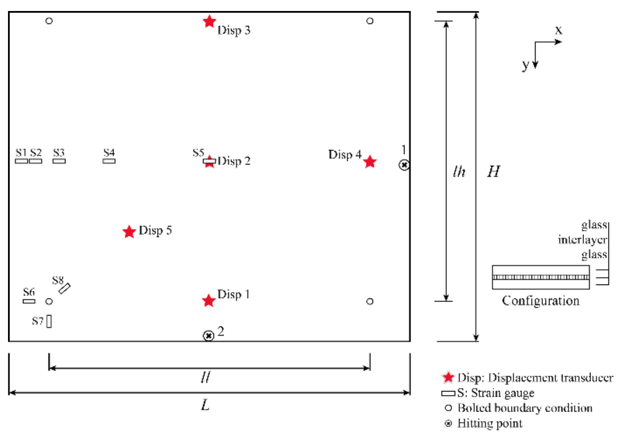
2. Material and Test program

2.1. Materials and specimens

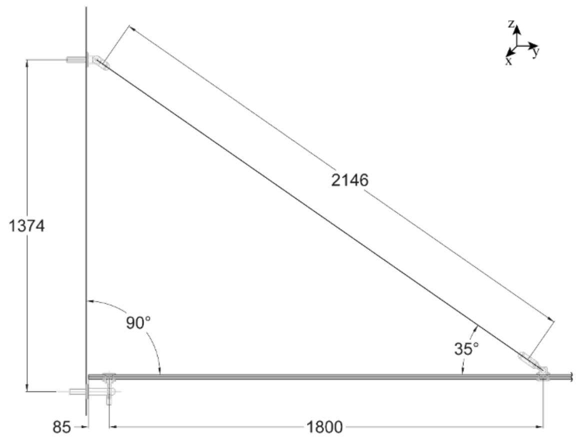
Experimental tests were carried out on point-supported LG plates. The specimens were manufactured by 2-ply 10mm-thickness glass with a 1.52mm-thickness polymeric film (SG), with a length of $2200\ \mathrm{mm}$ and a width of $2085\ \mathrm{mm}$. The thickness of $10\ mm$ of the glass plies is to be intended as the nominal thickness. The actual thickness was evaluated with a caliper, repeating the measure on at ten different points, showing a difference between the actual and the nominal value less than 5%. The total four specimens can be divided into two groups: (i) 2-ply thermally toughened glass; and (ii) 2-ply heat-strengthened glass; The details of the specimens are shown in Table 1 and Figure 1.

Table 1: The details of specimens.

Specimen Tag	Glass type	Glass thickness	Size of the laminated glass plates			
			lh	ll	L	H
[-]	[-]	[mm]	[mm]	[mm]	[mm]	[mm]
Temp10-A1	Thermally toughened	10	1800	1800	2200	2085
Temp10-A2		10	1800	1800	2200	2085
Ind10--A1	Heat-strengthened	10	1800	1800	2200	2085
Ind10—A2		10	1800	1800	2200	2085



Details of specimens



Sketch of the test setup

Photo of the test setup

Fig. 1: Specimen and test program.

2.2. Test program

Experimental program

LG plates were supported with articulated point fixing bolts under out-of-plane uniform area pressure (as shown in Figure 1b &c). The coordinate axes are defined in Figure 1b, where the 'x', 'y', and 'z' axis are along with the direction of length, width, and thickness. The four articulated point fixing bolts can rotate around the 'y' axis. An area pressure of $1\mathrm{kN/m^2}$ was applied by sandbags on the top surface of the LG plates. The area pressure was held for at least 15 mins. The deformation of the specimens was captured by five draw wire sensors (SX50 Series, WayCon Positionsmesstechnik GmbH, Germany), and eight strain gauges (as shown in Figure 1a).

The mechanical response of undamaged and damaged 2-ply laminated glass plates was investigated in this study. Different loading scenarios were characterized as follows:

- Configuration 0, vertical area pressure ($1\mathrm{kN/m^2}$) was loaded on the undamaged LG plates, with the total applied load equal to 459 kN;
- Configuration I, vertical area pressure ($1\mathrm{kN/m^2}$) was loaded on the LG plates with the bottom ply broken, with the total applied load equal to 459 kN;
- Configuration II, overflipping the deformed shape obtained after the tests on Configuration I, vertical area pressure ($1\mathrm{kN/m^2}$) was loaded on the LG plates with the top ply broken, with the total applied load equal to 459 kN;
- Configuration III, vertical area pressure ($1\mathrm{kN/m^2}$) was loaded on the LG plates with both plies broken, with the total applied load equal to 459 kN;

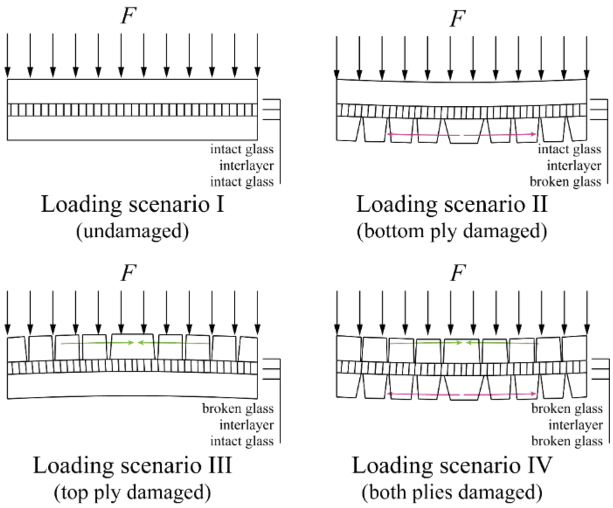


Fig. 2: Loading scenarios.

It should be noted that the Configuration III was only conducted on the specimens manufactured by heat-strengthened glass. LG plates made by thermally toughened glass lost the bearing capacity in the case of both glass plies broken.

Numerical modelling

Finite element modelling is recommended by Guidance for European Structural Design of Glass Components (Feldmann, M et al. 2014) to investigate the performances of point-fixing LG plates. In this study, the mechanical behavior of LG plates with 'Configuration 0' was simulated by the common commercial finite element (FE) software ABAQUS. There are three main aspects to be considered to simulate the mechanical behavior of LG plates. These components are listed as follows: (i) material models of laminated glass plates; (ii) finite element type and mesh; (iii) the boundary conditions and the load application;

The material properties of glass and interlayers are mentioned in the paper published by previous researches (Biolzi et al. 2010; Zhou et al. 2023). In this study, the glass was modeled using 8-node linear brick, incompatible elements (C3D8I). Owing to its removed shear locking and much reduced volumetric locking, linear elements in C3D8I can be subjected to bending. In addition to improving the simulation efficiency, such elements can simulate the deformation of the specimen as accurately as possible. The fine mesh size was 10 mm in the transverse and thickness direction, and 20 mm in the longitudinal direction. An 8-node three-dimensional cohesive element (COH3D8) was applied to model the behavior of PVB. Considering the LG plates are in the elastic deformation region during the whole tests, a finite-thickness adhesive layer model was used, based on a continuum-based constitutive response. The cohesive element connected two neighboring glass piles and they have matched meshes. As a result, they are connected by sharing nodes. The point-fixing boundary conditions are built following the experimental situation. The verification of the finite element model was conducted against with the experimental results.

3. Results

The responses of LG plates with different configurations are presented in this section. The deformation at the location of 'Disp1' (Figure 1a) is chosen as the representative value due to the fact that the displacement at this point is always the largest among all the monitored points (as shown in Figure 3 & Figure 8). It would be conservative to predict the load-bearing capacity when taking the deformation at the location of 'Disp1' into consideration, which would lead to a safer design approach.

Considering that the loading process is accomplished by sequentially adding sandbags, the resulting load-displacement curve exhibits a sawtooth pattern. To better represent this curve, a quadratic curve fitting technique has been employed to smooth the data through optimization. Figure 4 shows the comparison between the original and the fitted data, and it indicates that the fitted curve is consistent with the experimental results. It should be mentioned that the deformation data presented in the following sections has been processed through optimization.

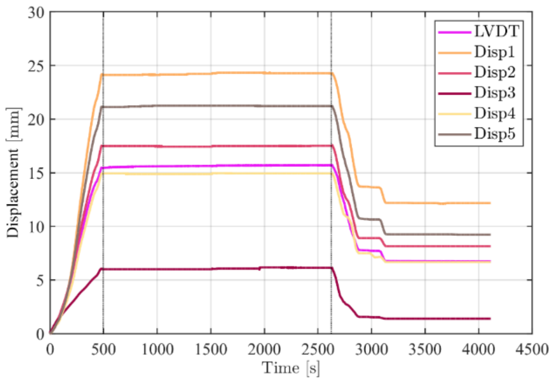


Fig. 3: Time history of deformation of Temp10-A1 with Configuration 0.

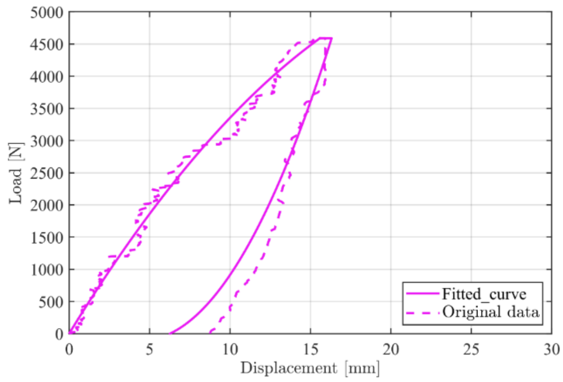


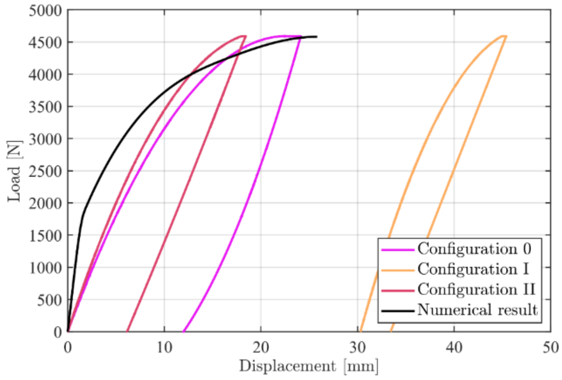
Fig. 4: Comparison between the original and the fitted data.

3.1. Load-displacement relationship

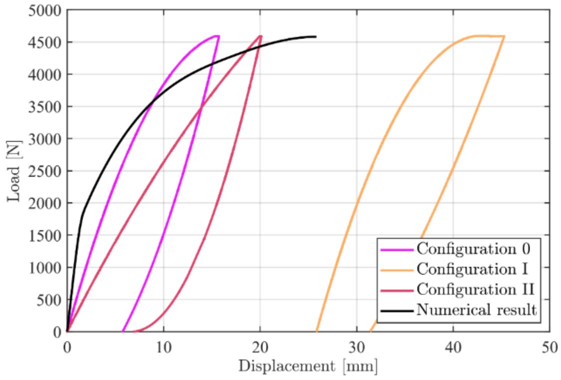
The load-displacement relationship of point-fixing laminated glass plates under out-of-plane uniform pressure is shown in Figure 5. The damage modes are shown in Figure 6 and Figure 7. The fitted model can well characterize the mechanical performances of LG plates. The maximum deformation (d_{max}) corresponds to the total applied load ($459\ \mathrm{kN}$), and the residual deformation (d_{res}) after removing the load are reported in Table 2. It should be noted that the curves of Configuration 0 and Configuration II start from the origin (0,0), while others from the residual deformation after breaking the glass ply.

Figure 5 indicates that: (i) the stiffness of LG plates manufactured by heat-strengthened glass is always larger than those made by thermally toughened glass, whether undamaged or damaged; (ii) the stiffness of broken LG plates is dependent on the hitting (breaking) location. The stiffness of broken LG plates with the hitting point at 'A1' is larger than that with the hitting point at 'A2'; (iii) the stiffness of broken LG plates can be larger than that of undamaged ones, this could be explained by the redistribution of internal stress in broken thermally toughened glass (Figure 6) and the interaction between glass shards in broken heat-strengthened glass (Figure 7).

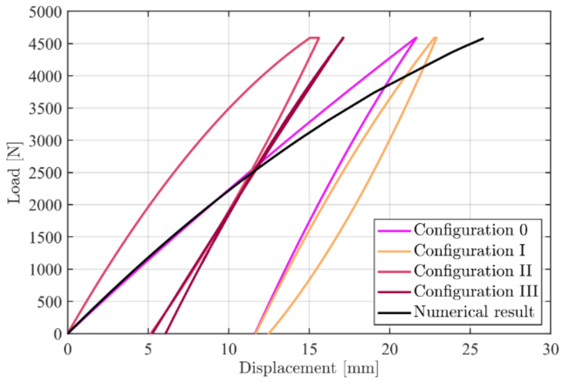
The deformation contour of LG plate is obtained through numerical simulation and shown in Figure 8. The maximum deformation happens not at the center but at the outer edge furthest from the support. This is consistent with the experimental results shown in Figure 3, which indicates the numerical simulation can well characterize the mechanical behavior of point-fixing laminated glass plates under out-of-plane uniform pressure. Figure 5 Relationship between load and displacement



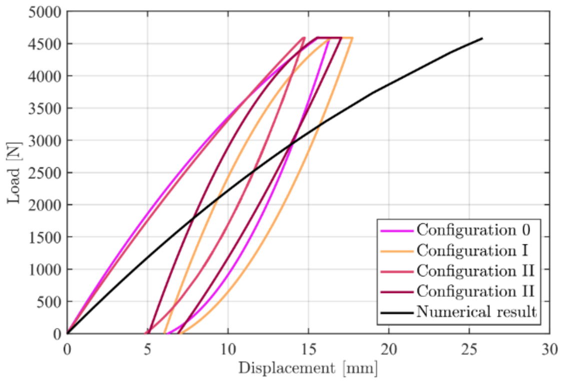
Load vs. Displacement of Temp10-A1



Load vs. Displacement of Temp10-A2



Load vs. Displacement of Ind10-A1



Load vs. Displacement of Ind10-A2

Fig. 5 Relationship between load and displacement.

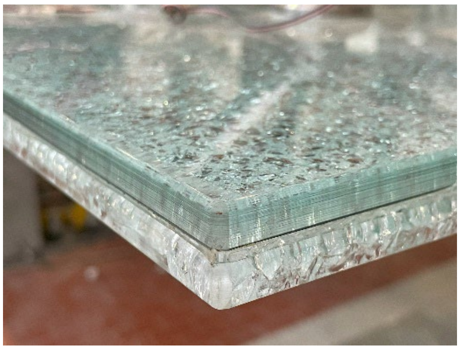
Table 2: Experimental results obtained on LG plates.

Specimen Tag	Configuration 0		Configuration I		Configuration II		Configuration III	
	$d_{max,0}$	$d_{res,0}$	$d_{max,I}$	$d_{res,I}$	$d_{max,II}$	$d_{res,II}$	$d_{max,III}$	$d_{res,III}$
[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
Temp10-A1	24.12	11.99	45.38	33.42	18.44	6.14	-	-
Temp10-A2	15.74	5.78	45.28	31.38	20.15	6.82	-	-
Ind10--A1	21.66	11.63	22.91	12.48	15.61	5.16	17.12	6.08
Ind10—A2	16.31	6.26	17.73	7.05	14.77	4.86	17.04	6.89

3.2. Post-failure behavior

The slope of the load-displacement curve can be an index to characterize the stiffness of the LG plates (Biolzi et al. 2022a; Biolzi et al. 2022b;). A summary of the results of test configurations is depicted in Figure 9. The results indicate that the hitting (breaking) location on the glass ply has a great influence on the LG plates made by thermally toughened glass, but not much on LG plates made of heat-strengthened glass. This could be explained by the internal stress restored in thermally toughened glass, which would redistribute upon the breakage happens. Different hitting point would lead to different stress trajectories across the interlayer. On the other hand, the internal stress in the heat-strengthened could be negligible, therefore the hitting point has little effect on its post-failure behavior.

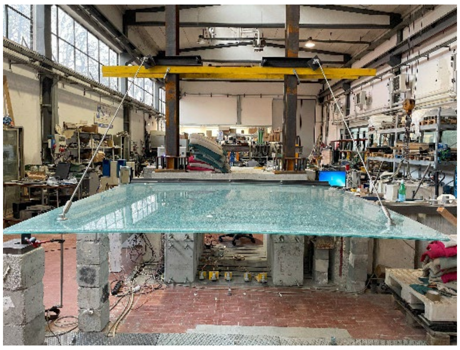
The post-failure behavior of point-fixing LG plates under out-of-plane uniform pressure is also associated with the glass types. The stiffness of LG plates made by heat-strengthened glass is always larger than that made by thermally toughened glass. The larger glass fragments of the bottom layer lead to better performance due to its stronger tension-stiffening effect (Zhao et al. 2019).



Lateral view of Configuration I

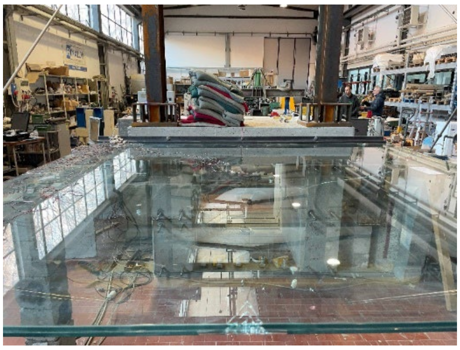
Overview of Configuration I

Top view of Configuration II



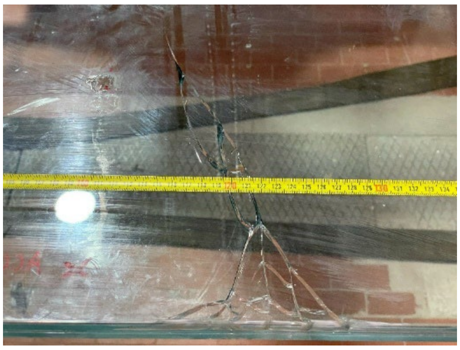
Overview of Configuration II

Fig. 6: Failure modes of thermally toughened glass.



Overview of Configuration I

Details of the crack



Overview of Configuration II

Overview of Configuration III

Fig. 7: Failure modes of heat-strengthened glass.

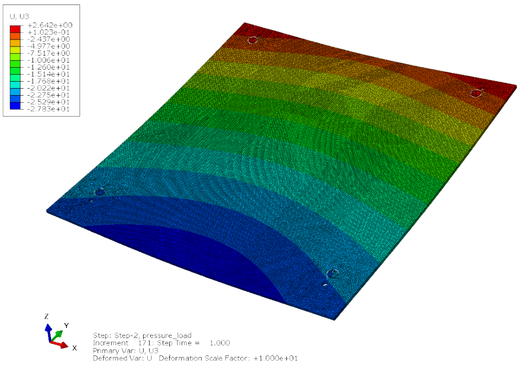


Fig. 8: Deformation contour of LG plate.

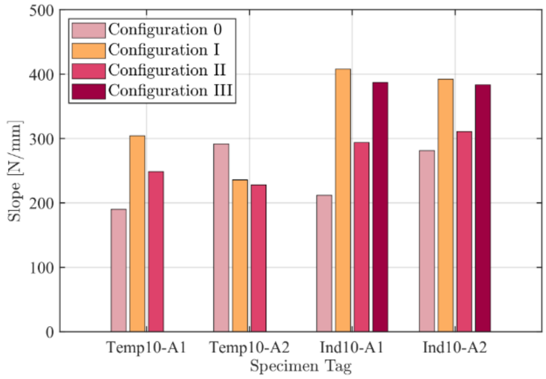


Fig. 9: Comparison between slope of the force–displacement response of the considered specimens.

4. Conclusions

In this study, the post-failure behavior of point-fixing laminated glass plates under out-of-plane uniform pressure is investigated by experimental tests at different test configurations. The numerical simulation is also conducted to characterize the deformation contour of LG plate. The experimental results including load-displacement relationship and post-failure behavior were analyzed and discussed. The post-failure behavior of LG plates is characterized by stiffness. The post-failure performance is dependent on the glass types, and the hitting location. Finally, it can be remarked that further studies will be carried out through numerical results to investigate the effect of glass thickness, interlayer thickness, and size effect on the post-failure behavior of LG plates.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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