NON-LINEAR ANALYSIS WITH EXPERIMENTAL INVISTIGATION OF BENT GLASS CURTAIN WALLS.

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ABSTRACT

Although bent laminated glass has been utilized recently in constructing buildings, the curves at ASTM E1300 do not display its design. Designers now have to utilize a base for these kinds of glass curtain walls. As far as authors are aware, no one has done a thorough analysis of bent laminated glass LG. Thus, experimental and theoretical results for pressure-loaded Non-Linearly bent laminated glass panes are provided and explored in this study. Four Bent Glass Panes with different thicknesses were experimentally tested for failure under pressure load. Utilizing the Abaqus software, finite element analysis (FEM) was performed to compare the experimental data. In order to identify appropriate element types and supporting conditions that the experimental model might performed; a numerical analysis was carried out using the ABAQUS 6.14 program. The test panel was attached to a sealed chamber that the authors constructed and silicone-glued. To simulate a positive pressure on the test panel's outside, the chambers inside air was sucked out. The tested system had a displacement transducer and strain gauge attached to detect the displacement and strain when the chamber's pressure decreased. The element that can most closely resemble a thin Bent glass light is the shell element. This experimental study's outcome serves as a document for. The result from this experimental study provides paper for non-linear bent laminated glass for further investigations and developments on such type

Keywords: Bent Glass pane, pressure load, finite element, displacement, displacement transducer, and strain gauge.

1. INTRODUCTION

The ASTM International Standard E1300 (ASTM, 2016) [1] is consulted by architectural glass designers in the US and numerous other nations. ASTM International released the most recent edition of ASTM E1300 in 2016. The ASTM (2016) [1] methodology is limited to glass constructions that are rectangular flat. A nonlinear finite difference analysis model described in Vallabhan (1983) and Vallabhan and Chou (1986) [2] is the stress analysis technique utilized to develop ASTM (2016). Because of the necessary cutting resources, Vallabhan and Chou (1986) [3] suggested using a finite difference methodology to accomplish the finite element method. The techniques for carrying out nonlinear finite element analysis have greatly advanced. Since the results were published, nonlinear finite element analysis techniques have seen substantial development. Engineers can now utilize widely-used finite element software to analyze stresses and deflections in glass panels, thanks to the analysis approach introduced by ASTM (2016). For a flat rectangular glass lite, a flat deformed glass lite, and a curved glass lite, the authors developed nonlinear finite element models. They then applied a glass failure prediction model (GFPM) to the model output. The author determined the LR and probability of failure.

The aim of this research is to examine how compressive loads affect curved glass panes that are utilized as curtain walls. The nonlinear analysis of curved laminated glass LG is presented in this article. The thickness of 6 mm was the only thickness examined in previous researches. Yet, the author of this paper displays other thicknesses of 12 mm, 16 mm, and 20 mm, with two layers of glass and a 1.52 mm thick PVB interlayer in between. To ascertain the failure probability and load capacity (LR) of curved glass panes, the authors created a nonlinear finite element model and applied the glass failure prediction model (GFPM) to the nonlinear finite element model's results. The authors present experimental results on full-sized curved glass measured using strain gauges. The advancement of glass cracks and the start of impact damage are essential to the failure process. under the influence of a glass-like rigid body. As a result, patterns of defects have been found, and models have been developed to forecast how resistivity would affect this particular kind of glass in engineering applications. The author will next demonstrate how to use FEM Abaqus to apply the GFPM and produce an analysis of a curved glass lite. Next, the LR of the curved glass pane is calculated and compared, showing how the strength of the curved glass structure increases as panel thickness increases.

2. Literature review

Laminated glass is so resilient that it can take several impacts without breaking. Even with extremely powerful blows, the PVB interlayer keeps the glass in place and inhibits forced penetration. A literature review shows that many studies have been conducted on its effectiveness. However, failure study of monolithic and composite glasses utilized in constructions. Large-scale, low-velocity projectile strikes are relatively rare.

Using available finite element software, James G. Soules, MSCE (2020) [4] demonstrated modeling curved glass lite and subsequently provided a comparison of analytical results for curved glass lite with experimental data from strain gauges. He then demonstrated how to use his GFPM—which was created by Beason et al. (1984) [5] to analysis results of a curves glass lite. In order to show how much stronger the curved glass structure than the flat glass structure, the LR of the curved glass lite is calculated and compared to the Load Resistance of flat glass with the same plan dimensions of the bent glass pane.

Levy's [6] non-linearity formulation analysis of simply supported pane without in plane edges response does not apply to glass panes. El-shami et al. [7] produced a FE model for a nonlinear of a monolayer rectangular glass pane that can process thin and thick lite. Philip, M. [8] created an analysis method for researching curved pane elements. The theory development procedures are scripted and abstracted to run on a basic visual platform in order to perform numerical analysis. Asik, M.Z., Tezcan, S., [9] also developed a numerical model of LG for design that is safer. The output of this model is compared with that of the experimental model and the finite element model. Fildhuth and her Knippers [11] succeeded in that endeavor, producing a whole glass shell composed of bent (hot or cold) glass. They focused on the geometry, the bonding of all-glass panels, and the interaction of glass components and structures.

The nonlinear behavior of lite-shell structures for different parameters was studied by Bagger [12]. Facet size, flaws, and connection properties are a few examples. In 2004, Feraboli and Kedward [13] conducted some experimental research to ascertain the velocity response of composite panels. Numerous research included in the discussion claim that this difficulty resulted from the range of several experimental samples investigations and the assessment of their impact evaluation.

The Composite Structural Impact Performance Assessment Program (CSIPAP) was created more recently by Feraboli and Kedward (2006) [14] to assess the impact performance of composite structures that are subjected to repeated impacts. Critical impact pressure, energy dissipation, time, and contact coefficient recovery are among the characteristics that this software considers.

Ivanov (2006) [15] published a FE model of a Laminated glass lite. In the model, the strain and stress curve throughout the thickness of the pane and along its axis was resulting of linear FEM analysis. Also, He developed a numerical model for triple-glazed beams matchmaking with a bending differential curvature equation and the PVB interlayer shear interaction differential equation.

In 1999, Duzer et al. [16] introduced a strong model for LG stress analysis. They modeled layers and their interactions using his 3D solids. A viscoelastic linearity model used for the PVB layer. There was a debate on the behavior and intensity of LG beams by Norville et al. (1998) [17]. In their discussion, they pointed out that as compared to monolayer glass panes, LG beams have superior bending strength at a variety of thicknesses. They noted in their discussion that LG beams have higher bending strength at many thicknesses compared to monolayer glass pane. This is clear because LG pane is thicker than monolayer glass in almost all nominal glass thickness specifications. Also, they discovered that monolayer glass of the same dimension as laminated glass does not represent the upper limit of strengthing laminated glass.

A numerical model for composite glass lite based on non-linear strain-displacement relationships was recently presented by Asik and Tezcan (2005) [18]. Using this model, the linear and nonlinear behaviors of a triple glass substrate were examined in relation to LG pane's behavior.

Due to the lack of information available on the exact method to calculate the load Resistance LR of bent glass, there is need for more investigate the effect of pressure loads on bent glass panes with various thickness used as curtain walls. This article presents the nonlinear analysis of bent laminated glass LG.

3. Experimental Work

Four Bent LGs with rectangular dimensions 1000 x 1000 mm, glass thicknesses 12 mm, 16 mm, 20 mm, glass Poisson's ratio V = 0.22, modulus of elasticity E = 70 Gpa. The measured thickness of the

LG was 13.52 mm, 17.52 mm, and 21.52 mm. The inter -layer was made of PVB with a thickness of 1.52 mm. Operation under uniform pressure load with simple support in all planes. Comparing with experimental data, the shear modulus of PVB was assumed to be G_{INT} = 690 kPa.

A four bent glass lite were tested to simulate a bent LG lite. The lite has dimensions of (1,000×1,000×13.52) mm and a radius of curvature of 934.6 mm as shown in Figure. (1).

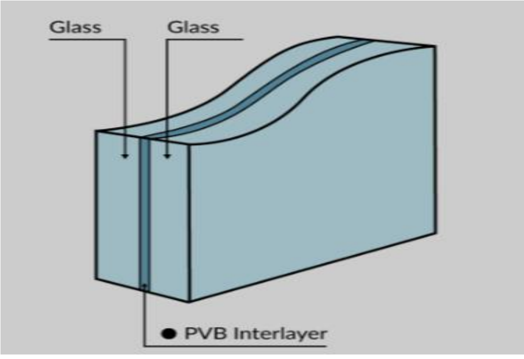

Figure 1 Laminated glass (LG)

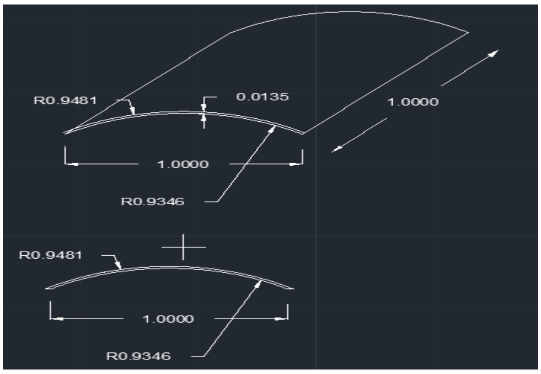

Figure 2 Geometry of Laminated Glass lite.

The closed chamber was prepared in a workshop at the Department of Industrial Engineering, Faculty of Engineering, Menoufia University. A steel lite with the same angle size (60 x 60 x 5) mm and a thickness of 4.0 mm is used to construct the chamber. Figure (3) shows the dimensions and cross section of the chamber. Steel lites were cut to the required size and welded using fillet welding to form the chamber. I reinforced it by welding two horizontal angles to the ends. The final chamber shape is shown in Figure (3). Generate negative pressure in the glass, make a 12mm diameter hole on the side of the chamber body as shown in the photo, and sucked out the air inside through the ejector.

Structural silicone was used to attach the glass lite to the chamber. Figure (4) shows the arrangement of displacement transducers and strain gauges to measure the strain at different points on the test lite. Five strain gauges were installed and two linear variable differential transformers (LVDTs) were installed in the center and quarter spans. The pressure inside the chamber was measured with a pressure transducer. The above device was connected to a data acquisition system called National Instruments LabVIEW 2014 F1 x64 Figure (5) for measurements. Figure (6) shows the test setup and test equipment

Figure 3: Chamber preparations.

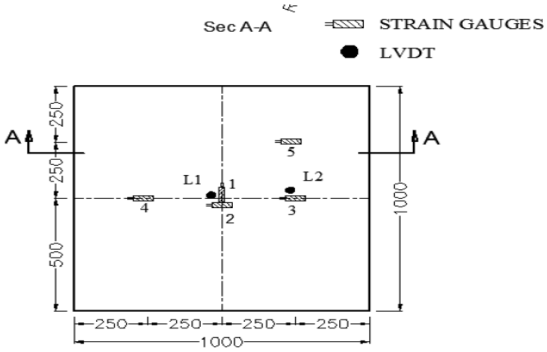

Figure. 4: Measuring devices locations

Figure 5: The position of strain gauges and displacement transducer

Figure. 6: The National Instruments LabVIEW 2014 F1 x64 deceive & Dial Gigue

The tested lites ID and the description of each specimen are illustrated in Table 1. All dimensions, in mm.

Table 1: Bent Glass Lite Description.

No.	Bent Glass ID	Description
1	T6-1	First specimen Laminated Bent Glass lite with two layers of Glass thickness of 6 mm and a PVB with thickness1.52 mm
2	T6-2	Second specimen Laminated Bent Glass lite with two layers of Glass thickness of 6 mm and a PVB with thickness1.52 mm
3	T8	Third specimen Laminated Bent Glass lite with two layers of Glass thickness of 8 mm and a PVB with thickness1.52 mm
4	T10	Fourth specimen Laminated Bent Glass lite with two layers of Glass thickness of 10 mm and a PVB with thickness1.52 mm

Lite specimen loading started from zero load and the dial gauges readings were recorded. The pressure increased gradually and the readings of the three dial gauges were taken for each load step until Bent lite failure. Bent lite capacity till failure was noticed until the lite could not resist. Two LVDT gauges were placed at the top to read the axial deformation of lite under compression Figure. 5. The first LVDT gauge was at the center, the second was at the quarter of the lite. The average of these recorded readings was calculated to give the total axial displacement due to the pressure. For each LVDT gauge, the reading at every loading stage was recorded and the axial extracting was calculated by subtracting the values from the initial reading of the LVDT gauge (before loading). To get precise results, the axial extracting was calculated for each LVDT gauge. The behavior of the test specimens was observed throughout the testing. Table 2 summarizes the test results.

4. Finite Element Modeling

The dynamic manifest module and ABAQUS package 6.10 are present in both glazing variants. Laminated glass and PVP used it to model and simulate compressive loads. Optional 3D finite element models were created using the integrated ABAQUS/CAE graphical interface module.

- The author chose to use a Shell Extrusion element for modeling bent LG panes in FEM. The shell element is recommended for thin shells which the smallest shear deformation. The element the author used allows for improving convergence and eliminates the errors of shear lockup.
- Create Shell Composite Section with multi layers.
- The bent glass lite is symmetrically at the two axis and simple supported on the four edges.
- Figure 7 shows the edge boundary conditions model. Figure 8 showed Mesh of laminated glass plate with PVB inter. The edge conditions are used for developing model for a bent LG lite simply supported edges. the boundary edge conditions were developed to simulate results of the bent LG test samples.
- The model material properties should be elastically, isotopically material with Young's Modulus of 70 GPa and Poisson's Ratio of 0.22.
- The nonlinearity geometric FE functionality should be on with an appropriate increment.
- The model units used in this model was MPa for the uniform pressure load, and Young's Modulus. Glass pane unite dimensions were millimeters.

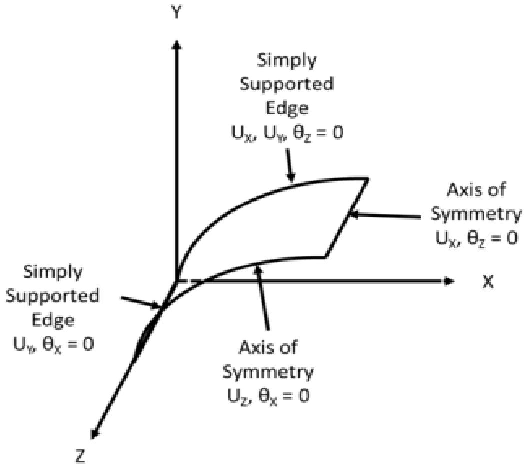

Figure: 7 Boundary Conditions used in Analysis

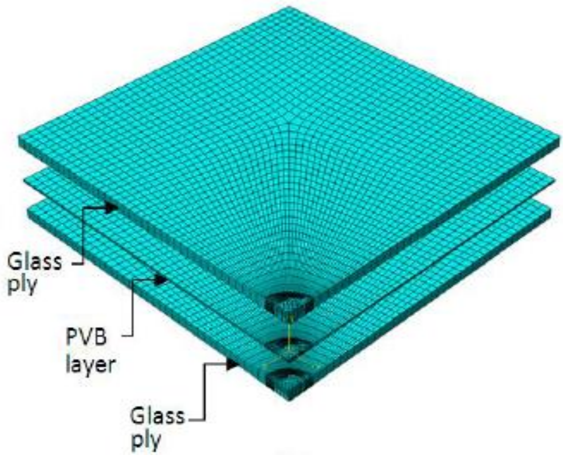

Figure 8: Mesh of laminated glass plate with PVB inter layer

Laminated glass lite are used in two separate portions of this study. viewed and made a interlayer for PVP. The glass lite or PVP interlayer was modeled using the deformable option. glass lite with lamination 1000 mm x 1000 mm in planning.

The single layer monolithic glass panels have a thickness of 12mm, 16mm and 20mm respectively, with upper, and lower glass laminated. The glass layer thicknesses were 6 mm, 8 mm, and 10 mm. The thickness of the PVB interlayer is 1.52mm.

Briefly, the authors treat the bent LG lite with simply supported edges that is subjected to lateral loads. modeled. A thin curved glass lite will undergo a large lateral deflection depending on the thickness of the lite when subjected to a lateral load. Due to the membrane effect, large deflections because of tensile or compression strain in the central of the bent glass lite, according to the direction of the pressure. strain in the membrane due to bending was combined with tensile and compressive stresses in the outer fibers. The bent LG lite is stiffer than linear elastic theoretical predicts, resulting in geometrically nonlinear load-deflection and A load-strain relationship curves.

Bent LG panes are supported at steel model that use neoprene or similar gasket material to hold the glass to the steel model. This technique of attachment presented.

The bent LG edge of the glass pane allows deformation on the upper surface tangent to the curvature of the bent LG lite, without surface resistance occurs on the tangent of curvature, so it is caused tension or membrane strength depending on the direction.

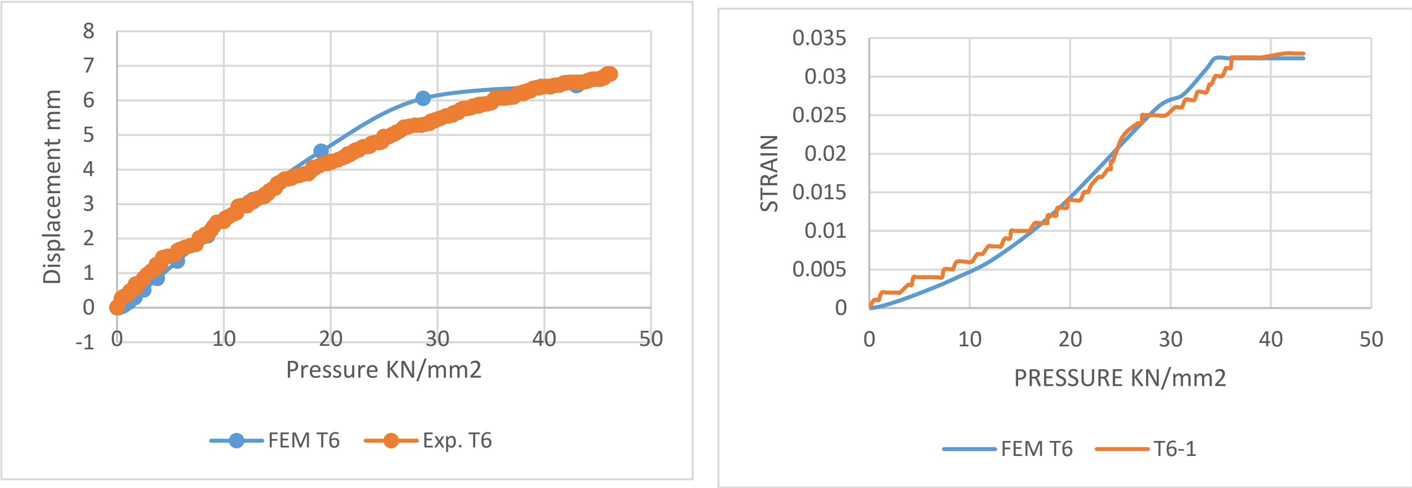

Figure 9: Exp. and Num. Load-Displacement and Strain Center Curves T6

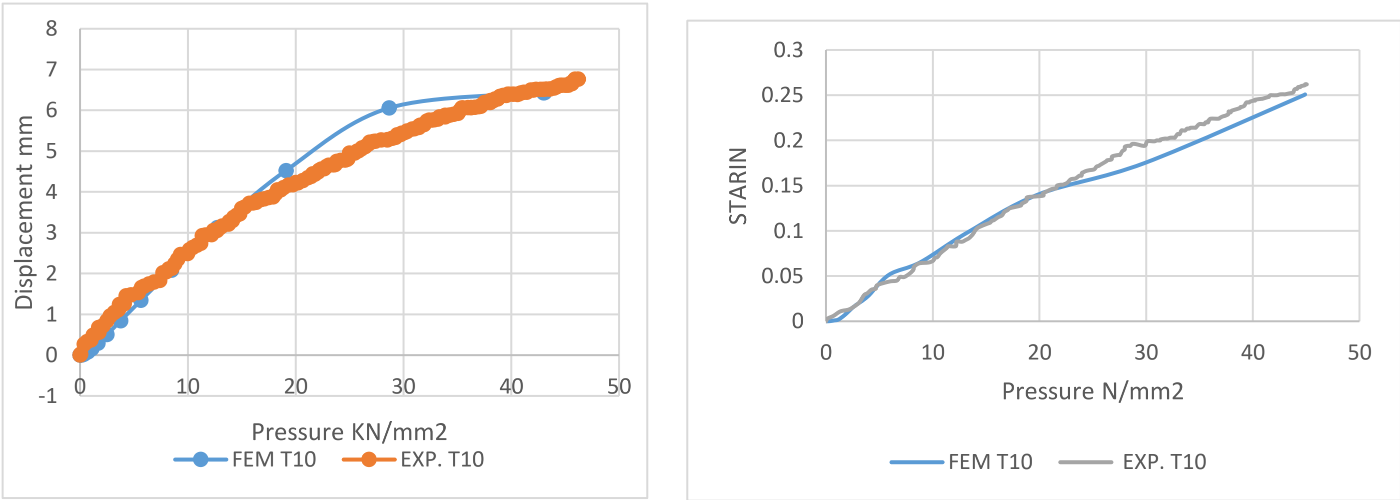

Figure 10: Exp. and Num. Load-Displacement and Strain Center Curves T8

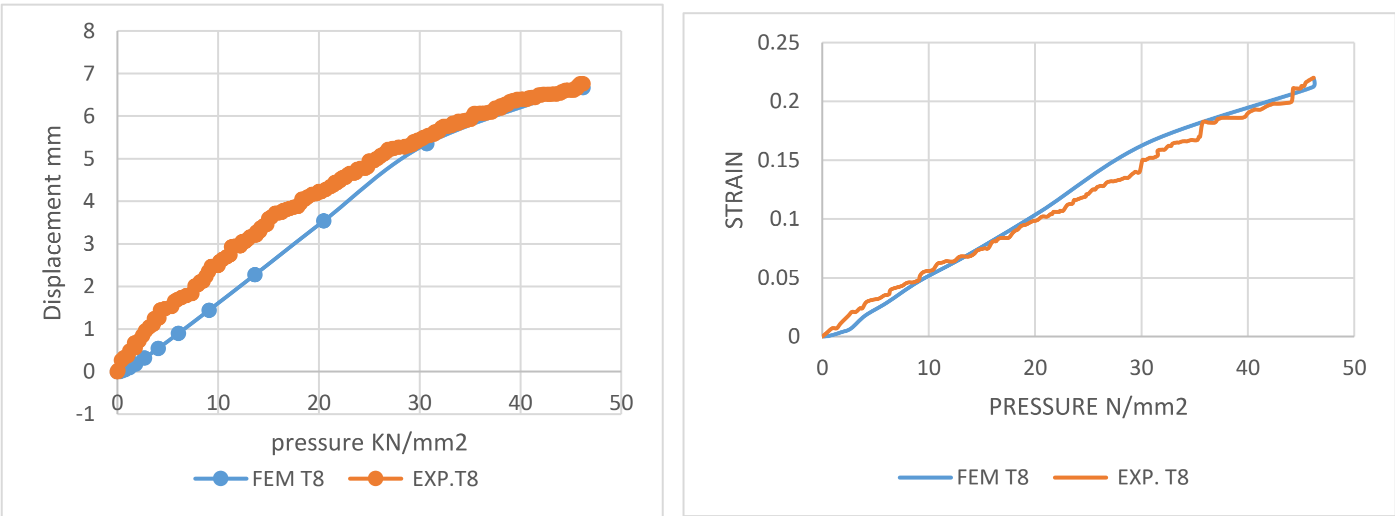

Figure 11: Exp. and Num. Load-Displacement and Strain Center Curves T10

In this study, four finite element models were developed in Abaqus. The displacement, displacement, and failure pattern were predicted from the finite element models. Results of finite element models were arranged beside experimental results in order to validate numerical analysis and to indicate whether finite element models are reliable and have similar behavior to real bent glass lite. The pressure load until bent glass lite failure obtained only from experimental tests and are represented as well.

5. Results and Discussion

With the variables thickness T6-1, T6-2, T8, and T10, the displacement at the center of the bent glass sheet was measured over the same range of pressures used to measure the stress in the bent glass lites. The comparison of the external pressure is shown in Figurers 12, 13. The comparison of center displacement is shown in Figurer 14. The comparison of quarter displacement is shown in Figurer 15. Measured displacement and calculated displacement, as well as measured stress and calculated stress, do not correspond with one another

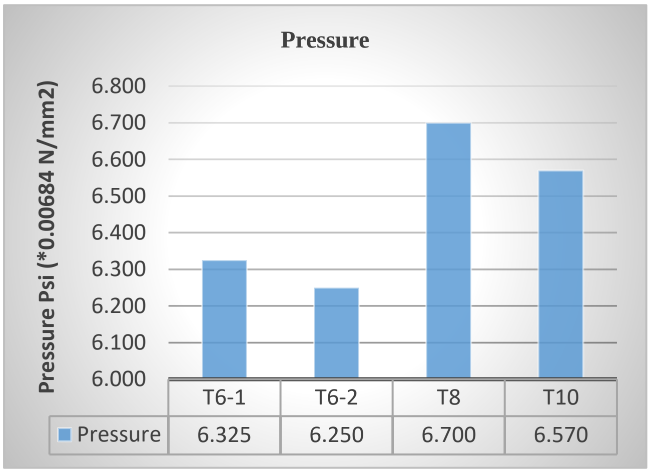

Figure. 12 The Comparison of the External Pressure at Four Glass Lites

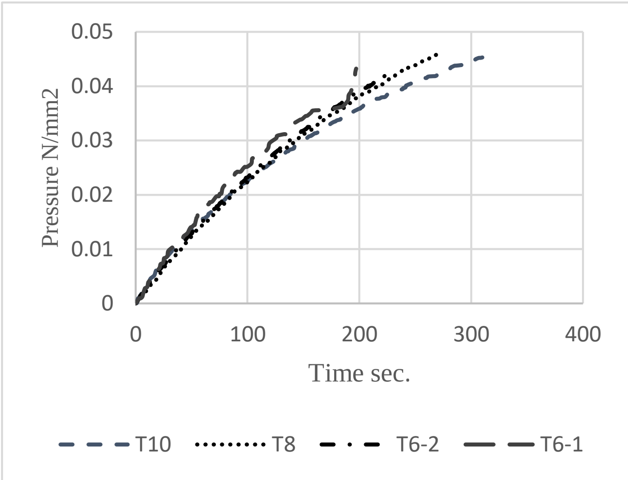

Figure. 13 The Comparison of the External Pressure at Four Glass Lites

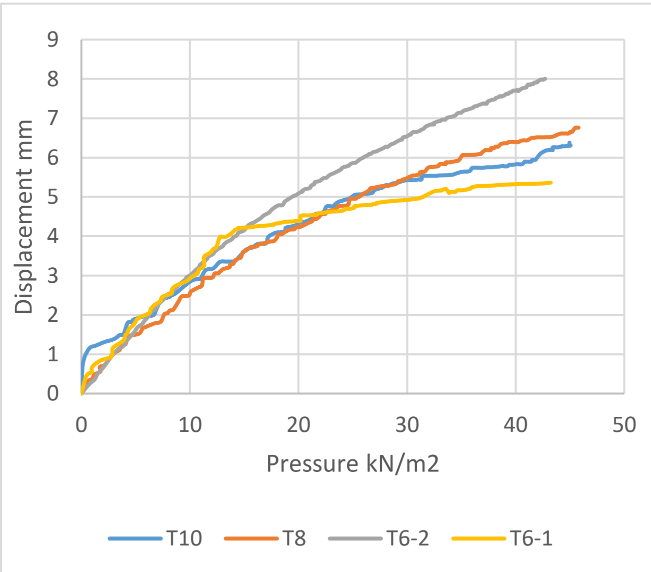

Figure. 14 The Comparison of the Displacement- Pressure Curve at Mid-Span for the Four Lites

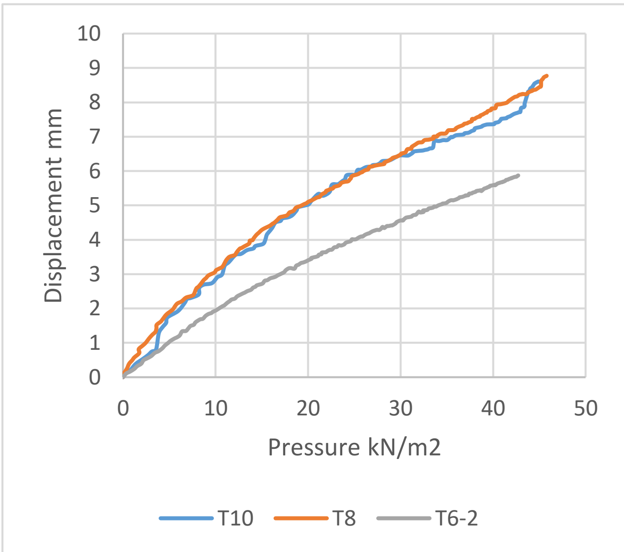

Figure 15 The Comparison of the Displacement- Pressure Curve at Quarter-Span for the Four Lites

The author established the LR for the investigation's Bent LG Lite. Table 2 provides a comparison of Pressure. According to the analysis, the pressure load case results in a glass thickness of 8 mm, with an overall lite thickness of 17.52 mm, demonstrating greater resistance to pressure than a glass lite thickness of 10 mm, with an overall lite thickness of 21.52 mm. The two T6 lites, each of which has a 6 mm thickness and an overall thickness of 13.52 mm, exhibit somewhat equivalent pressure resistance to that of the T8, and T10 lites.

The comparisons of the effect of pressure on the contact force and lite mid-span strain are shown in Figure. 16. The experimental results show that the strain increases very slowly with pressure in Figure. 17.18. The pressure curves also indicate over-predictions for the first contact ending time from the wave propagation analytical method.

Table 2 The Pressure comparison, LVDT Center and LVDT Quarter summarized

Glass Thickness	Pressure KN/mm^2	LVDT Center mm	LVDT Quarter mm
T6-1	43.23	6.1574	6.6927
T6-2	42071	5.87175	8.0031
T8	45.79	6.7617	8.7715
T10	44.90	6.3775	8.6074

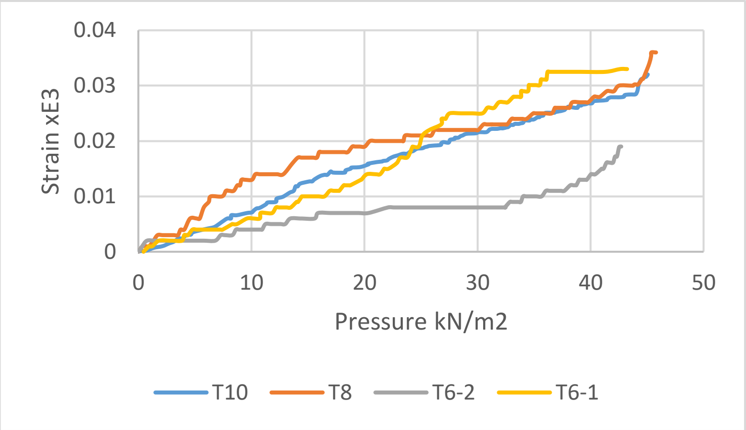

Figure. 16 Strain- Pressure Curve at Mid-Span for the Four Lites

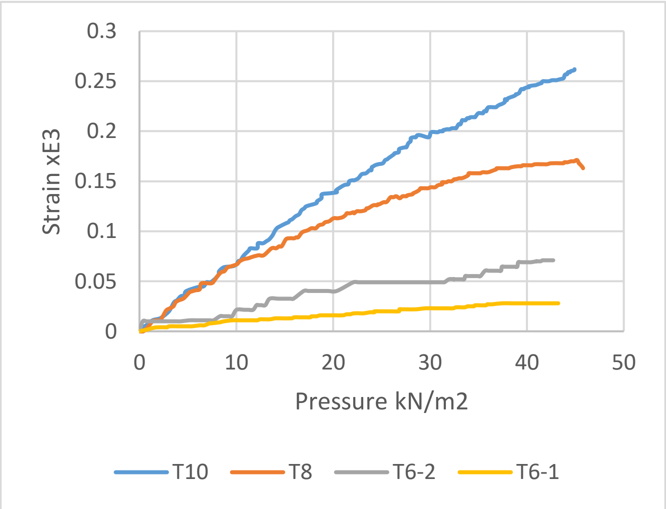

Figure. 17 Strain- Pressure Curve at Quarter-Span at X – direction for the Four Lites

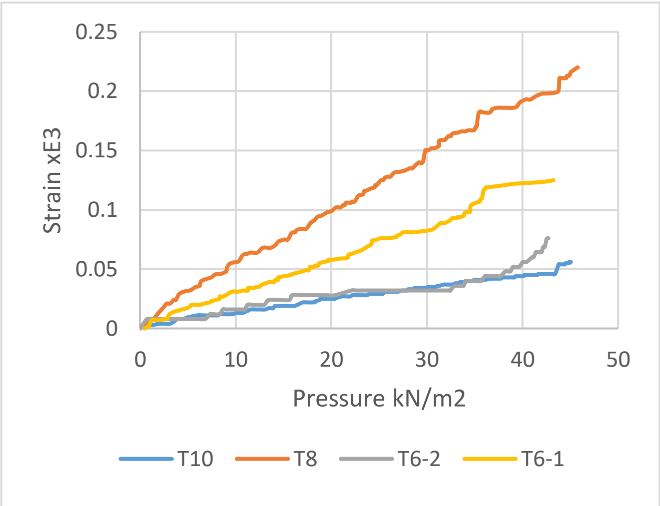

Figure. 18 Strain- Pressure Curve at Quarter-Span of Y-direction for the Four Lites

By changing the glass layer thickness, Figurers 14, 15, and 16 show the comparison of the pressure and strain between the four lites show wave propagation analytical method. The wave propagation shows that the strain increases with increasing the glass thickness. All results are compared to understand the most effective shape and dimensions to the bent LG lite. It is obvious that using the laminated bent glass with thickness 8 mm show more efficient than showing improvement in resistance pressure and strain compared to lite with thickness 10mm and6mm. However, the laminated bent lite glass with thickness 10mm shows more duration resistance compared to glass thickness 6mm and 8mm.6 The result of tested laminated bent glass lites are shown in Figure. 17, 18, and 19, which, illustrates the failure shape of experimental.

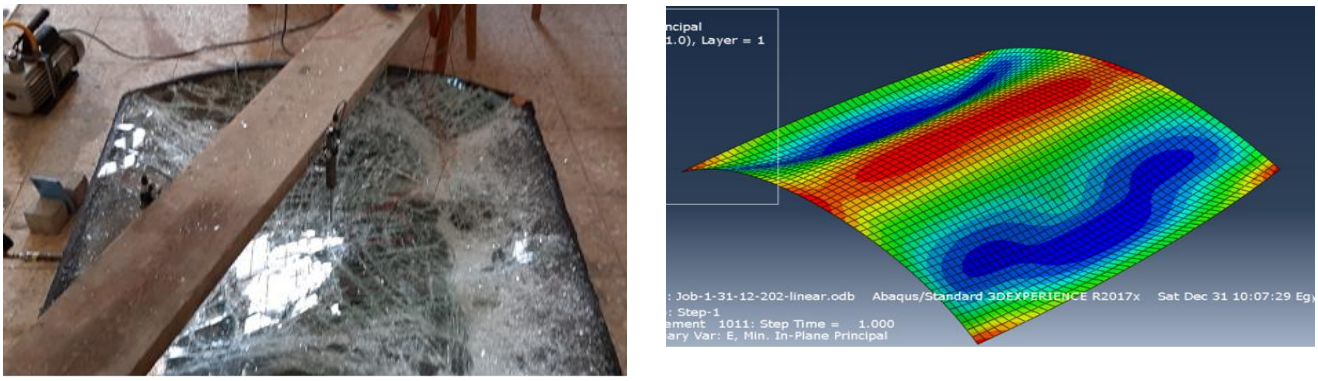

Figure. 19: Exp. and Num. Deformed shape T6 Non-Linear Analysis

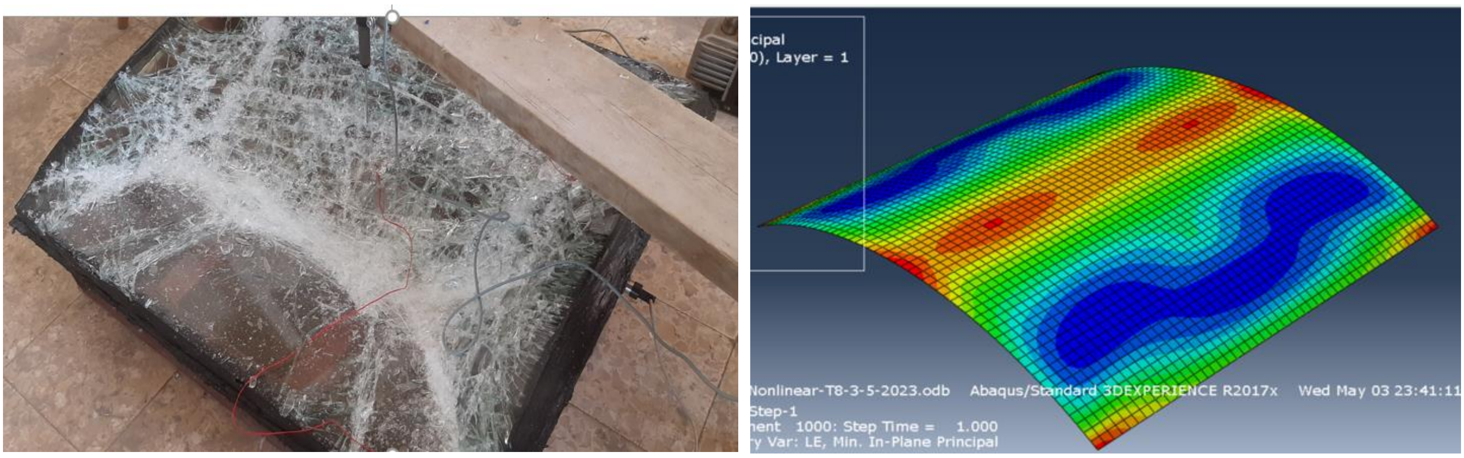

Figure. 20 Exp. and Num. Deformed shape T8 Non-Linear Analysis

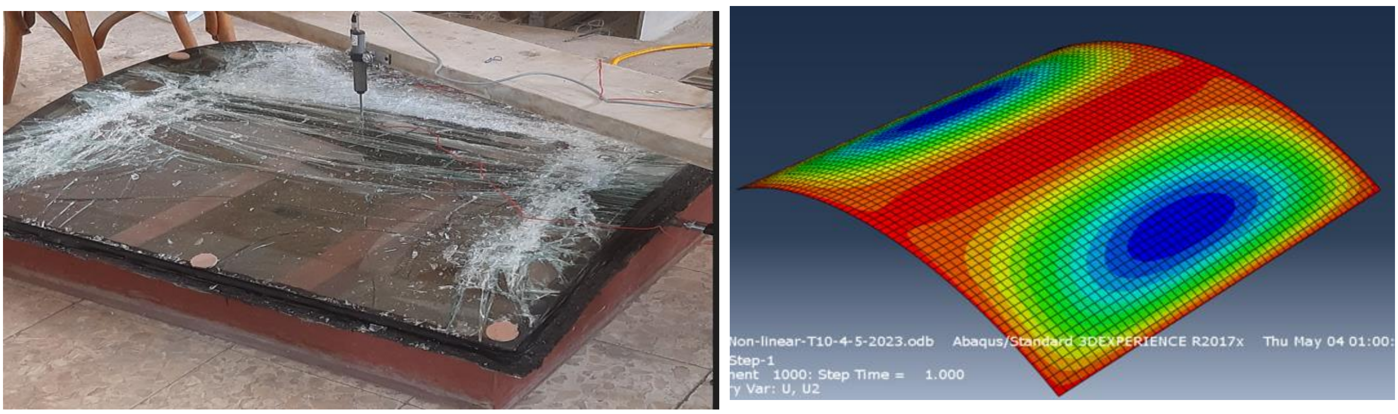

Figure. 21: Exp. and Num. Deformed shape T10 Non-Linear Analysis

6. Conclusions

An experimental program was conducted on a bent LG lite as a curtain wall with different glass thickness under pressure. Based on the above findings, the following conclusions can be drawn:

The bent LG lite T8 sample showed the best results compared to the rest of the samples in its resistance to pressure load, which was 6.7 Psi. in the opposite of lite T10 sample did not show the best results compared to the rest of the samples in its resistance to pressure load, as it was assumed that the pressure load on it would reach greater than the sample T8, which was 6.57 Psi.

The best element capable of simulating a thin-bended glass plate is the shell element in the current research at Abaqus CAE

The best sample tested in the case of bent glass lite was the T8 sample, as it showed maximum strength to pressure with appropriate deflection and appropriate strains with the collapse deformation.

The two simple T6 showed different results in bearing pressure and the maximum deflection may be due to many factors that may be in the industry in the factory or a difference in the clamping force or due to test setup that can be studied in the future.

The curve that showed smoothness in showing the results is Strain Quarter X

The LVDT Center Curve showed that T6-2 has the largest deflection compared to the other simples, although its pressure load is less than the T6-1 sample.

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