Al-Azhar Engineering 16th International Conference

Vol. 19, No. 72, July 2024, 281 - 299

NON-LINEAR ANALYSIS AND EXPERIMENTAL VERIFICATION OF BENT GLASS CURTAIN

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Citation:

S.S. Abd El Kareim, M.S. El Nagar and M.M. El-Shami, “Non-Linear Analysis and Experimental Verification of Bent Glass Curtain,” Journal of Al-Azhar University Engineering Sector, vol. 19, pp. 281 - 299, 2024.

Received: 26 December 2023

Revised: 17 February 2024

Accepted: 16 March 2024

DoI:10.21608/auej.2024.258488.1565

ABSTRACT

A Bent Laminated Glass is commonly used in the residential and commercial structures, its methodology is not present in the curves and tables at the ASTM E1300. Therefore, it has become a need for architects to use basis for this type of glass. To the best of knowledge authors no one study the bent laminated glass in details. Therefore, in this article, experimental and numerical results for such Non-Linear bent laminated glass panes tested under comparison loading are presented and discussed. Four Bent Glass Panes with different thicknesses were experimentally tested for failure under compression load. Experimental results were compared with finite element; FE analysis with the Abaqus program. Behavioral properties; analyzes were performed including ultimate loads, deflections, and failure modes. A numerical sensitivity analysis was performed using ABAQUS 6.14 software to find suitable element types and support conditions that the experimental model could simulate. The authors created a closed chamber as a support system for the test panel. The internal air in the chamber was evacuated to simulate a positive pressure on the outer surface of the panel under test. A displacement transducer and strain gauge were attached to the tested system to measure the displacement and strain as the pressure in the chamber decreased. The results of the analysis were presented and discussed. The results from this experimental and numerical study provide basis for non-linear bent laminated glass for further investigations and developments on such type

KEYWORDS: Bent, compression, Glass, displacement, and strain.

التحليل اللا خطى للالواح الزجاجية المطوية (المنحنية) المستخدمة فى الواجهات.

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الملخص

يمثل هذا البحث النتائج العملية والنظرية للتحليل اللاخطى للالواح المطوية المستخدمة فى الواجهات لكل من الزجاج المصفح والزجاج المتالف . حيث ان استخدام الالواح الزجاجية فى تصميم المبانى الحديثة اكثر شعبية فى التصاميم المعمارية للواجهات. الاختبارات المعملية للتحميل للوحات ستشمل الابعاد المختلفة للقطاعات والطبقات المتعددة والشروط الحدودية المهمة, وسيتم تعيين الترخيم والانفعالات فى كل من الضغط والشد وحتى حدوث الانهيار وقياس الطاقة المختزنة والخصائص الانشائية. وسيتم

استخدام طريقة التحليل العددى لايجاد الحلول التقريبية للمعادلات التفاضلية للعينات المختبرة باستخدام برامج الحاسب وعمل مقارنة للنتائج العملية مع النظرية للتوصل الى معادلات لتصميم الالواح الزجاجي المطوية فى التكسيات للواجهات. كما اظهرت النتائج ان الواح الزجاج المطوية ذات القطاعات المختلفة مقاومتها اعلى فى تحمل قوة الرياح عن الالواح الزجاجية المسطحة لنفس السمك كما انها اظهرت نتائج يمكن الاستعانة بها مع مزيد من الابحاث المستقبلية فى كود الزجاج

الكلمات المفتاحية : الألواح الزجاجية المطوية، قوة الضغط، احمال الرياح، التحليل العددى، الترخيم، قوة الشد والضغط، الترخيم والانفعالات.

1. INTRODUCTION

Glass is being used more and more in today's construction industry. Failure Visible and subtle quality deterioration in glass applications is becoming increasingly common. However, there is very lack information available on the exact method to calculate the load Resistance LR of bent glass for single-layer and double-layer laminated glass.

Due to architectural requirements, bent glass panes are now widely used in modern residential and commercial buildings. Typically, rubber seals are used to attach the glass pane to the support system. It is logical to assume that the disk edge is elastically displaced laterally in the plane and that the ability to rotate around an axis parallel to the disk edge determination is not restricted.

Architectural glass designers in the United States and many other countries refer to ASTM International Standard E1300 (ASTM, 2016) [1]. In the architectural field, accepted procedures are followed to determine the load-bearing capacity of glass. The latest version of ASTM E1300 was published by ASTM International in 2016. The ASTM (2016) [1] approach is only suitable for rectangular flat glass structures. The stress analysis method used to create ASTM (2016) is a nonlinear finite difference analysis model defined in Vallabhan (1983) and Vallabhan and Chou (1986) [2]. To implement the finite element method, Vallabhan and Chou (1986) [3] proposed the use of a finite difference approach due to the required chopping resources. The methods available for performing nonlinear finite element analysis have evolved significantly since the publication of the results. Thanks to the analysis method introduced by ASTM (2016), engineers can now calculate stresses and deflections in glass panels using widely used finite element software. The authors created nonlinear finite element models for a bent laminated glass pane and applied a glass failure prediction model (GFPM) to the model output. The authors determined the LR and probability of failure.

The purpose of this study is to investigate the effect of wind pressure loads on curved glass panes used as curtain walls. This article presents the nonlinear analysis of curved laminated glass LG. All Previous studies only investigated a thickness of 12 mm. However, in this article, the author shows various thicknesses of 13.52 mm, 17.52 mm, and 21.52 mm, consisting of two layers of glass and a 1.52 mm thick PVB interlayer. The authors developed a nonlinear finite element model and applied the glass failure prediction model (GFPM) to the output of the nonlinear finite element model to determine the failure probability and Load Resistance LR of curved glass panels. The authors present experimental results on full-sized curved glass measured using strain gauges. Impact damage initiation and glass crack progression are critical to the failure mechanism. Under the influence of a hard body made of glass. The resulting details are the identification of defect patterns and the creation of models to predict the effects of resistivity on this type of glass in engineering applications. Next, the authors will show how to apply the GFPM using FEM Abaqus to output an analysis of a curved glass pane. The LR of the curved glass panels is then determined and compared, demonstrating the increase in strength of the curved glass structure with increasing panel thickness.

The durability of laminated glass allows it to withstand multiple impacts without sustaining damage. The PVB interlayer holds the glass in place and prevents forced penetration, even under very strong impacts. A review of the Literature shows that many studies have been conducted on its effectiveness. Analysis of parts such as glass and other fragile parts. Although, the author studies the failure analysis of composite and monolithic glasses used in structures. Cases of low-velocity, large-scale projectile impacts are relatively rare.

Soules, J.G., MSCE (2020) [4] demonstrated modeling of curved glass panes using commercially available finite element software and then presented a comparison of analytical results for curved glass panes and experimental results from strain gauges. size curved glass pane. Next, he presented a method for applying his GFPM.

An analysis program for studying curved pane elements was created developed by Philip et al. (2014). [5]. A mathematical model of laminated glass was Created also presented by Asik, M.Z., Tezcan, S., (2005) [6] for analysis and safer design. The output of this model is compared with that of the experimental model and the finite element model. In that effort, Fildhuth, T. and Knippers, J., (2012) [7] created an entire glass shell made of bent (hot or cold) glass.

For a nonlinear study of a monolithic rectangular glass pane that can process thin and thick panes, El-Shami, M.M. and Norville, H.S. (2011) [8] created a new finite element model. Numerical analysis is performed by scripting and abstracting the theory development steps to run on a simple visual platform.

They focused on the geometry, the bonding of all-glass panels, and the interaction of glass components and structures. Bagger, A. (2010) [9] investigated the nonlinear behavior of pane-shell structures for various factors. Examples: facet size, defects, connectivity characteristics. To determine the velocity response of composite panels.

More recently, Feraboli and Kedward (2006) [10] developed the Composite Structural Impact Performance Assessment Program (CSIPAP) to evaluate the impact performance of composite structures subjected to repeated impacts. This program takes into account parameters such as critical impact force, energy dissipation, contact time, and contact coefficient recovery (COR).

Ivanov, I.V., (2006) [11] published a finite element model of an LG beam. In his model, the strain and stress distribution throughout the thickness of the beam and along its axis was determined as a result of linear finite element analysis. The author developed a mathematical model for triple-glazed beams consisting of a bending curvature differential equation and his PVB interlaminar shear interaction differential equation.

Recently, Asik and Tezcan (2005) [12] presented a mathematical model for composite glass beams based on nonlinear strain-displacement relationships. This model was used to study the linear and nonlinear behavior of a symmetric triple glass substrate in comparison with the behavior of LG pane. some experimental studies were carried out by Feraboli and Kedward in 2004 [13]. According to several studies cited in the discussion, this challenge arose from the variety of parameters in experimental studies and their impact-on-impact evaluation.

Duzer et al. (1999) [14] presented a robust model for stress analysis of LG. The authors used the 3D solids to model layers and their interactions. The PVB material was modeled as linear viscoelastic. Norville et al. (1998) [15] presented a discussion on the behavior and intensity of LG beams. They noted in their discussion that LG beams have higher bending strength at many thicknesses compared to monolithic glass beams. This is simply because LG construction is thicker than monolithic glass in almost all nominal glass thickness specifications. They also found that monolithic glass of the same thickness as LG does not necessarily represent the upper limit of LG's strength. A comprehensive finite element model of laminated glass (LG) panels was created by El-Shami, M.M., Vallabhan, C.V.G., Kandil, K.S. and Tawfik, O.M. (1997) [16].

Vallaban et al. (1993) [17] developed a mathematical model to analyze laminated glass. Experimental tests were performed to validate the numerical model. They found that the shear modulus of the PVB interlayer at room temperature varied as a function of shear stress. Their model had limited applicability to simply supported rectangular disks. However, engineers often use non-rectangular glass sheets, and in some cases, the glass sheets have holes in them. These problems are very difficult to solve.

Norville et al. (1993) [18] that the fracture strength of a new fully tempered and thermally strengthened LG exceeds that of a new fully tempered and thermally strengthened monolithic pane with a similar geometry. Behr et al. (1993) [19] discuss the strength and behavior of LG compared to monolithic window glass with similar geometry. They also reported the results of load tests on similarly sized laminated glass beams and single-pane glass beams.

Minor, J.E., and Reznik, P.L., (1990) [20] announced that the LG fracture strength at room temperature is comparable to the fracture strength of a monolithic glass with the same rectangular dimensions and nominal thickness made of the same type of glass. They also reported that the fracture strength of LG decreased with increasing temperature. Norville, H.S., (1990) [21] reported the results of destructive testing of LG samples. In these tests, the strength of LG met or exceeded the strength of a new monolithic glass panel with the same nominal dimensions.

Vallaban et al. (1985) [22] found that for certain aspect ratios: The maximum principal stress of a laminated glass unit, which is a stack of two glasses without an interlayer, is less than the maximum principal stress of a monolithic glass with the same dimensions and the same lateral pressure.

Vallaban et al. (1985) [21] found that for certain aspect ratios: The maximum principal stress of a laminated glass unit, which is a stack of two glasses without an interlayer, is less than the maximum principal stress of a monolithic glass with the same dimensions and the same lateral pressure. Beason and Morgan (1984) [22], developed to the results of an analysis of curved glass panes. The LR of the curved glass pane is then determined and compared to the LR of flat glass with the same planar dimensions of the curved glass pane to demonstrate the increased strength of the curved glass structure compared to the flat glass structure.

Hooper, J.A., (1973) [23] reported that the shear modulus and interlayer thickness vary inversely in his LG beams subjected to bending loads. Pilkington ACI, (1971) [24] reported that LG made from flat and float glass failed at loads comparable to monolithic glass of the same rectangular dimensions and nominal thickness. Quenett, R., (1967) [25] conducted tests on LG using bending and impact loads. He reported a tendency for the elastic modulus of LG to increase as the interlayer thickness decreased. Glass panes cannot be used in Levy, S., (1942) [26] formulation of nonlinear analysis of simply supported panes with no in-plane response at the edges.

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.

2. Experimental Work

Four Bent LGs with rectangular dimensions 1000 x 1000 mm, nominal thicknesses 13.52 mm, 17.52 mm, 21.52 mm, showed in Figure (2) glass Poisson's ratio V = 0.22, modulus of elasticity E = 70 Gpa (70000 N. /mm2). 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 (i.e. lateral displacement and rotation around the vertical of the planes equal to zero). Comparing with experimental data, the shear modulus of PVB was assumed to be GINT = 690 kPa (0.69 N/mm2).

Four bent glass panes were tested to simulate a curved laminated glass pane. The panes have plane dimensions of (1,000×1,000) mm and a radius of curvature of 934.6 mm as shown in Figure (2).

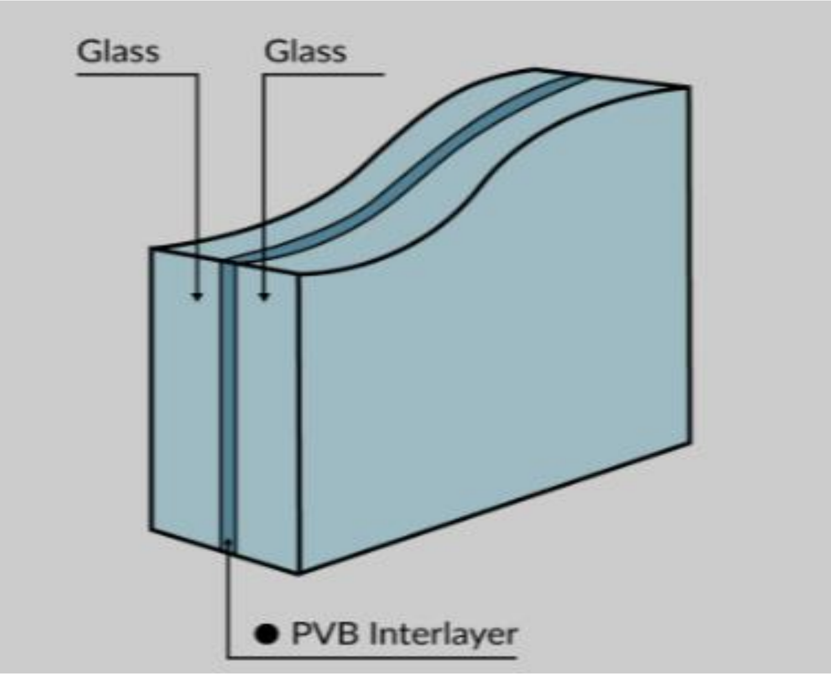


Figure 1 Laminated glass (LG) [29]

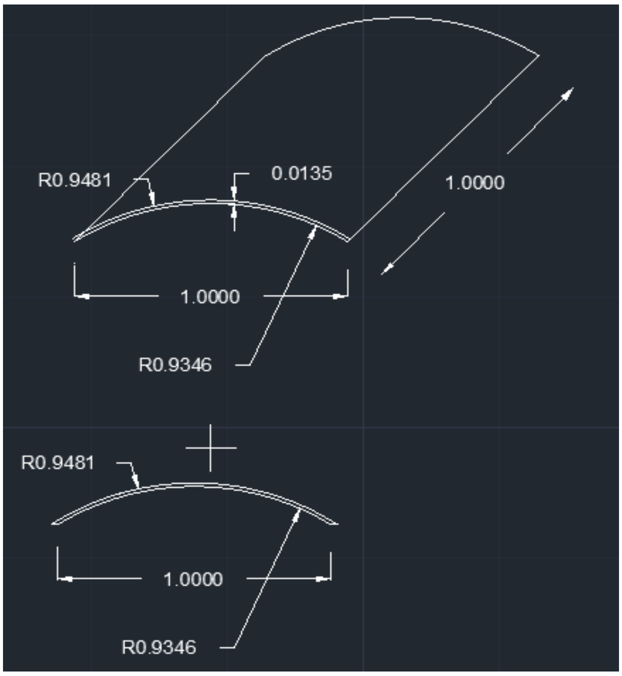


Figure 2 Geometry of Laminated Glass lite.

The closed chamber was prepared in a workshop at the Department of Industrial Engineering, Faculty of Engineering. A steel pane 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 panes were cut to the required size and welded using fillet welding to form the chamber. The author 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 pane to the chamber. Figure (4) shows the arrangement of displacement transducers and strain gauges to measure the strain at different points on the test pane. 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.

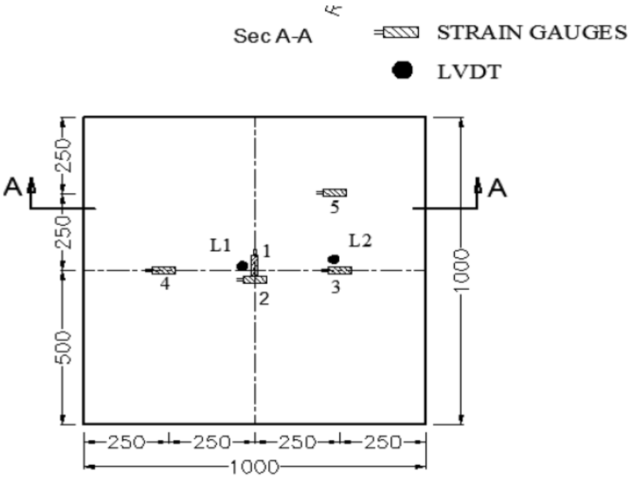


Figure. 4: Measuring devices locations

Figure 5: The position of strain gauges and displacement transducer

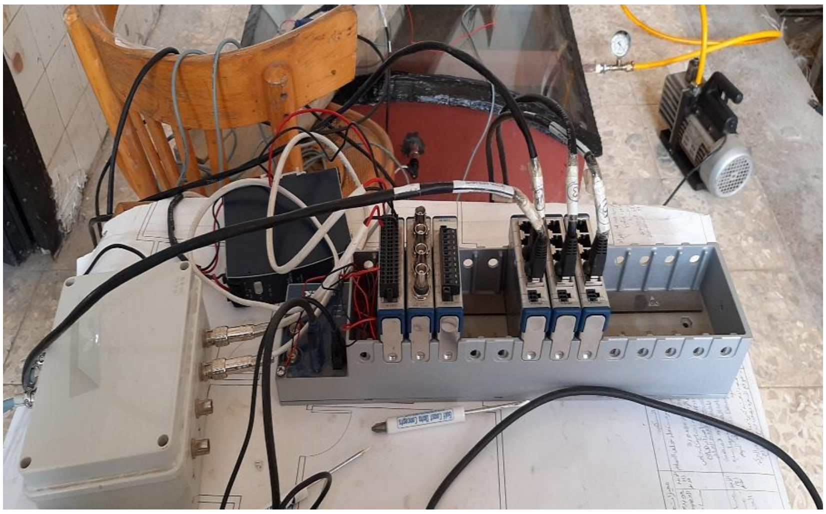


Figure. 6: The National Instruments LabVIEW 2014 F1 x64 deceive & Dial Gigue

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

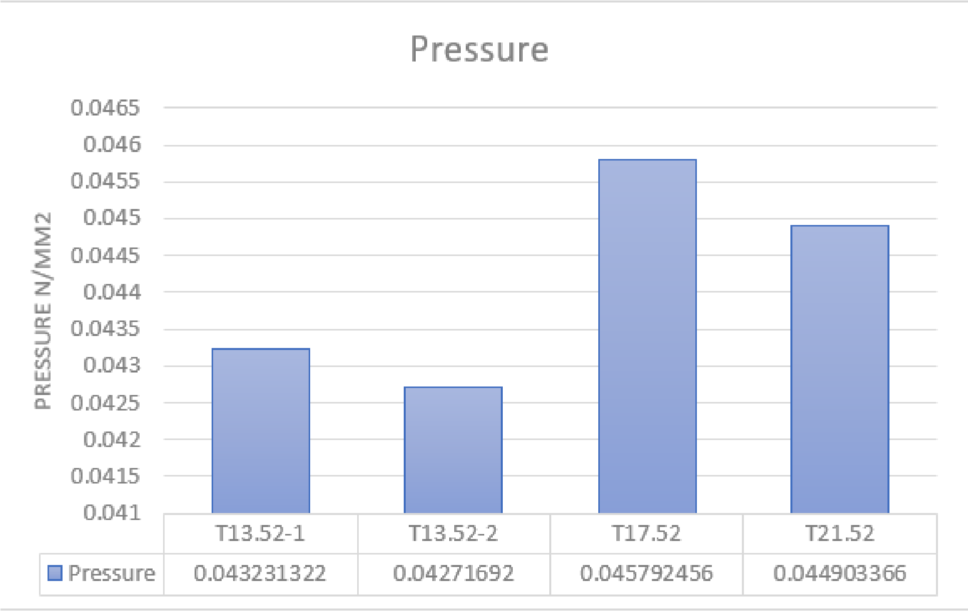
Table 1: Bent Glass Lite ID.

No.	Bent Glass ID	Description
1	T13.52-1	First specimen Laminated Bent Glass lite and a PVB with thickness1.52 mm
2	T13.52-2	Second specimen Laminated Bent Glass lite and a PVB with thickness1.52 mm
3	T17.52	Third specimen Laminated Bent Glass lite and a PVB with thickness1.52 mm
4	T21.52	Fourth specimen Laminated Bent Glass and a PVB with thickness1.52mm

Pane 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 pane failure. Bent pane capacity till failure was noticed until the pane could not resist. Two LVDT gauges were placed at the top to read the axial deformation of pane under compression Figure. 5. The first LVDT gauge was at the center, the second was at the quarter of the pane. 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.

3. Results and Discussion

With the variables thickness T13.52-1, T13.52-2, T17.52, and T21.52, the displacement at the center of the bent glass pane was measured over the same range of pressures used to measure the stress in the bent glass panes. The comparison of the external pressure is shown in Figurers 7, 8. The comparison of center displacement is shown in Figurer 9. The comparison of quarter displacement is shown in Figurer 10.



	T13.52-1	T13.52-2	T17.52	T21.52
▨ Pressure	0.043231322	0.04271692	0.045792456	0.044903366

Figure. 7 The Comparison of the External Pressure at Four Glass Panes

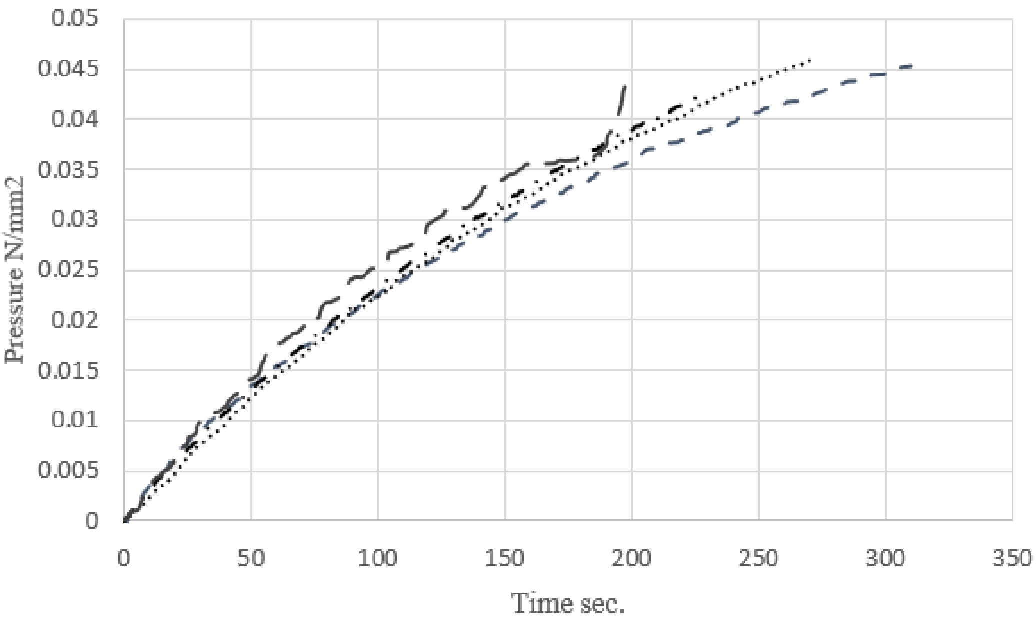


Figure. 8 The Comparison of the External Pressure at Four Glass Panes

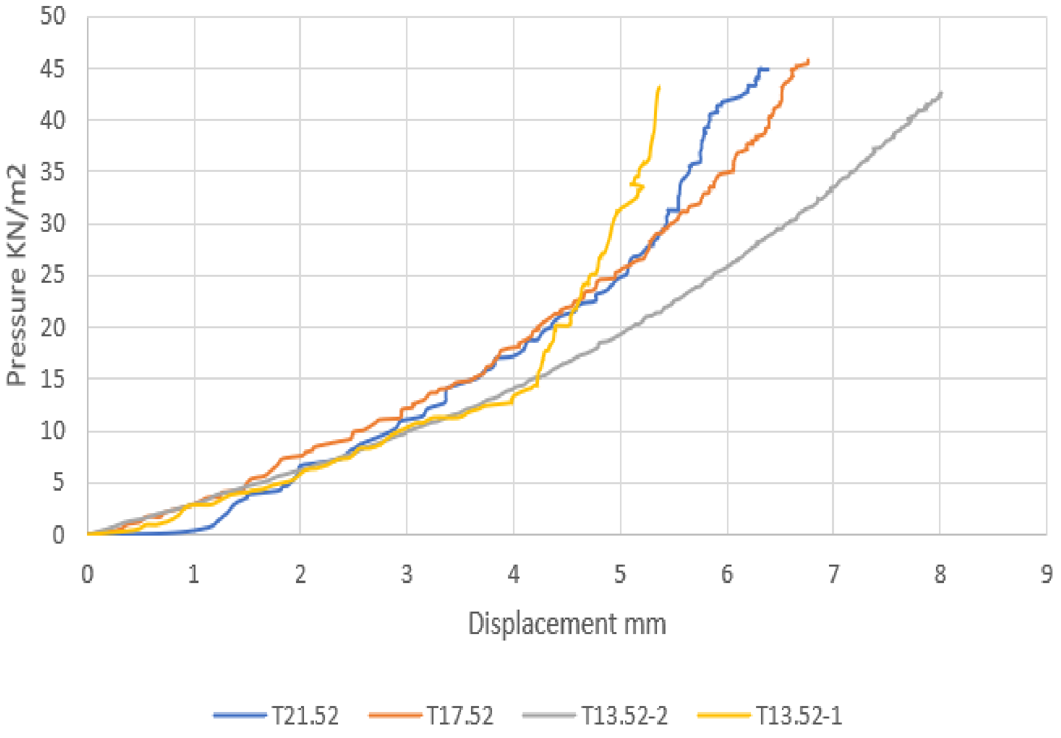


Figure. 9 The Comparison of the Displacement- Pressure Curve at Mid-Span for the Four Panes

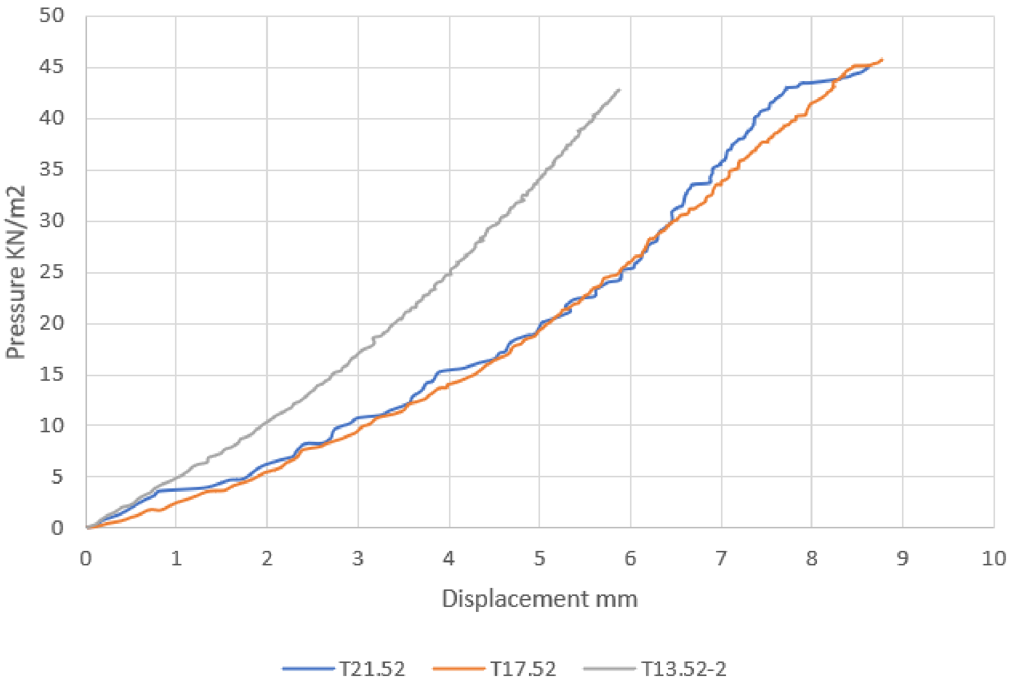


Figure 10 The Comparison of the Displacement- Pressure Curve at Quarter-Span for the Four Panes

At Figure 9 showed at pressure 42 kN/mm2 the lite T13.52-1 gives the least displacement while T13.52-2 lite gives the highest displacement. This may be due to the test setup or Manufacturing defects.

At Figure 10 noticed that the lite T13.52-2 gives the least displacement while T17.52 and T21.52 gives higher displacement, due to bending manufactory to form the curved shell.

The author established the LR for the investigation's Bent LG Pane. Table 2 provides a comparison of Pressure. According to the analysis, the pressure load case results in a glass thickness of 17.52 mm, demonstrating greater resistance to pressure than a glass pane thickness of 21.52 mm. The two T13.52 panes, exhibit somewhat close pressure resistance to that of the T17.52, and T21.52 panes.

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	42.71	5.87175	8.0031
T8	45.79	6.7617	8.7715
T10	44.90	6.3775	8.6074

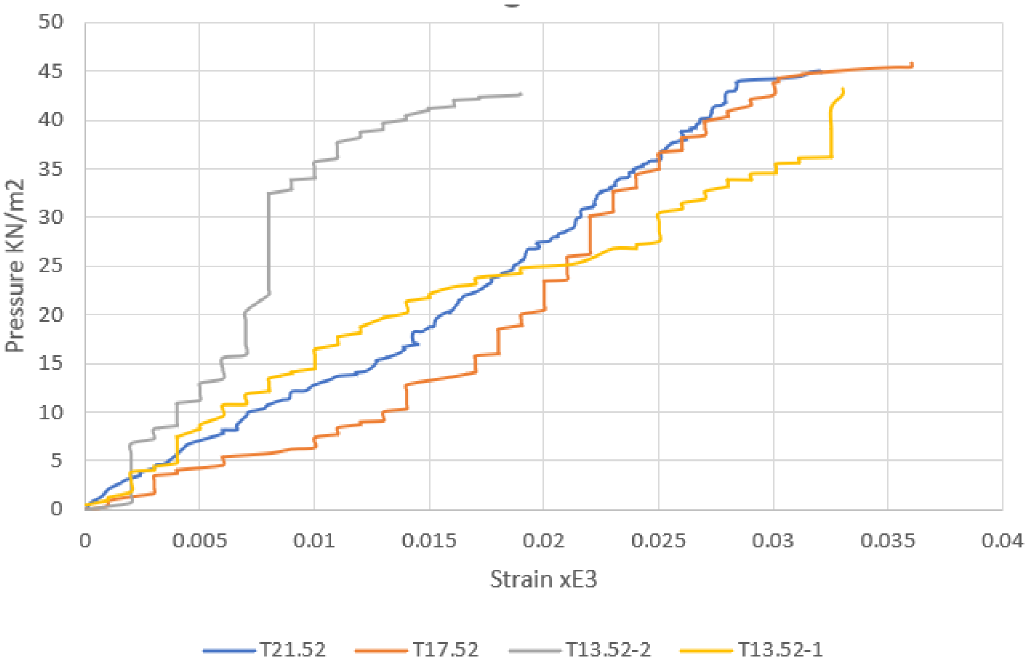


Figure. 11 Strain- Pressure Curve at Mid-Span for the Four Panes

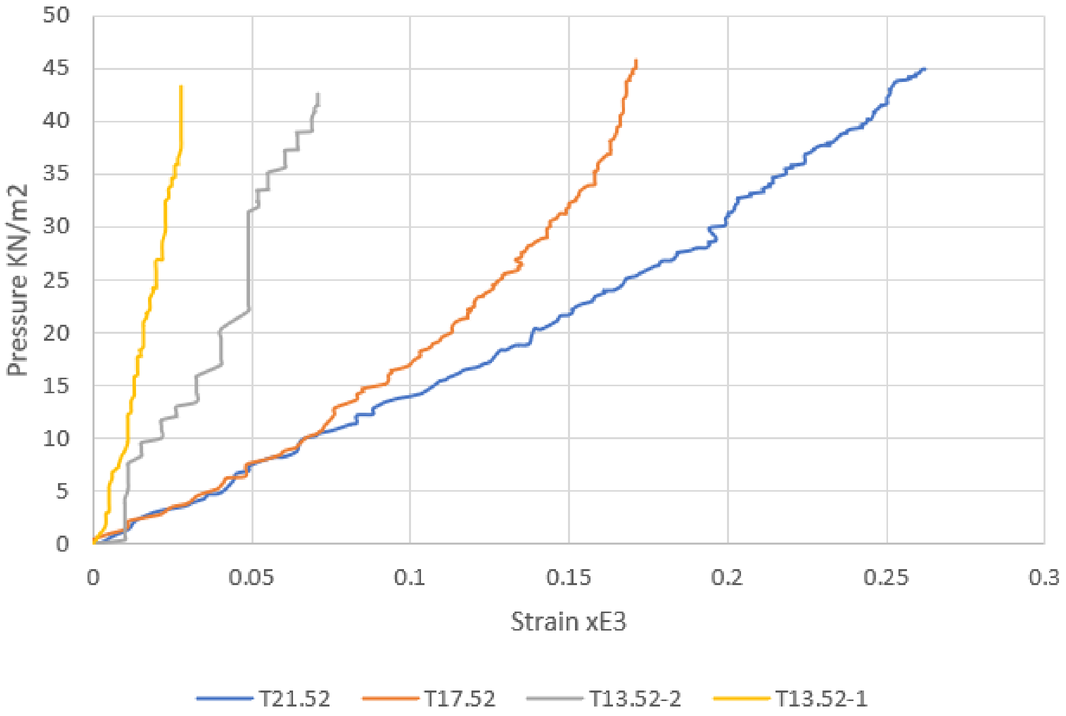


Figure. 12 Strain- Pressure Curve at Quarter-Span at X – direction for the Four Panes

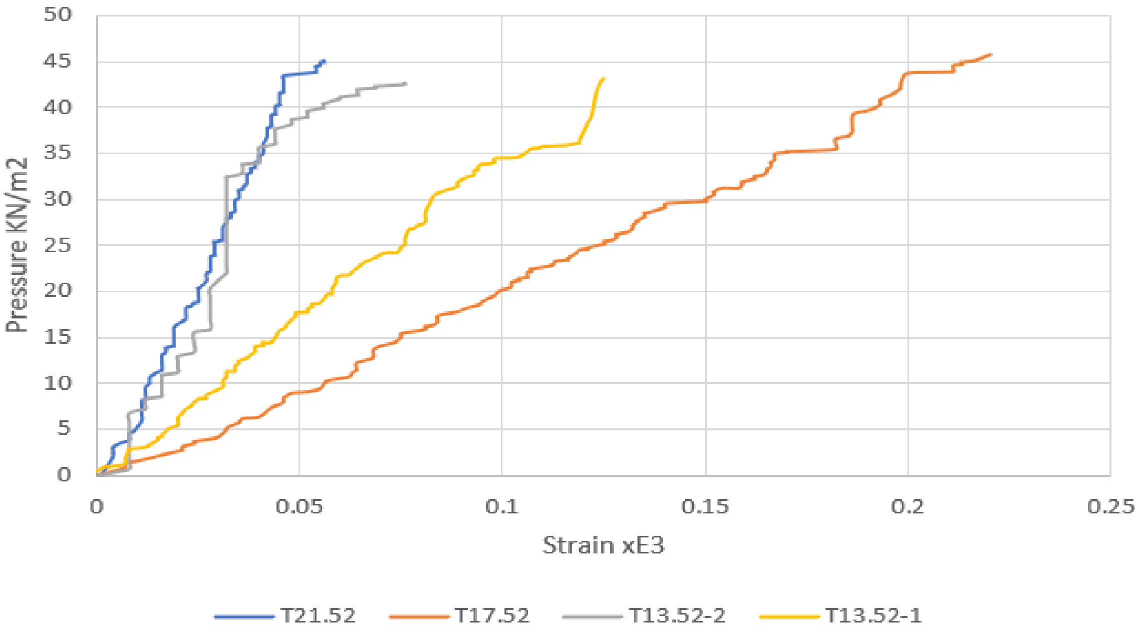


Figure. 13 Strain- Pressure Curve at Quarter-Span of Y-direction for the Four Panes

The comparisons of the effect of pressure on the contact force and pane mid-span strain are shown in Figure. 11. The experimental results show that the strain increases very slowly with pressure. The pressure curves also indicate over-predictions for the first contact ending time from the wave propagation analytical method. The behavior of the test specimens was observed throughout the testing.

Figure 11 showed that for pressure 42 kN/mm2 the strain in T17.52 and T21.52 give values greater than lite T13.52, and this will be studied during the theoretical evaluate of the results.

There is no any buckling expected in the failure model because the glass was going on non-linear geometric in which the membranes in all directions become factor in the stiffness matrix to reduce the lateral displacement and stresses.

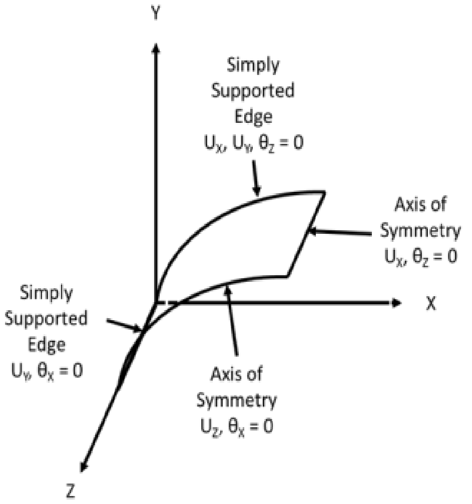
By changing the glass layer thickness, Figurers 11, 12, and 13 show the comparison of the pressure and strain between the four panes show wave propagation analytical method. The wave propagation shows that the strain increases with increasing the glass thickness. All results are compared to understand the most effective shape and dimensions to the bent LG pane. It is obvious that using the laminated bent glass with thickness 17.52 mm show more efficient than showing improvement in resistance pressure and strain compared to pane with thickness 21.52 mm and 13.52mm. However, the laminated bent pane glass with thickness 21.52 mm shows more duration resistance compared to glass thickness 13.52 mm and 17.52 mm.

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 use in modeling bent laminated glass panes in finite element software. the element recommended is a commonly used element for thin shells where shear deformation is small. The glass lite specimen modeled meets the definition of a thin shell. The element recommended by the author allows for better convergence and eliminates the problem of shear lockup.
- Create Shell Composite Section with multi layers.
- Because the bent glass lite is symmetrical about two axis and is simply supported on all four edges.
- Figure 14 shows the edge conditions and symmetry conditions used in the model. These edge conditions and symmetry conditions are recommended for any model developed for a bent glass lite simply supported along all for edges. the model edge conditions were varied to obtain results consistent with the bent glass test specimen.
- Consistent with values used for glass in ASTM (2016) the model should be based on using an elastic, isotropic material with Young’s Modulus of 70 GPa (10.4 x 106 psi) and Poisson’s Ratio of 0.22. Specify the boundaries and the initial circumstances.
- The finite element nonlinear geometry functionality must be turned on with an appropriate increment set for use in the nonlinear iterative solution.
- Commercially available finite element analysis software typically requires the use of consistent units. The model used in this study used MPa for the uniform pressure

load, Young's Modulus, and resulting principal stresses. Glass lite dimensions used were in millimeters.



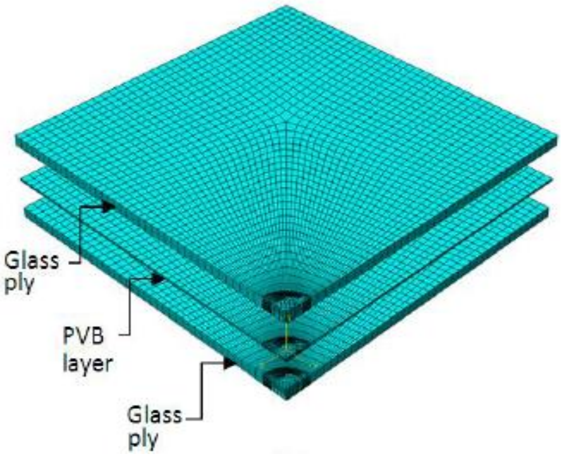


Figure: 7 Boundary Conditions used in Analysis [4]

Figure 8: Mesh of laminated glass plate with PVB interlayer [4]

This type of edge conditions of attachment produces simply supported edges that are prevented from deflecting out of the x-z plane (Figure 14), are allowed to rotate in the lateral direction, and are allowed to deform in the plane tangent to the curve of the glass pane. If the bent glass lite is structurally glazed to the frame, the structural glazing will provide rotational stiffness as well as inhibiting deformation significantly.

Laminated glass panes are used in two separate portions of this study. The glass pane or PVP interlayer was modeled using the deformable option. Glass pane with lamination 1000 mm x 1000 mm in planning, but only a quarter symmetrical cut. Considered is a dimension of 500 mm x 500 mm.

The purpose of using quarter cuts is to minimize the computation time of the simulation. The single layer monolithic glass panels have a thickness of 13.52 mm, 17.52 mm and 21.52 mm respectively, with top, and bottom glass laminated. The Glass layers thicknesses were 6 mm, 8 mm, and 10 mm. The thickness of the PVB interlayer is 1.52mm.

Briefly, the authors treat the curved glass pane as a curved pane with supported edges that is subjected to lateral loads. modeled. A thin curved glass pane will undergo a large lateral deflection (depending on the thickness of the pane) when subjected to a lateral load. Due to the membrane effect, large deflections cause a build-up of tensile or compressive strain in the central fibers of the curved glass pane, depending on the direction of the load. Strain in the membrane due to bending are combined with tensile and compressive strain in the outer fibers. The curved glass sheet is stiffer than linear elastic theory predicts, resulting in geometrically nonlinear load-deflection and A load-stress relationship arises.

The curved edge of the glass sheet allows deformation on the surface tangent to the curvature of the glass sheet, but no resistance occurs on the surface tangent to the curvature, so it is caused by tension or membrane behavior depending on the direction. Curved glass bricks exhibit geometrically nonlinear behavior similar to flat rectangular glass bricks.

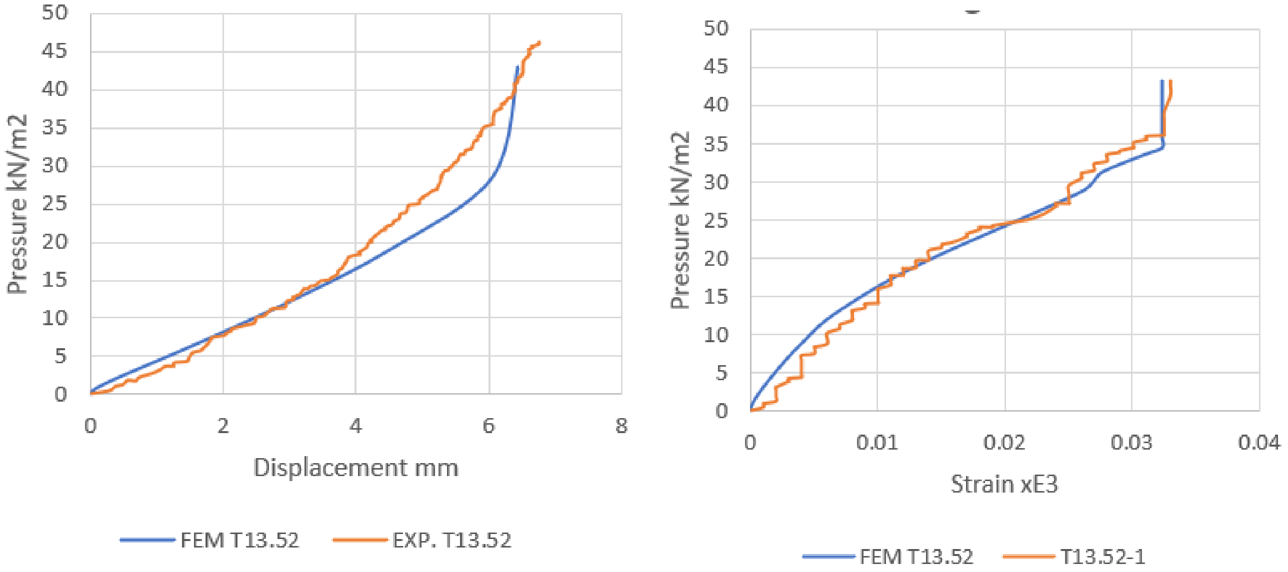


Figure 15: Exp. and Num. Load Displacement and Strain Center Curves T13.52

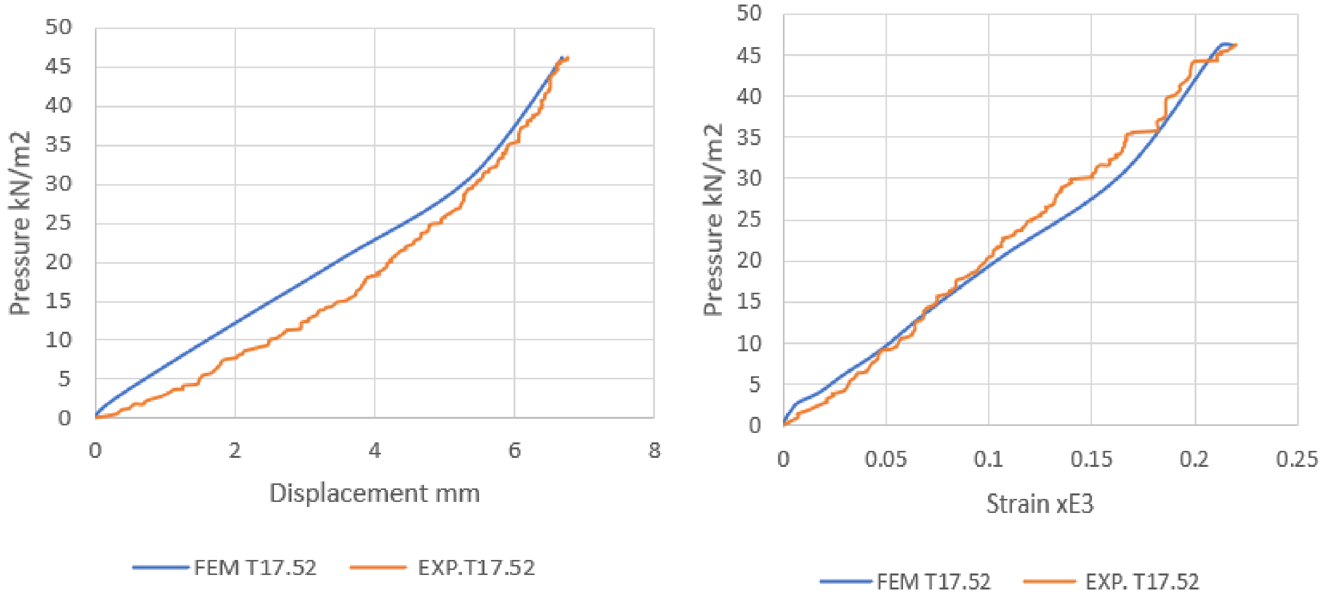


Figure 16: Exp. and Num. Load-Displacement and Strain Center Curves T17.52

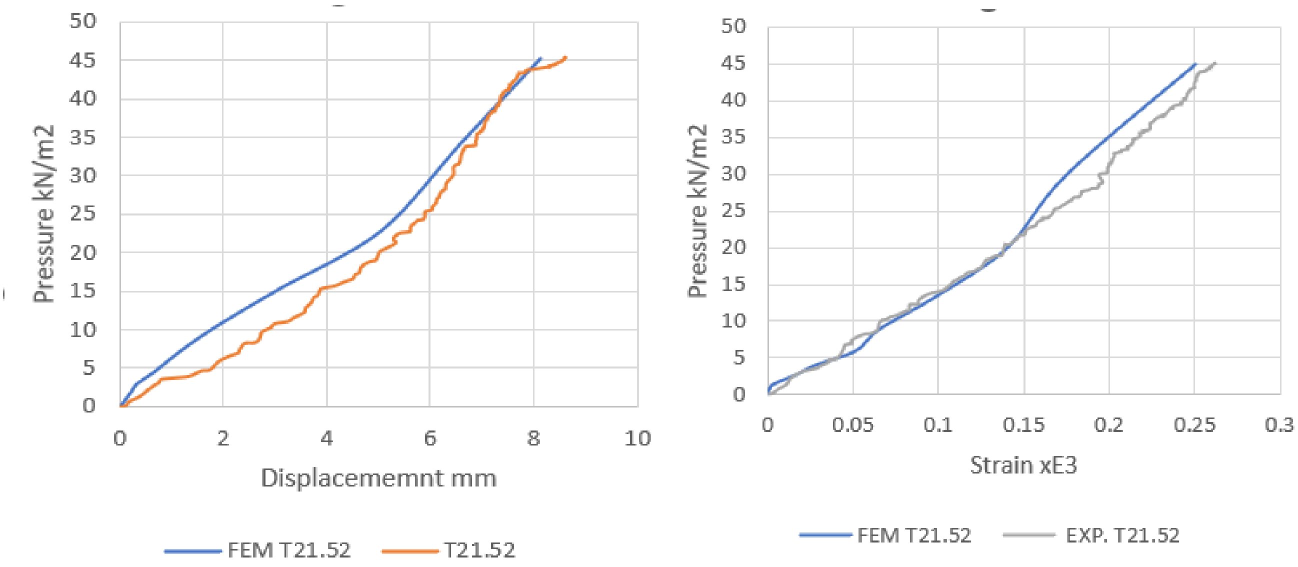


Figure 17: Exp. and Num. Load-Displacement and Strain Center Curves T21.52

In this study, four finite element models were developed in Abaqus. The 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 panes. The pressure load until bent glass pane failure obtained only from experimental tests and are represented as well.

The comparison result of experimental and numerical laminated bent glass panes are shown in Figure. 18, 19, and 20, which, illustrates the failure shape of experimental, and showed similar in failure deformation between the experimental and numerical studies

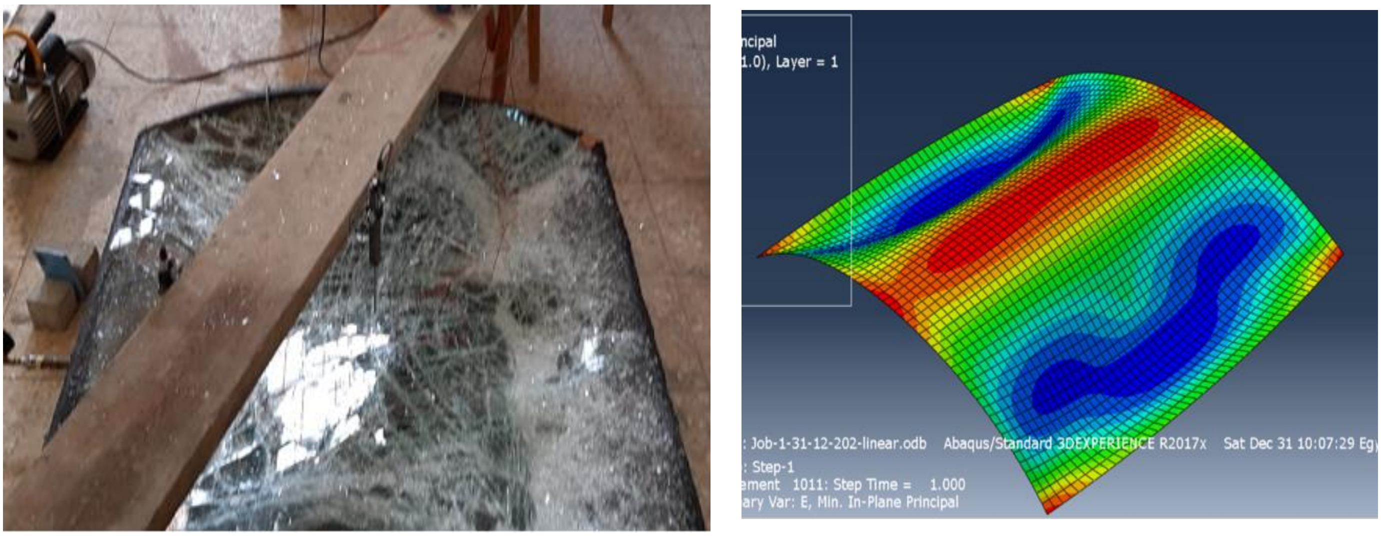


Figure. 18: Exp. and Num. Deformed shape T6 Non-Linear Analysis

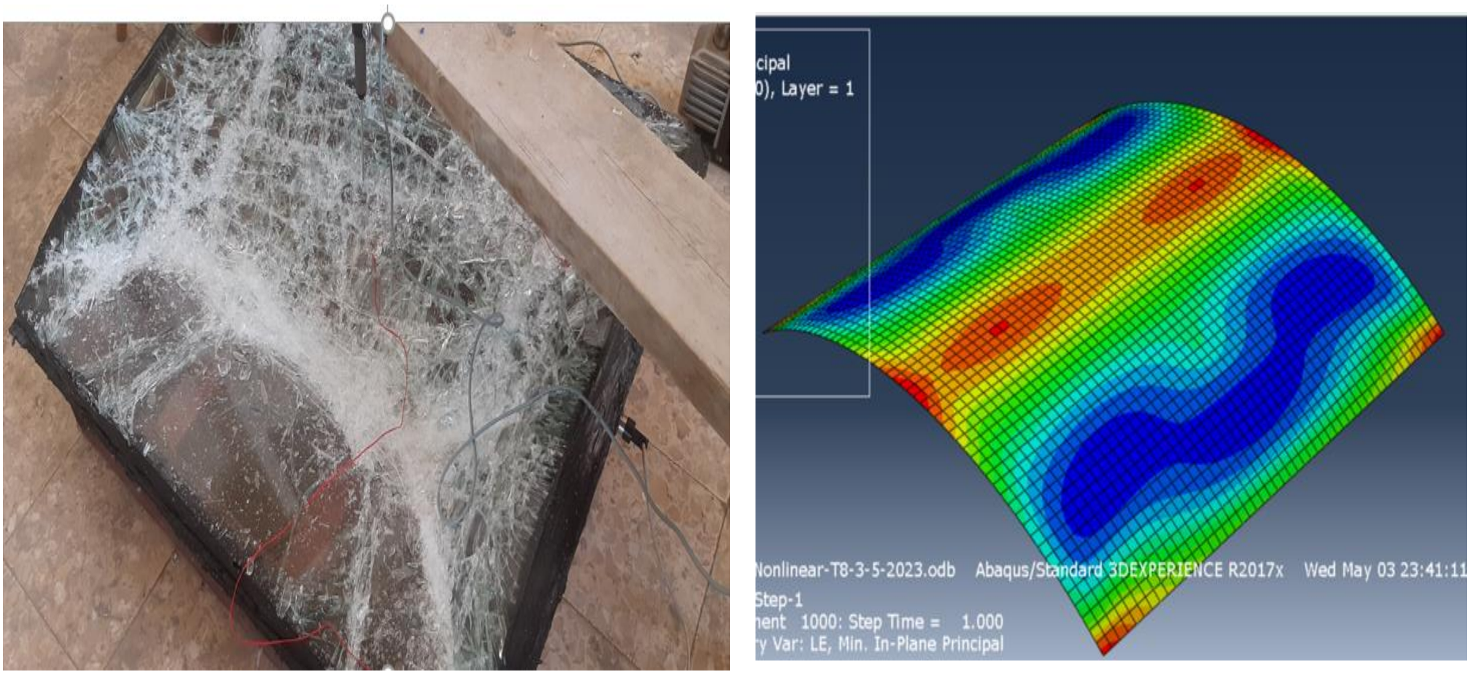


Figure. 19 Exp. and Num. Deformed shape T8 Non-Linear Analysis

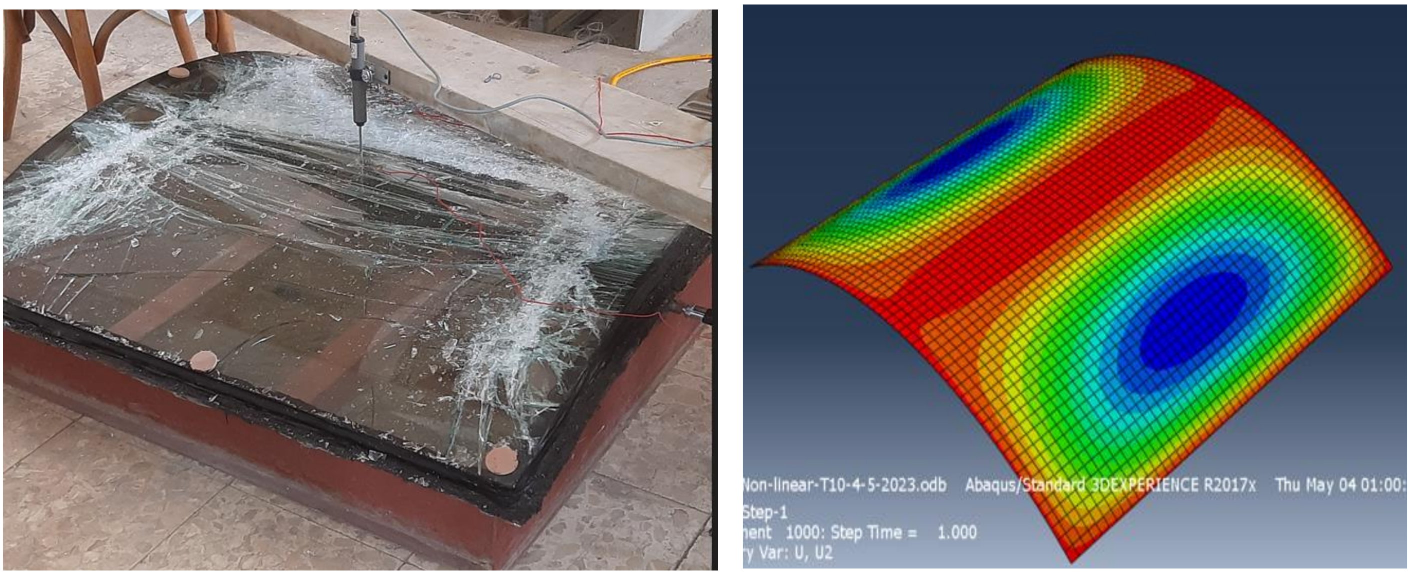


Figure. 20: Exp. and Num. Deformed shape T10 Non-Linear Analysis

5. Conclusions

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

The bent LG pane T17.52 sample showed the best results compared to the rest of the samples in its resistance to pressure load, which was 45.79 kN/m2. in the opposite of pane T21.52 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 T17.52, which was 44.90 kN/m2.

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

The best sample tested in the case of bent glass pane was the T17.52 sample, as it showed maximum strength to pressure with appropriate deflection and appropriate strains with the collapse deformation.

The two simple T13.52 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 LVDT Center Curve showed that T13.52-2 has the largest deflection compared to the other simples, although its pressure load is less than the T13.52-1 sample.

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

6. Future work

Going forward, we recommend that you do the following:

1. To study of different geometric shapes for resistance pressure.
2. To carry out additional tests on thickness of 10 mm to determine its actual behavior.

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