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Development of Connection of Glass Beam: A Numerical Study

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Abstract: *Glass, a fragile material that gains popularity in building construction, has been developed to sustain with high loads. This structural glass would not work effectively if the connection has not been able to transfer the loads properly. The study aims to optimize bolted connection of structural glass. We focus on the geometry optimization of the bolt to deal with heavy external loading that requires a strong connection. Numerical parametric studies are conducted by investigating four factors: material of insert, shape, diameter, and material of bolt, which play roles on stress distributions at glass-bolt contacts. The insert made of materials softer than glass and steel improve the initial contact condition. Shapes of bolt change not only its stiffness but also location of stress concentration. Larger diameter and higher elasticity of bolt can develop stiffness increasingly that could reduce stress concentration as well. Based on the numerical parametric studies results, we can choose an effective geometry, which provides a connection with high load resistance.*

Keywords: Bolted connection; Finite element analysis; Optimization; Stress concentration; Structural glass

1. INTRODUCTION

In the last decade, the usage of glass material in Cambodia increases remarkably not only for architectural elements but also for structural elements. To be a structural element, glass needs to sustain with heavy load and requires strong connections that can transfer the load to other elements in building properly. We will study on the bolted connection for glass structure that is a sensitive problem for glass as a brittle material. In literatures, some works had investigated on this kind of problem. However, the load carrying is still limited to deal with heavy load if compared to other material like steel or concrete structures.

According to the previous studies, the load carrying of glass connection is incompatible because of the local failure at the connected areas. Thus, it is important to develop and provide design tools for estimating the load capacity of assembly for glass structure. This study aims to optimize the geometry of bolted connection to obtain high load capacity with minimum stresses distribution to glass surface. Annealed glass plate is used in numerical modeling to investigate the load capacity of connection and stresses distribution due to external loads.

This study will focus on how to make a strong glass connection by studying on influences of insert materials, bolt diameter and stiffness, bolt shapes without insert materials and with insert Aluminum that will be performed in commercial software Abaqus/CAE v.6.13-1.

2. METHODOLOGY

2.1 Introduction

This section presents about bolted glass connection based on hypotheses from the literatures as an important information to current study, which aims to response to the research objective as developing capacity of connection for glass structure. To analyze this problem, numerical simulation by finite element modeling is performed in numerical software Abaqus/CAE ver.6.13-1. Furthermore, this section also presents geometry and mechanical behavior of each materials, which will be used in this study in order to simulate in numerical software. To validate the numerical simulation in this study, the results from literature (Frocht, M. M., & Hill, 1940) as mentioned in Section 3.1.1 is used to compare with current study through the same input parameters. Then result of approximate solution based on section 2.3 is also presented to verify with both results. After validating the results, further parametric studies will be conducted by investigating on influence of different geometries and materials as components of the connection in order to obtain an acceptable result.

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2.2 Finite element modeling by using Abaqus/CAE

2.2.1 Geometry

For geometry in this study, it is consisted of length 2h = 680mm x width 2b = 240mm and glass thickness t = 19mm. There are two holes and their diameters depend on each parametric study as illustrated in Fig.2.1. According to Fig.2.1. The geometry is symmetry. Therefore, there is only a half-length (h) of the glass plate is simulated in commercial software Abaqus/CAE.

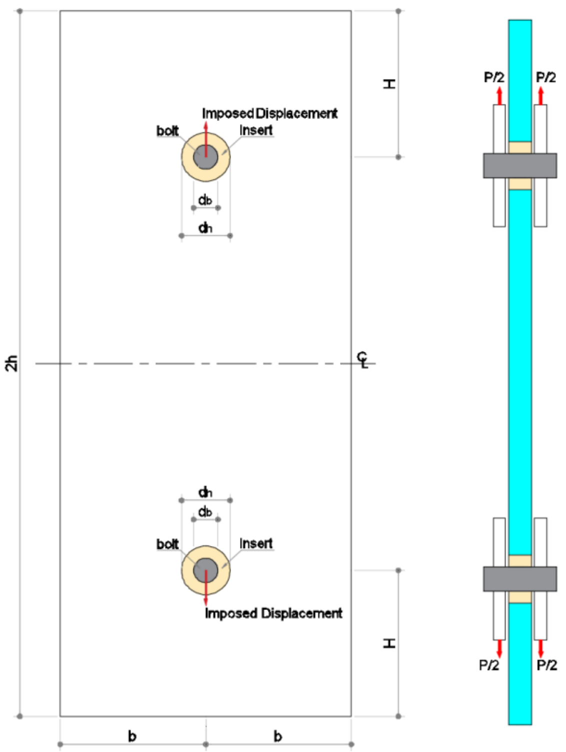


Fig.2.1. Schematic of geometry to investigate load capacity and stress distribution of pinned joint.

2.2.2 Finite element modeling of test

In this section, we use FE software Abaqus/CAE to simulate testing modeling and solid modeling of glass, bolt and insert materials as shown in Fig.2.2. An attention is paid on the modeling of contacts problem. Two different contacts between deformable bodies are considered: on one hand between the steel connector and insert materials, and on the other hand between insert materials and glass plate. Glass is supposed to be elastic, aluminum and steel are supposed as elastoplastic (Bernard and Daudeville, 2009) and each behavior of components above are shown in Fig.2.3. The problem in this study considers non-linear and three-dimensional. Besides, friction and clearances between the different parts are taken into account as friction coefficient μ_{ib} and μ_{ig} = 0.2 (Nielsen et al., 2009). Surface-to-surface contact with finite sliding option is used to define the contact relationship. Moreover, for this problem we used imposed displacement at both center sides of the bolt by applying on vertical upward direction U_2 and U_y.

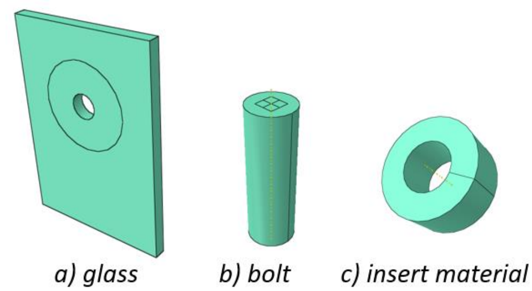


Fig.2.2. Solid modeling of glass, steel bolt and insert materials in Abaqus/CAE.

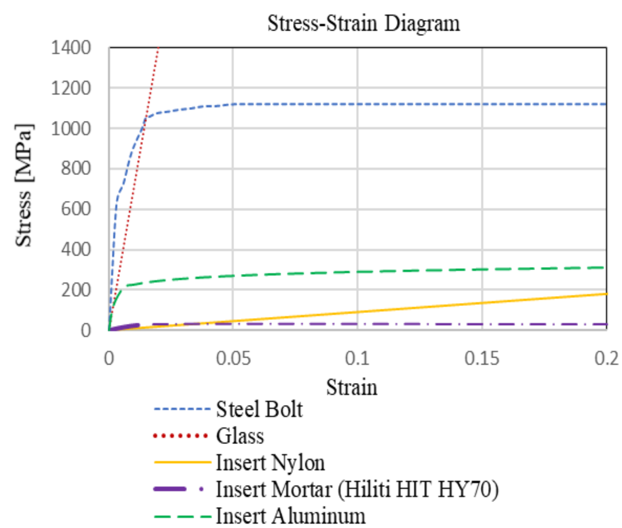


Fig.2.3. Behavior of materials modeled in Abaqus/CAE.

2.3 Approximate solution to determine maximum principal stress

To determine maximum principal stress at connected area due to stress concentration, we have approximate solution as mentioned in Frocht, M. M., & Hill, 1940 for solving contact problem between bolts and conforming hole in a semi-finite panel as shown in Fig. 2.1.

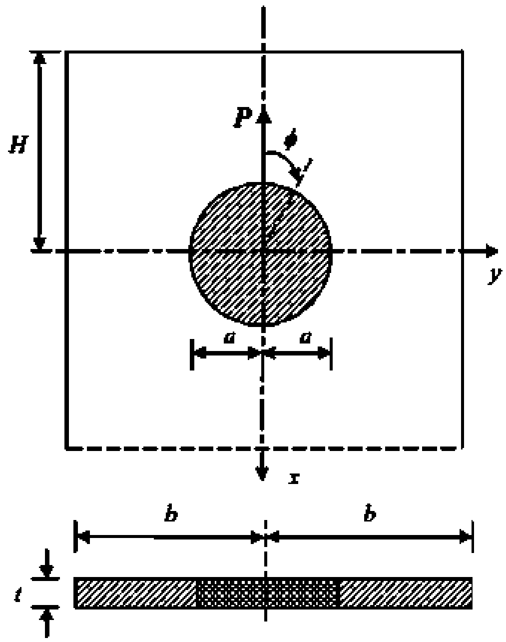


Fig.2.4. Schematic of investigating geometry (Maniatis, 2006).

The maximum principal stress is denoted:

$$\sigma_{\max} = K_{tn} \cdot \sigma_N \,, \qquad \text{(Eq. 1)}$$

Where,

$$\sigma_N = \frac{P}{2 \cdot t \cdot (b-a)} \,, \qquad \text{(Eq. 2)}$$

The stress concentration factor K_{tn} in case clearance $\Delta R = 0$ ($r = a$) can be approximately determined with:

$$K_{tn} = 12{,}882 - 52{,}714 \cdot \left(\frac{a}{b}\right) + 89{,}762 \cdot \left(\frac{a}{b}\right)^2 - 51{,}667 \cdot \left(\frac{a}{b}\right)^3 \,,$$

(Eq. 3)

3. RESULTS AND DISCUSSION

3.1 Numerical parametric studies

Five factors are performed in numerical parametric studies according to finite element modeling as described in Section 2.2.2.

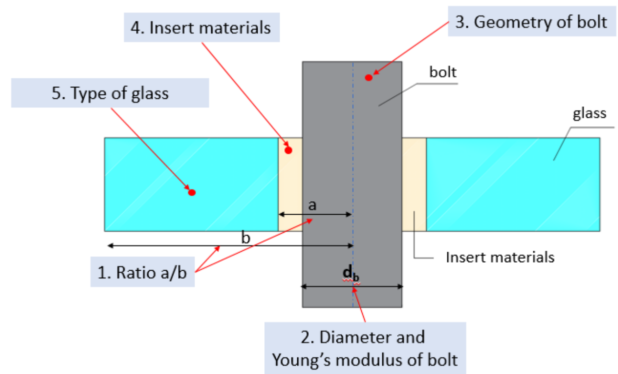


Fig.3.1. Schematic of connection's components which considered in numerical parametric studies.

3.1.1 Influence of ratio a/b

In this case, we use geometry of glass plate with 2b = 100mm, h = 600mm, thickness t = 10mm. And hole diameter is variable under applying constant load P = 30kN. To determine maximum principal stress on hole surface of glass plate due to stress concentration, approximate solution (described in Section 2.3) is used then we will compare results from approximate solution with reuslts from FEA in literature. Then we will try to model this problem with the same materials and process by using Abaqus in order to ensure that the results of current modeling is accetable. According to Fig.3.2, we used relation of maximum principal stress and ratio a/b under constant force P = 30kN for observing the result from three methods as introduced above.

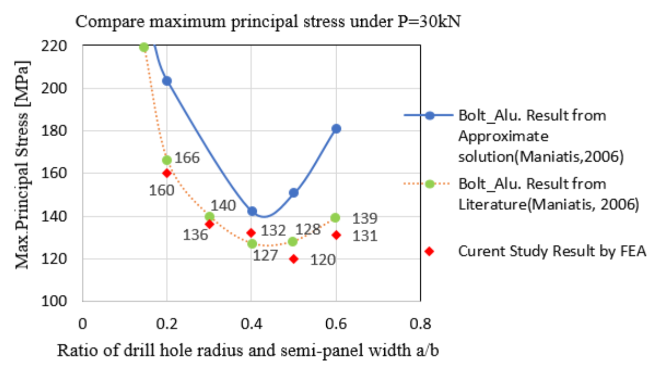


Fig.3.2. Results of influence of ratio a/b

The results above showed that when ratio of hole diameter (a) and semi-width (b) lies in the range of $0{,}1 < a/b \leq 0{,}2$, the stresses increase enormously and tend to infinity. It means maximum principal stress is increasingly. Then when ratio a/b at range a/b>0.2 so maximum principal stress decrease until reach a minimum value. Afterward, if we increase ratio a/b until a/b=0.5 so the maximum principal stress arises again. Thus, based on three curves in Fig.3.2 we could see the results from approximate solution and FEA is similar for shape of curves. However, the value of both results is a bit quite different because approximate method was derived by Frocht, M. M., & Hill, 1940 examined experimentally by using Aluminum panels with a hole in its center and aluminum and steel bolts. For result of FEA from literature and current study is a bit different. Thus, based on the results above we could use the concept from this modeling for further investigations in order to obtain an effective shape of glass connection with high resistance.

3.1.2 Influence of diameter and Young's Modulus of bolt

This section discusses about influence of variations of diameter and stiffness of bolt which described in Table 1 in order to investigate stress concentration around the hole area.

Table 1. Description of geometry

Descriptions	Diameter of hole [mm]	Imposed Displacement [mm]	Dimension of bolt (d_bxh_b) [mm]
GH20-WOI-nb20	20	1.5	20x60
GH20-WOI-nb20-2E_s	20	1.5	20x60
GH40-WIO-nb40	40	1.5	40x60

- ***Force-displacement***

According to the results below, we observe that under the same imposed displacement of 3mm force of larger bolt diameter is higher than small diameter. Thus, we are able to conclude that a rigid bolt provides high load resistance of connection. Similarly, force of higher Young's Modulus also provides high load capacity under displacement of 3mm.

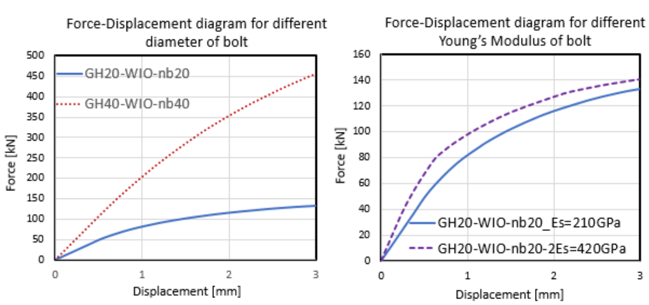


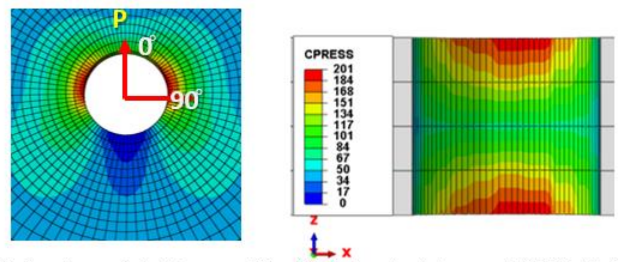
Fig.3.3. Diagram of force-displacement relationship.

- ***Maximum, minimum principal stress and contact pressure (CPRESS)***

In this section, we investigate maximum principal stress at angle 90˚, minimum principal stress at angle 0˚and contact pressure (CPRESS) around the hole on surface of glass as shown in Table 2.

Table 2. Result of max., min. principal stress and CPRESS

Descriptions	Force P=50kN			
	Max. principal stress [MPa]	Min. principal stress [MPa]	CPRESS [MPa]	Displacement of bolt $U_{b,50kN}$ [mm]
GH20-WOI-nb20	79	-162	181	0.26
GH20-WOI-nb20-2Es	64	-111	149	0.17
GH20-WOI-nb40	53	-52	67	0.12



Distribution of max. principal stress around the hole area at angle 0˚and 90˚. *Distribution of contact pressure (CPRESS) of bolt type* GH20-WOI-nb20

Fig.3.4. Schematic of distribution of max., min. principal stress and CPRESS around the hole area.

According to Table 2, we observe that bolt diameter 40mm provides small value of maximum, minimum principal stress and CPRESS under constant force P = 50kN as well as bolt which has high Young's Modulus ($E = 2E_{steel}$). Thus, we see that for high stiffness of bolt is able to reduce stresses on glass's surface.

3.1.3 Influence of geometries of bolt

Based on influence of diameter of cylindrical bolt in previous section, we observed that failure of glass located at end edge of the hole due to tensile stress at angle 90˚, which located perpendicular to direction of the force. Therefore, expansion contact area between bolt and glass is investigated to avoid failure due to small crack of the glass immediately, which will create surface damage before fully load distribution. Then we propose different bolt shapes to increase contact surface at connected area as shown in Table 3. Bolt type A and B, we try to increase contact surface on the hole area. For bolt type C is chamfer shape based on concept from literature (Bernard and Daudeville, 2009).

Table 3. Description for different shapes of bolt

Descriptions	Diameter of hole [mm]	Imposed Displacement [mm]
GH20-WOI-Bolt_Type-A 	20	2
GH20-WOI-Bolt_Type-B 	20	2
GH40-WOI-Bolt_Type-C 	40	2

- ***Force-displacement***

In Fig.3.5. demonstrates that under displacement of 0,8mm we obtain force of the three different types of bolt is similarly as illustrated in diagram below.

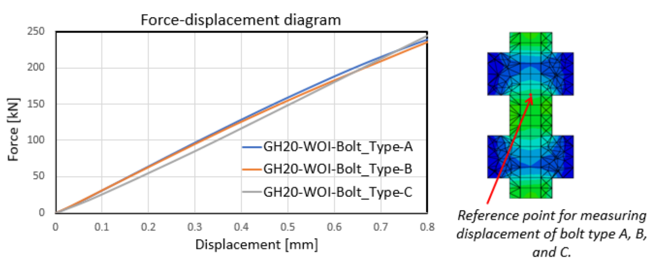


Fig.3.5. Diagram of force-displacement relationship and reference point for measuring displacement of bolt.

- ***Maximum, minimum principal stress and contact pressure (CPRESS)***

Table 4. Result of max., min. principal stress and CPRESS for different types of bolt

Descriptions	Force P = 50kN			
	Max. principal stress [MPa]	Min. principal stress [MPa]	CPRESS [MPa]	Displacement of bolt $U_{b,50kN}$ [mm]
GH20-WOI-Bolt_Type-A	66	-96	639	0.0782
GH20-WOI-Bolt_Type-B	79	-124	137	0.0792
GH40-WOI-Bolt_Type-C	135	-288	221	0.0908

In Table 4. For bolt type A and B provide smaller value of maximum and minimum stress than bolt type C under constant force P = 50kN. However, for contact pressure of bolt type C is smaller than bolt type A that has thicker thickness above connected area on surface of glass. Therefore, we can conclude that for bolt, which has large contact area to glass's surface and thin thickness will be able to reduce stresses on surface of glass effectively as well as bolt type C as chamfer shape.

3.1.4 Influence of insert material

This section presents about influence of different insert materials between bolt and glass. Generally, in joint area high local stress occurs at the edge of the hole. For steel construction, local stress-peak can be reduced by local plastic due to the plastic materials behavior (Bernard and Daudeville, 2009). However, according to natural of glass, glass is a brittle material therefore a ductile material should be used at interface of the bolt and glass. In this study, there are three inserts which commonly used in previous research as described in Table 5 are investigated which aims to provide uniformly stresses on surface of glass over the contact area and enables to avoid a localize loading.

Table 5. Description of bolt geometry with insert materials

Types of insert material	Diameter of hole [mm]	Imposed Displacement [mm]	Thickness of insert [mm]	Dimension of bolt (d_bxh_b) [mm]
GH40-WINylon10-nb20	40	4	10	20x60
GH40-WIMortar10-nb20	40	6	10	20x60
GH40-WIAlu.10-nb20	40	4	10	20x60

- ***Force-displacement***

According to Fig.3.6, we observe that Mortar insert provides the lowest load capacity and remain constant from displacement in approximately 4mm. For the same displacement of 8mm, its load capacity reaches only 29kN while 117kN for Nylon and 150kN for Aluminum. Therefore, only Aluminum material provides higher load capacity with small displacement.

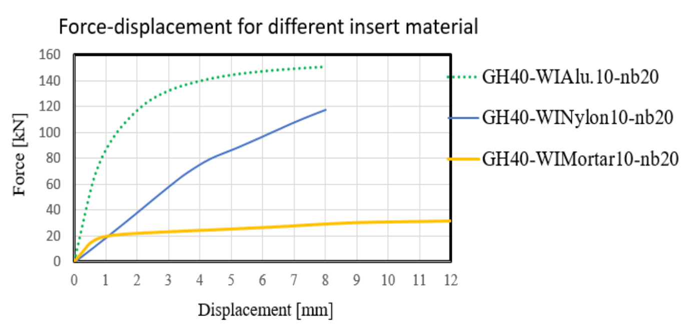


Fig.3.6. Diagram of force-displacement relationship.

- ***Maximum, minimum principal stress and contact pressure (CPRESS)***

Table 6. Result of max., min. principal stress and CPRESS for different types of insert material

Descriptions	Under Force P = 30kN			
	Max. principal stress [MPa]	Min. principal stress [MPa]	CPRESS [MPa]	Displacement of bolt $U_{b,50kN}$ [mm]
GH40-WINylon10	37	-52	56	0.795
GH40-WIMortar10	22	-36	77	4.509
GH40-WIAlu.10	28	-34	45	0.141

Based on Table 6 , we observe that maximum principal stress of Mortar insert is smaller than Nylon and Aluminum under force 30kN, despite load capacity of this insert is very small. And CPRESS of Aluminum insert is smaller than other two and load capacity of this kind of insert materials is also high. Therefore, we obtain that bushing materials which be able to transfer uniform load with small stresses concentration from steel connector to glass surface is Aluminum.

3.1.5 Influence of types of glass material

Generally, structural application of glass rarely uses monolithic of glass plate. In this section, we will investigate bolted connection with laminated glass, which composed of two and three layers of annealed glass by bonding with PVB material as following:

a). Monolithic of annealed glass

b). Laminated glass with 2 layers of annealed glass

c). Laminated glass with 3 layers of annealed glass

We use interlayer materials as PVB material to connect one glass plate to another plate. Mechanical properties of PVB are Young's Modulus: E_{PVB} = 5,2MPa and Poisson's ratio: υ = 0,45 (CAMILLA, BENGTH,2005).

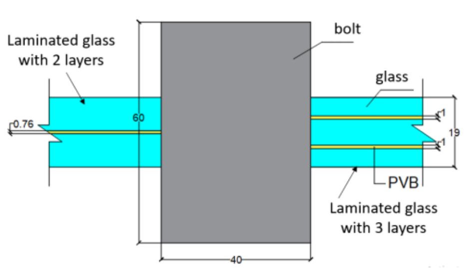


Fig.3.7. Schematic of connection's components with laminated annealed glass composed with 2 and 3 layers.

- ***Force-displacement***

According to Figure.3.8 shows that monolithic annealed glass plate provides smaller displacement than laminated two and three layers under the same force P = 200kN. The main reason of these results may occur in decreasing stiffness of laminated glass plate by filling a soft stiffness as interlayer PVB.

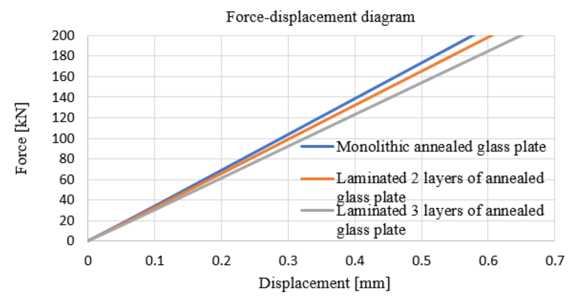


Fig.3.8. Diagram of force-displacement relationship for different types of glass plate.

- ***Force-CPRESS***

According to Figure.3.9, we plotted relationship of force-CPRESS for different types of composite layer. The result below shows that monolithic of annealed glass provides smaller value of CPRESS than laminated 2 and 3 layers of annealed glass plate under force P = 200kN. Moreover, for value of CPRESS for laminated 3 layers of annealed glass is higher than 2 layers under the same force 200kN.

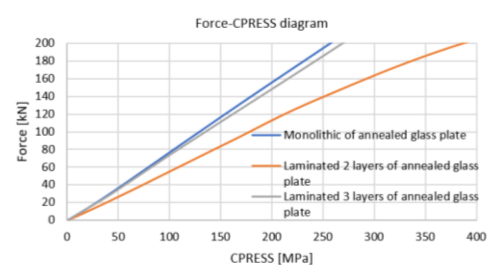


Fig.3.9. Diagram of force-CPRESS relationship for different types of glass plate.

- ***Distribution of contact pressure on monolithic and laminated annealed glass***

This section demonstrates distribution and value of contact pressure under force 95kN on monolithic, laminated 2 and 3 layers of annealed glass as dedicated in Fig.3.10.

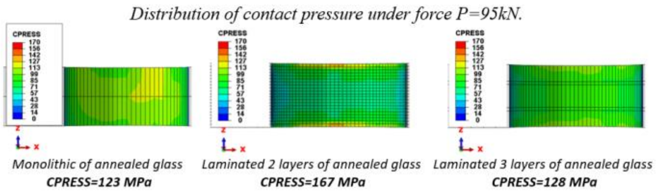


Fig.3.10. Distribution and value of contact pressure on monolithic, laminated 2 and 3 layers of annealed glass's surface under force 95kN.

3.1.6 Combination of parametric studies

As several parametric studies have been performed above then we observed that cylindrical bolt with larger diameter provided small stresses concentration but the problem is completely high stresses at edge of the hole immediately while loading is not fully transferring from steel connector to glass surface. To avoid this aspect, we proposed expanding contact surface between bolt and glass but the stresses concentration of those kinds of bolt shape is higher than cylindrical bolt and its load capacity are higher as well. Then, the usage of insert materials between bolt and glass was performed. Through the investigation, we obtained that Aluminum insert is a great option to decrease stresses concentration in glass surface. In this section, different types of bolt shape composed with Aluminum insert are investigated to obtain the effective geometry. There are six types of bolt shapes, which based on concept bolt type B and C as following below.

Table 7. Description of different shapes of bolt shape with Aluminum insert

Descriptions	Hole diameter [mm]	Imposed displacement [mm]
GH40-WIAlum.-Bolt_Type-C1 	40	1.5
GH40-WIAlum.-Bolt_Type-C2 	40	1.5
GH30-WIAlum.-Bolt_Type-C3 	30	1.5
GH40-WIAlum.-Bolt_Type-C4 	40	1.5
GH40-WIAlum.-Bolt_Type-B1 	40	1.5
GH40-WIAlum.-Bolt_Type-B2 	40	1.5

- ***Force-displacement***

According to Figure.3.11 shows that displacements of bolt type B2, C2, and C4 is smaller than bolt type B1. C1, and C3 under the same force 200kN. Moreover, we observe that bolt type C3 provides the highest displacement among other types.

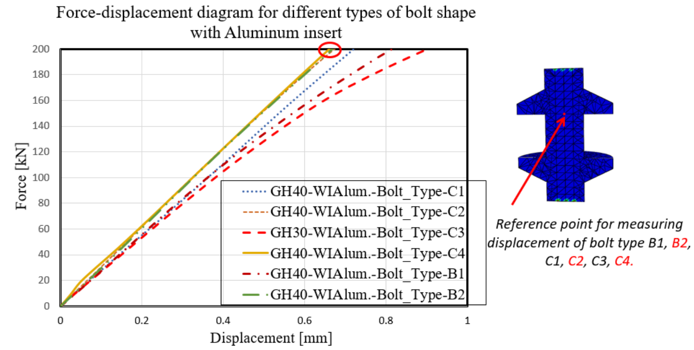


Fig.3.11. Diagram of force-displacement relationship for different types of bolt shape with Aluminum insert.

- ***Maximum, minimum principal stress and contact pressure (CPRESS)***

Based on stresses concentration around the hole area of these six bolt types as presented in Table 8 shows that bolt type B1 and B2 produce smaller maximum principal stress and CPRESS than other types under force 50kN. Bolt type C3 and C4 provide the highest CPRESS among other four types as well as displacement of these two types is also a bit higher.

Table 8. Result of max., min. principal stress and CPRESS for different bolt shapes with Aluminum insert

Descriptions	Force 50kN			
	Max. principal stress [MPa]	Min. principal stress [MPa]	CPRESS [MPa]	Displacement of bolt $U_{b,50kN}$ [mm]
GH40-WOI-Bolt_Type-B1	49	-73	65	0.09
GH40-WOI-Bolt_Type-B2	50	-74	67	0.081
GH40-WOI-Bolt_Type-C1	71	-83	86	0.093
GH40-WOI-Bolt_Type-C2	84	-86	82	0.078
GH30-WOI-Bolt_Type-C3	133	-197	186	0.089
GH40-WOI-Bolt_Type-C4	66	-65	142	0.083

According to the results of maximum principal stress and CPRESS for different types of bolt with Aluminum insert demonstrates above bolt type B1, B2, C1 and C2 provide a small value of stresses concentration compared with bolt type C3 and C4. In this section, the loads of bolt type B1, B2, C1 and C2 are increased until 350kN to observe variation of this kind of bolt correspond to applying force. According to the result as illustrated in Figure.3.12, we obtain bolt type B2 and C1 produce smaller CPRESS than B1 and C2 under force 350kN.

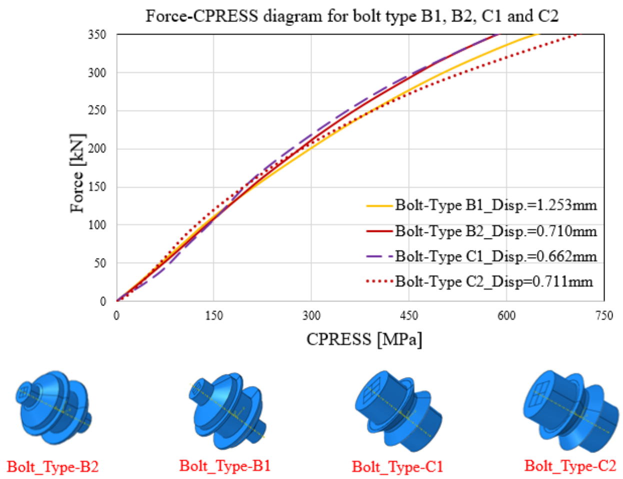


Fig.3.12. Diagram of force-CPRESS relationship for bolt type B1, B2, C1 and C2.

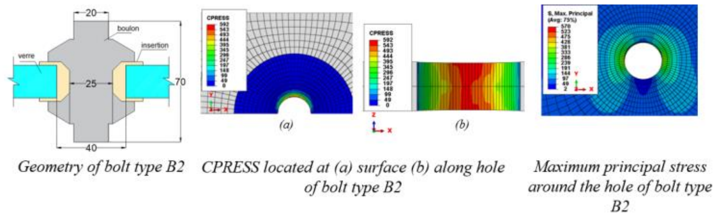


Fig.3.13. Schematic of geometry, distribution of contact pressure and maximum principal stress for bolt type B2.

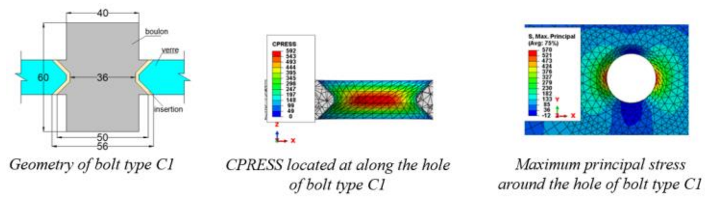


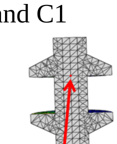
Fig.3.14. Schematic of geometry, distribution of contact pressure and maximum principal stress for bolt type C1.

4. CONCLUSIONS

According to Table 9, we observe that bolt type C1 and B2 are similar by comparing contact pressure. The reason that bolt type C1 provide high stress inside surface of glass's hole because when we try to expand contact area between steel bolt and glass by chamfering inside surface then the middle thickness gets thinner which will create surface cracking of glass possibly. For bolt type B2 we observe that even its upper diameter is smaller than type C1 (40mm) so influence of stiffness of bolt type B2 also affect its load transferring. Especially, it can reach the results, which is similar to bolt type C1 that its stiffness is bigger than bolt type B2. In this case, further parametric study should be conducted by increasing diameter and decreasing length of bolt type B2 that be able to compare with bolt type C1. According to the results shown in Fig. 3.12**,** we recommend to use the bolt of shape C1 and B2. C1 with length l_b = 60 mm and mid-length diameter $d_{b,mid}$ = 36mm provides high resistance (350kN) at displacement of bolt 0.83mm and low value of maximum principal stress around the hole area is 71MPa under force 50kN. For bolt type B2 with l_b = 70 mm and $d_{b,mid}$ = 25mm provide high resistance (350kN) at displacement of bolt 0.7mm and low value maximum principal stress around the hole is 50MPa under force 50kN.

Table 9. Result of maximum principal stress, CPRESS, displacement and dimension for bolt type B2 and C1

Description	Force P = 350kN			
	Dimension lb x db,mid. [mm]	Displacement of bolt [mm]	CPRESS [MPa]	Max. principal stress [MPa]
Bolt type B2	70 x 25	0.71	590	377
Bolt Type C1	60 x 36	0.83	583	569



Reference point for measuring displacement of bolt.

5. RECOMMENDATIONS FOR FUTURE WORK

5.1 Modeling of glass material

In this study, we use the annealed glass with the properties modeled as purely elastic material to investigate on geometry optimization of the bolted connection. In general, structural glasses are safety glasses made of tempered laminated glass which present the residual stress and multi-layers glass. The obtained effective geometry of bolted connection should be validated with tempered laminated glass which if fully modeled. Another material-modeling problem is that the property of glass at contact is not elastic but also densification. This last consideration of glass's properties would make the modeling more complete.

5.2 Bolted connection

Experimental method should also be conducted to verify the load capacity and stress concentration around the drill holes area to confirm the numerical modeling's results. Moreover, we still can study on the geometry optimization by studying on the variation of angle of chamfer's edge of the hole. For general structures beside beam and column such as slab system, the assemblies resist not only the in-plane loading but also the out-plane loading such as lateral bending and torsion. Furthermore, the effect of hole's spacing must be also investigated.

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