CONCEPT OF NONLINEAR ANALYSIS AND DESIGN OF GLASS PANELS

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ABSTRACT

This paper discusses the concept of the reason why non-linear analysis leads to an economical design is explained and the finite element program, **NASHELL**©, is employed to demonstrate the large deflection behavior of thin glass and aluminum plates. Surface stress is plotted for the ease of understanding of nonlinear behavior when the glass undergoes large deformation. Owing to possible saving in material weight, nonlinear and large deflection plate theory has been commonly used in western countries like United States and Canada. With the trend of globalization, it appears that Hong Kong engineers need to equip themselves on various new techniques for enhancing their competitiveness and non-linear analysis and design is considered to be one of these advanced techniques. Glass panel is commonly used in curtain walls and glass structures.

Keywords

Glass and aluminum panels, large deflection analysis, finite element method, testing

INTRODUCTION

Glass plates are widely used as glazing panels in buildings to date and it has a unique and important quality of transparency and acceptable strength (So, Lai and Chan[1]). Its provision of unobstructed view to the occupants has made it highly competitive against other types of facades. However, in Hong Kong and elsewhere, the failure of glass panels is common and the direct falling of glass debris onto the street level may also cause casualties. Studies have shown that breakage of glass is due to the concentrated tensile stress on the surface flaw. Due to the difficulty in estimating the density, orientation and location of these flaws in glass panels, the failure probability instead of direct specification of failure load for a glass panel is usually used as a reference for safety of glass structures. Generally speaking, the probability of failure (POF) of 8/1000 is acceptable for most purposes. In congested area, the POF should be further reduced.

In recent years, the extensive construction of high rise buildings in many cities in China and in Hong Kong has further highlighted the importance of conducting more research in the safety of the structures. Glass panels are usually fixed to a building as building envelop. Typically the glass is held in place by means of adhesive strength of silicone sealant and/or mechanical fixing.

To evaluate the stress in a glass panel numerically, the classical close-form solution method, the finite difference method and the finite element method can be used. Generally speaking, the classical method solving directly the equilibrium equation using the strong formulation can only be used in some very simple cases. The finite difference method involves less computational work than the finite element method but may be limited to standard or simple plate geometry. For glass panels with odd shape and under complicated boundary conditions such as the edges are not completely or fully restrained along their sides, these methods may be too complex, if not impossible. The finite element method is generally considered to be the most versatile in terms of flexibility.

SUPPORT CONDITIONS OF GLASS PANELS

Glass panels are commonly used in modern building facades. When they are used as fixed lights or window sashes in curtain wall systems (Figure 1), they are usually supported on four sides by structural sealant or gaskets. When the glass panels are used in glass wall system, they can either be fixed by structural sealant to glass fin (Figure 2) or by mechanical fixings to backing steel structures (Figure 3). Glass can be used as structural elements as well. For example, the glass fin in glass wall system (Figure 4) or glass beam (Figure 5) in glass roof system.

Figure 1: Curtain Wall Specimen

The overall dimension is 16.2 m (w) (4.05 + 12.15) m x 21.6 m (h).

The dimension of the fixed panel is 2.48 m (w) x 3.24 m(h).

Figure 2: Glass Wall Specimen

The facial glass is fixed to the glass fin by structural sealant.

Figure 3: Glass Wall Specimen
The facial glass is mechanically fixed to the tension rods.

Figure 4: Glass Wall Specimen
The glass is used as structural elements as glass fin.

Figure 5: Glass Roof Specimen
The glass is used as structural elements as glass beam.

Four side simply supported panel

For glass panel used in the curtain wall system, it is commonly held in place by means of adhesive strength of silicone sealant. When glass panel subjected to the design wind load, it usually deforms more than its thickness. Under this situation, its behavior cannot be modeled accurately by linear theory.

A plate under the linear assumption for its behaviour does not consider the effect of change of geometry and therefore it resists external loads or pressure by the bending action, in a similar way of a beam with one end pin and the other end roller taking lateral load. However, when the two ends of the beam is restrained against lateral movement and its deflection is significant, a catenary, cable or membrane action is developed. The grossly deformed member will activate an internal component against the external load and this mechanism is much more efficient than the bending action since the former is much stiffer. A large deflection theory for plated structure is therefore generally more efficient when used in design, especially for thin plate where the bending stiffness is small and the membrane can be developed after lateral deflection. The added advantage for using large deflection theory for plates over beams is the natural formation of relatively rigid internal support from material along the four sides of the plate, instead of rigid support provided by external supports or boundary conditions.

Figure 6 shows an example of glass panel with an overall dimension of 2.0 m by 2.0 m and having a thickness of 8.0 mm. The glass panel is simply supported at 4 edges and subjected to a uniform distributed load over its surface.

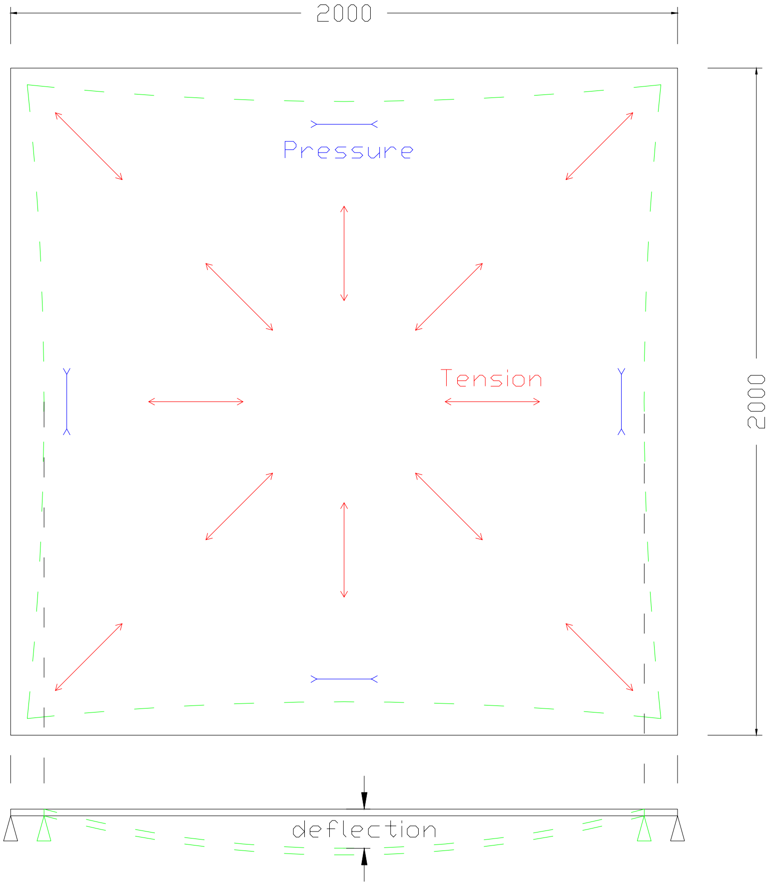

Figure 6: Glass panel of 8 mm thick subjected to UDL

When under wind pressure, the centre diagonal fiber deforms and a component is developed against the external wind. To maintain equilibrium, the fiber along the four sides will be in compression to provide ‘supports’ to the tension diagonal fiber. The larger the deflection, the more effective action will be developed in the system.

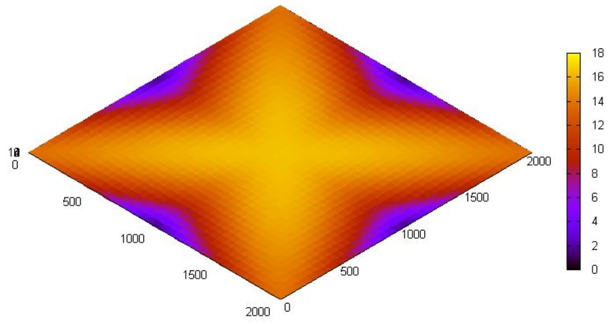

Figure 7a: Linear Theory (1kPa)

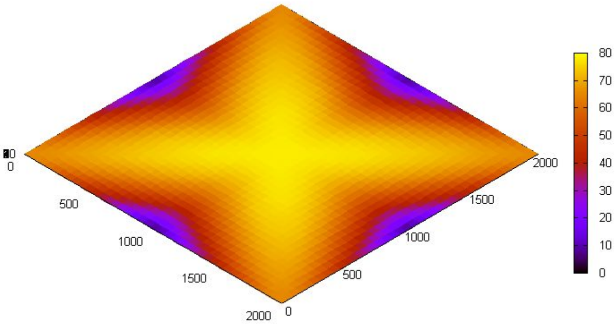

Figure 7b: Linear Theory (5kPa)

Figures 7a and 7b show the stress patterns by linear plate bending theory analysis of glass panel subjected 1 kPa and 5 kPa wind load respectively. Because the linear theory does not consider the change in geometry of the plane, therefore, the stress pattern does not changed with respect to increase in the wind load. The maximum stress occurs at its center.

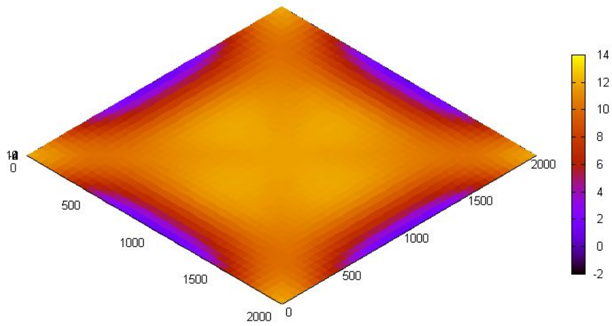

Figure 7c: Non-linear Theory (1kPa)

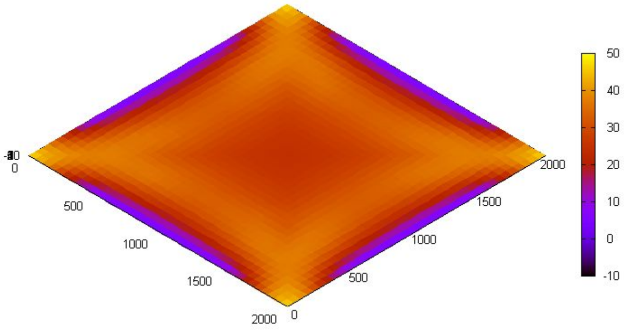

Figure 7d: Non-linear Theory (5kPa)

Figures 7c and 7d show the stress patterns by nonlinear theory analysis of glass panel subjected 1 kPa and 5 kPa wind load respectively. From Figure 7c, we observe that the membrane action already developed when the glass panel subjected to the loading of 1 kPa. The stress levels along the two diagonals are more or less the same. However, this situation has been changed when the panel is further loaded to 5 kPa (Figure 7d). The maximum stress appears at the 4 corners of the plate rather than at its center.

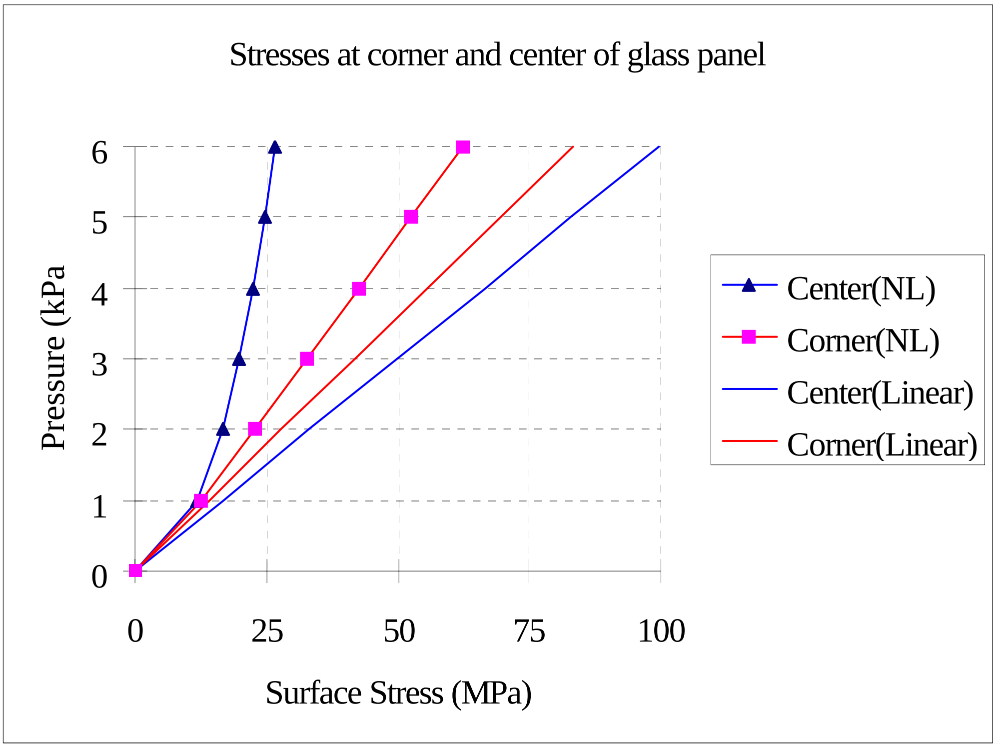

Figure 8a: Pressure vs Stress for glass panel

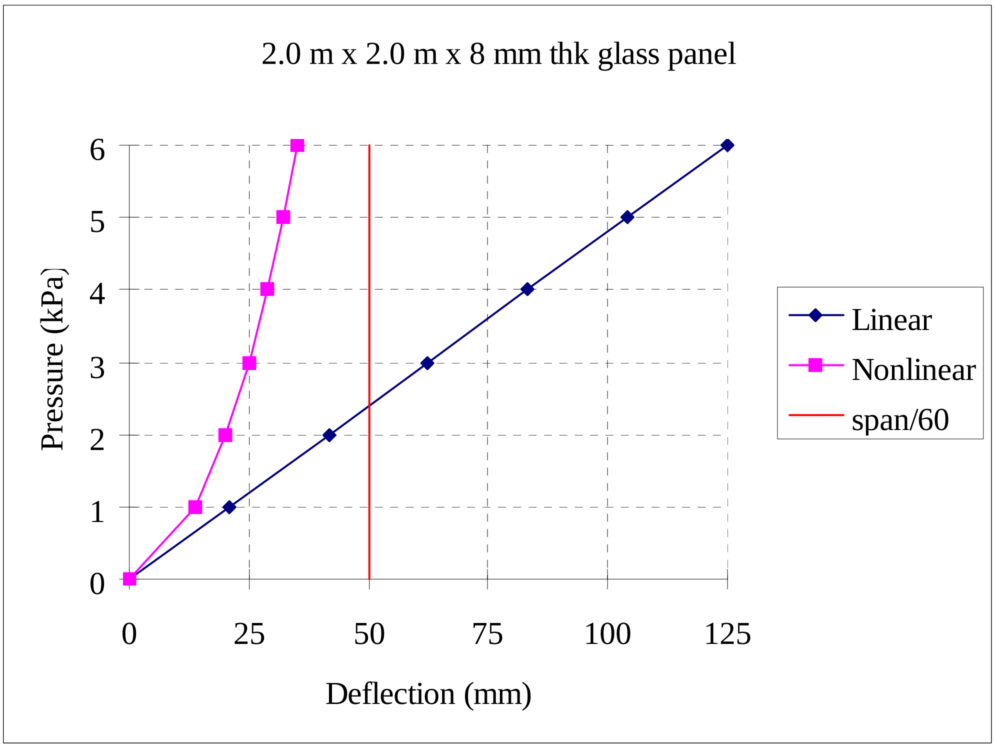

Figure 8b: Pressure vs Deflection for glass panel

Four points supported panel (Mechanical fixings)

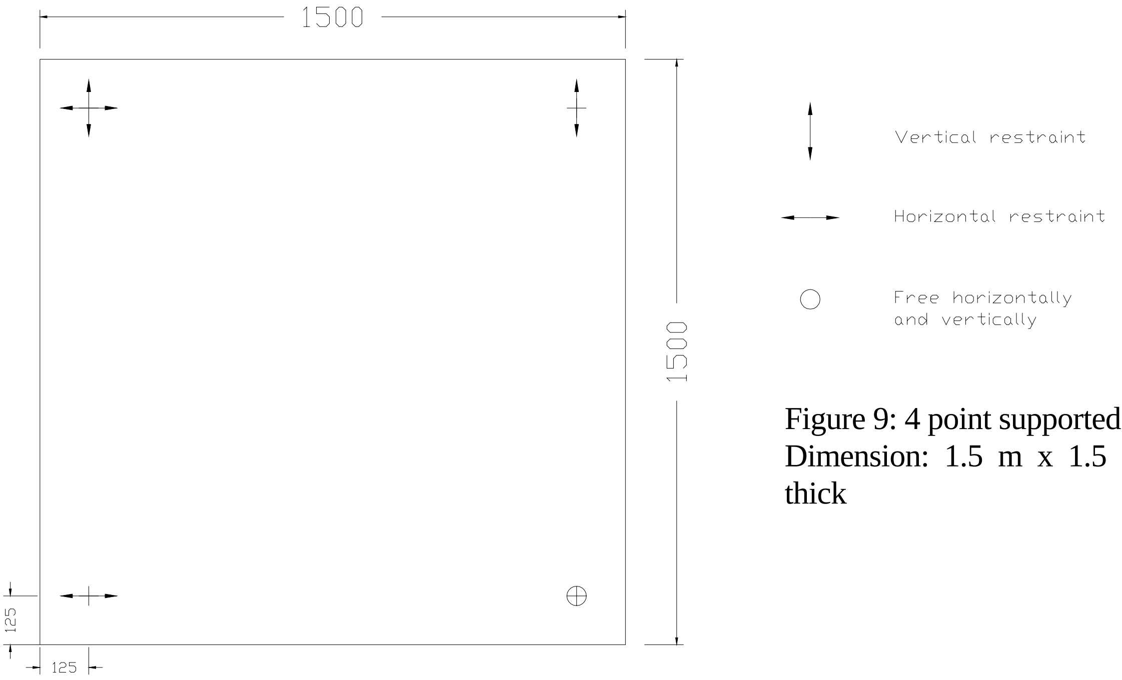

Figure 9: 4 point supported glass panel Dimension: 1.5 m x 1.5 m x 12 mm thick

Figure 9 shows a glass of dimension 1.5 m x 1.5 m x 12mm thick subjected to uniformed distributed loading. The restrains conditions of the point supports are shown in Figure 9 and the results are presented in Figures 10 and 11.

When subjected to loading of 5 kPa, the maximum stress and deflection for linear analysis are 45.4 MPa and 26.1 mm respectively. For nonlinear analysis, the maximum stress and deflection are 37.1 MPa and 21.8 mm respectively. There differences in the linear and nonlinear analysis of 4-points supported plate are not very significant. It is because the membrane stresses cannot be built up effectively as in the case of 4-sides supported condition. For comparative purposes, a nonlinear analysis of the example with all 4-points restrained in both lateral directions has been carried out. The maximum stress and deflection are reduced to 23.8 MPa and 12.1 mm respectively.

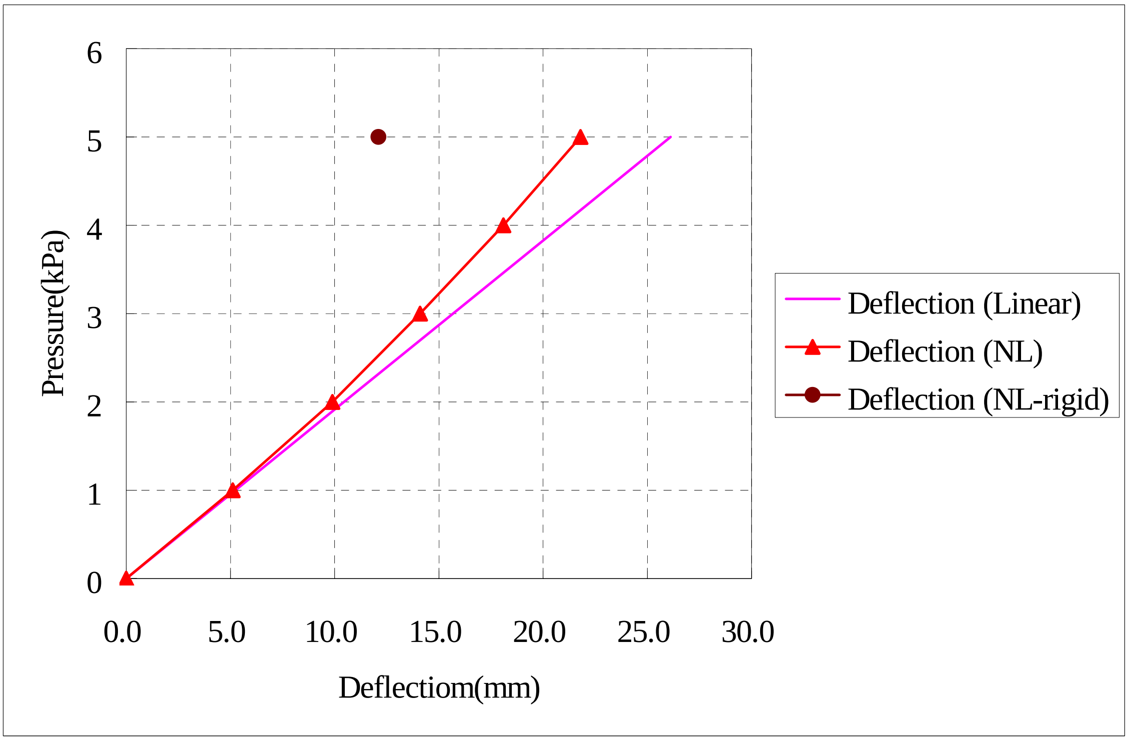

Figure 10a: Deflection of the 4-points supported glass panel

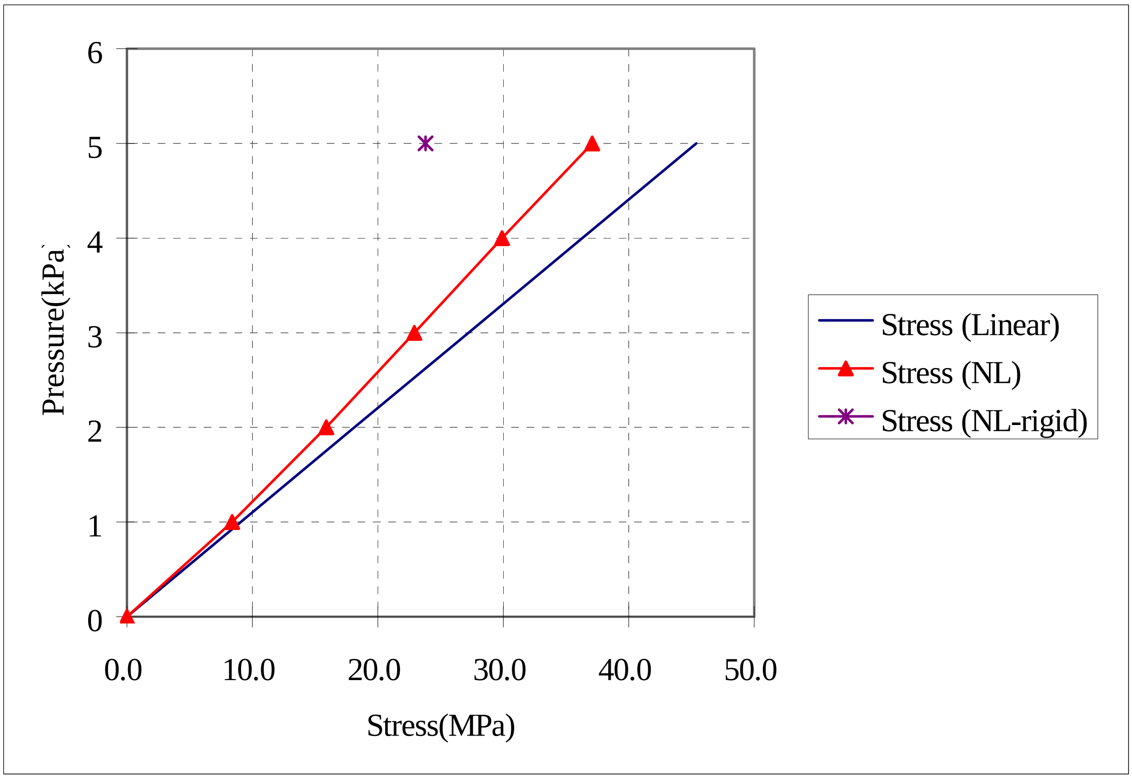

Figure 10b: Surface stresses of the 4-points supported glass panel

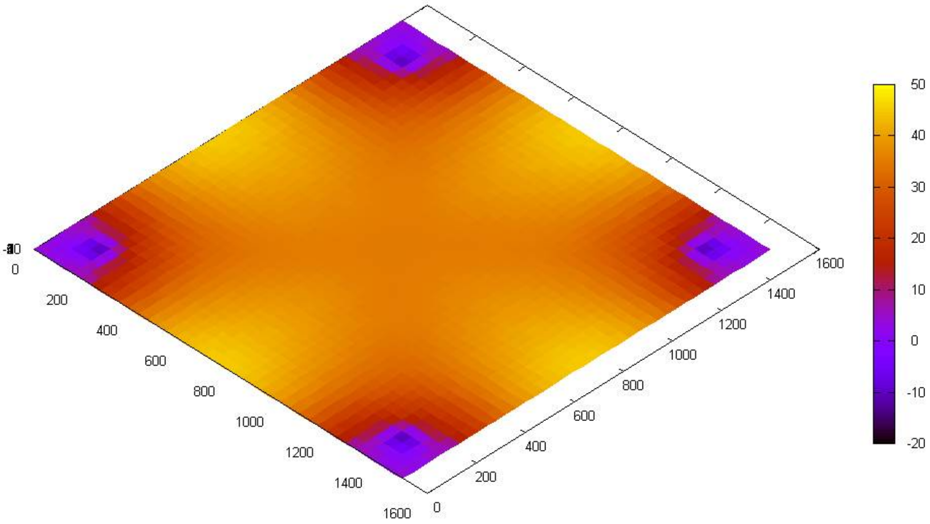

Figure 11a: Linear analysis under UDL of 5 kPa

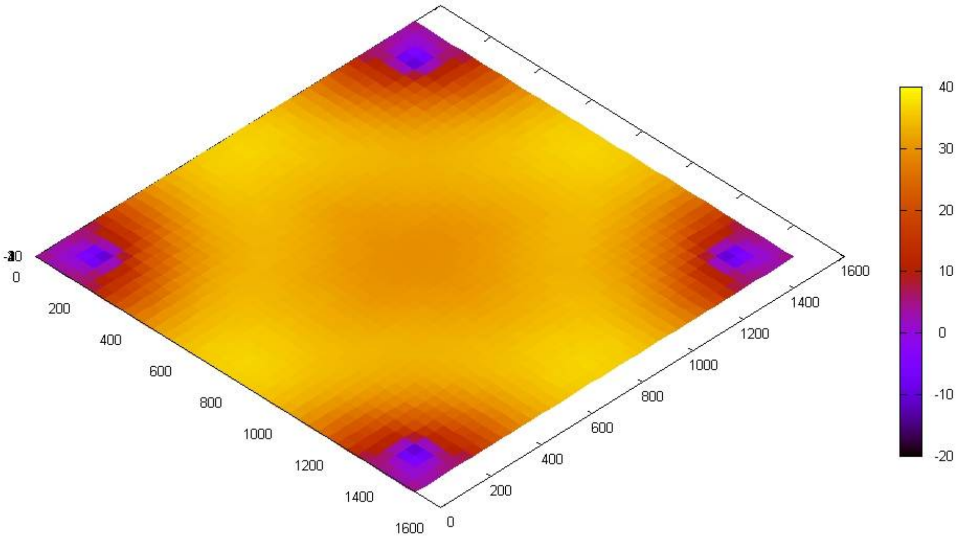

Figure 11b: Nonlinear analysis under UDL of 5 kPa

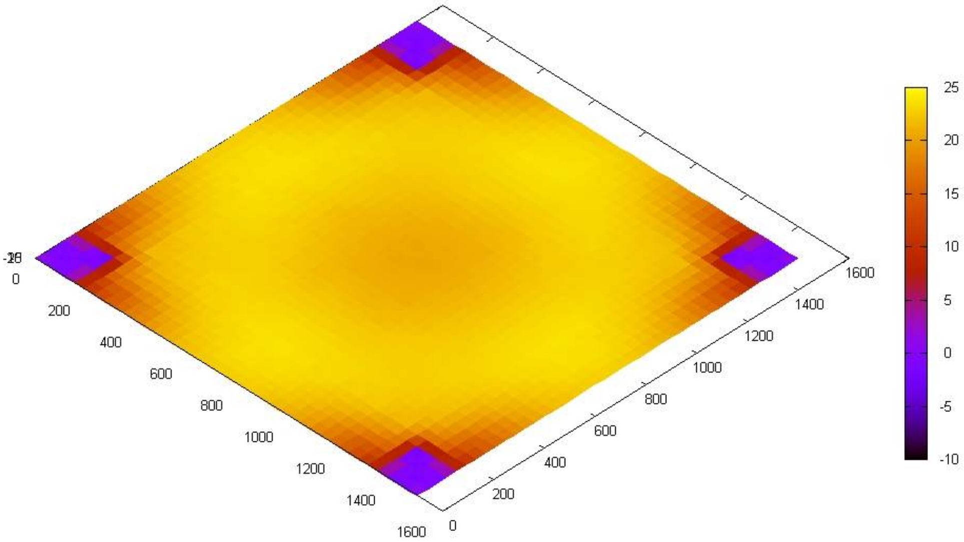

Figure 11c: Nonlinear analysis (rigid constrain) under UDL of 5 kPa

When using glass furnished with holes, the designer must pay attention to the placement of hole to fulfill the requirements of national standards e.g. the hole must be at least 6.5 times the thickness of glass away from the corner. Detailed requirements can be found in ASTM C1048. In order to deal with unavoidable stress concentration around the fixings holes, heat strengthened or tempered glass must be used. The glass panels should also be heat-soaked as a quality check to reduce the incidence of nickel sulphide inclusions in the plane. Figure 12 shows a spontaneous breakage of glass panel caused by the inclusions.

Figure 12: Spontaneous breakage of tempered glass

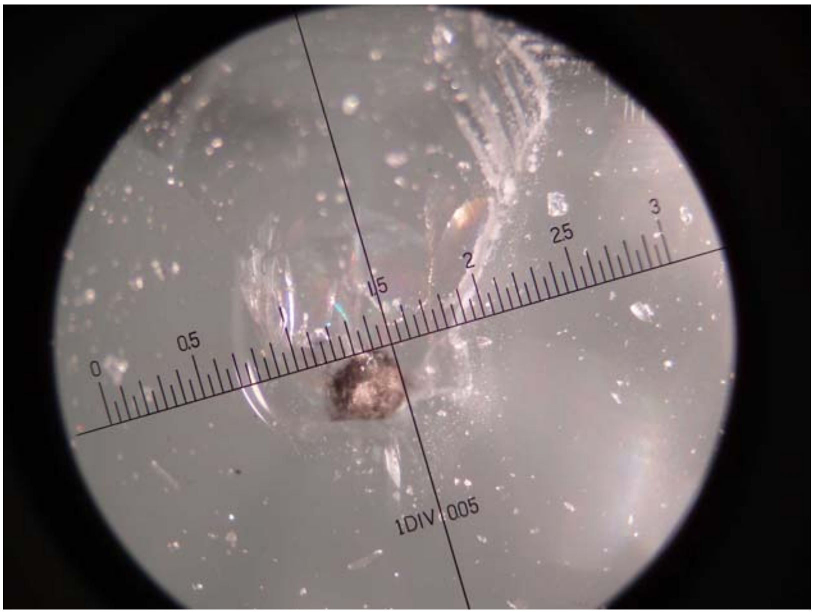

Figure 13: The inclusion (approx 0.35 mm dia.) found in the breakage origin (butterfly pattern)

Figure 14: Glass failure during the performance test

Figure 15: Closer look at the fixings

Glass fin/beam

In modern façade, there is a tendency to maximum the transparency of building. One possibility might be to reduce the size of framing member by the use of tension structure (Figure 2). Another possibility might be to extend the use of glass to load carrying elements. When glass uses as the load carrying elements, it is usually in form of glass fin (Figure 4) in vertical or slightly sloped direction and glass beam (Figure 5) in horizontal direction. Glass fins/beams are generally simply supported.

Nowadays, glass fins of span longer than 10 m are commonly used. Figures 16 and 17 show a glass wall specimen with glass fin of span up to 19 m is adopted.

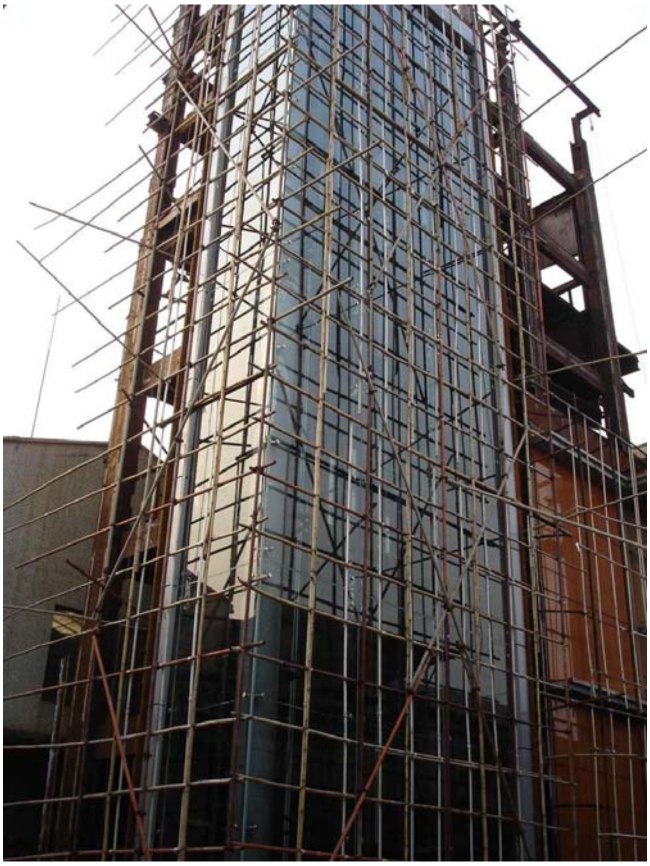

Figure 16: Glass Wall Specimen

Figure 17: View from inside

With this span length, it is not possible to manufacture the fin in one piece. Therefore, structural splices are required. A half sized fin test (Figure 18) has been carried out to verify the performance of the moment splice joint. With the help of the fin test, designer has the chance to visualize any deficiencies or unaware problems before the full-scaled mockup is tested

Figure 18: Testing of structural splice joint

Figure 19: Specimen tested to failure

When the glass is used as glass beam, special care should be given to give extra redundancy in the design. The glass roof as shown in Figure 5 has a glass beam formed with 3 layers of glass pane laminated together (Figure 20).

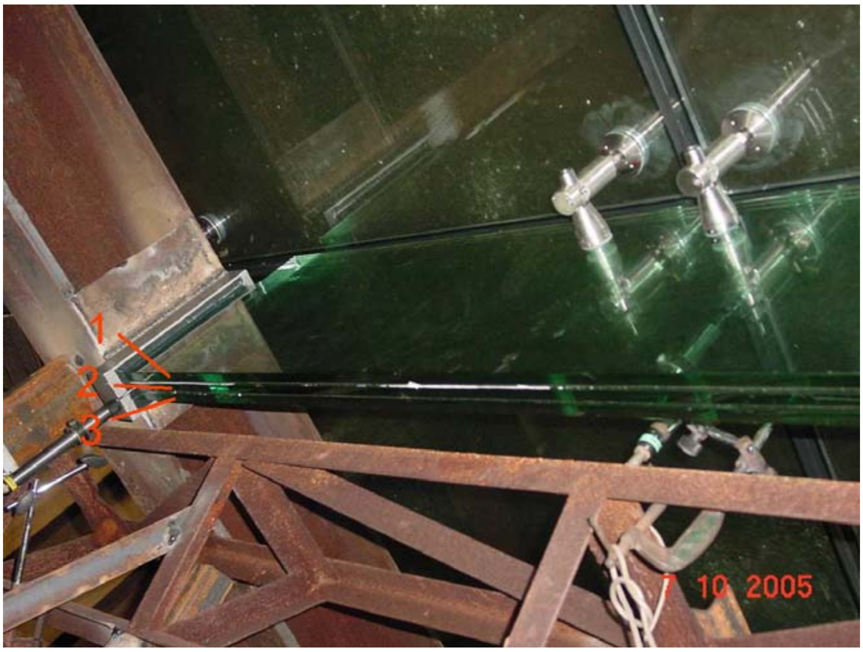

Figure 20: Glass beam formed by 3-layer of glass pane

CONCLUSIONS

In this paper, the nonlinear large deflection finite element program, **NASHELL**[2], based on the discrete Kirchhoff plate bending element and constant strain triangular element with vertex rotation is employed to analyze glass panes, which have been used in numerous projects in Hong Kong and China with success without report of breakage during visit of typhoon. For demonstration of the geometrically nonlinear effect, surface stresses are plotted in the large deformation range. Care on the design of point-fixed glass panes and glass beams is also highlighted in this paper.

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