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ORIGINAL ARTICLE

Structural behavior of architectural glass plates

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Abstract Architectural designers frequently use glass plates that have shapes other than rectangular in both residential and commercial buildings. Commonly, one sees glass plates with trapezoidal, triangular, hexagonal, and circular shapes. For example; window glass in aircraft control tower cabs leans outward to enable ground controllers to have a good view of operations. Consequently, aircraft control tower cabs have glass plates that have trapezoidal shapes. This paper deals with the structural behavior of glass plates other than rectangular shapes. A higher order finite element model based upon Mindlin plate theory was employed to analyze different shapes of glass plates. First, a comparison between experimental and finite element results for a tested trapezoidal glass plate is presented, which shows a very good agreement. Then, the finite element model was used to compare load-induced stresses with those for bounding rectangular shapes. Results of analysis are presented and discussed.

1. Introduction

Designers of architectural glazing use nonrectangular glass plates, and therefore considerable interest has been generated within the glazing design community. Architects and engineers are encountering difficulty with glass design processes for shapes other than rectangular. This difficulty arises from two reasons: (a) an inability to perform nonlinear analysis on glass plates with large deflection and (b) an inability to perform failure predication analysis. A thin glass plate might undergo deflection up to 10 times its thickness before fracture. Of course the linear plate theory is no longer applicable to this analysis because of the development of membrane stresses in addition to bending stresses. Many researchers have contributed to nonlinear analysis of glass plates. The research is classified into two categories, theoretical investigations and

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experimental testing. The Glass Research and Testing Laboratory (GRTL) at Texas Tech University (TTU) has made substantial contributions to this subject.

Kaiser [7] solved a square plate using a finite difference technique. His model was limited to a maximum lateral displacement of 2.5 times the plate thickness. Levy [8] conducted a formulation for nonlinear analysis of simply supported plates with zero in plane reaction at the edge, which is not suitable for glass plates. Pilkington [11] compared monolithic glass strength to the strength of laminated glass (LG) plate specimens made with sheet and float glass. This comparison was for rectangular shapes only. Beason [2] presented an analytical model using von Karman [15] equations and Galerkin method technique to calculate the strength of glass plates. Vallabhan [12] actually formulated the model and developed a finite difference model for rectangular glass plates which is relatively efficient when compared to that of previous investigators.

Vallabhan et al. [13] developed a mathematical model for LG plates based on the finite difference method. The comparison of results with the experimental ones was fairly good, but the mathematical model needed improvement. El-Shami et al. [6] developed a new finite element model for nonlinear analysis of monolithic rectangular glass plates that is capable of handling thin or thick plates. Norville et al. [9] presented a discussion concerning the behavior and strength of LG beams. They also observed that monolithic glass having the same thickness as LG does not necessarily provide an upper bound for LG strength. Vallabhan and El-Shami [14] improved the model of El-Shami et al. [6] to handle shapes other than rectangular, especially trapezoidal glass plates. Recently, El-Shami and Norville [5] developed a sophisticated finite element model for LG plates.

In this paper, nonlinear finite element models (FEM) are employed for both monolithic and laminated glass (LG) plates. Experimental results of tests which were conducted at the Glass Research and Testing Laboratory (GRTL) at Texas Tech University for monolithic and LG trapezoidal glass plates are compared with the FEM results. Then the FEM is applied for glass plates with triangular, hexagonal and circular shapes. Finally the results are discussed and the conclusion is drawn.

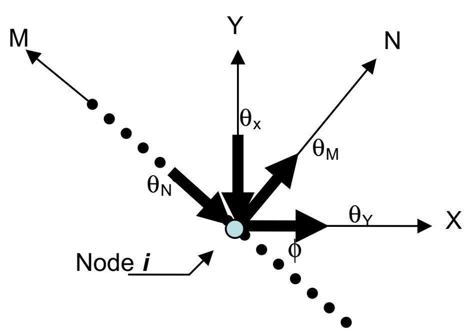

Figure 1 Boundary conditions for inclined side.

2. Finite element model

Since lateral deflections of the panels are large compared to their thickness, nonlinear plate theory is necessary in the analysis. The analysis is based upon Mindlin plate theory using von Karman's [15] assumption. The finite element models for monolithic and LG plates have been mentioned in the previous publications [5,6,14]; however, they are listed here for completeness only. For a monolithic plate, the element has 9 nodes with 5 degrees of freedom for each node. The displacements and rotations are:

$$u = \sum_{i=1}^{9} N_i(\xi,\eta)u_i, \quad v = \sum_{i=1}^{9} N_i(\xi,\eta)v_i, \quad w = \sum_{i=1}^{9} N_i(\xi,\eta)w_i$$
$$\theta_x = \sum_{i=1}^{9} N_i(\xi,\eta)\theta_{xi}, \quad \theta_y = \sum_{i=1}^{9} N_i(\xi,\eta)\theta_{yi} \tag{1}$$

where N_i, $i = 1,\ldots,9$ are the shape functions [16]. The total nonlinear stiffness matrix $[K_l]$ is calculated as [3]:

$$[K_l] = \int_V [B_l]^T[D][B_0] + [B_0]^T[D][B_l] + [B_l]^T[D][B_l]\,dV \tag{2}$$

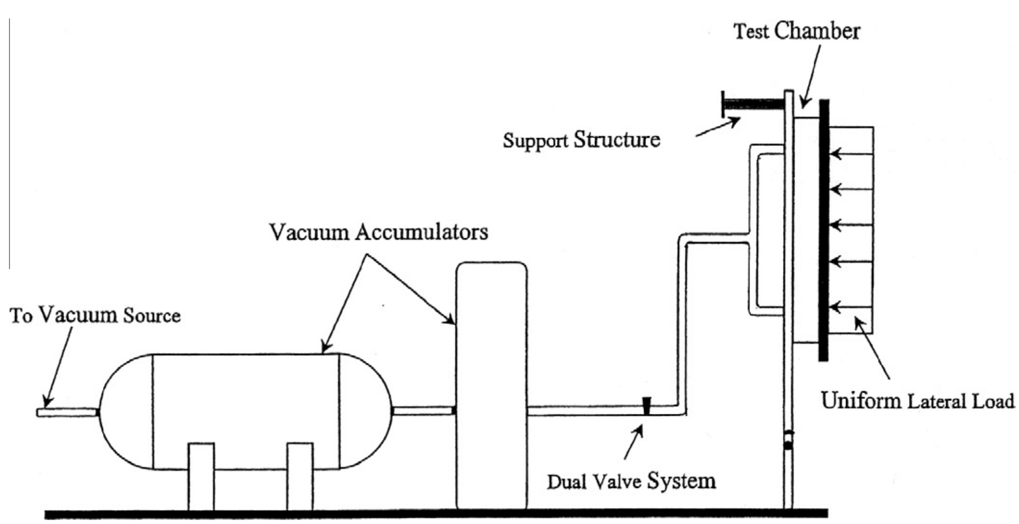

Figure 2 Test setup facility.