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ORIGINAL ARTICLE

Structural behavior of window laminated glass plies using new interlayer materials

Mostafa El-Shami *, **Sayed Mahmoud**

Department of Construction Engineering, College of Engineering, University of Dammam, Saudi Arabia

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KEYWORDS

Laminated glass;
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Abstract In most cases for the structural design of architectural glazing systems under a wide range of environmental conditions, the designers follow procedures provided by model building codes to design window glass. These codes commonly use design charts to determine design strength based on nominal glass thickness and aspect ratio. Glass plies are the principal components of laminated glass (LG) where a thin ply of elastomeric material Polyvinyl butyral (PVB) is used to bond glass plies (normally two plies) to form the LG. Because of the reduction in LG design strength by most building codes and design guidelines, designers avoid architectural LG applications, other than for safety consideration. In this research a higher order mathematical model based on Mindlin plate theory is presented. LG was modeled using finite element methodology with new interlayer (NI). It consists of two plies of PVB with a hard ply of film material in between. In the FEM, properties of PVB/film material can be easily controlled regardless of their thicknesses. The finite element model (FEM) was extended to account the design recommendations of ASTM (2012) to develop the design charts for LG with NI. The current FEM was verified and used to study the stresses transformation through NI. Design charts for samples of LG with NI were developed and presented. It has been found that using NI enhances the total behavior of LG and reflects on the design charts for this type of interlayer material.

1. Introduction

In most cases, designers of architectural glazing follow procedures provided by model building to design window glass. These codes commonly use design charts to determine design strength based on normal glass thickness and aspect ratio. Depending on the design recommendation used, monolithic glass plies are stronger than LG with a range of 10–50% for the same dimensions and thicknesses (ASTM, 2012; BOCA National Building Code, 1995).

Researchers have studied factors that affect the behavior of LG including: the glass thickness, glass type, temperature,

* Corresponding author at: Department of Construction Engineering, University of Dammam, Bldg. 800, P.O. Box 1982, Dammam 31441, Saudi Arabia.
E-mail addresses: melshami@uod.edu.sa (M. El-Shami), elseedy@hotmail.com (S. Mahmoud).
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aspect ratio, and the hardness of interlayer material. Nagalla et al. (1985) reported advanced theoretical work comparing layered glass to monolithic. Das and Vallabhan (1988) developed a theoretical, non-linear model for LG plies as sandwich plates. A mathematical model, developed by Norville et al. (1998), explains nonlinear analysis of LG under wind pressure. Using the finite element method, Van Duser et al. (1999) conducted another model to simulate LG behavior.

El-Shami and Norville (2002) developed a very sophisticated mathematical model that simulates LG's performance under wind pressure. Their model was compared with test results conducted for rectangular and trapezoidal LG at structural lab of Texas Tech University. These experimental results verified their mathematical model.

El-Shami et al. (2012) modified their mathematical model in El-Shami and Norville (2011) to simulate the nonlinear analysis of triangular window glass. Recently, El-Shami et al. (2010) studied the structural behavior of glass plies other than rectangular shapes. They used a higher-order finite element model to analyze several examples with trapezoidal, rectangular, triangular, and hexagonal shaped glass plies (monolithic and LG).

Because of the reduction in LG design strength by most building codes and design recommendations, designers avoid architectural LG applications other than for safety consideration. To overcome this problem, new interlayer materials have been introduced by glass industry to increase the strength of LG plies. One of these new interlayer materials is NI (see Fig. 1). The strength argument persists, because no rational model exists that provides an adequate explanation of the experimental data. This research presents a higher finite element model to study the performance of LG using NI.

The aim of this research is to investigate the behavior of LG plies with NI under the effect of wind pressure. In addition, it investigates the optimum dimensions for glass and NI plies leading to a minimum effect on the structural efficiency of this type of structures. A higher finite element model is employed and modified to take into account the effect of NI. Mindlin plate element with 9 nodes and 5 degrees of freedom for each node is used. The methodology consists of a tangent element stiffness matrix with an incremental procedure to analyze LG. The advantage of this element is that it can solve any shape of LG with different boundary conditions. The value of the stiffness of NI can be changed smoothly in this model.

2. Finite element model

This section describes briefly the formation of the FEM used in the analysis. The authors employed a nine-nodded quadrilateral flat element in this analysis. When solving plate problems with complex geometry; it is preferable to use nonlinear Mindlin plate theory. Mindlin plate theory follows the same assumptions as von Karmen does (see El-Shami and Norville (2002)) except that normal to the middle surface before deformations does not remain normal after deformations (Cook, 1995). The displacement functions for an element may be written as:

$$\begin{aligned} u &= u_o(x,y,z) + z\theta_y(x,y,z) \\ v &= v_o(x,y,z) - z\theta_y(x,y,z) \\ w &= w_o(x,y,z) \end{aligned} \tag{1}$$

where u_o, v_o and w_o are displacements at middle surface given by Cartesian coordinates. θ_x and θ_y are the rotations about the x and y axes; respectively (Zienkiewicz, 1977; Shabani et al., 2012). The displacements lead to the total strain vector given as:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = \begin{Bmatrix} u_{,x} + \frac{1}{2}(w_{,x})^2 + z\theta_{y,x} \\ v_{,y} + \frac{1}{2}(w_{,y})^2 - z\theta_{x,y} \\ u_{,y} + v_{,x} + w_{,x}w_{,y} + z(\theta_{y,y} - \theta_{x,x}) \\ \theta_y + w_{,x} \\ -\theta_x + w_{,y} \end{Bmatrix} \tag{2}$$

The subscripts "x" and "y" stand for the abscissa and ordinate axes of the Cartesian coordinates; respectively. $u_{,x}$ denote the 1st differentiation of u with respect to x-axis, and so on for the rest of the functions. Finally, Z denotes the distance from middle surface. Fig. 2 illustrates a cross section of LG with NI. Now, there are 5 plies, two plies of glass, two plies of PVB, and one ply of film along the thickness. Due to the strength of the film material compared with the PVB, we can consider it as intermediate ply. El-Shami and Norville (2011) presented a model for LG with PVB interlayer. This model will be expanded here to simulate the current LG unit with the new material interlayer. Based on this model of El-Shami and Norville (2011), the authors will consider the LG as a ply of glass, a PVB interlayer, a ply of film, a PVB interlayer, and finally a ply of glass. Since all of the plies are bonded together, it can be assumed that there will be a continuity of displacements along the thickness between glass and film plies, respectively. PVB interlayer (due to its weakness with respect to both glass and film material) transfers the displacements between the glass and film plies through shear strains energy. At the same time, bending and membrane strain energies will be

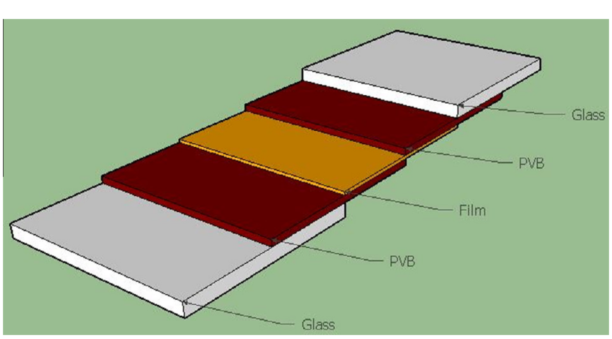

Figure 1 Isometric of NI.

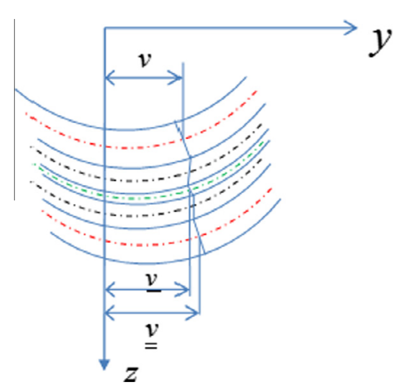

Figure 2 Cross section of LG with NI.

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