Composite Structures 169 (2017) 2–9

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Buckling of multilayered laminated glass beams: Validation of the effective thickness concept

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ARTICLE INFO

Article history:
Received 31 July 2016
Revised 18 November 2016
Accepted 11 January 2017
Available online 17 January 2017

Keywords:
Laminated glass
Structural composites
PVB
Bucking
Structural stability
Viscoelasticity

ABSTRACT

Stability of laminated structural glass is one of the design requirements to be considered due to the brittle and slender nature of this kind of glass elements. Since laminated glass is mainly manufacture with viscoelastic interlayers, its mechanical properties are temperature and time dependent. This implies that, i.e., the critical load of a laminated glass beam subject to constant compressive load decreases with time as well as with temperature.

In this paper, the equations of the Euler Theory for buckling of monolithic beams are extended to multi-layered laminated glass beams using an effective stiffness. This proposal is based on the idea of calculating the thickness (time and temperature dependent) of a monolithic element with bending properties equivalent to those of the laminated one, that is, the deflections provided by the equivalent monolithic beam are equal to those of the layered model with viscoelastic core.

In this work, the analytical predictions are validated by compressive experimental tests carried out on a simply supported beam composed of three glass layers and two polyvinyl butyral (PVB) interlayers. Moreover, a finite element model was assembled to validate the proposed methodology for any boundary conditions. The results shown that a good accuracy can be obtained with the proposed equations being the errors less than 7% for all the experiments and simulations considered.

1. Introduction

Laminated glass is a sandwich or layered material which consists of two or more plies of monolithic glass, whose mechanical behaviour is commonly assumed linear elastic, and one or more interlayers of a polymeric material which show a viscoelastic behaviour i.e. their mechanical properties are time (or frequency) and temperature dependent [1,2].

Multi-layered laminated glass panels can be used for many different applications due to the added thickness and strength. They are commonly used in accessible glazing, i.e. floors, roofs and other horizontal glazing accessible to the public or at least for cleaning and maintenance [3]. In these applications, resistance against impact caused by a hard or soft body, the post-breakage behavior as well as the slip resistance must be examined [3]. Multilayered glass beams are also interested in acoustics and structural dynamics in order to reduce the acoustic transmission and amplitude of vibrations.

If laminated glass elements are subject to compressive loads, the structural stability is one of the design requirements because laminated glass elements are brittle and slender. Due to the fact that the stiffness of the interlayer is temperature and time dependent, the same can be said about the critical load, i.e., the critical load of a laminated glass beam subject to constant compressive load decreases with time.

The concept of effective thickness has been proposed in recent years [4–6] based on the quasi-elastic solution. This method consists of calculating the thickness (time and temperature dependent) of a monolithic element with bending properties equivalent to those of the laminated one, that is to say, the deflections provided by the equivalent monolithic beam are equal to those of the layered model with viscoelastic core. The concepts of effective Young modulus and effective stiffness [7] can be used interchangeably with the same accuracy.

Several analytical models have been proposed for determining the critical load of a simply supported laminated glass beam [8–11]. Aenlle et al. [12] extended the Euler Theory to laminated glass beams using an effective stiffness (or effective thickness) and the effect of the boundary conditions is considered through the buckling ratio β.

In this paper, equations for predicting the critical load of multi-layered glass beams with different boundary conditions are proposed based on the methodology proposed by Aenlle et al.

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http://dx.doi.org/10.1016/j.compstruct.2017.01.040

Nomenclature

$A_1 = bH_1$ area of glass layer 1 in laminated glass
$A_2 = bH_2$ area of glass layer 2 in laminated glass
$A_3 = bH_3$ area of glass layer 3 in laminated glass
E glass Young modulus of glass layers
$E_t(t)$ viscoelastic relaxation tensile modulus for polymeric interlayer
$G_t(t)$ viscoelastic relaxation shear modulus for the polymeric interlayer
H_1 thickness of glass layer 1 in laminated glass
H_2 thickness of glass layer 2 in laminated glass
H_3 thickness of glass layer 3 in laminated glass
$H_{TOT} = H_1 + H_2 + H_3 H_{12} = t_1 + \left(\frac{H_1+H_2}{2}\right) H_{23} = t_2 + \left(\frac{H_2+H_3}{2}\right) I$ second moment of area
$I_1 = b\frac{H_1^3}{12} I_2 = b\frac{H_2^3}{12} I_3 = b\frac{H_3^3}{12} I_{T2} = I_1 + I_2 = b\frac{H_1^3+H_2^3}{12} I_{T3} = I_1 + I_2 + I_3 = b\frac{H_1^3+H_2^3+H_3^3}{12} I_{TN} = Nb\frac{H^3}{12} K_2(t,T)$ viscoelastic bulk modulus
L length of a glass beam
T temperature
T_0 reference temperature

Lowercase Letters
a_T shift factor
b width of a glass beam
t time
t_1 thickness of polymeric layer 1 in laminated glass
t_2 thickness of polymeric layer 2 in laminated glass

Greek letters
η_2 loss factor of the polymeric interlayer of laminated glass
ν Poisson ratio of the glass layers
$\nu_2(t,T)$ viscoelastic Poisson ratio of the polymeric interlayer

[12] which uses the Euler Theory [13] of monolithic beams, the quasi-elastic solution [6] and the effective stiffness concept [7]. In order to validate the model, the critical load of a laminated glass beams, made of three annealed glass plies and two PVB interlayers, were predicted using the effective stiffness concept and validated by experimental tests and numerical models. Moreover, the effect of the number of layers in the critical load of multi-layered glass beams are investigated and some recommendations are proposed for the design of these elements subject to compressive loadings.

2. Theory

The critical load of a simply supported linear-elastic monolithic beam, according to the Euler Theory is given by [13,14]

$$P_{crit} = \frac{\pi^2 EI}{L^2} \tag{1}$$

Eq. (1) can be extended to laminated glass beams [8–10] using an effective $EI(\mathrm{t,T})_{\mathrm{eff}}$, i.e.:

$$P_{crit}(\mathrm{t,T}) = \frac{\pi^2 \mathrm{EI(t,T\ )_{eff}}}{L^2} \tag{2}$$

In the case of a simply supported laminated glass beam composed of 2 glass layers and one linear-viscoelastic interlayer (see Fig. 1) the following expression for $\mathrm{I(t,T)_{eff}}$:

$$\mathrm{EI(t,T)_{eff}} = EI_{T2}\left(1 + \frac{Y_{B2}}{1 + \frac{EH_1H_2t_1}{G_t(t,T)(H_1+H_2)}\frac{\pi^2}{L^2}}\right) \tag{3}$$

can be derived from the models proposed in [8–10], where

$$Y_{B2} = \frac{bH_{12}^2 H_1 H_2}{I_{T2}(H_1 + H_2)} \tag{4}$$

The critical load of an elastic monolithic beam with different boundary conditions can also be calculated with Eq. (1) but using the buckling ratio β i.e.:

$$P_{crit} = \frac{\pi^2 EI}{(\beta L)^2} \tag{5}$$

Aenlle and Pelayo [12] proposed to extend Eq. (5) for laminated glass beams using the equation:

$$P_{crit}(t,T) = \frac{\pi^2 \mathrm{EI(t,T)_{eff}}}{(\beta L)^2} \tag{6}$$

where $\mathrm{EI(t,T)_{eff}}$ is an effective stiffness. In the case of a laminated glass beams with 2 glass layers and one linear-viscoelastic interlayer (Fig. 1) Aenlle and Pelayo [12] derived an expression for $\mathrm{EI(t,T)_{eff}}$ from the model of Galuppi and Royer Carfagni [6] which is given by:

$$\mathrm{EI(t,T)_{eff}} = \mathrm{EI_{T2}}\left(1 + \frac{Y_{B2}}{1 + \frac{EH_1H_2t_1}{\mathrm{bG_t}(t,T)(H_1+H_2)}\psi_B}\right) \tag{7}$$

where [12]:

$$\psi_B = \frac{\pi^2}{(\beta L)^2} \tag{8}$$

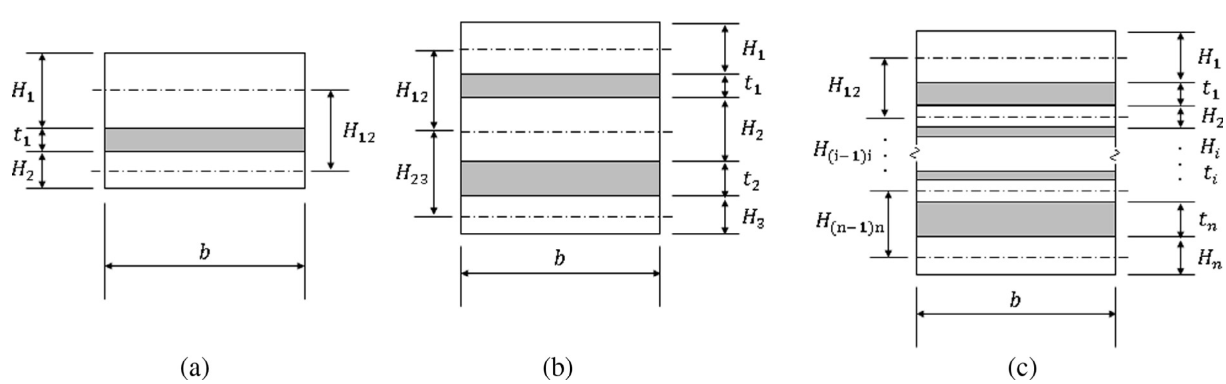

Fig. 1. Section of laminated glass beams (a) 2 glass layers (b) 3 glass layers and (c) N glass layers of equal thickness.