Composites: Part B 55 (2013) 109–118

Contents lists available at SciVerse ScienceDirect

Composites: Part B

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

The effective thickness of laminated glass: Inconsistency of the formulation in a proposal of EN-standards

Laura Galuppi, Gianni Royer-Carfagni *

Department of Industrial Engineering, University of Parma, Parco Area delle Scienze 181/A, I 43100 Parma, Italy

ARTICLE INFO

Article history:
Received 15 February 2013
Received in revised form 17 April 2013
Accepted 20 May 2013
Available online 1 June 2013

Keywords:
A. Glasses
A. Layered structures
B. Mechanical properties
C. Laminate mechanics
Structural standards

ABSTRACT

The project of EN-standard PrEN-13474 records a simple method to calculate the effective thickness of laminated glass, i.e., the thickness of a monolith with equivalent bending properties in terms of stress or deflection. This is supposed to depend upon the shear-stiffness family of the interlayer only. Here, paradigmatic examples show that this approach leads to inconsistent results. The formulation is too simplistic, being based upon a theory that does not consider size-effect, type of constraint and load conditions, which instead heavily affect the shear coupling of glass plies through the interlayer. Another formulation is mentioned, that gives very accurate results with no additional computational difficulty with respect to the PrEN-13474 approach.

1. Introduction

Laminated glass is a composite widely used in civil, automotive, aeronautics and shipbuilding industry. It is made of two or more glass plies bonded by thermoplastic polymeric interlayers through a treatment in autoclave at high pressure and temperature; this improves the safety, because in case of glass breakage shards remain attached to the interlayer, reducing risks of injuries.

In the pre-glass-breakage phase, the polymeric interlayers are too soft and thin to provide flexural stiffness, but they can transfer shear stresses among glass plies that constrain their relative sliding [3]. The laminate response is intermediate between the two borderline cases usually referred to [15] as *layered limit* (frictionless sliding glass plies) and *monolithic limit* (perfect shear coupling through the interlayer).

The literature is rich of contributions that aim at determining the actual degree of shear coupling in the most various conditions. A precise calculation requires a complex numerical analysis because the response of the polymer is nonlinear, viscoelastic and temperature dependent. A common practical simplification consists in considering both glass and polymeric interlayer as linear elastic [12], taking into account *a priori* the viscoelastic properties of the polymer through an equivalent elastic shear modulus, calibrated according to temperature and characteristic duration of design actions. A full three-dimensional analysis usually provides accurate results, but it is very time consuming; layered-shell elements may be used that already take into account the competing stiffness between glass and interlayer, but such elements are not available in most commercial numerical codes.

This is why, especially for preliminary design, it is very useful to rely upon approximate calculation methods. The most common approach consists in defining the *effective thickness* of laminated glass, i.e., the thickness of a monolith with equivalent bending properties in terms of stress and deflection. More precisely, the effective thickness of a laminated glass plate is the (constant) thickness of the homogeneous plate that, under the same boundary and load conditions, presents the same maximal stress or maximal deflection, which is obviously dependent on the shear coupling offered by the interlayer and, hence, on its shear stiffness. This is a very practical definition because it allows to use simple FEM elements in the computations, but the problem consists in how to determine readily the value of the effective thickness.

Different theoretical approaches have proposed various expression for the effective thickness of laminated glass, a few of which have been incorporated in structural standards. A classical contribution, conceived of for a concrete slab and a steel beam bonded by shear connectors, is associated with the name of Newmark et al. [14], who considered a linear and continuous relationship between the relative interface slip and the corresponding shear stress. The model is applicable to any composite beam consisting of two elements with bending stiffness, connected by an interface with negligible thickness that transfers shear forces. Therefore, it can be conveniently used for laminated glass, but, as it has been discussed in [9], it is not able to provide simple explicit expressions for the effective thickness. The most used approach for the

* Corresponding author. Tel.: +39 0521 905917; fax: +39 0521 905924.
E-mail address: gianni.royer@unipr.it (G. Royer-Carfagni).

1359-8368/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.05.025