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Enhanced Effective Thickness of multi-layered laminated glass

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ABSTRACT

The stiffness and strength of laminated glass, a composite of glass layers bonded together by polymeric interlayers, depends upon shear coupling between the glass plies through the polymer. In the design practice, this effect is commonly considered by defining the effective thickness of laminated glass, i.e., the thickness of a monolith with equivalent bending properties. Various theories have been proposed to calculate such a value for a package of two layers of glass and one polymeric interlayer, but extrapolation to a higher number of layers gives in general inaccurate results. Here, the *Enhanced Effective Thickness* method, previously proposed for two-glass-layer composites, is extended to the case of laminated glass beams made (i) by three layers of glass of arbitrary thickness, or (ii) by an arbitrary number of equally-thick glass layers. Comparisons with numerical experiments confirm the accuracy of the proposed approach also in these cases.

1. Introduction

Laminated glass is a composite widely used in civil engineering, as well as in automotive, aeronautics and shipbuilding, thanks to its transparency, strength and other advantageous aspects, such as sound-insulation capability and non-catastrophic post-glass-breakage response. Its traditional use as an infill panel is the most popular, but an alternative structural use has emerged in which glass elements contribute to the overall load bearing capacity of the structure or sub-structure [1]. Laminated glass is typically made of two glass plies bonded by a thermoplastic polymeric interlayer with a treatment in autoclave at high pressure and temperature. This process induces a strong chemical bond between the materials, due to the union between the hydroxyl groups along the polymer and the silanol groups on the glass surface. Through lamination, safety in the post-glass-breakage phase is increased because fragments remain attached to the interlayer; risk of injuries is reduced and broken glass maintains a certain cohesion that prevents catastrophic collapse.

In the pre-glass-breakage phase, the polymeric interlayers are too soft to present flexural stiffness *per se*, but they can provide shear stresses that constrain the relative sliding of the glass plies [2,3]. Of course, the degree of coupling of the glass layers depends upon the shear stiffness of the interlayer [4]. Thus, the flexural performance is somehow intermediate between the two borderline cases [5,6] of (i) *monolithic limit*, with perfect bonding between glass plies (shear-rigid interlayers) and (ii) *layered limit*, with frictionless sliding glass plies. Since stress and strain are much lower in the monolithic than in the layered limit, to avoid redundant design a large number of theoretical studies have been devoted, also in recent years, to this subject [7–9], with a wealth of experimental activity [10–12].

In general, the modeling of composite laminated structures with a "soft" core is one of the most active research fields of the last decades, since an accurate stress analysis is required to design structural parts. Hence, several theories have been developed to describe the structural behavior of sandwich beam [13,14]. In particular, the well-know First-Order Shear Deformation approach [15], based on the assumption that planes normal to the midplane remain straight, but not necessarily normal to it, after deformation has been followed by many authors in last decades (see, among others, [16–18]). This theory usually provides good results in terms of maximum displacement under appropriate choice of the shearing rigidity.

Nevertheless, the precise calculation of the coupling offered by the interlayer is quite difficult and usually requires numerical analysis, complicated by the fact that response of the polymer is nonlinear, viscoelastic and temperature dependent. A common practice is to consider the polymer as linear elastic, accounting for its viscoelasticity through an equivalent elastic modulus, assumed equal to the relaxed modulus under constant strain after a time comparable with the characteristic duration of the design action.

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