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Analytical approach *à la* Newmark for curved laminated glass

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ABSTRACT

A method of solution that extends to the case of curved laminated structures the traditional approach developed by Newmark et al. for straight beams is presented. The method is specialized to curved laminated glass, a composite formed by two external glass layers that sandwich a very thin polymeric interlayer. The effect of curvature on the shear coupling of glass plies through the interlayer is examined in the paradigmatic example of a laminated beam with constant moderate curvature under radial loading with different boundary conditions, varying the initial camber, the end constraints and the elastic properties of the polymer. Comparisons with numerical experiments confirm the accuracy of the proposed modeling. In general the response of a curved structure is greatly influenced by the axial force it undergoes, and such internal action is mainly governed, for fixed applied loads, by the boundary conditions at the extremities. The axial force produces the arch-response of the structure, which is not substantially affected by the shear coupling of glass through the interlayer. On the other hand, such coupling has major effects on the bending properties.

1. Introduction

The type of sandwich structure considered here is formed by the composition of two thick and curved external layers, with membrane and bending stiffness, and a compliant core, much thinner than the external layers. The core does not present bending stiffness *per se*, but it can provide the shear coupling of the external layers. Moreover, it constrains the relative out-of-plane displacement of the external layers because, due the hypothesis of small thickness, one can consistently assume that its height does not change in the deformation. The modeling of composite laminated structures with a shear-compliant core is one of the most active research fields of the last decades [1–4]. The key role played by the interlaminar shear stress on the composite laminates response has been evidenced since the seminal works by Pagano [5–7] and Reddy [8,9]. Other works have focused on curved laminated beams composed by perfectly bonded plies with considerable bending stiffness [10–12]. The present article deals with the particular case of curved laminated glass, which represents a paradigmatic benchmark example for the use of theories of this kind.

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. Through lamination, safety in the post-glass-breakage phase is increased because fragments remain attached to the interlayer, reducing the risk of injuries. Its traditional use as an infill panel is the most popular, but in recent years its noteworthy load bearing capacity has been fully exploited in structural applications [13,14]. In the pre-glass-breakage phase, the polymeric interlayers can provide shear stresses that constrain the relative sliding of the glass plies [15,16]. Of course, the degree of coupling of the glass layers depends upon the shear stiffness of the interlayer [17]. Thus, the flexural performance is intermediate between the two borderline cases [18,19] of *monolithic limit* (shear-rigid bonding of the glass plies) and *layered limit* (free-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 performed [20–25], corroborated by a wealth of experimental activity [26,14,27,28]. Several practical methods to readily calculate the response of laminated glass structures, such as those by Refs. [29,19,30,31] for the case of beams, and by Refs. [32–35] for the case of plates, have been proposed. A particular attention has also been paid to the buckling of laminated glass [36–40] and to hybrid laminated glass unit [41,42].

The aforementioned studies consider *flat* glass only, although *curved* laminated glass is increasingly being used in modern architecture to construct free-form roofs and façades. Curved glass is traditionally produced through hot-forming processes. In *sag*

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