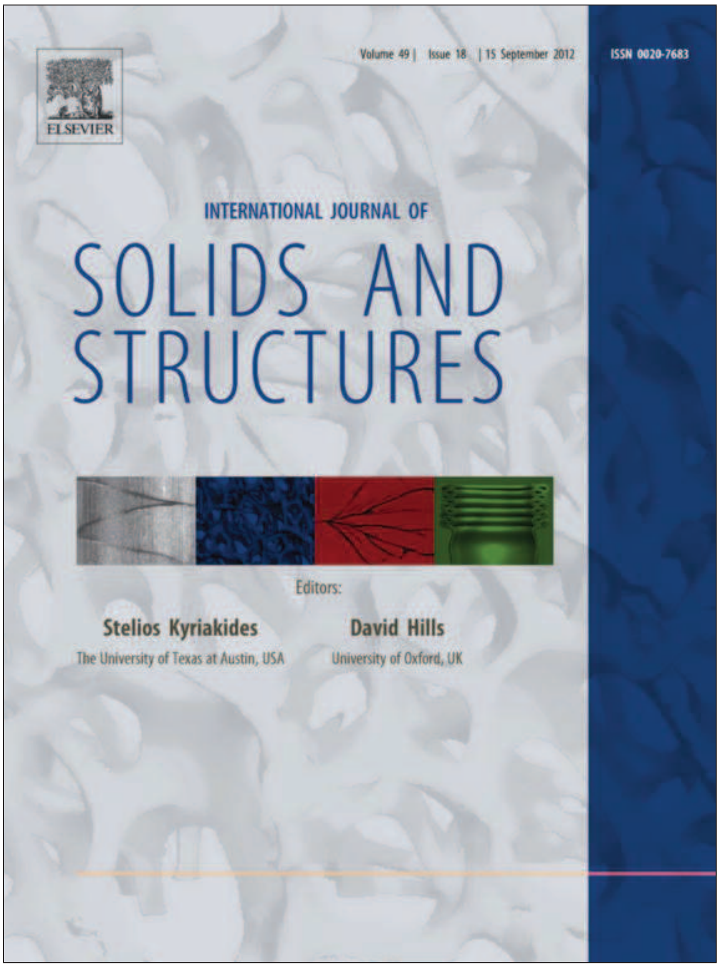
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Laminated beams with viscoelastic interlayer

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ABSTRACT

We analytically solve the time-dependent problem of a simply-supported laminated beam, composed of two elastic layers connected by a viscoelastic interlayer, whose response is modeled by a Prony's series of Maxwell elements. This case applies in particular to laminated glass, a composite made of glass plies bonded together by polymeric films. A practical way to calculate the response of such a package is to consider also the interlayer to be linear elastic, assuming its *equivalent* elastic moduli to be the relaxed moduli under constant strain, after a time equal to the duration of the design action. The obtained results, that are confirmed by a full 3-D viscoelastic finite-element numerical analysis, emphasize that there is a noteworthy difference between the state of strain and stress calculated in the full-viscoelastic case or in the aforementioned "*equivalent*" elastic problem.

1. Introduction

Three-layered sandwich structures, that can be schematized as the composition of two external elastic elements bonded by one interlayer with inelastic response, are commonly used in modern constructions. The applications may range from structural insulating panels, consisting in a layer of polymeric foam sandwiched between two layers of structural board, to steel beams supporting concrete slabs connected by ductile studs, to wood elements made of layers glued together. Although the problem considered here is general and may apply to various cases, the particular application to which it will be specialized is that of laminated glass.

Laminated glass is a composite structure 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 materials, due to the union between hydroxyl groups along the polymer and silanol groups on the glass surface. In this way, safety in the post-glass-breakage phase is increased because the fragments remain attached to the interlayer: risk of injuries is reduced and the damaged element maintains a certain cohesion that prevents catastrophic detachment from fixings.

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 (Behr et al., 1993). The degree of coupling of the two glass layers depends upon the shear stiffness of the polymeric interlayer (Hooper, 1973); thus, flexural stiffness is somehow intermediate between the two borderline cases usually referred to as *layered limit*, i.e., frictionless relative sliding of the plies, and *monolithic limit*, i.e., perfect bonding of the plies (Norville et al., 1998). Since stress and strain in the monolithic limit are much lower than in the layered limit, appropriate consideration of the shear coupling offered by the interlayer is important to achieve an economical design. A number of studies have pursued this issue (Asik and Tezcan, 2005; Bennison and Davies, 2008; Ivanov, 2006).

The response of the polymer is highly viscoelastic and temperature dependent. There are three main commercial polymeric films: Polyvinyl Butyral (PVB), Ethylene Vinyl Acetate (EVA), and Ionoplastic polymers (IP) (Bennison and Davies, 2008; Bennison et al., 2001). PVB is a polyvinyl acetate with addition of softeners that imparts plasticity and toughness, enhancing adhesion-strength and increasing glass transition temperature T_g up to 20–25 °C. Commercial EVA is a polyolefine with addiction of vinyl acetate that improves strength and ultimate elongation, to attain mechanical properties that are similar to PVB. A somehow innovative materials is IP, a ionoplast polymer that, when compared with PVB, presents higher stiffness ($>100\times$PVB), strength ($>5\times$PVB), glass-transition temperature ($T_g \sim 55\,^{\circ}$C).

In general, the rheological properties are furnished by the manufacturer in the form of tables, which record the relaxed shear modulus of the polymer under constant shear strain as a function of temperature and time. Such values are used in the common design practice, by considering the polymer as a linear elastic materials whose shear modulus is chosen according to the environmental temperature and the characteristic duration of the design load (Bennison and Stelzer, 2009). Depending upon polymer type, room-temperature T and characteristic load-duration t_0, the relaxed shear modulus of the interlayer may vary from 0.01 MPa

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