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The design of laminated glass under time-dependent loading

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ABSTRACT

Laminated glass is a layered sandwich structures composed of elastic glass plies bonded by viscoelastic polymeric interlayers, which produce the mechanical shear-coupling of the plies under flexural loads. Here, we analytically solve the time-dependent problem of a simply-supported three-layered sandwich-beam with linear-viscoelastic interlayer under a loading/unloading history, showing that its gross response is strongly affected by the rheological properties of the polymer, here modeled by Wiechert–Maxwell units. The results, confirmed by numerical simulations, are compared with those obtainable with an approximate solution, commonly used in the design practice, where the interlayer is modeled by an equivalent linear-elastic material, whose properties are calibrated according to temperature and characteristic duration of the applied loads. For this, practical design rules to account for superimposition of applied loads are proposed.

The qualitative properties of the two approaches are analytically discussed, evidencing those load-histories under which the approximate solution is, or is not, conservative for what stress and deflection evaluation is concerned.

1. Introduction

Laminated glass is a composite sandwich structure made of two or more glass plies bonded together by polymeric interlayers, with a process at high pressure and temperature in autoclave referred to as *lamination*. The interlayers are too soft and thin to present appreciable flexural stiffness, but nevertheless they can provided shear stress that constrains the relative sliding of the glass plies, thus increasing the stiffness and load bearing capacity of the composite package. In general, it is customary to identify [1] the two borderline cases of (i) interlayers with no shear-stiffness and free-sliding glass-plies as the *layered limit* and that of (ii) shear-rigid interlayers and perfectly bonded glass-plies as the *monolithic limit*.

In order to achieve a reliable and economical design, it is necessary to take into account the shear coupling provided by the interlayers, but its evaluation is complicated by the viscoelastic response of the polymer, that is highly time and temperature dependent. In the design practice it is common to consider approximate solutions, at various levels of accuracy. Geometric non-linearities are usually important because of the slenderness of the laminated panel [2,3], but can be neglected, at least as a first-order approximation, when the loads are mainly orthogonal to the panel surface and no in-plane forces are present. Furthermore, for what concerns the material behavior, the most used simplifying assumption is to consider that the polymer is a linear elastic material, whose elastic shear modulus depends on temperature and characteristic duration of the design actions. For ease of reference, such data are usually provided by manufactures under the form of tables. These are commonly obtained by performing creep tests under constant shear strain at various temperatures, and by measuring the shear stress as a function of time; it is then immediate to calculate the *secant stiffness* of the interlayer and the end of each characteristic time interval. Because of this, in the sequel this kind of approximate solutions will be referred to as the *secant stiffness solution* (SSS). As it will be widely discussed in the present paper, to assume the SSS approximation is equivalent to neglect the *memory effect* of the polymer, i.e. the dependence of the stress not only on the current strain but on the strain history. The use of SSS is particularly effective because there are several practical methods to readily calculate the response of laminated structures composed of linear elastic layers, such as those proposed by Newmark et al. [4], Bennison and Stelzer [5], Foraboschi [6], Galuppi and Royer-Carfagni [7] for the case of beams, and by Ašik [2], Foraboschi [8], Galuppi and Royer-Carfagni [9] and for the case of plates, to mention just a few.

In [10], the authors have considered the paradigmatic case of a simply-supported composite beam with viscolastic interlayer, under constant loading. The time-dependent problem has been solved analytically, in order to obtain the *full viscoelastic solution* (FVS), modeling the response of the polymer by various types of

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