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Dynamic torsion tests to characterize the thermo-viscoelastic properties of polymeric interlayers for laminated glass

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HIGHLIGHTS

- New procedure for the experimental characterization of laminated glass interlayer.
- Specimens of laminated glass made with PVB interlayer were tested in torsion.
- The method of reduced variables was applied to build up a master-curve.
- The obtained results were compared with other results from the literature.
- Case studies were numerically analysed.

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ABSTRACT

The mechanical behaviour of laminated glass is strongly influenced by the coupling capability of interlayer that, in turn, depends on the shear modulus of the polymer. An accurate determination and a comprehensive description of the thermo-viscoelastic properties of polymeric interlayer is necessary to reliably predict the laminate behaviour in structural applications, both by simplified methods in which the mechanical behaviour of the polymer is described as elastic ("secant stiffness" approaches) and by step by step analysis, in which articulated load and temperature histories are reproduced.

In this paper, a test procedure is proposed to perform dynamic tests on polymer interlayer, that revels to be more simple and more reliable than the procedures presently in use; the first results of an experimental analysis on polyvinyl butyral laminated glass specimens are reported and the generalyzed Maxwell constitutive model obtained from the tests on the material is compared with analogous models reported in the literature. Some case studies are considered in order to evaluate the influence of the assumed constitutive behaviour on the response of structural elements.

1. Introduction

Laminated glass is a composite material made of two or more glass plies among which thin layers of polymer are interposed. Several polymers are employed as interlayer: these are requested to be not crystalline, weakly cross-linked and consequently highly amorphous. These amorphous polymers are characterized by a transition, without latent heat, from hard solid (glassy) state to highly viscous liquid, passing through the rubbery temperature range in which the material becomes viscoelastic [13,44]. Among the polymer materials used as interlayer, Poly-Vinyl-Butyral (PVB) is the most widely used; at room temperature it behaves as a rubber. For this reason, in case of glass breakage, the interlayer is able to produce a bridge ligament among glass fragments: in fact, the glass fracture is not able to propagate within the soft polymer, but deviates at the interface between glass and interlayer [7,35,42,43].

As well as avoiding the fall of glass fragments in case of glass breakage, the polymeric interlayer is able to produce coupling between the glass panes even in the serviceability domain; this ability, although related to the geometric characteristics of the laminated unit and to the boundary conditions [22,23,48], strongly depends on the interlayer shear stiffness [4,11,15,16,29,47]. In fact, the polymeric interlayer, whose flexural stiffness is negligible compared to that of glass plies, provides shear connection between the glass panes. In this way, laminated glass flexural stiffness takes a value between the layered (lower bound) and monolithic (upper bound) limits. It bottoms out to the layered limit when interlayer shows no shear stiffness and the composite behaves like

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superimposed panes without friction: the flexural stiffness of the laminate is the sum of the flexural stiffness of the composing panes. It reaches the monolithic limit when interlayer stiffness guarantees the perfect coupling among the glass panes.

Laminated glass structures can be subjected to various load conditions, whose duration varies from few seconds to several years, and also to various thermal conditions and thermal changes. In the light of the thermo-viscoelastic properties of the interlayer, the coupling ability of the interlayer strongly depends on both the temperature and the load duration which the structure is subjected to. For this reason, a comprehensive analysis of laminated glass elements or structures can be performed if an accurate characterization of thermo-viscoelastic properties of interlayer polymer has been carried out. However, simplified methods are commonly employed for simple load conditions and for some structural elements, widely used in civil engineering applications, in which the mechanical behaviour of the polymer is described as ideally elastic, provided a shear modulus, considering the load duration and the temperature, is defined. Considering that, in structural usages, glass always remains in the linear elastic range up to brittle failure, these simplified approaches describe a generic laminated glass plate as a laminated composite made of elastic phases. In this way, laminated glass can be modeled using generalized Newmark models [37], widely employed for schematizing such phenomena, in case of composite elements made of other materials as, for example, steel–concrete interactions in reinforced concrete [10,31]. Analytical solutions of composite beams and plates, schematized as described above and subject to specific boundary and load conditions, can be found in the literature [17–20]. Although analytical methods are very accurate, simplified methods are widespread in the technical practice, based on the definition of appropriate effective thicknesses; these can be quickly and easily applied, even in wider load and constraint conditions, but paying the penalty of lower accuracy. Such simplified methods permit to evaluate the maximum deflection (or stress) of the composite element, referring to a monolithic plate of such thickness (effective thickness) that, if subject to the same load and boundary conditions, undergoes the same deflection (or stress) of the composite element. Hence, it is necessary to define a deflection–effective thickness and a stress–effective thickness to be used for the evaluation of maximum vertical displacement of the composite element and of maximum stress in glass. For example, draft prEN16612(2013) [40] proposes a simplified method to determine the effective thicknesses for several panes laminated glass units, depending on a coefficient that accounts for the shear transfer capability of the interlayer. This is defined as a function of the load duration, of the temperature that is associated to it, and of the "stiffness family" of interlayer polymer as per prEN16613(2013) [41]. The formulas reported in prEN16612(2013), first proposed by Bennison et al. [49] for the analysis of layered glass, were originally formulated by Wolfel [51] referring to simply supported composite beams under an evenly distributed load. This restriction (limit) is not explicit in prEN16612(2013), that proposes the use of effective thicknesses independent of load and boundary conditions and independent of geometrical factors, as interlayer thickness, even though they have been proved to be influential [24]. Therefore, expressions proposed in prEN16612(2013) for the determination of effective thickness are used in practical calculations to analyse laminated glass units subject to load and boundary conditions different from the ones they were referred to and leading, as discussed at length in [24], to predictions endowed with low accuracy. In this regard, recently published Italian Instructions [36], at the moment under public inquiry, suggest a more accurate method (Enhanced Effective Thickness method - EET) for the definition of the effective thickness of laminated glass. The EET method, developed by Galuppi and Royer Carfagni [21,23], is based on the minimization of elastic strain energy, performed assuming approximating shape functions for the deformation of the laminated plates. Shape functions suitably chosen for the specific load and boundary condition, provide effective thickness values directly serviceable in practical calculations, and able to estimate with sufficient accuracy, with respect to elastic FEM analysis, maximum displacement of laminated unit and maximum stress in glass [26].

These methods can be easily used to calculate maximum deflection and stress with good accuracy, especially in the preliminary phases of the design procedure [21], deferring to a successive time, if necessary, more accurate analysis. Indeed, also the use of simplified methods, that employ an equivalent elastic shear modulus that accounts for temperature and load duration, requires a thorough characterization of the thermo-viscoelastic properties of the polymeric interlayer. Anyhow, these methods are not recommended to evaluate local effects, such as stress concentrations around holes and/or at contact points. Moreover, in the case of structural elements subjected to articulated load and thermal histories [22,25], impulsive loadings, such as those occurring during an explosion, or particular structural problems such as the after effect in cold bended structural elements [14], it is mandatory to accurately characterize the thermo-viscoelastic response of the polymer and apply an appropriate step by step analysis.

A proper mechanical characterization of the polymeric interlayer requires tests performed at different temperatures and load duration. In this regard, draft prEN16613(2013) [41] suggests, in the case of isotropic polymer, to perform cyclic tests on specimens made of an interlayer not adhered to glass and subject to traction, with prescribed temperatures and frequency. Only in the case that interlayer polymer is non isotropic, a test is suggested where the polymer is adhered to glass and is subjected to tangential stress. Draft prEN16613(2013), in turn, refers to UNI EN ISO 6721-1 (2003) [45] that describes several test methods and test devices to perform dynamic tests on plastics. The procedure suggested in prEN16613(2013) for isotropic polymers has been recently used for example by Hooper et al. [30], who investigated the behaviour of PVB over a wide range of strain magnitudes and strain rates, in order to define a mechanical model for the interlayer, apt to describe pre- and post-crack behaviour of laminated glass.

In authors' opinion, the test method proposed in prEN16613(2013) to characterize isotropic interlayer materials shows some inconsistent issues:

1. mechanical characterization is carried out subjecting the interlayer to tensile test, that is to a stress state very different from the one that occurs inside the laminated plate, which is mainly a shear stress state;
2. starting from tensile tests, Young modulus is determined (as a function of load duration and temperature) and tangential modulus is derived from it, by means of expressions valid when dealing with isotropic linear elastic materials, assigning a conventional value of Poisson coefficient;
3. tests are performed on interlayer prevented from adhering to glass; in so doing, the mechanical tests do not consider eventual deviations of the mechanical response of polymer due to local variation of chemical structure induced by the adhesion to glass in the lamination process.

Moreover, draft prEN16613(2013), after describing accurate methods to determine the thermo-viscoelastic properties of interlayer, reduces such information to a simple distinction among four "stiffness families" that is a very rough parameter to characterize the viscoelastic properties of an interlayer.

In order to overcome the pointed out drawbacks, a mechanical characterization procedure is proposed, in this paper, based on