

Full length article

Study of the time-temperature-dependent behaviour of PVB: Application to laminated glass elements



F. Pelayo*, M.J. Lamela-Rey, M. Muniz-Calvente, M. López-Aenlle, A. Álvarez-Vázquez, A. Fernández-Canteli

Department of Construction and Manufacturing Engineering, University of Oviedo, Campus de Viesques, 33203 Gijón, Spain

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ABSTRACT

The mechanical behaviour of laminated glass elements is governed by material properties of the interlayer, the Polyvinyl Butiral (PVB) being the most used interlayer material in these elements. PVB is a viscoelastic material whose mechanical properties (Young's modulus, shear modulus, etc.) depend mainly on the load application time and the temperature. Thus an adequate mechanical characterization of the PVB must be performed in order to predict the response of laminated glass elements with a good accuracy

In this work, PVB specimens were subjected to static relaxation tests and to dynamic experimental tests (frequency domain) at different temperatures from -15°C to 50°C using a DMTA equipment. Then the curves at different temperatures were related using the William-Landel-Ferry (WLF) Time-Temperature Superposition (TTS) model to obtain the mastercurve of both the time and frequency domain Young's moduli of the PVB. Finally, a viscoelastic Prony based model was fitted to the experimental data and used, afterwards, to simulate numerically the static and dynamic behaviour of different laminated glass elements at different temperatures. The numerical simulations were compared with the static and dynamic experimental results achieving a good accuracy in both the static deflections and the natural frequencies. With respect to the damping, the discrepancies are less than 22%.

1. Introduction

Laminated glass elements are nowadays of great interest in mechanical and structural applications due to their advantages with respect to standard monolithic glass [1,2], such as vibration and noise isolation as well as the safety improvement. This composite material consists of two or more layers of monolithic glass with one or more polymer interlayers. Although the monolithic glass presents a brittle non-linear behaviour [3], in the pre glass-breakage is usually considered as a linear-elastic material [4,5]. On the other hand, the polymer interlayers present, in general, a viscoelastic behaviour, Polyvinyl Butiral (PVB) being the most used interlayer material which is usually characterized as linear-viscoelastic [4]. The viscoelastic behaviour of the PVB governs the entire behaviour of the laminated glass so that an adequate characterization of the interlayer material must be undertaken for a proper design of laminated glass elements [6–9].

A full viscoelastic analysis is recommended when a precise design of a laminated glass element is needed but it is time consuming and requires to make the calculations in finite element program [9]. In order to simplify the calculations, the mechanical behaviour of the interlayer

can be considered as a linear elastic material, taking at each time its equivalent elastic modulus $E(t)$ [10–14], i.e. neglecting the memory effect of the viscoelasticity. This simplification is assumed when the calculations are carried out with the effective thickness concept proposed recently by [4] and extended and applied by different authors [5,9,13,14]. Several analytical models proposed for the calculation of laminated glass elements also consider this assumption [10–12].

As a viscoelastic material, the mechanical properties of PVB are mainly dependent of the load application time and the temperature working conditions [15,16]. Hereafter, we will simply refer to the properties of the PVB as time and temperature dependent.

This time and temperature dependence implies that a large number of assays should be carried out in order to cover all the material working conditions. However, in those so-called simply thermo-rheological materials [16], both variables (time and temperature) can be related through the Time-Temperature Superposition (TTS) principle [17,18] so, a series of stretch time experiments at different temperatures can be shifted to a reference temperature in order to obtain a broad-band time master curve at the corresponding reference temperature (see Fig. 1).

* Corresponding author.

E-mail address: fernandezpelayo@uniovi.es (F. Pelayo).

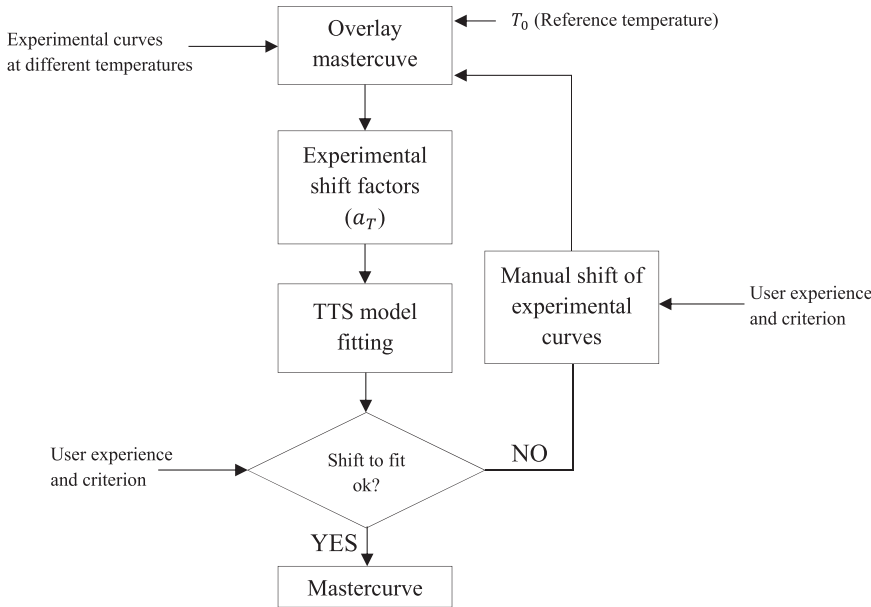


Fig. 1. General steps of the time-temperature superposition method.

Although this principle is a valuable tool for obtaining the mechanical properties of viscoelastic materials that obey the TTS, an automatic method to shift all the curves does not exist. The shifting can be done manually, using overlapping guess algorithms or, i.e. a minimization interpolation process but, in any case, a good knowledge of the master curve construction process is required [19,20]. A schematic description of the steps to develop a TTS fit is presented in Fig. 1.

Several methods to determine the horizontal shift factor, a_T , that relates temperature and time, have been proposed in the literature [21,22]. However, within the glass transition zone, the WLF [23] model is widely used in the last 6 decades since a good agreement has been observed for a large number of materials.

In the case of PVB, the WLF model has been used by different authors [4,24], to obtain the master curve of the material. If the master curve is obtained by a simple overlapping of the curves corresponding to different temperatures, omitting the recommendations indicated by William, Landel and Ferry [23] to fit properly the model, as well as its limitations, the fitted master curve can only represent adequately the material behaviour at one specific reference temperature. Thus if the master curve obtained by a simple overlapping is used to predict the static and/or the dynamic response of laminated glass elements at temperatures different to the reference temperature, significant large errors are expected. Therefore, an in-depth study concerning the applicability of the WLF for constructing the master curves of PVB is needed.

In this work, the WLF model is applied to determine the master curve of PVB for the relaxation modulus, $E(t)$, as well as for the complex modulus, $E^*(\omega)$ of the material. The WLF constants of both master curves were compared being the results in good agreement. On the other hand, the relaxation $E(t)$ master curve of the PVB was fitted to a Generalized Maxwell model, using Prony series, which was used to obtain successfully the complex modulus $E(\omega)$ by analytical interconversion.

Finally, the PVB material model is applied to the analysis of laminated glass elements. Static and dynamic experiments were carried out on a laminated glass plate and a multi-layered laminated glass beam at different temperatures. The experimental results were compared with those provided by a finite element model (FEM) using the viscoelastic mechanical properties of PVB obtained in this work. A good accuracy was encountered between the numerical simulations and the experimental results.

2. Time-temperature superposition principle: the WLF equation

The main idea of the time-temperature superposition is to construct broadband time master curves (usually span several decades of time) from stretch time curves (2 or 3 decades) of the material obtained at different temperatures (see Fig. 1). The principle can be applied indistinctly to the construction of any viscoelastic modulus, such as relaxation $E(t)$, creep $D(t)$ or complex $E^*(\omega)$. Hereafter, for the sake of simplicity the relaxation modulus $E(t)$ will be used but the methodology can be extended to the other viscoelastic functions in time or frequency domain, respectively.

To start the process of fitting a TTS model, an overlay master curve is necessary. The overlay master curve is initially obtained by overlapping the individual curves corresponding to the different tested temperatures (see Fig. 2). To obtain the initial overlay master curve (see Fig. 2), each individual curve at temperature T_i has to be horizontally time-shifted to the corresponding time interval in the overlay master curve at reference temperature T_0 (see Fig. 2), that is:

$$E(t, T_0)_i = a_{Ti} E(t, T_i) \quad (1)$$

where $E(t, T_0)_i$ is the time-shifted curve, $E(t, T_i)$ is the original curve and a_{Ti} is the “time shift factor” (see Fig. 2), hereafter, simply denoted as “shift factor”.

In the glass transition zone, the WLF equation is widely used to obtain the horizontal shift factor, a_T , which relates the curves corresponding to two different temperatures, e.g. T and T_0 and which is given by [25]:

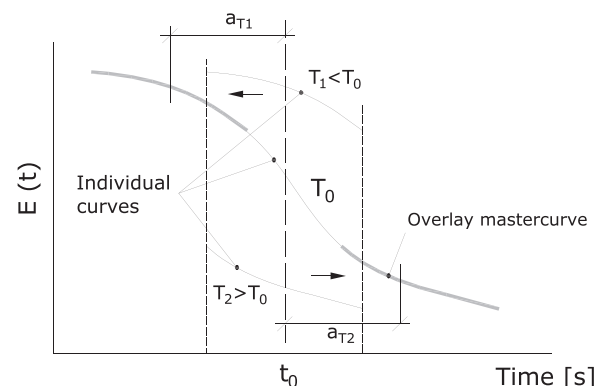


Fig. 2. Schematic of the master curve creation process.

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