Construction and Building Materials 182 (2018) 66–79

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The mechanical behaviour of polyvinyl butyral at intermediate strain rates and different temperatures

Chen Suwen[a,*], Chen Xing[b], Wu Xiqiang[b]

[a] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, PR China
[b] College of Civil Engineering, Tongji University, Shanghai, PR China

HIGHLIGHTS

- Dynamic tensile tests are conducted on PVB specimens at different temperatures.
- True stress-strain curves are obtained for different strain rates and temperatures.
- Strain rate effect and temperature effect on the mechanical property are discussed.
- Empirical formulae are derived for key mechanical property parameters.
- Dynamic constitutive equations at different temperatures are proposed based on G'Sell model.

ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 12 April 2018
Accepted 9 June 2018

Keywords:
Polyvinyl butyral (PVB)
Tensile test
Mechanical behavior
Strain rate effect
Temperature effect
Constitutive equation

ABSTRACT

Polyvinyl butyral (PVB) is often used in laminated glass and windscreen for its high ductility and good adhesion with glass. Previous studies have shown that the mechanical properties of PVB are both rate-dependent and temperature-dependent. To investigate mechanical properties of PVB material under different strain rates and different temperatures, a series of tensile tests on 1.52 mm-thick PVB specimens are carried out, covering designed engineering strain rates from 0.1/s to 300/s and temperatures from −30 °C to 40 °C, using an Instron high-speed servo-hydraulic testing machine and temperature box. Corresponding true stress-true strain curves are obtained. The testing results are then analyzed and empirical formulae are derived for key mechanical property parameters. Finally, based on G'Sell model, dynamic constitutive equations are given at different temperatures for PVB.

1. Introduction

Polyvinyl butyral (PVB) is a polymer material with excellent properties including good optical clarity, high adhesion strength, high ductility. It has been used as a primary interlayer material for laminated glass for architectural facade and windscreen in automobiles. When the glass cracks, the fragments will be retained on the interlayer and debris ejection can be prevented. Furthermore, cracked laminated glass can still dissipate energy by large deformation in PVB interlayer. Therefore, PVB plays an important role in the post-crack behavior of laminated glass. In order to achieve a better understanding of laminated glass under dynamic loading such as impact and blast, the dynamic material property of PVB should be thoroughly studied.

Studies have been carried out on the static mechanical property of PVB, and it has found that PVB is a nonlinear material with significant deformability and is sensitive to strain rate and temperature. Dynamic mechanical analysis (DMA) have been conducted to investigate the small strain behavior of PVB, and it is found that the small strain behavior of PVB can be well described by a viscoelastic model, in which a generalized Maxwell series is used to account for the time-dependent shear modulus of the interlayer [1–3]. The obtained results can be applied to analyze the response of pre-crack laminated glass subjected to quasi-static loading such as wind pressure. On the other hand, the large-strain behavior of PVB would be important when analyzing the post-crack behaviour of laminated glass due to that the PVB acts as the connections between glass fragments and can undergo large elongation before rupture. Based on the theory of constitutive relation of rubber, hyper-elastic model can be adopted to describe the nonlinear elastic behaviour of PVB, such as Blatz-Ko model [4] Mooney-Rivlin model [5,6] and the Ogden model

---

* Corresponding author.
E-mail addresses: swchen@tongji.edu.cn (S. Chen), 14cx@tongji.edu.cn (X. Chen), 1988xqwu@tongji.edu.cn (X. Wu).

https://doi.org/10.1016/j.conbuildmat.2018.06.080
0950-0618/

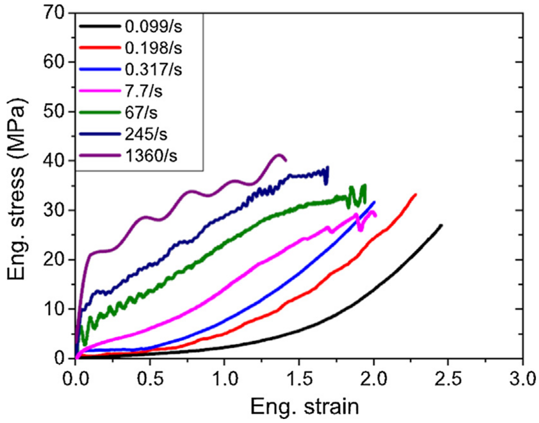

Fig. 1. Strain rate effect on PVB's mechanical behavior [11].

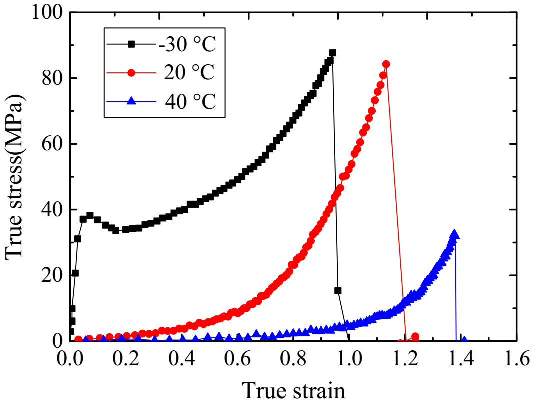

Fig. 2. Temperature effect on PVB's mechanical behavior [13].

[7,8]. The stress-strain relationship can be derived based on given strain energy functions.

The strain rate effect of PVB is of interest when considering dynamic loading such as impact and blast loading. Dynamic tensile tests have been conducted to investigate the strain rate effect in different strain rate ranges, such as 0.07 s^{-1}–89 s^{-1} by Bennison et al. [9], 0.0067 s^{-1}–118 s^{-1} by Iwasaki et al. [10], 0.2 s^{-1}–400 s^{-1} by Hooper et al. [3], 0.008 s^{-1}–1360 s^{-1} by Zhang et al. [11]. From these tests, it can be observed that the PVB behaves quite different at quasi-static region and dynamic region. Under low-speed tensile tests, PVB shows viscoelastic material property while behaves as 'elasto-plastic' material under high-speed tensile tests. As shown in Fig. 1, the engineering stress-engineering strain relationships always have an initial steep increase followed by a sudden change into the softening stage, in which the stiffness increases slowly with the elongation of specimen. This phenomenon can be attributed to the fact that PVB transforms from a rubbery material into a glassy material when the strain rate increases [3,9–11]. It should be noted that most of the above tests were conducted at room temperature (20 °C ± 5 °C).

As PVB material exhibits different mechanical properties at different temperatures, which will subsequently affect the blast resistance of architectural laminated glass, the temperature effect on the mechanical property of PVB material has also drawn attentions from researchers [12,13]. The temperature range investigated in relevant studies usually corresponds to ambient temperatures of different seasons and different locations. For example, Chen et al. [13] has conducted low speed tensile tests at different temperatures (−30 °C, 20 °C and 40 °C). The results show that the mechanical behavior of PVB was significantly affected by temperature. Transition from a glassy material at low temperature to a rubbery material at high temperature has been observed (Fig. 2). Morison et al. [12] investigated the coupling effect of strain rate and temperature on PVB material, considering three temperatures (5°C, 22 °C and 35 °C) and strain rates ranging from 30 s^{-1} to about 300 s^{-1}. It was found that the Young's modulus and yield strength of PVB material increases with the strain rate and decreases with temperature. However, the hardening modulus changes irregularly with strain rate at different temperatures.

For investigating the behavior of laminated glass subjected to blast or impact, different material models for PVB have been adopted in numerical modelling, including elastic model [14], nonlinear elastic model [15], linear viscoelastic model [16,17], hyperelastic model [18–20], bilinear plastic model [13,21–23] and Zhu-Wang-Tang model [24] (an empirical model). However, most of the generated models and numerical studies are limited to room temperature (20 °C ± 5 °C). This should be attributed to the limited testing data at different temperatures. In order to achieve a more accurate prediction of the dynamic behavior of laminated glass at different temperatures, the material properties of PVB corresponding to different strain rates and a wider temperature range are needed.

In this paper, tensile tests of PVB specimen under 7 tensile speeds (0.004 m/s, 0.02/s, 0.2 m/s, 1 m/s, 2 m/s, 4 m/s and 6 m/s, corresponding to designed strain rates of 0.2/s, 1/s, 10/s, 50/s, 100/s, 200/s and 300/s respectively) and 4 different temperatures (−30 °C, −5 °C, 25 °C and 40 °C) are carried out using a high speed INSTRON testing machine and temperature box. The true stress-true strain curves at different strain rates and temperatures are obtained. The testing results are analyzed and empirical formulae are derived for key mechanical property parameters, which has then been applied to propose a strain rate and temperature dependent stress-strain relationship for PVB material.

2. High-speed tensile test schemes

In this study, tensile tests are conducted at 7 loading speeds (0.004 m/s, 0.02/s, 0.2 m/s, 1 m/s, 2 m/s, 4 m/s and 6 m/s, corresponding to designed strain rates of 0.2/s, 1/s, 10/s, 50/s, 100/s, 200/s and 300/s respectively) and 4 temperatures (−30 °C, −5 °C, 25 °C, 40 °C). 3–5 repeated tests were conducted for each set of loading speed and temperature. Specimens are labeled in form of A-B-C, in which A, B and C represent testing temperature, designed engineering strain rate and specimen number respectively. For an example, specimen 25 °C-100/s-3 represents the third specimen with the designed engineering strain rate of 100/s at the test temperature of 25 °C.

2.1. PVB specimens

The origin PVB film adopted in current work is produced by DuPont™ (Butacite® PVB), which is widely applied both in architectural laminated glass and automotive windshield. The origin PVB film is post-processed by Jingang Glass Technology Co., Ltd. PVB interlayer in laminated glazing undergoes high temperature and high pressure during manufacture process, which may affect its in-situ mechanical properties of PVB [13]. In order to better coincide with the actual situation, all the test specimens in this study have experienced a similar process. A semi-finished laminated glass was made firstly with two outer glass panels sandwiching 4 layers of 0.38 mm thick PVB origin film, and non-adhesive glass fiber layer was inserted between glass and PVB. After the process of heating and compressing, the glass panels and PVB layers are bonded together completely. Then the water cutting machine is