

Research on Temperature and Strain Rate Dependent Viscoelastic Response of Polyvinyl Butaral Film

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ABSTRACT

The mechanical behavior of polyvinyl butyral (PVB) film plays an important role in windshield crashworthiness and pedestrian protection and should be depth study. In this article, the uniaxial tension tests of PVB film at various strain rates (0.001 s^{-1} , 0.01 s^{-1} , 0.1 s^{-1} , 1 s^{-1}) and temperatures (-10°C , 0°C , 10°C , 23°C , 40°C , 55°C , 70°C) are conducted to investigate its mechanical behavior. Then, temperature and strain rate dependent viscoelastic characteristics of PVB are systematically studied. The results show that PVB is a kind of temperature and strain rate sensitive thermal viscoelastic material. Temperature increase and strain rate decrease have the same influence on mechanical properties of PVB. Besides, the mechanical characteristics of PVB change non-linearly with temperature and strain rate. Finally, two thermal viscoelastic constitutive model (ZWT model and DSGZ model) are suggested to describe the tension behavior of PVB film at various strain rates and temperatures. Tension response of PVB at 0°C - 70°C is simulated based on ZWT model, while tension response of PVB at -10°C is described using DSGZ model. The fitting results show good agreement with its corresponding experimental results. Results may provide basic experimental data and theoretical support to explore energy absorbing characteristics and safety design of PVB laminated glass.

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INTRODUCTION

Polyvinyl butyral (PVB) film serves as a preferred interlayer material for automotive windshield[1] and construction curtain[2]. As a typical viscoelastic material[3, 4], its mechanical properties are significant influenced by temperature and strain rate. Therefore, the investigation on temperature and strain rate dependent viscoelastic response of PVB is a hot topic of current research.

Several experimental studies on mechanical behavior of PVB interlayer have been carried out. The compressive behavior of PVB as well as its constitutive relations under various loading conditions have been investigated by Xu[5, 6] and Liu[7]. However, the PVB interlayer film exhibits tensile deformation during the impact process[8]. Thus, uniaxial tensile tests of PVB interlayer have been at low strain rates by Liu[7], Chen[9] and Iwasaki[10], and its corresponding constitutive models has also been established. Iwasaki[10] and Yang[8] conducted the uniaxial tensile experiments of PVB interlayer and also investigated its rate dependent constitutive behavior at high strain rates range (118 s^{-1} to 3768 s^{-1}). Moreover, the viscoelastic mechanism has also attracted more and more attention to describe the mechanical properties of PVB interlayer [11]. Liu[12], Hooper[13] and Zhang[14] investigated the dynamic viscoelasticity of PVB interlayer using Dynamic Mechanical Analysis (DMA), Instron testing system and low impedance Split Hopkinson Tension Bar (SHTN) method at various temperature, heating rate and vibration frequencies. Besides, Generalized Maxwell model, Fractional Derivative Maxwell model and thermal-viscoelastic

Zhu-Wang-Tang (ZWT) constitutive model were also employed to describe its dynamic tensile response. Charitidis et al.[15] conducted compression creep experiments of carbon nanotube/polyvinyl butyral composites to explore its long term viscoelastic behavior, and revealed that a higher loading rate results in a greater primary creep deformation and leads to an increase of the total creep deformation. Furthermore, Xu et al.[16] carried out uniaxial tension creep and stress relaxation tests to investigate the viscoelasticity of PVB and SentryGlas® Plus film.

However, fewer studies are available for systematical investigation on temperature and strain rate dependent mechanical behavior of PVB film, which is particularly important to understand its viscoelastic characteristics. In this research, uniaxial tension experiments under various strain rates and temperatures are carried out to obtain its systematical tension mechanical behavior. Afterwards, the temperature and strain rate dependent viscoelastic response is systematically analyzed. Finally, thermal viscoelastic constitutive model is established on the basis of ZWT model and DSGZ model.

Experimental Details

Experimental Setup

The uniaxial tension experiments under different strain rates (0.001 s^{-1} - 1 s^{-1}) and temperatures (-10°C - 70°C) are conducted on a tension experiment system, which consists of a hydraulically driven testing

machine (INSTRON 8872), a temperature controller and a CCD (Charged-coupled Device) camera. The basic structure of the experimental system is illustrated in Fig. 1. A dumbbell-shaped specimen (DIN 53504[17]) is introduced with dimensions show in Fig. 2, which is fixed by the clamber. Considering the inevitable slight slide between specimen and clamber, the CCD camera is utilized to record the deformation of specimen which can further be converted to the strain between gauge lines. Seven temperatures, i.e. -10°C , 0°C , 10°C , 23°C , 40°C , 55°C , 70°C (ASTM D1349[18]), adjusted by temperature controller are employed to investigate the thermal-dependent effect of PVB. Furthermore, four loading rates 1.56 mm/min, 15.6 mm/min, 156 mm/min, 1560 mm/min corresponding to the initial strain rates of 0.001 s^{-1} , 0.01 s^{-1} , 0.1 s^{-1} , 1 s^{-1} are applied to study the rate-dependent effect of PVB. The detailed experimental conditions are listed in table 1, and all the experiments are conducted in the humidity of 20%-30%.

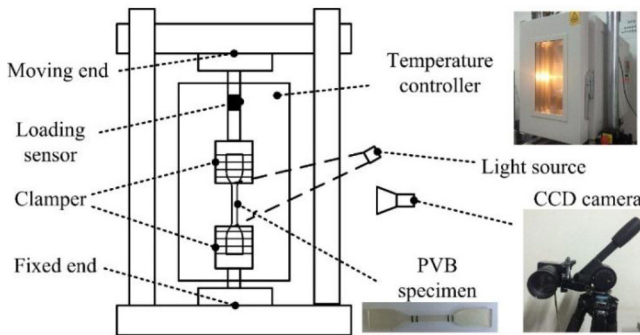


Figure 1. The schematic diagram of tension experiment system.

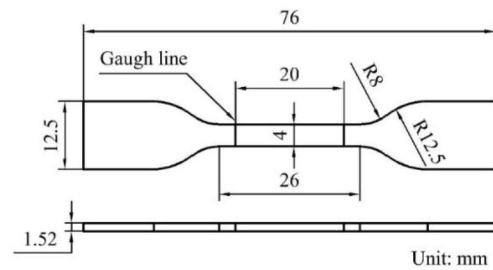


Figure 2. The structure and dimensions of PVB specimen.

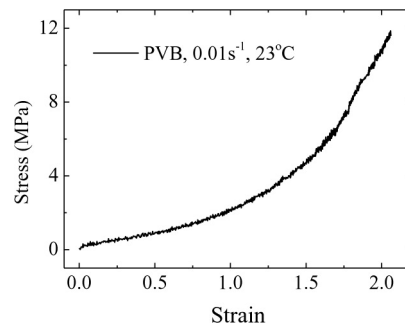
Experimental Results and Analysis

In order to ensure repeatability, each experiment has been conducted at least twice and an arbitrary set is selected for subsequent analysis. PVB softening occurs during the experiments, besides strain rate throughout specimen is not consistent, therefore the real strain rate of gauge section is different from initial strain rate. The strain-time curves obtained by CCD camera are differentiated to calculate real strain rates in gauge section and the corresponding results are shown in Table 1. As can be seen, the real strain rates are not stable and differ from initial strain rates obviously.

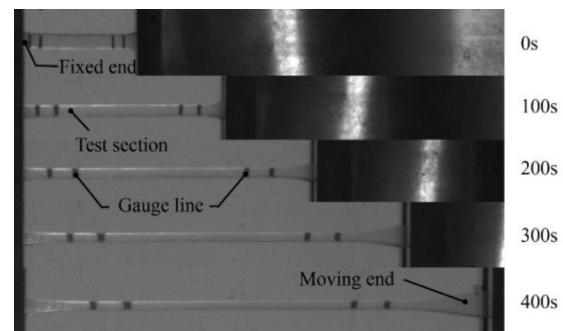
Table 1. The relationship between initial strain rate and real strain rate.

Experimental condition	Real strain rate
0.001 s^{-1} , 23°C	$4 \times 10^{-4}\text{ s}^{-1}$ - $6 \times 10^{-4}\text{ s}^{-1}$
0.01 s^{-1} , 23°C	$2 \times 10^{-3}\text{ s}^{-1}$ - $8 \times 10^{-3}\text{ s}^{-1}$
0.1 s^{-1} , -10°C ~ 70°C	0.02 s^{-1} - 0.14 s^{-1}
1 s^{-1} , 23°C	0.2 s^{-1} - 1 s^{-1}

Fig. 3 gives a typical PVB tension stress-strain curve and its corresponding deformation process at low strain rate (0.01 s^{-1}) and room temperature (23°C). As can be seen, the stress-strain behavior shows a typical exponential relation, thus PVB displays obvious nonlinear viscoelastic properties at low strain rate and room temperature. At the beginning, stress increases slowly with the strain, then the slope grows steeper as strain increases. Molecule pronation together with segments micro-Brownian motion occur firstly, then molecular chains elongates from the best crimped state gradually which leads to the increase of deformation resistance.



a. Stress-strain relationship.



b. Deformation process of specimen.

Figure 3. Tension behavior of PVB at 0.01 s^{-1} , 23°C .

A typical PVB tension stress-strain curve and its corresponding deformation process at low strain rate (0.01 s^{-1}) and low temperature (-10°C) is illustrated in Fig. 4. As shown, PVB behaves as an elastoplastic material, and its stress-strain behavior can be divided into three stages: elastic-viscoelastic stage, necking stage and plastic flow stage. Y point in Fig 4(a) represents yield point indicating the start point of necking. Before Y point, linear elastic, linear viscoelastic and nonlinear viscoelastic appear sequentially in elastic-viscoelastic stage, together with bond lengths and angles of polymer molecules changes. Then necking stage begins which can be clearly observed in Fig 4(b). The frozen polymer molecule chains start to move which leads to the stress decrease in this stage. In