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The mechanical properties of ionoplast interlayer material at high strain rates

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ABSTRACT

Ionoplast material has been recently introduced and extensively used as interlayer material for laminated glass to improve its post-glass breakage behavior. Due to its sound mechanical performance, the applications of laminated glass with ionoplast interlayer have been widely extended to the protection of glass structures against extreme loads such as shock and impact. The properties of this material at high strain rates are therefore needed for properly analysis and design of such structures. In this study, the mechanical properties of ionoplast material are studied experimentally through direct tensile tests over a wide strain rate range. The low-speed tests are performed using a conventional hydraulic machine at strain rates from $0.0056\ s^{-1}$ to $0.556\ s^{-1}$. The high strain-rate tests are carried out with a high-speed servo-hydraulic testing machine at strain rates from approximately $10\ s^{-1}$ to $2000\ s^{-1}$. It is found that the ionoplast material virtually exhibits elasto-plastic material properties in the strain rate range tested in this study. The testing results show that the material behavior is very strain-rate dependent. The yield strength increases with strain rate, but the material becomes more brittle with the increase in strain rate, with the ultimate strains over 400% under quasi-static loading, and decreasing to less than 200% at strain rate around $2000\ s^{-1}$. The testing results indicate that simply applying the static material properties in predicting the structure responses of laminated glass with ionoplast interlayer subjected to blast and impact loads will substantially overestimate the ductility of the material and lead to inaccurate predictions of structure response. The testing results obtained in the current study together with available testing data in the literature are summarized and used to formulate the dynamic stress–strain curves of ionoplast material at various strain rates, which can be used in analysis and design of structures with ionoplast material subjected to blast and impact loads.

1. Introduction

Because of the increased threats from windborne debris impacts on glass windows owing to the increased wind speed with climate change, and the increased threats of bombing attacks owing to the increased terrorism activities, protection of glass windows against impact and blast loads is critical for people protection since glass windows are the relatively weaker sections in a structure, and glass fragments have been identified as the source for most casualties in such events [1,2]. Laminated glass windows have been proved effective for mitigating glass fragment threats as compared to the monolithic glass windows [2–7]. The most commonly used interlayer material for laminated glass, polyvinyl butyral (PVB), is soft, very ductile and exhibits viscoelastic material properties. After glass breakage, PVB interlayer will stick the shattered glass fragments together therefore prevent them from flying into the room. The interlayer material with large ductility will continue to deform and dissipate the imposed energy. However, due to the limited stiffness and strength of PVB, laminated glass with PVB interlayer offers relatively poor residual load-carrying capacity after glass breakage [8]. Rupture of PVB under large blast and impact loads results in the complete collapse of the window structure and lead to the failed interlayer and shattered glass fragments flying together into the room. Therefore, materials stronger and more ductile than PVB that can be used as interlayer material in laminated glass are constantly sought.

SentryGlas®Plus (SGP) by DuPont® is a well-known and commonly used ionoplast material for the replacement of PVB interlayer. As an ionoplast material, SGP primarily comprises of ethylene/methacrylic acid copolymers. It also contains small

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amounts of metal salts which improves its bonding performance to glass ply. SGP behaves elasto-plastically under tensile loading. It is stated to offer up to five times the tearing strength and a hundred times the rigidity of conventional PVB material. As a result, SGP is more and more commonly used as the interlayer in protective designs of glass structures.

Understanding the mechanical properties of SGP material at different strain rates is of great importance for reliable analysis and design of glass structures because the laminated glass structure might be subjected to loads of different rates, ranging from quasi-static to high-rate impact and blast loads. Belis et al. [8] conducted uniaxial tensile tests on 25 SGP specimens at five loading speeds in the quasi-static range. The testing results revealed an elasto-plastic behavior of SGP. It was found that the yield stress is amplified when the loading speed increases. Similar observation was reported by Bennison et al. [9]. Using a servo-hydraulic testing machine, Bennison and his co-workers tested SGP specimens in the strain rate range from 0.1 s^{-1} up to 125 s^{-1}. The yield stress was found to increase from about 31 MPa to 36 MPa. It was also revealed that the ultimate strain of SGP decreased with the strain rate [9]. The dynamic material property of SGP at other strain rates especially at strain rates above 100 s^{-1} has not been widely reported in the literature yet.

In this study, the mechanical properties of ionoplast material SGP under the tensile loading at various strain rates are investigated experimentally. SGP specimens are firstly pulled at low speeds to study its behavior under quasi-static loading conditions. High-speed servo-hydraulic machine is then employed to carry out high-speed tensile tests on SGP specimens. The responses of SGP material at strain rates from approximately 10 s^{-1} to 2000 s^{-1} are investigated. The deformation-to-fracture behavior of SGP material is monitored by a high-speed camera. The stress–strain curves of SGP material are presented and analyzed. The results obtained in this study can be used to model SGP material behavior under different strain rates.

2. Theory and methodology

2.1. Testing systems

Experimental techniques commonly used to determine the material tensile properties at different strain rates include conventional screw driven load frame, servo-hydraulic machine, pendulum or drop weight impact machine, high-speed servo-hydraulic machine, and Split-Hopkinson Pressure Bar system. The conventional testing systems including the screw driven load frame and conventional servo-hydraulic machine can normally test material tensile strength at a strain rate up to 1 s^{-1}. Split-Hopkinson Pressure Bar (SHPB) is commonly used to determine the material strength at high strain rates ($\dot{\varepsilon} \geqslant 100\ s^{-1}$). To test the material tensile properties, the tensile SHPB usually requires the testing specimen to be firmly glued on both ends respectively to the incident and transmitter bars to ensure the tensile stress wave can travel through the specimen before it fractures. It is therefore not suitable for polymer materials such as SGP, as the glue could significantly alter the material properties. The pendulum or drop weight impact system and the high-speed servo-hydraulic machine have been widely used to determine material strength at strain rate above 1 s^{-1}. Dumbbell shaped specimens similar to those used for quasi-static tests are most commonly adopted for the dynamic tensile tests. Due to the inherent difficulties, the strain rates that can be achieved by a drop weight impact machine is usually restricted by the drop height and therefore limited to 1–100 s^{-1}. Moreover, during a test the velocity of the actuator is also coupled with the response of the specimen. In other words, it is difficult for the drop weight impactor to maintain a constant testing velocity. In this study, servo-hydraulic and high-speed servo-hydraulic machines are used to perform the low-speed and high-speed tensile tests. The testing setups and machine information are described in details in section three and four.

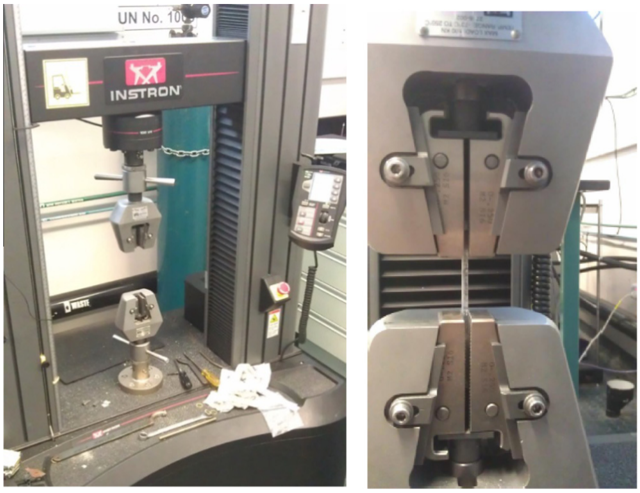

Fig. 1. INSTRON hydraulic machine for low-speed test.

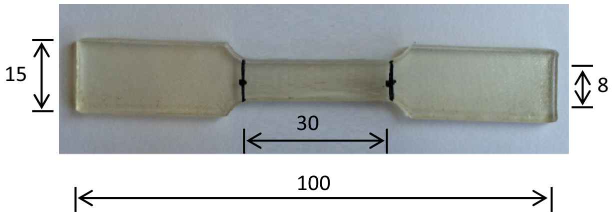

Fig. 2. Illustration of specimen geometry for low-speed test.

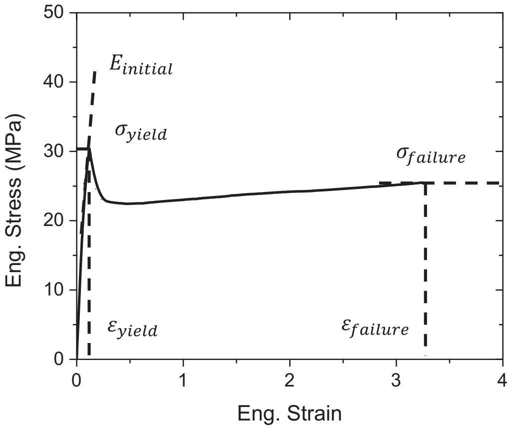

Fig. 3. Typical engineering stress–strain curve for SGP material.

2.2. Testing requirements for high-speed tests

To ensure the validity of testing data for a material test, it is critical to assure the specimen is under the state of stress equilibrium. For low-speed tests, the specimens are in quasi-static equilibrium,