

Modeling and Experimental Studies of Crack Propagation in Laminated Glass Sheets

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ABSTRACT

Polyvinyl Butyral (PVB) laminated glass has been widely used in automotive industry as windshield material. Cracks on the PVB laminated glass contain large amount of impact information, which can contribute to accident reconstruction investigation. In this study, the impact-induced in-plane dynamic cracking of the PVB laminated glass is investigated. Firstly, a drop-weight combined with high-speed photography experiment device is set up to investigate the radial cracks propagation on the PVB laminated glass sheet. Both the morphology and the velocity time history curve of the radial cracks are recorded and analyzed to investigate the basic mechanism of the crack propagation process. Afterwards, a three-dimensional laminated plate finite element (FE) model is set up and dynamic cracking process is simulated based on the extended finite element method (XFEM). Good agreements between the experimental and numerical results on the radial crack velocity time history and the crack morphology validate the effectiveness of the FE model. Results may provide an experimental technique as well as useful finite element model of PVB laminated glass for further systematically studies to explore the fracture mechanism and safety design improvement of PVB laminated glass.

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INTRODUCTION

Polyvinyl Butyral (PVB) laminated glass serves as one of the most important components in automotive to protect vulnerable road users as windshield[1]. Due to the adhesiveness of the interlayer, glass fragments are still firmly bonded to PVB interlayer after the impact to minimize the stabbed and scratched danger. Cracks on the laminated windshield contains a large amount of accident information, therefore accident reconstruction analysis by extracting useful information from the cracks of the laminated windshield is a hot topic of current research.

Several theoretical studies and experimental research have been carried out to investigate the quasi-static and dynamic mechanical properties of brittle materials. Lawn et al.[2, 3] presented fracture mechanics of brittle solids and theoretically described the evolution of the radial crack system in the far field of sharp-indenter contacts. Quasi-static mechanical behavior of PVB laminated glass has been studied by Timmel[4] and Xu[5]. Park and Chen[6] studied the interactions between cracks driven by dynamic loading and interfaces perpendicular to the cracks. Dynamic crack initiation and propagation properties have been investigated by Yao[7] and Arakawa[8] using the method of dynamic caustics combined with the high-speed photography system. Vandenberghe et al. [9] interpreted the variation of dynamic crack patterns on brittle plate based on Griffith's theory of fracture combining bending

elastic energy and fracture energy. Dynamic fracture behavior of the glass was observed and analyzed by Chai[10], Cook[11] and Nie[12]. Chen et al.[13, 14] investigated the initiation and propagation properties of in-plane cracking on the PVB laminated glass experimentally. Meanwhile, some numerical studies focused on the damage patterns and the crack growth mechanism of automotive glazing. The extended finite element method allowing displacement discontinuous is presented and developed by Belytschko[15], Dolbow[16], and Moes[17]. Zhao et al.[1, 18] studied the failure characteristics and impact resistance of the PVB laminated windshield using finite element method based on continuum damage mechanics (CMD) and energy release rate criterion. Zang et al.[19] simulated the impact fracture process of single glass plane and laminated glass plane to study the impact fracture behavior of the two models using discrete element method. Xu et al.[20] used the extended finite element method (XFEM) to investigate the radial and circumferential crack propagation characteristics of windshield plate.

However, few research focus on the combination of experimental research and numerical studies to investigate the dynamic fracture propagation mechanism. Any attempt to accurately study the fracture mechanism of the PVB laminated glass could only be reached via proper modeling techniques with the experiment data embedded verified by the corresponding impact tests, which is our fundamental

motivation for this research. In this study, the radial crack propagation process of the PVB laminated glass plate is obtained by high-speed photography system to analyze its fracture mechanism. Afterwards, laminated glass plate finite element (FE) model is built using a layered structure. Finally, the FE model is validated by the comparison of simulation results and experimental results.

EXPERIMENT DETAILS

Experimental Specimen

The PVB laminated glass specimen used in the experiment is a rectangular plate with the dimension of 200mm×150mm shown in [Figure 1](#). The PVB interlayer is 0.76 mm thick sandwiched by two sheets of 2 mm-thick soda-lime glass. The specimen adopts the same processing method as the automotive laminated windshield under compression at 10 bar and 120 °C[5]. The laminated glass specimen is fixed by two steel frames, with a rubber interlayer between the specimen and the frame in order to avoid the damage of the specimen and eliminate the residual stress. The tightening torque of the bolts is set to 4 N · m simulate the clamped boundary conditions of the automotive windshield. The vertical impact load is applied in the center of the specimen by the impact direction convertor (shown in [Figure 1](#)) which convert the vertical load into horizontal load under the impact of a free-falling drop-weight with mass of 2 kg at the initial height of 700 mm (i.e. with the impact velocity of 3.7 m/s). The impact direction convertor is made of 45 steel. The end part of the impact direction convertor is equipped with an impact head which can be designed into different shapes. In this study, we use the hemispherical shape of the impact head.



Figure 1. The PVB laminated glass specimen and the impact direction convertor.

Experimental Setup

The high-speed photography system is used to record the real-time dynamic crack propagation process. The schematic illustration of the experimental system is shown in [Figure A1](#). The experimental system consists of a high-voltage charging controller, a multi-spark box, two field lenses (an objective one and an eyepiece one) with 4.0 m focal length and 0.4 m diameter, a 4×4 array light source together with a 4×4 array film camera to receive the light and record the crack photo information. We design the optical system shown in [Figure A1\(b\)](#) in order to ensure images on the film arranged in the same chronological order according to the ignition of the spark plug. The light emitted by the spark plug is transferred into

parallel light by the objective lens and gathered in the corresponding array film camera by the eyepiece lens after projecting through the specimen. The final test images are recorded on the film in the dark box. The delay controller is used to receive the impact signal and control the ignition time of each spark plug. The time interval of the delay controller can be set between 1 microsecond and 999 microseconds to meet the test requirements. An electric-light receiver is placed in front of the array spark plug in order to record the real ignition time of the spark plug and verify whether the system is working properly. An oscilloscope is used to receive the voltage signal from the electric-light receiver transferred by the optical signal. Finally, ignition time is judged by observing the recorded signals on the oscilloscope.

At the beginning of the experiment, the drop-weight is moved to a specific height and released to generate different impact energy. The vertical impact is transferred into horizontal impact through impact connecting rod and impact direction convertor, finally applied to the center part of the specimen. The circuit of delay controller is connected and sends a trigger signal to the delay controller when the drop-weight impacts the connecting rod. Then the delay controller output the signal to the multi-spark system. The 16 spark plugs ignite according to the predetermined time interval sequentially, while the optical recording system will record the corresponding 16 images.

Verification of Experimental Device

A series of pre-experiments are conducted to verify the experimental system via efficiency calibration. Here, we apply the impact efficiency (η) to calibrate the experimental system, which is described as:

$$\eta = \frac{E_{\text{impact}} - E_{\text{rebound}}}{E_{\text{impact}}} = \frac{mgh_{\text{impact}} - mgh_{\text{rebound}}}{mgh_{\text{impact}}} \quad (1)$$

where E_{impact} is the impact energy, E_{rebound} is the rebound energy, m is the mass of the drop-weight, h_{impact} is the impact height of the drop-weight, and the h_{rebound} is the rebound height of the drop-weight. Table A1 shows that with the increase of the impact height, the impact efficiency increases. With the increase of the impact height, the glass breakage level increases and more energy can be absorbed by the laminated plate, especially the PVB interlayer. Therefore, the PVB interlayer plays a critical role in the energy absorption process. As we can see from Table A1, the impact efficiencies of the pre-tests are all greater than 90%. Most of the impact energy are transferred to the impactor by the impact direction convertor and the efficiency of the experimental system is high enough.

MODEL AND METHOD

Model Setup

A cylinder with hemispherical head is used to model the impactor. The impactor has a mass of 2 kg by applying an equivalent density in order to simplify the complex structure of the impactor. The three-dimensional laminated plate FE model is developed with solid elements according to the specimen of PVB laminated glass. The layered structured of the laminated sheet is modeled using 15 layers of three-dimensional eight-node reduced integration solid (C3D8R) elements with shared nodes at their boundaries: the outside 6 C3D8R elements representing the glass layer and the inside 3 C3D8R elements standing for the PVB layer shown in Figure 2. The C3D8R can solve the displacement accurately, and the accuracy of analysis will not be affected when the distortion of the grid exists, so C3D8R is suitable in this simulation. Each material needs at least three elements in the longitudinal direction with more than two integration points to ensure the accuracy of the results in order to analyze the longitudinal situation. The glass plate FE model is meshed using 1mm×1mm surface size element with a mesh convergence study and consists of 112500 elements in total.



Figure 2. The structure of the laminated plate FE model.

To take advantage of the symmetry of the model, only one quarter of the model is used in the simulations shown in Figure A2. The model just needs to be mirrored when we analyze the simulation results. The boundary condition of the glass plate model is assumed to be clamped (full model), which consistent with the real experimental condition. In terms of the impact condition and material properties, simulations are limited to normal and center impact with the velocity of 3.7 m/s. The contact form between the impactor and glass applies the surface-to-surface contact without friction. The PVB interlayer is modeled as linear viscoelastic model using the prony series with only one term based on:

$$G(t) = G_{\infty} + (G_0 - G_{\infty})e^{-\beta t} \quad (2)$$

where $G(t)$ is the relaxation modulus, G_0 is the short time shear modulus, G_{∞} is the long time shear modulus and β is the decay factor[1]. The elastic modulus E and Poisson's ratio ν of PVB are given below:

$$E = \frac{9KG_0}{3K + G_0} \text{ and } \nu = \frac{3K - 2G_0}{6K + 2G_0} \quad (3)$$

where K represents the bulk modulus of PVB[1]. The maximum allowable principal stress σ_{glass} of different soda-lime glass are different due to its intrinsic stochastic flaws, usually from 10 MPa to 60 MPa, and the simulation with σ_{glass} of 60 MPa fit well with the experimental results. Other material and impact parameters are shown in Table A2.

Fundamentals of XFEM

The extended finite element method extends the classical finite element method by enriching the solution space with discontinuous functions. The element mesh in XFEM is generated regardless of the existence and location of the cracks.

The discontinuous displacement field across the crack facing away from the crack tip can be expressed in the form below[16]:

$$\mathbf{u}^h = \sum_{i=1}^n N(\mathbf{x}) \left(\mathbf{u}_i + \mathbf{b}_i H(\mathbf{x}) + \sum_{l=1}^4 \sum_{j=1}^2 \mathbf{c}_{il} F_l^j(\mathbf{x}) \right) \quad (4)$$

where n is the total number of nodes in the mesh, $N_i(\mathbf{x})$ is the shape function associated with node i , $\mathbf{u}_i$ are the classical DOFs of node i , $\mathbf{b}_i$ and $\mathbf{c}_{il}$ are the DOFs associated with $H(\mathbf{x})$, and $H(\mathbf{x})$ is the Heaviside enrichment function. The crack tip function $F_l^j(\mathbf{x})$ is given below[16]:

$$F_l^j(\mathbf{x}) = \left\{ \sqrt{r} \sin\left(\frac{\theta}{2}\right), \sqrt{r} \cos\left(\frac{\theta}{2}\right), \sqrt{r} \sin\left(\frac{\theta}{2}\right) \sin(\theta), \sqrt{r} \cos\left(\frac{\theta}{2}\right) \sin(\theta) \right\} \quad (5)$$

where r and θ define the crack-tip based local polar coordinates of integral points.

Simulation Method

In our study, the maximum principle stress criterion is applied to simulate the failure of glass layer, and the maximum principle stress criterion is given below:

$$f = \begin{cases} 0, & \sigma_{\text{max}} < 0 \\ \frac{\sigma_{\text{max}}}{\sigma_{\text{max}}^0}, & \sigma_{\text{max}} \geq 0 \end{cases} \quad (6)$$

where f is the maximum principle stress ratio, σ_{max}^0 represents the maximum allowable principal stress. It refers that a purely compressive stress does not cause the crack initiation, and the crack is assumed to initiate when the maximum principle stress ratio f reaches a value of one.