Impact Experimental Investigation of PVB Laminated Glass Based on High-Speed Photography: An Initial Attempt

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Abstract: In this paper, a high-speed photography method combined with drop-weight test is used to study the dynamic cracking behavior of PVB (polyvinyl butyral) laminated glass subject to low-speed impact. Crack patterns, paths and velocities, derived from a series of dynamic photos, are thoroughly analyzed to explore the characteristics cracking propagation. In addition, given the different the experimental conditions, i.e. different crack velocities, cracking speed (including maximum speed and speed-time history curve) are examined and compared.

Keywords: PVB laminated windshield; high-speed photography; crack

1. Introduction

PVB laminated glass, consisting of a PVB interlayer sandwiched by two layers of soda-lime glass sheets, has become the standard material for automobile windshield. Due to the polymer's excellent viscosity and energy-absorbing characteristics, the windshield can provide a relatively better protection compared for pure glass windshield for both drivers and pedestrians in vehicle accidents. Generally, radial and circumferential cracks could be found on the windshield after a vehicle-pedestrian accident [1], which is important evidences for accident investigation and reconstruction. To provide a more illuminating theory for material selection and pedestrian protection, as well as accident reconstruction, a further understanding to crack initiation and propagation is in pressing need.

Earlier studies on PVB laminated glass focused on using the finite element simulation or theoretical model to explain the dynamic response of windshield glass after impact. Timmel et al. [2] developed a smeared model based on a finite element solver to investigate the dynamic response of the windshield during impact. Zhao et al. [3,4] used constitutive model based on continuum damage mechanics to study the response of the laminated automotive glazing. Xu et al. [5] used the extended finite element method (XFEM) to analyze low-speed head impact on a windshield. Herndon et al. [6] carried out several experiments on automotive glazing under quasi-static and dynamic loading conditions to find out how the glazing could withstand occupant interaction. But none of the studies included the crack propagation research. These numerical investigations are mainly based on the empirical data of each component material which may not provide sufficient mechanical exhibition of current composite windshield.

Meanwhile, the optical method of high-speed photography, as a direct tool in fracture mechanics analysis, has now been widely employed to study the fracture and cracking characteristic of different materials. Takahashi and Arakawa [7] combined high-speed photography and caustic method to carry out a series experiments to obtain crack velocity, acceleration and dynamic stress-intensity factor. Yao et al. [8,9] also conducted several dynamic experiments using the same method on PMMA to obtain crack development characteristics. These experiments give us important clues to study the dynamic cracking behaviors of PVB laminated windshield.

In this paper, by combing the drop-weight test and high-speed photography method, the dynamic response of PVB laminated glass specimens under impact are experimentally studied. Patterns, cracking propagation, as well as the speed of the cracks are obtained. Moreover, by setting up different experimental speeds, crack propagation characteristics are compared.

2. Experimental Setup

2.1. Experimental Apparatus

The high-speed photography system includes a 4×4 array spark generator, two convex lenses and 4×4 array camera, as shown in Fig.1. The generated sparks are considered as point light sources, the interval between which can be set from 1μs to 9999μs. Two lenses including the objective one and the eyepiece one, with 1550mm focal length and 400mm diameter, provide the paralleling lights which transmit through the specimen and ensure clear photos capture. The impact load is applied at the centre

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point of the specimen by an impactor which is struck by a drop weight with initial height h=1000mm. Synchronization of impact loading and the high speed camera is realized by a contact circuit. It will be connected when the falling weight contacts the top surface of the impact convertor, triggering with set-in-advance intervals, which is 10μs in this experiment.

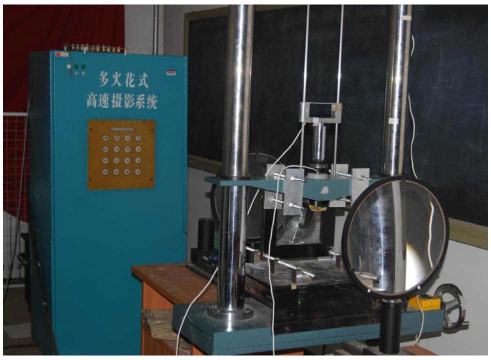


Figure 1. High-speed photography experimental system

2.2. Specimen

The PVB laminated glass specimen is a rectangular plate, with the dimension of 200mm×150mm. The PVB interlayer is 0.38mm thick sandwiched by two sheets of 2mm-thick soda-lime glass. Two steel frames are used to fix the specimen, with a rubber interlayer between the specimen and the frame in order to protect the glass and reduce the residual stress.

2.3. Mechanical Property of PVB Laminated Glass

Table 1. Mechanical properties of glass and PVB interlayer

Material	Parameters
Glass	E=74GPa; ρ=2500kg/m3; ν=0.25
PVB film	K=20GPa; ρ=1100kg/m3

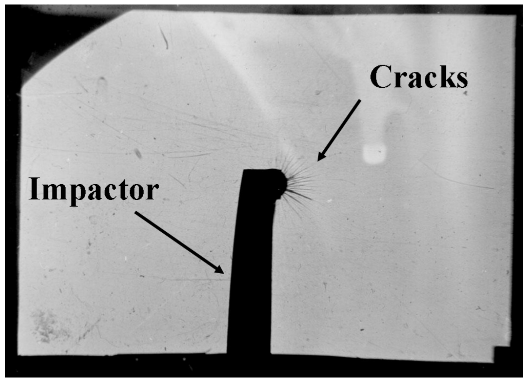
where E is the Young's modulus, K is the bulk modulus, ρ is the density and ν is the Poisson's ratio.

Figure 2. Specimen after impact

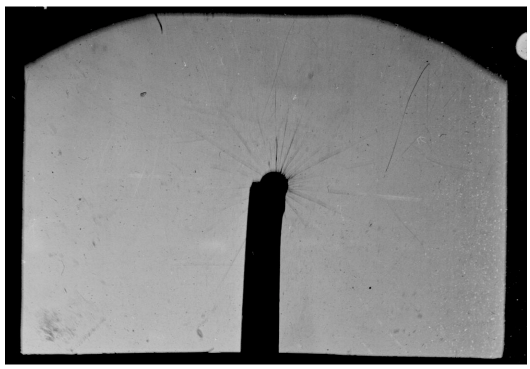
3. Result and Discussion

3.1. Crack Patterns

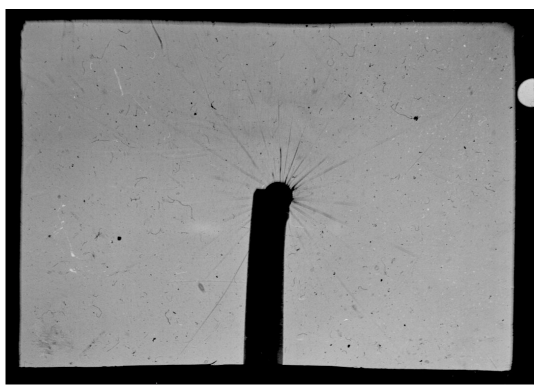
Fig.2 shows the specimen after impact. Fig.3 (a)-(i) demonstrates a series of high-speed photographs of dynamic fracture of PVB laminated glass specimen. Two kinds of cracks including radial cracks and circumferential cracks can be observed from both the photos and the specimen. The circumferential cracks only appear after 100μs. This phenomenon strongly supports the result given in Xu [1, 10] that the radial crack comes before the circumferential one. The crack tip positions at each time point derived from these photos will be used to obtain further fracture parameters such as crack length and speed.



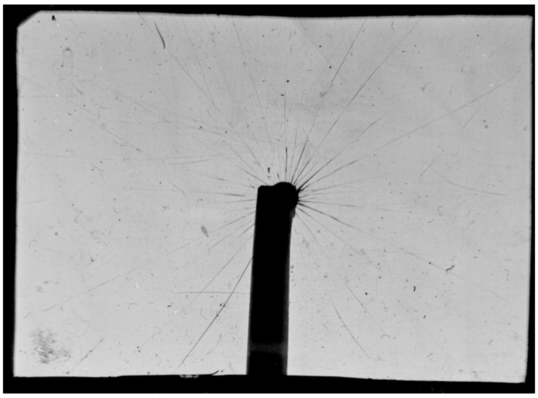
(a) t=10μs



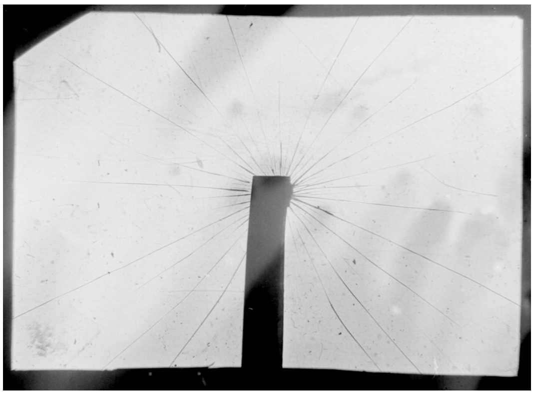
(b) t=20μs



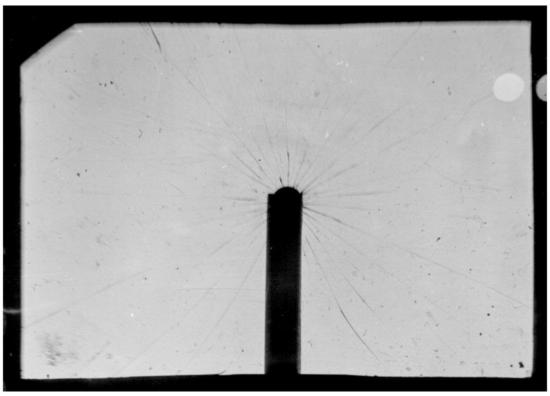
(c) t=40μs



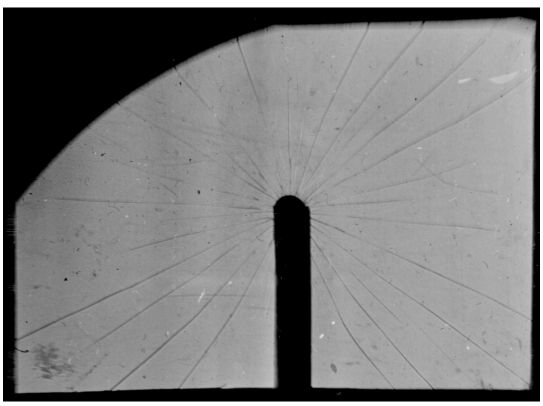
(d) t=60μs



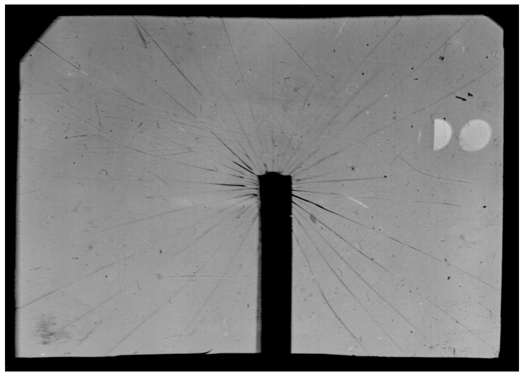
(e) t=70μs



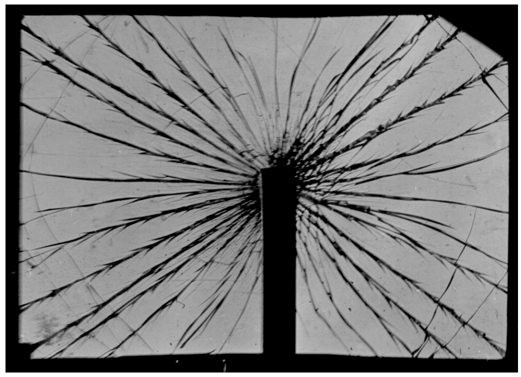
(f) t=80μs



(g) t=90μs



(h) t=100μs



3(i) t=600μs

Figure 3. Dynamic cracking evolution under the impact height of 1000mm, impact weight of 2kg

3.2. Crack Velocity

Due to the inevitable internal stochastic flaws inside the glass, the lengths of cracks in each photo are not the same. Therefore, the average lengths of cracks are calculated in order to obtain the crack growth history. Fig.4 shows the crack growth history during 0μs~80μs after impact. Solid lines are acquired through optimized fitting procedure.

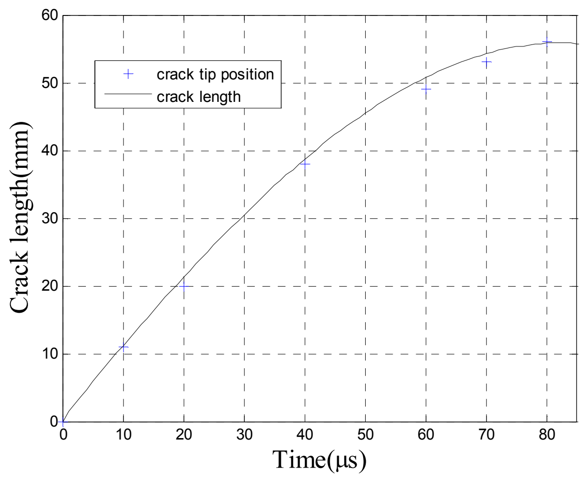


Figure 4. Crack growth history under the drop height of 1000mm

Crack velocity history is calculated from crack growth history by numerical derivation, as shown in Fig.5. It is observed that the maximum crack velocity appears at the initiation period (about 2us), which is $v_{max} \approx 1080$m/s. Then the propagation speed decreases with the increase of crack length, till the crack reaches the boundary. The average velocity during 10μs and 60μs is $v_{avg} \approx 851$m/s. At the very beginning, the cracking speed soars up to the maximum propagation speed and gradually decreases. Usually, the cracking speed-time curvature will go into the stable cracking speed domain [11]; however, in our cases the speeds gradually drop to a very low speed rather than stably cracking. That's mainly due to the small size of our experiment specimen and the crack quickly approaches the boundaries.

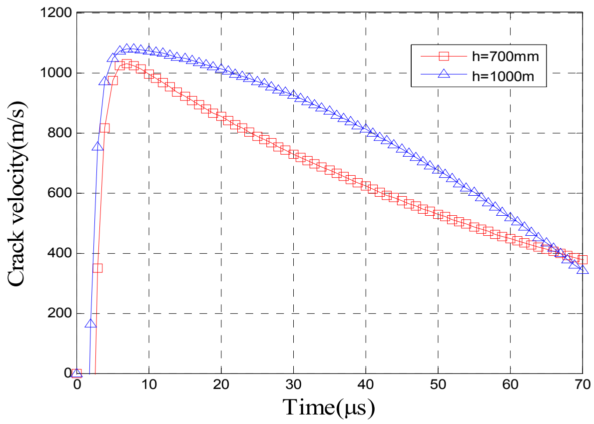


Figure 5. Velocity under different initial heights

3.3. Lower Initial Drop Height

To investigate the relationship between initial height of drop weight and crack velocity, the same experiment is conducted with initial height h=700mm. The crack velocities under different experimental speeds are compared in Fig.5. The result indicates that with lower initial height, which also means lower impact energy, the crack propagation trend remains the same, but the crack velocity is reduced obviously. The maximum velocity v_{max} drops 4.5%, from 1080m/s to 1031m/s and the average velocity v_{avg} drops 18.3%, from 851m/s to 695m/s, respectively.

4. Summary

Dynamic response and crack propagation characteristics of PVB laminated glass is studied by high-speed photography. Specimen-focused images are recorded from the start time of fracture to 600μs. Both radial and circumferential cracks are visualized, with radial ones appearing first. The tip locations and velocity of radial cracks are derived from the photos. Moreover, by lowering initial height of the drop, it is found that lower impact energy will decrease the velocity of cracks. This initial attempt shows the validity the experimental method and further cracking propagation characteristics will be harvested promisingly.

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