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Short communication

Different driving mechanisms of in-plane cracking on two brittle layers of laminated glass

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A B S T R A C T

In this paper, both the high-speed photography system and drop-weight platform are employed to investigate the in-plane crack propagation behavior in laminated glass plates. Firstly, the initiation and propagation of in-plane cracking on both glass plates are recorded in a time history manner, which shows that the radial cracks on the backing and impacted glass sheets are completely overlapped, with the sequence that cracks on impacted plate appear long after the full growth of those on backing plate. However, it is experimentally discovered that cracks on two glass sheets generate along the different cracking propagation paths, due to the different cracking mechanisms: the cracks on backing layer are motivated by in-plane stress concentration while the one on impacted layer are caused by stress concentration in depth direction brought by each generated crack on backing layer as initial flaw. Thus, a re-initiation criteria model is suggested to describe the transverse cracks on impacted layer. Further, a qualitative relationship between the inter-plate cracking delay and two parameters (i.e. the interlayer thickness and loading speed) is concluded, which further confirms the new fundamental driving mechanism of in-plane cracking on impacted glass plate.

1. Introduction

Polyvinyl Butyral (PVB) laminated glass has been widely employed in the automobile industry to protect pedestrian and passenger from external projectiles and glass fragments in the car accident. Therefore, the study of the fracture morphology of PVB laminated glass subject to dynamic loading is in pressing need to predict the mechanical behavior of PVB laminated glass [1] as well as the reconstruction of the impact information [2,3].

Experimental studies about the in-plane cracking of brittle glass plates [4–8] have been reported extensively, which mainly focus on the cracking mechanism of homogeneous single plate. Researchers usually have interests in studying the relationship between the dynamic stress intensity factor and crack velocity [9,10]. Recently, the cracking morphology investigations [11] are of great interest to establish the relationship between radial crack number on mono-layer plate material and impact parameters. However, few research attempts have been made except the preliminarily impact fracture experiments [12,13] to investigate the radial crack propagation behavior in of PVB laminated glass. While the preliminarily investigation on the in-plane cracking mechanism of the laminated material generally ignores the inter-plate effect [14,15], which only focus on one side of the plates. To bridge these gaps, the crack propagation images on both sides of the laminate plates are recorded using high-speed photography.

In this paper, a simple cracking initiation law for all the generated cracking on both plates is elucidated. The fracture mechanics analysis is presented from the perspective of the stress wave on the in-plane crack initiation on both glass plate sides. Further, parametric experimental studies are conducted on the effect of the thickness of interlayer and loading speed to confirm the mechanism analysis on loaded-side cracking law. This research may lay a solid foundation to the future study of cracking phenomena in laminated structures which is highly needed in designing transportation tool and architecture structure.

2. Material and methods

2.1. Specimen and loading

The PVB laminated glass specimen used in the experiments is the same as that used in Refs. [12,13], which is consisted of a PVB interlayer and two brittle glass sheets (For PVB interlayer: Young's

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modulus $E_P = 0.1$ GPa, Poison's ratio $\nu_P = 0.49$, density $\rho_P = 1100\ \text{kg/m}^3$; for glass: Young's modulus $E_g = 70$ GPa, Poison's ratio $\nu_g = 0.22$ and density $\rho_g = 2500\ \text{kg/m}^3$). In this study, the in-plane dimension of the plate specimen is 200 mm × 150 mm. The thickness of the glass on both sides is 2 mm while the thickness of the PVB interlayer varies from 0.76 mm to 3.04 mm during our parametric experimental study. All specimens are prepared with the pressure at 10 bar and 120 °C, which is the same manufacturing process as those used in automotive windshield.

The impact tests are performed on drop-weight experimental platform with various loading speeds at room temperature. The specimen is clamped within two metal cover sheets with thin layers of rubber pad inside to avoid possible scratches and stress concentration on the sample surface and distribute the boundary force more uniformly. The impactor perpendicular to the specimen plane provides the concentrated loading on the center of the specimen. The impactor shape is cylindrical with 10 mm diameter and the top is hemispherical. The total length of the impactor is 25 mm.

2.2. Experimental setup

The high-speed photography system in combination with the drop-weight platform [12,13] is employed in the dynamic fracture experiments [16,17]. The high-speed photography system (Fig. 1) is used for recording in-situ quantification of the dynamic crack growth while a 2 kg drop-weight (Fig. 1) provides the impact energy for the dynamic loading with the maximum height of 1000 mm (i.e. 4.4 m/s loading speed). The error in the loading speed of the drop-weight varies from 1% to 3%. The minimum time interval value of the high-speed photography system can reach to 1 μs, which is sufficiently accurate for our investigation.

Once the drop-weight slides down at certain height on the sliding track causing the impact, a trigger signal is generated by means of a time sequence controlled circuit, resulting in the orderly ignition of 16 spot lights in the high-speed photography system and recording 16 images with the crack information.

3. Results

3.1. Crack morphology

Based on the final fracture patterns of PVB laminated glass specimen, all the pieces of glass plates after impact are connected to the PVB layer (Fig. 1). Fig. 2 shows a typical crack propagation process which contains a series of selected sequence of images depicting the radial crack growth in PVB laminated glass specimen at the loading speed $v_d = 3.7$ m/s, with PVB thickness $h = 0.76$ mm. Here, time $t = 0$ μs is used to denote crack tip initiation for the radial cracks on supported glass layer. It is clear that the radial cracks (Fig. 2(a)–(d)) initiated firstly on the "supported glass layer", then the radial cracks on the "loaded glass layer" generated after about $t = 600$ μs as shown in Fig. 2(f). On the other hand, it's also interesting to observe that the cracks on the two glass layers are completely overlapped even though they propagate at totally different times.

3.2. Radial in-plane crack on supported-side plate

In fact, the stress wave dominated inertial effects during impact loading on the PVB laminated glass play an important role in crack propagation [18,19]. Due to the high modulus of glass material and the fixed mode of the specimen, the plate is small enough to ignore the bending deformation during the impact. For the convenience of

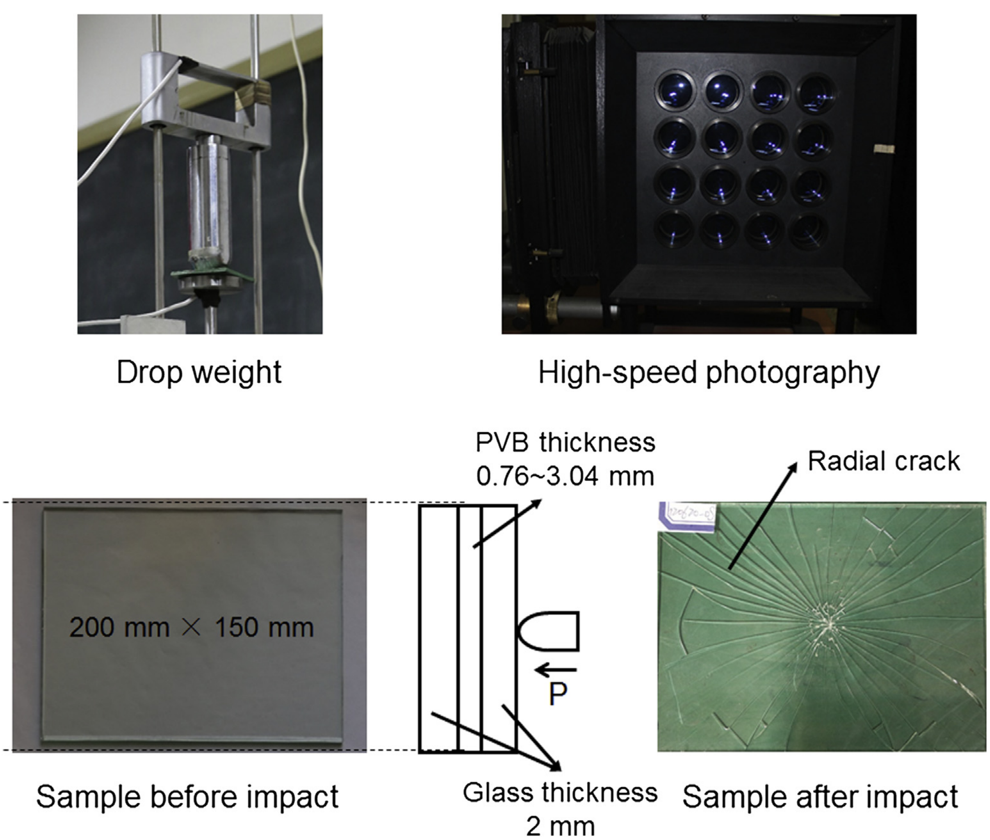

Fig. 1. The drop-weight experiment platform combined with the high-speed photography as well as the glass sample.