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Dynamic failure of annealed and chemically strengthened glass under compression loading

Muhammad Zakir Sheikh[a,b,c,*], Zhen Wang[a,b,c], Tao Suo[a,b,c], Yulong Li[a,b,c], Fenghua Zhou[d], Sohail Ahmed[a], Uzair Ahmed Dar[a], Yanpei Wang[a]

[a] School of Aeronautics, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, PR China
[b] Joint International Research Center of Impact Dynamics and Its Engineering Application, Northwestern Polytechnical University, Xi'an 710072, Shaanxi, PR China
[c] Shaanxi Key Laboratory of Impact Dynamics and Engineering Application (IDEA), Northwestern Polytechnical University, Xi'an 710072, PR China
[d] MOE Key Laboratory of Impact and Safety Engineering, Ningbo University, Ningbo 315211, PR China

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ABSTRACT

The goal of this article is to explore the dynamic mechanical behavior of annealed and chemically strengthened glass used in transparent laminated structures for buildings, armor and aerospace applications. Static compression (SC) tests were first conducted using the universal testing machine followed by dynamic compression (DC) tests at an average strain rate of $650\,s^{-1}$ and $350\,s^{-1}$ using modified Split Hopkinson pressure bar (SHPB) for annealed and strengthened glass, respectively. In DC tests, high-speed photography and flashlights were made synchronous with a loading pulse to spot the damage/crack initiation, propagation, and fracture process in both types of glasses. Static tests data concerning the compressive strength revealed that annealed glass (AG) showed strain rate sensitivity, in contrast to this chemically strengthened glass (CSG) showed no substantial strain-rate sensitivity. In DC tests compared to SC tests, it was found that both types of glass are rate sensitive and compressive strength remarkably increased at high strain-rate loading. The glass fracture process for both AG & CSG is also analyzed through high-speed imagery recorded during DC tests. The crack initiation, propagation, and glass debris are also discussed to explicate the failure mechanism of glass specimens.

1. Introduction

Glasses (non-crystalline ceramics) are largely used in aircraft windscreens, military vehicles, bulletproof windows for automobile, high-speed trains, hurricane & earthquake resistance buildings because of their high impact resistance, good optical properties, being lightweight and low production cost [1, 2]. The development in glass strengthening using thermal [3] or chemical process has motivated engineers and designers to use glasses in a variety of civil, military and aerospace applications. The tempering or strengthening process improves the glass mechanical and thermal properties by reducing the surface flaws [4, 5]. The chemically strengthening process especially also called ion exchange method yields a uniform and high strength compressive layer on the glass external surfaces of compressive strength 1 GPa and thickness of up to several mm [6, 7]. The bird strike, debris, blast and bullet impact performance of transparent glasses are extremely complex and mechanical characterization of glass types under static and dynamic loading is the key research area for designers of impact-resistant structures [8, 9]. Researchers have tried numerical and experimental techniques to understand the performance of glass at low and high-velocity impacts. The authors [10–14] studied the dynamic response of various glass types to low-velocity impacts, high-speed bullet and shock response from blast loading are explored by [15–21]. T J Holmquist et al. [22] performed quasi-static compression and tension tests on float glass and dynamic compression tests to study the rate effect on glass strength were performed using SHPB. These test results were used to develop the dynamic material model named as Johnson Holmquist Ceramic constitutive model (JH2 model) to simulate the blast and penetration problems. The authors in reference [23] studied the dynamic behavior and specific energy absorption of different types of glass materials through SHPB tests and found that borosilicate glass has a higher strain, strength, and absorbed energy in comparison to other glasses. Also, the effect of surface polishing on strain and energy absorption of transparent specimens were investigated. The brittle

* Corresponding author at: School of Aeronautics, Northwestern Polytechnical University, 127 West Youyi Road, Beilin District, Xi'an 710072, Shaanxi, PR China.
E-mail addresses: sheikhzakir@mail.nwpu.edu.cn (M.Z. Sheikh), wang_zhen@mail.nwpu.edu.cn (Z. Wang), suotao@nwpu.edu.cn (T. Suo), liyulong@nwpu.edu.cn (Y. Li), zhoufenghua@nbu.edu.cn (F. Zhou), s.ahmed@mail.nwpu.edu.cn (S. Ahmed), uzair@mail.nwpu.edu.cn (U.A. Dar), wangyanpei@mail.nwpu.edu.cn (Y. Wang).

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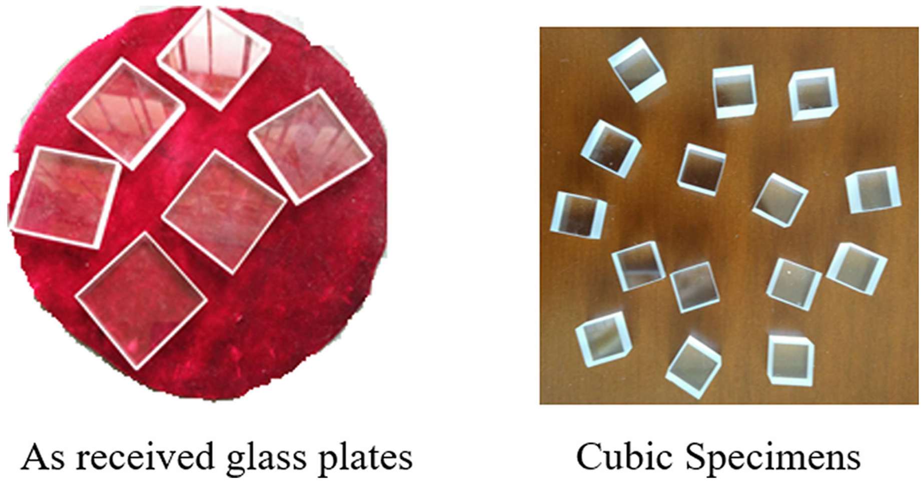

Fig. 1. Glass plates and specimens.

nature of glass poses challenges in the high strain-rate test to get equilibrium state, the published literature [24–30] is available on accurate material characterization, crack initiation & damage propagation of glass and transparent ceramic materials using modified Kolsky (Split Hopkinson) bar and high-speed photography. Zhang Xihong et al. [14, 30] investigated the dynamic compressive and tensile properties of annealed float glass using modified SHPB and indicated that both compressive and tensile are rate sensitive. The glass fracture process is also discussed using high-speed images and the specimen fully ruptures when most of the longitudinal cracks propagated through the specimen. However, the work of Peroni et al. [29] on the optical glass specimens in compression and tensile loading, exhibited non-sensitivity of strain-rate to compressive strength but the appreciable rise in tensile strength at higher strain-rate. Xu Nie et al. [26] conducted dynamic combined loading experiments on borosilicate glass at an average loading rate of $250\,s^{-1}$ using SHPB and a high-speed camera. They found that the strength of specimens decreases with the increasing shear stress component. In [20], the ballistic impact resistance of laminated glass composite using chemically strengthened soda-lime silicate was evaluated. They reported that compressive strength of strengthened glass is 3.7 times higher than that of parent glass (un-strengthened) at the high-strain rate. Phillip Jannotti et al. [25, 31] conducted ball impact test on strengthened and un-strengthened lithium aluminosilicate glass bars to observe the damage propagation. They established that the presence of high strength compressive layer in strengthened glass has a strong influence on damage and fragmentation behavior compared with un-strengthened glass. In recent past, Iman Mohagheghian et al. [13, 32] studied the bending and failure mechanisms of single and laminated glass windows made of thermally and chemically toughened glass plates at low and high-speed loading. They used the high-speed digital image correlation (DIC) to see the deformation and strain at the back surface of the laminated glass windows. Liangbao Jiang et al. [33] analyzed the fracture process of thin CSG made from aluminosilicate for various residual stress levels and found improvement in flexural strength of CSG for higher compressive strength and lower central tensile strength. In our recently published work [34], on the dynamic three-point bending tests on scratched and un-scratched aluminosilicate AG and CSG specimens, it was found that the CSG show better performance to blunt surface scratches.

The advancement in strengthening of glass through chemical process has provided opportunity to design efficient and lightweight transparent laminated structures. In design of windshield for an aircraft and high-speed train it is important that material should resist the potential impact from bird and stone, respectively. The main objective of this work is to study the mechanical behavior of annealed and chemically strengthen glass at low and high strain-rate. Because the windshields are laminated structures made from combination of two to three glass layers. This research will help the designers and engineers to choose combination of CSG and AG layer according with respect to strain-rate response and failure process in optimized design of impact resistance transparent structure for potential threats e.g. bullet, bird, stone and blast impact.

In this work, we have performed static and dynamic compression tests on annealed and chemically strengthened aluminosilicate glass specimens using a modified SHPB to investigate the effect of strain-rate on compressive strength of both types of glasses. Strain gauges were glued to the specimens to record the strain history and average failure strain at both low and high strain-rate loadings. In SC tests the AG showed strain-rate sensitivity on compressive strength, however, no substantial rate sensitivity was shown by CSG specimens. In DC tests, both AG & CSG found rate sensitive and compressive strength was considerably increased at high strain-rate loadings. The high-speed photography is used to monitor the failure process of both types of glass in DC tests and the crack initiation, propagation and final rupturing of specimens were recorded. The stress time history is also linked with high-speed images to explain the dynamic failure process. The phenomenon of rate dependency in both types of glass is also explained by analyzing the failure mechanism. In the subsequent sections, the experimental techniques, test results, and findings are presented in this paper.

2. Experimental procedure

2.1. Materials and specimens

In the current research, the annealed and strengthened aluminosilicate glass as received plates (TM Glass-China) of size 50 mm × 50 mm × 8 mm with mirror polish surface finish are used to cut the cubic shaped specimens of size 8 mm for static and dynamic compression tests. The specimens were ground and polished as shown in Fig. 1, the parallelism accuracy of 5 μm on opposite surfaces was maintained to reduce the stress concentrations effects around edges. The chemically strengthened glass top and bottom surfaces because of the ion-exchange process has the residual compressive strength of approximately 600 MPa (measured using surface stress meter FSM-6000LE) with the layer thickness of 150 μm with matching tensile stresses in the interior of the glass (as shown in Fig. 2). The advantage of this residual stress outcomes as the source of stored elastic energy in CSG.

The volume of both the strengthened and annealed glass is measured using water displacement method to get the density. The longitudinal wave speed (c_L) was measured using ultrasonic instrumentation