International Journal of Impact Engineering 77 (2015) 108–119

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Dynamic material model of annealed soda-lime glass

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ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form
12 November 2014
Accepted 14 November 2014
Available online 21 November 2014

Keywords:
Dynamic material model
Annealed float glass
Soda lime
Johnson-Holmquist ceramic model
High strain rate
Blast
Impact

ABSTRACT

Glass is an omnipresent material which is widely used as façade in buildings. Damage of glass windows and the associated glass fragments induced by impact and blast loads impose great threats to people in the vicinity. Much effort has been directed towards understanding glass material properties, and modeling of glass window responses to impact and blast loads. For reliable predictions of glass structure performances under dynamic loadings, an accurate dynamic constitutive model of annealed float glass, which is commonly used for glass windows, is therefore needed. In current practice, the Johnson-Holmquist Ceramic (JH2) model is most commonly used in simulating glass plate responses to impact and blast loads. In this study, the accuracy of the JH2 model in modeling annealed float glass material, especially at high strain rate is examined in detail. Static compressive tests and dynamic compressive tests using Split Hopkinson Pressure Bar (SHPB) are carried out on soda-lime glass specimens sampled from commercially used annealed float glass panes. These testing results are used together with the authors' previous testing data and data reported by other researchers in the literature to determine the constitutive constants for the JH2 model, including Equation of State (EOS), strength criterion and strain-rate effect. The JH2 model with new material constants is then programmed in commercial code LS-DYNA. To verify the model, it is used to simulate a SHPB compressive test on a 15 mm by 15 mm (diameter by length) glass specimen, a field blasting test on a laminated glass window of 1.5 m by 1.2 m in dimension, and a full-scale laboratory windborne debris impact test on a laminated glass window. The simulation results demonstrate that the JH2 model with the new material constants for annealed glass gives good predictions of glass material and glass window responses to impact and blast loads.

1. Introduction

Annealed soda-lime glass is an omnipresent construction material that has been widely used for windows and façade in buildings. Due to its relatively low strength and brittleness, glass is very fragile especially in face of extreme loads, such as shock and impact loads. Under impact and blast loads the fractured annealed glass, which is jagged and flying at high velocity, could cause enormous casualties. Post-event investigations on terrorist bombing attacks, accidental explosions and cyclone induced debris impact have cited the fractured glass façade and windows as a major threat to the safety of structures and residents. For instance, in the Norway attacks in 2011, the shock wave from the car bomb shattered almost all the windows of the Oslo executive government building. 209 victims out of the total 325 injuries were associated with glass laceration [1]. Similarly, after the 1974 cyclone Tracy, the post-event investigation concluded that one of the most remarkable factors contributing to the wide-scale overturning and damage of houses was the overwhelming internal pressure following the windward window failure due to windborne debris impact [2]. A number of studies have been carried out to analyze the responses of glass windows under such extreme loading conditions [3–8], and to seek respective retrofit techniques [3,9]. Nevertheless, there is still a lack of integrated and systematic study on annealed glass dynamic material properties and development of dynamic material models to simulate glass window response. Consequently, many previous studies could only adopt static material model, which left the accuracy of results in doubt [5,6]. Therefore, to better analyze and design glass windows for personnel and property protection, it is necessary to more thoroughly understand glass dynamic material properties, which will lead to better analysis and prediction of glass window behavior against impact and blast loads.

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http://dx.doi.org/10.1016/j.ijimpeng.2014.11.016

Glass is an idealized isotropic and brittle material. However, variations in its chemical compositions and manufacturing processes lead to diversified glass material characteristics and properties. Glass is produced by heating a mixture of raw minerals above a transition point. The molten glass is then floated on top of molten tin after which it is slowly cooled without quenched in the annealing lehr. Soda-lime glass commonly used for structural glass windows is mainly made of SiO_2 (about 50–75% mass proportions). Comparatively, borosilicate glass with higher SiO_2 ratio is normally stronger and has better temperature shock resistance, which is often chosen for reagent. Manufacturing processes also lead to various glass strengths and fracture characteristics. For instance, the standard float process produces annealed glass, which is very low in strength and breaks into large jagged shards with sharp ends. By heating and quickly cooling annealed glass yields heat strengthened glass, which leads to higher strength. Uniformly heating annealed glass to a temperature of up to 700 °C and immediately cooling it produces fully tempered glass, which has very high strength as a result of the pre-stress introduced to glass during the tempering process. Tempered glass is generally four to five times stronger than annealed glass. It also shatters into numerous fine pieces, which is comparatively less threatening. Despite the advantages of heat strengthened and tempered glass, due to its low cost annealed soda-lime glass has been ubiquitously used for structural glass windows. Considering the overwhelming usage in building structures and serious consequences that always lead to mass injuries, the current study focuses on the investigation of annealed soda-lime glass.

Recently, many researches have been directed towards fully unveiling the dynamic behaviors of different types of glass. For instance, the dynamic deformation and fracture behavior of borosilicate glass with confined or unconfined stresses were investigated intensively [10–14]. Strain-rate effect and surface condition influences on the borosilicate glass strength were evaluated experimentally [15]. Similarly, for soda-lime glass, the fracture process and densification behavior under shock load were investigated thoroughly through plate impact tests [16–19]. The dynamic increment effect on uniaxial compressive strength and split-tensile strength (determined by splitting a cylinder across the diameter, also known as the Brazilian test) of soda-lime glass were recently studied [20,21]. The studies demonstrated that glass behaves very differently under dynamic and static loadings. Like other construction materials such as concrete and steel, glass is also strain-rate sensitive. Its ultimate strength is amplified when the deformation rate is significant. Bulk damage could be triggered by high intensity stress under dynamic loading, where the influence of glass surface flaw is less prominent because there is limited time for cracks to find the relatively weaker sections to develop [21]. Both the compressive and tensile dynamic increment factors (DIF), which are the ratio of dynamic ultimate strength to the corresponding static ultimate strength, are determined with respect to the strain rates the tested glass specimen experienced. Using a modified SHPB device, Zhang et al. [21] performed dynamic compressive tests on annealed glass at the strain rates from 98 s^{-1} to 376 s^{-1}. A bi-linear relation between glass compressive DIF and strain rate was found. In the same study, tensile tests carried out through split-tensile test found a similar trend on the tensile DIF vs. strain rate relationship. It should be noted that in determining the glass material constants of JH2 model, compressive tests were conducted at two strain rates only, while split-tensile tests were only performed at static state [22]. The lack of dynamic tensile tests was mainly because the results were used to model glass ballistic performance, where glass tensile strength was considered less crucial. However, when modeling thin glass pane response to lateral loads, glass tensile strength will strongly influence glass pane behavior. A better strength model for glass in the tensile region is deemed necessary. With more and more thorough studies on annealed glass dynamic compressive and tensile strengths at various strain rates, modification and determination of updated constants of JH2 model for annealed glass can be achieved to better model the glass behavior, especially for glass windows subjected to impulsive lateral loads.

Most previous researches on soda-lime glass showed that the glass is capable of bearing over 1.0 GPa uniaxial compressive stress [20,22]. The split-tensile strength of float glass in JH2 model is also well over 100 MPa [22]. These results were found inconsistent with some recent testing results on annealed soda-lime glass [21]. The discrepancy is believed to be attributed to the differences in sample surface conditions. As pointed out by Nie et al. [15] that glass strengths exceeding 1.0 GPa were produced by submersing the specimens in acid fluid to blunt out surface cracks. This could be suitable for transparent armor for military purpose but is not a process in producing construction glass panes. Therefore, existing material constants for annealed soda-lime glass overestimates the material strengths of glass commonly used for windows. To better predict the glass window responses, modifications of material constants are therefore required for JH2 model.

Based on the experimental tests, some glass dynamic material models have been developed. These models could be categorized into three levels: micro-level (molecular) model [23]; explicit crack model [24]; and macro-level (continuum) model. Considering computational efficiency, the first two categories are less suitable for studying full-scale glass windows. Therefore they are not elaborated herein. Based on glass flaw distribution, Grujicic et al. [25] formulated a continuum level glass model for ballistic impact. The idea of shielding zone was introduced as glass damage propagates. However, this model is less suitable in simulating thin glass pane under lateral loads. Johnson-Holmquist Ceramic (JH2) model [22] for float glass is another macro-level model, which was developed in the early 1990's. JH2 model is a well-defined material model which considers strain-rate effect, material damage and also confinement effect. It has been popularly used in simulating glass response to shock and impact loads [3,26]. Modifications of the original JH2 model have been made over the years to improve the adaptability for different types of brittle materials. For instance, by conducting laboratory and ballistic experiments, Holmquist et al. [27] determined the material constants explicitly for aluminum nitride (AlN). The original JH2 model was later modified with the capability of phase change so as to better model the behavior of AlN [28]. For glass material, Holmquist and Johnson [29] related material strength to its location (in the interior, on the surface or adjacent to failed material) and surface condition. They also included thermal softening, damage softening, and time-dependent softening, and etcetera into the modified model. These new features were illustrated to provide better predictions of glass response under ballistic impact. Nevertheless, these improvements are not necessarily crucial to model the behavior of architectural glass windows under relatively low-speed impact and blast loading. The complexity of the above modification requires more computational resources. Considering the fact that the original JH2 model is well understood and overwhelmingly used, and has also been implemented in many commercial codes, such as LS-DYNA, conducting laboratory tests on low strength architectural annealed glass and determining new material constants for JH2 model for better prediction of architectural annealed glass window responses to impact and blast loading is important.

In this study, compressive SHPB tests are further carried out on glass specimens sampled directly from commercially used window glass sheets. Experimental data together with those obtained in the previous tests [21] and available testing data reported by other