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Experimental study on critical breaking stress of float glass under elevated temperature

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ABSTRACT

Cracking and subsequent fallout of glass may significantly affect fire dynamics in compartments. Moreover, the breaking tensile stress of glass, a crucial parameter for breakage occurrence, is the least well known among mechanical properties. In this work, a series of experiments were conducted, through mechanical tensile tests, to directly measure the breaking stress of float glass using Material Testing System 810 apparatus. Clear, ground and coated glass samples with a thickness of 6 mm were measured under ambient conditions, with a room temperature of 25 °C. The breaking stress of smooth glass samples was also measured at 75 °C, 100 °C, 125 °C, 150 °C, 200 °C, 300 °C and 400 °C, respectively. The results show that surface treatment may decrease the critical tensile stress of glass panes. The average breaking stress also fluctuates considerably, from 26.60 to 35.72 MPa with the temperature variations investigated here. At approximately 100 °C, critical stress reached the minimum value at which glass breakage occurs more easily. In addition, the thermal expansion coefficient was established using a thermal dilatometer, to obtain the maximum temperature difference float glass can withstand. It is intended that these results will provide some practical guidelines for fire safety engineers.

1. Introduction

Architectural features with glass panels are extensively used due to their transparency, energy saving potential and architectural aesthetics [1,2]. As Fig. 1 shows, an increasing number of newly constructed buildings are employing glass facades, instead of concretes or steels. However, as the weakest part of a building, glass will break easily when subjected to a fire. The sudden venting resulting from fallout of glass panes may provide a corridor for fresh air to enter the compartment, and an outlet for fire spread, accelerating fire development. Emmons [3] first highlighted the importance of this structural problem. Subsequently, many experimental [4–9] and numerical [10–15] investigations have been conducted to analyze glass breaking behavior and mechanisms. For example, Shields et al. [4] conducted some full scale experiments to investigate the single and double glazing behavior exposed to fire. Joshi and Pagni [5] analyzed the failure strength using Weibull distribution based on numerous experiments. Skelly et al. [8] conducted a comparative study of edge-protected and edge-unprotected glass panes, and found that the maximum temperature difference a glass pane can withstand between the central and the edge was 90 °C. Following these pioneering studies, Wang et al. [11,14], using finite element method, developed a three-dimensional model to calculate the stress distribution, and according to the results crack initiation and propagation of glass in a fire can be well predicted. The consensus of prior research is that excessive thermal stress, induced by the thermal gradient in glazing assembly, is the primary cause of glass breakage. The compressive strength of glass is far higher than its tensile strength, so when a single glass pane is subjected to fire, its tensile strength will be easily exceeded when the temperature difference attains a critical value [16].

Although Pagni asserts that tensile strength is the most important parameter for glass breaking in fires [5,17,18], it remains the least well known among the mechanical properties of glass. Little research has been conducted into glass tensile stress, especially direct measurement of this parameter. Joshi and Pagni [5] conducted 59 experiments to determine breaking stress distribution using a four-point method. All of their experiments were conducted at room temperature. There was a large variation, from 36.5 to 128 MPa, in the breaking strength of glass for nearly identical specimens. Xie et al. [19] measured the breakage stress of float glass of

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different thicknesses at 20 °C and 200 °C. They concluded in their prediction model that the critical breakage stress of glass samples depends on their thickness. Shields et al. [4] measured fire induced strain using temperature compensating strain gauges in a compartment fire, and then calculated thermally induced stresses using a simple relationship.

In the limited prior work, only clear glass samples were tested: the correspondence between breaking stress and temperature increase is still unknown. Due to the variety of glass panes commonly utilized in modern buildings, as shown in Fig. 1, more experimental investigations concerning different types of glass should be conducted to determine their strength. Moreover, it is anticipated that if breaking strength varies with increasing temperature, it will significantly affect breakage occurrence. Therefore, it is necessary to develop a database of various kinds of glass under environments with different temperatures [19], which would be helpful for a better understanding of the breakage mechanism. This is effectively the motivation of the present study.

Quasi-static tensile experiments were conducted using Material Testing System 810 (MTS 810) in this work to explore the strength of different kinds of glass. Ground, coated and clear glass samples were selected as the research objectives because of their wide use in buildings. In addition, to examine the differences in glass strength with variations in room temperature and fire scenario, glass tensile strength was also directly measured at 75 °C, 100 °C, 125 °C, 150 °C, 200 °C, 300 °C and 400 °C. These experimental results may help to reveal the differences in breaking strength under various conditions and provide a reference for a prediction model of glass breakage in fires. A detailed comparison and discussion of the effects of environmental temperature and glass surface treatment are also presented.

2. Experimental apparatus and glass samples

MTS 810, manufactured by a USA corporation, is a versatile, multi-purpose servohydraulic testing system for static and dynamic tests [20]. It has been extensively employed in material testing [21,22]. To ensure precision, the apparatus at the USTC Experimental Center is calibrated every year by the National Measurement Association. As shown in Fig. 2(a), a system including high-temperature furnaces and environmental chambers has been installed to enable the mechanical testing of materials and components across a broad range of temperatures. During the quasi-static tests, the environmental temperature can range from −129 to 540 °C. As the glass temperature at breaking time in fires generally falls within this range, it was suitable for our purposes.

In each test, both ends of the glass sample were gripped by two steel jaws, as shown in Fig. 2(b). Since the glass surface was too smooth to be held, the holding section of each sample was roughened in advance, and a piece of abrasive paper was placed between sample and jaw to provide sufficient frictional force. Moreover, an extensometer was positioned in the center of each sample to measure displacement during the pulling process. At room temperature, these experiments were relatively easy to conduct, but the difficulty was increased as the environment grew hotter. To conduct tests at precise temperatures, an R-Type thermocouple was attached to the glass sample to measure the glazing temperature. Once this temperature reached a given point, a temperature controller maintained the environmental temperature in the chamber at a constant value. As glass is a material with low thermal conductivity, each tensile test would not start until the desired temperature had been maintained for more than 2 h. This ensured that the entire glazing had reached the desired temperature when it was pulled. The whole process was controlled by comprehensive MTS software, as shown in Fig. 2(c).

Before each tensile experiment, the angle and position of the jaw were calibrated carefully, to avoid the risk of sample breakage during the clamping process. Through preliminary experiments, it was found that the optimal clamping pressure and pulling speed for brittle glass testing, both at room temperature and in hot environments, were 2.5 MPa and 50×10^{-3} mm/s, respectively. These parameters were controlled at constant levels throughout each experiment.

Float glass with a thickness of 6 mm was employed in this work. According to the MTS 810 requirements for testing ceramic material, all the glass samples, as shown in Fig. 3(a), were designed in the shape of a ‘dog-bone’. The overall length and width of each sample were 265 mm and 20 mm, respectively. The central part of the sample, with a length of 55 mm and width of 10 mm, was the testing section, where breakage generally occured during tensile experiments. The test section and holding section of the samples were smoothly connected through an arc with a radius of 5 mm. A water jet cutter was used to cut the samples. Its pressure was adjusted to 300 MPa, so that the water could be ejected through a nozzle with a diameter of 1 mm. As edge conditions may have influence on glass breaking, this cutting method ensured that the cross sections were relatively clean and smooth, as shown in Fig. 3(b). The edge conditions in different glass samples were nearly identical which could minimize the effect of edge condition on glass breaking. In addition, the properties of these samples were also nearly identical as the samples for testing were all cut from one large pane. To compare the effect of different surface treatments, some samples were frosted or coated with a film by a

(a) Ground glass (b) Coated glass (c) Clear glass

Fig. 1. Glass facades in modern buildings, photographed in Suzhou.