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Bearing capacity of tempered glass panel in point supported glass facades against in-plane load

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ABSTRACT

Tempered glass panels in the point supported glass facade (PSGF) are usually subjected to large in-plane load. In order to investigate the bearing capacity of tempered glass panels against in-plane load, three tests are firstly carried out. Afterwards, finite element method (FEM) is adopted to study stresses around holes under different loading conditions and explore the influence of the in-plane load on the stress distribution of the glass panel. It is concluded that stresses around holes in tempered glass panels are principally affected by the in-plane load, while stresses at centers of the surface and edges are mainly controlled by the out-of-plane load. When the in-plane load is relatively high, the out-of-plane load is probably able to reduce stresses at some points around holes, contributing to the improvement of the load-bearing capacity of tempered glass panels. If the in-plane load is large enough, specimens are bound to experience state transitions which are caused by large plastic deformation of stainless steel bolt fittings and result in the rapid increase of stresses on glass panels. Therefore, by enhancing the shear strength of bolt fittings one can improve the bearing capacity of tempered glass panels in the PSGF against the in-plane load.

1. Introduction

Glass facades successfully win more and more favor of architects nowadays, due to a series of excellent characteristics, such as the perfect transparency, outstanding energy-saving potential and good-looking appearance [1–3]. PSGF is a novel kind of glass facade system and has been widely used in the recent years.

Glass panel, acting as a vital part in the PSGF, usually employs the tempered glass. As is known from the previous studies [4,5], the strength of ordinary float glasses is severely weakened by surface flaws and the tensile stress on the surface easily gives rise to the failure of the glass. Dissimilar from the float glass, the tempered glass experiences a tempering process, in which the glass is heated to its melting temperature, usually above 600 °C, and subsequently cooled down [6–9]. This process will produce the residual compressive

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stress, approximately equivalent to 100 MPa, on the surface of the glass panel, and tensile stress in the interior. The prestress generally presents the parabolic profile along the thickness direction of glass panel and makes the tempered glass several times stronger than the ordinary float glass. Many scholars have conducted intensive researches about the residual stress in tempered glasses. Among them, Nielsen et al. [10] carried out a parametric study on the minimal value of the residual compressive in-plane stress on the surface of the hole, σ_{rc}^{min}, and concluded that (a) the value of σ_{rc}^{min} was principally controlled by the total dimension of the plate over the dimension of the hole and (b) the rate of cooling and amount of material available to carry the stress seemed to govern the magnitude of σ_{rc}^{min}. Aben et al. [11] revealed that the direct measurement of compressive stress on the surfaces of the glass panels was challenging and expensive for glass manufactures, whereas the measurement of the edge stress was relatively convenient. Accordingly, they experimentally studied the correlation of the edge stress and surface stress. As a result, they found that the surface stress was practically equal to the edge stress.

In order to spread the use of tempered glass in engineering applications, a substantial number of researchers have studied the mechanical performance of tempered glass panels. Ni et al. [12] adopted three fire scenarios to investigate the response of glass facades under high temperature. They confirmed that the double glazing with the glass thickness of 6 mm would fail at the temperature of about 600–800 °C and although the tempered glass would be broken into small pieces, all parts still held as a whole. Wang et al. [13] investigated the influence of tempered glass panels on the monolayer cable net system. Their main conclusion was that glass panels could enhance the overall structural stiffness whereas this effect became smaller with the increase of the stiffness of cable net itself. Campione et al. [14] focused on the behavior of the laminated glass panels that withstood the collective effect of the self-weight and the distributed transversal load. Their research showed that the fully tempered glass panel remained elastic until failure and therefore it is suitable for structural applications. Furthermore, they proposed a simplified model to predict the experimental behavior and failure mode. With the intent of studying the complicated stress distribution on the tempered glass panel connected by the clamping joints, Feng et al. [15] carried out bending test and warping test on glass panels. They found that the maximum tensile stress caused by warping distortion was significantly higher than that caused by bending effect which was usually triggered by the wind load in the engineering. Fam et al. [16] compared the structural performance of laminated and non-laminated tempered glasses. They highlighted that the laminated glass was safer as the fractured glass still remained intact. Additionally, the lamination was able to increase the flexural strength, stiffness and strain energy of glass panels. In other studies, Pankhardt [17,18] investigated the static and time dependent load-bearing capacity of glass panels with four-point bending tests.

In the practical engineering, glass panels in the PSGF are customarily subjected to different kinds of loads, caused by self-weight, wind effect, temperature variation, seismic excitation, installation error and so on. However, they can be classified into two types, namely the out-of-plane load and the in-plane load. Admittedly, the out-of-plane load is the most common one withstood by the glass panel. Prior studies principally focus on the bending effect caused by the out-of-plane load. Furthermore, in the Chinese code CECS 127 [19], only the magnitude of the out-of-plane load is taken into account when designing the glass panel and the effect of the in-plane load is neglected. However, the in-plane load is usually significant under the effects of temperature variation, installation error and especially the seismic action. Nevertheless, limited studies focus on the bearing capacity of tempered glass panels against the in-plane load. Sivanerupan et al. [20] applied in-plane load on tempered glass panels in tests, however, their aim was to study the in-plane drift capacity of the PSGF system. Biolzi et al. [21] experimentally investigated the damage and fracture behavior of laminated glass beams subjected to in-plane load. Nevertheless, the length of beam specimens was much larger than the width and thickness, whereupon the test data and results were not valuable references for tempered glass panels.

The motivation of this paper is to analyze the bearing capacity of tempered glass panels in the PSGF against in-plane load. The research starts by three tests. In the first test, glass panels are subjected only to the in-plane load. In the second and third tests, glass panels withstand the combined effect of out-of-plane and in-plane loads. However, bolt fittings, which support the glass panels, are subjected to the tensile load in the second test and withstand the compressive load in the third test. Subsequently, numerical analyses are conducted for the further study of the stress distribution around holes and the effect of the in-plane load on the tempered glass panel. It is noted that aim of the paper is to study the bearing capacity of glass panels in macroscopic view and the strength of tempered glass panels is assumed to be enhanced due to the residual stress, however, the specific effect of residual stress on the stress distribution in glass panels is not deeply discussed in this paper for the sake of brevity.

2. Experimental study

2.1. Specimens and measuring method

Glass panels adopted in tests are four-point supported glasses, which are widely used in the engineering. Stainless steel countersunk bolt fittings are employed to support glass panels, as shown in Fig. 1(a). The upper surfaces of countersunk bolt fittings level with glass panels, thus the artistic appearance of glass facades will not be disturbed and the cleaning of glass panels is convenient [22]. Countersunk bolt fittings consist of three parts: cylinder, sub-plate and shaft, as presented in Fig. 1 (b). In order to accord with bolt fittings, holes of glass panels are designed to be conical surfaces, as illustrated in Fig. 1(c). The maximum diameter of the hole is 44 mm and the minimum diameter is 36 mm. In addition, the thickness of tempered glass panels is 12 mm. It is worth mentioning that the upper end of the shaft has a shape of a sphere, what can be used to adjust the glass panel and reduce installation error in some degree. Additionally, glass panels and bolt fittings are assembled according to the Chinese code CECS 127 [19].