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A critical flaw size approach for predicting the strength of bolted glass connections

James Watson [a,*], Jens Nielsen [b], Mauro Overend [a]

[a] Department of Engineering, University of Cambridge, UK
[b] Department of Civil Engineering, Technical University of Denmark, Denmark

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ABSTRACT

The use of bolted connections in glass installations is common place in contemporary architecture. However, it is difficult to predict the load bearing capacity of these connections accurately due to the several factors that influence the strength of glass in the region of the bolt hole, namely: the complex stress state, the inherent strength of glass and the magnitude of residual thermal stresses. This paper proposes a critical flaw size approach for bolted connections. The approach uses a numerical tempering model and non-linear finite element analysis to determine the sizes of the critical flaws around the bolt hole, from destructive tests on bolted glass components subjected to in-plane loading. The critical flaw sizes determined by this approach agree with the flaw sizes obtained from optical microscopy. These flaw sizes are subsequently used to plot lifetime prediction curves for the bolted connections that are useful for real-world applications.

1. Introduction

Since the invention of the float glass process in the 1950s, the use of glass in buildings has increased substantially. This is due to the trend in architecture towards a higher degree of transparency in buildings ranging from large rectangular plates in curtain walls and cable-net façades to glass floors, staircases and roofs in and around buildings. This move to transparent building components has spawned new visually unobtrusive connections, of which the most common is bolted supports that are also known as point fixings [1]. These consist of a stainless steel bolt through a hole in the glass with an intermediate bushing (e.g. Aluminium, POM or nylon) to relieve bearing stresses. The stresses in the glass are the result of the bolt bearing onto the bolt-hole region. The load-transfer between the glass and the bolt assembly may either be purely axial and in the plane of the glass (e.g. spliced glass fin connections) or a combination of in-plane and out-of-plane loading resulting from multiple loads acting simultaneously on the glass component (e.g. façade panel connection that must safely transfer in-plane self-weight of glass and out-of-plane wind loads). The underlying theory and the general approach proposed in this paper are applicable to any type of bolted connection, however the experimental validation and the lifetime prediction curves presented in this paper are limited to axially loaded bolted connections.

The sizing of bolted connections is not a straightforward task for several reasons. The glass used in these structurally demanding applications is heat treated. The heat treatment process rapidly quenches the surfaces of the glass from above the glass transition temperature. The mechanisms that govern the resulting residual stresses are complex, but a simplified explanation is that during cooling, the surface layers cool and solidify before the core regions. When the core solidifies, it contracts thereby inducing a parabolic stress distribution through the thickness with compressive stresses in the surface and tensile stresses in the core. The tensile strength of heat treated glass is therefore composed of two elements as shown in Fig. 1a the residual compressive stresses (f_{rk}) induced by the heat treatment that help to prevent cracks opening, thereby increasing the apparent tensile strength of glass and (b) the inherent strength of glass after the residual surface stresses have been overcome or when the glass is in its annealed state (i.e. $f_{rk} = 0$).

Variations in these residual stresses (the magnitude of which is dependent upon the precise geometry) have been noted around discontinuities (e.g. corners, holes, etc.) due to the local effects on cooling rate [2–4]. As it is not possible to accurately measure the residual stress variations at the boundary of a hole experimentally, there is a need for modelling the tempering process. The first model for predicting residual stresses in glass is more than 90 years old [5], however the objective at the time was to optimise the annealing process. The next step was the so-called "instant freeze" model by Bartenev in 1948 [6], where the glass was assumed to be a viscous fluid above a certain temperature and an elastic solid below that temperature. The next development was

* Corresponding author. Tel.: +44 7721636975.
E-mail address: jw484@cam.ac.uk (J. Watson).

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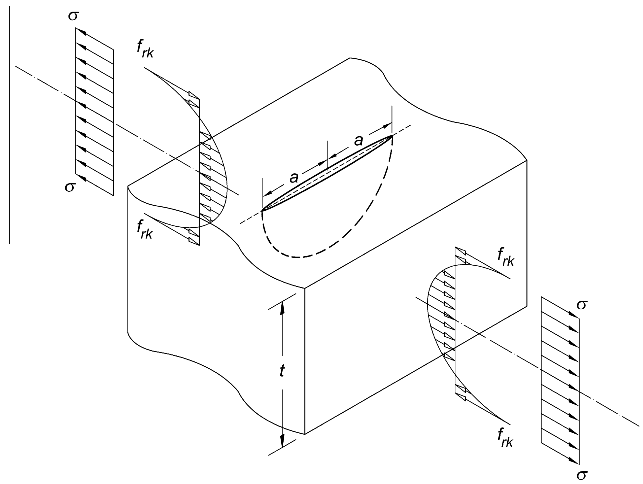

Fig. 1. Geometry of a half-penny flaw ($t \gg a$) showing residual stresses (f_{rk}, hollow arrows) and stress resulting from axial load (σ, filled-in arrows).

to account for the relaxation of stresses in glass at different temperatures [7]. The most recent major improvement of the basic equations in the tempering model was due to Narayanaswamy who in 1971 [8] proposed a model including the structural state of the glass, by introducing Tool's concept of fictive temperature [9]. With the general increase in computational power, these models were extended and implemented for full 3D analysis using Finite Element Analysis (FEA) [2–4]. These models have been available for several years and they could provide the designer with important information about the residual stress state around holes and edges in tempered glass; however the use of such models in engineering design is rare.

In addition, the inherent strength of glass (i.e. the remaining strength after the residual stresses have been overcome) is difficult to predict accurately as it is governed by the flaws on its surface. The relationship between stress intensity at the tip of a stress-raising flaw located at (x,y) on the glass surface and the crack-opening surface stress, originally proposed by Irwin [10] can be extended to account for the presence of a residual surface stress commonly found in thermally or chemically strengthened glass:

$$K_I = [\sigma(x,y) + f_{rk}(x,y)]Y\sqrt{\pi a_f} \tag{1}$$

where $\sigma(x,y)$ is the tensile surface stress, induced by the loads and acting normal to the flaw, $f_{rk}(x,y)$ is the residual surface stress normal to the flaw (compression is expressed as a negative value), a_f is the larger of the crack depth or half the crack length, and Y is a geometry factor that accounts for the crack geometry and the proximity of the specimen boundaries ($Y = 0.713$ for half penny shaped cracks and $Y = 1.12$ for straight front plane edge cracks in a semi-infinite solid) [11]. Fast fracture occurs when $K_I \geqslant K_{IC}$, where K_{IC} is the critical stress intensity factor (or plane strain fracture toughness).

Furthermore when $0.33 \lesssim K_I/K_{IC} < 1$ and in the presence of humidity, a flaw of initial size, a_i, will grow sub-critically until it reaches a critical size, a_f, that triggers fast fracture (at $K_I = K_{IC}$). This phenomenon, first characterised by Wiederhorn [12], forms the basis of the lifetime prediction of ceramics and has been researched extensively since the 1960's [13–15].

There are three principal methods for determining the strength of glass: (a) The maximum stress approach; (b) The random flaw population approach (also known as the stochastic approach) and; (c) The critical flaw size approach (also known as the single flaw model or the flaw size design method). These methods are relevant to this study and are reviewed briefly here.

1.1. Maximum stress approach

The aim of this approach is to ensure that the maximum principal crack-opening stress ($\sigma_1 + f_{rk}$) recorded anywhere on the glass specimen does not exceed the design strength of annealed glass (f_{gd}, also known as the inherent design strength of glass):

$$\left[\frac{\sigma_1}{\gamma_{M,A}} + \frac{f_{rk}}{\gamma_{M,v}}\right] \leq f_{gd} \tag{2}$$

where $\gamma_{M,A}$ and $\gamma_{M,v}$ are the material partial factors for annealed glass and the residual surface stress respectively. The implicit assumption here is that the orientation of the critical flaw does not affect the strength of the glass. For real-world applications where the flaw orientation is random and/or unknown this implies that the state of stress is uniform equibiaxial i.e. $\sigma(x,y) = \sigma_1 = \sigma_2$.

Due to the lack of recommendations for sizing bolted connections in glass structures, practising engineers tend to use the simplest and most conservative form of the maximum stress approach. This ignores the inherent strength of glass (i.e. $f_{gd} = 0$) and failure is therefore deemed to occur when the residual surface stress is overcome [16]. A more accurate version of the maximum stress approach is to account for the inherent strength of glass (i.e. $f_{gd} > 0$), the magnitude of which is obtained from destructive testing of nominally identical specimens (by quantifying σ in Eq. (3) and substituting for f_{gd} in Eq. (2)). Overend et al. [17] showed that this approach leads to significant errors when determining the strength of bolted glass components.

1.2. Random flaw population approach

The random flaw population approach accounts for the variations in size, location and orientation of surface flaws by expressing the probability of failure P_f as a two-parameter Weibull distribution [18–20].

$$P_f = 1 - \exp\left[-\frac{A}{A_0}\left(\frac{\sigma(x,y) + f_{rk}(x,y)}{\theta_0}\right)^{m_0}\right] \tag{3}$$

where m_0 and θ_0 are the interdependent Weibull parameters determined from load-testing of nominally identical glass components. This approach is unattractive for manual computation, but design charts and simplified equations can be produced for a small number of design permutations. This method has gained popularity for sizing uniformly loaded glass panels with linear supports (e.g. curtain wall glass infill panels) and forms the basis of sizing charts in design standards intended for simply supported glass panels [21–23]. Overend and Zammit [15] used this approach, to formulate a numerical algorithm that computes the characteristic tensile strength of float glass by piecewise summation of the surface stresses. Consequently the random flaw population approach can be used on any glass component that can be successfully analysed by means of FEA.

The principal limitations of this approach are:

1. It difficult to account for more than one flaw population on any component. This is particularly relevant for bolted connections where the flaws accumulated on the surface of the plate are likely to differ significantly from the flaws in and around the bolt holes that are generated during the drilling process.
2. This approach does not provide an explicit relationship between the statistical parameters and the physical characteristics of the critical flaw.

In a recent paper Overend et al. [17] showed that the random flaw population approach can provide accurate predictions for the strength of bolted glass connections, but the selection of the