Failure analysis of tempered glass structures with pin-loaded joints

Q.D. To\textsuperscript{a,b}, Q.-C. He\textsuperscript{b,*}, M. Cossavella\textsuperscript{a}, K. Morcant\textsuperscript{a}, A. Panait\textsuperscript{a}, J. Yvonnet\textsuperscript{b}

\textsuperscript{a}Centre Scientifique et Technique de Bâtiment (CSTB)
84 Avenue Jean Jaurès, 77447 Marne-la-Vallée Cedex 2, France

\textsuperscript{b}Laboratoire de Mécanique (LaM), Université de Marne-la-Vallée
5 Boulevard Descartes, 77454 Marne-la-Vallée Cedex 2, France

Abstract

Pin-loaded joints are frequently used to assemble tempered glass plates. To prevent such structures from fracture, a holed glass plate is reinforced by a steel ring and glued to it through a soft resin layer. The present work first models and identifies the mechanical behaviour of the constituent materials and then analyzes the failure process of tempered glass structures with pin-loaded joints, in which unilateral contact, friction, damage and residual stresses are involved. The numerical results obtained by the finite element method are in good agreement with the experimental ones issuing from the real size test.

Key words: Contact, Reinforced pin-loaded joints, Failure analysis, Tempered glass, Finite element method.

1 Introduction

During the last decade, glass has been widely used as a structural building material owing to the recent progress made in manufacturing technology. Nowadays, tempering procedures are employed to strengthen glass so as to render it safer and more durable. Although still costly, tempered glass has many specific aesthetic features and particular physical properties which make it indispensable to architects and engineers in many situations. In France, tempered glass
is involved in many important buildings like those of Roissy Airport and Radio France. Figure 1 shows an example where tempered glass is used in a roof system.

In tempered glass structures, load-bearing elements are frequently assembled from separate prefabricated glass sheets by means of bolted connections. There are two types of bolted connections: friction-grip joints and pin-loaded joints. As suggested by their names, a friction-grip joint realizes the transmission of tangential stresses by the friction subsequent to the tightening of HS bolt, and a pin-loaded joint transfers stresses via the direct contact between the bolt and the holed plate with or without reinforcement. In the recent papers of Panait et al. (2004, 2006), friction-grip joints have been studied by a coupled experimental and numerical approach. The present work aims to investigate the bearing strength of pin-loaded joints.

The pin-loaded joint under investigation comprises a moving part and a fixed part. The former consists of a steel bolt and an inner copper ring while the latter is formed of an outer steel ring, a resin layer and a glass plate (see Fig. 2). The inner ring inside the outer ring is rotatable in order to adjust the bolt’s axis during the erection. The outer ring serves as reinforcement for the glass plate and is glued to the holed glass plate by the resin layer.
The pin-loaded joint described above is a complex composite system. Analyzing its failure behavior is a tough task for three reasons. First, both elastic-brittle and elastoplastic materials are involved. Second, bi-lateral interface and unilateral contact problems are concerned. Third, the residual stresses in the tempered glass plate must be taken into account. In the past, works were carried out on the elastic analysis and failure analysis of pin-loaded joints (see Noble & Hussain (1969), Lin & Lin (1999), Hyer & Klang (1969), To et al. (2006), Ramazan et al. (2006), Tserpes et al. (2002) and the cited references). However, to the best of the authors’ knowledge, they did not account for the ring reinforcement and the residual stresses. This can be explained by the fact that tempered glass is a rather new structural material.

The present paper is organized as follows. Section 2 is dedicated to the experimental identification of the mechanical characteristics of the resin and tempered glass needed for our investigation. In Section 3, the failure analysis of a glass structure with pin-loaded joints is performed using the three-dimensional finite element method, and a real sized test is realized to check the validity of the numerical results. Finally, a few conclusions are drawn in Section 4.

2 Modelling and identification of the mechanical behaviour of constituent materials

2.1 Resin

The resin used in bolted connections is a cured mixture of an Epoxy resin and a hardener, which often contains voids before undergoing any loading (see Fig. 3). Its mechanical behavior is similar to that of hardened cement paste: (a) under tensile loading, it behaves as an elastic-brittle material; (b) under compressive loading, it acts like an elastoplastic material due to microcracking. The uniaxial behaviour is idealized as illustrated by Fig. 4: (i) before a traction attains a certain critical value \( \sigma_{cr} \), the resin remains elastic; (ii) when \( \sigma_{cr} \) is achieved, fracture takes place; (iii) when a compression is lower than the yielding stress \( \sigma_y \), the resin is elastic; (iv) once \( \sigma_y \) is attained and the compressive strain is still smaller than the crushing strain \( \epsilon_c \), the resin has an elastoplastic behaviour; (v) when \( \epsilon_c \) is reached, the failure of the resin is considered to occur. This uniaxial behaviour is extended to the multiaxial stress state by combining the Rankine criterion and the Drucker-Prager criterion with a bilinear hardening law (Fig. 4). More precisely (see, e.g. Chen...
(1989)), the latter reads:
\[
f = \alpha I_1 + \sqrt{J_2 - \frac{|\sigma_y|(1 - \sqrt{3} \alpha)}{\sqrt{3}}} \leq 0, \quad \alpha = \frac{\sin \phi}{\sqrt{3(3 + \sin^2 \phi)}},
\]  
(1)

where \(I_1\) and \(J_2\) are the first and second stress invariants defined by
\[
I_1 = \sigma_1 + \sigma_2 + \sigma_3, \quad J_2 = \frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right],
\]  
(2)

and \(\phi\) is the angle of friction.

Fig. 3. Pre-existing voids inside the resin

Fig. 4. Uniaxial behaviour and biaxial tensile failure - compressive yield surface

To determine the resin’s material parameters, two tests have been done on cylindrical samples of dimensions \(L = 20\text{mm}\) and \(D = 10\text{m}\) (Fig. 5). In the first compression test, the uniaxial compressive stress-strain relation is determined
as shown in Fig. 6. Remark that the obtained compressive stress-strain curve comprises an elastic part (an almost straight line) followed by an inelastic part due to microcracking. In the second test known as splitting test, the tensile strength $\sigma_{cr}$ (see Fig. 7) is calculated by

$$\sigma_{cr} = \frac{2F_{\text{max}}}{\pi DL},$$  \hspace{1cm} (3)

where $F_{\text{max}}$ is the maximal applied force.

![Compression and splitting test schemes](image)

**Fig. 5.** Compression and splitting test schemes

The material parameter values identified for the resin are summarized as follows:

- elastic properties: $E = 2500$ MPa, $\nu = 0.22$;
- tensile strength: $\sigma_{cr} = 11$ MPa;
- initial compressive yield stress: $\sigma_y = -50$ MPa corresponding to $\varepsilon_y = -0.02$;
- maximum compressive yield stress: $\sigma_{\text{max}} = -65$ MPa corresponding to a strain $\varepsilon = -0.03$;
- crushing strain: $\varepsilon_c = -0.045$ associated to a stress $\sigma = -58$ MPa.

Concerning the angle of friction $\phi$ which was not identified by our tests, we take $\phi = 20^0$. By (1), we obtain $\alpha = 0.11$. 

![Uniaxial compression test](image)

**Fig. 6.** Uniaxial compressive test
At this point, a complete model for the resin has been established and will be used later in the finite element analysis.

2.2 Tempered glass

The behaviour of tempered glass at normal temperature is isotropically elastic and brittle. However, its strength depends on the load duration and the residual stress state. The time effect is mainly due to stress corrosion crack phenomena where a crack is attacked by water vapor and extended up to the critical size (Wiederhorn, 1967). The degradation of strength is recognized to follow the static fatigue power law (Wiederhorn, 1975) and takes place principally on the surface. Thus for tempered glass, the superficial residual stresses play an important reinforcement role on the tensile strength.

An effective approach to determining the residual stresses consists in using the finite element method to simulate the tempering process and in validating the numerical results about the residual stresses by photoelasticity. For illustration, the distribution of the residual hoop stress is shown in Fig. 8 where use is made of a cylindrical coordinate system with the origin O placed at the center of the hole. The residual hoop stresses in the middle of the plate, at the edge and at the edges of holes are respectively presented in Fig. 9.

The failure stress $\sigma_f$ of tempered glass at a point on the surface is considered to be the superposition of the time-independent residual compressive stresses $\sigma_{res}$ and the strength $\sigma_{fg}(t)$ of the float glass.

$$\sigma_f(t) = \sigma_{res} + \sigma_{fg}(t).$$ (4)
The float glass failure stress $\sigma_{fg}(t)$, however depends on the load duration, surface quality and size. According to the available data, as in the work of Carré (1996), $\sigma_{fg}$ ranges from 30 MPa to 50 MPa. According to the Eurocode, $\sigma_{fg}$ is equal 32 MPa for a load duration of 20 minutes. In the present paper, $\sigma_{fg} = 35$ MPa is adopted.

The tensile hoop strength at the edges of holes (3a-3b) is of special interest, since it is responsible for the failure in our analysis (see Fig. 8 and Fig. 9). We take $\sigma_f = 35 + 120 = 155$ MPa at the point 3a, and $\sigma_f = 35 + 85 = 120$ MPa at the point 3b.

![Fig. 8. Distribution of the residual hoop stresses $\sigma_{\vartheta\vartheta}$ in one-eighth of the holed plate](image)

![Fig. 9. Residual hoop stresses $\sigma_{\vartheta\vartheta}$ along the thickness at the middle of the plate (1a-1b), at the edges (2a-2b) and at the edges of holes (3a-3b)](image)

Up to failure, the glass is isotropically elastic with the following material constants:
- Young’s modulus: $E = 70000$ MPa,
- Poisson’s coefficient: $\nu = 0.22$. 
3 Numerical simulation and experimental investigation of failure process of a tempered glass plate with pin-loaded joints

As pointed out at the beginning of this paper, predicting the failure of a tempered glass plate with reinforced pin-loaded joints is complicated by the involvement of several nonlinear phenomena like unilateral contact, friction, damage and elastoplasticity in addition to residual stresses. In the present paper, a coupled numerical-experimental approach is proposed to investigate this problem. A structure composed of a 19 mm thick glass plate with two reinforced pin-loaded joints (see Fig. 10) is constructed. Two opposite increasing displacements are applied on the two bolts until the structure fails. We first analyse the structure by the finite element method and realize a real size test on the structure, and then compare the relevant numerical and experimental results.

![Tempered glass plate with two pin-loaded joints](image)

Fig. 10. A tempered glass plate with two pin-loaded joints

The mentioned glass plate with joints is numerically modelled and analyzed with the help of MSC MARC, a general purpose finite element code. This software contains many readily integrated material models as well as robust algorithms for special problems like unilateral contact, coupled phenomena, etc...

All the structural components, i.e. glass plate, bolts, resin, inner and outer rings, are meshed by 3D isoparametric solid elements with 8 nodes. Owing to the fact that the problem is symmetric with respect to 3 orthogonal planes, the model is further reduced to one eighth with appropriate boundary conditions (see Fig. 11). The external load is an increasing displacement applied on the head surface of each of the two bolt at a small constant rate.
Besides the resin and the glass discussed in the previous section, the mechanical properties of the other materials involved in the analysis are provided below

- bolt (stainless steel): $E = 200\,000$ MPa, $\nu = 0.3$;
- inner ring (copper): $E = 70\,000$ MPa, $\nu = 0.22$;
- outer ring (stainless steel): $E = 200\,000$ MPa, $\nu = 0.3$;

- friction coefficient between polished stainless steel and polished copper in normal environment: $\mu = 0.2$.

The resin-glass and resin-outer ring interfaces are considered perfect.

The dispositive of the real size test is shown in Fig. 12. One bolt is held fixed while the other is submitted to increasing displacement.
The failure process of the structure evidenced by the FEM analysis is confirmed by the experimental test. More precisely, the failure process can described as follows (see Fig. 13 and Fig. 14):

- The first crack initiates in the resin at the point near the interface with the steel ring, since the highest tensile stress occurring at that point exceeds the tensile strength (11 MPa).
- The cracked zone then develops quickly inside the resin and along the interface, tending to separate the left part from the ring. The right part remains glued to the ring but highly compressed and exhibits irreversible plastic strain.
- The glass becomes heavily stressed and fails when stress attains the tensile strength $\sigma_f = 120$ MPa at the middle point 3b of the hole edge.

In terms of global failure load, the finite element result gives 70 kN while the experimental value is 65 kN (see Fig.15). Therefore, the numerical simulation is also globally validated by the real size test.

Fig. 13. Experimental failure modes in the resin and glass

Fig. 14. Cracked zone in the resin and stress concentration in glass
4 Conclusions

In this paper, the failure process of tempered glass structures with pin-loaded joints has been studied by a coupled experimental-numerical method. First, the mechanical behaviour of the constituent materials, including the resin and tempered glass, is modelled and identified. Then, combining the FEM and the real size test, the failure process of a tempered glass structure with pin-loaded joints has been identified. Our present study completes our previous one (Panait et al. (2006)). Consequently, a complete and efficient approach is now available both for the design and optimisation of glass structures with friction-grip joints or pin-loaded joints.

References


