Load bearing capacity of connections in tempered glass structures

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Abstract

In the design of high load bearing capacity beams made of tempered flat glass, connections cannot be avoided when large span or high stiffness beams are considered. The aim of this paper is to propose a method that can help the design of dowel type joints in tempered glass structures in buildings. The studied technology is derived from the one used for hanging glass in facades.

In a first step, residual stresses due to thermal tempering are modelled with the Finite Element Method. Narayanaswamy's model is used to describe the thermo-mechanical behaviour of glass. The different heat transfers are identified and modelled for a given tempering process. In a second step, the state of stresses due to the loading of the metallic connector is analysed. The numerical prediction of stresses is validated by means of experiments. The superposition of these two stress states is combined to get a design criterion for holed tempered glass plates loaded by dowel type joints.

1. Introduction

For the making of load-bearing structural elements, glass presents many disadvantages : first of all, its brittleness does not allow any irreversible strain, then its sensibility to the mechanical damage of its surface can make fall its strength by several magnitude orders and finally the presence of a fracture sub-critical propagation phenomenon causes, under constant loading, a reduction in material strength.

These reasons make that there is a lack of knowledge on glass long-term behaviour. That is why, in France, offices of control for construction require a relatively important global safety factor (about 7) as well as a full-scale test for any glass structure to be realised. The global safety factor comes from a coefficient equal to 3.5, classical for brittle materials which includes uncertainties on loading and on material, and a coefficient 2 due to the strength reduction estimated over 50 years.

Thermal tempering is a way of reinforcement of the glass surface. It allows not only an increase in the glass tensile strength since it is necessary to overcome the surface precompression in order to break the material, but also a certain immunity against the sub critical cracking, at least as long as the applied tension does not exceed in absolute value the surface precompression. Everywhere in the world examples of glass structures can be observed. Fig. 1 and 2 show glass beams supporting a glass roof at the Louvre laboratory of French museums, as well as the full-scale tests carried out for this occasion in the Building Scientific and Technical Centre.

In the design of high load bearing capacity beams made of tempered flat glass, it is necessary to distinguish the completely different stress states in members and in the connection zones. The prediction of the load bearing capacity of tempered glass plates with no connections was previously carried out [1]. Connections cannot be avoided when large span or high stiffness beams are considered.

Currently, limits in the possibilities of structural connections between glass elements and other materials are encountered. The aim of this paper is to propose a design method for dowel type joints in tempered glass structures in buildings. This technology, shown in Fig. 3, is derived from the one used for hanging external glazing for facades. For such applications, loading is in the plane of the glass plate.

In order to study the potentiality of this kind of connection, it is necessary to calculate the impact of the loading of the metallic connector on the thermally tempered glass. In the connection zone, the stress state is the superposition of the one due to the thermal tempering and the stress state induced by the metallic connector on annealed glass.

The following of the paper will focus separately on these two different analyses. The problem is solved in an experimental and a numerical way. The material studied is a 19 mm thick glass. Different geometries of holes are considered (Fig. 4 and table 1).

2. Finite Element computation of residual stresses near holes in tempered glass plates

Previous studies of glass tempering have been concerned with the calculation of residual stresses in infinite plates, i.e. far away from edges and possible holes, by means of 1D modelling [2]. The computation of residual stresses in the vicinity of a straight edge (2D modelling) was carried out in [1] but this analysis was not taking into account, in an exhaustive way, heat transfer occurring during the tempering process.

The presented contribution concerns the prediction of residual stresses, not only close to straight edges, but also in the vicinity of chamfered holes in 19 mm thick glass plates (3D modelling). A thermo-mechanical calculation is carried out with the Finite Element Method (FEM). The knowledge of both the mechanical behaviour of glass and the temperature history in the whole plate during the tempering process, are then necessary.

2.1. Mechanical behaviour of glass during tempering

The model of Narayanaswamy is used [3]. This model includes the viscous and the structural relaxation phenomena. Glass is considered as a thermorheologically simple material.

The viscoelastic behaviour of glass is described in terms of stress relaxation by means of a generalised Maxwell model. Relaxation shear and bulk moduli are described with instantaneous and deferred moduli and expanded into Prony's series [4].

The thermorheological feature consists in considering that temperature and time are two dependent variables of state. Thus, the knowledge of glass behaviour at a reference temperature allows knowledge to be obtained at any other temperature by the intermediary of reduced time [4].

The structural relaxation is a direct consequence of the thermodynamical definition of glass: the structural state of glass depends on the cooling rate. This phenomenon is taken into account using the concept of fictive temperature, which represents the temperature of the liquid having the same structural state as considered glass [5].

2.2. Identification of heat transfer phenomena during tempering

The cooling by air throw is modeled by a forced convection. Far away from edges, the forced convection is characterized by a heat transfer coefficient and by the air temperature. For the modeling of the tempering of holed plates, several coefficients are defined (in the hole, on straight edges…). In addition, because of the high temperature at the beginning of the tempering process, the modelling of the thermal radiation is necessary. Radiation is a complex phenomenon in glass which is a semi-transparent medium since infra-red waves are not stopped by the first molecular layers.

2.2.1. Modeling of the thermal radiation

This heat transfer is split into two flows which emanate from surfaces on one hand and from the volume on the other hand.

For that, surface and volume emissivities of glass plates are defined in the following way:

- the surface emissivity is defined for the spectral field where glass is opaque, the radiative transfers take place only on the surface;
- the volume emissivity is defined for the spectral field where glass is semi-transparent, the radiative transfers occur in all the volume of glass.

It is supposed that radiative transfers take place in a uniform way in all the volume.

The different emissivities were identified in the case of infinite plates for various mean temperatures of plates [6]. Their expressions are put into polynomial forms. Such a polynomial form is easily exploitable with the FE code ABAQUS. On each Gauss point (i), the emitted radiative flow (respectively absorbed) is calculated by multiplying the volume emissivity by (σT_i^4) (respectively σT_{ext}^4), divided by the thickness of the glass plate. σ is the Stefan-Boltzmann coefficient, T_i and T_{ext} are Gauss point temperature and exterior environment temperature respectively. On the surface, the flow corresponding to the opaque spectral field, which results from a similar calculation with the surface emissivity, is added. The pertinence of this methodology is shown in [7].

2.2.2. Identification of forced convection coefficients

The convection coefficients in the different areas of perforated plates are identified using a hollow aluminium model, representative for the external surface of a 400x400x19 mm3 glass plate. Figure 5 shows this model. The interest of this model is the possible instrumentation by thermocouples in such a way that they do not disturb the air flow.

The model was submitted to real conditions of tempering but was heated to a temperature such as the radiation is negligible. The temperature was recorded on different points of the perforated plate during the tempering. Solving the heat equation for these tests enables to identify the actual forced convection coefficients of perforated thick glass plates.

2.3. Calculation of residual stresses

The various phenomena of heat transfer are identified allowing an accurate prediction of residual stresses due to the tempering of thick glass plates. This stress state is axisymmetrical since thermocouples reveal cooling symmetries in previous experiments.

The comparison between the residual stresses in perforated plates with large chamfers calculated by a FEM simulation and those obtained by means of photoelastic methods is very satisfactory particularly close to the edge and the hole (Fig. 6 and 7).

3. Loading of the metallic connector

This part presents the analysis of stresses in the vicinity of a chamfered hole in a glass plate loaded by a dowel type connection. This analysis is both experimental and numerical.

3.1. Description of the tests and experimental protocol

The perforated glass plate is glued to two metallic fixing plates that can rotate with the frame of the testing machine (50 ton MTS). The steel connector is fixed to the horizontal cross-piece of the testing machine. The vertical displacement rate is 0,5 mm/min (Fig. 8). Far from the hole, the glass plate is under tension.

Annealed and thermally tempered glass were tested. More than 120 test were carried out. All the results are given in [8]. The deviation is quite low although glass is sensitive to defects such as other brittle materials.

3.2. Other analyses

3.2.1. Fractography:

At the end of each test, the origin of the rupture was investigated in order to estimate the failure stress by the measurement of the smooth fracture surface [8].

3.2.2. Photoelasticity:

Photoelastic measurements were carried out during tests with a polariscope in the zone located above and on the sides of the joint. Thanks to these measurements, it is possible to follow the isochromatic fringes. The images obtained during tests are used for the validation of the FEM modelling of these tests.

3.3. Finite Element modelling of tests

The FE code Abaqus is used. It is necessary to model the two contacts: on one hand between the steel connector and the aluminium washer, and on the other hand between the washer and the glass plate chamfer. All these contact areas are conical, the contact frictions are taken into account. Glass is supposed to be elastic; aluminium and steel are supposed to be elastoplastic. The problem to solve is non linear and three dimensional. Initial prestressing due to the connector is introduced by prescribing a displacement to the connector towards the glass chamfer, this displacement is identified thanks to a photoelastic analysis. For the simulation of the mechanical tests performed on thermally tempered glass, previously calculated residual stresses are added to the stresses induced by the connector.

A local failure is assumed to occur in glass when the maximum principal stress reaches a critical value. Such a criterion is classical for brittle materials in which failure is due to a mode I fracture. The failure stress estimated by the measurement of the smooth fracture surface was compared with the calculated maximum principal stress at the observed location of failure during tests. The mean deviation between the measured and predicted failure stresses for both annealed and tempered glass is less than 10%, which is of the same order of the precision of the stress measurements by fractography.

For the simulation of the photoelastic images, the equation of propagation of the electrostatic field E of the light is integrated on every point in the thickness of the glass plate [9].

This methodology allows to take into account the change of the secondary principal directions in the thickness due to shear gradients in complex geometries.

The intensity of light $I=E^2$, or the phase delay Δ, are then calculated for the prediction of the light extinction. Fig. 9 shows an example of comparison between images obtained from an experiment and from a simulation for a loading of 94 kN and a mean chamfer (on tempered glass).

Thus the numerical simulation is validated.

4. Application : design criterion for connections

From these results, it can be seen that is possible to accurately determine the value of the load involving the surface decompression (one principal surface stress becomes positive). It is proposed to consider this load as the design limit value. It is then guaranteed that sub critical cracking cannot occur. Long-term strength is assured (residual stresses can be guaranteed over 50 years [10]) and the partial safety factor equal to 2 corresponding to the long-term behaviour of glass is not necessary anymore. Moreover, this solution allows avoiding consideration about critical defects (localisation, propagation…). Table 2 gives surface decompression loads (in kN) obtained in this study for various geometries and initial prestresses.

These results correspond to a loading in the plane of the glass plate. This numerical modelling allows to identify the hole optimal geometry for connections: large chamfer and diameter.

5. Conclusion

This study deals with the context of the structural glass, i.e. the use of glass in building structures. The accent is related here to the structural connections between members made out of flat glass. The modelling of a dowel type connector inserted in a holed glass plate is developed with the Finite Element Method. This model leads to a design criterion of the connection area guaranteeing the safety of the structure with time. Such a design criterion could allow to remove the partial safety factor equal to 2, relating to the strength reduction in time. The use of the numerical simulation could also allow to reduce or to avoid the full-scale tests required by offices of control for building.

Besides, to ensure the *in situ* control of structures, it is proposed to use photoelasticity. By carrying out photoelastic images on existing structures, the stress state in the glass is obtained. It is then possible to check a possible surface decompression in order to grant certificates of guarantee for in service structures.

6. References

[1] Carré H., Daudeville L., "Load bearing capacity of tempered structural glass", *ASCE Journal of Engineering. Mechanics*., vol. 125, n°8, 1999, p. 914-921.

[2] Narayanaswamy O.S., Gardon R., "Calculation of residual stresses in glass", *Journal of American Ceramic Society*, vol. 52, n°10, 1969, p.554-558.

[3] Narayanaswamy O.S., "A model of structural relaxation in Glass", *Journal of American Ceramic Society*, vol.54, n°10, 1971, p. 491-498.

[4] Gy R., Duffrene L., Labrot M., "New insights into the viscoelasticity of glass", *Journal of Non-Crystalline Solids*, vol.175, 1994, p. 103-117.

[5] Tool A.Q., "Relation between inelastic deformability and thermal expansion of glass in its annealing range", *Journal of the American Ceramic Society*, vol.29, n°9, 1946, p.240-253.

[6] Banner D., Klarsfeld S. “Influence of composition upon the apparent conductivity and emissivity of glass as a function of thickness and temperature”, Thermal conductivity 21, edited by Cremers and Fine, Plenum Press, New York USA (1990).

[7] Bernard F., Gy R., Daudeville L., “Finite element computation of residual stresses near holes in tempered glass plates”, *Glass Technology*, vol. 43C, 2002, p.290-295

[8] Bernard F., Daudeville L., Gy R., “Sur le dimensionnement des structures en verre trempé”, *Revue Française de Génie Civil*, vol. 6, n°7-8, 2002, p.1359-1380 (in french)

[9] Aben H., Guillemet C., *Photoelasticity of Glass*, Berlin, Springer-Verlag, 1993

[10] Gy R., “Creep and Recovery of a thermally tempered glass plate at room temperature”, Glass Processing Days, Helsinki, 13-16 june 1999

Figures and captions

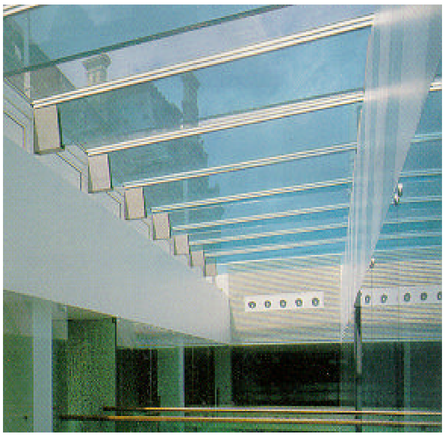

Fig. 1. Example of glass structure – Louvre museum

Fig. 2. Full-scale test of a beam

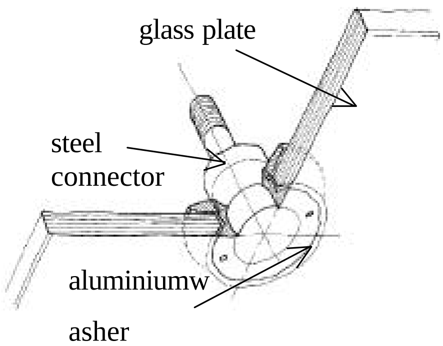

Fig. 3. Schematic view of the connection

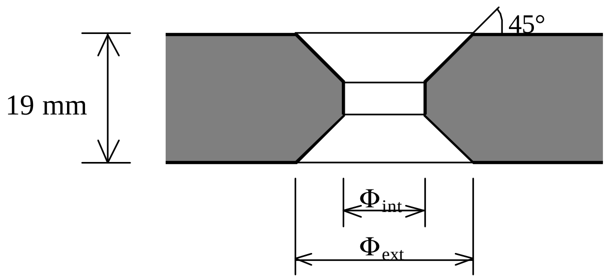

Fig. 4 .Chamfered hole

Designation	Φ_{int} (mm)	Φ_{ext} (mm)
a1	38	40
a2	54	56
b1	24	40
b2	40	56
c1	30	40

Table 1. The five different studied geometries

Fig. 5. The holed model b2

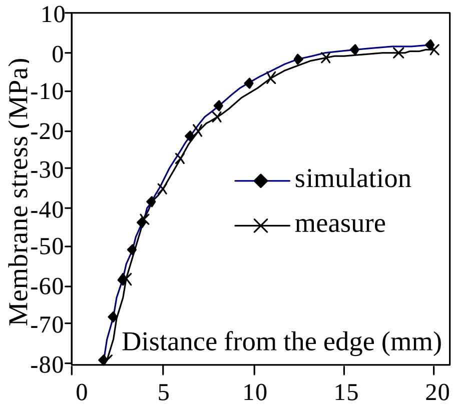

Fig. 6. Results close to the straight edge

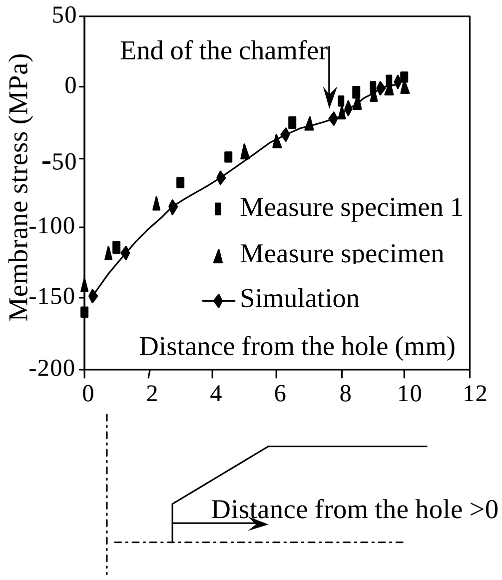

Fig. 7. Results in the vicinity of the hole b1

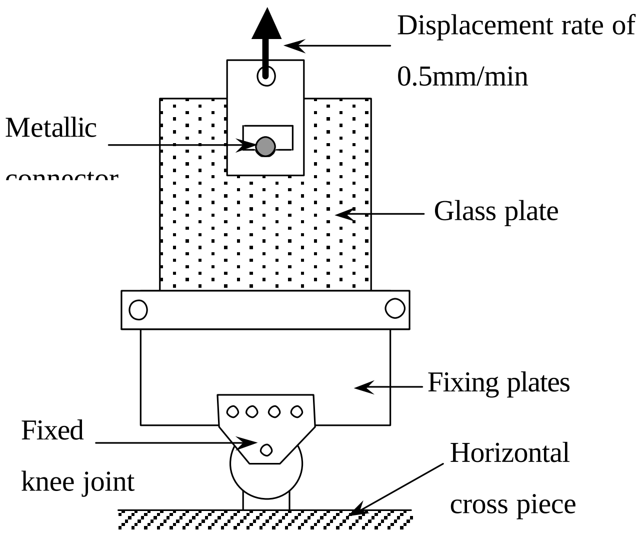

Fig. 8. Test set-up

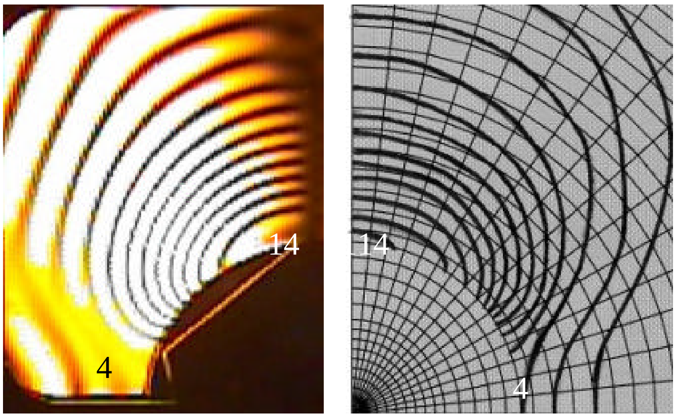

Fig. 9. Comparison between observed (left) and predicted (right) photoelastic fringes

	Surface decompression load (kN)				
prestress (N.m)	0	10	20	25	30
Hole b1	69.3	69.8	71	*	*
Hole b2	77.5	78.3	79.5	80.1	80.9
Hole c1	57.5	59.6	60.9	62	62.3

* failure during the prestressing

Table 2. Surface decompression loads (in kN) for the studied joints