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Point fixings in annealed and tempered glass structures: Modeling and optimization of bolted connections

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ABSTRACT

In the design of high load bearing elements made of tempered flat glass, connections cannot be avoided when large spans or high stiffness beams are considered. This paper investigates bolted connections in glass structures; the main objective is to determine the optimal joint. This work is performed through the determination of stress states due to both thermal tempering and in-plane loading. The modeling of the thermal tempering is performed with the FE software Abaqus and additional user subroutines. Experiments on industrial tempering line with specific set-up allow the determination of the air flow in the hole and then of the forced convection coefficients. The radiative heat transfer is also modeled numerically and the semi-transparency of glass in the near infrared is considered. In order to calculate residual stresses, the visco-elasticity of glass and the structural relaxation phenomena are taken into account. The computed stresses are checked against photo-elastic measurements. As various holes are considered, this study allows to determine the hole geometry for which the tempering process is the most effective. For the study of the consequences of in-plane loading, a large experimental campaign has been performed. The studied connection is derived from countersunk supports. The influences of different parameters as the hole geometry, the nature of the washer between glass and metallic connector as well as the glass-washer material friction coefficient were investigated. The modeling of these tests is performed with the FE software Abaqus. This modeling takes into account the ductility of the materials, the friction and the clearances between the parts. This modeling is validated thanks to failure stress measurements. The combination of modeling and experiments leads to identify optimal connection.

1. Introduction

Glass is a material that has been used for a long time in windows as a filling material and has much to offer in this regard due to its possibility to carry high compressive stresses.

For several years, there has been a trend in architecture to use glass not only as a part of the building envelope, but also as material for load bearing elements. This represents a special challenge because of the glass brittleness. In the most frequent cases, glass columns or beams are used. In the design of such structures made of tempered flat glass, connections cannot be avoided, especially when large spans or high stiffness beams are considered. The key differentiation in point bearing is done between glass panes fixed on their corner or edges and those fixed in drilled hole [1]. In the second case, loads are transferred via compound point-support or steel bolts to the glass hole. To avoid any contact between steel and glass a suitable layer or bushing material, such as aluminum or plastic, has to be applied.

Point-bearing in holes are also divided in types with a plate on each surface of the glass pane (raised head point fixture) and those with conical drillings (countersunk point fixture).

The use of point fixings with conical holes is interesting for several reasons. From an architectural point of view, the even glass surface is not disturbed by an additional plate and from a point of view of maintenance, an even surface is more convenient to clean.

A lot of structures all around the world present such connections; one of the main examples in France is the large facade of the "Cité des Sciences et de l'Industrie" at Paris [2]. Fig. 1 presents a schematic view of the used connection [2].

The two only ways for the design of a glass plate with such point-bearing is by means of 3D FE modeling and of extensive experiments in scale 1:1. For the FE modeling, the point-bearing itself as well as the surrounding area have to be modeled accurately to get close-to-reality results.

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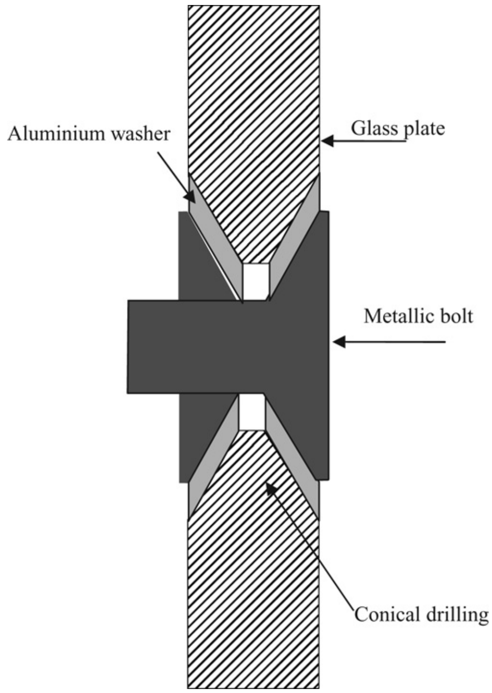

Fig. 1. Schematic cross section of the studied connection.

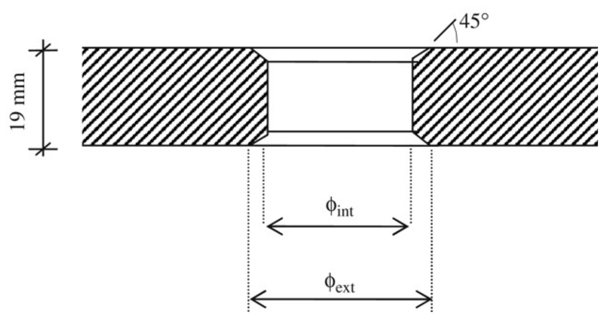

Fig. 2a. Cross section of cylindrical holes a1 and a2.

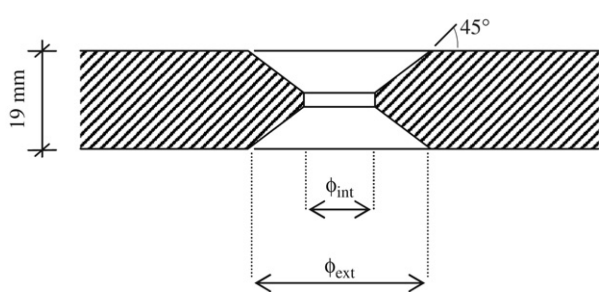

Fig. 2b. Cross section of conical holes b1 and b2.

2. Objectives of the study

The aim of this paper is to propose a complete modeling of such connections. The technology used is derived from the countersunk point fixture and from the one shown in Fig. 1.

Contrary to facades where loads (wind especially) are out of the plane, glass structures carry in-plane loadings. That is why only symmetrical geometries of holes in glass plates are considered in this work.

Another advantage of an accurate 3D FE modeling is the possible determination of the optimal connection. Then, particularly five different holes geometries are considered in this work. All of them are presented in Figs. 2a–2c and Table 1. 19 mm thick Planilux®glass plates, produced by Saint-Gobain, are studied.

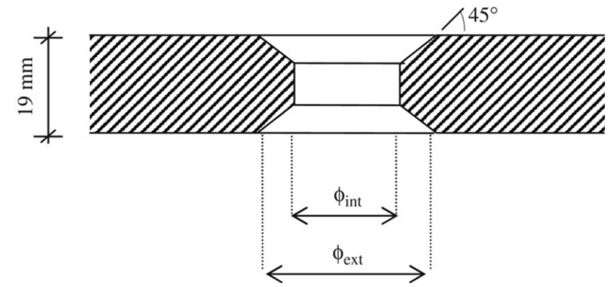

Fig. 2c. Cross section of mean chamfer hole c1.

Table 1
The five different studied geometries.

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

Besides, thermally tempered glass can also be required for some structures. Then the complete modeling and optimization of this kind of connections needs the determination of stress states due to both thermal tempering and metallic connector in-plane loadings. The present paper focuses on these two separated studies. The problem is solved in a numerical way and validated by means of experimental measurements.

A recent study [3] has concerned also numerical and experimental investigations on the stress distribution of bolted connections under In-Plane loads but, contrary to the present paper, these examinations are limited to drill holes with a cylindrical shape and to annealed glass. Some details also, especially on the connector and the interlayer shapes are different.

3. FE computation of residual stresses in connection area

3.1. Presentation of the thermo-mechanical computation

Previous analyses of glass tempering have been concerned with the calculation of residual stresses in infinite plates by means of a 1D modeling [4]. The computation of residual stresses in the vicinity of a straight edge (2D modeling) was carried out in [5] [5bis] and near holes in [6] or [7], but these previous analyses did not take into account, in an exhaustive way, the heat transfers 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 modeling). A thermo-mechanical calculation is carried out with the Finite Element Method (FEM). Knowing both the mechanical behavior of glass and the temperature history in the whole plate during the tempering process, is then necessary.

The thermo-mechanical behavior of glass was widely studied in the literature. Narayanaswamy [4] proposed a model that includes both structural and viscous relaxation phenomena, and that considers glass as a thermorheologically simple material. The implementation of this model in the FE software Abaqus is described in [8]. The parameters of the model are provided in [9].

3.2. Identification of heat transfers

The temperature history in the whole plate during the tempering process can be estimated while taking into account accurately the whole heat transfers. The analysis of the heat