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Behaviour of monolithic and laminated glass exposed to radiant heating

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HIGHLIGHTS

- Experimental results on heat transfer in fire situations through structural glass.
- A model for heat transfer applicable by e.g. finite element modelling.
- Characteristic thermal and optical properties of the glass relevant for response to fire exposure.

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ABSTRACT

Glass is seeing a growing interest as a structural material as a result of its relatively good strength to weight ratio and the obvious aesthetic benefits of its use in buildings. However due to the sensitivity of glass to thermal shock and the considerably temperature-dependent behaviour of interlayer materials as a result of their visco-elastic nature, the mechanical behaviour of laminated glass will be severely influenced by exposure to fire. Relatively little research has been conducted in the past to study the response of load bearing structural glass, and laminated glass in particular to radiant heating. This paper represents an effort to try to understand the effects of through depth radiation absorption and temperature conduction through laminated glass with a view to ultimately developing a model for studying load bearing glass exposed to elevated temperatures, such as those that would be expected in a fire. The paper reports on an experimental research programme in which several monolithic and laminated glass configurations were exposed to a radiant heat flux to study the different phenomena that occur upon exposure to fire conditions, including the ratios of absorbed, transmitted and reflected heat flux to the incident heat flux. The paper then presents a numerical heat transfer model which is developed based on these experimental results and that is able to determine the evolution of the temperature profile as a result of a given incident heat flux. The effectiveness of the heat transfer model is demonstrated through comparison with the temperatures measured during the experimental work.

1. Introduction

Glass has been used for centuries as a structural material in windows and glazing [1]. As a result of continuous improvements in production and processing, combined with the development of the state of knowledge regarding its structural performance, glass is increasingly used as a load-bearing material for structural elements such as beams, columns, fins, walls, staircases, etc. [2–4]. However, due to its variable strength and inherent brittleness, failure prediction of such glass load-bearing elements remains a key issue [5,6]. To increase robustness and performance when panes crack, modern structural glass construction relies on laminating multiple panes of glass together using a polymer interlayer. This concept is called laminated glass (LG) [7]. The polymer interlayer is typically less stiff than the glass itself and of much lower thickness. As cracks develop in the glass, adjacent panes are able to bridge the developing cracks through shear interaction via the polymer interlayer allowing the element to deform and redistribute the load through the adjacent panes. Although the study of the post-breakage performance and robustness of LG components is receiving more and more attention [8,9], much is still unknown about the behaviour in extreme events such as fire. The changes in structural and material properties at very high temperatures (particularly those of the interlayer materials) and the effect of combined fire loading and mechanical loading may result in progressive or sudden failure. There are some examples of studies of the response of glazing to fire, e.g. in [10] Harada et al. report

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on 50 experiments to measure the initial time to crack of float glass panes, and in [11] Pagni reviewed the literature and proposes a method for determining glazing failure time. However there are very few experimental studies in the literature of the response of structural glass to fire. Wang et al. studied the effect of rate of heating on crack initiation in window glass breakage [12] and found that a faster temperature increase caused crack initiation at a lower temperature than a slower rate of heating. In [13], Xie et al. studied the critical stress of float glass of thicknesses from 4 to 12 mm at both ambient temperature and at a temperature of 200 °C. They found that at ambient temperatures increased thickness float glass had a higher critical breakage stress; whereas at increased temperatures had a lower critical breakage stress.

The procedure for assessing the fire resistance of structures comprises three stages: (1). developing a model of the fire to determine the thermal exposure to the element, (2) performing a heat transfer analysis to determine the temperature distribution in the element, and finally (3) analysing the structural response of the element accounting for temperature dependent material properties and thermal strains that may develop [14]. Traditionally, the modelled fire is represented by one of the standard temperature–time curves originally constructed for certification of elements exposed to fire resistance testing. A more detailed analysis can be performed using a variety of models ranging from nominal low temperature smouldering temperature–time curves to CFD models that can take more complex geometries into account and model the smoke spread and the distribution of fuel and its burning characteristics. Nevertheless, the fire model is typically assumed to be rather independent of the type of structural elements and the materials they consist of. Therefore, the same representations for fire that are used for the more traditional structural materials such as concrete, steel, timber and masonry may be considered applicable for structural glass.

The differentiation from the analysis of the traditional structural materials in a fire starts with the heat transfer model as glass allows a substantial portion of the radiation to be transmitted through the exposed surface and even through the full thickness of the element, while traditional non-transparent materials absorb and reflect the relevant frequencies of incident radiation at the exposed surface. The combination of surface reflection, through-thickness absorption and emission effects, potential internal reflections at material boundaries in LG, and the need for spectral models due to wavelength-dependent properties of the glass and interlayer materials as well as any surface coatings, give rise to a complex heat transfer problem. Consequently, the construction of a practical yet sufficiently accurate heat transfer model is desirable and will be presented here. This could in the future allow an initial screening of glass structures exposed to different fires. However, the composition of a structural response model is beyond the scope of this research, although it is undoubtedly the end-goal.

This paper describes an experimental test programme which was set up to assist in the construction of a heat transfer model for glass structural elements, where the transmittance, absorptance and reflectance of several monolithic soda lime silica glass (SLSG) and laminated SLSG configurations were measured. Additionally, the tests allow for a description of the phenomena that occur at elevated temperatures in glass and laminated glass so that the overall response can be assessed in the future and any unforeseen processes in the heat transfer mechanisms can be explained. In the experimental programme, specimens of different configurations are exposed to a radiant heat flux, emitted by a mixture of propane gas and air ignited at the surface of a radiant panel, while the reflected and transmitted heat flux as well as surface and interlayer temperatures are measured. The paper also includes a description of the heat transfer model and a comparison of the measured temperatures from the tests with the calculated temperatures from the model.

2. Materials

2.1. Test programme

The test programme is comprised of monolithic specimens in different configurations (glass panes with thickness of 6, 10 or 15 mm, of which some specimens were treated with a pyrolytic low-emissivity surface coating) and LG specimens with different layups of laminate (6 mm and 10 mm thick glass panes laminated with either PolyVinyl Butyral (PVB) or SentryGlas (SG) interlayers), as summarised in Table 1. Each of the laminated glass specimens had a welded 0.5 mm type K thermocouple (TC) inserted in the interlayers during the manufacture of the specimens, as depicted in Fig. 1(c).

Additionally, several specimens were subjected to a simplified test procedure that allowed for the determination of only the transmittance.

2.2. Preparation of the specimens

Prior to testing, all samples were cleaned using a combination of water and an alcohol-based cleaning agent, Fig. 1(a).

The thermocouples located in the interlayers were shielded from direct heating by transmitted radiation by fixing small pieces of aluminium tape (thickness 70 μm) with a surface area of approximately 1 cm^2 on the exposed surface between the thermocouples and the radiant panel, as illustrated in Fig. 1(b). As these thermocouples were installed during the lamination of the specimens, their position could be fixed with only limited accuracy; however since the view factor from the radiant panel to the specimen was large and the thermocouples were attached within the central third of the specimen, the influence of these minor differences in position on the results of the tests is negligible.

To measure surface temperatures, additional thermocouples of 0.5 mm diameter were fixed to the surfaces of each specimen: one thermocouple was fixed to the exposed surface and two thermocouples were fixed to the back surface, as illustrated in Fig. 2(a, b). Similar to the thermocouples in the interlayer, the surface mounted thermocouples were positioned in the central 3rd of the specimen's surface to minimize the influence of heat losses at the edges of the specimens (which would lead to cooler edges) on the surface temperature measurement. The vertical positioning of the thermocouples was chosen to avoid shading of a heat flux gauge to be positioned centrally behind the glass specimen (described later) by the aluminium tape used to fix the thermocouples. To avoid direct heating of the thermocouples by radiative heat transfer, the thermocouples on the exposed surface were also shielded using small pieces of aluminium tape which also served to fix the thermocouples to the surface. Such a piece of aluminium tape was sized to cover the stripped wire part of the thermocouple, while maintaining a minimal surface area to prevent occurrence of a cold spot. The thermocouples on the back surface were fixed in a similar way as the thermocouples on the exposed surface, and a piece of aluminium tape was also applied on the exposed surface directly between these thermocouples and the radiant panel to shield then from direct radiation, as shown in Fig. 1(c). Two thermocouples were fixed on the back surface: one shielded by a small piece of aluminium tape, and one shielded by a larger piece of aluminium tape. The thermocouple shielded by a small piece of aluminium tape may still be heated directly by refracted radiation; however, the larger piece of aluminium tape may create a cold spot that causes an incorrect measurement of the surface temperature.