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Performance of Structural Glass during Fire

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ABSTRACT: Glass has become an important ingredient in today's architecture with the wants of making buildings increasingly transparent. It is critical that the effect of fire on the glass structure is understood. Now, since glass is often used as a structural element, the resistance to fire load is imperative. This paper will highlight current industry standards for fire resistant glazing and the range of products and systems available. Current products available in the market would be reviewed and possible modifications to increase transparency of the system will be attained. Glass performance for various fire resistance classes will be discussed in detail. The potential for using FEA to investigate glass performance during fire load will be considered and numerical results will be compared with experimental results for the fire test of a simple glass component.

1 INTRODUCTION

The idea of implementing precautions against the effects of fire in buildings is not new. As knowledge increases over the years so has sophistication of precautions against fire. In current regulations, the requirement for structural stability states that structure should remain stable for reasonable period.

Fire resistant classes depend on building zone and specification. Fire safety engineering can provide an alternative approach to the code prescriptive measurements, especially in case of complex buildings or novel structural materials.

It is generally considered by fire consultants that *"normal glazing will fail in very early stages of fire where glass is required to resist the effects of fire, the glass units should either be assembled from specially toughened glass or wired glass is used"* Purkiss (2007)

It is the author's opinion that the extent to which structural glass systems are developed and is limited by their capability to resist fire.

2 THEORETICAL BACKGROUNDS

Structural fire engineering design requires a firm understanding of number of phenomena
- Fire behaviour
- Thermal response of member or system when subjected to fire
- Structural response of member or system when subjected to fire
- Behaviour of mitigation or suppression systems and their effect on structural element

2.1 *Fire behaviour*

The standard fire curves as presented in figure 1, are the simplest way to represent the behaviour of a fire within a design approach. The standard temperature –time relationships were developed to allow classification of building materials and elements in standard fire resistance furnace tests. Those curves do not represent real fire scenarios, as they do not take into account ventilation, fire load, compartment size or thermal characteristics of materials in the compartment.

The factors influencing the severity of fire are:

- Fire load type, density and distribution
- Combustion behaviour of the fire load
- Compartment size and geometry
- Ventilation conditions
- Thermal properties

The occurrence of flashover defines a transition in the fire development process, many fire models are classified as pre or post flashover models. Computational fluid dynamic models can model all stages of the fire.

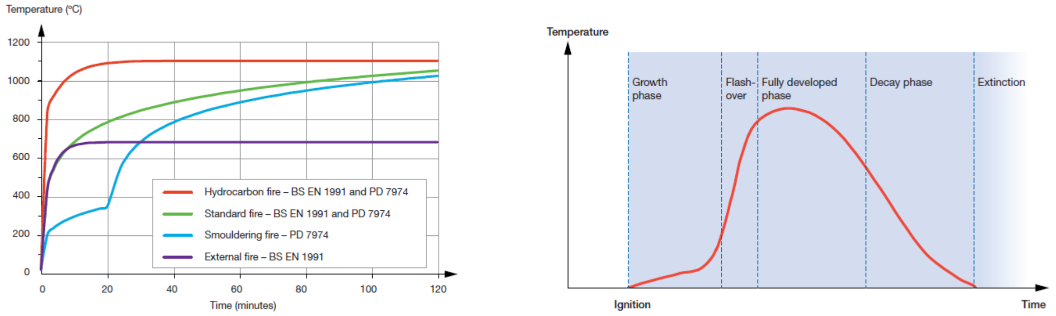


Figure 1a.) Standard fire curves, b.) Real fire stages

2.2 *Thermal response of member or system when subjected to fire*

The temperature distribution through a structural member is dependent on the radiation and convective heat transfer coefficients at the member's surface and conduction of heat within the member. For materials with a high thermal conductivity such as steel, it may be sufficiently accurate to ignore thermal gradients within members and assume a uniform temperature. Estimating the heat transfer in materials with low thermal conductivity and/or high moisture content, such as concrete and masonry becomes extremely complex due to the high thermal gradients.

Heat transfer is the method to evaluate the energy transfer that takes place between material bodies as a result of a temperature difference. The three modes of heat transfer are conduction, convection and radiation. The thermal analysis can be divided into two parts:

1. The transfer of heat by convection and radiation across the boundary from a fire to a member.
2. The transfer of heat by conduction within a member.

Behaviour of typical construction materials and glass when exposed to the temperature load are stated below.

- Steel

An empirical calculation method to estimate the temperature response of the bare steel is presented in codes and design guides. The method is based on a lumped mass model where it is assumed that the temperature is uniform with the cross-section.

- Concrete

Due to low thermal conductivity, high thermal gradients will occur through concrete members, which together with the effects of the mass transport of water or water vapour, makes estimating the temperature distribution through the members very difficult. Ignoring the effects of moisture will result in a conservative estimate of temperature, providing spalling does not occur. Annex A of BS EN 1992-1-2 gives a temperature distribution based on standard fire curve.

– Glass

Glass is created at high temperature and will return to liquid form if heated sufficiently. Glass products made for fire protection are enhanced with the addition of substrates, laminates and other technologies to maintain rigidity at high temperature. The most common temperature challenge in glass is not ‘high temperature’ but ‘thermal endurance’. Normal 6mm-thick float glass will rupture if heated to 75 °C and plunged into 20 °C water (a temperature differential of 55 °C).This is known as thermal shock. For this reason, many glass products are toughened. Toughened float glass can resist temperature differential of around 250-300 °C.

To further increase resistance of glass to thermal shock manipulation in chemistry is required. Borosilicate glass and metallic glasses have been researched in the past with positive applications across various fields of engineering.

Other temperature properties of standard float glass:

- Thermal conductivity – (K value) 1.05W/m °C.
- Softening point – 737 °C.
- Annealing range – 480°C to 560 °C.
- Strain point – 523°C.
- Mean specific heat – 1162 J/kg °C (25 °C to 850 °C).
- Coefficient of linear thermal expansion – 88 x 10-7/ °C (lower than most metals).

2.3 *Structural response of member or system when subjected to fire*

The simplest method for predicting the structural behaviour of buildings in fire is to analyse individual members at the fire limit state using partial load and material safety factors, which take into account realistic loads at the time of fire and actual material strengths. These methods take into account the reduction in strength and stiffness of materials during a fire.

All materials lose strength and stiffness at elevated temperature. The material properties – temperature relationship for the common construction materials, such as steel is provided by the relevant design codes, which can be used for advanced analysis.

Qi et al (2006) presents the degradation of the stiffness (Young’s modulus) of glass at different temperatures.

The basic responses of structures are:

1. Thermal expansion and thermal curvature

All materials will expand, to some extent, when heated. If a non-uniform temperature distribution forms through the section, thermal curvature will occur with the element generally deflecting towards the heat source. Any resistance to the free movement of axial thermal expansion or thermal curvature will induce internal stresses within the member. In addition, due to assuming plane sections remain plane, any non-linear temperature distribution through an element will induce internal thermal stresses.

2. Creep and transient strains
3. Spalling, which is for concrete, timber.
4. Cracking

Here, an important distinction needs to be made as glass differs from other materials. When a window pane of ordinary float glass is first heated, it tends to crack when the glass reaches a temperature of about 150 – 200 °C with gradient between exposed and shielded areas up to 80 °C. Tempered glass was studied by Xie et al. (2007) and depending on thickness, the thermal gradient needed to shatter glass was reported as being up to 590 °C. The first crack usually initiates from the glass edge, this is primarily due to initial flaws from the processing of the glass sheet. Rounding and polishing glass edges will decrease the probability of breakage to some extent.

“In terms of external fires, at a heat flux of 9 kW m^{-2} some experimental results on ordinary glass showed the possibility of fallout, but the probability of fallout does not become high until about 35 kW m^{-2} is reached. Double-glazed windows can resist approximately 25 kW m^{-2} without fall-out. Tempered glass is able to resist fluxes of 43 kW m^{-2}, at least under some conditions.” Babrauskas (2008)

3 REGULATIONS

EN 13501-2 defines the following classes of fire resistance:

3.1 *E - Integrity*

Integrity E is the ability of the element of construction to eliminate the transmission of fire to the unexposed side by restricting the passage of flames. However, this does not stop radiant heat and as a result of which an auto ignition of materials close to the unexposed face may take place. As there is no insulation requirement, the temperature on the non fire side can reach the same as that of the fire side.

3.2 *I - Thermal insulation*

Thermal insulation I is the ability of the element of construction to limit the transmission of heat from the fire side to the non-fire side. It restricts the conduction of heat (I) and radiation (W) whilst providing integrity (E). A mean temperature of 140 °C shall not be exceeded close to the surface of glass and at no point shall the ambient temperature exceed 180°C.

3.3 *W - Radiation*

Radiation W is the ability of the element of construction to restrict radiant heat from fire to non fire side. Maximum heat radiation 1m away from the glass shall be less than 15 kW/m^2 .All elements that have fire resistance classification of I, by default satisfy the W requirement for the same period. For instance, an element with fire rating of EI 30 will perform for integrity, radiation and insulation. However, elements where radiation is significant and insulation is not significant then, the fire rating of EW may be chosen. For e.g. in case of pool fire where radiant heat is significant.

4 REVIEW OF CURRENT PRODUCTS

4.1 *Market study*

Places where glass is usually used as a fire resistant barrier are partition walls inside offices, escape routes, fire doors and outer/inner facades. There are numerous products available in the market that provides fire resistance at different fire classes. The most common are listed below:

- Standard wired glass
- Float glass with Low E coating
- Borosilicate glass
- Ceramic glass
- Laminated glass consisting of intumescent interlayer
- Laminated glass consisting of intumescent gel

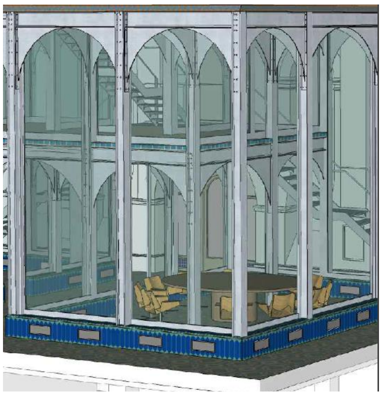
From the wide range of products available in the market for EI fire resistance, it would not be wrong to say that most of them have a very similar build up. The intumescent interlayers normally range between the thickness of 1mm - 1.65mm and are generally UV unstable and therefore when used externally, this glass is laminated with a PVB/similar interlayer to block UV. The interlayers are heat sensitive and start to react at around 80°C - 100°C, however this may vary from product to product. A product offered by Vetrotech uses a different technology, which is effectively an intumescent gel rather than an interlayer, although the gel is thicker than typical intumescent interlayers, it is UV stable. Considering the products available in the market that use intumescent interlayers, we found from our preliminary desk study and product literature that AGC Pyrobel glass interlayer has structural properties, that means the laminated glass panel performs compositely under static short term loading (wind, barrier load). However, in fire the intumescent interlayer restricts the heat flow from fireside to non-fireside.

In regards to EW products, there are products on the market that have a Low E coating to reflect back/disrupt radiation from the fire to non-fire side for example, Vetroflam glass by Vetrotech, which used different composition of glass during the float process, is then tempered and also has a Low E pyrolytic coating added to it. Such products are useful where radiation is the main concern and not the conduction. A study performed by Csoke Koudijs (2012) concluded that if Low E coating and a certain glass build-up of IGU was used, it was possible to get a very impressive performance under fire. They were able to reduce the radiation of 41 kW/m2 from fire side to 2 kW/m2 on the non fire side using an IGU incorporating a Low- E coating.

4.2 *Project related difficulties*

The need to study and research the topic of fire resistant glazing arose whilst working on a new international airport project. Firstly, we understood the principles of fire resistance and quickly realized that it is not only the glass but also the frame system along with other assemblies associated with it that must be considered in conjunction. The glass beading material, sealing material, their thicknesses and fixings are all equally significant in resisting fire. With most design firms/architects, there is a desire to make the frame obsolete in order to have as much clear area as possible. Unfortunately, such systems are not standard in the market and developing a bespoke system could be expensive and have considerable impact on the project schedule.

In another project, the architect envisaged jumbo glass panels without intermediate transoms. Currently it is not possible to manufacture such large-scale fire resistant glazing, consequently it has been necessary to reduce the panel size and introduce an intermediate transom as presented in Figures 2a b.



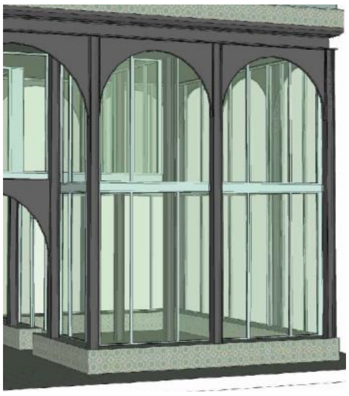


Figure 2 a)Architectural intension (left), b) standard fire resistant glazing system with intermediate transom (right).

There are three different factors which limit the dimension of fire resistant glass panel:

a) maximum panel size that the company can fabricate depending on their machinery capability

b) maximum tested panel size under a certified butt joint glazing system

c) maximum tested panel size under a certified fully framed system.

These limiting dimensions are specified for the orientation of the panels, a rectangular panel of certain dimension may be certified in a portrait orientation but not in landscape orientation. Further to this, it may be necessary to carry out a project specific assessment of the design. Therefore an understanding of what can be achieved without going through a testing route is not very well labelled and requires a fair amount of study and past experience.

5 FE MODELLING

Fire tests on structures are generally expensive and have a significant impact on project schedule. Development of accurate prediction methods to simulate and verify the behaviour of structures in fire is a prime research topic of many academics. The starting point of FEA simulations is usually to mimic the standard fire resistance test on an isolated structural component. The results of those simulations can provide vital information about performance and ultimate load capacity of structural members as well as verify numerical models. More advanced analysis of complete structural systems is the next step, where interaction between components can be considered accordingly. Many researchers due to its versatility prefer the finite element approach.

Commercially available structural software usually have an option to modify the mechanical properties of examined materials at elevated temperatures as well as to perform transient heat transfer analysis to obtain the temperature distribution within a member exposed to a thermal load. The behaviour of structure in fire is non-trivial; it is linked with material and geometrical non-linearity. Software should have the capability to simulate this complex behaviour sufficiently accurate with advance tools to tackle solver convergence difficulties.

The modelling procedure is to input all data required to represent the structure geometry, boundary conditions, induced actions and material properties. A pre-fire structural analysis should be performed to acquire information about the performance of structure in service temperatures. Subsequently, transient heat analysis is carried out to obtain the temperature distribution in time and space. Afterwards nonlinear transient analysis is deployed to obtain information about structural performance of the element (stress, displacements)

Analysing structural glass is notoriously difficult, due to its stochastic nature and brittle failure. Advanced probabilistic methods could be applied to express the required outputs in a non-deterministic way.

An added difficulty in fire analysis is the complex behaviour of materials at elevated temperatures as well as thermal cracking. Developed tensile stresses due to the high expansion coefficient could exceed glass strength; hence, numerical model should incorporate this. Further information can be found in published literature Parry (2009) and Hietaniemi (2005).

Glass significantly softens around 550 °C (transition temperature) where it changes from a solid to a viscous liquid state. Change between storage and loss modulus will dictate performance of the glass. A material exhibits a smooth change in the thermal expansion coefficient, conductivity and specific heat. Special care shall be given to polymer interlayers, as the transition and melting temperatures of these are lower than that of glass. These parameters are necessary to carry out coupled structural - thermal analysis.

Some examples of thermal calculations for glass applications, which can be carried out using FE software, are illustrated in following figures. In Figures 3 a, b, c, the calculated temperature and heat flux across a multi-layered component is presented. The structural performance of a simply supported beam 1m long subjected to fire is presented in Figure 3d where loss of integrity occurred in the eighth minute.

Identifying, real behaviour of a glass component by methods of numerical analysis is a complex and challenging task. Simplifications and limitations should be known prior to commencing any advance analyses.

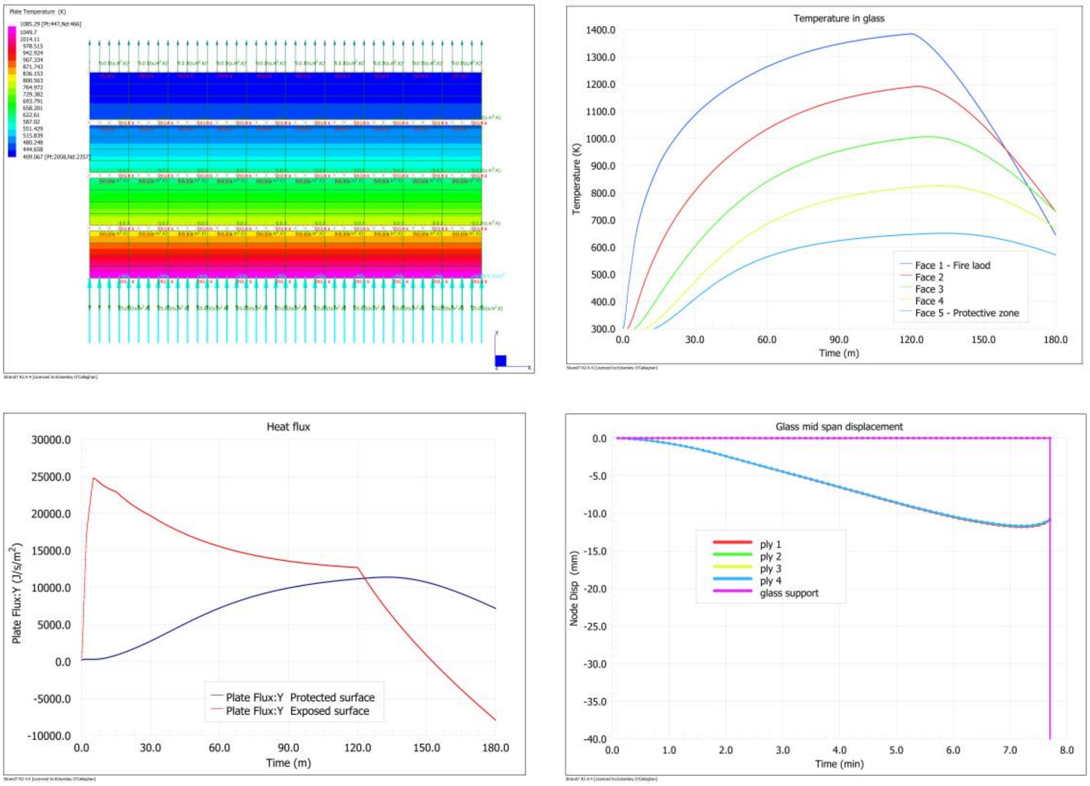


Figure 3 a, temperature plot at 30 min, b. temperature vs. time, c. heat flux vs. time, d. deflection vs. time

6 GLASS TEST

As discussed in the previous chapter, numerical modelling of glass structures in fire is challenging and further research is required to capture the behaviour of real structures. Hence expensive full-scale tests are usually relied upon, to validate the fire resistance of component prototypes, non-conventional materials or structural systems.

Test results of a multi laminated glass component are presented in the Figures 4a,b. From the results, it is clear that the chosen glass composition and support condition has a very limited fire resistance. After temperature in the furnace reached around 600 °C, complete loss of integrity occurred suddenly. In Figures 5a,b the glass component before and after the test is presented. It should be noted that the test procedure differed from a typical fire protection test, as the glass component was exposed to the heat flux in all directions. Free standing self-supporting structures within one fire compartment could be exposed to such conditions.

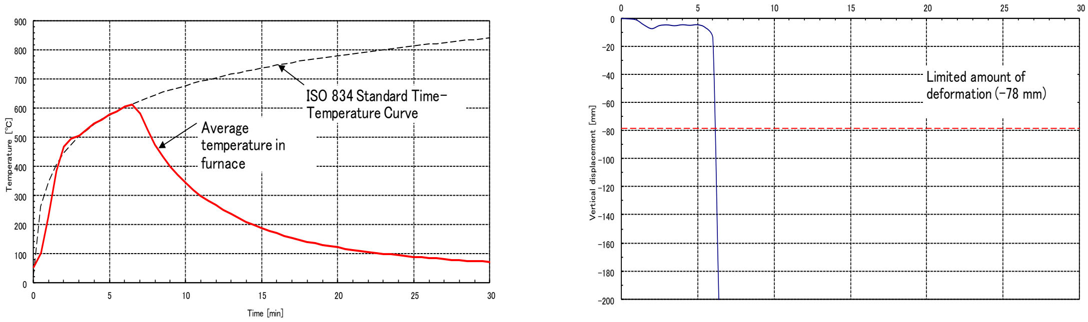


Figure 4 a) Measurement of temperature in furnace, b) Time-vertical displacement relationship

Figure 5 a) Glass component before and b) after fire resistance test

7 CONCLUSION

The performance of structures in fire is complex and solid theoretical knowledge is required to understand the problem, especially if components are made from structural glass. Complex behaviour of glass in fire brings challenges for designers and numerous research topics for academics. It is a beneficial for industry to recognise above challenges, so ideas are interchanged and subsequently new products can emerge on the market. In the current competitive environment, architects and engineers are looking to add significant visual statements to distinguish their designs from others. This is very difficult to achieve with off shelf products, while developing bespoke solution can significantly increase cost and prolong project schedule. The difficulty to capture behaviour of glass components in fire by numerical analysis usually results in expensive fire resistance tests. External mitigation techniques to increase fire resistance were omitted from this paper and the current state of art should be investigated by authors in the future.

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