Kingston University London

THERMAL AND STRESS ANALYSIS OF GLAZING SYSTEMS UNDER FIRE CONDITIONS

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1. INTRODUCTION

The cracking and subsequent fallout of glazing could significantly affect the dynamics of fires in compartments. The sudden venting resulting from the fallout of a window glass may result in backdraft or flashover depending on the development stage of the fire. The need for research on glazing behaviour in fires was first identified by Emmons [1]. There are two main physical processes involved when a glass pane is subjected to fire in a compartment: (i) heat transfer from the fire source and combustion gases to the glass and (ii) mechanical stress distribution and glass fracture. Pagni [2] suggested a glass breaking criterion based on the glass temperature rise, and subsequently developed a theoretical model for heat transfer and glass breakage which was implemented in the Break1 code [3]. Existing heat transfer models for glazing applications have been reviewed by Cuzzillo and Pagni [4]. The simplest heat transfer model treats the glass as a lumped mass and uses constant heat transfer coefficient. Another approach treats the glass as a distributed mass that absorbs radiation through its thickness with non-linear radiative boundary conditions [4]. Sincaglia and Barnett [5] developed a glass fracture model with emphasis on radiation wavelength dependence; this approach was implemented in the zone type BRANZFire computer code by Parry et al. [6]. All these studies were mainly concerned with heat transfer modelling, prediction of the time to first crack occurrence and the temperature distribution in the glass pane. However they did not provide more detailed information on the stress distribution in the glass which may be useful for a better understanding of the breakage mechanism.

Some experimental studies were conducted to understand the behaviour of glazing in fires. Among others, Skelly et al. [7] tested the behaviour of framed and unframed glass panes exposed to compartment fires by measuring temperatures and the time of first crack. Harada et al. [8] also measured the time to first crack occurrence for glass panes subjected to different radiant heat fluxes. Experiments were conducted on large glass panes exposed to wood cribs fires in a compartment by Shields et al. [9]. These experimental data have provided valuable information for models validations.

In more recent studies, attempts have been made to predict the window glass fallout in compartment fires. Pope and Bailey [10] developed a Gaussian glass breakage model that was implemented in the CFD code Fire Dynamics Simulator (FDS) developed at the National Institute of Standards and Technology (NIST) [11]. In simulations, the breaking temperature of a glass pane is selected from the results of a Gaussian distribution where the average breaking temperature and standard deviation are user-defined quantities. Once any point on the pane reaches its pre-defined breaking temperature, the pane is removed (fallout) [10]. Hietaniemi [12] proposed a probabilistic approach to predict glass fallout. The time and glass temperature at the first occurrence of a crack was modeled using Break1 [3] and Pagni's

criterion, together with a Monte Carlo method to account for the probabilistic nature of parameters such as thermal and mechanical properties of the glass. The glass fallout criterion is based in [12] on a prescribed number of successive breakages obtained from literature experimental data. Hietaniemi's approach for fallout prediction was employed by Kang [13] using FDS [11], Break1 [3] and Pagni's breakage criterion. The entire glass pane is removed (fallout) when the number of glass breakages exceeds typically three [13].
Although these recent studies [10, 12, 13] to predict fallout have their own merits they seem to be more computer based and too simplistic, more research is needed to validate them and provide a more robust theoretical justification of the physics of fallout they are employing. Fallout prediction is beyond the scope of the present study. However, the probabilistic nature of the glass breakage mentioned in [10, 12] that has been little researched should clearly be accounted for in models. Glass panes produced from the same batch may have different mechanical properties because the edge conditions after cutting would not be exactly the same. These differences in the properties of the glass pane resulting from the manufacturing, which is of statistical or probabilistic nature, would be reflected in the actual breakage characteristic of the glass.

In previous studies, the present authors have developed an accurate and advanced radiation heat transfer model, based on the Spectral Discrete Ordinates Method (SDOM) which addressed some deficiencies of literature models [14, 15, 16]. The model is spectral, accounts for the diffuse nature of the radiation incident on the glass pane and provides a better handling of the boundary conditions. Validation studies of the one-dimensional (1D-SDOM) radiation model have been presented in terms of temperature distribution in the glass and the time to first crack occurrence [14, 15]. In order to simulate the dynamic interaction between the fire and the glass pane, the spectral radiation model was implemented into FDS [11]. Validation and application results of the coupled tool, referred to as FDS-SDOM, were presented in [16]. The glass breakage criterion employed in nearly all studies [2-6, 14-16] is based on Pagni's criterion [2] which states that glass fracture occurs when the temperature increase in an exposed portion of the glass is sufficient to induce a pre-determined failure stress in the shaded edge: $\Delta T \geq (1 + s/H)\frac{\sigma_{max}}{E \cdot \beta}$.
However this criterion has some limitations: (i) it was developed for a uniform exposure of the glass pane to fire, which is not the case for many real fire scenarios and (ii) it does not account for some real physical parameters of the glass such as the edge conditions (probabilistic nature) which could strongly influence fracture time.

To address these limitations, a 3D stress and conduction model, and a failure probability model have been developed by the present authors and coupled with the previous tool FDS-SDOM. The overall aim is to predict the thermal and stress behaviour of the glazing assembly (glass pane and frame) subjected to typical fire conditions, and also the time for crack occurrence in the glass pane based on a probabilistic approach.

2. MATHEMATICAL MODELLING

The modelling approach employed for thermal and stress analysis, and the time of first crack occurrence in the glass pane is comprised of the following sub-models: a heat transfer and spectral radiation model, a thermal stress model and a probability of failure model for glass breakage. For some verification scenarios, these sub-models have been implemented into the CFD code FDS. Only brief descriptions of sub-models are provided here.

2.1 Heat Transfer Model

2.1.1 Energy equation and boundary conditions for heat transfer

For a compartment fire, the temperature distribution in a glass window is determined from the transient energy equation for a differential element of glass. In 3D Cartesian geometry, this equation is expressed as:

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \dot{q}_{rad} \qquad [1]$$

The first three terms on the right-hand side (RHS) of Eq.(1) represent the conductive heat flux in the glass determined by Fourier's Law. The local total radiative source term, $\dot{q}_{rad}$, also called the divergence of the radiative heat flux arises from the absorption and emission of thermal radiation by the medium.

Boundary conditions are needed to solve Eq. (1).

On the surface of the glass pane exposed to fire (x=0):

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=0} = h_f\left(T_f - T_{gf}\right) + \int_0^\infty \alpha_\lambda \cdot q_{\lambda,f} d\lambda - \int_0^\infty \varepsilon_{\lambda,g} \cdot I_{b,\lambda}(T_{gf})\pi d\lambda \qquad [2]$$

On the surface of the glass pane exposed to ambient (x=L):

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=L} = h_\infty\left(T_{g\infty} - T_\infty\right) + \int_0^\infty \varepsilon_{\lambda,g} \cdot I_{b,\lambda}(T_{g\infty})\pi d\lambda - \int_0^\infty \alpha_\lambda \cdot q_{\lambda,\infty} d\lambda \qquad [3]$$

To determine the 3D temperature distribution in the glass, Eq.(1) is integrated over time using the finite difference method and over the volume with the finite-element approximation for the geometry. The local total radiative source term in the glass, $\dot{q}_{rad}$, is calculated from the spectral discrete ordinates method (SDOM) described below.

2.1.2 The spectral discrete ordinates radiation model (SDOM)

The absorption, emission and transmission of radiation in a glass pane are spectral phenomena which should be accounted for in calculations. The Spectral Radiative Transfer Equation (SRTE) in an absorbing and emitting, non scattering medium such as glass can be written as [17]:

$$\mu \frac{\partial I_\lambda}{\partial x} + \xi \frac{\partial I_\lambda}{\partial y} + \eta \frac{\partial I_\lambda}{\partial z} = K_{g\lambda}\left[I_{b\lambda} - I_\lambda\right] \qquad [4]$$

The Discrete Ordinates Method [18] is based on the separation of the angular dependence from the spatial dependence of the intensity in the SRTE. This is achieved by choosing a set of discrete directions spanning in the angular range of 4p. For each discrete direction, m, Eq.(4) becomes [18]:

$$\mu^m \frac{\partial I_\lambda^m}{\partial x} + \xi^m \frac{\partial I_\lambda^m}{\partial y} + \eta^m \frac{\partial I_\lambda^m}{\partial z} = K_{g\lambda}\left[I_{b\lambda} - I_\lambda^m\right] \qquad [5]$$

The following radiative boundary conditions are used to solve Eq. (5) at x=0 and x=L respectively [19]:

$$I_\lambda^m = \varepsilon_{\lambda g} I_{b\lambda}(T_{gf}) + 2(1 - \varepsilon_{\lambda g} - \tau_{\lambda g}) \sum_{m',\xi<0}^{N_d} \mu^{m'} |\xi^{m'}| I_\lambda^m (x = 0) \quad [6]$$

$$I_\lambda^m = \varepsilon_{\lambda g} I_{b\lambda}(T_{g\infty}) + 2(1 - \varepsilon_{\lambda g} - \tau_{\lambda g}) \sum_{m',\xi>0}^{N_d} \mu^{m'} |\xi^{m'}| I_\lambda^m (x = L) \quad [7]$$

The radiative boundary conditions at the others boundaries in y and z directions take a similar form. Eq.(5) is integrated over each control volume to determine the local intensity field I_λ^m. The total radiative source term, $\dot{q}_{rad}$, used in Eq.(1) is given by:

$$\dot{q}_{rad} = \sum_{all\ \lambda} K_{g\lambda} \left[4\pi I_{b\lambda} - \sum_{m=1}^{N_d} w^m \mu^m |\xi^m| I_\lambda^m \right] \quad [8]$$

2.2 Thermal Stress Model

The thermal stress model employed is an adaptation of the model in [20] which was modified by the authors and validated for thermal loads applied to glass. The reader may refer to [20] for more details. The solutions adopted to solve the thermal stress are the potential energy and the Galerkin approaches which are used to determine the global and element displacement vector, q.

The element stress, $\sigma = [\sigma_x, \sigma_y, \sigma_z, \tau_{yz}, \tau_{xz}, \tau_{xy}]^T$, and strain, $\varepsilon = [\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{yz}, \gamma_{xz}, \gamma_{xy}]^T$, vectors in the glass can be obtained from:

$$\sigma = D\varepsilon = DBq \text{ and } \varepsilon = Bq \quad [9]$$

where D is the material matrix and B a (6x12) matrix [19,20].

Once the temperature field is calculated from Eq.(1), if the glass temperature changes by DT(x,y,z), the thermal stress can be calculated by:

$$\sigma = D(\varepsilon - \varepsilon_0) \quad [10]$$

where $\varepsilon_0 = [\alpha\Delta T, \alpha\Delta T, \alpha\Delta T, 0, 0, 0]^T$

Principal stresses, strains or Von Mises stresses could be calculated with the method.

2.3 Glass breakage criterion

Glass fracture generally initiate at an edge defect resulting from the manufacturing process or when the glass is cut to size. When the glass pane is exposed to fire, breakage occurs when the thermally induced tensile stresses in the shaded area reach the tensile defect strength. The new approach proposed here to predict glass fracture is an improved alternative to existing methods such as Pagni's criterion. It involves a full failure probability analysis and is based on Weibull statistics.

2.3.1 Pagni's criterion

The Pagni's glass breakage criterion [2] relates the average temperature over the glass thickness with a correlation deduced from the Hook's law and the thermal coefficient of linear expansion:

$$\Delta T = \overline{T}_{exposed} - T_{framed\,edge} \geq (1 + s/H) \frac{\sigma_{max}}{E \cdot \beta} \quad [11]$$

This most widely used criterion assumes a uniform exposure of the glass pane to the fire. This is not the case for some compartment fires where the glass heating is non-uniform as it is exposed to both upper hot and lower cold gas layers [6]. Also some real physical parameters of the glass such as the edge conditions which could strongly influence fracture time are not accounted for. In the present work, the non-uniform heating effect is accounted for in the stress distribution model. The variability in the edge conditions are modelled with a probability of failure model.

2.3.2 Probability of failure model

The approach used for glass fracture was developed and validated at Pilkington [21]. It quantifies the probability of the glass material failure due to thermal and load stress. The method involves a full failure probability analysis and is based on Weibull statistics. It takes into account different types of glass and edges conditions (as-cut, grounded, and polish edge) and employs the principal stresses to predict the overall probability of failure (OPF) of the glass. The model was validated against a wide range of experimental data. The Weibull modulus values, which are different for each type of glass, were obtained from a compilation of experimental data, for each type of glass and edge finish [21].

3. CONCLUSIONS

A model was developed to predict spectral radiation and conduction heat transfer, thermal stress and strain, and the probability of failure of a glass pane in fire conditions. The approach could represent an alternative to Pagni's criterion in particular where non-uniform exposure of the glass pane is expected. It also provides a better understanding of the stress distribution prior to breakage. Numerical simulations have been carried out in order to verify the accuracy of the model. The temperature, stress and strain predicted agree reasonably well with the predictions of ANSYS. A relatively good agreement is also obtained between the model and experimental data for the time of first crack occurrence. The study shows the importance of accounting for spectral radiation and the probabilistic nature of glass failure. It could help in the development of a more rigorous approach for glass fallout prediction.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge Pilkington plc for their support of this research.

NOMENCLATURE

c	specific heat of glass *(J/kgK)*
E	Young's Modulus *(N/m²)* → (N/m^2)
H	glass pane half width *(m)*
h	convection heat transfer coefficient (W/m^2K)
I_λ	spectral radiation intensity $(W/m^2.Sr.mm)$
$K_{g\lambda}$	glass spectral absorption coefficient (m^{-1})
k	glass thermal conductivity *(W/mK)*
L	thickness of the glass pane *(m)*
N_d	number of discrete direction in *SDOM*

$\dot{q}_{rad}$	radiative source term *(W/m³)*
s	glass shaded edges width *(m)*
T	temperature *(K)*
t	time *(s)*
w^m	weight of direction m in SDOM
x	coordinate variable (m)
y	coordinate variable (m)
z	coordinate variable (m)

Greek symbols

α	absorptivity or coefficient of linear expansion
β	coefficient of thermal expansion *(1/K)*
D	difference
ε	emissivity or strain
λ	wavelength *(mm)*
m, x, h	direction cosines
ρ	density *(kg/m³)* or reflectivity
σ_{max}	maximum tensile stress *(N/m²)*
σ	stress (N/m²)
g	shear strain
τ	transmissivity, shear stress

Subscripts

b	blackbody
f	relative to the fire side
g	relative to the glass
gf	glass surface on fire side
g∞	glass surface on ambient side
∞	relative to ambient side
l	spectral

Superscripts

m	discrete direction in SDOM

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Table 1- Overall probability of failure (OPF) predicted with Model-FDS and experimental values of time to first crack for different incident heat fluxes.

Incident Heat Flux	Experimental data (time of first crack) [8]	50% OFP (Model-FDS)
5.840 kW/m^2	**207 s**	**203 s**
6.690 kW/m^2	**144 s**	**150 s**
9.110 kW/m^2	**90 s**	**98 s**