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Temperature and Thermal Stress Simulation of Window Glass Exposed to Fire

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Abstract

In a compartment fire environment, the high temperature encountered could induce important stresses in glass panes, resulting into cracks and possible fallout of the glazing. The aim of the present work is to investigate thermal stress distributions in a glazing system for fire scenarios. A two dimensional glass thermal stress model to calculate the transient temperature and thermal stress distributions in a typical window glass under fire conditions was developed based on the Kong's work. The basic thermal conduction equation and thermal stress equation for glass were discretized by using the Galerkin method. A computer program based on the model was also developed. For validation purposes, simulations have been carried out using literature experimental data on glazing behavior in an enclosure fire. The glass surface temperature (exposed side) and thermal stress distributions in the glass pane were calculated. The simulation results of the transient temperature and thermal stress are overall in line with the experimental data reported in literature. The major principal thermal stress distribution in the glass at the time of first crack is consistent with the experimental crack patterns. The calculated maximum stress is located at the top edge of the glass pane, as the first crack recorded by experiments. The model does not predict second or later cracks. These results illustrate the relatively good predictions and usefulness of the developed simulation code.

Keywords: fire dynamics simulator; glass; thermal stress; finite element method

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1. Introduction

Once a fire gets going, windows previously closed may crack and break out. The fire developmental results will often be drastically different, depending on whether the windows break or not. Thus, predicting the time of glazing fall-out, when part of the wall becomes a new vent, is essential to proper field modeling of compartment fires. The window pane crack is caused by the increasing stress of the glass, which is induced by the rising up temperature in the fire situation. Therefore, the calculation of the temperature distribution is the first step and then is the calculation of stress fields of the glass in fire.

The performance of glazing in fire has been tested on single and double pane glazing[1-4]. Keski-Rahkonen [5] first predicted that a temperature difference of about 80 °C based on his theoretical analysis of glass cracking in fires. Pagni et al [6] predicted 58°C as the temperature difference for crack initiation. Kelly et al[7] conducted a series of experiments in an unusual small-scale fire test room. Experiments in an ISO compartment at the FireSERT Centre of the University of Ulster have been performed and suggest that the glass remains in place until a crack is initiated on each of the four window edges[8]. Bifurcating cracks then propagate and join, isolating a large portion of the pane from its support.

Although some experimental works were done and reliable results were got, however, the tests are limited for theirs expensive and materials consuming. Computer simulations were less reported comparing with the experimental works[9]. Herein, the finite element method is employed to calculate the temperature distribution on the glass in fire, and then the thermal stress distribution is calculated based on the temperature distribution.

2. Two-dimensional simulation for glass exposed to fire

2.1. Simulation method of two-dimensional analysis

Finite element method (FEM) is a potential tool to quantify the thermal stress in the solid materials, and therefore, it was taken to analysis the thermal stress of glass in fire. For the glass plane, the thickness is much smaller in size than the length and width directions, and then two dimensional FEM was taken here. First, the temperature of the glass is calculated and then the thermal stress was calculated based on the temperature result.

The basic thermal conduction differential equation for the 2D solid is[10]:

$$D[T(x,y,t)] = \kappa(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) + q_v - \rho c \frac{\partial T}{\partial t} = 0$$

Where the D is the integral region, T is the temperature, t is the time, κ is the thermal conductivity, q_v is the inner heat flux, ρ is the density and c is the specific heat capacity. By using the Galekin method, the above equation is change to the following equation for further calculation in finite element method.

$$\frac{\partial J^D}{\partial T_l} = \iint_D [(\frac{\partial W_l}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y}\frac{\partial T}{\partial y}) - q_v W_l + \rho c W_l \frac{\partial T}{\partial t}]\mathrm{d}x\mathrm{d}y - \oint_\Gamma \kappa W_l \frac{\partial T}{\partial n}\mathrm{d}s \quad (l = 1,2,\cdots,n)$$

Where J is functional, W is weight function of weighted residual method. For the 2D thermal stress, the basic equation is given as following:

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x} + \dfrac{\partial \tau_{yx}}{\partial y} + X = \rho \dfrac{\partial^2 u}{\partial t^2} \\ \dfrac{\partial \sigma_y}{\partial y} + \dfrac{\partial \tau_{xy}}{\partial x} + Y = \rho \dfrac{\partial^2 v}{\partial t^2} \end{cases}$$

Where the σ_x and σ_y are the x and y direction normal stress, τ_{yx} and τ_{xy} are the shear stress, X and Y are the body forces in x and y direction, u and v are the displacements in x and y direction. For the thermal stress calculation, the displacement method is used to calculate the displacement, and then to calculate the thermal strain and then the thermal stress. Similar with the temperature variation, by using the Galerkin method, the displacement equation is got as following.

$$\iint_D W_l[\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + X - \rho \frac{\partial^2 u}{\partial t^2}]\mathrm{d}x\mathrm{d}y = 0 \quad (l = 1,2,\cdots,n)$$

$$\iint_D W_l[\frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + Y - \rho \frac{\partial^2 v}{\partial t^2}]\mathrm{d}x\mathrm{d}y = 0 \quad (l = 1,2,\cdots,n)$$

2.2. Numerical conditions

Here we verified the FEM program by comparing the calculated results with the experimental results got from the Shields's publication[4]. The numerical conditions are set to the same with the experiments, and the details are described as following.

As described in Shields's publication[4], the fire compartment is 1.7 m high, 1.5 m wide, and 1.6 m length. The vent was 1240 mm high × 120 mm wide. The wood crib measured approximately 500 mm× 500 mm ×500 mm and was arranged in an eight 30 mm ×30 mm stick high stack with 30 mm spacing. The total mass of the fuel was approximately 19.0 kg, and the cribs were located in the center or in a corner of the room. Two glass windows were set in the wall, the large one is 965 mm high × 787 mm wide, and the small one is 483 mm high × 787 mm wide with the 12.5 mm shaded wide. The glass used in the experiments was 6 mm thick ordinary float glass. The gas temperature profiles within the room and the shades and exposed glass surface temperature were measured using type K sheathed thermocouples. Three thermocouples on the glass surface and three thermocouples in the shaded region located in bottom, middle and top, respectively.

Fire Dynamics Simulator (FDS) version 5.0 was used to simulate the above test. By comparing the gas temperature got from the FDS with that got from experiments, the reliable FDS results were obtained, and then they were used as the input parameters for the calculation of glass temperature in the program of two dimension glass thermal stress (2DGTS).

When the glass exposed to the fire, the heat transfer from the fire to the glass is mainly contributed by heat radiation from the flame and heat convection from the hot gas layer. While the heat transfer inside the glass is confined by the three basic boundary conditions. The first boundary condition is that the boundary temperature is known, and the second is that the boundary heat flux is known, and the third is that the temperature of fluent substance and the heat transfer coefficient are known. Here, the glass surface exposed to the fire is under the effect of convection and radiation, and then the hot gas layer temperature and radiation flux were got from the FDS result.

To get the perfect result of the thermal stress distribution, the FDS results were compared with the experiment results. Fig.1 is the hot gas temperature plots before the glass surface at the same given point 2, 3 and 4, respectively. The locations of point 2, 3 and 4 are shown in Fig.1, which are located at the top, middle and bottom of the room, respectively. It can be seen that the simulated hot gas temperature are very near close the experimental result, and then they were used as the input data for the calculation of glass temperature and thermal stress. At the same time, the radiative heat fluxes also were detected in the FDS simulation for the calculation.

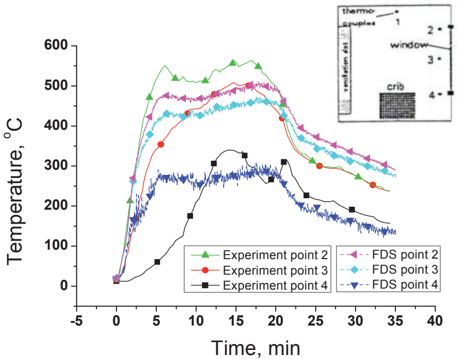


Fig.1 Gas temperature comparison between experiment and FDS at same given points

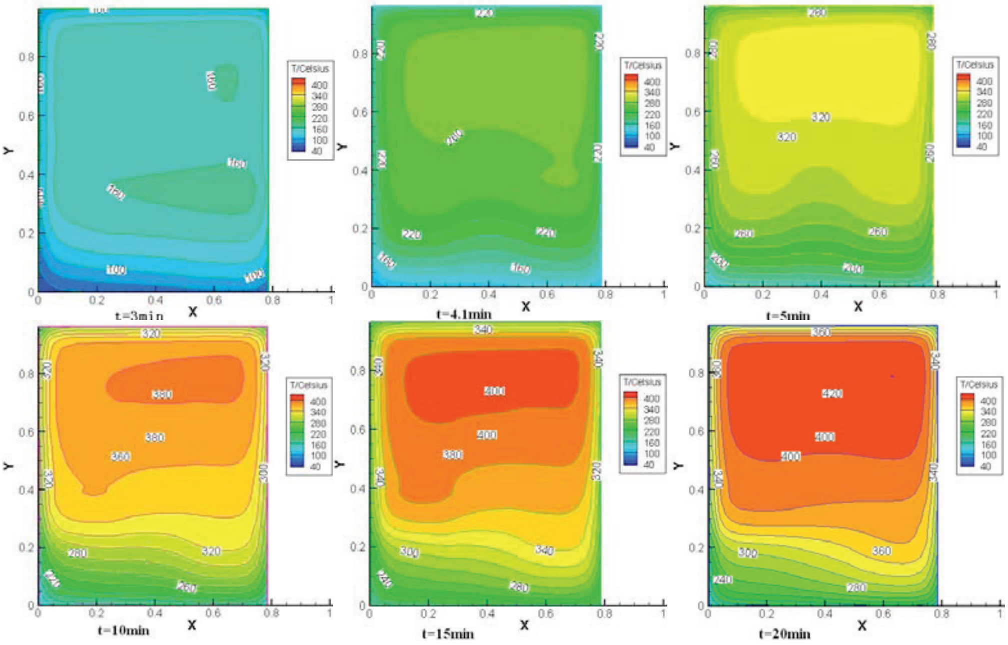
Triangle mesh was taken in the finite element calculation, 3564 nodes and 6890 elements were created and ordered in the 965 mm high × 787 mm wide glass pane. The original temperature of the glass is equal to the ambient temperature 25 °C. The glass specific heat capacity is 0.88 kJ $kg^{-1}K^{-1}$, density is 2530 kg m^{-3}, thermal conductivity is 0.937 W $m^{-1}K^{-1}$, Young's modulus is 8.0×10^{10} Pa, Poisson's ratio is 0.23 and the coefficient of linear thermal expansion is 8.0×10^{-6} K^{-1}.

As the glass is embedded into frame, in the perfect condition is fixed, however, in most case there are small gap between the glass and the frame, which means that the glass may be not fixed by the frame. As the displacement of the glass is very small even in fire condition, and then the free and fixed displacement conditions were compared in the calculation of thermal stress.

3. Simulation results and discussions

3.1. Temperature distribution

The no.1 experiment in Shields' publication [4] was simulated by using FDS with the same conditions, and the hot gas layer on the glass surface and radiative heat flux were taken as the input data for the calculation of glass temperature. Total 5×7 points were input and then interpolated to the whole glass pane in the 2DGTS program. Fig.2 shows the temperature history of the large glass pane. From the ambient temperature, the glass temperature increasing with the fire growing, at the 4.1 minute the glass temperature in the center reaches 260 °C. The first crack was reported at 4.1 minute in the experiment. And then, the second crack was reported at 5 minute with the maximum temperature of 320 °C. The highest temperature can reach to more than 420 °C at 20 minute. The temperature history at the given points 2, 3, and 4 got from the simulation were compared with the experimental results as shown in Fig.3. It can be seen that the simulated results are much similar each other in trend than the experimental results, however, the temperatures are very close. At the three locations, the simulated glass temperatures increase fast than the experimental results, which maybe caused by delay response of thermocouples on the glass surface. But at later, the experimental temperatures reach to the equivalent level with the simulated temperature.



t=3min t=4.1min t=5min
t=10min t=15min t=20min

Fig.2 Simulated large glass pane temperature distribution of experiment no.1 with free edges

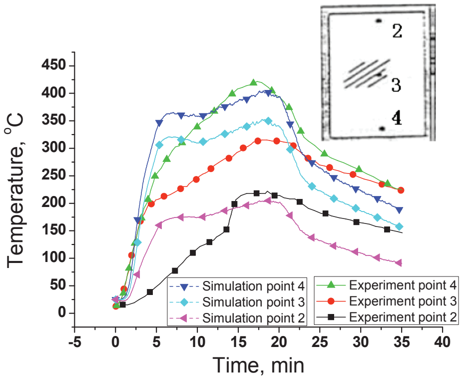


Fig.3 Glass temperature comparison of 2DGTS with experiment at exposed fire points

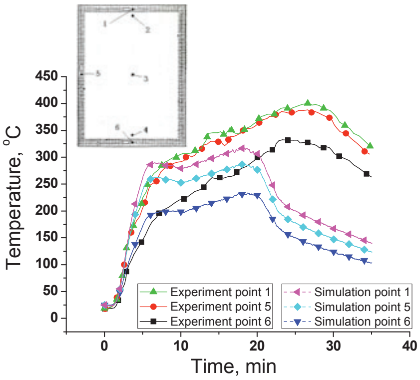


Fig.4 Glass temperature comparison of 2DGTS and experiment at shaded points

For the shaded edges, the temperature difference with the exposed area is thought as the main cause of the glass crack in fire. And then the temperatures also were detected in two methods as shown in Fig.4. The locations of point 1, 5 and 6 in XY plane are shown in Fig.2, corresponding to the top, left middle and bottom respectively. The similar results were found here compared with the exposed area, but one difference is that the experimental temperature decreased more slowly after reached to the peak temperature, it's because the frame blocked the heat release to the environment.

The temperature difference between the glass surface temperature and the shades edge temperature for the top edges of the glass is approximately 77 °C, which is near the Keski-Rahkonen prediction[5], temperature difference is about 80 °C. The above results indicated that the simulated result is close the experimental result, which can be used to simulate more fire scenario with glass window exposed the fire.

3.2. Thermal stress distribution

The thermal stress growing history was calculated based on the temperature distribution by FEM, the edges are free and the thermal stress in x direction is shown in Fig.5, and y direction shown in Fig.6. The experimental result was reported that the glass cracked at 4.1 minute and 5 minute twice, respectively. The thermal stress after crack was no longer displayed here, as the thermal stress will be rebuilt after the first crack.

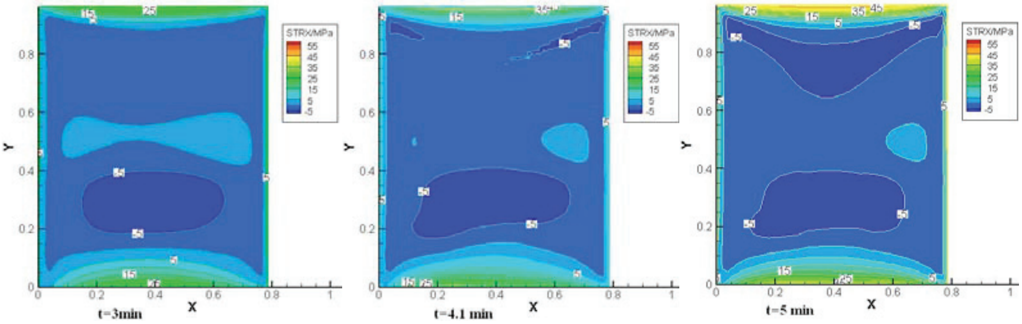


Fig.5 Simulated large glass pane thermal stress distribution of experiment no.1 in x direction under free edges

In the free edges, with the fire growing, the glass temperature rising up too, and then the thermal stress are building in the glass. From the Fig.5, it can be seen that the thermal stress in x direction increase more quickly in the top edge. At the 4.1 minute when the glass crack firstly, the tensile stress reaches to 35 MPa, at 5 minute later, the tensile stress reaches to 45 MPa at the top edge in x direction. As the glass edges are free, the glass near edges can expand when temperature increasing, and then it's under the effect of tensile stress. In the centre of the glass pane, the glass is constrained by the outer glass, and then with the temperature increasing, it is difficult to expand, and therefore it is under the effect of compressive effect. The compressive stress is just 5 MPa, which is small comparing it with the tensile stress in x direction.

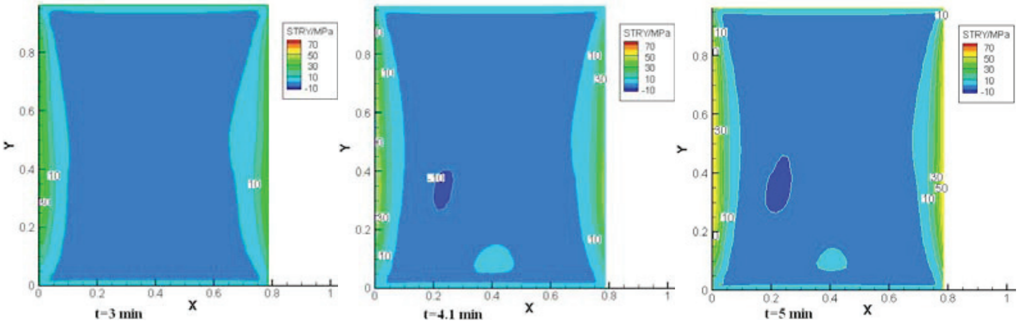


Fig.6 Simulated large glass pane thermal stress distribution of experiment no.1 in y direction under free edges

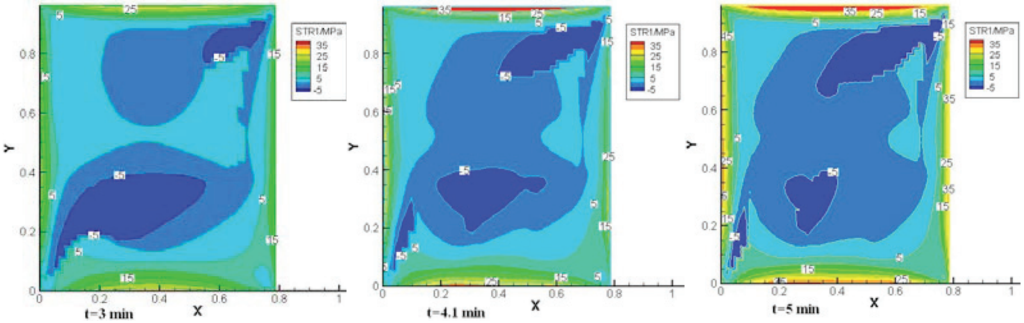


Fig.7 Simulated large glass pane major principal stress distribution of experiment no.1 with free edges

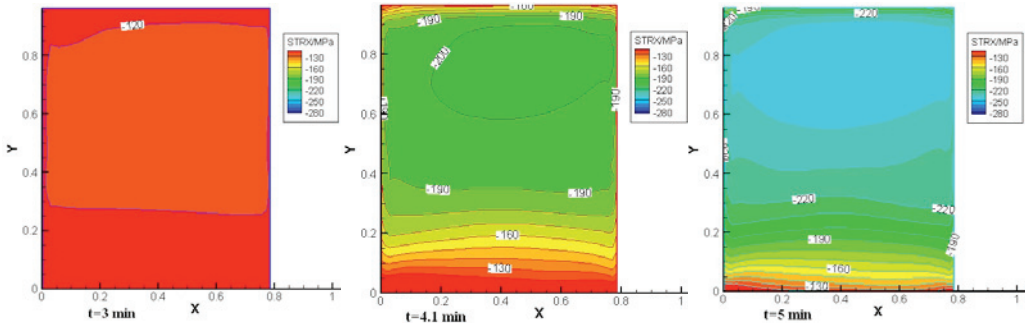


Fig.8 Simulated large glass pane thermal stress distribution of experiment no.1 in x direction under fixed edges

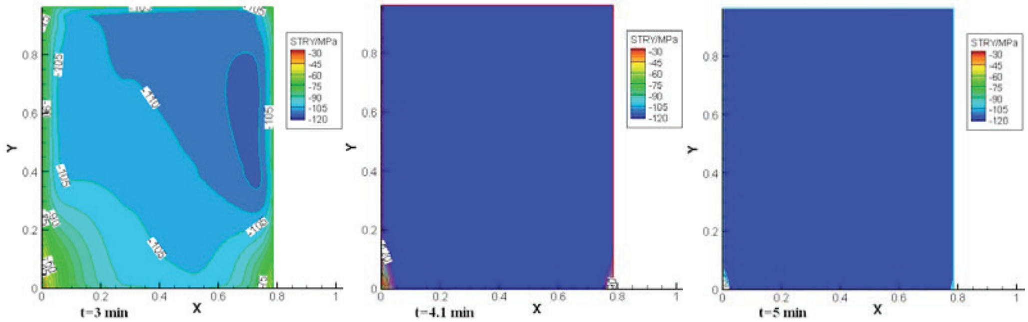


Fig.9 Simulated large glass pane thermal stress distribution of experiment no.1 in y direction under fixed edges

The thermal stress in y direction is displayed in Fig.6. Similar result was got in y direction, and the tensile stress can reaches 30 MPa, at 5 minute later, the tensile stress reaches to 50 MPa at the top edge in y direction. The compressive stress is just 10 MPa, which is small comparing it with the tensile stress in y direction.

The glass faults of different types are characteristics of the stress field in which they formed. The shear fracture makes an angle of less than 45 degrees with the major principal stress direction. The major principal stresses of the glass were shown in Fig.7 at 3, 4.1 and 5 minutes, respectively. It can be seen that the major principal stress developing to tensile stress in four edges and to compressive stress in the center of the glass. At the top right and bottom left corners of the glass, the principal stress changes greatly, which is easy to cause the crack of the glass.

Fig.8 shows the thermal stress in x direction developing process when the edges were fixed. The glass undergoes the compressive stress effect both in the edges and in the center. At 3 minute, the glass compressive stress in x direction reaches to 120 MPa, which is much higher than that of free edges at the corresponding time. At 4.1 minute, the stress built larger and larger, but the center is becoming larger than that of edges. To 5 minute, the center compressive stress even reaches to 240 MPa. In y direction, the thermal stress distribution is shown in Fig.9. It was shown that the compressive stress in y direction is smaller than that of in x direction. At 3 minute, the compressive stress express as a layer distribution with larger in center smaller in edges. When it developed to 4.1 and 5 minutes, the layer disappear and reach to a uniform distribution with the value of 120 MPa.

The major principal stress with edges fixed was shown in Fig.10, it can be seen that the major principal stress rising up very quickly, and at 3 minute it reaches to 130 MPa. At the first crack time, 4.1 minute, the stress reaches to 200 MPa in the centre and 110 MPa in the edges, and at the left bottom corner of the glass, it changes sharply, which is easy induce the crack of glass. At the 5 minute, the stress rising up to 240 MPa in the centre and 130 MPa in the edges.

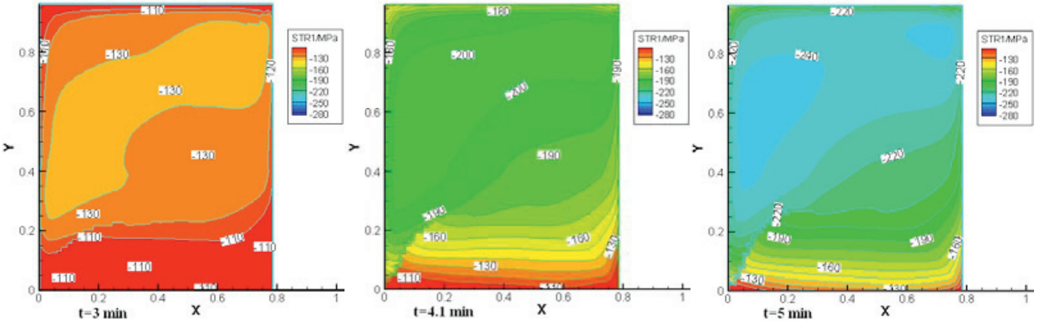


Fig.10 Simulated large glass pane major principal stress distribution of experiment no.1 with fixed edges

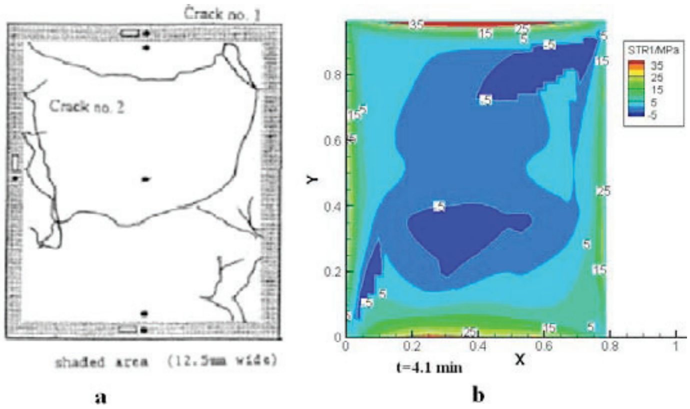


Fig.11 Comparison of experimental glass crack and simulated major principal stress distribution at the first crack

Comparing the thermal stress in free edges and fixed edges, the max tensile stress in free edges is about 35 MPa in x direction and 30 MPa in y direction at the first crack, which is less small in value than the compressive stress in fixed edges, 200 MPa in x direction and 120 MPa in y direction, respectively. The experimental results were reported that tensile stress values exhibited the range of 16-24 MPa for the large panes. Therefore, the thermal stress under free edges is more agree with the experimental result, which was discussed further in following.

The contour plots of major principal stress under free edges and experimental crack plots were shown in Fig.11 [4]. At the right top corner, the stress gradient changes greatly from compressive stress (5 MPa) to tensile stress (25 MPa) where the first crack occurred in the experimental. As the glass is brittle material, when the tensile stress exceeds the limited stress, the crack is induced[11]. The experimental value and the simulated value are agreed with each other well. After the first crack, the stress field of the glass was rebuilt and no longer be discussed here.

4. Conclusions

In this work, a two-dimensional simulation code of glass thermal stress was developed. It can simulate the transient response of the temperature and thermal stress in the window glass during a fire.

The two-dimensional simulation code was developed using Fortran 95 for glass thermal conduction and thermal stress in fire. The two-dimensional time dependent temperature distribution in the glass is calculated first and then the thermal stress is simulated based on it by finite element method. Numerical study case was selected from a publication paper, and the calculation results are compared with the corresponding experimental results. The simulation results of the transient temperature coincide well with the experimental results. The thermal stress is also agrees with the experimental result before the glass cracked, and the first crack located at where the principal stress maximal in value. These results indicate the accuracy of the developed simulation code of the transient response of the temperature and thermal stress distribution in the window glass during a fire.

Furthermore, the three-dimensional simulation code is necessary to develop for better prediction of the crack, bifurcation and fall-out of glass in fire.

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