View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Elsevier - Publisher Connector

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 62 (2013) 717 – 724

Procedia Engineering

www.elsevier.com/locate/procedia

The 9th Asia-Oceania Symposium on Fire Science and Technology

Thermal shock effect on the glass thermal stress response and crack propagation

Qingsong Wang, Haodong Chen, Yu Wang, Jinhua Sun*

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, China

Abstract

Window glass breakage in a building fire could change the oxygen supply because of the entrance of fresh air. To investigate the break behavior of window glass under various rates of temperature rise, a finite element method was employed to solve the linear dynamic response equilibrium of the system. The Coulomb-Mohr criterion and SIFs based mixed-mode criterion were employed to predict the crack initiation and growth, respectively. A total of 12 rates of temperature rise were designed from 150 K/s to 0.75 K/s for a centre-heated and edges-shaded glass pane. The maximum thermal stresses are located at the shaded part between the hot and cool glass layer, which is where the cracking is initiated. Under a rapid rate of temperature rise, a smaller temperature rise could result in a bigger dynamic stress which is then followed by crack initiation. Under a slower rate of temperature rise, the dynamic effect becomes weaker and the thermal stress can be evaluated using the static method.

© 2013 International Association for Fire Safety Science. Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology

Keywords: Thermal shock; Thermal stress; Glass; Crack; Finite element method

1. Introduction

In a building fire, the glass is heated gradually in the early stage of fire; however, if flashover occurs in a compartment, the glass is heated rapidly, which could result in a thermal shock. Thermal shock occurs when a thermal gradient causes different parts of an object to expand by different amounts. This differential expansion can be understood equally in terms of stress or strain. At some point in time, this stress can exceed the strength of the material, causing a crack to form. If nothing stops this crack from propagating through the material, the glazing will lose its structural integrity. Glass objects are particularly vulnerable to failure from thermal shock, due to their low strength and low thermal conductivity. If the glass is then suddenly exposed to extreme heat, the shock will cause the glass to break.

The problems of glass cracking and fall-out were first raised in 1986 by Emmons [1], and then, some experimental work was conducted on single glass panes [2-4] and multi glass panes [5-7] under the effect of fire or heat radiation. The experimental results suggested that the main breakage mechanism for a single pane of glass exposed to a radiant heat source is due to the thermal gradients between the shaded and exposed regions of the glass. This conclusion is confirmed by Skelly et al. [8], Shields et al. [4, 7] and other researchers [9, 10]. Some mathematical and simulation work was also performed to analyze thermal stress growth and distribution [11, 12]. Keski-Rahkonen proposed a model to predict the temperature and stress fields within a single pane of glass exposed to a radiation source [13, 14]. The development of a more advanced mathematical model by Pagni et al. [15-17] predicted breakage of single pane soda glass windows due to differing thermal gradients between shaded and exposed regions. Thermal stresses over the glass panes upon uneven heating in a fire were investigated and discussed by Chow et al. [11]. Tofilo and Delichatsios [18] considered the importance of bridling stress

* Corresponding author. Tel.: +86 551 6360 6425; fax: +86 551 6360 1669.
E-mail address: sunjh@ustc.edu.cn.

1877-7058 © 2013 International Association for Fire Safety Science. Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology
doi:10.1016/j.proeng.2013.08.118

(due to axial elongation) and flexing stress (due to normal deformation) upon the glass by analytical and numerical methods. However, little experimental or numerical data for rapid heating of glass has been reported.

Thermal shock is always caused by rapid and extreme temperature changes, which is very dangerous for the glass integrity. Therefore, the objective of this work is to investigate the effect of the rate of temperature rise on the glass thermal stress building up, and crack initiation and propagation, using a finite element method.

2. Thermal stress and crack formulas

2.1. Dynamic response models

The stress dynamic response model also was employed in our previous study [19], and it is simply stated here. The equations of equilibrium governing the linear dynamic response of a system of finite elements is [20]:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{R} \tag{1}$$

where **M**, **C**, and **K** are the mass, damping, and stiffness matrices; **R** is the vector of externally applied loads; $\mathbf{U}, \dot{\mathbf{U}}$ and $\ddot{\mathbf{U}}$ are the displacement, velocity, and acceleration vectors of the finite element assemblage. The Newmark integration scheme can be understood to be an extension of the linear acceleration method. It is an explicit method and the most important aspects are the possibility of unconditional stability for nonlinear systems and second-order accuracy. The possibility of unconditional stability and second-order accuracy allows the use of a large time step, and the explicitness of each time step involves no iterative procedure. Therefore, the effective Newmark method was taken to solve the dynamic thermal load response of glass. For the detailed information, please refer the related publications [19, 21].

2.2. Thermal stress model and crack criterion

A thermal stress model have been proposed in our previous study [19], and it is simply introduced here. Thermal stress is caused by temperature difference upon the glass, if the temperature rise $\Delta T(x, y, z)$ with respect to the original state is known, then the associated deformation can be considered easily. For glass, the temperature rise ΔT results in a uniform strain, which depends on the coefficient of linear expansion α of the material [22]. The detailed method was presented in our previous studies [19, 23].

Coulomb-Mohr criterion was employed to predict the crack initiation. Crack occurs when the maximum and minimum principal stresses combine for a condition which satisfies the following Eq. (2):

$$\frac{\sigma_1}{S_{ut}} - \frac{\sigma_3}{S_{uc}} \geq 1 \tag{2}$$

where S_{ut} and S_{uc} represent the ultimate tensile and compressive strengths. Both σ_3 and S_{uc} are always negative, or in compression.

Stress intensity factors (SIFs) based mixed-mode criterion is used mode to predict crack growth in present work. It assumes cracks start to grow once the following Eq. (3) for the stress intensity factors is satisfied [24, 25].

$$(\frac{K_{I}}{K_{IC}})^2 + (\frac{K_{II}}{K_{IIC}})^2 = 1 \tag{3}$$

where, K_I and K_{II} are the stress intensity factors for the fracture modes I and II, respectively, which are obtained from the simulation. K_{IC} and K_{IIC} denote the individual fracture toughness values of the fracture modes I and II.

3. Statement of problem and simulation procedure

3.1. Simulation model of the problem

In building, the window glass is embedded into window frames for fixing, and about 2 cm is shaded by the frame. In case of fire, the shaded areas are not exposed to the fire radiation directly, therefore, the temperature is lower than the central region of the glass. The central region of the glass temperature rising is mainly dominated by the radiation from the fires.

The shaded area temperature rise is caused by the heat conduction from the direct heated region of the glass and the heated frame. In general, the shaded area temperature rise is smaller than that of the central parts of the glass. At the back side of the glass, the temperature rise is controlled by the heat conduction rate from the front side and heat convection rate to the environment. This temperature is smaller than that of the front part of the glass too. The temperature differences between the shaded part and the uncovered part, between back side and the front side will build up the thermal stress between them because of its expansion.

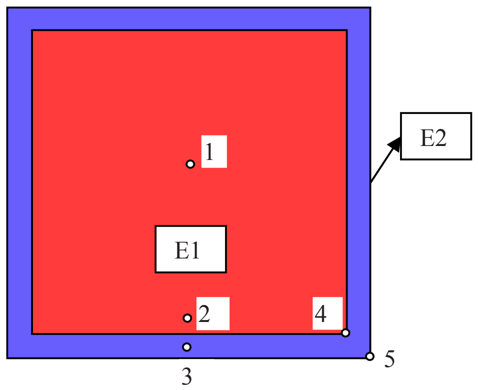

Fig. 1. Glass heated conditions, (a) E1 is exposed fire and E2 is shaded by frame.

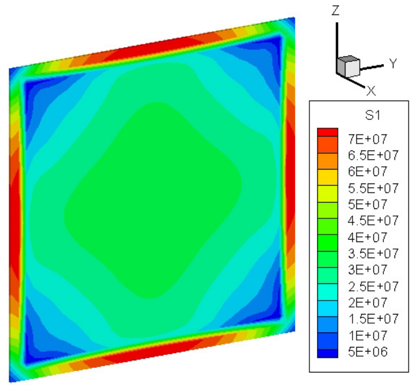

Fig. 2. One typical thermal stress distribution of glass just before crack initiation.

With the consideration of the heating condition of glass in case of fire, one glazing situation was designed to investigate the thermal stress distribution and crack propagation as shown in Fig. 1. There are two parts for the glass to be considered in temperature rising, E1 and E2. E1 denote the glass exposed to the fire directly and E2 is shaded by frame. In case of fire flashover, the temperature of air is rising sharply and causes the glass temperature rising correspondingly. The rapid temperature rise could cause a thermal stress concentration and possible to make the glass crack. To investigate this kind of thermal shock effect, 12 kinds of temperature rises of glass were designed to study the influence on glass crack, which are listed in Table 1.

Table 1. Simulation time step and crack parameters for the designed cases

Case No.	Time (s)	Time step (s)	Heating rate (K/s)	Crack time (s)	Temp. diff. at crack (K)	Max σ_1 (MPa)	Static σ (MPa)
1	1	0.01	150.00	0.54	81	75.5	45.9
2	2	0.02	75.00	1.20	90	81.6	51.0
3	5	0.05	30.00	3.30	99	76.1	56.1
4	10	0.10	15.00	7.20	108	81.7	61.2
5	20	0.20	7.50	15.20	114	77.5	64.6
6	30	0.30	5.00	23.40	117	75.4	66.3
7	40	0.40	3.75	32.00	120	76.1	68.0
8	50	0.50	3.00	40.00	120	73.0	68.0
9	60	0.60	2.50	49.20	123	75.3	69.7
10	100	1.00	1.50	84.00	126	74.4	71.4
11	150	1.50	1.00	129.00	129	75.1	73.1
12	200	2.00	0.75	172.00	129	74.0	73.1

Table 2. Glass properties and other parameters used in simulation [26, 27]

Properties	Symbol	Value	Units
Thermal expansion co-efficient	α	9.0×10^{-6}	K^{-1}
Modulus of elasticity(Young Modulus)	E	6.3×10^{10}	Pa
Poisson's ratio	v	0.22	--
Density	ρ	2500	kg/m^3
Ultimate tensile strength	σ_{ut}	7.3×10^{7}	Pa
Ultimate compressive strength	σ_{uc}	7.3×10^{8}	Pa
Glass size	--	0.006×0.6×0.6	m^3
Shaded edge width	d	0.02	m
Mesh number	--	2×36×36	--

A glass is an inorganic non metallic material that does not have a crystalline structure. Typical glasses range from the soda-lime silicate glass for soda bottles to the extremely high purity silica glass for optical fibers. The practical tensile strength of glass is about 27 MPa to 62 MPa. However, glass can withstand extremely high compressive stresses. Therefore, most glass breakage is due to tensile strength failure. Glass is weak in tensile strength is because that it is normally covered in microscopic cracks which generate local stress concentrations. Glass does not possess mechanisms for reducing the resulting high localized stresses and so it is subject to rapid brittle fracture.

The soda-lime silicate glass is widely used in windows and it is a kind of brittle materials, which is selected in this work. This kind of glass properties and simulation parameters are shown in Table 2.

3.2. Simulation procedure

The simulation in this study basically follows the method proposed by our previous study [19, 23]. In this method, two models were employed, one is thermal stress model and another is crack model based on the stress model. In the thermal stress model, the finite element method was taken to simulate the dynamic thermal stress filed using a Newmark time integration. And then the crack occurrence is predicted by Coulomb-Mohr criterion. If the crack is initiated, the program will get into the crack model. In the crack model, five crack growth criterions are provided to predict the crack growth direction and crack length, where the stress intensity factors (K_I, K_{II} and K_{III}) are calculated. In this work, the SIFs based mixed-mode criterion was employed. Furthermore, the effects of stress re-distribution due to the crack extension are taken into account in order to properly estimate the stress intensity factors at an arbitrarily extended crack tip. In order to avoid an excessive numerical cost, a proper mesh pattern is arranged in the vicinity of a crack tip by refining crack tip meshes. Only the elements surrounding the tip are refined by a fractal way. With the crack propagation, the refined tip mesh is moving too, and the ever refined elements back to the original mesh after the crack path through.

4. Thermal stress and crack path obtained by simulation

4.1. Thermal stress distribution

Twelve cases were simulated to investigate thermal shock effect on the glass thermal stress growth. Fig. 2 shows one typical thermal stress distribution before the stress is big enough to damage the glass. It can be seen that the first principal stress mainly grows at the shaded edges, where the temperature is always keeping at initial value. The temperature of the glass central part is rising, and then there is a growing temperature difference between the center and edges. The temperature difference results in a thermal stress which could break the glass at last. The maximum tensile stress locates at the four edges and smaller stress locates at the four corners, the center shows a moderate value.

For comparison, one simple way to calculate the static thermal stress is using the following equation [28]:

$$\sigma = E\alpha(T - T_0) \tag{4}$$

where σ is the normal failure stress, E is Young's Modulus, α is the coefficient of linear thermal expansion, T is the heated glass temperature and T_0 is the shaded glass temperature.

4.2. Dynamic behavior of first principal stress (σ_1)

The largest principal stress locates at the shaded edges, and it is growing with the temperature difference increasing. At a rapid temperature rising, such as 150 K/s (case 1), the stress fluctuates seriously at later stage before crack initiation. The thermal stresses at point 1, 2 and 3 are shown in Fig. 3(a). It can be seen from Fig. 3(a) that the stress σ_1 is increasing with the center temperature increasing. The value at point 3, which is at the edge, is the biggest one and the value at point 2 is the smallest one. The maximum values are 17.9 MPa, 12.2 MPa and 62.4 MPa at point 1, 2 and 3, respectively. After the temperature is larger than 360 K, the value at point 3 starts to fluctuate with the temperature rising, and at higher temperature, the stresses at point 1 and point 2 starts to fluctuate too. This waving is caused by the thermal shock on the glass, which could cause the glass break at lower temperature difference. When the temperature rises with a slower rate, the thermal stress growth histories are similar with each others. Fig. 3(b) and Fig. 3(c) show the first principal stress evolutions with 150 K temperature rise within 10 and 100 seconds, that are case 4 and case 10, respectively. The stress σ_1 at point 3 is increasing with the temperature increasing and show some waving behavior at later stage, which is similar with that of case 1. However, the amplitude is becoming smaller and smaller with the heating rate decreasing. The stress behavior at points 1 and 2 shows the same trend with that of point 3. In case 10 the stress fluctuation at points 1 and 2 even cannot be distinguished anymore, the thermal shock effect becoming to zero. Except the above three typical cases discussed here, the other cases also were simulated and they show the similar behaviors, and the detailed values are listed in Table 1.

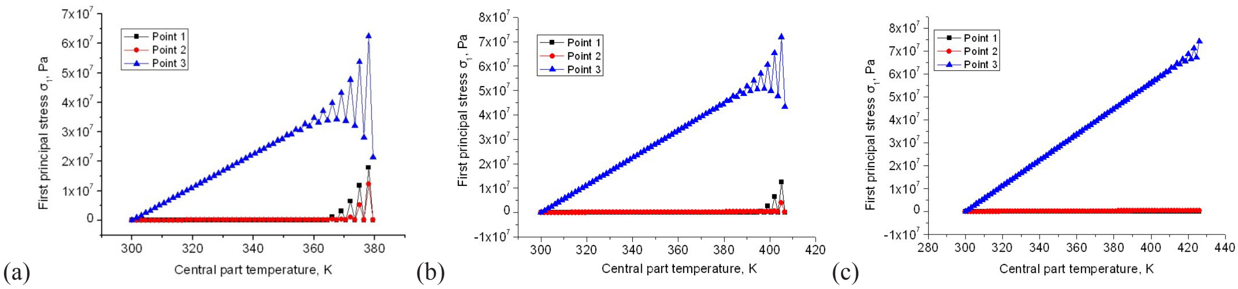

Fig. 3. First principal stress at given points under a 150 K temperature rise within (a) 1, (b) 10 and (c) 100 seconds, that is case 1, 4 and 10, respectively.

4.3. Crack initiation and crack path

The above analysis shows that the maximum first principal stress locates at the edge between the hot and cool glass parts. Therefore, the first crack will onset from here, which is improved by the simulations and the results are shown in Fig. 4. The crack initiation locations are at edge, which may be at top or bottom, left or right. It is because the four edges have the same value and any of them is possible to crack. The crack propagation and the final paths show some differences. Generally, they can be divided into three kinds of crack patterns: (1) pass through the center and split the glass into two parts, such as case 4, 8, 9, 11 and 12; (2) to the center and change to the corner, such as cases 3, 5, 6 and 7; (3) to the center and turn back to form an island, such as cases 1, 2 and 10. For the pattern 1, the crack starts from one edge center to the opposite edge with little direction changes, and the path line is smooth. For the pattern 2, the first crack path is similar with pattern 1 before it goes to the corner, and then, it follows a zigzag path line to the corner. For the pattern 3, the crack starts from one edge and it turn back to the original edge again after a short propagation, and finally forms an island.

4.4. Comparison and discussions

The thermal stress causes the glass break when it is big enough, however, when the temperature rising rate is different, the thermal stress is different even in the same temperature difference. The 12 cases with different temperature rising rate were simulated and some key parameters are listed in Table 1. For an easy comparison, the temperature difference between the hot and cool parts, dynamic first principal stress obtained from the simulation and the static stress obtained from an empirical Eq. (4) were plotted in Fig. 5. With the center temperature rising time increase, that is the heating rate decreasing, the temperature difference just before crack is increasing too. This indicates that under a rapid heating rate, a smaller temperature rise could break the glass. On the thermal stress aspect, with the center temperature rise time increasing, that is the heating rate decreasing, the trend of dynamic stress is decreasing with some fluctuating. The static stress is increasing because the temperature difference is increasing. The stresses obtained by two methods are going to closer and closer, which indicates that at a lower temperature rising rate, the dynamic effect becoming weaker. In case of fire, if the fire developing very quickly, such as flashover, which could cause the glass temperature rising fast too, and then the glass is under a bigger crack risk potential.

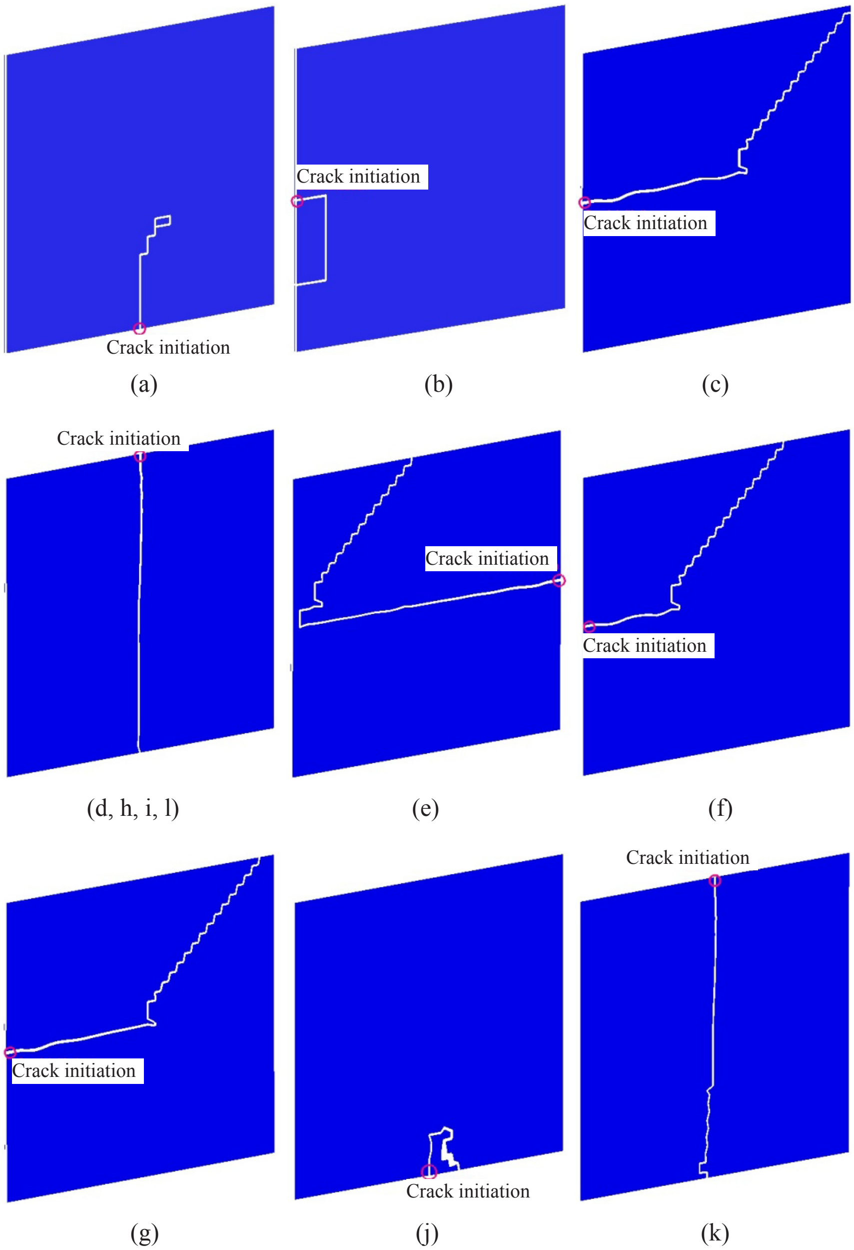

Fig. 4. Final crack path of glass under a 150 K temperature rise. (a) case 1; (b) case 2; (c) case 3; (d) case 4; (e) case 5; (f) case 6; (g) case 7; (h) case 8; (i) case 9; (j) case 10; (k) case 11; (l) case 12.

The first principal stress σ_1 is a key parameter to predict the glass crack initiation, the value difference obtained from the dynamic FEM and theoretical calculation is shown in Fig. 6. It can be seen that with the temperature rising time increasing, the difference is becoming smaller and smaller. The difference drops from 29.6 MPa to 0.9 MPa corresponding to the temperature rising rate drops from 150 K/s to 0.75 K/s. It also indicates that when the temperature is below 1 K/s, the dynamic thermal stress is very close to the static thermal stress, and therefore, the thermal stress can be evaluated using a static stress under such a lower temperature rising rate. The above analysis shows that under a rapid temperature rising rate, above 50 K/s, the dynamic stress response is big and cannot be omitted in the prediction of glass crack. Under a slower temperature rising rate, the dynamic effect is less and the thermals stress can be evaluated using a static method simply.

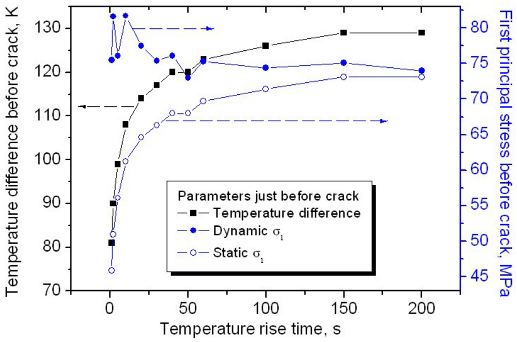

Fig. 5. Comparasion between dynamic stress and static stress.

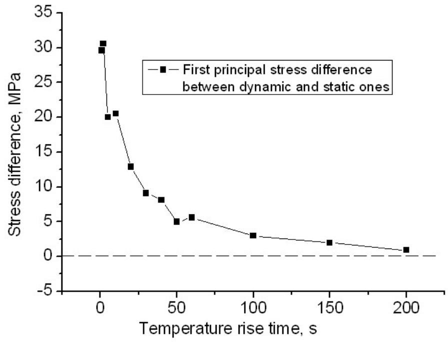

Fig. 6. First principal stress difference between dynamic and static ones.

5. Conclusions

The dynamic thermal stress responses were simulated in this paper using a finite element program. The general linear dynamic response equilibrium of a system is solved using the Newmark method. The Coulomb-Mohr criterion was employed to predict the crack initiation and SIFs based mixed-mode criterion was employed to predict the crack growth. The maximum stress is located at the edge of the glass pane between the hot and cool glass parts, and the stress fluctuates seriously at later stage before crack initiation. The crack initiation locations are at any of the four edges of the pane. Under a rapid rate of temperature rise, a smaller temperature rise could result in a bigger dynamic stress, which cannot be ignored in the prediction of glass cracking. Under a slower rate of temperature rise, the dynamic effect becomes weaker and the thermal stress can be simply evaluated using a static method.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (Grant No. 51120165001), National Basic Research Program of China (973 Program, Grant No. 2012CB719700), the Fundamental Research Funds for the Central Universities (Grant No. WK2320000014) and Program for New Century Excellent Talents in University (No. NCET-12-0514).

References

[1] Emmons, H. W., 1986. "The Needed Fire Science," Fire Safety Science - Proceedings of the 1st International Symposium, International Association for Fire Safety Science, pp. 33-53.
[2] Klassen, M. S., Sutula, J. A., Holton, M. M., Roby, R. J., 2010. Transmission Through and Breakage of Single and Multi-Pane Glazing Due to Radiant Exposure: State of Research, Fire Technology 46, p. 821.
[3] Zhang, Q. W., Zhang, H. P., Nan, J. L., Yang, J. P., Zhu, J. Y., 2005. Behavior of Single Window Glazing in Full-scale Enclosure Fire Test, Progress in Safety Science and Technology, Vol V, Pts a and B 5, p. 1078.
[4] Shields, T. J., Silcock, G. W. H., Flood, M., 2002. Performance of a Single Glazing Assembly Exposed to a Fire in the Centre of an Enclosure, Fire and Materials 26, p. 51.
[5] Chow, W. K., Hung, W. Y., Gao, Y., Zou, G., Dong, H., 2007. Experimental Study on Smoke Movement Leading to Glass Damages in Double-skinned Façade, Construction and Building Materials 21, p. 556.
[6] Klassen, M. S., Sutula, J. A., Holton, M. M., Roby, R. J., Izbicki, T., 2006. Transmission Through and Breakage of Multi-pane Glazing due to Radiant Exposure, Fire Technology 42, p. 79.
[7] Shields, J., Silcock, G. W. H., Flood, F., 2005. Behaviour of Double Glazing in Corner Fires, Fire Technology 41, p. 37.
[8] Skelly, M. J., Roby, R. J., Beyler, C. L., 1991. An Experimental Investigation of Glass Breakage in Compartment Fires, Journal of Fire Protection Engineering 3, p. 25.
[9] Bowditch, P. A., Sargeant, A. J., Leonard, J. E., Macindoe, L., 2006. Window and Glazing Exposure to Laboratory-Simulated Bushfires, Bushfire CRC, Victoria, Australia.
[10] Xie, Q. Y., Zhang, H. P., Wan, Y. T., Zhang, Q. W., Cheng, V.D., 2008. Full-scale Experimental Study on Crack and Fallout of Toughened Glass with Different Thicknesses, Fire and Materials 32, p. 293.
[11] Chow, W. K., Gao, Y., 2008. Thermal Stresses on Window Glasses upon Heating, Construction and Building Materials 22, p. 2157.

[12] Fah, T. C., 2001. A Photoelastic Study of Thermal Stresses in Window Glass Exposed to Radiant Heat, In: Chau, F.S., Quan, C. (Eds.), Second International Conference on Experimental Mechanics, pp. 457.
[13] Keski-Rahkonen, O., 1988. Breaking of Window Glass Close to Fire, Fire and Materials 12, p. 61.
[14] Keski-Rahkonen, O., 1991. Breaking of Window Glass Close to Fire, II: Circular Panes. Fire and Materials 15, p. 11.
[15] Joshi, A. A., Pagni, P. J., 1994. Fire-induced Thermal Fields in Window Glass. I—Theory, Fire Safety Journal 22, p. 25.
[16] Joshi, A. A., Pagni, P. J., 1994. Fire-induced Thermal Fields in Window Glass. II—Experiments, Fire Safety Journal 22, p. 45.
[17] Cuzzillo, B. R., Pagni, P. J., 1998. Thermal Breakage of Double-Pane Glazing by Fire, Journal of Fire Protection Engineering 9, p. 1.
[18] Tofilo, P., Delichatsios, M., 2010. Thermally Induced Stresses in Glazing Systems, Journal of Fire Protection Engineering 20, p. 101.
[19] Wang, Q. S., Zhang, Y., Wang, Y., Sun, J. H., He, L. H., 2012. Three Dimensional Dynamic Stress Prediction of Window Glass under Thermal Loading, International Journal of Thermal Sciences 59, p.152.
[20] Bathe, K. J., 1996. Finite Element Procedures Prentice Hall, Upper Saddle River, New Jersey.
[21] Newmark, N. M., 1959. A Method of Computation for Structural Dynamics, Journal of the Engineering Mechanics Division 85, p. 67.
[22] Chandrupatla, T. R., Belegundu, A. D., 2002. Introduction to Finite Elements in Engineering, 3ed. Prentice Hall, Upper Saddle River, NJ.
[23] Wang, Q. S., Wang, Y., Sun, J. H., He, L. H., 2012. Crack Initiation and Path Prediction of Float Glass with Various Constrain Conditions under Thermal Loading, The Fourth International Conference on Crack Paths, Gaeta, Italy.
[24] Tabiei, A., Wu, J., 2003. Development of the DYNA3D Simulation Code with Automated Fracture Procedure for Brick Elements, International Journal for Numerical Methods in Engineering 57, p. 1979.
[25] WU, E. M., 1967. Application of Fracture Mechanics to Anisotropic Plates, Transactions of the ASME. Journal of Applied Mechanics 34, p. 967.
[26] Chowdhury, H., Cortie, M. B., 2007. Thermal Stresses and Cracking in Absorptive Solar Glazing, Construction and Building Materials 21, p. 464.
[27] Mai, Y., Jacob, L., 1980. Thermal Stress Fracture of Solar Control Window Panes Caused by Shading of Incident Radiation, Materials and Structures 13, p. 283.
[28] Pagni, P. J., 2002. "Thermal Glass Breakage," Fire Safety Science--Proceedings of the Seventh International Symposium. International Association for Fire Safety Science, pp. 3-22.