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Thermal cracks of large area insulating glasses

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ABSTRACT:
On the basis of developed expert opinion on the causes of cracking in large-area insulating glass units, the impact of glass painting, window shading and placing non-ventilated insulating panels on the inside of the glass in close proximity to the formation of thermal stresses in the glass was presented. The principles of determining deflections and stresses in large-area glazing caused by environmental loads are discussed. It has been shown that sticking foil on the glass or applying paint coatings that completely or partially cover the window can lead to thermal cracking of the glass.

KEYWORDS:
building glass; double glazing; glass cracking; thermal cracks

1. Introduction

The formation of stresses in the glass panes is usually caused by the deformation of the glass panes as a result of their stretching, twisting or deflection. Another significant cause of mechanical stress in glass without the action of external forces is temperature change. The glass breaks when these stresses exceed the tensile strength of the glass. The tensile strength of glass itself is never the same: all kinds of micro defects or edge damage drastically reduce its tensile strength. Glass cracking can have many causes, and whether the causes of glass breakage were thermal or mechanical can only be determined on the basis of a thorough analysis. In addition to the typical causes of glass breakage such as bending, damage to the rim or impact, you should also consider, among other issues, errors during the use of windows or the use of inappropriate sun protection systems inside the rooms. The article presents the results of the expertise of glass cracking in the exhibition hall of the Municipal Art Gallery in Częstochowa. During its modernization, in order to protect against excessive sunlight, large-area windows were covered with black paint that strongly absorbs sunlight. In addition, thermally insulating screens were installed inside the room in close proximity to the glass panes without ensuring proper ventilation of the gap between the window and the thermal insulation mat. Heaters installed near the windows also had an impact on the formation of thermal tensions in the glass.

2. Heat transfer in double glazing

Solar radiation falling on the surface of the transparent partition is partially reflected, partially absorbed and partially transmitted. The light transmittance of glass τ is on average 90%, the reflection coefficient ρ for glass is 7-8%, and for double glazing it is about 15%. The reduction in light transmittance ε caused by glass absorption is 2%. The intensity of solar radiation completely absorbed by the glass is:

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$$I_1 = I_c \cdot \varepsilon_1 \tag{1}$$

where:
ε_1 – absorption coefficient,
I_c – the intensity of the total solar radiation falling on the glass [W/m^2].

The heat flux generated in the glass as a result of absorption of solar radiation is transferred by convection and radiation to the interior and exterior of the room according to formula [1]:

$$I_1 = h_{se} \cdot (t_1 - t_e) + h_{si} \cdot (t_1 - t_i) \tag{2}$$

where:
h_{se}, h_{si} – respectively heat transfer coefficient on the outer and iner surface [W/(m^2·K),
t_1 – glass temperature [K],
t_e, t_i – respectively temperature of the indoor and outdoor air [K].

In the case of an insulating glass unit, the following factors should be taken into account when calculating the temperature on the inside of the glass:

- transfer of heat on the inside and outside of the glass between the glass surface and the air by convection and by radiation;
- heat conduction through glass,
- heat exchange in a sealed gas-filled chamber by conduction, convection and radiation.

The values of h_e and h_i for double-glazed units without coatings with an emissivity lower than 0.837 on the external surfaces are: h_i = 8 W/(m^2·K), h_e = 23 W/(m^2·K). For uncoated soda-lime glass, we assume a corrected emissivity value of 0.837. For double-glazed units with a coating with an emissivity of less than 0.837 on the surface facing the interior of the room, the h_i value is calculated from the formula:

$$h_i = 3.6 + 4.4 \cdot (\varepsilon/0.837) \tag{3}$$

The effective emissivity is used to calculate the heat transfer between the mutually parallel glazing surfaces facing the air-filled or corresponding gas-filled space between the panes in a double-glazed unit. For an insulating glass unit painted on the room side with matt black paint, its emissivity is 0.9. Therefore, the heat transfer coefficient on the surface of the inner pane will be higher and the glass will heat up faster compared to uncoated glass.

A component of every double-glazed unit is at least one hermetically sealed space called the inter-pane space. As this space is filled with air or noble gas, the adjacent panes of glass behave like a membrane, i.e. they flex inwards and outwards in the space between the panes when the pressure changes [1]. When glazing is loaded by a change in the temperature of the gas in the chambers relative to the initial temperature, the change in the stiffness of the constituent panes influences the loads and deflections in the glazing assemblies in a manner analogous to the loading by a change in atmospheric pressure. On this basis, it is reasonable to assume that the application of a paint coating or the application of a film to the glazing causing a change in the stiffness of the glazing also affected the loads and deflections in the glazing set.

3. Distribution of environmental loads on insulating glass units

The individual panes of glass of an insulating glass unit work together to transfer loads, with this depending on the geometrical parameters of the glass and the temperature, external pressure at the point of manufacture and installation. The redistribution of loads from wind, temperature and isochoric pressure only applies to insulating glass units supported articulately at all edges. The uniform load from the combination of actions is distributed to the individual glass panes of the insulating glass unit in proportion to the contribution of their flexural stiffness to the stiffness of the entire insulating glass unit, taking into account gaseous bonding [2]. The following manufacturing and incorporation conditions should be taken into account in the calculations: ΔH height difference between mounting and generation, ΔT temperature difference between generation and insertion points, $\Delta\rho_{met}$ the difference in meteorological pressure at the installation site and at generation. The values of these parameters in relation to the seasons are summarised in Table 1.

Table 1
Values of fixed climatic conditions [2]

Combination of impacts	ΔT [K]	$\Delta\rho_{met}$ [kN/m^2]	ΔH [m]	ρ_o [kN/m^2]
Summer	+20	–2	+600	+16
Winter	–25	+4	–300	–16

If additional installation conditions are present, the values in Table 1 are increased by the isochoric pressure increment depending on the value of the corrective temperature increment. The proportion of the external and internal stiffness of the glass panes of an insulating glass unit is determined from the formulae:

$$\delta_e = \frac{h_a^3}{h_a^3 + h_i^3}, \quad \delta_i = \frac{h_i^3}{h_a^3 + h_i^3} \tag{4}$$

where: h_i, h_a – the thickness of the inner and outer panes of glass.
The gas coupling factor φ is calculated from the formula:

$$\varphi = \frac{1}{1 + (a/\tilde{a})^4} \tag{5}$$

where:
a – the shorter edge of the glazing unit,
$\tilde{a}$ – characteristic edge length according to the formula:

$$\tilde{a} = 28.9 \cdot \sqrt[4]{\frac{h_{SZR} \cdot h_a^3 \cdot h_i^3}{\left(h_a^3 + h_i^3\right) \cdot B_v}} \tag{6}$$

where:
h_{SZR} – distance between panes [m],
B_v – edge factor dependent on the width-to-length ratio of the glazing unit.

4. Determination of deflection and bending stresses

In the static calculations of rectangular panes articulated at four edges according to standard [3] the relationships were adopted:

$$w_{max} = k_4(a^4/h^3) \cdot (F_d/E) \tag{7}$$

$$\sigma_{max} = k_1(a^2/h^2) \cdot F_d \tag{8}$$

where:
w_{max} – maximum deflection,
σ_{max} – bending stress,
F_d – resultant load resulting from the load combination.

The coefficients k_1, k_4 appearing in the above formulae express the non-linear member corresponding to the membrane forces that are revealed by large deflections of the glass sheets. These coefficients depend on the proportion of the external dimensions of the glass panes $\lambda = a/b$ and the normalised load expressed by the formula:

$$p^* = (A/4h^2)^2 \cdot (F_d/E) \tag{9}$$

where:
A – glazed area,
h – thickness of glass panel.

In the case of linear analysis, $p^* = 0$ should be used for the calculation. For the determination of the coefficients k_1, k_4 the tables and mathematical relations given in standards [4, 5].

5. Assessment of the causes of broken glazing in the Municipal Art Gallery building in Częstochowa

The following are the results of an expert opinion on determining the causes of glass cracking in the windows of the west facade of pavilion of the Municipal Art Gallery in Częstochowa (Fig. 1).

Fig. 1. Western elevation of the Municipal Art Gallery building in Częstochowa

Segment F of the building of the Municipal Gallery of Art in Częstochowa constitutes the north-western corner of the object consisting of a complex of 6 pavilions forming a one-storey complex with a fragmented body. All pavilions featured an aluminium and glass façade in the form of strips of corrugated aluminium sheet and window displays. The window panels were 3 m high, divided by horizontal crossbars with the largest central pane measuring 1.0 m x 2.0 m, the lower and upper panes measuring 1.0 x 0.8 m (Fig. 2). In the building, insulating glass units were installed in which the thickness of the two panes of glass was 5 mm and the gap between the glass panels was 12 mm.

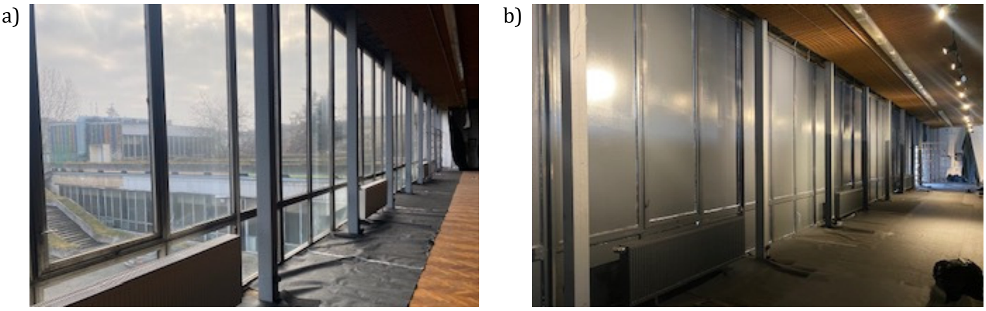

Fig. 2. Windows in the exhibition hall: a) before renovation, b) after renovation

On the first floor of the building is the largest hall of 480 m^2, which for a number of years was not used during June and August due to the temperatures exceeding 30°C, making it impossible to use as an exhibition hall (Fig. 2a). A refurbishment of the hall was carried out in 2022 to save on heat loss in winter and to insulate the hall from solar heating in the summer. The refurbishment work included painting the showcases with two-component epoxy paint using the spray method and insulating the showcases with thermal insulation matting on an independent wooden frame (Fig. 2b).

After the renovation of the tapestry room, the internal temperature was normalised and remained between 19°C and 25°C, while almost all the double-glazed windows developed cracks on the inside (Fig. 3).

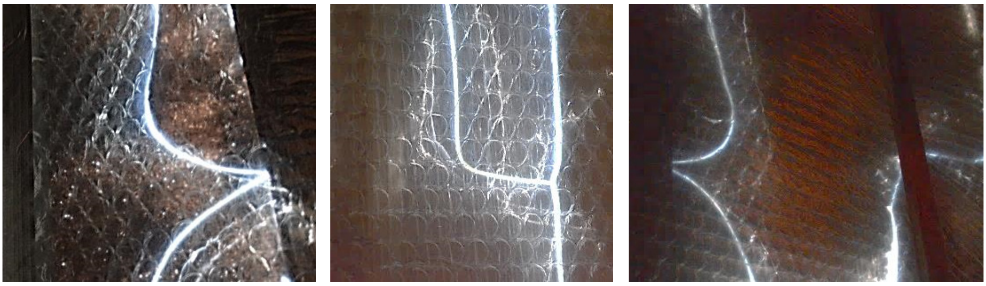

Fig. 3. Cracked glass on the inside

Visual inspection confirmed the presence of cracks extending at right angles from the side edges of the windows with no chipping at the edges of the glass panes. The outgoing cracks are in some cases divided into several cracks also running rectilinearly. The hooked end of the crack or the splintering occurring in the area of the change of direction of the crack was rare.

An insulating glass unit made of float glass 5/12/5 with dimensions b x a = 2000 x 1000 mm was used for the calculations. The glazing was subjected to a characteristic wind load of a maximum p_k = 500 Pa. The glass was supported on all edges. The contribution of the stiffness of the individual panes of insulating glass to the stiffness of the entire pane, determined according to the relationship (4), is: for the outer pane δ_e = 0.5, for the inner pane δ_i = 0.5. The edge factor B_v depends on the dimensions of the plate and is determined based on Kirchhoff's plate theory, with the Poisson's ratio assumed for glass v = 0.23. Since a/b = 1000/2000 = 0.5, hence according to B_v = 0.0501. The characteristic edge length was calculated according to formula (6) is*:* $\tilde{a}$ = 568.5 m. The gas coupling coefficient according to formula (5) was: φ = 0.094. Finally, the value of the characteristic load per individual panes of insulating glass was: $w_{k,e}$ = 311.8 Pa, $w_{k,i}$ = 258.2 Pa. The reduced design loads per individual panes of glass were: w_e = 467.3 Pa, w_i = 387.3 Pa, respectively. The maximum deflection under linear bending theory, when subjected to a reduced characteristic load uniformly distributed, was determined from the relationship (7).

The maximum stresses under linear bending theory, when bending along the x, y axis under the action of a reduced design load uniformly distributed, were to be determined according to the relationship (8). The permissible stresses for float glass were determined from the relationship:

$$f_{g,d} = k_{mod} \cdot \frac{f_{g,k}}{\gamma_M \cdot k_A} \cdot \gamma_n \tag{10}$$

where:

$f_{g,k}$ – characteristic strength of unreinforced glass, $f_{g,k}$ = 45 N/mm^2,
k_{mod} – coefficient dependent on load duration, for wind k_{mod} = 0.72,
k_A – coefficient for economies of scale k_A = $A^{0.04}$, A – glass surface m^2, k_A = 1.03,
γ_n = 1.0, γ_M = 1.8. For the case under consideration: $f_{g,d}$ = 17.48 MPa.

The calculation result for the outer pane was: $\sigma_{e,x}$ = 11.23 MPa and for the inner pane: $\sigma_{i,x}$ = 9.29 MPa.

The calculations showed that in the period prior to the refurbishment of the exhibition hall, the maximum deflections of the glazing did not exceed the permissible deflection at the centre of the span of the vertical glass panes supported at all edges $f_{dop} \leq a/100 = 1000/100 = 10$ mm. The stresses in the glazing did not exceed the permissible stresses $f_{g,d} = 17.48$ MPa. In order to take into account the heating of the internal pane due to the positioning of the thermal insulation mat in close proximity to the window and the lack of ventilation of the gap between the window and the mat, additional calculations had to be carried out for the load combination taking into account the corrective temperature increase: $\Delta T = 35$ K. The numerical calculations further assumed that, during the winter period, the indoor temperature in the building, within the windows of the exhibition hall, was $t_w = +20$°C and the steady-state outdoor temperature $t_z = -10$°C. The temperature difference between inside and outside was therefore 35°C. As the inside of the glass was coated with a spray layer of black latex paint that absorbed heat from solar radiation, it was assumed that a temperature rise of 5°C at the surface of the glass should be included in the thermal gradient value. Since the thickness of the glazing was: $h = 0.005$ m and the thermal gradient at steady state was: $dt = 35/0.005 = 7000$ K/m. The calculations showed that at a temperature difference of 50°C between the heated central area of the glass and the colder edge area (along the aluminium profiles), the stress difference reached approximately 22 MPa. At the most unfavourable load combination, tensile stresses of 20 MPa were present in the edge area, leading to thermal cracks.

6. Conclusions

Calculations carried out have shown that if there is a temperature difference within one pane of the order of $\Delta T = 40$ K, this does not necessarily cause the glass to break. In the case of a greater temperature difference and when the glazing is heated unevenly, dangerous stresses develop in the cross-section of the glass, which can lead to breakage. Factors causing excessive heating of the glazing include the application of light-impermeable film to the glazing, painting the glazing with black paint and the positioning of heating units and thermal insulation too close to the window. In such situations, it is necessary to use double-glazed windows with toughened safety glass.

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Pęknięcia termiczne szyb zespolonych o dużej powierzchni

STRESZCZENIE:

Na podstawie opracowanej ekspertyzy przyczyn pękania szyb zespolonych o dużej powierzchni przedstawiono wpływ malowania szkła, zacienienia okien i umieszczenia od strony wewnętrznej w bliskiej odległości niewentylowanych paneli izolacyjnych na powstanie termicznych naprężeń w szkle. Omówiono zasady wyznaczania ugięć i naprężeń w przeszkleniach o dużej powierzchni wywołanych obciążeniami środowiskowymi. Wykazano, że naklejanie na szybę folii lub nanoszenie powłok malarskich całkowicie lub częściowo przesłaniających okno może prowadzić do pęknięć termicznych szyb.

SŁOWA KLUCZOWE:
szkło budowlane; szyba zespolona; pękanie szkła; pęknięcia termiczne