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Thermal Glass Stress Analysis – Design Considerations

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The use of glass in windows and curtain walls, in residential as well as in high-rise buildings, is something that requires great care in design and execution. Apart from complying with typical structural engineering practices and ensuring, for example, that the glass thickness is sufficient to withstand wind loads, impact loads etc. it is necessary always also to consider the thermal-stress resistance of the glass employed as well as the temperature distribution across glass and façade components. This topic is not new as it began to be analysed with the emergence of the first body tinted basic glass types. All the analysis done today is based on a linear approach and a more or less simplified algorithm. But modern constructions make it necessary to recognize special details and to acquire a more detailed view of the construction and use of such windows and curtain walls. Glass manufacturers can assist in this by helping to analyse the thermal stress characteristics but also the temperature distribution in different constructions. It is necessary here also to evaluate the different boundary conditions, which vary from location to location. The paper will begin by describing the basic methods for analysing the thermal-stress resistance of glazing units. But it will then go on to show the influence of the boundary conditions on the final result. The paper will also show the effect of a detailed 2D FE analysis in specifically analysing critical locations in curtain walls, such as shadow boxes or spandrel areas.

Keywords: Glass, Temperature, Temperature difference, Thermal stress, Glass breakage

1. Introduction

Thermally-induced stress in glass is not a new topic. It has been under discussion for many years already. Several methods for determining the extent of thermal stress in glass have been developed. This paper aims to describe how thermal stress in glass is developed and what parameters influence the temperature of glass. It describes the best-known methods and standards as well as the methods used for analysis. It also describes a simple case study carried out on a “shadow box” construction in order to point up the relevant differences.

2. Basics

When we talk about the influence of temperature on glass, we are referring to three main issues:

- Risk of glass breakage due to thermal shock
- Maximum and minimum temperature of glass components
- Maximum and minimum temperature of air space

2.1. Risk of glass breakage due to thermal shock

Thermal stress is caused by temperature differences on the glass pane. If the temperature difference is sufficiently great, the thermal stress can cause breakage to develop from the edge of the glass. Glass fracture in modern curtain wall systems can be generated on days with typically clear sky conditions, with strong sun irradiation, and with high daily ambient-air temperature-levels. The central glass area heats up rather quickly, while shaded areas – particularly, for example, the glass edge area, which remains concealed by the frame profile – remain relatively cool. This difference in degrees of expansion between the warmer centre and the cooler edge of the glass can, if the temperature difference is sufficiently high, lead to local tensile stresses, which can in turn lead, where they reach a certain magnitude or in combination with other effects, to glass breakage.

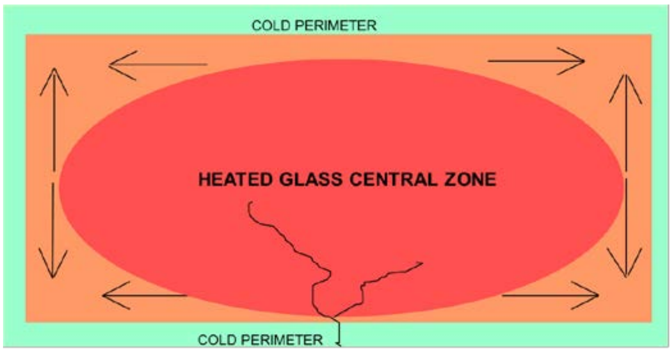


Fig. 1 Example of a heated unit

The analysis of thermally induced stresses in glass involves the consideration of three specific glass zones:

- Center of the glass exposed to sunlight - unshaded
- The shaded part of the central zone
- Glass edge area

In the case of special designs and constructions, the problem of analysis is a little more complicated. Here, the opaque element behind the glass (e.g. insulation) reflects thermal flow back onto the glass. This has the effect of warming up the air-space between the opaque element and therefore the glass itself. Typically, in such a scenario the temperature will be higher and the temperature differences greater than for non-opaque glass. In the case of an opaque element four zones needs to be analyzed:

- The central zone of the glass exposed to sunlight, located at a greater distance from an opaque element
- The central zone of the glass exposed to sunlight, located nearly directly in front of an opaque element
- The central zone in shadow, located close to an opaque element
- The edge of the glass, located at a greater distance from an opaque element

The basic idea behind thermal stress analysis is that of calculating the resulting temperature difference on the glass, i.e. the temperature difference between the warmer central area of the glass pane and the cooler shaded glass area and/ or the glass edge areas. This is done for each different glazing-type and design configuration (which includes shading, blinds or backups etc.) as well as for the four seasons of a whole year. This allows a decision regarding the appropriate glass treatment: namely, whether additional edge grinding is to be carried out or whether the glass is to be subjected to further heat treatment, such as heat strengthening or thermal toughening, in order to increase its stability in the face of temperature differences.

2.2. Maximum and minimum temperature of components

Knowing the maximum and minimum temperature of the different components (glass, primary and secondary sealant, interlayers of laminated glass and laminated safety glass, etc.) is important if faults, damages or degradations of such materials are to be avoided and in order to secure the durability of the products they compose.

2.3. Maximum and minimum temperature of air space

Insulating glass units are hermetically sealed systems. This means that gas (air or inert gases like argon and krypton) is enclosed in the IGU-cavity between two or more panes. It is an isochoric condition. This means that the volume remains constant. Climatic effects imply internal load effects caused by the expansion of the gas volume.

The expansion of the enclosed volume is limited by the inner and the outer pane. Due to the fact that the panes are not absolutely rigid, the actual state is balanced between an isochoric and an isobaric limit state.

The load brought to bear in each individual case varies depending upon the external conditions and the geometrical properties. “Geometrical properties” in this case include the dimension of the cavity, the dimensions of the IG unit and the thickness of the inner and the outer pane. “External conditions” include:

- Variations in atmospheric pressure Δp_{atm},
- Variations in temperature of the enclosed gas ΔT, and
- Variations in elevation ΔH, which can result an increasing pressure in the cavity

This means that the variations in temperature can be taken from the relevant product standards (default values). It is preferable, however, to use individually calculated temperatures referring to the actual glazing configuration, to the specific window and/or curtain-wall design, and to the specific project conditions.

3. Standardization

Within Europe as a whole, there exists no single European standard dealing with the above-mentioned aspect of thermal glass stress. There exists only one product standard, applicable in France alone, which provides a “full concept” as regards thermal stress in glass. In other countries there exist only “company rules” or guidelines but no comprehensive calculation standard. In the US, there exists an ASTM standard dealing with thermal stress but it applies to single glazing units alone. Moreover, it is not as detailed as is the French standard. The main guidelines and rules applying in Europe are the following:

3.1. FIV 01(1997)

This document created by Federation of Glass Industry (FIV) in Belgium is no longer used. The FIV method is a very simple calculation method and it can only be used to perform thermal-stress calculations for non-opaque glass-types (single glazing or double glazing units) with or without the combination of shadows and/ or internal blinds. It is not possible to use this method to calculate special designs and constructions such as spandrels or shadow boxes etc.

3.2. John Colvin method (2004- formerly known as the “Pilkington Method”)

This method is similar to the FIV method. It can be used to perform thermal-stress calculations for non-opaque glass-types with or without shadows, with or without internal or external blinds, and with or without “backups” such as spandrels or shadow boxes. All options can be calculated based on simplified equations and the use of different coefficients, for example different shadow types. It is not, however, possible to define directly, when using this method, the exact glass design or construction. Climatic data are defined in terms of average solar radiation (without influence of orientation) and with diurnal range (without influence of season).

This method is a relatively simple one and therefore does not address the current need for a more detailed analysis. It was conceived with single glazing and double glazing mainly in mind. It is not recommended that it be used for triple glazing units or for special designs and constructions. The results are quite “conservative” and mainly on the “safe side”.

3.3. NF DTU 39 P3 (1993, revision 2006)

This French standard provides a method for calculating/evaluating the risk of glass breakage due to thermal shock. The method has been in use for a long time already and is by now accepted worldwide. The main problem with it is that the definition of the boundary conditions applies, in many regards, only to France.

The standard makes it possible to calculate, in a transient state, using the finite difference method, the resulting transitory temperatures on the unshaded and shaded glass center, as well as on glass edge areas, by reference to the external changes in air temperature, sun position and intensity. No heat conductivity is assumed between glass edge and center.

The standard supposes external areas of shade to be present in every case (i.e. surrounding buildings, recessed facades...). Special instances of external shade/ shadows, such as horizontal sun louvers, overhangs or exterior blinds, are also taken into account, along with their influence in terms of geometry, duration of effect and intensity of shade cast.

The procedure followed for all orientations is the same: first the most critical season is determined; then, the maximum resulting temperature difference $\delta\theta_{max}$, is calculated with a view to further evaluation as regards admissible stress. For the spandrel or ventilated applications, the steady state approach is applied. For each pane on which any degree of shade is cast, three zones are considered.

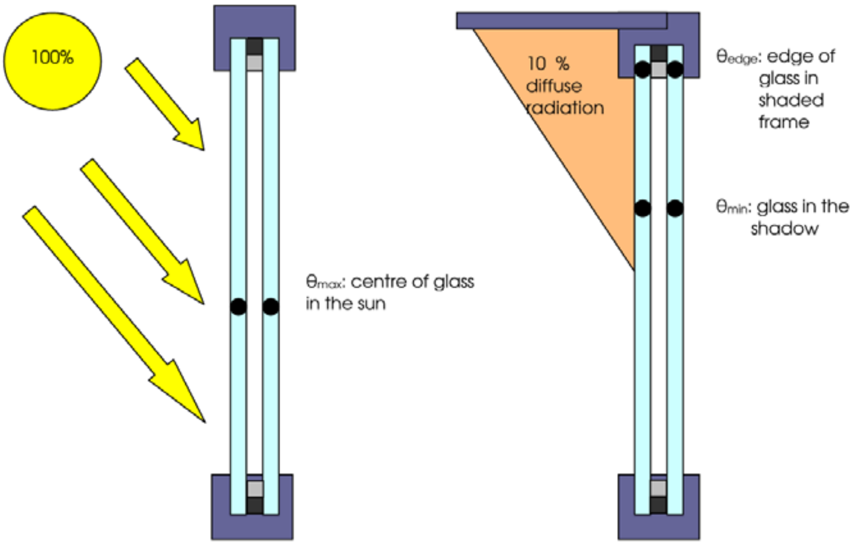


Fig. 2: Description of glazing temperatures considered (left side: centre of glass in the sun, right side: glass and frame in the shade). If a blind is present, the calculations are carried out for both the "blind up" and the "blind down" scenario. The zones with/without sun and with/without blind are both taken into account. Then the maximal temperature difference is determined. A similar procedure is used for sliding doors, partly opened

This French standard applies the following approach. The thermal stress induced by temperature difference on the glass sheets must be lower than the admissible stress:

$$\sigma_{th} < \sigma_{adm} \tag{1}$$

σ_{th} = thermal stress induced by temperature difference and σ_{adm} = admissible stress

This standard was made in ninetees, but, in its main principles, it remains up to date. The method can be used for carrying out calculations on single glazing and double glazing units but also on the nowadays more and more common triple-glazed units.

A further parameter to be considered is definition of the influence of frames and spacer bar systems. In the past we had frames with U_f-values of around 5.5 – 7.0 W/m^{2}K. Nowadays, frames tend to have standard U_f-values around 1.0 to 1.5 W/m^{2}K. Not only are standard metal spacers used but various different types of warm-edge spacer bars are also common. This means that the minimum temperature of the glass in the frame can be slightly lower at the pane and slightly higher at inner pane.

4. Influence of boundary conditions

Both the current French standard NF DTU 39 P3 and EN ISO 522022 (previously EN 13363) describe the physical laws and/or principles involved in calculating the maximum and minimum temperatures and therefore also the temperature differences. What is missing, and what is the most important, are the definition of boundary conditions and their influence.

The values/conditions which exert a major influence on the result are, amongst others:

- The energy characteristics of the glass
- The location (altitude and latitude) → climatic data
- The inclination of the glass, types of support, frame and used spacer
- The presence of shade

- For glass located in front of an opaque element there is an additional factor to consider, namely the detailed geometry and thermal properties of that element.

4.1. The energy characteristics of glass

The most important factor is the effective energy absorption of the glass pane. Where the absorption is a higher one, the central zone of the glass exposed to sunlight will warm up faster than will be the case with glass with a lower absorption coefficient. On the other hand, the minimum temperature of the glass located in the frame will be the same (no solar radiation). This means the temperature difference will be higher and thus the thermal stress as well.

4.2. The location

The climatic data applicable to the location of the building has a major impact and is also one of the most important influencing factors. Every location, specified by latitude and altitude, has its own sun path and solar radiation. These factors exert significant influence on the amount of solar radiation and on the ambient temperature, too. Solar radiation here is the sum of both direct and diffuse radiation.

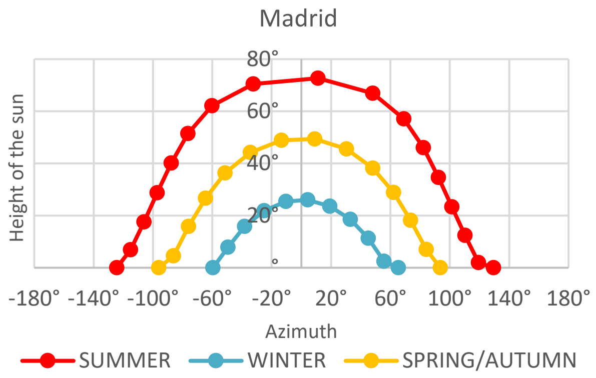
The solar altitude can be described in detail depending on the height of the sun and the azimuth. The level of solar radiation can be assessed on the basis of these latter data. E.g. for a location closer to the equator, the elevation angle will be higher. So, if we have the same building/ construction and if we change only the location, it will be necessary to carry out the thermal simulation once again.

The following example should illustrate this effect.

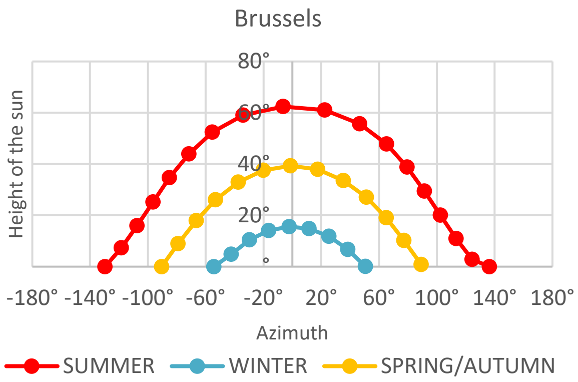
The graphs show 3 cities in Europe with different altitudes/latitudes:

- Madrid (40.5°N/-3.6°E)
- Brussels (50.9°N/4.5°E)
- Helsinki (60.3°N/25°E).

As we can see below, the sun is higher in Madrid and the solar radiaton over a horizontal area of glass is higher as well, though it is lower for vertical glazing. For buildings, solar radiation needs to be adjusted to the inclination of the window or curtain wall.



a)



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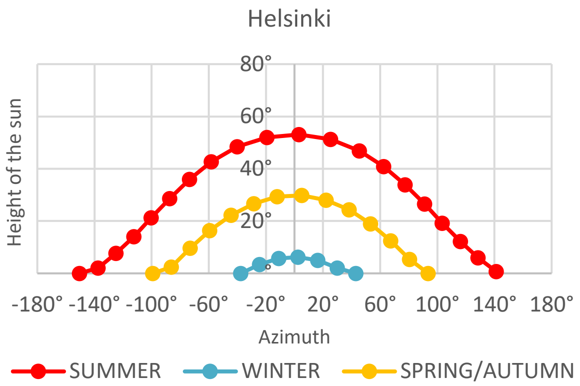

c)

Fig. 3: Sun path a)Madrid, b)Brussels and c)Helsinki

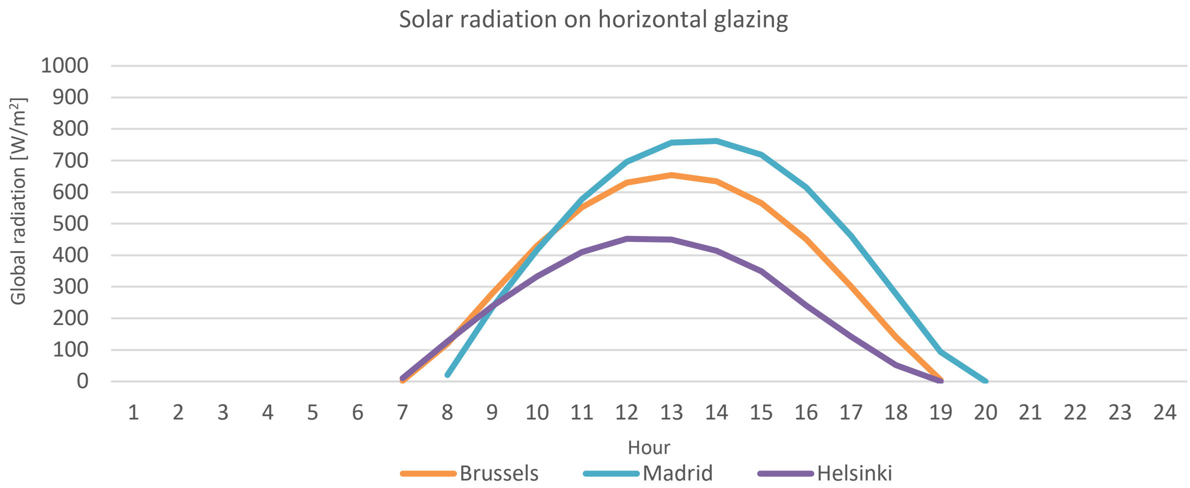

Fig. 4: Solar radiation for **horizontal** glazing in spring

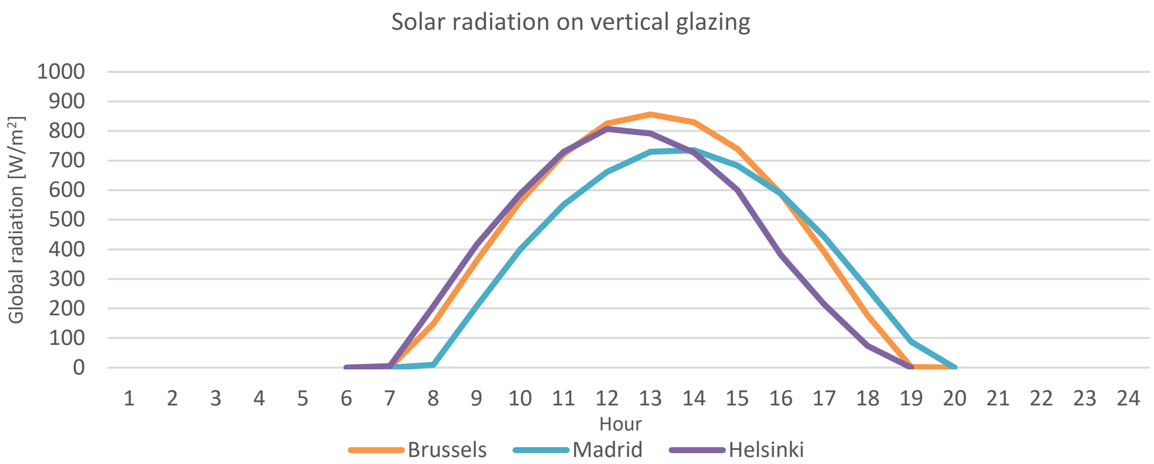

Fig. 5: Solar radiation for **vertical** glazing on southern façade in spring

4.3. The inclination of the glass and types of support, frame and spacer bars for IGUs

These items of information are required for thermal evaluation. The more precise the information is, the more accurate will be the evaluation.

The glass support exerts different influences on thermal stress and also on admissible stress. The influence exerted depends on the type of support. In the case of free edges and glazing installed at a slope, there is added stress, caused by dead load, which in turn results in a lower admissible thermal stress.

The inclination of the glass also impacts solar radiation, which can vary quite significantly as a result, as is clear from these values for Madrid, June 21st:

- Horizontal – 943 W/m^2
- 45°Slope, South – 922 W/m^2
- Vertical, South – 428 W/m^2

The type of frame can influence the thermal behaviour due to the following factors:

- The differing thermal conductivity of materials and their geometry
- Energy absorption coefficients that depend on the colour of the frame (e.g. white 30%, dark grey 65%, black 95%)

The different spacer bar systems used for insulating glass units have a direct effect in terms of the temperature of the individual panes due to the thermal properties of the spacer.

The thermal performances of the frame and the spacer bar system can help to avoid low temperatures arising on the glass, thus reducing the risk of glass breakage due to thermal shock and also risk of condensation.

Finally, the heat capacity of the frame can also play a role, e.g. massive frames with high heat capacity would absorb a lot of energy.

4.4. The presence of cast shadow

We assume shadows will be cast on buildings in almost every case (except roof glazing), either by other constructions (frames, walls, awnings, balconies) or by nearby objects (other buildings, trees, columns etc.)

There are three categories of shadow:

- No cast shadow (no construction or other parts of the building, no surrounding structures which can cast shadow on the glass → Rather rare)
- Mobile shadow (due to movement of the sun and the great distance of the shadow-casting parts of the building, the cast shadow moves quickly across the glass),
- Static shadow (shadow caused by surrounding structures, constructions or parts of the building; this type of shadow will be present for longer periods; it can move but not disappear)

Static shadow is the most critical scenario. This type of cast shadow influences the amount of diffuse solar radiation, which in turn influences temperature of the shaded zone.

4.5. The geometry of the façade type and the glazing configuration and/or the thermal properties of the opaque element

Such details could be an internal backup/ obstacle (e.g. suspended ceiling, spandrel, shadow boxes, heater).

The typical construction detail of a spandrel part will have a glazing on the outer side, followed by an air gap and then the solid structure. There are two general types:

- Shadow box: transparent glazing, typically as an IGU + opaque element
- Spandrel: fritted glass as single glass or IGU + opaque element

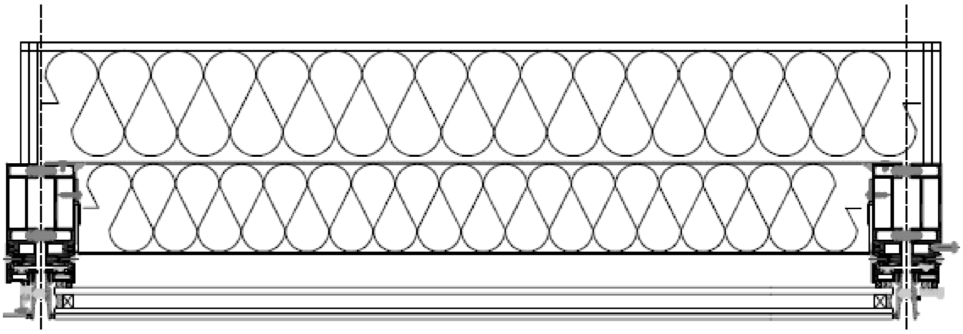

Fig. 6: shadow box – with transparent glass

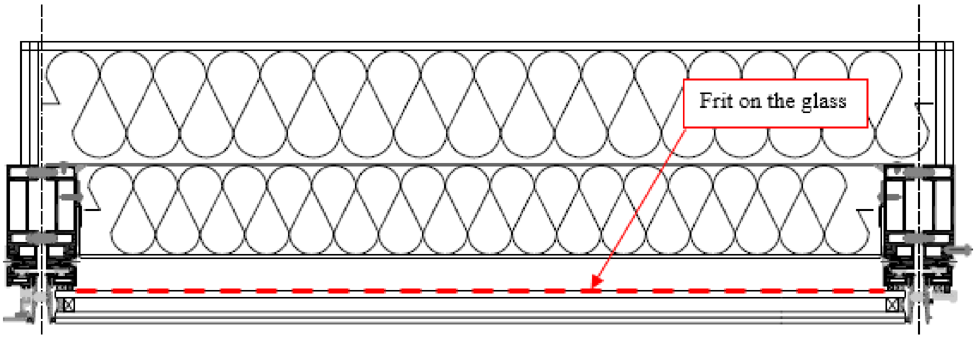

Fig. 7: spandrel – with fritted glass

The spandrel part is defined in terms of its thermal resistance, depending on thermal conductivity λ, along with the thickness of the materials used and the solar energy absorption/reflection of tthe surface.

The following example shows the effect of different thermal resistances of the construction, as well as the influence of the different colors of the surface. The example describes a shadow box with a double-glazed unit, the distance between glass and the opaque part is 40 mm. The outside temperature is 30°C, solar radiation 850 W/m^2.

Table 1: Example of the influence of the color of the surface in shadow box

Construction of the opaque element	Color of surface	Thermal resistance R[m^{2}K/W]	Max.temperature of inner pane [°C]
3 mm aluminium sheet 100 mm mineral wool 3 mm aluminium sheet	white	2.58	127.4
3 mm aluminium sheet 20 mm mineral wool 3 mm aluminium sheet	white	0.53	84.9
3 mm aluminium sheet 100 mm mineral wool 3 mm aluminium sheet	black	2.58	188.9
3 mm aluminium sheet 20 mm mineral wool 3 mm aluminium sheet	black	0.53	119.5

5. Temperature difference x thermal stress

For many years, the temperature difference limit for annealed glass has been set at $\Delta T= 30 – 40°C$. This limit is still used today. But it is no longer sufficiently appropriate. It is necessary always to take into account the influence of shadows, supporting structures, the frame and the inclination of the glass on the final assessment of this limit. A temperature difference is also not a charateristic value because it depends on, for example, the edge quality of glass.

The present, unsatisfactory situation can be remedied in two different ways:

- to define only "new" ΔT or
- to define admissible thermal stress.

Using the "thermal stress" method is more appropriate, because several other factors can hereby easily be drawn into the analysis, and because it is a typical engineering practice to compare stresses instead of fixed values. Therefore, this approach is more readily accepted by architects, designers or engineers.

Table 2: Example of influence of shadow, supporting, frame and slope on respectively admissible stress ΔT.

Type of the glass	Supporting	Cast shadow	Slope of glass	Admissible ΔT	Admissible stress
Annealed glass, cut edge	4-sides	yes	vertical	35°C	20 MPa
	Other			28°C	16 MPa
Annealed glass, smooth ground edge	4-sides	yes	vertical	42°C	24 MPa
	Other			33°C	19,2 MPa
Annealed laminated glass, cut edge	4-sides	no	5° from horizontal	32°C	16 MPa
	Other			20°C	10 MPa

6. Tools and methods of calculation

There is a wide range of available software tools for calculating temperatures of glass and façade components. Yet, there are very few tools that address the need to analyse thermals stress in glass.

Coming from the thermal calculations for assessing U-values of windows and curtain walls or for isothermal calculations, these software solutions can also be used to assess temperature differences in glass.

However,the input data and software models need to be adjusted in different ways to fit these other types of analysis.

The main anlayzig principles are:

- 1D simulation
- 2D simulation
- 3D simulation

The methods of calculation are:

- steady state
- transient state

6.1. 1D simulation

1D simulation is an easy definition of the construction. Only one dimension can be defined and it is not possible to define the construction or detail more precisely. The construction or detail is calculated in one direction only (from outside to inside). The influence of the frame and spacer can only be calculated using defined coefficients.

This method is fast and it can be used for non-opaque glass types with simple visual transmittance, as well as for "easy" constructions (e.g. with blinds). In special constructions, no influence of flaking or a second direction lead to an overestimated result (high temperature and high temperature difference). Neither the detail nor the construction can be defined precisely, so the calculations tend to be conservative.

Steady state: Here, the climatic data (solar radiation and outside temperature) have to be changed or defined to take into account the influence of changing climatic conditions over time. The outside temperature is lower than the real temperature. To reach steady state it would require around 90 minutes. But such a thing could never happen in reality. The maximum temperature of an air space is calculated using $(T_{max,pane1}+T_{max, pane2})/2$. No frame or edge effects are considered. Examples of the software on the market include Vitrage Decision, THMSTR, Physalis.

Transient state: This method offers the possibility of specifying the real climatic data, which should be defined for a typical year. For example, Vitrage Decision calculates in a transient state, but not using the real climatic data. The calculated outside temperature and monthly amplitude is taken over 3 days every 15 minutes. The maximum solar radiation for every season is defined, but only on the basis of the sun path for France. These data will not really accurately apply to other countries. The maximum temperature of the air space is calculated in the same way as in the steady-state method.

6.2. 2D simulation

With 2D simulation, a more precise definition can be achieved. It is possible to directly define the detail of the construction, with all its materials, its characteristics, its dimensions etc. It is a Finite-Elements-Method. The temperature distribution, as influenced by the construction and the materials, is calculated in two directions.

This method requires more time to be properly applied. On the other hand, for special cases, it is a good approach, in as much as it produces a result closer to reality, showing the influence of the two directions and the "real" behaviour of the different materials along with their influence on temperature distribution.

Steady state: The definition of climatic data should be the same as for 1D steady state. If we use the real outside temperature/ solar radiation, the result we get will be unrealistically high. There are various different tools on the market for this kind of analysis (e. g. WinIso2D, Bisco, Flixo, etc.). The results of the different tools are very similar as the principal of calculation are plus minus the same, because of the physical laws/ principles. It is the definition of the boundary conditions that is more important. The user, consequently, is the most important factor.

Transient state: The definition of climatic data should be the real data for a typical year, collected at least every 20 minutes. It is possible to see the influence of changes in temperature or solar radiation. This method too requires more time if it is to be applied properly.

6.3. 3D simulation

With this method, it is possible to define precisely the dimensions and the influence of three directions. But the preparatory work and the calculation need much more time.

Steady state: It is necessary to adjust climatic data (as in 1D simulation). It involves more work, but the result is very close to 2D simulation. An example of the software is WinIso3D.

Transient state: Here, it is possible to define real climatic data with the influence of sun path, changing of temperature/heat fluxes over time. Also the influence of the dimensions and the construction is adjustable. This method requires more time, but the results are closer to reality. The calculation takes into account the convection and radiation.

6.4. Dynamic tools

Special tools for calculations with convection, conduction and radiation as well as in real time and dimensions. This method is extremely complex. Special knowledge is needed, and a great deal of time. It is also a very expensive tool (i.e. Ansys Fluent). After the validation it is possible to use the result instead of more expensive testing.

7. Case study

The following case study is intended to show the difference between a 1D and 2D analysis for a typical construction of a shadow box. It illustrates the use of a more simplified method as well as of the detailed one.

7.1. Input data

Our calculation presupposes the use of a shadow box measuring 600 x 600 mm located in a building in Brussels, Belgium. For the calculation, we checked all orientations, but the results in the tables are for the most critical ones only.

Composition of the shadow box:

- 6 mm Stopray Vision-72 pos.2 – 15 mm Argon 90% - 4 mm Planibel Clearlite
- 27 mm air cavity, not ventilated
- 3 mm aluminium sheet, dark grey color (energy absorption 65%, thermal conductivity λ=160 W/mK)
- 130 mm mineral wool (thermal conductivity λ= 0.039 W/mK)
- 3 mm aluminium sheet

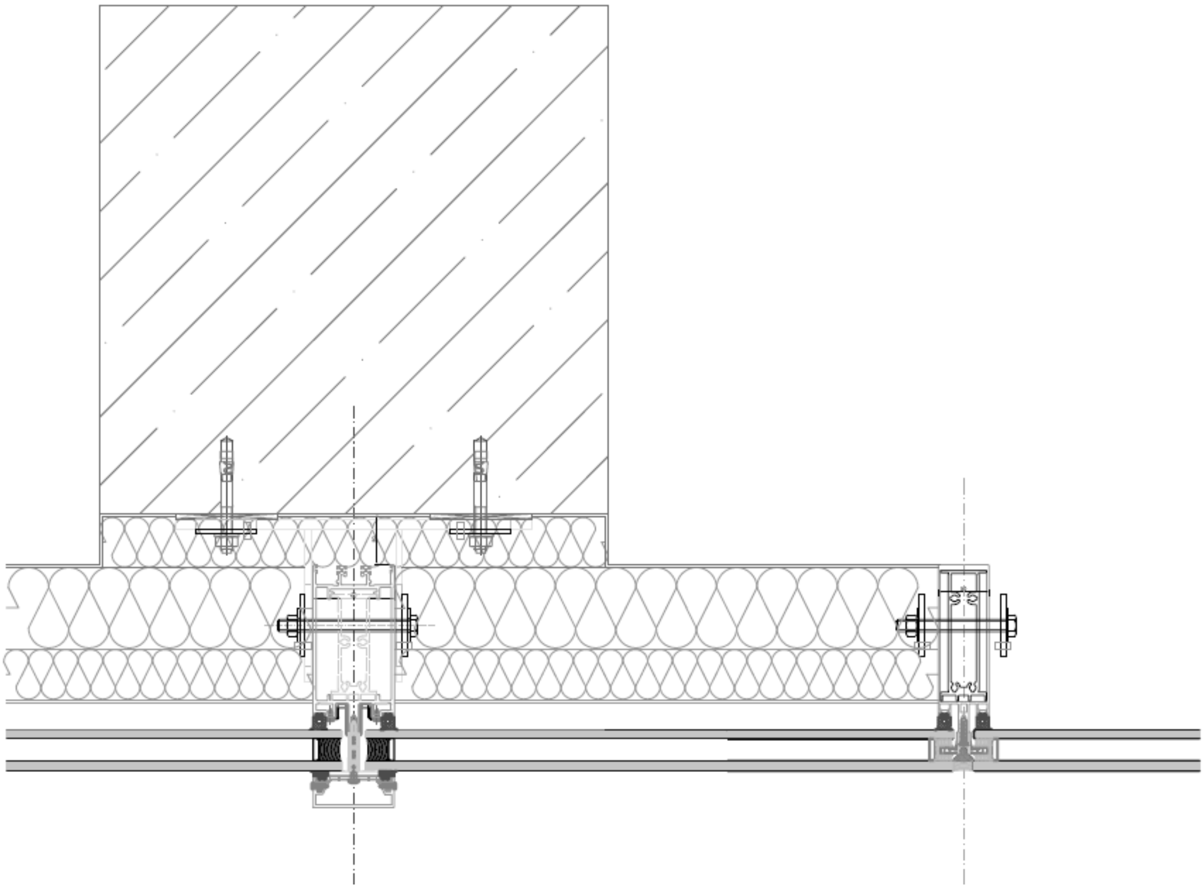

Fig. 8: Shadow box – with transparent glass

As can be seen in Figure 8, two different curtain wall types are considered. One is a capped aluminium system, with a thermal break (on the left), and the other is part of a structural sealant glazing with steel profiles and no thermal break (on the right).

7.2. Calculation method

For the case study, we used the following three calculation methods and tools:

- Method according to French standard NF DTU 39 P3, 1D simulation – Vitrages Decision
- Method according to French standard NF DTU 39 P3, 2D simulation – WinIso2D
- John Colvin method, 1D - THRMST

7.3. Climatic data and boundary conditions

As mentioned above, each method has its own way of defining boundary conditions. In order better to elucidate the differences between the methods, the calculations were first carried out using data produced according to the method in question and then, in the second case, they were carried out once again using also climatic data from Meteonorm.

Calculations were carried out for the following boundary conditions:

- Boundary conditions from Vitrages Decision, calculation in Vitrages Decision
- Boundary conditions from Meteonorm, calculation in Vitrages Decision
- Boundary conditions from Meteonorm, calculation in WinIso2D
- Boundary conditions according to John Colvin method, calculation in THRMST
- Boundary conditions from Meteonorm, calculation in THRMST

Table 3: THE MOST CRITICAL CLIMATIC DATA FOR PANE 1 for max. temperature

	Orientation	Season	Solar radiation [W/m^2]	Outside temperature [°C]
VD – data from VD	East/West	summer	733	32
VD – data from Meteonorm	East	summer	915	30.2
WinIso2D – data from Meteonorm	East	summer	915	30.2
THMRST - data from John Colvin tool	All	N/A	N/A	N/A
THMRST - data from Meteonorm	All	N/A	N/A	N/A

Table 4: THE MOST CRITICAL CLIMATIC DATA FOR PANE 2 for max. temperature

	Orientation	Season	Solar radiation [W/m^2]	Outside temperature [°C]
VD – data from VD	SE/SW	autumn	792	22
VD – data from Meteonorm	East	summer	915	30.2
WinIso2D – data from Meteonorm	East	summer	915	30.2
THMRST - data from John Colvin tool	All	N/A	N/A	N/A
THMRST - data from Meteonorm	All	N/A	N/A	N/A

Table 5: THE MOST CRITICAL CLIMATIC DATA FOR PANE 1 for max. ΔT

	Orientation	Season	Solar radiation [W/m^2]	Outside temperature [°C]
VD – data from VD	South	winter	803	2
VD – data from Meteonorm	SW	winter	925	-2
WinIso2D – data from Meteonorm	SW	winter	925	-2
THMRST - data from John Colvin tool	All	N/A	739	24
THMRST - data from Meteonorm	All	N/A	925	32

Table 6: THE MOST CRITICAL CLIMATIC DATA FOR PANE 2 for max. ΔT

	Orientation	Season	Solar radiation [W/m^2]	Outside temperature [°C]
VD – data from VD	South	winter	803	2
VD – data from Meteonorm	East	summer	915	30.2
WinIso2D – data from Meteonorm	SW	winter	925	-2
THMRST - data from John Colvin tool	All	N/A	739	24
THMRST - data from Meteonorm	All	N/A	925	32

7.4. Result

Prima facie, the climatic data from Meteonorm are the most critical case: solar radiation is the highest and the outside temperature as well. When looking at the table of the results, it can be seen that the result is the "best" one based on a 2D calculation with climatic data from Meteonorm, as compared to 1D simulation with "milder climate" in Vitrages Decision and also in THMRST. This applies in particular to the inner pane because the 2D FE method considers the thermal conductivity of the construction in two directions, and it is due to the use of multiple coefficients by 1D methods.

Table 7: Difference between a 1D and 2D analysis

	Max. temperature Pane 1 [°C]	Max. temperature Argon [°C]	Max. temeprature butyl [°C]	Max. temeprature Pane2 [°C]	Max. ΔT Pane 1 [°C]	Max. ΔT Pane 2 [°C]	Thermal stress Pane 1 [MPa]	Thermal stress Pane 2 [MPa]
VD – data from VD	59.50	106.30	---	154.70	30.40	123.10	17.24	69.80
VD – data from Meteonorm	64.70	122.00	---	179.30	37.40	139.10	21.21	78.87
WinIso2D – data from Meteonorm	73.30	96	90.00	97.23	49.08	67.51	27.83	38.28
THMRST - data from JC tool	N/A	N/A	N/A	N/A	24.77	117.29	14.04	66.50
THMRST - data from Meteonorm	N/A	N/A	N/A	N/A	27.71	123.73	15.71	70.15

7.4.1. Results for a spandrel with the same composition, but with a black-enamelled inner pane

Table 8: Difference between a 1D and 2D analysis – SPANDREL + black frit #4

	Max. temperature Pane 1 [°C]	Max. temperature Argon [°C]	Max. temeprature butyl [°C]	Max. temeprature Pane2 [°C]	Max. ΔT Pane 1 [°C]	Max. ΔT Pane 2 [°C]	Thermal stress Pane 1 [MPa]	Thermal stress Pane 2 [MPa]
VD – data from VD	64.00	133.30	---	203.70	37.70	168.50	21.38	95.54
VD – data from Meteonorm	70.80	151.50	---	232,80	43.30	194.30	24.55	110.17
WinIso2D – data from Meteonorm	86.09	140	112.31	142.41	66.44	113.59	37.67	64.41
THMRST - data from JC tool	N/A	N/A	N/A	N/A	26.42	144.48	14.98	81.92
THMRST - data from Meteonorm	N/A	N/A	N/A	N/A	29.79	157.95	16.89	89.56

7.5. 2D simulation

The 2D simulation can precisely define the construction and the materials used and also to take into account the type of frame and spacer bar, together with their geometry and thermal properties. In the calculated example, the difference between an aluminum frame and a structural glazing façade can clearly be seen.

In summer, the high thermal conductivity of the frame (aluminum λ=160 W/mK) causes it to heat up and thereby also warming up its surroundings. The highest temperature of the inner pane is located close to the aluminum frame. The highest temperature of the outer pane is located close to the edge of the structural glazing, because this part is exposed to the sun and the energy absorption of the glass edge is high (black color 95%).

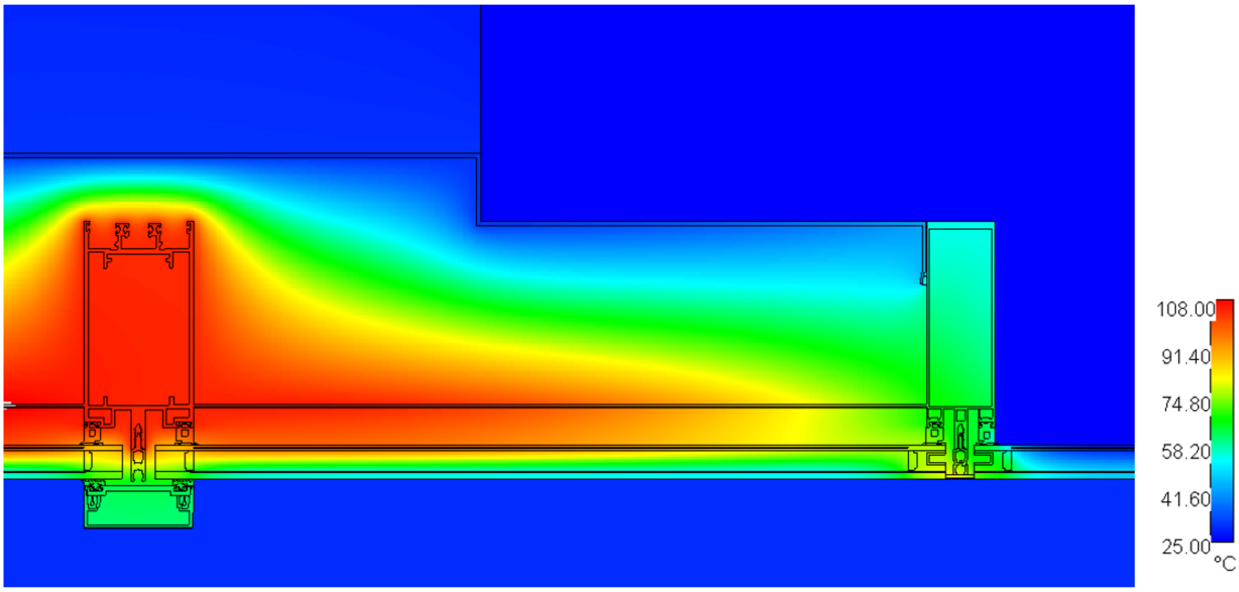

Fig. 9: MAX. TEMPERATURE IN SUMMER – 2D calculation

In winter, the high thermal conductivity of the aluminum frame is the reason why the lowest temperature of the inner pane is located in the frame. The temperature of the inner pane, in the case of structural glazing, is higher because the glass is exposed to diffuse radiation (in a frame there is no radiation).

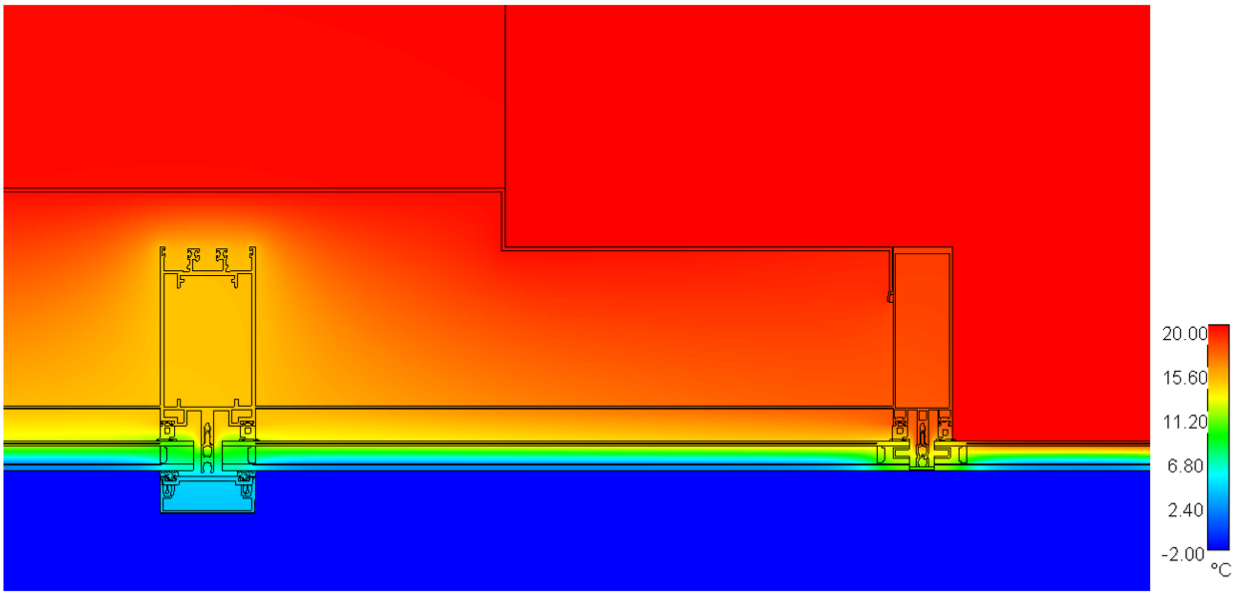

Fig. 10: MIN. TEMPERATURE IN WINTER – 2D calculation

8. Conclusion

The term ‘thermally safe’ does not exclude the possibility of thermal stress breakages.

It means that the calculated risk of thermal breakage with good glass edges is low (free from cracks which have crushing damage associated and free from chips).
The experience has shown that when glass is assessed by any of the described methods and is declared as “thermally safe” and of a glass breakage that occur in a building is related to thermal stress, many other factors could have caused this breakage as well:

- damaged edges, or
- parameters which have not been taken into account, e. g. installation of a massive blackout blinds after facade completion or
- a combination of both of the above.
- Building during erecting with low inside temperatures

This means that it will always remain a risk assessment, e. g. from the glass manufacturer... and it should always be assessed on a case-by-case assessment basis. There is no fixed rule on responsibility. But it can be agreed upon if necessary.

Assessing thermal stress in glass is up to now not usual. Only experienced manufacturers or architects who are specifying a thermal stress analysis are taking care about that topic. Thermal glass stress analysis should be always done in relation to the structural calculations of glass. It should be “standard” to check glass in small as well as large project in terms of their integrity against thermal influences and their combinations. Very often the window or curtain Wall Company as well as the glass manufacturer do not know, for example, if and which blinds or curtains are installed. Therefore, the building owner together with the architect should have an interest to verify glass against thermal stress. Or on the other a “guide” with recommendations or information should be handed over what the glass can withstand or not.

References

Röhner, Joachim, RBGT, Thermal Stress in Glass, Presentation (2016).
Meteonorm, Global Meteorological Database, Handbook part II.: Theory, Version 7.1 (July 2015).
NF DTU 39 P3 Travaux de bâtiment – Travaux de vitrerie-miroiterie – Partie 3: Mémento calculs des contraintes thermiques, AFNOR (2006).
John Colvin, Thermal Stress Analysis