# Windows film to Glass: Numerical simulation software for avoiding thermal stress

Karthik Vengatesan
karthik.vengatesan@tecnico.ulisboa.pt
Instituto Superior Técnico, Universidade de Lisboa, Portugal
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**Abstract**

Window films plays a crucial role in replacement of inefficient window glass from the energy efficient point of view in buildings. But one of the engineering concerns before installing a film on a window is to know if the new structure (glass + film) will with-stand the thermal stress induced by solar radiation. Generally, under no shading conditions the temperature of the central area of glass will be at higher temperature while the glass edges (covered by frame) will remain at lower temperature.

When a film is applied to a glass, its intrinsic thermal properties are changed and it give rise to increased temperature difference between the central area of glass and its edges when compared with those obtained when no film is applied. High temperature difference will induce thermal stress that could lead to glass breakage from its edges towards the central area. The temperature difference depends on type of glass, for instance a monolithic float glass can withstand up to 40 °C while a tempered glass can withstand up to 200 °C.

Until now, there is no single dedicated tool in window film industry to calculate the temperature difference, which will allow to predict the breakage of glass. The tool (*FG-Breakage*) developed in this work allows to determine the maximum temperature difference between different areas of glass in order to predict this fatal consequence. The tool considers the possibility to choose all types of glasses and films available in International Glazing Database (IGDB), region specific weather conditions (temperature, season, solar flux) and other parameters like window orientation or tilt. This tool can be used by engineers or architects at design stage, who are engaged in using these films to turn normal windows into energy efficient glazing window.

## 1. Introduction

According to International Energy Agency (IEA) data [1], the building consumption represents the largest energy consuming sectors in the economy, with about one-third of the final energy being consumed by buildings for space heating and cooling needs. As the building sector is expected to be the key enabler of future sustainability in our global economy, unlocking the potential of energy efficiency in building sector would be the key priority for all countries in near future [2].

Traditionally window glazing systems are known as energy losers due to the fact that they are the weakest part of building envelope, being responsible for a substantial quantity of heat loss and gains. Recent regulations have enforced the use of the latest generation of windows and building envelope technologies to reduce the energy consumption in buildings. However, these technologies must have market acceptable costs and in general they are more easily introduced in new buildings than into existing buildings. In this context, window films find most of their applications and they were ranked first in both fastest payback and highest probability of success under available energy conservation technologies by US Department of Energy [3].

In most of existing buildings the main applications for window films are:

- Natural lighting, outdoor visual and ventilation.
- Positively impact a building's heating and cooling loads and thereby reduces utility cost.
- Increased A/C equipment life.
- Improve occupant comfort, aesthetics and appearance.

On other hand, when applying a window film to a glass the optical properties will change, leading to higher absorption of solar radiation and thus increasing the temperature of glass and thereby increasing the probability of thermal breakage in glass.

Currently, there are some available software tools that are used by glazing industries to compute the temperature and optical properties of a glazing system. These includes, Window 7.4 and Optics 6 developed by Lawrence Berkeley National Laboratory or Ansys. Window 7.4 is used to determine the thermal performance of a window glazing system including temperature calculation at central point of glass based on a comprehensive heat transfer model[4]. Optics 6 allows to compute the spectral properties of a complex glazing system that consist of vast library of applied films and glass types[5]. Also, Ansys (a general purpose-finite element modelling software) can also be used to determine the temperature at any point of a modelled window glazing system.

## 2. Methodology

Until now each window film manufacturer uses their own method to assess the compatibility of window films with specific glazing construction against thermal breakage. These methods may include calculating the expected edge stress based on the safety criteria of installation condition [6] or through a film compatibility chart that shows weather a film is suitable for a glass type or not. Some window film manufacturers include compatibility checks as a part of their warranty coverage program as well.

The tool (*FG-Breakage*) developed in this thesis, provides a single platform to check thermal breakage compatibility of all combination of window films with monolithic glass, based on the data shared by all manufactures to the International Glazing Database (IGDB) and approved by National Fenestration Rating Council (NFRC). It should be noted that there are no data available for single window films, data available in the IGDB corresponds to window film applied to a reference glass(base substrate), usually a 3mm or 6mm plain glass with low iron content [7]. The tool has been developed using Microsoft Excel VBA programming language with Access database shared by IGDB and it is used to compute the maximum temperature difference that may lead to thermal breakage of a glass when a film is applied it. The basic algorithm behind *FG-Breakage* is schematized in *Figure 1***.** In order to perform the calculation, initial checks considering heat pockets, type of glass, type of film, blind existence, glazing tilt angle, location and season are considered.

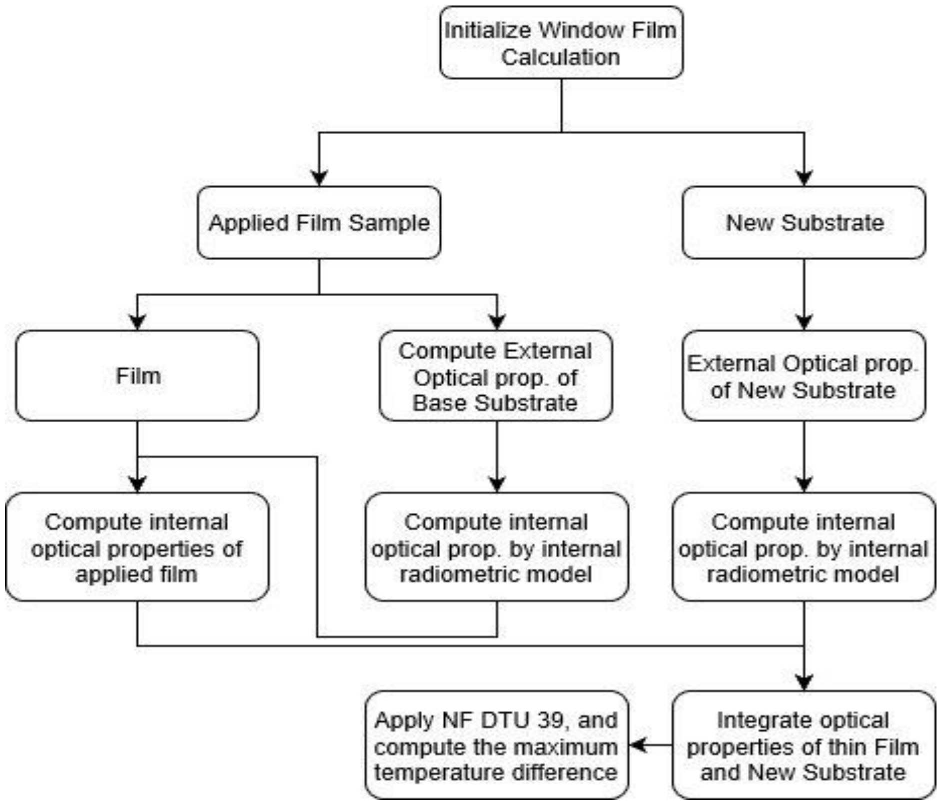



*Figure 1: Algorithm of FG-Breakage code*

## 2.1 Optical properties

Initially, the calculation of spectral properties (transmittance and reflectance) of new window film to glass is initialized by choosing the type of glass (new substrate) and the desired film from the IGDB (as referred before, data of the film refers data of the film applied to a reference glass). Then according to standard EN 410 [8] and external radiometric model [5] the equations 1 and 2 are used to compute the spectral properties of the reference and the new substrates.

$$\tau_e = \frac{\sum_{\lambda=300nm}^{2500nm} \tau(\lambda)\, S_\lambda\, \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda\, \Delta\lambda} \quad \rho_e = \frac{\sum_{\lambda=300nm}^{2500nm} \rho_o(\lambda)\, S_\lambda\, \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda\, \Delta\lambda} \tag{1}$$

$$T_{i,j} = \frac{T_{i,j-1}\ T_j}{1 - R_{j-1,i}^b\ R_j^f};\ R_{i,j}^f = R_{i,j-1}^f + \frac{T_{i,j-1}^2\, R_j^f}{1 - R_{j-1,i}^b\ R_j^f};\ R_{j,i}^b = R_j^b + \frac{T_j^2 R_{j-1,i}^b}{1 - R_{j-1,i}^b\ R_j^f} \tag{2}$$

Where FG-Breakage uses IGDB data ($\tau(\lambda), \rho_o(\lambda)$) to compute solar transmittance ($\tau_e$) and reflectance ($\rho_e$) along the wavelength with the relative spectral distribution ($S_\lambda\, \Delta\lambda$) as per the standard EN 410 [8]. While $T_{i,j}$ and $R_{i,j}^{f,b}$ are the spectral transmittance and reflectance of multilayer glazing (more than one glass) system as per external radiometric model and $i, j$ represents glazing layers.

Considering the internal radiometric model [5] and the computed external spectral properties ($T_s$,$R_s$) of the base substrate from the above equation 2, it is possible to compute the internal spectral properties ($r_s$, $\tau_s$) of base substrate, that will be used to extract the spectral properties of only the film ($t_c, r_c^f, r_c^b$) through the following equations.

$$r_s = \frac{\beta - \sqrt{\beta^2 - 4(2-R_s)R_s}}{2(2-R_s)} \quad where\ \beta = T_s^2 - R_s^2 + 2R_s + 1 \tag{3}$$

$$\tau_s = \frac{[(1-r_s)^4 + 4r_sT_s^2]^{\frac{1}{2}} - [1-\ r_s]^2}{2r_s^2T_s} \tag{4}$$

$$t_c = \frac{T_c\ (1 - r_s\ r_c^f\ \tau_s^2\ )}{(1-r_s)\ \tau_s}; r_c^f = \frac{R_c^f - r_s}{\left[1 + r_s\left(R_c^f - 2\right)\right]\tau_s};\ r_c^b = R_c^b - \frac{t_c^2\ r_s\ \tau_s^2}{1 - r_s\ r_c^f\ \tau_s^2} \tag{5}$$

Finally, the computed spectral properties of film are integrated with the new substrate properties by the equation 6 that includes computed internal spectral properties ($r_s$, $\tau_s$) of new substrate to which film is going to be applied[8].

$$\rho_1 = r_c^f - \frac{r_s\ t_c^2\tau_s^2}{1 - r_sr_c^b\ \tau_s^2};\ \rho_2 = r_s + \frac{r_c^b\ [1-r_s]^2\ \tau_s^2}{1 - r_sr_c^b\ \tau_s^2};\ \tau_c = \frac{[1-\ r_s]\ \tau_s\ t_c}{1 - r_sr_c^b\ \tau_s^2} \tag{6}$$

$$A_j = \frac{T_{1,j-1}\ A_j^f}{1 - R_{j-1,1}^b\ R_{j,L}^f} + \frac{T_{1,j}\ R_{j+1,L}^f\ A_j^b}{1 - R_{j,1}^b\ R_{j+1,L}^f};\ A_j^{f,b} = 1 - T_j - R_j^{f,b} \tag{7}$$

Then, with the computed spectral properties of window film with new substrate ($\rho_1, \rho_2, \tau_c$), the absorption ($A_j$) of each glass layers are computed and *j* represents glazing layers. Later, the computed absorption values are used to determine the maximum temperature difference that leads to breakage of glass.

## 2.2 Calculation of Temperature difference

At present, there are limited number of standards and methods to estimate the risk assessment of thermal breakage in glass (without film). Each of these practices are different from others based on their parameter of influence, application domain and precision [9]. In this work, the French Norm DTU 39 [10] will be considered, due to its widespread use and its applicability in varied scenarios like vertical sliding and internal sliding case with blinds. The *FG-Breakage* code, has extended the application of this Norm to the case of glass with applied film.

According to French Norm DTU 39 [10], in order to find the maximum temperature difference, $\delta\theta_{max}$ the window is divided into three zones as follows:

- Temperature of glass inside the frame (*zone 1*)
- Temperature of glass subjected to maximum solar flux (*zone 2*)
- Temperature of glass subjected to shade – usually 10% of maximum flux or diffuse flux (*zone 3*)

For calculation of the temperature of glass edges trapped inside the window frame (*zone 1*), $\theta_1$ is calculated by:

$$\theta_1 = \frac{h_i \,.\, \theta_i + h_e \,.\, \theta_e}{h_i + h_e} \tag{8}$$

Where $h_i$ and $h_e$ are the internal and external heat transfer coefficient of glass surface and $\theta_i$ and $\theta_e$ are the internal and external temperature, which are tabulated according to climatic condition depending on the season and location[10], [11]. While for calculating the temperature of zone 2 ($\theta_2$) and zone 3 ($\theta_3$) in a glazing system, the maximum global solar flux ($\Phi$), which depends on season and orientation of window is used for the case of zone 2 and diffuse solar flux (10% of maximum solar flux) is used for the case of zone 3. Both are calculated following the equations 9-11, depending on the glazing type (single or double) based on French Norm DTU 39 [10].

Single glazing:

$$\theta_2 = \frac{h_i \,.\, \theta_i + h_e \,.\, \theta_e \; + A \,.\, \Phi}{h_i + h_e} \tag{9}$$

Double Glazing:

$$\theta_{2e} = \frac{h_t . (h_i \,.\, \theta_{ai} + \alpha_{2e} . \Phi) + (h_i + h_t) \,.\, (h_e \,.\, \theta_{ae} \; + \alpha_{1e} \,.\, \Phi)}{(h_i + h_t) \,.\, (h_e + h_t) - h_t^2} \tag{10}$$

$$\theta_{2i} = \frac{h_t . (h_e \,.\, \theta_{ae} + \alpha_{1e} . \Phi) + (h_e + h_t) \,.\, (h_i \,.\, \theta_{\text{ai}} \; + \alpha_{2e} \,.\, \Phi)}{(h_i + h_t) \,.\, (h_e + h_t) - h_t^2} \tag{11}$$

Where $A$ is the absorption of glass in single glazing system. While for the case of double glazing, $\theta_{2e}$ and $\theta_{2i}$ are the temperature of external and internal glass subjected to maximum solar flux ($\Phi$), $h_t$ is the heat transfer coefficient of air gap between the glasses and $\alpha_{1e}$,$\alpha_{2e}$ are solar absorption of two glasses [10]. Then the maximum temperature difference can be computed as:

Single Glazing:

$$\delta\theta_{max} = Max((\theta_2 - \theta_3), (\theta_2 - \theta_1)) \tag{2.12}$$

Double glazing:

$$\begin{aligned} \delta\theta_{\text{max1}} &= Max((\theta_{2e} - \theta_{3e}), (\theta_{2e} - \theta_1)) \\ \delta\theta_{max2} &= Max((\theta_{2i} - \theta_{3i}), (\theta_{2i} - \theta_1)) \end{aligned} \tag{2.13}$$

Finally, following the French Norm DTU 39 [10] the calculated temperature difference is compared with the tabulated permissible temperature difference available in appendix section of the document for each glass to check whether the choice of film is safe or not.

## 3. Results and discussion

As referred above, the FG-Breakage tool computes the maximum temperature difference that lead to thermal breakage of glass with applied film. The user should choose the type of glazing to perform the calculation (single, double or vertical sliding case), the window film (if needed) and the initial conditions: climate zone, glazing tilt angle, season and consideration of blinds.

In case of a double glazing with applied film, first the optical properties of window film applied to new substrate are extracted using the formulations previously mentioned. Then, by considering the parameters of French Norm and applying the multilayer radiometric model the maximum temperature differences are computed for each orientation and finally the results can be used by building engineers or architects for choosing a safe and adequate film type for a glazing system. *Figure 2*, shows the results of FG-Breakage code when a double-glazing window is chosen in a climatic condition I3 in Portugal [11], during summer and no blind was assumed.

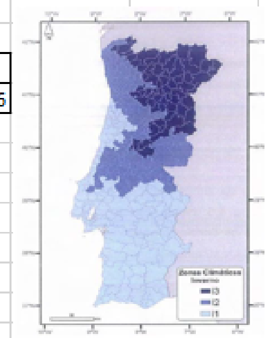
**Double Glazing Thermal Breakage Calculation**

**Glass Type**

| NFRC_ID | Type | FileName | ProductName | Thickness | Conductivity | Tsol | Rfsol | Rbsol |
|---|---|---|---|---|---|---|---|---|
| 21025 + Film | Monolithic | PLANILUX 10mm. | Saint-Gobain | 10 | 1 | 0.362 | 0.086 | 0.093 |
| 21025 | Monolithic | PLANILUX 10mm. | Saint-Gobain | 10 | 1 | 0.757 | 0.070 | 0.070 |

**Air Gap**

| Gap | Conductivity | Viscosity | Cp | Density | Prandel No. | Thickness |
|---|---|---|---|---|---|---|
| Air | 0.024 | 0.000017 | 1006 | 1.2924 | 0.720 | 0.016 |



**Conditions**

| | | | |
|---|---|---|---|
| Climate Zone | I3 | Blind / Drapes | no |
| Glazing Tilt | 90 | | |
| Season | Summer | | |

**Maximum Temperature Difference**

| Glass 1 | | | | Glass 2 | | | | |
|---|---|---|---|---|---|---|---|---|
| Orientation | Winter | Spring / Autumn | Summer | Orientation | Winter | Spring / Autumn | Summer | User Input |
| NE | 7.67 | 21.80 | 25.26 | NE | -3.68 | 2.92 | 4.64 | Output |
| E | 23.96 | 31.68 | 30.34 | E | 4.40 | 7.82 | 7.16 | |
| SE | 34.23 | 33.95 | 24.83 | SE | 9.50 | 8.95 | 4.42 | |
| S | 35.82 | 30.92 | 18.52 | S | 10.28 | 7.44 | 1.29 | |
| SW | 34.23 | 33.95 | 24.83 | SW | 9.50 | 8.95 | 4.42 | |
| W | 23.96 | 31.68 | 30.34 | W | 4.40 | 7.82 | 7.16 | |
| NW | 7.67 | 21.80 | 25.26 | NW | -3.68 | 2.92 | 4.64 | |

*Figure 2: Output of Double-glazed window from FG-Breakage*

For calculation purpose, it has been considered a double-glazing system with the first layer (which is facing external environment) being a Saint-Gobain monolithic glass (*NFRC 21025)* with a window film (*NFRC 2732)* and the second layer being the same monolithic glass but without film. The maximum temperature difference values obtained (in green in *Figure 2*) are then compared with the maximum permissible temperature difference available in Appendix section of DTU 39 document, to predict the thermal breakage phenomenon of each glass in the glazing system. According with the Appendix, a monolithic glass with tilt angle greater than 60° can withstand a maximum temperature difference of 42° C [10]. Comparing this with the results obtained, it could be observed that this value will be never reached (in any condition) and it can be concluded that the glass will not break with the selected film.

In order to validate the results from *FG-Breakage*, they are compared with those obtained using Optics 6 and Window 7.4, which are the most commonly used tools by glazing industries. Additionally, the results are compared with Ansys, which is a general purpose numerical simulation tool. Since, in all the cases the maximum center point temperature is calculated, it is used as a reference value to compare the results and to have a discussion on it.

## 3.1 Optical properties

The results of spectral properties (solar transmittance, $T_{sol}$ and front/back solar reflectance, $R_{fsol}/R_{bsol}$) obtained using the FG-Breakage tool were compared with those obtained from Optics software, to compute the optical properties of a complex glazing system [12]. *Table 1* shows the computed results obtained from FG-Breakage and Optics 6 codes for the most commonly used Saint-Gobain monolithic (*NFRC 21025)* and coated glass (*NFRC 21431)* with and without window film (*NFRC 2732)*. Laminated glass cannot be considered because the details of different layers of glass are not shared by manufacturers to IGDB.

*Table 1: FG-Breakage results compared with those obtained with Optics 6*

| Glass NFRC ID | Type | Product Name | Film NFRC ID | FG-Breakage | | | Optics 6 | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | $T_{sol}$ | $R_{fsol}$ | $R_{bsol}$ | $T_{sol}$ | $R_{fsol}$ | $R_{bsol}$ |
| 21025 | Monolithic | SSG Planilux 10mm | N/A | 0.757 | 0.070 | 0.070 | 0.756 | 0.070 | 0.070 |
| 21431 | Coated | SSG Plaintherm 10mm | N/A | 0.673 | 0.260 | 0.227 | 0.673 | 0.260 | 0.228 |
| 21025 | Monolithic | SSG Planilux 10mm | 2732 | 0.362 | 0.086 | 0.093 | 0.363 | 0.086 | 0.093 |
| 21431 | Coated | SSG Plaintherm 10mm | 2732 | 0.362 | 0.202 | 0.116 | 0.318 | 0.268 | 0.139 |

The computed spectral properties by *FG-Breakage* obtained following the European Standard EN 410 are similar to results obtained from Optics. The variation of spectral properties with the wavelength for glass NFRC 21431, which are also calculated by code are represented in *Figure 3*. Since, Optics represent only the profile of spectral properties along the entire wavelength it could be seen, that the profile of spectral variation obtained from *FG-Breakage* is similar to the one obtained from Optics 6. Some of the optical data available in IGDB have lots of missing data with respect to relative spectral distribution specified by the standard EN 410 [8]. So, the missing optical data were interpolated in FG-Breakage code and consecutive spectral properties were obtained for each glazing types. Later, these spectral properties will be used in radiometric model to compute the external and internal spectral properties.

Considering the data from *Table 1* when the film is applied to the glass, the results obtained from *FG-Breakage* code are similar in the case of monolithic glass and there are slight differences for the coated glass. A possible reason behind this difference can be due to the limitation of calculating the refractive indices for the case of the coated substrate with *FG-Breakage* code. Since the direct measurement (through spectroradiometers) of all spectral properties involves manual errors and time-consuming process, there is a need for a simpler computation method for determining the approximate spectral properties so *FG-Breakage* would be a reliable tool [5].

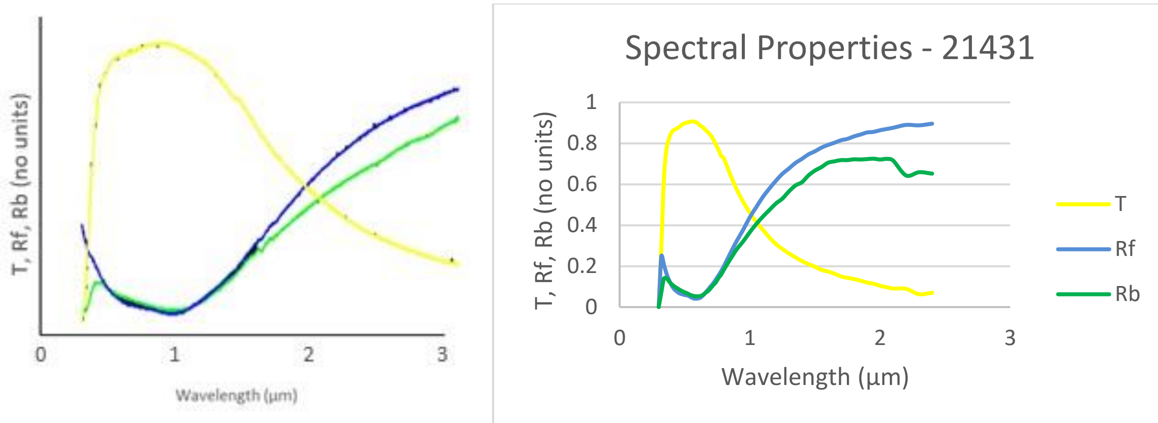



*Figure 3: Spectral properties variations with wavelength of a 10mm coated glass (NFRC 21431) obtained from Optics 6 (Left) and FG-Breakage(Right)*

### 3.2 Temperature

The results of temperature obtained using FG-Breakage code were compared with those computed using Window 7.4 and Ansys software, which can predict the temperature of central area in a glazing system. Here we have considered two cases, the first case involves a scenario of comparing temperature for a single glazing system using Window 7.4; and the second case involves a scenario of validating temperature for a double-glazing system with window 7.4 and Ansys. For both cases, the same glass which were considered in previous section was used considering a size of 1000 x 1000 x 10 $mm^3$. The environmental conditions considered are those defined by the French Norm (adapted for Portugal) which are: maximum solar flux of 881 $W/m^2$, outdoor environmental condition of 32°C, heat transfer coefficient 13 $W/m^2K$ indoor environmental condition of 25°C and heat transfer coefficient of 9 $W/m^2K$[10]. While for the case of double glazing, a standard air gap of 16mm with aluminum frame is designed in Autodesk Inventor software to perform simulation in Ansys.

*Table 2* shows the results of temperature in the central area of glass obtained with the *FG-Breakage* and Window 7.4 for the case of single glazing system with and without applied film. It can be observed that the results are quite similar, being the maximum difference (within a 6% relative error) registered for the coated glass with film. The results obtained from Window 7.4 involves numerical approximation from the imported spectral data from Optics 6 software and considering it as a reference value to compare with the results obtained from *FG-Breakage*. This variation (less than 6% relative error) is acceptable among the glazing manufacturer community.

For the case of double glazing system, the temperature results of *FG-Breakage* are compared with results from Ansys and Window 7.4 (*Table 3*). In order to compare the results of *FG-Breakage* and Ansys it has been considered the results from Window 7.4 as reference value due to its widespread application in the glazing industry. The pictorial representation of thermal gradient obtained from Ansys simulation tool is schematized in *Figure 4* and it could be observed that for a glazing system the temperature of the central area of glass will be at higher temperature.

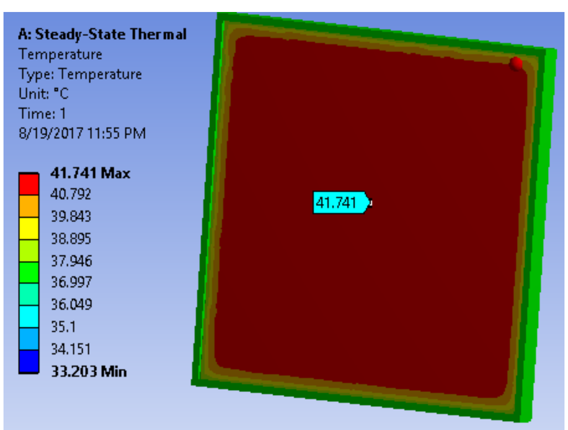
*Table 2: Comparison of FG-Breakage results with Window 7.4 for single-glazed system.*

| Glass NFRC ID | Type | Product Name | Film NFRC ID | FG-Breakage(°C) | Window 7.4(°C) |
|---|---|---|---|---|---|
| 21025 | Monolithic | SSG Planilux 10mm | N/A | 36.08 | 36.40 |
| 21431 | Coated | SSG PLANITHERM 10mm | N/A | 31.80 | 31.75 |
| 21025 | Monolithic | SSG Planilux 10mm | 2732 | 51.25 | 52.05 |
| 21431 | Coated | SSG PLANITHERM 10mm | 2732 | 46.59 | 44.15 |

From the results obtained, it could be observed that the values of temperature obtained from *FG-Breakage* and Window 7.4 are quite similar but considering the results obtained from Ansys, it is possible to observe that values are quite different, being the relative error close to 10%. This could be related with the assumptions that are considered while performing simulation i.e. for the case of Ansys simulation characteristics of frame were considered, while for FG-Breakage and Window 7.4 codes did not (frame can act as a sink and thus temperature of central area can decrease). Also, there exist different methodologies for computing the maximum temperature of a glazing system: in case of Windows a one-dimensional heat transfer model based on experimental measurements and numerical modelling of selected heat transfer cases was used, while in case of ANSYS, basic heat transfer equation was used by finite element methods to solve three-dimensional energy equation.

*Table 3: Comparison of FG-Breakage results with Window7.4 and Ansys for double-glazed system.*

| Glass NFRC ID | Type | Product Name | Film NFRC ID | FG-Breakage(°C) | Window 7.4(°C) | Ansys (°C) |
|---|---|---|---|---|---|---|
| 21025 | Monolithic | SSG Planilux 10mm | N/A | 44.32 | 46.00 | 41.75 |
| 21431 | Coated | SSG Planitherm 10mm | N/A | 32.59 | 32.85 | 33.32 |
| 21025 | Monolithic | SSG Planilux 10mm | 2732 | 67.91 | 67.05 | 60.52 |
| 21431 | Coated | SSG Planitherm 10mm | N/A | 34.77 | 36.85 | 38.11 |



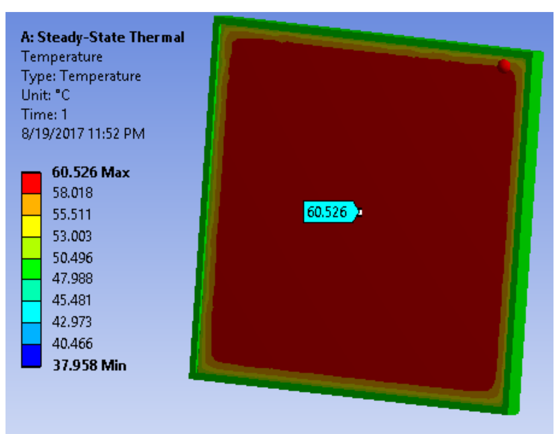




*Figure 4: Temperature profile in Ansys for two cases.*

## 4. Conclusions

Multiple conclusions can be drawn, amongst which the most important are summarized as follows:

- Based on the closer numerical results obtained from Optics, Window 7.4 and *FG-Breakage* codes, it indicates that *FG-Breakage* results are reliable to perform window film to glass breakage compatibility checks
- Though the French Norm DTU 39 have limited their calculation procedure on thermal breakage of glass, the results obtained indicate it can also be used to perform calculations of thermal breakage when window film is applied.
- Thermal stresses of glazing system are mainly influenced by solar radiation and temperature changes according to their localization, orientation, shading conditions, etc. A verifiable calculation method for thermal fracture remains a challenge as existing numerical approximation method simplifies the real case scenarios. For example, in this work the fatigue suffered by glass pane when exposed to cyclic weather conditions was not considered.

## 5. Acknowledgements

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