Windows Film to Glass: Numerical simulation software for avoiding thermal stress

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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September 2017

Acknowledgements

I would like to thank my supervisor, Prof. Victoria Corregidor Berdasco for her constant support during different phases of the thesis. Her encouragement, guidance and her transmission of valuable lessons were fundamental to the completion of this work. She gave me full support and flexibility to be investigative, independent and creative. Thank you very much.

I am eternally grateful to Erasmus Mundus for financially supporting my studies for past two years.

I would also like to thank Mr. Carlos Miguel from Impersol for sparking this idea and providing me all the required data.

And most importantly MSc. Guilherme Vendeirinho from Impersol for providing me constant support, suggestion and sharing ideas without which this investigation would be much more difficult and for all the interest and availability to answer my technical questions.

To all my university friends who accompanied me on this journey and helped me with all their knowledge and fun sharing moments.

I owe my parents for their interminable support, for always being there during the good times and bad times.

I want to thank my fiancée, for always being there, besides the distance between Chennai and Lisbon, for always reminding me what matters the most and for all her patience and love.

Finally, thank you one and all who were important for me during this period and contributed to my success.

Resumo

As recentes normas europeias impõem aos edifícios que adotem novas soluções eficientes em termos energéticos. As películas de controlo solar para vidros desempenham um papel crucial na substituição de janelas ineficientes. Ao mesmo tempo, uma das maiores preocupações a ter em conta antes da instalação de uma pelicula num vidro é averiguar saber se a nova estrutura (película + vidro) resistirá ao *stress* térmico induzido pela diferença de temperatura no vidro causada pela radiação solar. Geralmente, considerando a ausência de sombreamento, a temperatura na área central do vidro atingirá a sua temperatura mais alta comparativamente com a sua zona periférica, que permanecerá a uma temperatura mais baixa devido, sobretudo, ao efeito de sombreamento da caixilharia.

Quando uma pelicula é aplicada num vidro, as propriedades térmicas intrínsecas são alteradas dando origem à um aumento da diferença de temperatura entre a área central do vidro e a sua zona periférica, comparativamente com as diferenças de temperatura que se verificam na ausência de película. Esta diferença de temperatura induzirá as tensões que provocam a quebra do vidro, desde a sua aresta, em direção ao centro do vidro. A diferença de temperatura depende do tipo de vidro, i.e., um vidro monolítico pode suportar diferenças térmicas até 40 °C, enquanto um vidro temperado pode suportar até 200 ° C.

Até agora, não há uma única ferramenta dedicada na indústria das peliculas para vidros para calcular esta diferença de temperatura, que permitirá prever a ocorrência de quebra de vidros devido à instalação de películas. A ferramenta (*FG-Breakage*) desenvolvida neste trabalho permite determinar a diferença máxima de temperatura entre as diferentes áreas do vidro, a fim de prever essa consequência fatal. A ferramenta considera a possibilidade de escolher qualquer tipo de vidro e películas (disponíveis numa base de dados International - IGDB), condições climatéricas específicas da região (temperatura, estação, fluxo solar) e outros parâmetros como orientação ou inclinação do vidro. Esta ferramenta pode ser usada por engenheiros ou arquitetos durante as primeiras etapas do desenho do projecto, na qual são utilizadas as películas de controlo solar para transformar janelas normais em janelas energeticamente eficientes, quer no Inverno, quer no Verão.

Palavras-chave: eficiência energética, peliculas para virdros, quebra de vidros, IGDB.

Abstract

Recent regulations have enforced existing buildings to take up new energy-efficient solutions to reduce their energy loss through building envelop. In which, Window film solution plays a crucial role in the replacement of inefficient window glasses. But one of the major engineering concerns before installing a film on a window is to know whether the new structure (film + glass) will withstand the thermal stress induced by solar radiation. Generally, under no shading conditions, the temperature of the central area of glass will be at a higher temperature while the glass edges (covered by frame) will remain at a lower temperature.

When a film is applied to a glass, its intrinsic thermal properties are changed and it gives rise to the increased temperature difference between the central area of glass and its edges when compared with those obtained when no film is applied. The 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 the 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 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 the design stage, who are engaged in using these films to turn normal windows into energy efficient glazing window.

Keywords: Energy-efficient, Window film, Thermal breakage, IGDB.

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Abbreviations

PSA - Pressure Sensitive Adhesive

GEA - Global Energy Assessment

$\mathrm{GtC0_2}$ - Gigatons of Carbon Dioxide

HSG - Heat Strengthened Glass

IEA - International Energy Agency

IGDB - International Glazing Database

IGU - Insulating Glass Unit

LBNL - Lawrence Berkeley National Laboratory

Low-E - Low - Emittance

NFRC - National Fenestration Rating Council

NIR - Near-Infrared Radiation

NiS - Nickel Sulfide

$\mathrm{NO_x}$ - Nitrogen Oxides

PVB - Poly Vinyl Butryl

PVC - Poly Vinyl Chloride

$\mathrm{SO_x}$ - Sulphur Oxides

TOGH - Toughened Glass

UV - Ultraviolet

WAA - Water Activated Adhesives

Symbols and units

Φ - Solar flux (W/m²)

α - Absorption of glass component (N/A)

A - Maximum amplitude of average daytime temperatures for 10 years (°C)

h_e - Heat transfer coefficient to the outer surface (W/m²K)

h_i - Heat transfer coefficient to the inner surface (W/m²K)

f_1- Frame factor (N/A)

f_2- Shadow factor (N/A)

E - Elastic modulus of glass (MPa)

α_g- Expansion coefficient of glass (1/K)

$\tau(\lambda)$- Spectral transmittance of the glazing (N/A)

$\rho_o(\lambda)$- Spectral reflectance of the glazing (N/A)

λ - Wavelength (nm)

$S_\lambda \, \Delta\lambda$- Relative spectral distribution (N/A)

$T_{i,j}$ - External transmittance of a glazing system (N/A)

$R_{i,j}^{f}$- External front reflectance of a glazing system (N/A)

$R_{i,j}^{b}$- External back reflectance of a glazing system (N/A)

A_j - External absorption of a glazing system (N/A)

τ_s - Internal transmittance of a glass substrate (N/A)

r_s - Internal transmittance of a glass substrate (N/A)

$e_{i,j,k}$- Thickness of glass element (mm)

$\theta_{i,j,k}$- Temperature of glazing elements (°C)

$\theta_{ai,ae}$ Temperature of internal and external environment (°C)

hc_{ij}- Convective heat transfer coefficient between glazing elements (W/m²K)

hr_{ik}- Radiative heat transfer coefficient between glazing elements (W/m²K)

σ - Tensile stress of glass (MPa)

1 Introduction

Glass is one of the most commonly used material in architecture nowadays. Due to its appealing nature of transparency and varied use, it cannot be avoided in the modern lifestyle. The use of glass in buildings (windows, façade, roofs etc.) requires a profound understanding of its failure behavior. This document is focused on prediction of thermal breakage failure due to the temperature difference across its surface, for instance by solar heating when a window film is applied. The relevance of this study lies in the fact that very little guidance is available to estimate the thermal fracture of glass till date, despite it is widely acknowledged risk [1].

In this first chapter, the background and my inclination towards this work are explained. First, the problem is defined and then the objectives and methodology followed are exposed. At the end of this chapter, the outline of the dissertation is provided.

1.1 Context

1.1.1 Current Energy concerns

The rapid economic growth and the improved standard of living nowadays have raised many concerns worldwide about current trends in energy consumption. Based on World Energy Outlook's Reference Scenario [2], the amount of energy need is expected to get doubled by 2050, by which the expected increase in global energy service demand is about 10 times. Thus, in order to make a sustainable energy transition, the need for energy efficiency remains as an action priority and it plays a fundamental role in supporting it.

Energy efficiency is taking its place as a major energy resource in the context of national and international efforts to attain sustainability. To have a better understanding of the need for energy efficiency, the *Figure 1.1*, demonstrates energy efficiency is one of the key action priorities to tackle future energy problems [3].

The International Energy Agency (IEA) in its, report on Modernizing Building Energy Codes indicates high-performance envelopes as a priority in the cold areas of US, EU, and Russia, where an overall reduction of 33% in building energy request could be obtained, which accounts for 17% of the 3.2 $GtC0_2$ savings directly attributable to buildings in 2050 [4].

Improving the energy efficiency has been identified as a key enabler to maintain the current standard of living as well as to reduce the harmful emission of gases such as CO_2, NO_x, and SO_x or to at least maintain them at current levels [5]. Climate change, which is occurring all over the world, refers to a change in the weather pattern over a period of time. Experts believe that the world will be getting warmer, which can't be explained just by natural variability. As the human interventional activities with nature, especially industrialization and urbanization have made the planet warmer [6], the environmental concerns have risen sharply on global agenda and gave rise to the foundation of Intergovernmental panel on climate change. Thus, an environmental consideration should be taken as a topmost priority in future developments.

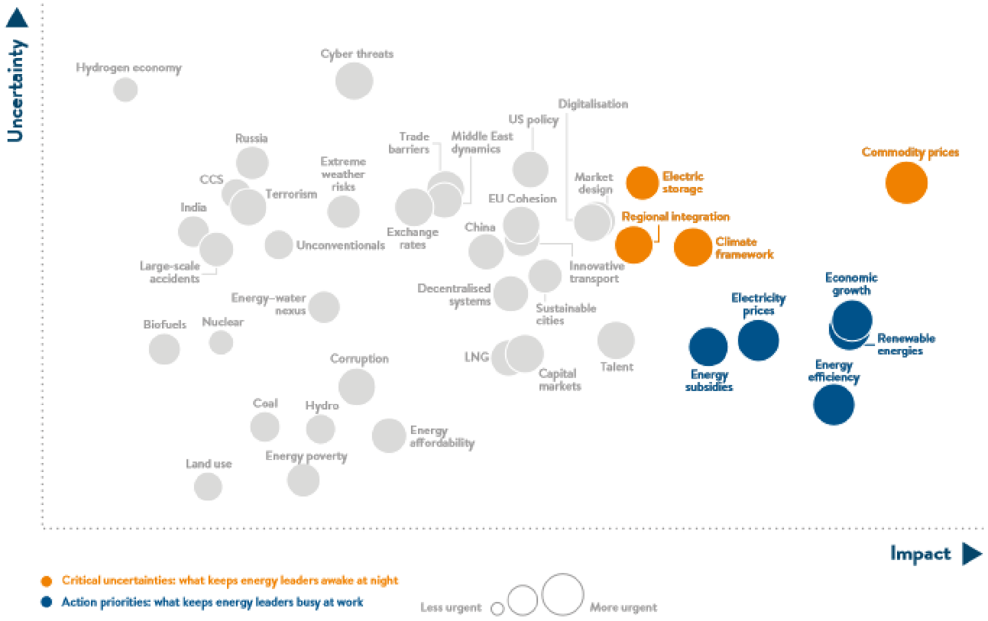


Figure 1.1: Top critical uncertainties and action priorities of energy issues – 2017 [3]

1.1.2 Energy use in buildings

In today's world, energy accessibility has played an important role, such as creating comfort, supplying drinking water, generating power for our day today appliances and so on. Based on IEA data information [4], the building consumption represents the largest energy consuming sectors in the economy, with about one-third of the final energy and half of global electricity being consumed by building sector. This is pictorially represented in the below *Figure 1.2,* which shows the final energy consumption by sector-wise final energy consumption. Consequently, they are also responsible for one-third of global CO_2 emissions. Because of that, an increased attention on energy usage in building sector around the world has increased in recent years.

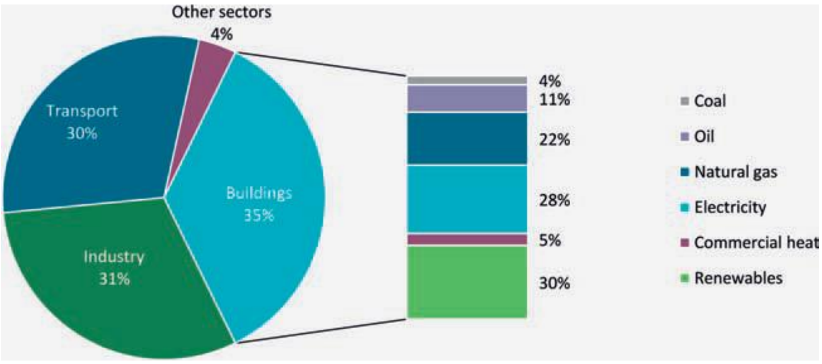


Figure 1.2: Final energy consumption by sector and buildings energy mix, 2010 [4]

In fact, the demand for heating and cooling system is expected to be the tripled between 2010 and 2050, being its current estimation accounts for nearly 60% of global energy consumption in buildings [4]. At the national level, it accounts for 20-40% of the individual country total final energy use. Per capita, energy use in buildings of colder countries is between 5-10 times higher than in warm, low-income regions, such as Asia or Africa [7]. This represents direct opportunities to reduce building energy consumption, improve energy security and CO_2 reduction due to the fact that heating and cooling needs are mostly provisioned from fossil fuel in most of the countries.

The building sector is expected to play a significant role in our global economy as a key to the future sustainability due to their design, construction, and its operational activities are significant contributors of energy-related sustainability challenges [4]. Nowadays, technologies and standards that allow the building sector to be more sustainable are already available. Unlocking the potential of energy efficiency in building sector would be the key priority for all countries in near future [7]. On another hand, the International Energy Outlook 2016 [8] shows that two-third of economically viable energy efficiency potential will remain unleashed due to the absence of concrete policy push.

A study on final energy end-use of building [7], reveals it is possible to achieve significant (50% or more) reduction in energy use of existing buildings. Once the gross energy requirement has been reduced by a factor of two or more, it will be possible to meet the energy requirement with on-site renewable energy generations like solar photovoltaic, thereby reducing net energy requirement to zero.

In this sense, one of the fundamental challenges in today's scenario around the world is replacing fossil fuels with renewable energies. All the frequent practices have been intensified in order to utilize the earth and its environment as a source of energy [6]. *Figure 1.3*, shows the scenario constructed by Global Energy Assessment (GEA's) experts which demonstrate a reduction of approximately 46% of global final heating and cooling energy use is possible by 2050 in comparison with 2005 energy consumption. This reduction can be attained through the proliferation of today's best practice in building design, operation, and construction. The study also reveals that about - 126% increase in floor area during this period could be achievable by increased amenity and comfort without interceding in economic and population growth trends.

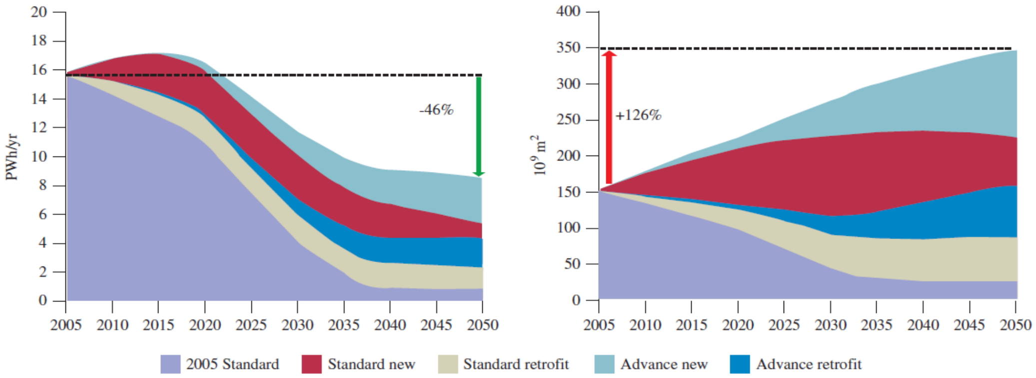


Figure 1.3: Global final building heating and cooling energy use 2050 projection [7]

1.1.3 Importance of window glazing system in buildings

The benefits provided by windows in buildings have been recognized for centuries. They include natural lighting, outdoor visual, ventilation or natural cooling among others. In addition, proper sizing and orientation can enable the window to positively impact a building's heating and cooling loads. It also, protects occupants from the harmful effects of UV rays and valuable furnishings from fading. It is architecturally accepted that window glazing (glass area) system is considered as the most fragile part of buildings in terms of energy indoor performance. And also, it is the only part of the building that has direct solar gain due to its transparency. Consequently, this part of building envelope should reap high consideration by architects and engineers [9].

However, 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 the substantial quantity of heat loss and gains. They are also considered as the friable part between indoor and outdoor environments, therefore, having a major influence on energy consumption.

1.2 Problem statement and motivation

1.2.1 Thermal breakage due to applied film

Recent regulations have enforced existing building to be more energy efficient due to their higher rate of energy loss through the building envelope. Therefore, the thermal properties of those building envelopes should be corrected to reduce the energy loss. One of the easiest way to change the building envelope properties especially on glass windows is the use of polymeric films. In this sense, the glass has a risk of thermal breakage that might be increased by the incorrect specification of window film.

The major cause of glass breakage is due to the propagation of thermal stress as a consequence of a temperature difference build on a glazed glass of building windows. *Figure 1.4*, depicts the formation of temperature gradient and tensile stress in a window glass, which may be induced by different sources of heating or cooling [10]. Usually, in single or multiple glazing, this gradient is established between the area of a window exposed to solar radiation and the closed peripheral zone in the frame of glazing or zone shaded by an external element like trees, buildings nearby, awning etc.

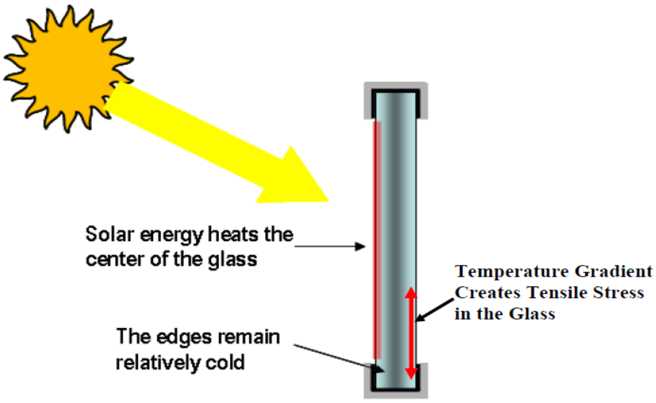


Figure 1.4: Tensile stress in window glass

Uneven heating due to direct sunlight makes glass expand and contract at a different rate. Since the warmer part will try to expand, thus leading to high tensile stress at colder parts (usually at the edges). When this stress exceeds the local glass edge strength, the glass will break. Thermal breakage will start at the colder area, perpendicular to the glass edge and the breakage pattern will depend on the built-up stress. A fully tempered glass has a significantly higher thermal strength to withstand chances of thermal breakage compared to annealed or heat strengthened glass.

There are many ways to deal with this problem today. But the most widely used traditional method for avoiding thermal fracture risk is to use heat strengthened glass even though this is not always a structural demand for a proposed design [11]. This is a conservative approach to reduce the risk of thermal breakage in glass due to temperature difference but on another hand, it leads to inefficient use of material and wastage problem.

1.2.2 Objectives and 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 [12] or through a film compatibility chart that shows a specific film is suitable for a particular glass type. Some window film industries include compatibility checks as a part of their warranty coverage program as well.

Knowing the problem, that there does not exist any reliable procedure to check window film to glass breakage compatibility, the main objective of this Master thesis aims to develop a computing tool which considers various parameters involved in thermal breakage phenomenon and can predict the breakage of glass on applying the window film. The tool developed, named *FG-Breakage,* would be important for architects and engineers by pointing out the thermal breakage risk associated with different thin films available in the market and by providing a suitable recommendation to avoid it. The tool has considered the thermal breakage methodology followed by French Norm DTU 39 and extended its applicability for window films.

In order to develop *FG-Breakage* computing tool the important factors to be considered are as follows,

- Identification of parameters that causes thermal breakage of the glass.
- Influence of window films on thermal breakage of glass.
- Calculating the maximum temperature difference that will lead to fracture of glass with film.
- Identification of proper validation methods for the obtained results.

A recent study revealed [11], that for a typical one-story building, heat loss through window accounts for 15-22%. Also, in countries with cold winter, low thermal resistance can cause discomfort for occupants adjacent to large window area. To summarise, the window system is of prime importance in modeling energy efficient buildings and thus it motivated me to study the problem of thermal breakage associated with it when a film is applied to it.

1.3 Thesis Structure

The dissertation consists of 6 chapters, as follows:

Chapter 1 provides an introduction to the work, including also the motivation and objective description.

Chapter 2 presents the state of art concerning glass production and window film technology. First, an introduction to glass material manufacture and its chemical composition with main properties are exposed, it also provides a brief overview of window film technology and the products available in the market are described.

Chapter 3 is focused on optical calculation involved in window film to glass structure. Initially, a brief overview of the solar spectrum and the importance of window films are explained. Later, measurement of optical properties and its numerical calculation are discussed in detail along with window film integration technique.

Chapter 4 takes consideration of the thermal breakage problem and its associated calculation. It starts with a brief explanation of the thermal breakage phenomenon. Later, it provides a brief description of calculation method followed by French Norm DTU 39.

Chapter 5 is dedicated to present the results obtained using *FG-Breakage*. The results are compared with other software and numerical approximation tools and a discussion is given.

Chapter 6 summarizes the conclusions and recommendations for the future work.

2 Literature Review and Background

Glass is one of the most widely constructing material used due to its combinations of strength, durability, and transparency among others. Since it offers the possibility of transmitting natural light, soon it earned a major influence on window glazing systems.

Numerous developments to improve the glass quality were made in last few decades, like the invention of float process, the introduction of new chemical treatments at the surface. Heat treatment process consists of heating the glass to a certain temperature followed by controlled cooling procedure until room temperature. Depending on the cooling rate the glass can be classified as heat-strengthened (HSG) or toughened glass. In latter case, the residual stress in the glass will be higher due to the faster cooling rate. It should be pointed out that the glass resistance is highly dependent on surface imperfections, since they reduce the tensile strength. The use of glass in building windows require a basic understanding of its production process which are described in the following section.

2.1 Glass Chemical Composition

Glass is an inorganic and non-crystalline amorphous compound formed as a result of melting raw materials (mainly silica sand (SiO_2)) at an elevated temperature followed by a cooling down process. In commercial glass plant, making of glass involves three basic ingredients – formers (silica), fluxes and stabilizers. The formers are the main constituent of glass, which is usually silica sand that is having a very high melting temperature around 1700 °C. To reduce the processing temperature of silica up to approximately 1000 °C, flux such as sodium carbonate (Na_2CO_3) is added, making also the process more practical and economical. But on other hand by adding sodium carbonate, the glass will be water soluble and not very durable. So, in order to make glass stronger and more durable stabilizers such as lime (CaO) and magnesia (MgO) are added. The basic chemical reactions of a glass making process are shown in the equation 2.1 [13].

$$\begin{gathered} Na_2CO_3 + SiO_2 \xrightarrow{1500\,℃} Na_2SiO_3 + CO_2 \\ Na_2SiO_3 + xSiO_2 \xrightarrow{Na_2SO_4} (Na_2O)(SiO_2)_{(x+1)} \end{gathered} \tag{2.1}$$

During the cooling process, the molten silica is transformed into an amorphous material known as vitreous silica, which is the purest form of glass. Also, during the cooling process, the viscosity increases and the mobility of the atoms is hindered, thus preventing arrangements and crystallization from occurring. The corresponding schematic view of the soda lime silica glass is provided below:

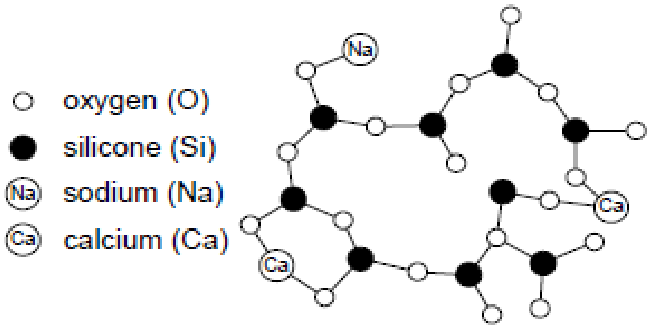


Figure 2.1: Schematic view of the irregular network of a soda lime silica glass [14]

The most familiar type of glass material used in construction is soda-lime glass, consisting of silica, sodium carbonate, calcium oxide and other additives. The percentage of each ingredient mentioned above will affect the thermal, mechanical and optical properties of the glass. *Table 2.1* shows the chemical composition of soda lime silica glass according to current European standards (EN 572-1 2004).

Table 2.1: The composition of soda-lime glass according to EN 572-1 2004.

Components	Structural formula	Soda-lime Silica Glass
Silica sand	SiO_2	69 – 74%
Lime (calcium oxide)	CaO	5 – 14%
Soda	Na_2O	10 – 16%
Boron-oxide	B_2O_3	–
Potassium oxide	K_2O	–
Magnesia	MgO	0 – 6%
Alumina	Al_2O_3	0 – 3%
others		0 – 5%

2.2 Primary Process for Float Glass

Currently, 90% of today’s flat glass production worldwide is manufactured by the float process. The major advantages of this production process is it's low-cost, its wide availability and its superior quality with high reliability [15]. *Figure 2.2* shows the complete production process involved in float process, which includes the following stages:

Melter: A finely grained raw ingredients of glass are mixed in a batch mixing process in a controlled ratio inside a furnace where it is heated to approximately 1500°C. Once molten, the temperature of the glass is stabilized to approximately 1200°C for a homogeneous specific gravity.

Tin bath: Glass from melter section flows gently over a refractory spout onto the mirror-like surface of molten tin starting at 1000°C and leaving as a solid ribbon at 600°C.

Annealing Lehr: Despite the tranquillity with which solid ribbon is formed, considerable stresses are developed in it float glass as it cools. Since too much stress will make glass to break beneath the cutter, they should be reduced, to relieve these stresses, the float glass undergoes heat-treatment in a long furnace known as Lehr.

Inspection: The float process is renowned for making perfectly glass perfectly flat, flaw free. So, to ensure the highest quality, an inspection takes place at every stage using manual and automated techniques.

Cutting: Finally, diamond wheels are used to trim off selvedges (stressed edges) and cut the ribbon to a size dictated by the computer.

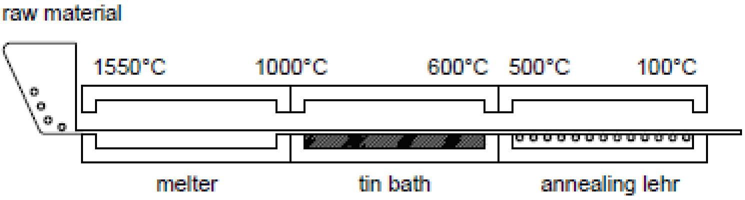


Figure 2.2: Production process for float glass [14]

2.3 Secondary Process for Float Glass

After the glass plate attains its final form, flat glass plates are often preceded further to produce glass products of the desired shape, performance, and properties. By treating the glass thermally or chemically, the tensile stress in the core and compressive stresses near the surface will be created.

2.3.1 Thermal Tempering

For structural glass application, tempering is the most important thermal post-treatment carried out after the primary process. The glass sheet is reheated to about 620-675 ° C where the glass is in the plastic phase. It is then suddenly cooled down by cold air. Accordingly, the outer side of the glass sheet cools more quickly than the core causing permanent stresses. In *Figure 2.3* it can be seen that the core is under tensile stress, while the zone near the surface is under compressive stress. The final product is called heat-toughened glass or tempered glass.

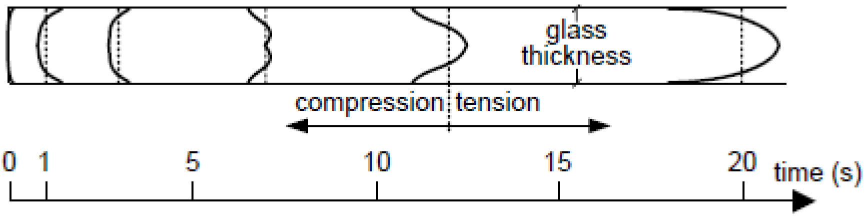


Figure 2.3: Transient stress field during the tempering process[15].

It is possible to perform the cooling process slower, resulting in residual stress and therefore the tensile strength gets lower. This is known as heat-strengthened glass (HSG). The properties are much better than that of float glass but worse than toughened glass. The typical residual compressive surface stress varies between 40MPa and 80MPa for heat-strengthened glass.

While normal annealed glass can withstand a temperature difference of about 40°C, HSG can withstand a temperature difference of 100 °C and thermally tempered glass, even at 200 °C. [16], The fracture pattern observed is a function of the energy stored in the glass. The HSG glass is difficult to break compared to ordinary annealed glass, but unlike toughened safety glass, it breaks typically edge to edge and in fragments.

2.3.2 Chemically Hardened Glass

The chemical tempering is an alternative process to generate different residual stress profile. Here, the glasses are dipped in a chemical liquid and it is only affected by a very thin zone of the glass. This process is very slow and creates a pressure zone on the surface at a rate of 20 microns per 24 hours. The advantage is that drilling or cutting glass afterward remains possible. The disadvantages are its slowness and expensive manufacturing process. The chemically tempered glass is rarely applied in building, it is used for special areas where tempering process can’t be applied, like glass with narrow bending applications.

2.3.3 Laminated Glass

Laminated glass is of great interest in structural application compared to simply tempered glass. It consists of two or more glass panels bonded together by a polymer interlayer, usually polyvinyl butryl (PVB). Though tempering improves the structural capacity of glass, it is still brittle in nature while laminated glass enables significant improvement of post-breakage behavior. Thus, laminated glass elements have high structural capacity compared to annealed or heat strengthened glass. The post-breakage behavior mostly depends on the interlayer material. Based on one or more special transparent interlayer the laminated glass will have a different post-breakage behavior and also it will have diverse applications as for instance fire protection, bullet or blast resistance [17].

2.3.4 Insulating Glass Unit

Insulating glass units or IGUs is a multi-glass layer consisting of two or more glass panels enclosed in a hermetically sealed airspace filled with noble gas, generally Argon or Krypton. All types of glass, either annealed or heat-treated glass (either HSG or toughened) can be used for IGUs [15]. It is mainly designed for building’s window and door systems to keep spaces warmer in the winter season and cooler in the summer season. Besides, it also reduces the thermal losses, saves energy and it improves the transparency reducing condensation on the warm air side. Usually, the panels are separated by a spacer and the whole unit is assembled by a secondary edge seal, which gives structural robustness. Modern IGUs have heat transfer coefficient (U-values) of 1.1 W/m^{2}K for double glazing and 0.7 W/m^{2}K for triple glazing. *Figure 2.4* below depicts the principle build of double glazed insulating glass units.

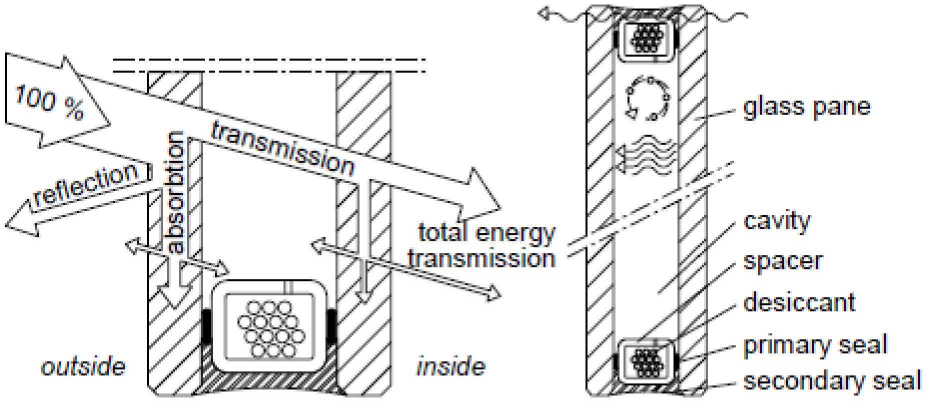


Figure 2.4: Double glazed insulating glass unit [15]

2.4 Properties of Glass

Glass properties (mechanical, thermal, electrical, optical, chemical, etc.) are very dependent on the glass composition and post-treatments. This section summarizes those properties which are more relevant to the scope of this master thesis, such as mechanical, thermal and optical properties since they can be easily modified when a polymeric film is applied on the surface of the glass.

Mechanical Property: The mechanical properties of glass are those properties that involve the reaction to an applied load and it will determine its ability to resist damage and prevent failure. These properties may include density, modulus of elasticity, compression resistance, etc.[18] The glass is an almost perfect elastic material, with isotropic behavior that exhibits brittleness. Some of these values are resumed in *Table 2.2* for a typical float glass.

Thermal Property: The thermal properties of glass can be simply defined as material properties that vary with temperature without altering the material's chemical identity. This may include specific heat, thermal conductivity and thermal expansion [18]. Glass behaves linearly elastic when the temperature is below the distortion temperature. It is important to understand thermal properties of glass when designing a glazing system as it might lead to increase in temperature. When the glass exposed to a sudden or gradual change in temperature, improperly chosen glass can even fail. Thus, information about thermal properties of glass will assist in selecting a suitable glass composition for an application.

Optical Properties: The optical properties of glass will determine how it will interact with light, being dependent on chemical composition, glass thickness, and the applied coatings [18]. Today, most engineers use advanced numerical tool to compute the optical properties of glass. The familiarity of few fundamental optical properties will help engineers to choose right materials according to their application, that includes refractive index, reflection, absorption, and transmission. As a summary, corresponding values for some of the properties discussed above are tabulated in below *Table 2.2* for float glass and more detailed characteristics will be shown in forthcoming chapters.

Table 2.2: Properties of float glass [20].

Properties	**Value for Float Glass**
Mechanical:	
Density	2500 kg/m3
Young's Modulus	70 000 MPa
Thermal:	
Specific Heat	0.8 J/g/K
Thermal conductivity	0.8W/mK
Thermal expansion	9.10-6 K-1
Optical:	
Refractive Index	1.52

2.5 Window Films

The concept of window film (an adhesive backed polymer) is not new, as its application for solar control flat glass application dates back in the early 1960s. Currently, there exist numerous films in the market that can modify the characteristics of a glazing system.

Nowadays, the main application of these films continues to be the control of the solar radiation that passes through the glass in order to increase the energy saving and the comfort. They have become an excellent alternative, from the economic and environmental point of view. As they provide an improved heat retention capacity and have a less environmental impact than creating a new window and disposing of the old one. Thus, window films assist in reducing the carbon footprint more effectively and at a lower cost than substituting old windows by new ones.

Furthermore, due to recent developments in new products that add new functionalities to the glass like light control, change of color of the glass, the possibility of digital impression, etc., the use of these films and their demand - by architects and designers - has been increasing gradually.

2.5.1 Components of window film

Window film constitute a complex structure involving several different membrane materials interleaved with each other. It is composed of a polyester substrate to which a scratch-resistant coating is applied on one side, a mounting adhesive layer and a protective release liner is applied to another side [19]. A standard window film might have up to eight layers (*Figure 2.5*) that can undergo several manufacturing processes. All components must have high optical characteristics to allow undistorted vision through the glazing of the window system. The performance and durability of window films depends on these layers and a brief description of each of these layers are:

Protective release layer: It is the outermost layer, it is usually made of polyester and generally serves to protect the adhesive from external contamination if exposed to air. It should only be removed before its application in the glazing.

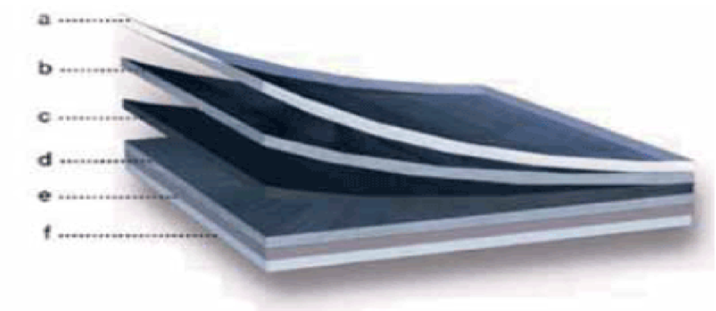


Figure 1:
Structure of a typical window film
a) release liner with silicone coating;
b) adhesive layer with UV inhibitor;
c) clear or tinted polyester film;
d) adhesive layer;
e) metallised layer for heat rejection on clear polyester film;
f) scratch-resistant coating.
Layer c may have added UV inhibitors for extended durability

Figure 2.5: Different layers of window film [19]

Adhesives: Adhesives used in window film can be of two types, pressure sensitive adhesive (PSA) and water activated adhesives (WAA). PSA form a bond with the glass by applying pressure forces, without the need of applying any kind of solvents to ensure the connection between the two surfaces. On the contrary, water activated adhesive requires water to ensure proper bonding with the surface of the glass.

High-Performance UV Resins: It can be incorporated with the adhesive or in the polyester layer. This resin improves the thermal performance of window film by reducing the solar gain and protecting the inner atmosphere of the building from the early degradation by UV exposure.

Polyester Film: This polyester membrane should offer a good physical, optical and thermal characteristics to films. It makes films to be durable, flexible and temperature resistant. It includes different types of finishes such as UV resin or adhesives, which makes it a very versatile material. The polyester may have incorporated metal oxides in order to reflect radiation at different wavelengths.

Lamination Adhesive: It is used to attach various polyester layers through the lamination processes. Sometimes they come embedded in their own membrane polyester.

Metallized Layer: The metal present in this layer is incorporated within the polyester membrane and it has the function of reducing solar gain through glazing. The metal used is typically aluminum and can reduce solar gain of about 80%, reducing also the visible radiation at about 15 to 70%.

Scratch Resistant Coating: It has a hard-acrylic coating that provides protection against normal wear and tear of polyester films due to varied environmental conditions.

2.5.2 Types of Existing films in Market

There is a wide variety of films available in the market, thus a proper selection of the film for a window is required, in order to substantially contribute to the improvement in thermal and energy performance of the glazing and at the same time the film should not contribute to increase in thermal stress of glass. The films found in the market [20] can be classified according to their main characteristics, as follows:

Solar control Film: It lowers the solar factor of the glazing, helping to control the increase in temperature of interior spaces and thereby reducing the energy consumption of the cooling systems.

Ultraviolet (UV) Protection Film: It prevents the entrance of the UV radiation and protects the interior space that might include an interior material layer, curtains or furniture. It is highly recommended for application in art galleries, museums, and shops as they help to prevent premature aging caused by prolonged exposure to UV rays.

Low Emissivity Film: It improves the thermal insulation of the glass and it also contributes to the reduction of energy expenses both in summer and winter, keeping the inside temperature at the desired levels of comfort.

Safety and security Film: It has the ability to absorb energy from an impact and hold the splinters resulting from a fall, protecting people and property and contributing to the durability of the glass. It is recommended for use in glazing schools and hospitals.

Decorative Film: There is a very large quantity of films for decorating interiors and exteriors glazing with varied ranges of colors and patterns that enhance the aesthetics of a glassed and increase the range of new designs in buildings possibilities.

3 Window Film to Glass: Optical Calculation

At present, there are several advanced glazing systems available in the market. For example, there are some special glass that have the ability to filter ultraviolet (UV) or infrared (IR) radiation from solar spectrum, or in some cases, they may reduce the transmittance of visible light or increases it by using anti-reflective glazing. For which, the optical properties of glazing system serve as an input data for the assessment of visual and thermal comfort in the building by means of dedicated tools. Thus, in order to understand the optical features of glazing system and calculation of its optical properties, this chapter focuses on understanding its basic concepts. Then the issue with direct measurement of optical properties and a brief overview of calculation procedure followed by the FG-Breakage tool to compute the changes in the optical properties on applying a film to specific glass are discussed.

3.1 Solar Radiation Spectrum

The solar radiation is the full spectrum of electromagnetic radiation coming from the sun and filtered by the atmosphere. It is divided into three parts: ultraviolet (UV), infrared (IR) and visible (VIS) radiation – commonly referred to as daylight which constitutes about half of the total energy of solar radiation reaching the earth surface. Also, the solar radiation reaching earth surface is further subdivided into diffuse and direct solar radiation, the diffuse radiation reaches earth after getting scattered by clouds or through other layers of atmosphere [21].

On the other hand, all objects emit infrared radiation, referred to as blackbody radiation. While for the case of the sun, it is called as near infrared radiation (NIR) and for other objects common on earth, i.e. 0 – 100 °C, it is referred as thermal infrared (IR) which is depicted in the *Figure 3.1* where the solar radiation at sea level and the radiation emitted by a warm object at 20 °C are compared. The wavelength range for each radiation type can also be seen. Note that in the following figures the wavelength scale is in logarithmic, which makes solar spectrum to look broader at low wavelengths than on a linear scale.

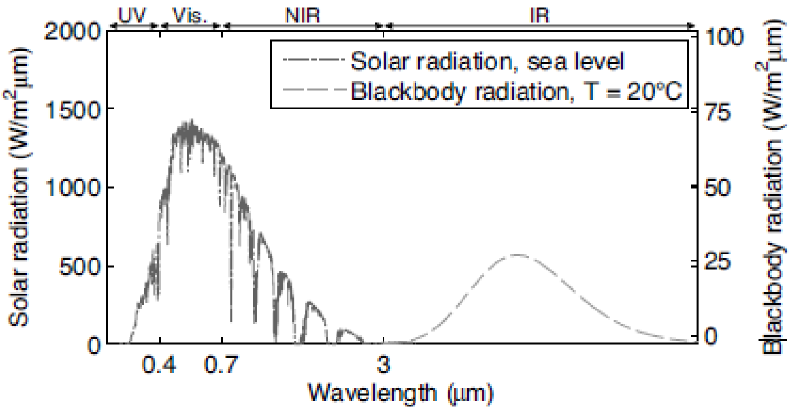


Figure 3.1: Solar spectrum at sea level together with blackbody radiation of 20 °C warm object [26].

In the case of a glazing system, there is a need to understand the solar spectrum characteristics because the optical properties of a window are obtained through the glazing interaction with the electromagnetic radiation to compute how much sunlight will be reflected, transmitted and absorbed by different panes. Based on which solar radiation enters through the glazing system it will contribute either to heating or to cooling needs of a building as well as it will be used to determine the thermal stress buildup in glasses.

3.2 Glazing Function

The simplified sketch of the window glazing system (glass part) is shown in *Figure 3.2.* It consists of several parts, in which the obvious part is the glazing, that consists of glass layers separated by air gaps. The glass layers are mounted directly on frame depending on its easy accessibility during use and repair. Nowadays, it is getting more common to seal the glazed unit by using spacers and it is normally referred to as insulated glass unit (IGU). This process facilitates the assembling of the window as well it makes possible to fill the gap with other gases or to apply a coating that requires protection from the environment. Conventionally the panes and surfaces are numbered from outside, so the first surface is the surface facing outside atmosphere. The spectral properties that are concerned to glazing system are normally transmittance, reflectance, and absorbance, which corresponds to the fraction of solar radiation that is transmitted, reflected or absorbed respectively by glazing area. These properties are functions of wavelength and can be either theoretically calculated or experimentally determined [22].

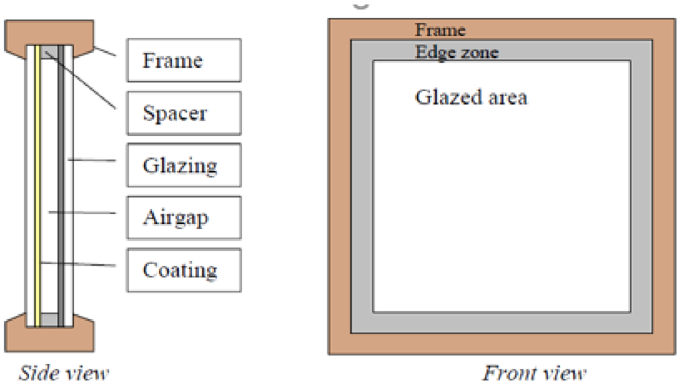


Figure 3.2: Schematic picture of window glazing system [22]

For a clear glass sheet, which has a very low extinction coefficient, the transmittance is high within the solar spectrum. But by applying a thin-film coating to the glazing, its spectral behavior can be changed to fit for different applications. For example, in the case of a very cold climate, that requires heating along all the year, an energy-efficient window should allow to enter as much of solar radiation as possible and thermal emittance should be low [22]. Hence window will collect as much energy as possible from solar radiation and will lose as little energy as possible to the outside i.e. the window should have high transmittance in the solar spectral region and as low emittance (high reflectance) as possible in the thermal spectral region. This type of window is commonly referred as low-emittance (Low-E) window and it usually has low-emissivity coating on the outer surface of the inner pane [21]. Its spectral properties for the ideal cold climatic condition are illustrated in below *Figure 3.3*.

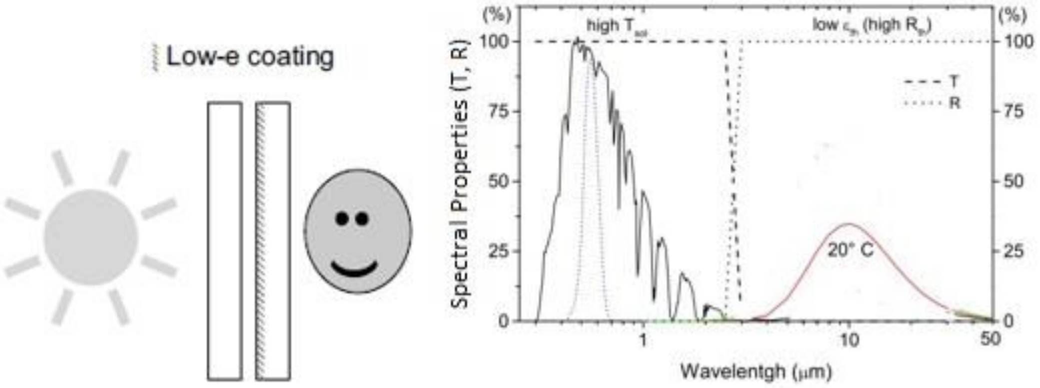


Figure 3.3: Position of coating for low-e window and its spectral properties T and R [21] [22]

In case of a warmer climate conditions, where overheating is a common problem, then the part of the solar spectrum (NIR) that is outside the visible spectral region can be blocked leading to a window with a high transmittance within the visible spectral region, i.e. high T_{vis}, and low transmittance elsewhere as illustrated in the *Figure 3.4.* In this situation, about half of the solar radiation is constituted by visible region, which means that about half of the solar radiation can be reflected from the window without affecting its visual aspect [22]. It is often accepted or even desired to have a reduced transmittance within the visible spectral region so that a lot of solar energy can be blocked before it enters the building to reduce the expensive cooling needs. A window with these optical properties is commonly referred as solar control window, which can be achieved with a low-e coating on their inner surface of outer pane [21].

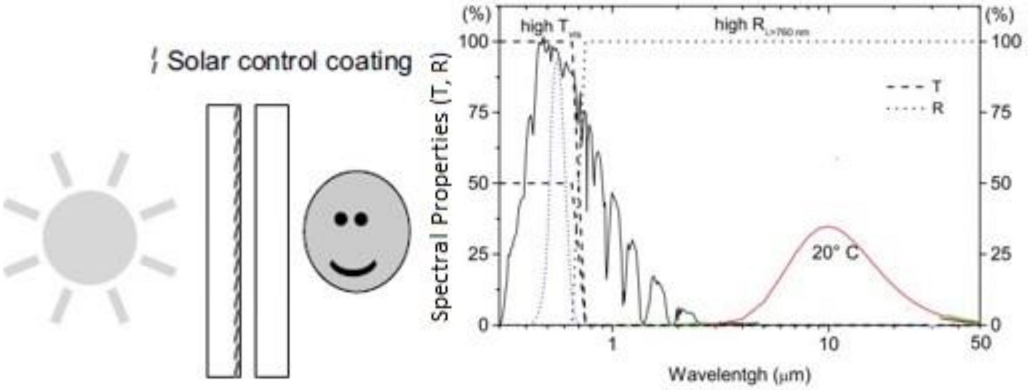


Figure 3.4: Position of coating for solar control window and its spectral properties T and R [21][22]

3.3 Measurement of Optical Properties

The glazing choice has an impact on the thermal comfort and energy performance of a building in all climates. Accurate, reliable and comprehensive measurement of the spectral optical properties of glazing materials is necessary in order to design a glazing system with appropriate energy labeling and performance rating. Direct measurement of all spectral properties involves time-consuming procedure, which requires spectroradiometers to measure properties like spectral transmittance and reflectance at normal incidence [23]. However, prediction of the properties of composite systems such as applied flexible films cannot be obtained directly due to its complex structure. The properties of a series of structures can be generated from those of the base structure. i.e. the properties of a coated or uncoated substrate could be extended to a range of available substrate of any thickness [24]. Similarly, a coating type could be transferred to any other substrate through appropriate calculations. Also in most of the cases, sunlight does not fall at normal incidence to a glazing surface, in fact it often strikes at angles for which transmittance and reflectance values are slightly different from their values at normal incidence. Results from an inter-laboratory comparisons organized by the European Union revealed that commercially available oblique incidence reflectance/transmittance accessories were often unreliable and many measurements were inaccurate [25]. A reliable procedure for extrapolating data from normal incidence to oblique incidence is thus needed for accurate annual energy performance calculations.

The optical calculations can be performed straightforward if the refractive indices are known at every point within the system. One fundamental problem with this approach is that the manufacturers may be unwilling to reveal the structure, properties, refractive indices or even thickness of layers with the accuracy needed to perform the calculation [23]. On the other hand, we could measure the properties that we need for each angle and polarization or any combination of layers through laboratory experiments, but the amount of data generated for all products would be impractical and furthermore oblique measurements do not yet fall within the scope of existing standards.

Although the optical properties of coated window films are not readily available, this does not mean that they cannot be determined, as some of the most complexes coated glazing surface has been successfully determined by both ellipsometric and radiometric techniques. But, in general, we could say it is a time-consuming process, so these led to the development of numerical approximation tool like Optics 6 [26]. Based on which *FG-Breakage* tool is developed using Microsoft Excel VBA programming to determine the approximate solutions that meet most of the required criteria without necessarily resulting in the true values. And the following sections will explain the calculation involved in finding the optical properties of glazing system.

3.4 Optical Property Calculation

3.4.1 Standard – EN 410

European standard EN 410 [27] specifies the methods for determining light and energy transmittance of solar radiation for a glazing in buildings. These characteristics data (spectral properties) serve as a basis for light, heating and ventilation calculations of any room and it can allow comparison between different types of glazing [27]. For computing the spectral properties (transmittance and reflectance) of a glazing type, EN 410 standard uses measured optical data obtained through a spectroradiometer - provided by the manufacturers to the International Glazing Database (IGDB). The database consists of around two million spectral data for all the glazing products that are available in market. The *FG-Breakage* tool also uses these data ($\tau(\lambda), \rho_o(\lambda)$) to compute transmittance (τ_e) and reflectance (ρ_e) along the wavelength by using the following equations:

$$\tau_e = \frac{\sum_{\lambda=300nm}^{2500nm} \tau(\lambda)\, S_\lambda\, \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda\, \Delta\lambda} \qquad (3.1)$$

$$\rho_e = \frac{\sum_{\lambda=300nm}^{2500nm} \rho_o(\lambda)\, S_\lambda\, \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda\, \Delta\lambda}$$

Where,

S_λ is the relative spectral distribution of the solar radiation;

$\tau(\lambda)$ is the spectral transmittance of the glazing;

$\rho_o(\lambda)$ is the spectral reflectance of the glazing;

$\Delta\lambda$ is the wavelength interval;

Table A 1 in Annex A indicates the values of relative spectral distribution $S_\lambda\, \Delta\lambda$ for the wavelength range of 300 – 2500 nm [27]. The *Table* is drawn up in such a way that $\Sigma\, S_\lambda\, \Delta\lambda = 1$.

3.4.2 External and Internal Radiometric Model

The radiometric model [23] provides a mathematical method to obtain the spectral properties of multi plane-parallel layered systems such as a typical window, which can be considered as a collection of (L) parallel plane layers whose thicknesses are large compared with wavelengths of incident sunlight as in *Figure 3.5* (by convention element 1 is outermost layer exposed to atmosphere)**.** Radiometric model is classified into external and internal radiometric model, where external model is used to calculate the spectral properties of each element in a glazing system and internal model calculates the spectral properties at their interfaces[23].

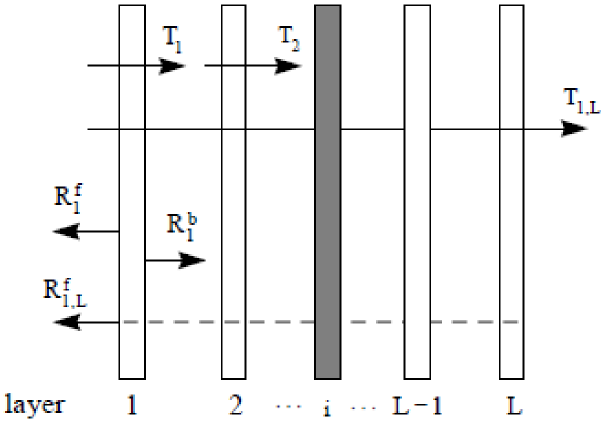


Figure 3.5: Window system consisting of L plane parallel layers separated by gas-filled gaps [23]

For a window composed of two glass elements (*i* and *j)* and applying the external radiometric model the net transmittance ($T_{i,j}$), the front reflectance ($R_{i,j}^f$) and back reflectance ($R_{i,j}^b$) for the subunit are given by:

$$T_{i,j} = \frac{T_{i,j-1}\, T_j}{1-R_{j-1,i}^b\, R_j^f};\; R_{i,j}^f = R_{i,j-1}^f + \frac{T_{i,j-1}^2\, R_j^f}{1-R_{j-1,i}^b\, R_j^f};\; R_{j,i}^b = R_j^b + \frac{T_j^2 R_{j-1,i}^b}{1-R_{j-1,i}^b\, R_j^f} \qquad (3.2)$$

Under this terminology, when the subscripts are equal then the spectral properties are referred to the single glazing layer. An iterative procedure is carried out until transmittance and reflectance values of entire glazing system have been determined.

Then absorption (A_j) of each element in a glazing system can be calculated from the values of transmittance and reflectance of the adjacent layers obtained through equation 3.3 and from the external absorbance of the isolated element.

$$A_j = \frac{T_{1,j-1}\, A_j^f}{1 - R_{j-1,1}^b\, R_{j,L}^f} + \frac{T_{1,j}\, R_{j+1,L}^f\, A_j^b}{1 - R_{j,1}^b\, R_{j+1,L}^f} \tag{3.3}$$

Where,

$$A_j^f = 1 - T_j - R_j^f$$

$$A_j^b = 1 - T_j - R_j^b$$

The external radiometric model discussed above in this section deals with light incident through the air on one side and emerging into the air on the other side. Now for internal radiometric model, let's consider the internal properties such as reflection and transmission through an interface or absorption within a medium. In most general case, we can consider a structure consisting of L layers and L+1 interfaces as in *Figure 3.6* [23].

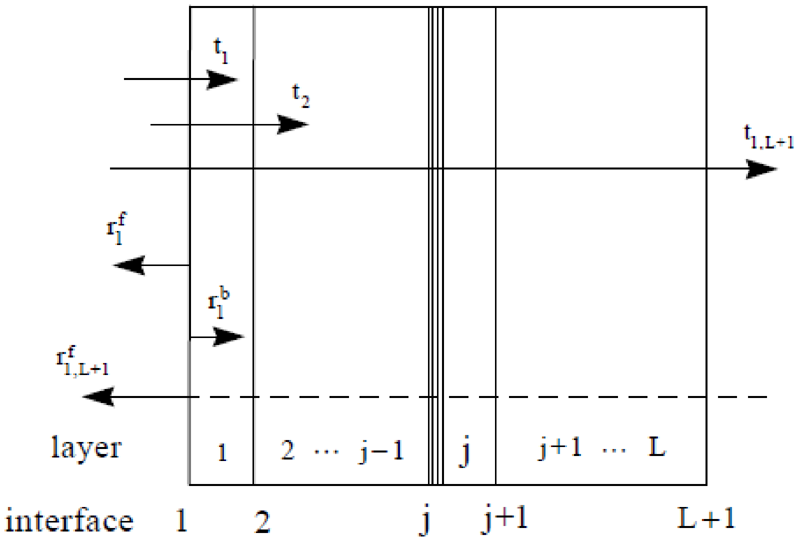


Figure 3.6: Stack of L layers separated by L+1 asymmetric interfaces [23].

The interfaces may be simple i.e. an infinitesimally thin boundary between homogeneous materials or might also be considered complex in the sense that they have a finite thickness, possibly consisting of many thin film layers. By analogy to the external model, with complex interface replacing the elements, similar expressions can be written directly for the system properties. An additional factor of τ_i is introduced to account for the possibility of absorption of a layer i. Then for subsystem bounded by interfaces *i* and *j* and new equations can be defined:

$$T_{i,j} = \frac{t_{i,j-1}\, t_j\, \tau_{j-1}}{1-r^b_{j-1,i}\, r^f_j\, \tau^2_{j-1}};\; R^f_{i,j} = r^f_{i,j-1} + \frac{t^2_{i,j-1}\, r^f_j\, \tau^2_{j-1}}{1-r^b_{j-1,i}\, r^f_j\, \tau^2_{j-1}};\; R^b_{j,i} = r^b_j + \frac{t^2_j\, r^b_{j-1,i} \tau^2_{j-1}}{1-r^b_{j-1,i}\, r^f_j\, \tau^2_{j-1}} \quad (3.4)$$

3.4.3 Base Substrate Solution

The base substrate is considered as an uncoated symmetric glass component, to which thin films will be applied. Thus, by the external radiometric model it can be completely characterized by two independent measured quantities (i.e.) external transmittance (T_s) and reflectance R_s, which it will be assumed as exactly same from both sides, ($R_s^f = R_s^b$). Through internal multilayer radiometric model (Equation 3.4), formulate the measured spectral quantities in terms of interfacial reflectance (r_s) of the substrate in the air and internal transmission (τ_s) [23] as follows:

$$T_s = \frac{(1 - r_s)^2\, \tau_s}{1 - r_s^2\, \tau_s} \quad (3.5)$$

$$R_s = r_s + \frac{(1 - r_s)^2\, r_s \tau_s^2}{1 - r_s^2\, \tau_s} \quad (3.6)$$

Thus, by solving the above quadratic equations it will come up with internal spectral properties (r_s and τ_s) in a closed form in below equations 3.7 and 3.8,

$$r_s = \frac{\beta - \sqrt{\beta^2 - 4(2 - R_s)R_s}}{2(2 - R_s)} \; where\; \beta = T_s^2 - R_s^2 + 2R_s + 1 \quad (3.7)$$

$$\tau_s = \frac{R_s - r_s}{r_s T_s} \quad (3.8)$$

The preferred way to solve τ_s is directly from T_s, as it avoids the measurement of R_s which carries a higher uncertainty than T_s. Hence, internal transmission can be represented by the following equation 3.9 in terms of T_s,

$$\tau_s = \frac{[(1 - r_s)^4 + 4r_s T_s^2]^{\frac{1}{2}} - [1 - r_s]^2}{2r_s^2 T_s} \quad (3.9)$$

3.5 Window Film Integration

The above internal characteristics data of base substrates can serve as the base for the calculation of spectral properties of a glass applied with a window film and it can be used for the comparison between different types of glazing [24]. A window film applied to an existing glazing may have a complex structure as discussed in the previous chapter. *Figure 3.7*, shows the structure of the typical substrate with window film where two polyester substrates are glued together with a “laminating” adhesive. The inner polyester layer may have a solar-control coating and outer layer may have an abrasion-resistant coating. Sometimes this can also be reversed to induce lower emittance effect.

To isolate the effect of the interface between air and adhesive, the adhesive layer is considered as substrate and all the rest of window film structure including polyester layers are considered as a complex interface. Thus, initially, this procedure involves the determination of internal spectral properties of the base substrate (glazing), that can be computed from the above equations 3.7 to 3.9. Later, these computed values are used to separate window film from base substrate to determine the spectral properties of the thin-film by using the equations 3.10 to 3.12. As the adhesive has the same reflective index of glass ($r_s = r_a$), then the absorption coefficient of adhesive can often be considered as zero ($\tau_a = 0$) [23].

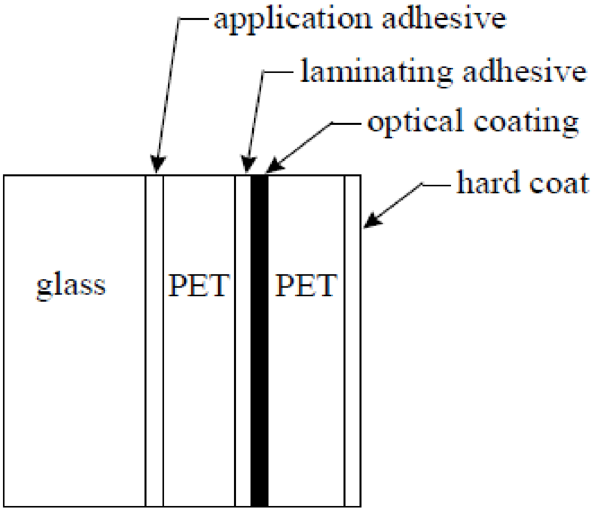


Figure 3.7: Structure of window film on glass substrate [23]

$$r_c^f(\lambda) = \frac{R_c^f(\lambda) - r_s(\lambda)}{\left[1 + r_s(\lambda)\left(R_c^f(\lambda) - 2\right)\right]\tau_s(\lambda)} \tag{3.10}$$

$$r_c^b(\lambda) = R_c^b(\lambda) - \frac{t_c^2(\lambda) r_s(\lambda)\, \tau_s^2(\lambda)}{1 - r_s(\lambda) r_c^f(\lambda)\, \tau_s^2(\lambda)} \tag{3.11}$$

$$t_c(\lambda) = \frac{T_c(\lambda)\,(1(\lambda) - r_s(\lambda)\, r_c^f(\lambda)\, \tau_s^2(\lambda))}{\left(1 - r_s(\lambda)\right)\tau_s(\lambda)} \tag{3.12}$$

In the above formulation, the following symbols were used to designate the intrinsic photometric characteristics of the thin film in the air-film-glass system.

$r_c^f(\lambda)$ – spectral reflectance of film for light incident from air towards film.

$r_c^b(\lambda)$ – spectral reflectance of film for light incident from glass towards film.

$t_c(\lambda)$ – spectral transmittance of air-film-substrate system.

The above optical characteristics values of a thin film are calculated from the measured spectral properties [$r_s(\lambda)$, $\tau_s(\lambda)$]. They are obtained when the film is applied to a reference and well characterized glass, which is defined in IGDB, their corresponding characteristics are as follows:

ρ_1 (λ) – spectral reflectance of the applied film on new substrate, measured in direction air-film-glass.

ρ_2 (λ) – spectral reflectance of the applied film on new substrate, measured in direction air-glass- film.

τ_c (λ) – spectral transmittance of the applied film on new substrate

From the above optical characteristics of thin film, the spectral characteristics of new system, that includes same thin film applied on different glass (new substrate), can be computed by using below equations from 3.13 to 3.15.

$$\rho_1(\lambda) = r_c^f(\lambda) - \frac{r_s(\lambda)\, t_c^2(\lambda)\tau_s^2(\lambda)}{D'(\lambda)} \tag{3.13}$$

$$\rho_2(\lambda) = r_s(\lambda) + \frac{r_c^b(\lambda)\, [1 - r_s(\lambda)]^2\, \tau_s^2(\lambda)}{D'(\lambda)} \tag{3.14}$$

$$\tau_c(\lambda) = \frac{[1 - r_s(\lambda)]\, \tau_s(\lambda)\, t_c(\lambda)}{D'(\lambda)} \tag{3.15}$$

Where,

$$D'(\lambda) = 1 - r_s(\lambda) r_c^b(\lambda)\, \tau_s^2(\lambda) \tag{3.16}$$

$\tau_s(\lambda)$and $r_s(\lambda)$are respectively the internal transmittance and the air-glass reflectance of the new substrate to which film is applied.

4 Thermal Breakage Calculation

The growing interest of glass in varied applications and interest of industry in its technical issue leads to focus on the thermal breakage in this thesis. In order to purpose a reliable engineering solution for window film industries, understanding its failure mechanism is vital. Window glass breakage has become a sensitive subject for both architects and engineers. The engineers will envelop design of window against glass breakage by considering factors influencing the glass breakage. Basically, this chapter deals with those influential factors, types of fracture and its associated standards.

4.1 Factors influencing thermal breakage

Thermal stress is a consequence of differential expansion due to buildup temperature gradient that exists between different areas of the glass. In a window, the edges of the glass are shielded from solar radiation by the frame, thus they will be colder than the central area of the window, which is exposed to the sun (*Figure 4.1*). The expansion of central area will cause the glass to stretch and yet be resisted by colder edges, which will develop a tensile stress. If this stretching of the edges becomes sufficiently large, then the resulting tensile stress will be sufficient enough to break the glass.

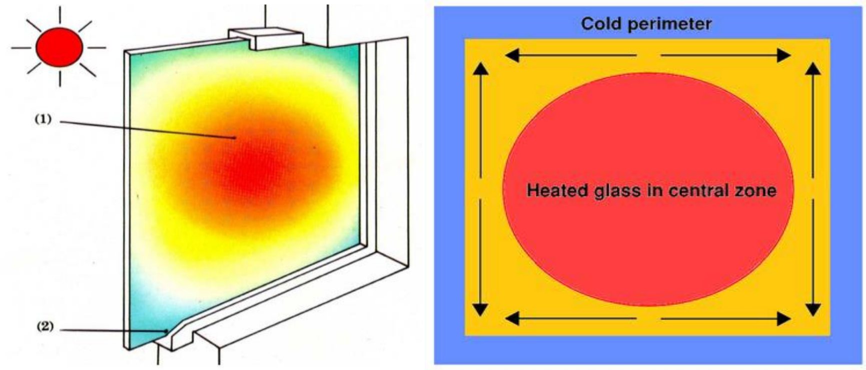


Figure 4.1: Principle of thermal stresses in a window under solar radiation [11]

Some of the important factors that can induce a thermal fracture in glass are listed below:

- Solar absorption and heat traps

The amount of solar radiation absorbed by the glass has a direct effect on its temperature, so it is an important factor that contributes to thermal stress. A high-performing solar control glass with an applied film will be considerably hotter than a normal clear glass due to its higher absorption of solar radiation. So, the solar control glass will have a greater risk of thermal fracture than a clear glass. In addition to these, blinds covering the window will reflect heat radiation and warms up the air gap between the glass and blind. This, in turn, causes the glass to become even hotter than by exposure to the sun and will lead to thermal fracture. The same effect will be caused by the presence of drop-down ceiling, heat absorbing or reflecting labels, decorations on the glass etc. [28]

- Shadows

The presence of shadows produces larger cool area in glazing. This may enable glass edges to stay even colder. The consequence is an increased temperature difference between the exposed and shaded areas of glass and thus an increase of the thermal stress and likelihood of a thermal fracture to occur. Shadows are commonly cast across glass by vertical mullions, balcony overhangs, eaves, columns etc. The resulting shadows might be static or mobile, being a static shadow is more critical because it produces a cooler area of glass than a mobile shadow [28].

- Edge strength

The crack will occur when the tensile stress in the glass edge exceeds a critical value. The magnitude of this critical value depends on the strength of the glass edge. A clean-cut edge is the strongest one as the cutting produces the least amount of damage to edges. A polished glass is the next strongest one. It also depends on the quality of glass edge as this will reduce its strength and increases the probability of failure due to thermal fracture. The strength of a damaged edge is highly variable so it is not possible to determine the risk associated with it, hence, for this reason, the process of assessment the risk of thermal fracture assumes clean cut edges. Since the edges of the glass are easily damaged by incorrect handling it is of great importance that glass is handled very carefully during glazing.

- Artificial heating and cooling

Presence of heating or cooling device that blows directly onto the glass can heat or cool the glass excessively, causing significant thermal stress in the glass.

- Frame type

The frame in which glazing part is fixed will affect the temperature of glass edges. An insulating material such as timber or vinyl will keep the glass edge cool while a conductive material such as aluminum will be influenced by the frame color. A dark color is more absorptive than white so will enable the frame to absorb more heat and thereby heating the glass inside the frame [11].

- Glass type

The type of glass will have a greater influence on risk analysis of thermal fracture. This is influenced by the capacity of the glass to absorb and release heat and the characteristic edge strength of glass. The internal stress levels of toughened glass and HSG are high enough to ensure that they are not subjected to thermal stress under normal solar or architectural conditions.

- Geographical location

As the solar exposure varies along the latitude (solar intensity increases as the location approaches the equator). It is important to consider the geographical location of the building when assessing thermal fracture of a glass window [1].

Table 4.1 summarizes the factors that can influence the thermal breakge.

Table 4.1: Parameters that can influence breakage of glass.

Climatic Consideration	Glazing Consideration	Architectural Consideration
• Geographic location • Temperature variation • Intensity of solar flux • Wind • Altitude	• Thermal inertia of frame • Nature of glazing • Type of glass • Edge conditions	• Orientation of glazing • Shadows • Blinds • Heat pockets • External heat source

4.2 Thermal fracture types

As an industrial practice, when glass breakage occurs the first step of the analysis is to identify the type of breakage through understanding the breakage pattern. In recent times, new high-performance glass are been manufactured by glass industries, being the breakage pattern not well known, thus increasing the breakage risk [29]. For example, the use of Low-E glass in IGU decreases the thermal transmittance but it increases the risk of thermal breakage. So, understanding characteristics of thermal cracks is of importance to identify the type of breakage. Generally, thermal breakage on glass can be identified based on its energy release – low and high. And they are briefly explained as follows:

Low energy release: It is the most common one because it is related to edge damage. Generally, this phenomenon is characterized by a single crack, as shown in *Figure 4.2* below. The occurrence starts with the propagation of micro-cracks associated with edge imperfection from the low value of tensile stress to increase the crack dimension up to critical one [11].

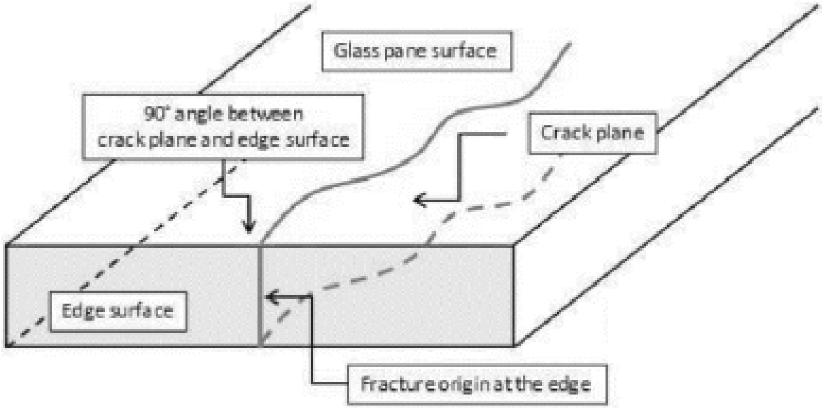


Figure 4.2: Low energy release thermal breakage [11]

High energy release: It occurs infrequently because it requires a very high thermal stress. Generally, this phenomenon is characterized by multiple cracks, as shown in *Figure 4.3* below. The initial cracks are branched off into a number of separated cracks at a short distance from its origin.

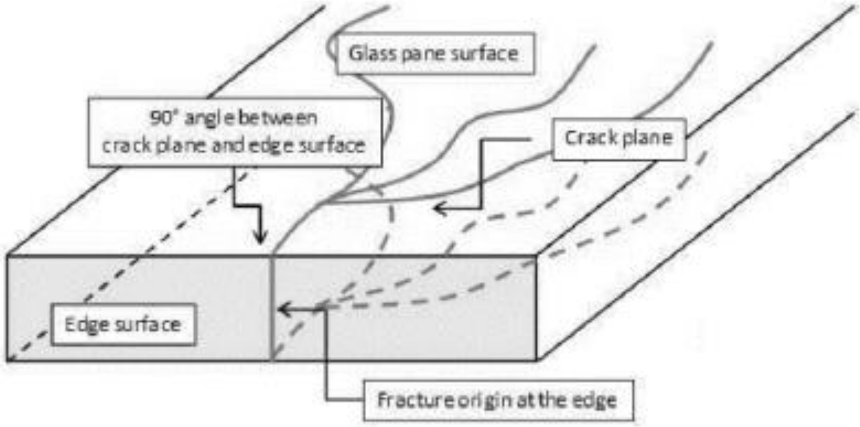


Figure 4.3: High energy release thermal breakage [11]

In both cases, the crack starts at 90 ° to the edges and surfaces of the glass. The characteristics of a crack caused by thermal breakage in the glass always start at 2/3 of edges in the perpendicular direction and result in “lazy/meandering” crack for 20-50mm and then branches out into one more direction. The number of branches or development of secondary cracks will depend on the amount of stress acting in the glass.

There is another type of thermal breakge, not related with the edges of glass but with the presense of nickel sulphide (NiS) impurities. Nickel sulfide glass breakage is a phenomenon of thermal fracture that is similar to thermal breakage of glass as shown in *Figure 4.4*, which is spontaneous in nature. Hence, attention should be paid off for identifying these types of glass breakage. In both cases, the main factor for thermal breakage is the solar flux, but the thermal breakage is generally referred to annealed float glass, while the breakage due to NiS inclusion is specific to thermally toughened glass which occurs as result of batch contamination of NiS during their float glass manufacturing process.

Figure 4.4: NiS (Nickel Sulphide) inclusions cause “spontaneous” glass breakage [11]

4.3 European standards

This section provides a brief review of different standards currently available for performing thermal breakage calculations for glass only. Each of these standards differs from their parameter of influence, precision and application domain.

4.3.1 Belgian Standard

The Belgian Standard [30] FIV 01 was published in 1997 by Fédération de l'Industrie du Verre and it describes a simplified assessment for thermal breakage in glass. The basis of calculation according to Belgian standard relies on the difference in temperature between the visible part of the glass and the part in the window frame. Two parameters are important for this, namely the energy absorbed by the glazing and the variation in daytime temperatures. This results in the following formula for calculating the base temperature difference between these two points for single glazing system:

$$\Delta T = \frac{\Phi * \alpha}{h_e + h_i} + \frac{A * h_e}{h_e + h_i} \tag{4.1}$$

Where,

Φ - Intensity of global solar radiation (W/m²)

α - Absorption coefficient of glass (N/A)

A - Maximum amplitude of average daytime temperatures for 10 years (°C)

h_e - Heat transfer coefficient to the outer surface (W/m²K)

h_i - Heat transfer coefficient to the inner surface (W/m²K)

Based on the external parameters, the calculated temperature difference (ΔT) is adjusted by Belgian Standard as follows:

- Influence of the inside blinds / curtains

$$\Delta T_1 = \Delta T + \Delta T'$$

Where $\Delta T'$ depends on the type of glazing system and the ventilated space and their values for single glazing system is summarized on the following *Table 4.2*.

Table 4.2: Temperature influence of inside blinds in Belgian standard [32].

Blind Type	**Ventilated Space (°C)**	**Non-Ventilated Space (°C)**
Open Weave	3	6
Closed Weave	4	7
Venetian Blinds	5	8

- Influence of Frame

Depending on material used for the window frame, the temperature difference will be multiplied by frame factor f_1, (*Table 4.3*).

$$\Delta T_2 = \Delta T_1 \, . f_1$$

Table 4.3: Influence coefficient of the type of frame in the Belgian standard [32].

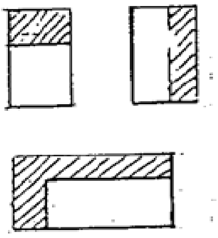
Type of Frame	**f_1**
Concrete	1
Steel with thermal break	0.8
Aluminium with thermal break	0.7
Wood/PVC	0.75

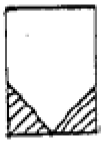
- Influence of the outside shadows

In Belgian standard, the effect of shadow on the glass is changed based on a shadow factor f_2, summarized on *Table 4.4***.**

$$\Delta T_3 = \Delta T_2 \, . f_2$$

Table 4.4: Shadow factor for single and double-glazing system in the Belgian standard [32].

Shadow Shape	**Single glazing or Outer glass of Double glazing**	**Inner glass of Double glazing**
	1.2	1.1

	1.5	1.2

According to Belgian standard, if $\Delta T_3 < 30\ °C$ then there is no need of using thermally treated glass. For other cases, thermally treated glass should be chosen. Once the temperature difference has been calculated, the resulting tensile stress σ, in the glass can be calculated as follows:

$$\sigma = E\,.\,\alpha\,.\,\Delta T_3$$

where,

E – Elastic modulus of glass (MPa).

α – Expansion coefficient of glass (1/K).

According to Belgian standard, only window that are in the shaded part of the *Figure 4.5* must be checked for thermal breakage, assuming the building is in the Northern hemisphere.

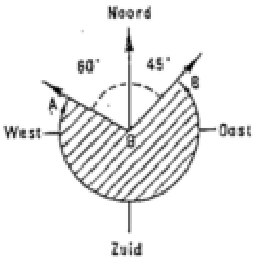


Figure 4.5: Thermal breakage risk: only in hatched region in the Belgian standard in the Northern hemisphere [30].

4.3.2 British Standard

British standard (CEN/TC129/WG8-N180E 2004) [14] is one of the simplest standard available nowadays to compute the thermal breakage behavior of glass, but it is only applicable for glasses manufactured by the company Pilkington. Contrary to Belgian standard, the calculation of temperature difference that leads to thermal breakage is not calculated by equations, instead it is determined from reference tables. If the amount of solar radiation, the amplitude of the daily temperature fluctuations and type of glass are known, the temperature difference may be read from the tables included in the standard. The amount of solar radiation and amplitude of the daily temperature fluctuations depend on geographical position and they can be extracted from an United Kingdom detailed map.

The occurring temperature difference ΔT, determined from tables is then corrected by effect of inner blinds, window frame material and outer shadow, which is quite similar to Belgian standard procedure. The glass breakage resistance is then verified by tabulated permissible temperature difference based on glass type and its edge finish. It could be observed from the *Table 4.5*, that the maximum ΔT for float glass with cut or beveled edge finish is 30 ºC, according to British Standard. This value can be higher if the edges of the glass are polished.

Table 4.5: Maximum permissible temperature difference according to British Standard [33].

Glass Type	**Cut or beveled glass (°C)**	**Polished glass (°C)**
Float glass, t < 12mm	35	45
Float glass, t = 15mm or 19mm	30	50
Float glass, t =25mm	26	35
Heat strengthened glass	100	100
Thermally toughened glass	200	200

4.3.3 French Standard

The improvements in section A1 of the French standard NF P 78-201-1/A1 (DTU 39) [1] made it more accurate than Belgian and British standards [30] since it considers both window and environmental characteristics. It involves the most precise, but time-consuming, method that consists of calculating the temperature difference between different areas of the glazing unit. The French method, considers slope, location and orientation of the glazing for each season.

The calculation of the temperature can be carried out in steady state regime, and it is only applicable for low thermal inertial frames. For other frames, these temperature differences must be calculated in a transient regime over a period of one day, depending on the season and the orientation of glazing, see section 4.4. Then the calculated maximum temperature difference obtained should be compared with maximum permissible temperature difference which are tabulated and reproduced in *Annex A, Table A 2.* On the other hand, the French Norm DTU 39 is limited to window glass, possibly equipped with shading devices and are not directly exposed to artificial heating sources. More details about this French Norm are given in section 4.4.

4.4 Thermal breakage calculation

This section will focus on the calculation procedure followed by the French standard (NF P 78-201-3/ (DTU 39-Part 3) 2006) [1]. The French norm, includes three methods to calculate the maximum temperature difference between different zones of glass as defined in *Figure 4.6* that lead to thermal breakage. Each of these methods is based on their influential parameters and it should be applied based on the needed precision and application of the glass.

According to French standard, in order to find the maximum temperature difference between each zone, $\delta\theta_{max}$ the window is divided into three zones as follows (*Figure 4.6*),

- 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) (Zone 3)

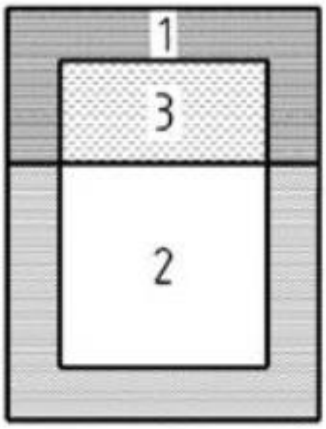


Figure 4.6: Zones in glazing system [1]

4.4.1 Calculation of Temperature Difference

To estimate the maximum temperature difference between two areas of the glass plane, it may involve simplified or detailed methods in order to consider the conduction of heat in dynamic regime in the frames of the window with high thermal inertia [1]. Here the hottest zone is normally the central zone of the glass on which the solar radiation strikes and heats up while the colder zones will be either the area of glass in shade or the glass inside the frame of the window.

To carry out the calculation, the following assumptions are considered,

- The glass temperature inside the frame (zone 1) depends only on the characteristics of the frames and its environment. i.e. it is independent of the energy characteristics and orientation of glass.
- The temperature in zone 2 and zone 3 of a glazing system are independent of the nature of the frame.

The three methods described in French Norm calculates the temperature of glass at each zone and then the maximum temperature difference among these zones are computed. A brief procedural description of the three calculation methods mentioned in French Norm DTU 39 are described below:

General Method: This method is applicable for any kind of window frames ranging from high to low thermal inertia materials. Here, the outside temperature (atmosphere temperature) is a function of time that varies along 24 hours of a day and the season.

While the maximum and diffuse solar flux are considered along with the change in orientation. This climatic outdoor temperature variation data are available for Portugal [31] and they are depicted in *Figure 4.7* for each season. Thereby, the temperature response for the glass inside the frame (Zone 1) is computed using finite element techniques at transient mode for each climatic season.

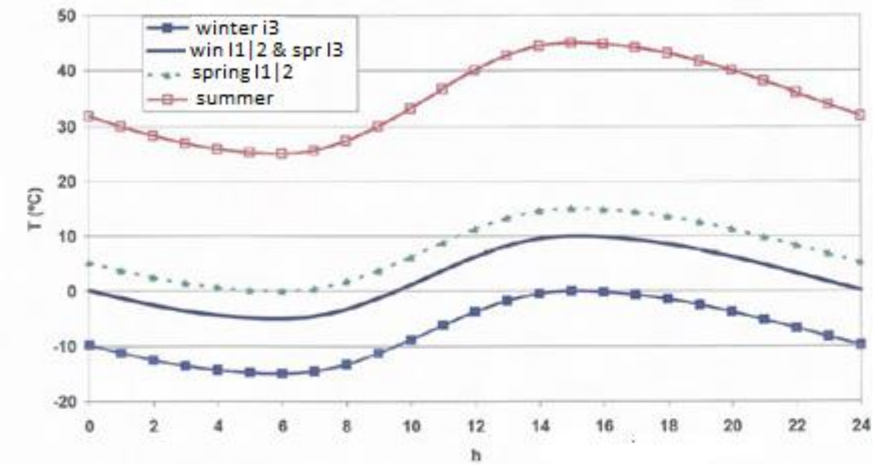


Figure 4.7: Outdoor air temperature variation for winter, spring and summer in Portugal [31]

Similarly, finite element techniques are used for computing temperature response at zones 2 and 3. The thermal resistance of glass is neglected and the temperatures of each element for the case of multiple glazing systems is computed by forming a heat balance equation (equation 4.2) governed by the conservation of energy law [1]. It includes the temperature of each element i.e. glass (θ_i and θ_j) and airgap (θ_k), radiative and convective heat transfer coefficient (hr_{ij} and hc_{ik}), thickness of each element (e_i, e_j, e_k) and incident solar flux on each element ($\alpha_{ei}.\Phi$).

$$e_i.c_v.\rho_v.\frac{d\theta_i}{dt} = \sum_{j=1}^{n} hr_{ij}.\left(\theta_j - \theta_i\right) + hc_{ik}.(\theta_k - \theta_i) + \alpha_{ei}.\Phi$$

$$e_k.c_a.\rho_a.\frac{d\theta_k}{dt} = \sum_{j=1}^{n} hc_{kj}.\left(\theta_k - \theta_j\right) \tag{4.2}$$

For the extreme components that are exposed to external and internal environmental conditions, the following terms are added:

- Inside: $+ h_i . (\theta_{ai} - \theta_i)$
- Outside: $+ h_e . (\theta_{ae} - \theta_i)$

- where h_i and h_e are convective heat transfer coefficient with respect to internal and external environment,

- θ_{ai} and θ_{ae} are the temperature of internal and external environment.

While for the case of ventilated blind or drapes, the possible ventilation of the space between the blind and glass is represented by introducing an exchange factor K_x that are computed as per NF DTU 39. Then the system of equation on considering blinds will be as follows,

$$e_k . c_a . \rho_a . \frac{d\theta_k}{dt} = \sum hc_{kj} . (\theta_k - \theta_j) + K_x . (\theta_k - \theta_i) \tag{4.3}$$

Considering the incident solar flux, total flux for sunny part (zone 2) and diffuse flux (10% of total flux) for shaded part (zone 3) are considered for calculation purpose.*Figure 4.8 - Figure 4.11*, depicts the global solar radiation flux and the diffuse radiation for glazing at NE, E, SE, S, SW, W, NW orientations and the coverage for vertical elements in winter, spring/autumn and summer conditions in Portugal [31]. In *Table 4.6***,** the values of the incident maximum solar radiation on the glazing are also presented.

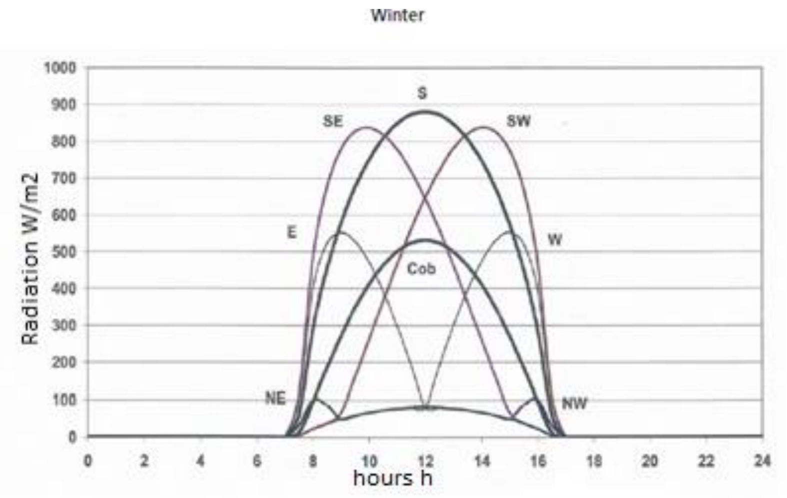


Figure 4.8: Global Solar Radiation Flux during Winter in Portugal adapted from [31]

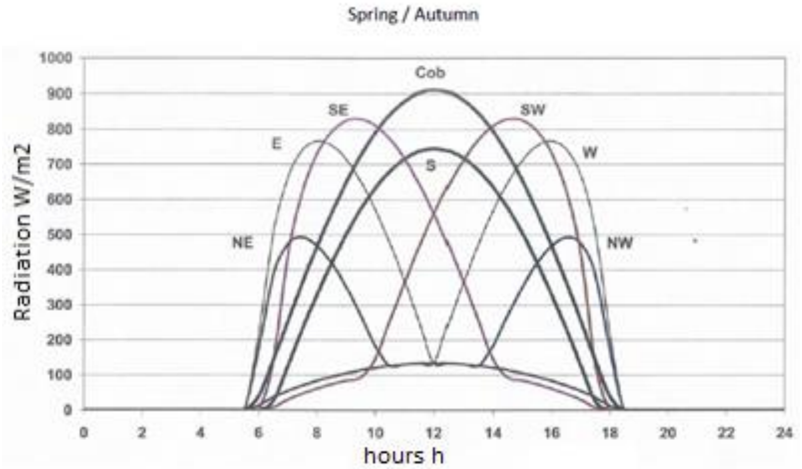


Figure 4.9: Global Solar Radiation Flux during Spring / Autumn in Portugal adapted from [31]

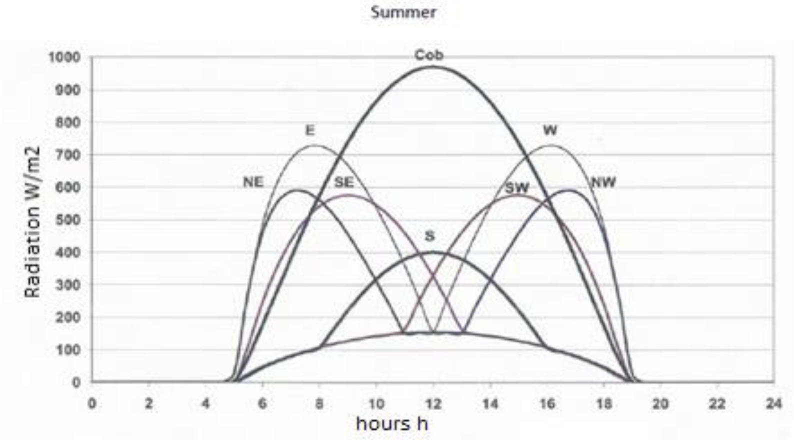


Figure 4.10: Global Solar Radiation Flux during Summer in Portugal adapted from [31]

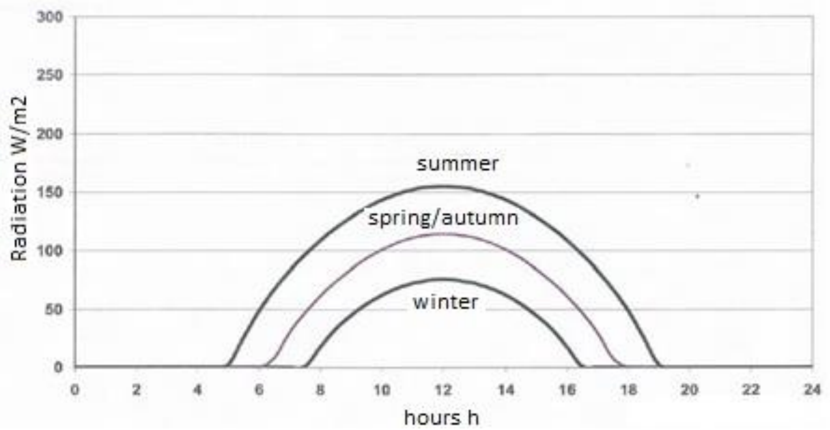


Figure 4.11: Diffuse Solar Radiation of Vertical Elements in Portugal adapted from [31]

Table 4.6: Maximum solar radiation values for each orientation in Portugal (W / m2)[34].

	Maximum solar radiation (W/m^2)		
Orientation	**Winter**	**Spring / Autumn**	**Summer**
NE	100	492	588
E	552	766	729
SE	837	829	576
S	881	745	401
SW	837	829	576
W	552	766	729
NW	100	492	588
Roof	532	910	970
Diffuse radiation	76	114	155

To summarize, the outside temperature and diffuse solar flux are dependent on time, season and global solar radiation. While the solar flux depends on the season, time of the day, façade orientation and its inclination. The calculation of the temperatures θ_1, θ_2, θ_3 of the various zones of the glazing is based on finite element techniques.

Simple Method: This method is only applicable for window frames with low thermal inertia materials like wood, PVC, aluminum etc. Here, the outside temperature is not a function of time as it was discussed in the previous method; the term $d\theta_i/dt$ becomes zero in order to perform a steady state analysis and the heat balance equation becomes as follows,

$$\alpha_{ie}.\Phi_s = \sum_j hc_{ij}.\left(\theta_i - \theta_j\right) + \sum_k hr_{ik}.\left(\theta_i - \theta_k\right) \tag{4.4}$$

The above equation includes temperature of glass elements as θ_i and θ_k, air gap by θ_j. While hc_{ij} and hr_{ik} are the convective and radiative heat transfer coefficient between each element. The solar flux to be considered here is the same as we discussed in previous method. Then similarly the calculation of the $\theta_1, \theta_2, \theta_3$ temperatures are computed using finite element techniques.

Manual Method: This method is applicable for varied scenarios like vertical sliding and internal sliding cases with blinds or grapes but it is limited to single and double-glazed systems with low thermal inertial frames. Here, the outside temperature is described by constant values which will depend on the geographical location of the building and the season. The calculation of the temperatures for different zones are performed manually. *Figure 4.12* shows the winter climate zones of Portugal and their reference air temperatures for winter, spring and summer seasons are tabulated in *Table 4.7* [34]. In this method, while the outside temperature depends on the season and location, the solar flux depends on season and orientation.

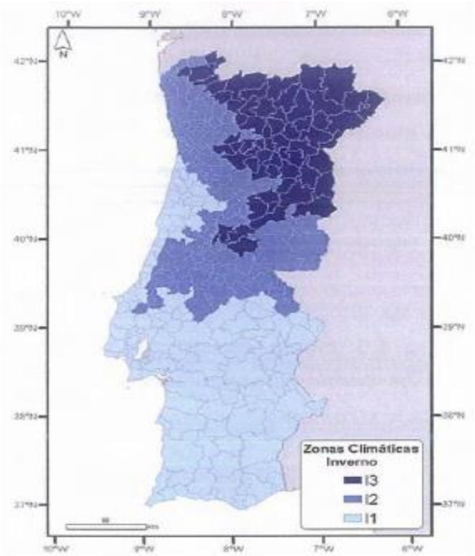


Figure 4.12: Winter climate zones of Portugal [32]

Table 4.7: Outside reference air temperatures [34].

	Outside reference air temperatures (°C)				
	Winter		Spring		Summer
Climate Zone	I1 & I2	I3	I1 & I2	I3	I1, I2 & I3
T_{max}	10	0	15	10	45
T_{min}	-5	-15	0	-5	25
Amplitude Range	15	15	15	15	20

For calculation of the temperature of glass edges trapped inside the window frame θ_1, equation 4.5 is applied:

$$\theta_1 = \frac{h_i\,.\,\theta_i + h_e\,.\,\theta_e}{h_i + h_e} \tag{4.5}$$

For calculating the temperatures of zone 2 ($\theta_2/\theta_{2e}, \theta_{2i}$) and zone 3 ($\theta_3/\theta_{3e}, \theta_{3i}$) in a single/double glazing system, the maximum global solar radiation (Φ) 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 in below formulation:

Single Glazing:

$$\theta_2 = \frac{h_i\,.\,\theta_i + h_e\,.\,\theta_e\ + \alpha\,.\,\Phi}{h_i + h_e} \tag{4.6}$$

Double Glazing:

$$\theta_{2e} = \frac{h_t.\,(h_i\,.\,\theta_{ai} + \alpha_{2e}.\,\Phi) + (h_i + h_t)\,.\ (h_e\,.\,\theta_{ae}\ + \alpha_{1e}\,.\,\Phi)}{(h_i + h_t)\,.\ (h_e + h_t) - h_t^2} \tag{4.7}$$

$$\theta_{2i} = \frac{h_t.\,(h_e\,.\,\theta_{ae} + \alpha_{1e}.\,\Phi) + (h_e + h_t)\,.\ (h_i\,.\,\theta_{\mathrm{ai}}\ + \alpha_{2e}\,.\,\Phi)}{(h_i + h_t)\,.\ (h_e + h_t) - h_t^2} \tag{4.8}$$

Then for the above two cases (single and double-glazed window) on adding blinds or drapes, the system of equation will be as follows,

Single Glazing:

$$\theta_2 = \frac{4.8\ (11{,}8\,.\,\theta_i + \alpha_{2e}.\,\Phi) + 16{,}6\ (11\,.\,\theta_e + 2{,}8\,.\,\theta_i + \alpha_{1e}.\,\Phi)}{285{,}72} \tag{4.9}$$

Double glazing:

$$\theta_{2e} = \frac{5{,}46\,.\,h_t.\,\theta_i\ + 11.\,(\mathrm{h_t} + 5{,}46).\,\theta_e + [(\mathrm{h_t} + 5{,}46).\,\alpha_{1e} + h_t.\,(\alpha_{2e} + 0{,}324.\,\alpha_{3e})].\,\Phi}{60{,}06 + 16{,}46\,.\,h_t} \tag{4.10}$$

$$\theta_{2i} = \frac{5{,}46.\,(11 + h_t).\,\theta_{ai} + 11.\,\mathrm{h_t}.\,\theta_e + [(\mathrm{h_t} + 11).\,(\alpha_{2e} + 0{,}324.\,\alpha_{3e}) + h_t.\,\alpha_{1e}].\,\Phi}{60{,}06 + 16{,}46\,.\,h_t} \tag{4.11}$$

Where, absorption of glass component (α_{ie}) is calculated based on formulations mentioned in previous chapter for each glass element. And then airgap convective coefficient (h_t) according to NF EN 673 is as follows:

$$h_t = 1/R \tag{4.12}$$

$$R_o = 1/(U_g - 0.17) \tag{4.13}$$

Let R be the effective thermal resistance of the glazing:

- During summer conditions:

$$R = 0.92\, R_o$$

- During winter conditions:

$$R = 0.78\, R_o$$

Then the maximum temperature difference can be computed as:

Single Glazing:

$$\delta\theta_{max} = Max((\theta_2 - \theta_3), (\theta_2 - \theta_1)) \tag{4.14}$$

Double glazing:

$$\begin{aligned} \delta\theta_{\mathrm{max1}} &= Max((\theta_{2e} - \theta_{3e}), (\theta_{2e} - \theta_1)) \\ \delta\theta_{max2} &= Max((\theta_{2i} - \theta_{3i}), (\theta_{2i} - \theta_1)) \end{aligned} \tag{4.15}$$

Finally, following the French Norm, the calculated temperature difference is compared with the tabulated permissible temperature difference found in *Annex A* [1]. The table includes data for different types of glass (not heat treated), considering shadow and no shadow areas and also inclination. If the computed temperature difference exceeds the values available in table, then the chosen system can be considered as not safe and not recommendable for being used as the probability of breakage is high.

Each method presented in French Norm DTU 39 is used for computing the maximum temperature difference occurring at glazing surface at different levels of complexity and precision. In which, the general method and simple method delivers an approximation of the actual condition of glazing system, but it does not include the varied scenario of glazing systems such as vertical sliding and internal sliding case with drapes and requires varied computing software to perform finite element techniques. On the other hand, manual method is carried out at steady state regime with a low thermal inertial frame and it can be applicable for varied scenarios[11].

In order to choose a reliable calculation method that can be adapted for computing the window film to glass breakage compatibility for all NFRC approved glasses in IGDB, in this work it has been considered the manual method described in the French Norm, due to its application in varied scenarios, integration with macro-enabled Excel worksheets and its applicability to single and double glazed with low inertial frames which are quite commonly used in Portugal. *Table 4.8* below shows the complexity involved and application domains for each of these methods.

Table 4.8: Thermal breakage calculation comparison of the three different methods followed by French Norm DTU 39.

	Thermal condition	**Application**
General Method	Transient	Suitable for a finite number of glazing layers with high or medium inertial frames.
Simple Method	Steady State	Suitable for a finite number of glazing layers with low inertial frames.
Manual Method	Steady State	Suitable for single and double-glazed layers with low inertial frames of varied scenarios-vertical or internal sliding.

5 Results and discussion

Alhough laboratory and field testing are useful tools for basic product evaluation, they are too expensive for initial product design and for reporting on all possible combinations of available products. For these reasons, the availability of an accurate and unbiased computing tool would be beneficial. Hence, this chapter will focus on briefing the developed tool -*FG-Breakage,* that computes maximum temperature difference that can be used to predict the glass breakage. Finally, in order to validate the results from *FG-Breakage*, the results are compared with those obtained using Optics 6 and Window 7.4, which are the most commonly used numerical approximation 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 common, it is used as a reference value to compare the results and to have a discussion on it.

5.1 The FG-Breakage tool

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 glasses, based on the data shared by all manufacturers with IGDB database and approved by National Fenestration Rating Council (NFRC). It should be noted that there are no data available for single window films, since data available at IGDB corresponds to window film applied to a reference glass(base substrate), which is usually a 3mm or 6mm clear glass [33]. The basic algorithm behind *FG-Breakage* is schematized in *Figure 5.1*. The tool is 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 glass when a film is applied to a specific glass.

The flowchart for computing the thermal breakage for the case of single and double glazing is schematized in *Figure 5.2***.** In order to perform the calculations, initial checks considering heat pockets (*Figure B.1*) and internal sliding cases (*Figure B.2*) are initialized to perform further calculations (a brief description of these situations is explained in Annex B along with vertical case scenario). In the *FG-Breakage* tool, the user can choose the type of desired glazing i.e. either single, double or vertical sliding case. And in each case, it can perform a calculation with or without window film by providing the required initial conditions. These include choosing climate zones, glazing tilt angle, season and blinds consideration.

In case of double glazing with window film, first, it has been extracted the optical properties of the window film applied to the new substrate using the formulations mentioned in the previous chapter. Then, considering the parameters of French Norm DTU 39 and applying the multilayer radiometric model (Chapter 3) the maximum temperature differences are computed for each orientation and later these results can be used by building engineers or architects for choosing film type for a glazing system.

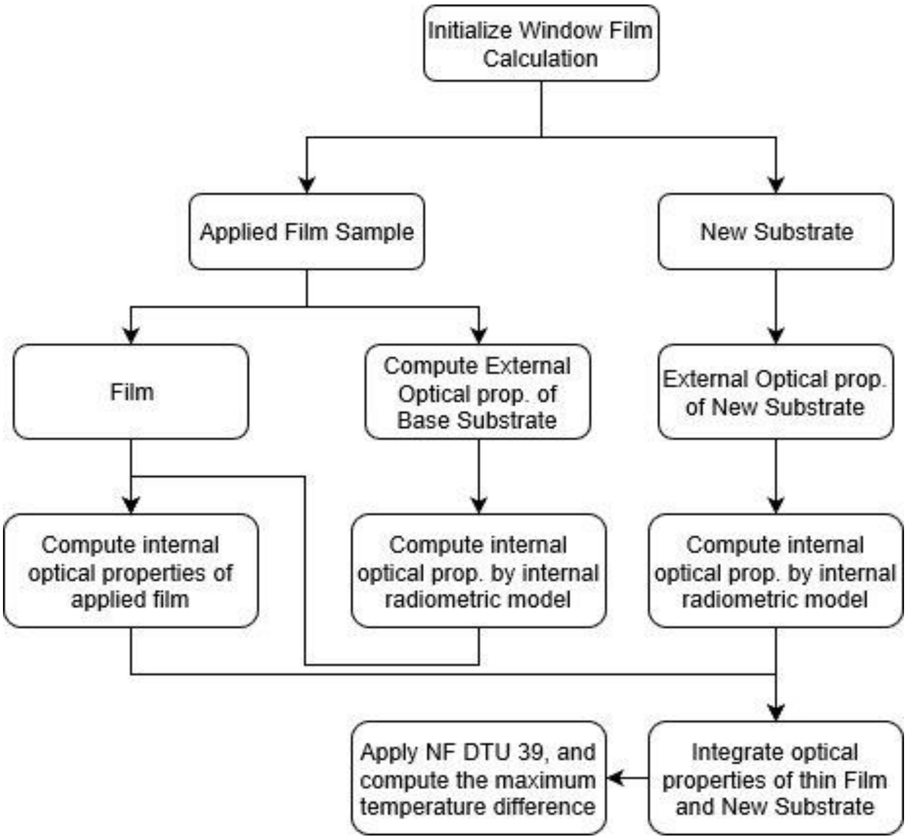


Figure 5.1: Algorithm of FG-Breakage code

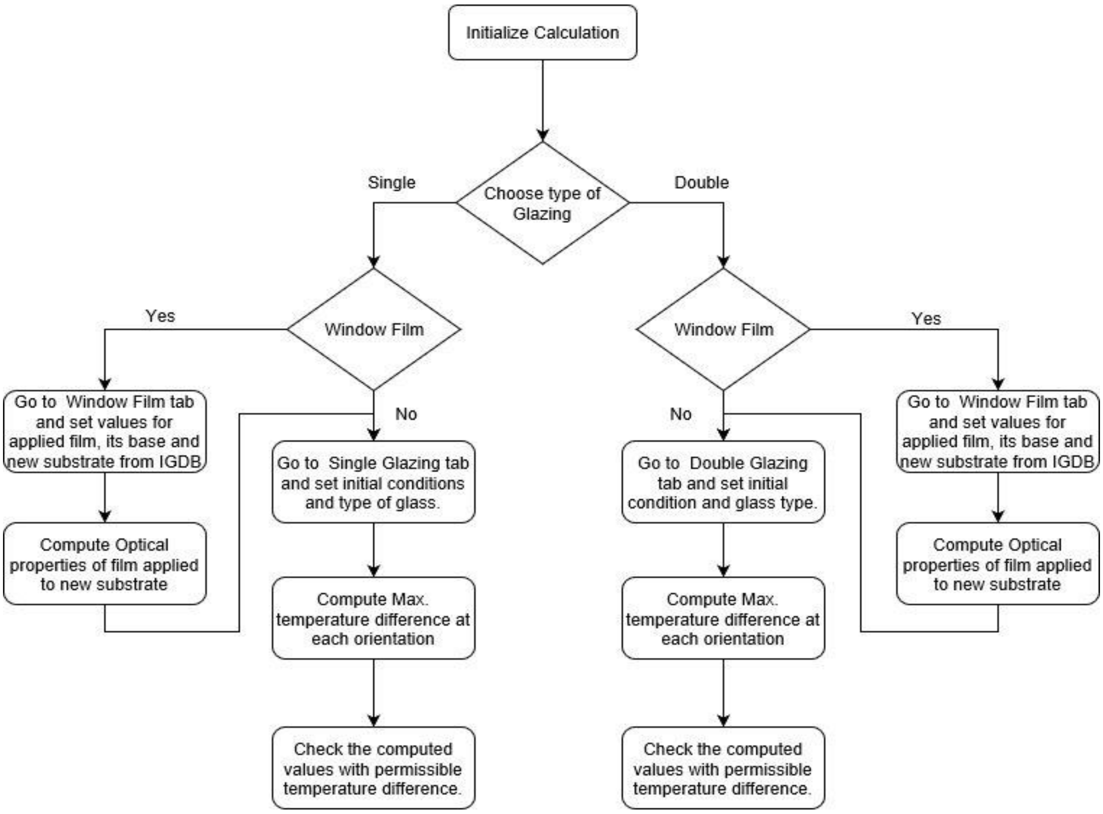
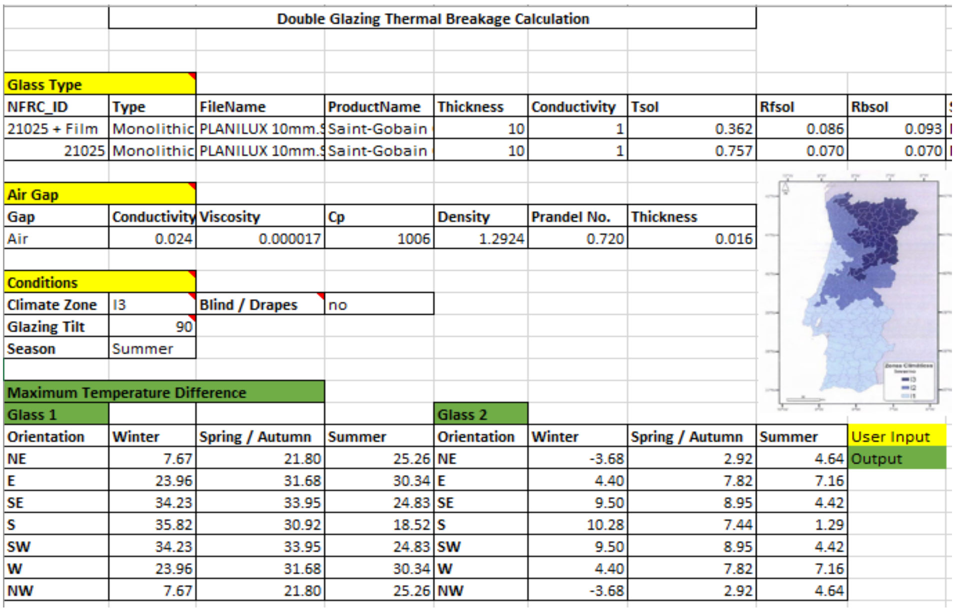


Figure 5.2: Flowchart for thermal breakage calculation

Figure 5.3, below shows the results obtained by means the *FG-Breakage* tool when a double-glazing window is considered. For calculation purpose, it has been considered the most commonly used Saint-Gobain monolithic 10mm thick glass (*NFRC 21025*) as layer one with a window film (*NFRC 2732*) and layer two as same monolithic glass without any film. The gap between these two glasses (16mm) is filled with air. It has been assumed that the system is going to be installed in a climate zone I3 and the summer conditions with no blinds installed. The final results are then compared with the permissible temperature difference available in Annex A from [1], to predict the thermal breakage phenomenon of each glass in the glazing system. From the *Table A 2* it can be observed that for a monolithic glass with tilt angle greater than 60° the glass can withstand a maximum temperature difference of 42 °C[1]. Comparing this value with the results obtained, it can be observed that for any orientation the maximum temperature difference achievable is lower than 42 °C and it can be concluded that the glass will not break and the selected film is compatible with glass under these considerations.



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
NE	7.67	21.80	25.26	NE	-3.68	2.92	4.64
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 5.3: Output results from FG-Breakage tool when a double-glazed window is considered.

5.2 Optical properties

Optics 6 [33] is public access software tool developed by Lawrence Berkeley National Laboratory to compute the spectral properties of a complex glazing system (films with and without glass) that consists of a vast library of available films and glasses that have been previously approved by the International Glazing Database (IGDB). The IGDB holds a full collection of optical data for all glazing products that are measured by means of spectroradiometer and then shared by the manufacturers. In order to submit a new film for approval by IGDB and to be able to be used by Optics, the tests must follow the standards dictated by the National Fenestration Rating Council (NFRC). The glazing shall be a single uncoated glass with a solar transmission exceeding 0.820 and a visible transmittance greater than 0.890, thereby ensuring that the film will have similar transmittance values or lower than the glass to which it is applied. The uncoated glass that meet these criteria are only three: 3mm plain glass, 3mm plain glass with low iron content and 6mm plain glass with low iron content [26]. The coated and uncoated glass shall be subjected to separate tests to determine their optical properties along the wavelength and the data shall be submitted together to IGDB. With these data, Optics 6 program is able to extract the data from film and then use them to calculate the spectral properties of other system, i.e. the film applied to any glass. In the context of this work, it is going to be used to compare the results of spectral properties (solar transmittance, T_{sol} and front/back solar reflectance, R_{fsol}/R_{bsol}) obtained from *FG-Breakage* code.

Table 5.1 shows the computed results obtained from *FG-Breakage* and Optics 6 codes for the cases most commonly used in construction: Saint-Gobain monolithic glass (*NFRC 21025)* and coated glass (*NFRC 21431)* with and without a window film (*NFRC 2732)*. It is not possible to compare data comprising laminated glass since the details of different layers of glass are not shared by manufacturers to IGDB.

Table 5.1: FG-Breakage result 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* code following the European Standard EN 410 (Chapter 3) are similar to those obtained by Optics 6. The variation of computed spectral properties with the wavelength are shown in *Figure 5.4***.** Since, Optics 6 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.

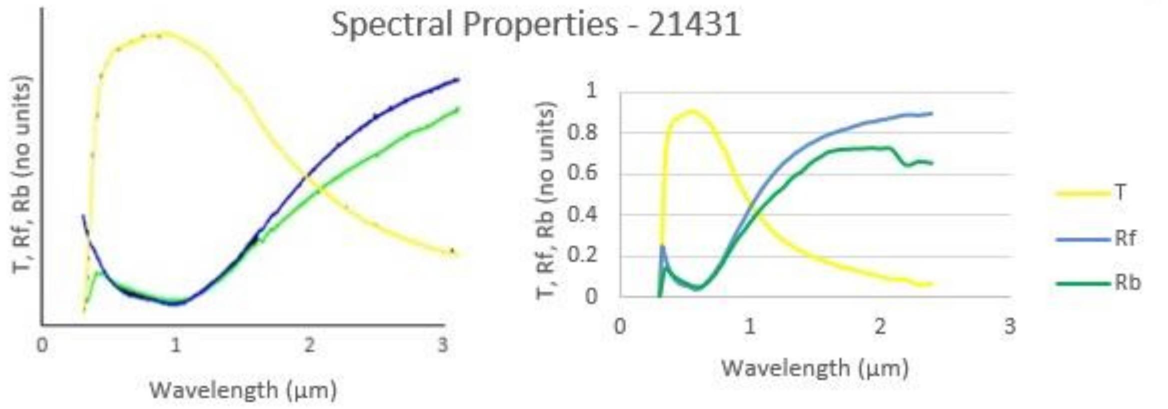


Figure 5.4: Spectral properties variations with wavelength of a 10mm coated glass (NFRC 21431) obtained from Optics 6 (Left) and FG-Breakage(Right).

The optical data available in IGDB have lots of missing data with respect to relative spectral distribution specified by the standard EN 410 [27]. So, the missing optical data were interpolated in *FG-Breakage* code and consecutive spectral properties were obtained for each glazing types**.** These spectral properties will be used in the radiometric model to compute external and internal spectral properties.

Considering the data from *Table 5.1* 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 is a slight difference in the results of 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 simpler computation method to determine the approximate spectral properties. *FG-Breakage* would be a reliable tool to perform these calculations and as well it should be noted that there exists a variation in obtained spectral values among different standards [23].

5.3 Temperature

5.3.1 Window 7.4

Window 7.4 [34] is a computer program developed by Lawrence Berkeley National Laboratory (LBNL) to determine the thermal performance of a window glazing system and it is widely used by glass manufacturers, engineers, students and architects.

In this software, the calculation of thermal properties for a glazing system is based on a comprehensive heat transfer model, with analysis of coupled conductive, convective and radiative heat transfer. It includes a mathematical model for calculating the temperature of each individual glass in a glazing system at the center, by considering the thermal and optical properties. The mathematical model is based on TARCOG algorithm, that considers the glazing system as an array of layers and gaps. In addition, it considers shading device as a planar layer[24]. Though this model provides a solution for a large array of glazing system only one shading layer can be present in a glazing system.

Similar to the case presented in the previous section, it has been considered the same glass (*NFRC 21025 and 21431)* with and without film for the case of single glazing system. Since, so far Window 7.4 is regarded as a reliable tool for computing the temperature of the central area of glazing system by glazing manufacturer, it has been chosen to compare the temperature computed from *FG-Breakage* code with those obtained with Window 7.4 software. To do so, the environmental settings of Window 7.4 were changed to those specified in the French Norm DTU 39 document [1], i.e. maximum solar flux of 881 W/m^2, outdoor environmental temperature of 32°C, heat transfer coefficient of 13 W/m^{2}K, indoor environmental temperature of 25°C and heat transfer coefficient of 9 W/m^{2}K.

Table 5.2 shows the results of temperature in the central area of glass obtained with the *FG-Breakage* and Window 7.4 codes for the case of single glazing system with and without applied film. From the *Table 5.2*, it can be observed that the results are quite similar, being the maximum difference (within a 5.5% 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 and thus *FG-Breakage* code can be considered as a quite reliable tool to compute the maximum temperature difference in a glazing system with and without an applied film.

Table 5.2: 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

5.3.2 Ansys

Ansys [35] is a general purpose-finite element modeling software used for numerically solving a wide variety of mechanical problems. In finite element modeling, the first step involves dividing the problem into subsections called elements. These elements can have different shapes such as lines, triangles or quadrilaterals based on the needed accuracy. Each element is characterized by a number of nodes which defines the geometry or shape of each element. After the domain has been discretized into elements, the approximate solutions are assumed to be over those each element. These solutions are called as interpolation functions or shape functions, and they are usually quadratic equations that can be easily differentiated. Similar to previous section, first it has been considered a double-glazed window with two glasses (NFRC 21025 and 21431) and then calculations are performed for the same two glasses with a window film (NFRC 2732) applied to the external glass using Window 7.4 and *FG-Breakage* codes. Additionally, here the results from other numerical approximation software like Ansys have been included in this study (*Table 5.4*).

In order to perform the above simulation in Ansys, a double-glazed window has been modeled with computer-aided design (CAD) software - Autodesk Inventor Professional 14.0 [36]. For modeling a real double-glazed window, two glasses of size 1000 x 1000 x 10 mm^3 were designed with an air gap of 16 mm and an aluminum frame of size 66 x 20 mm^2 with a rubber spacer between glasses and frame. Since the two glasses (NFRC 21025 and 21431) are formed through float process the corresponding properties were considered from Ansys library (*Table 5.3*). Flaws (defects) accompanied by glass material that includes manufacturing defects or micro-cracks along their edges were not considered to simplify the model, as no indications about how to compute them are mentioned in French Norm DTU 39 document.

Table 5.3: Material properties of double-glazed window from Ansys build-in library.

Glass			
Property	**Symbol**	**Value**	**Units**
Thermal Conductivity	k	1.4	Wm-1C-1
Density	ρ	2500	Kg m-3
Specific Heat	C_p	750	J Kg-1 C-1
Aluminium			
Property	**Symbol**	**Value**	**Units**
Thermal Conductivity	k	237.5	Wm-1C-1
Density	ρ	2689	Kg m-3
Specific Heat	C_p	951	J Kg-1 C-1
Rubber			
Property	**Symbol**	**Value**	**Units**
Thermal Conductivity	k	0.16	Wm-1C-1
Density	ρ	1190	Kg m-3
Specific Heat	C_p	1	J Kg-1 C-1

Later, the geometry created using Autodesk Inventor was imported into Ansys Workbench module via Inventor part exchange format file which is one of the default export files from Autodesk Inventor. Regarding the shape of meshing elements, standard mechanical shape checking criteria were selected as it had proven to be effective for linear, modal, stress and thermal problems. In order to control the mesh sizing, a proximity size function was used along with medium sized elements, the result of the meshed component is shown in *Figure 5.5*. As the model does not involve any complex curvatures, it would provide a reliable solution with less computing time and good processing speed.

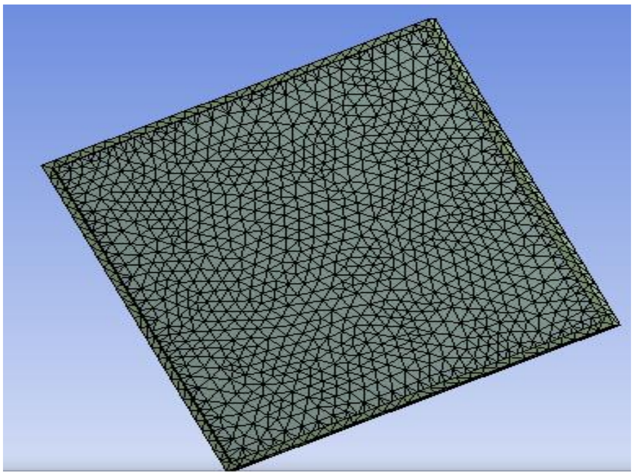


Figure 5.5: Meshed component

To simplify the heat transfer model and to avoid complication with conjugated heat transfer model, steady state condition was chosen which is quite similar to the condition used by the *FG-Breakage* code. *Figure 5.6*, shows the defined boundary conditions for the problem considered. For the purpose of this study, natural convective heat transfer coefficient was considered for both outdoor and indoor environmental condition based on the French Norm DTU 39 and for the convective heat transfer coefficient among the neighboring glass, the NF EN 673 standard has been considered [1].

A: Steady-State Thermal
Steady-State Thermal
Time: 1. s
6/30/2017 11:39 PM

A Conv. Exterior Glass: 32. °C, 13. W/m²·°C
B Conv. Interior Glass: 25. °C, 9. W/m²·°C
C Rad. Exterior Glass: 29. °C, 0.84 , 1.
D Conv. Ext. AirGap: 29. °C, 1.64 W/m²·°C
E Rad. Interior Glass: 29. °C, 0.84 , 1.
F Conv. Int. AirGap: 29. °C, 1.64 W/m²·°C
G Solar Flux Ext. Glass: 166.9 W/m²
H Solar Flux Ext. Glass: 120. W/m²

Figure 5.6: Boundary conditions considered in Ansys

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 summary of the results obtained from *FG-Breakage*, Window 7.4 and Ansys are tabulated in *Table 5.4* And the pictorial representation of thermal gradient obtained from Ansys simulation tool is schematized in *Figure 5.7* and it could be observed that for a glazing system the temperature of the central area of glass will be at higher temperature. 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 the simulation, for example:

- The frame can act as a sink and thus temperature of central area can decrease. For Ansys simulation the characteristics of frame are considered, while for FG-Breakage and Window 7.4 the characteristics of frames were not considered (although Window 7.4 can consider the frame characteristics).

- The methodologies for computing the maximum temperature of a glazing system are different. For Windows 7.4 they have used comprehensive one-dimensional heat transfer model based on experimental measurements and numerical modelling of selected heat transfer cases while in case of ANSYS, basic heat transfer equation was used by finite element methods to solve three-dimensional energy equation.

Table 5.4: 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

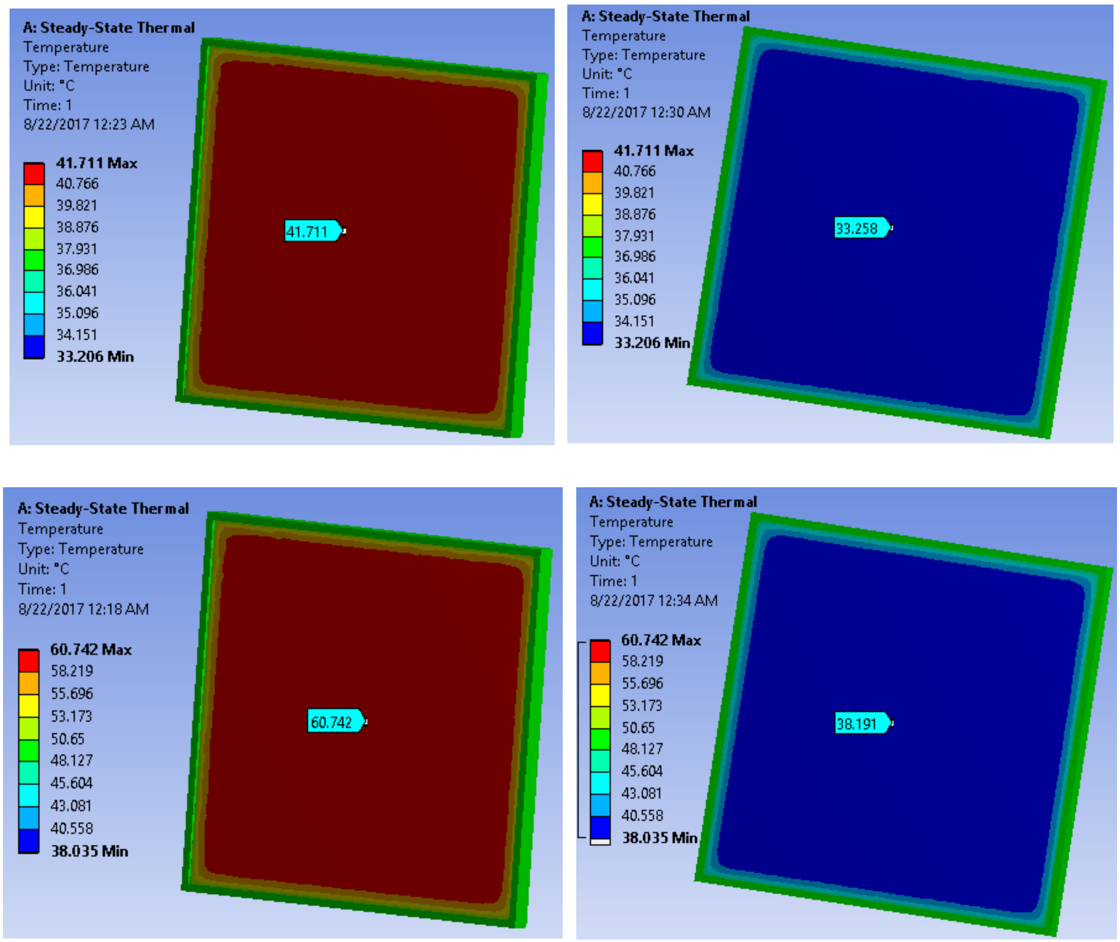


Figure 5.7: Temperature profile in Ansys for two cases.

6 Conclusion

6.1 Summary

The study fulfilled the objective to provide a better fundamental knowledge on the mechanisms of glass failure due to thermal breakage. Based on this knowledge it was possible to develop a new tool, named *FG-Breakage,* that could enhance the previous standardization work of French Norm DTU 39, which is only applicable to glass. The code can be used to compute the maximum temperature difference between different areas of glass and then to predict failures due to thermal breakage when a window film is applied to glass by comparing the calculated temperature difference with tabulated data on the French Norm DTU 39.

Based on this, multiple conclusions can be obtained and the most important are summarized as follows:

The present study exploits the need of a proper selection of film for the window at the design stage and the developed *FG-Breakage* tool can help to take a decision in order to minimize any risk factor associated with a thermal fracture when using films.

Though 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.

There are a wide variety of films available in the market, thus a proper selection of the film for a window is required, to substantially contribute to its improvement in thermal and energy performance of the building and at the same time the film should not contribute to the thermal stress of glass.

Based on the closer numerical results obtained from Window 7.4 and *FG-Breakage* codes, it seems that the *FG-Breakage* results are quite reliable to perform window film to glass breakage compatibility checks.

6.2 Future work

Current literature on thermal breakage with respect to applied films is not detailed enough, a existing calculation methods to evaluate thermal fracture of glass does not consider the use of applied films and its induced thermal inertia. So, proposing a simplified calculation method for multiple glazing based on the findings of above study would be interesting.

In the future, it would be interesting to do an experimental study with the use of solar simulators that could cause thermal breakage on glass pane with and without applied film to observe its breakage behavior and associated temperature difference.

Spectral properties of window serve as the input for analyzing the visual performance of buildings and its spectral behavior can be changed by applying a film over the glazing area. In future, it would be interesting to develop an indoor ambiance and visual comfort recommendation tool based on the computed spectral changes on applying the film to glass.

It would be even interesting to compare the results obtained from *FG-Breakage,* with results obtained through Belgian or British Standard.

The temperature gradient results in regard to thermal fracture investigation are done using ANSYS software under steady state condition. The comparison of the numerical set-up results described in the hereby thesis with results from Physibel transient thermal analysis software, like Bistra that includes a built-in solar processor and the variable ambient condition that can approximate reality, could also be an interesting addition to future investigations. Furthermore, additional parameters of influence could be investigated and their impact could be quantified by finite element software simulations.

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Appendix

Annex A

A.1 Relative spectral distribution of global solar radiation – EN 410

Table A 1: Normalized relative spectral distribution of global solar radiation [26].

λ (nm)	S_λ . Δλ	λ (nm)	S_λ . Δλ
300	0.0005	950	0.022
320	0.0069	1000	0.0329
340	0.0122	1050	0.0306
360	0.0145	1100	0.0185
380	0.0187	1150	0.0136
400	0.0235	1200	0.021
420	0.0268	1250	0.0211
440	0.0294	1300	0.0166
460	0.0343	1350	0.0042
480	0.0339	1400	0.001
500	0.0326	1450	0.0044
520	0.0318	1500	0.0095
540	0.0321	1550	0.0123
560	0.0312	1600	0.011
580	0.0294	1650	0.0106
600	0.0289	1700	0.0093
620	0.0289	1750	0.0068
640	0.028	1800	0.0024
660	0.0273	1850	0.0005
680	0.0246	1900	0.0002
700	0.0237	1950	0.0012
720	0.022	2000	0.003
740	0.023	2050	0.0037
760	0.0199	2100	0.0057
780	0.0211	2200	0.0066
800	0.033	2300	0.006
850	0.0453	2400	0.0041
900	0.0381	2500	0.0006

A.2 Permissible temperature difference for low inertial frames:

Table A 2: Permissible temperature difference for low thermal inertia frames [1].

Type of Glass (non-heat treated)	**Support On**	**With Shadow**			**Without Shadow**		
		β >= 60°	60°>β>=30°	30°>β	β >= 60°	60°>β>=30°	30°>β
Shaped Monolithic	periphery	42	38	34	48	43	38
Symmetrical laminate with all components >=4mm	others	34	28	21	38	31	24
Raw monolithic cut	periphery	35	32	28	40	36	32
Raw symm. Laminated, with all comp. >=4mm							
Shaped symm. Laminated with 1 of comp. <=3mm	others	28	23	18	32	26	20
Shaped non-symm. Laminated							
Raw cut or laminated	periphery	32	29	25	36	32	29
	others	25	21	16	29	23	18
Laminated non-symm. Cutting	periphery	26	24	21	30	27	24
laminated raw cut with 1 of the component <=3mm							
sawn symm. Lam. With all component >= 4mm	others	21	17	13	24	19	15
Laminated non-symm. Seen	periphery	25	22	20	28	25	22
	others	20	16	12	22	18	14
Armed	periphery	23	20	18	25	23	20
	others	18	15	11	20	17	13

Annex B

B.1 Heat pockets

The vertical glazing is considered as in front of heat pockets if:

d1 up to 0.80 m and h1 ≥ 0.5 d1 + 0.10 (m)

or

d2 up to h2 and h2 ≥ 0.10 m

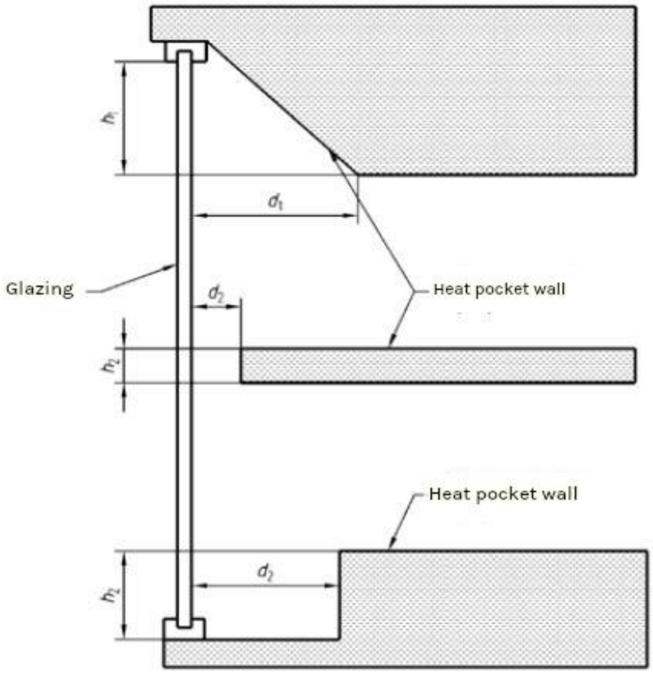

Figure B.1: Conditions for heat pocket design [1]

B.2 Internal Wall Sliding

In the semi-open position of internal wall sliding case, the frame comprises part of glazing concealed inside the wall. The temperature of glazing is a function of their position with respect to the insulation of the wall. The climatic condition to be considered are those of in *Table 4.7*.

Let ΣR_i be the sum of the thermal resistances of the insulation system on the inside wall with respect to glazing system. Then,

$$\sum R_i = \sum_j \frac{e_j}{\lambda_j} + \frac{2}{h_i}$$

Similarly, the sum of thermal resistance on the outside wall insulation system with respect to glazing system is given by,

$$\sum R_e = \sum\nolimits_m \frac{e_m}{\lambda_m} + \frac{1}{h_i} + \frac{1}{h_e}$$

e_m – thickness of material m

λ_m – thermal conductivity of material m

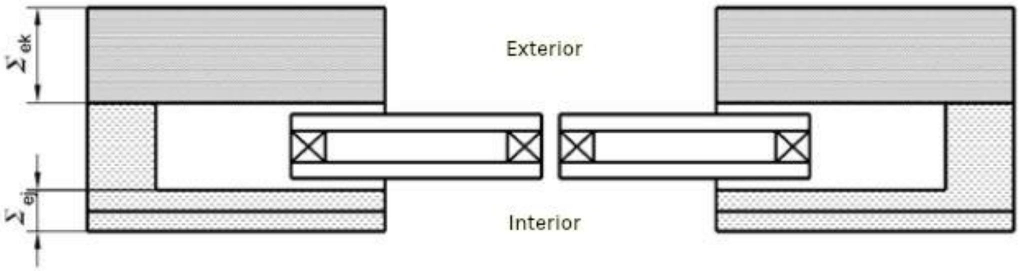

Figure B.2:Sliding Internal wall window [1]