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Structural glass in buildings: study of the deflection, durability, and breakage of laminated glass elements and polymeric interlayers

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TESI DOCTORAL

Universitat de Lleida

Structural glass in buildings: study of the deflection, durability, and breakage of laminated glass elements and polymeric interlayers

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Memòria presentada per optar al grau de Doctor per la Universitat de Lleida

Programa de Doctorat: Enginyeria i tecnologies de la informació

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Departament d'Informàtica i Enginyeria Industrial
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La Dra. Luisa F. Cabeza, Catedràtica de l'Escola Politècnica Superior de la Universitat de Lleida i el Dr. J. Ramon Castro, professor a temps complet de la Universitat de Lleida.

CERTIFICA:

Que la memòria *Structural glass in buildings: study of the deflection, durability, and breakage of laminated glass elements and polymeric interlayers* presentada per Xavier Centelles Soler per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, juliol 2020

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Summary

Have you ever imagined a building made up entirely of glass? Well, if you have, you are not the only one. Over the last two decades, many researchers, architects, and engineers have worked on the development of transparent enclosures and structural elements, achieving remarkable results.

Modern architecture demands more transparency in buildings, which can be attained by means of bigger windows, but also by including glass facades, roofs, and floors. Some singular buildings have even replaced conventional steel or reinforced concrete beams and with fully transparent laminated glass elements.

Larger glass surfaces and higher loads lead to higher stresses and deflections. In addition to that, the brittle nature of glass makes it prone to unexpected breakage during its service life. For that reason, when glass elements play a more significant role in the structural integrity, the safety requirements also become stricter. This means that structural elements made of glass must undergo careful structural calculation, and post-breakage safety must be guaranteed.

This PhD evaluates the structural performance of laminated glass through literature research, experimental testing, and numerical simulation. Some of the conducted experimental tests focus on the deformational study before initial glass fracture, while in others the failure of the specimens is reached in order to evaluate the post-breakage safety as well. Special attention is paid to the polymeric interlayer that creates a bond between glass sheets, because it plays a key role in both the pre- and post-breakage stages.

The results of this thesis show that, although glass is brittle, laminated glass elements can resist high loads and comply with safety regulations. However, it is essential to choose the right design parameters (e.g., type of glass, number of glass sheets, and interlayer material), because these can have a high impact on the mechanical behaviour, especially in case of accidental breakage.

Resumen

¿Te has imaginado alguna vez un edificio realizado íntegramente con vidrio? Si así es, no has sido el único. Durante las últimas dos décadas, muchos investigadores, arquitectos e ingenieros han trabajado para el desarrollo de grandes superficies acristaladas y elementos estructurales transparentes, alcanzando resultados destacables.

La arquitectura moderna demanda una mayor transparencia en los edificios. Este objetivo se puede alcanzar con mayores ventanas, pero también mediante el uso de fachadas, forjados y techos acristalados. Algunos edificios incluso han reemplazado las estructuras convencionales por vigas o columnas de vidrio laminado.

En este sentido, la demanda de mayores superficies acristaladas sometidas a estados de carga cada vez más exigentes comporta una evaluación técnica muy exigente de su estado tensional y deformacional. Además, la naturaleza frágil del vidrio lo hace propenso a sufrir roturas inesperadas durante su vida útil. Por esta razón las estructuras de vidrio laminado deben someterse a un cálculo minucioso y la seguridad en caso de rotura tiene que estar garantizada.

Esta tesis doctoral evalúa el comportamiento mecánico del vidrio laminado mediante un estudio bibliográfico, ensayos experimentales y simulaciones. Algunos de los ensayos llevados a cabo se centran en el estudio de las deformaciones, mientras que en otros se alcanza la rotura para evaluar también el comportamiento post-rotura. Se presta especial atención al intercalario polimérico que se usa para unir las láminas de vidrio entre ellas, por su rol determinante tanto antes como después de la rotura del vidrio.

Los resultados de esta tesis muestran cómo, a pesar de que el vidrio es frágil, los elementos de vidrio laminado pueden resistir cargas elevadas y cumplir con los requerimientos de seguridad. Sin embargo, es esencial elegir los parámetros de diseño adecuados, como el tipo de vidrio, el número y grosor de láminas de vidrio y el material intercalario, porque pueden tener un gran impacto en el comportamiento mecánico, especialmente en caso de rotura accidental.

Resum

T'has imaginat mai un edifici fet completament de vidre? Doncs bé, si ho has fet, no ets l'únic. Durant les darreres dues dècades diversos investigadors, arquitectes i enginyers han treballat en el desenvolupament de tancaments i elements estructurals transparents, assolint resultats destacables.

L'arquitectura moderna demanda una major transparència en els edificis, que pot ser assolida mitjançant finestres més grans, però també amb la implementació de façanes, forjats i sostres de vidre. Alguns edificis han substituït fins i tot les estructures convencionals de formigó armat o acer per bigues o columnes de vidre laminat.

El fet d'augmentar la mida i la càrrega sobre els elements de vidre es tradueix en un augment de les tensions i les deformacions. A més a més, la naturalesa fràgil del vidre el fa propens a patir ruptures imprevistes durant la seva vida útil. Els elements estructurals de vidre tindran requeriments de seguretat més estrictes; això vol dir que s'hauran de sotmetre a un càlcul minuciós i se n'haurà de garantir la seguretat post-ruptura.

Aquesta tesi doctoral avalua el comportament estructural del vidre laminat mitjançant la recerca bibliogràfica, assajos experimentals i simulacions. Alguns dels assajos experimentals duts a terme es centren en l'estudi de les deformacions abans de la ruptura inicial del vidre, mentre que en altres s'assoleix la ruptura per tal d'avaluar la seguretat port-ruptura. A més a més, es fa especial èmfasi en el material intercalari que uneix les làmines de vidre entre elles, per la seva importància en el comportament global del vidre laminat.

Els resultats d'aquesta tesi mostren com, malgrat que el vidre és fràgil, els elements estructurals de vidre laminat poden resistir càrregues elevades i complir amb els requeriments de seguretat. No obstant, és fonamental triar els paràmetres de disseny adequats, com el tipus de vidre, el número i gruix de les làmines de vidre i el material intercalari, perquè poden tenir molta rellevància, especialment en cas de ruptura accidental.

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Symbols

E	Young modulus	[$MPa=N/mm^2$]
$E(t)$	Relaxation modulus	[$MPa=N/mm^2$]
$E^*(\omega)$	Complex modulus	[$MPa=N/mm^2$]
$E'(\omega)$	Storage modulus	[$MPa=N/mm^2$]
$E''(\omega)$	Loss modulus	[$MPa=N/mm^2$]
t	Time	[s]
T_g	Glass transition temperature	[ºC]
δ	Phase shift of viscoelastic materials	[º]
ε_0	Initial strain	-
ε_e	Elastic strain	-
ε_p	Plastic strain	-
ε_v	Viscous strain	-
η	Viscosity	[$MPa\cdot s=N\cdot s/mm^2$]
σ_0	Initial stress	[$MPa=N/mm^2$]
σ_e	Elastic stress	[$MPa=N/mm^2$]
σ_v	Viscous stress	[$MPa=N/mm^2$]
ω	Frequency	[Hz]
ω	Frequency of oscillation	

Abbreviations

DMA	Dynamic mechanical analysis
DMTA	Dynamic mechanical thermal analyser
ESC	Effective Stiffness Concept
EVA	Polyethylene-co-vinyl acetate
PC	Polycarbonate
PMMA	Polymethylmetacrilate
PVB	Polyvinyl butyral
SLS	Serviceability Limit State
TTS	Time-temperature superposition
TPU	Thermoplastic polyurethane
ULS	Ultimate Limit State
UV	Ultraviolet

Chapter 1

1. Introduction, objectives, and PhD thesis structure

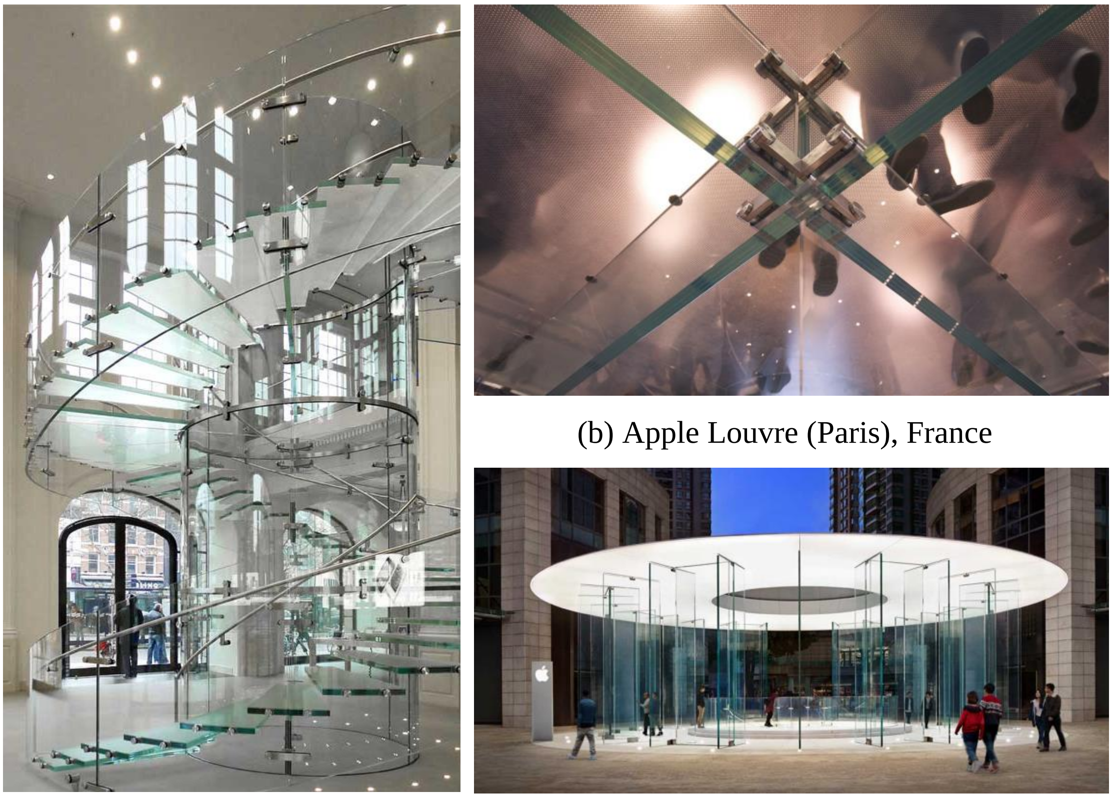
1.1 Introduction

1.1.1. Glass in buildings

The importance of the development of new materials throughout the history has been such that some of them have even named the periods in which its use prevailed. The Stone Age, the Bronze Age, and the Iron Age are examples of this. Glass has not marked any specific period in history, but its contribution and evolution has been remarkable in most of them.

For ages, glass has been a form of artistic expression, and it has also been a material of paramount importance in buildings, especially since the twentieth century in modern architecture. During that period, glass started as a decorative material, but new architectural trends brought more challenging proposals from a technological point of view. Since then and until the end of the century, the importance of steel and glass in buildings kept increasing. Another noteworthy event from that period was the irruption of polymers as construction materials.

Starting on the twenty-first century, the pace of technological developments in architecture grew exponentially, and thus the desire to create more challenging structures. The use of glass in buildings has since then evolved from small windows to fully glazed facades, floors, and roofs, with a continuously increasing glass surface size. More recently, some singular buildings have even added fully transparent beams and columns to support these surface elements (Figure 1).

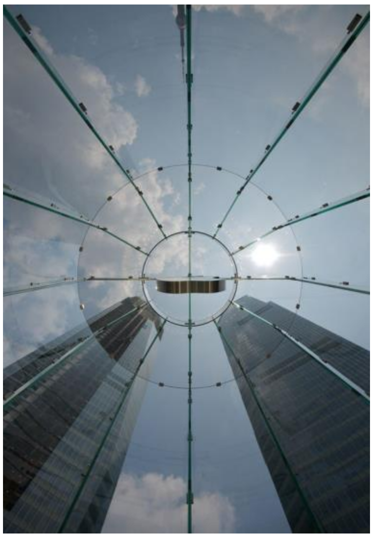


(a) Apple Leidseplein, Amsterdam (b) Apple Louvre (Paris), France (c) Apple Kunming, China

Figure 1. Glass staircases, beams and columns have replaced conventional structural materials in some singular buildings of the twenty-first century. Images from different Apple retail stores [1].

Laminated glass has become the flagship material of the most emblematic Apple retail stores across the world (Figure 2). The Apple Cube on the Fifth Avenue of New York (USA) was initially built in 2006. Its big dimensions (9x9x9 m^3), together with the fact that the walls and the roof were supported by laminated glass beams and columns, challenged the technological bounds of laminated glass at the time. However, only five years later, the building was redesigned, reducing the number of panels from 106 to 15, and the number of fittings from 250 to 40.

The size of single panels became even bigger in the Apple Pudong store (China), where the 13-metre-tall curved laminated glass panels required the creation of an unmatched production facility. Newer stores, such as the Apple Westlake in China and the Apple Causeway Bay in Hong Kong have already surpassed that single panel length, with 15-metre-tall laminated glass panels.



(a) Apple Fifth Avenue Mark II (USA) (b) Apple Pudong (China)

(c) Apple Zorlu (Turkey) (d) Apple Piazza Liberty (Italy)

Figure 2. Apple retail stores in (a) New York, USA, (b) Pudong, China, (c) Istanbul, Turkey, and (d) Milan, Italy [1].

The Zorlu Lantern of the Apple Zorlu store in Istanbul (Turkey) had a minimalist design, with four single panels for the walls, bonded only with silicone, without mechanical fixings, supporting a 10x10 m^2 carbon fibre reinforced polymer roof. The singularity of the Apple stores can be seen in many other stores, such as the Apple Piazza Liberty store in Milan (Italy), which had a curtain of water falling from two eight-metre-tall glass walls. This creates an impressive visual effect, especially challenging for the resistance to water exposure of the structural silicone that bonds the glass panels.

Apple created a new concept of retail store, with a minimalist design, cleaner internal spaces, and a dominant presence of transparent enclosures. These innovative ideas led other big corporations, such as Tesla or McDonald’s, to redesign their flagship stores (Figure 3).

(a) Tesla (Sydney, Australia) (b) McDonald’s (Chicago, USA)

Figure 3. Flagship retail stores of Tesla in Sydney and McDonald’s in Chicago.

1.1.2. Architectural glass performance

Construction materials have more and stricter safety requirements when used in structural applications. That is because structural elements are subjected to higher stresses and strains, and its breakage would have more severe consequences. In the case of glass, these requirements include, among other things, a better knowledge on its mechanical properties and its breakage mode.

The main reason why glass is used in buildings is because it is transparent, but it stands ahead any other transparent material, among other things, because it is very durable and fully recyclable [2]. However, glass is also brittle, highly susceptible to impacts, and lacks the capacity to deform plastically [3]. Glass panes have surface flaws that inevitably appear during its manufacturing, installation, or service life [4]. Due to its brittleness, these surface flaws may become larger cracks and grow uncontrollably when subjected to tensile stress, leading to glass breakage [5]. As a consequence, glass has a low tensile strength and a high variability in the rupture stress [6], since it depends on the size, shape, and amount of surface flaws [7].

There are some thermal and chemical processes that can increase the strength of glass, as well as its resistance to impacts and thermal variations, by intentionally adding residual surface compressive stresses [8]. Since glass generally breaks due to impacts or excessive tensile stresses on its surface, the main purpose of thermal and chemical strengthening is to create a pre-compressed region in the glass surface that compensates the initial tensile stresses caused by external loads (Figure 4). As a consequence, the maximum surface tensile stress decreases, and therefore both tensile and bending strength increase.

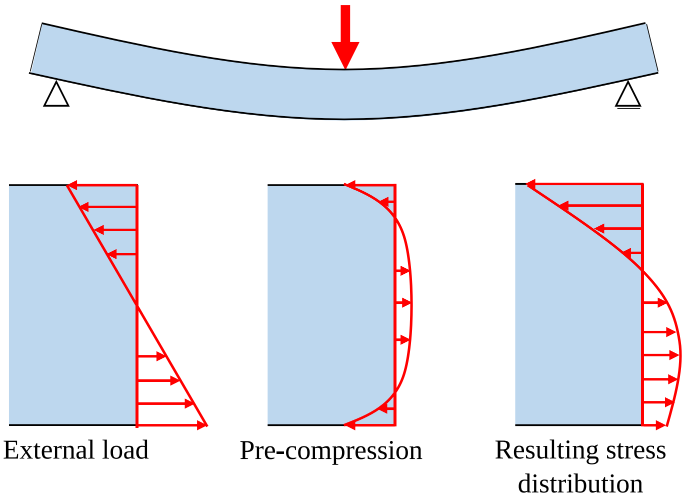
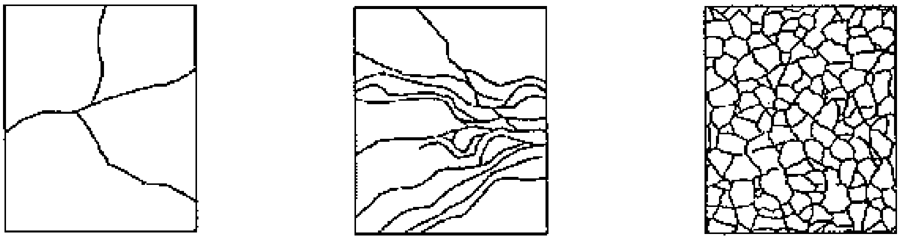


Figure 4. Stress distribution in the cross section of a heat-strengthened glass plate subjected to bending.

Thermal strengthening processes are less expensive and more common than chemical strengthening processes [9]. Depending on the degree of thermal strengthening, the resulting glass is classified as heat-strengthened or thermally toughened, also known as tempered [10]. The characteristic value of bending strength of annealed glass is 45 MPa, which can go up to 70 MPa in heat-strengthened glass and up to 120 MPa in thermally toughened glass [11]. Chemical strengthening processes are generally used in thin glass sheets [9], because the surface pre-compressed region is thinner. The characteristic strength of chemically strengthened glass can go up to 150 MPa [11].

The surface pre-compression of glass also affects its crack pattern in case of breakage (Figure 5) [12]. A pre-compressed glass sheet accumulates elastic strain energy, which is instantaneously dissipated in case of crack formation. The higher the degree of pre-compression, the higher the crack density, because there is a correlation between the elastic train energy dissipation and the crack surface [13].



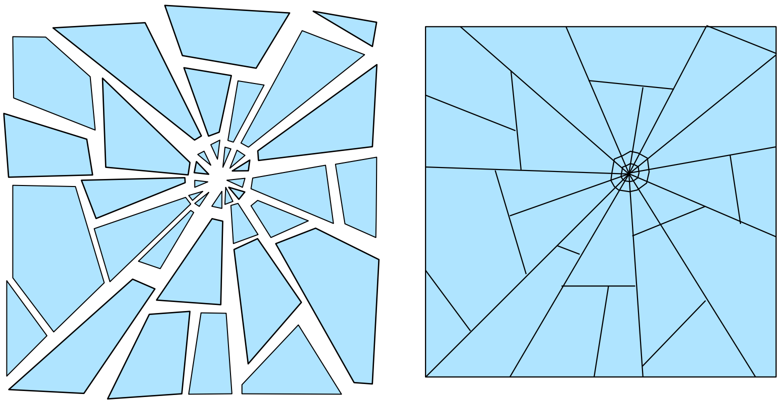
(a) Annealed (b) Heat-strengthened (c) Tempered

Figure 5. Crack pattern of (a) annealed glass, (b) heat-strengthened glass, and (c) thermally toughened or tempered glass. Retrieved from [14].

Increasing the tensile strength of glass is not enough to guarantee its safety in structures. That is because the strengthening process does not solve neither the problem of brittleness (although it may increase its toughness) nor the problem of unpredictability of the tensile strength. Furthermore, thermally toughened glass sheets may suffer spontaneous breakage caused by nickel sulphide inclusions [15], which occasionally appear when glass reacts with sulphur in the furnace during the fabrication process. This means that, in any case, unexpected glass breakage may occur, with all that this entails.

1.1.3. Laminated glass

The main risk of glass breakage is the projection of broken glass shards. Laminated glass prevents this from happening (Figure 6) [16]. Laminated glass is made from two or more glass sheets bonded together with a polymeric film between them that acts as an interlayer. The bond is created through the chemical union between hydroxyl groups from the polymeric interlayer and silanol groups from the glass sheet [17]. Said bond is created by subjecting the composite laminate to high temperature and pressure cycles in a chamber known as autoclave. In case of glass breakage, the broken glass shards remain adhered to the interlayer instead of scattering.



(a) Monolithic glass (b) Laminated glass

Figure 6. Sketch of the breakage of monolithic glass and laminated glass.

Stiff interlayers also transfer shear stresses between confronted glass sheets when subjected to out-of-plane bending (Figure 7). As a consequence, stiffer and thinner interlayers have a higher capacity to transfer shear stresses between glass sheets, and therefore present a more cohesive behaviour [17].

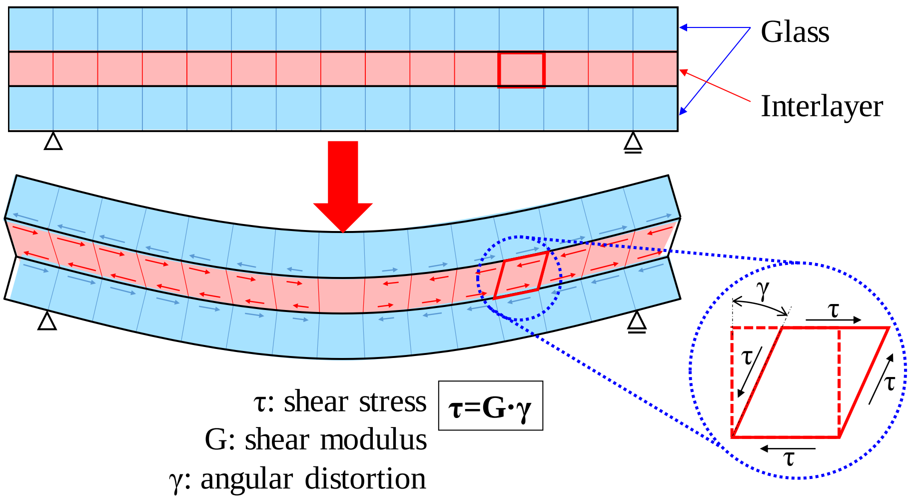


Figure 7. Transfer of shear stress in the interlayer of a laminated glass plate subjected to bending.

The mechanical behaviour of a laminated glass element under a bending load is in a midpoint between two limits: the layered limit, when there is no friction or shear transfer between confronted glass surfaces, and the monolithic limit, when there is a perfect bond, with no relative displacement between confronted surfaces (Figure 8) [18,19]. The stiffer and thinner the interlayer, the closer laminated glass is to the monolithic limit.

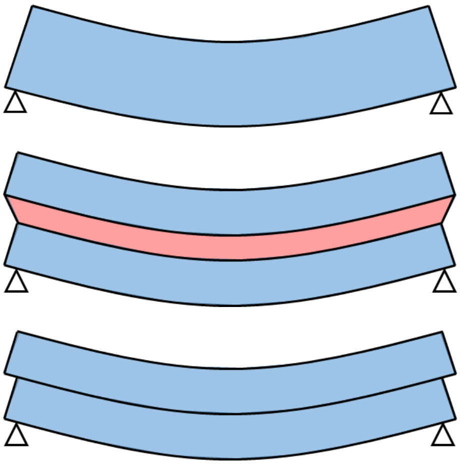


Figure 8. Comparison between the bending of a monolithic, a laminated, and a layered element.

Figure 7 shows how the angular distortion of the interlayer is bigger near the edges and progressively decreases as it approaches the central region. This means that the shear transfer between glass and interlayer is not homogeneous across the entire bond region. This gets even more complicated if the mechanical response of the interlayer is nonlinear [20,21] and viscoelastic [22,23], as it usually is. Instead, the calculation of the bending stiffness of a monolithic element (Figure 8) is much simpler. That is why a simplified method was developed to calculate the flexural response of laminated glass. It is known as Effective Stiffness Concept [6,19], and it consists on defining the bending stiffness of a monolithic element with the equivalent bending properties to the ones of a laminated element.

The strength and stiffness of the interlayer also plays a key role in the post-breakage behaviour of laminated glass. When a glass sheet breaks, the broken glass shards that remain bonded to the interlayer provide a certain level of residual load-bearing capacity [24], which will depend on the stiffness of the interlayer [25] and the size of the broken glass fragments [26].

Many published articles show that the shear stiffness of the interlayer material that bonds glass sheets together has a key role in the bending stiffness of laminated glass plates (Figure 7) [27–29], the lateral stability of laminated glass beams (Figure 9) [30,31], and the post-breakage behaviour of broken laminated glass elements [24,26]. The way it affects the lateral stability of beams is the same way it affects the out-of-plane bending stiffness: the stiffer the interlayer, the more cohesive the composite laminate, and therefore the higher the slenderness of the beam.

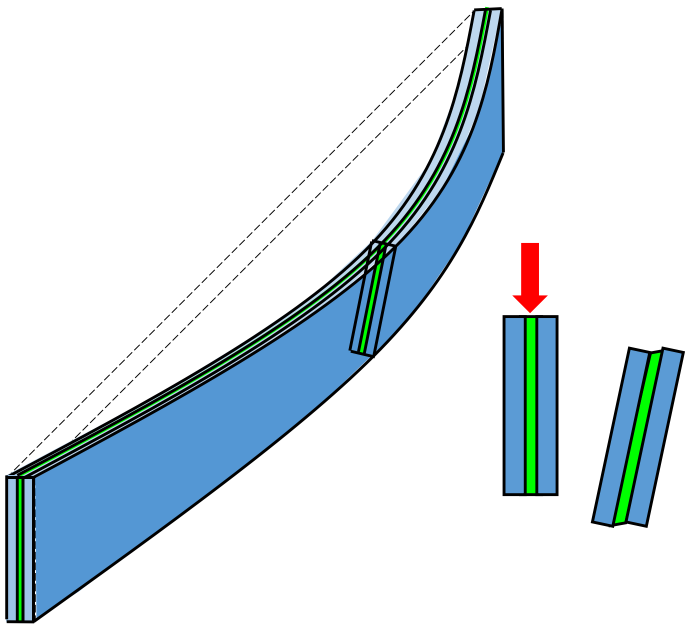


Figure 9. Lateral torsional buckling of a laminated glass beam.

1.1.4. Viscoelastic interlayers

The polymeric films used as interlayer materials are viscoelastic, which means, among other things, that its mechanical response to an external load depends on the working temperature and the load duration [22,23,32]. The mechanical response of a viscoelastic material combines an elastic response, in which the stress is proportional to the strain, ruled by the Hooke law ($\sigma_e = E \cdot \varepsilon_e$), and a viscous response, in which the stress is proportional to the strain rate, ruled by the Newton law ($\sigma_v = \eta \cdot d\varepsilon_v/dt$), in the case of Newtonian fluids.

In stationary tests, a constant stress or strain is applied on a viscoelastic material, which, as a consequence, experiences an instantaneous elastic response combined with a time-dependant response, known as creep (Figure 10) or stress relaxation (Figure 11) respectively. In dynamic tests, an oscillatory load or displacement is applied on a viscoelastic material, which has an oscillatory response, with an amplitude proportional to the applied load or displacement, and a temporal offset δ, also known as phase angle, which is higher when the viscous component is more predominant (Figure 12).

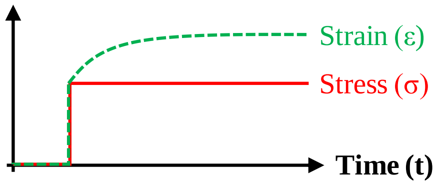


Figure 10. Creep experienced by a viscoelastic material under a constant stress in a stationary test.

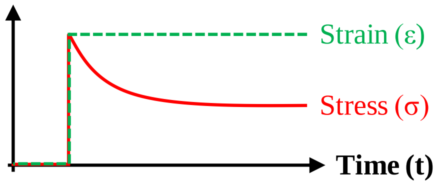


Figure 11. Stress relaxation experienced by a viscoelastic material under a constant strain in a stationary test.

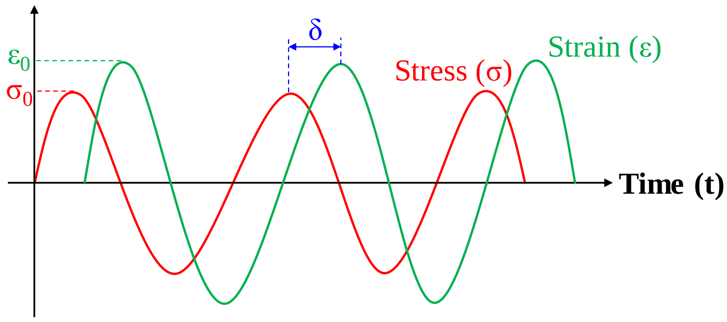


Figure 12. Mechanical response of a viscoelastic material under an oscillatory load.

It was previously indicated that the mechanical properties of laminated glass are affected by the shear stiffness of the polymeric interlayer. In addition to that, the shear stiffness of the interlayer is time- and temperature- dependant. As a consequence, the mechanical properties of laminated glass are also time- and temperature-dependant [27].

The bond with a polymeric interlayer solves the problem of glass shards scattering in case of breakage, but load-bearing elements also require a certain level of post-breakage strength. Since glass is brittle and sensitive to impacts, accidental glass breakage may happen, but structural elements (i.e., beams and columns) should have a progressive and safe breakage.

Some of the proposals to this end involve using steel bars or tensors as a reinforcement material [33], or designing hybrid beams, which combine glass with other construction materials, such as steel, wood or reinforced concrete [34], which provide the post-breakage strength and ductility that glass lacks. These solutions have proven to be effective, but their main drawback is the addition of an opaque material across the full length of the beam. There are also some fully transparent designs obtained either by adding sacrificial glass layers [21], or layers of transparent stiff polymers such as polycarbonate (PC) or polymethylmetacrilate (PMMA) [35–37].

1.1.5. Norms and experimental tests for laminated glass

There are different tests that aim to evaluate the strength of monolithic glass. The international standard ISO 1288 defines two test methods to evaluate the bending strength of glass: the coaxial double ring test (Figure 13) [38] and the four-point bending test (Figure 14) [39]. The results of the four-point bending test are influenced by the defects generated during the cutting process near the edges, where breakage generally starts [40], while the coaxial double ring test evaluates the bending strength of flat glass away from the edges. The standard ASTM C158 [41] also suggests performing a four-point bending test to determine the flexural resistance of glass.

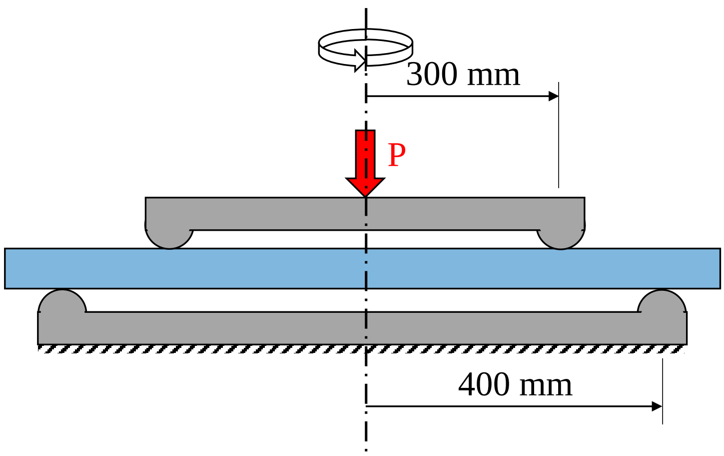


Figure 13. Coaxial double ring test proposed by the standard ISO 1288-2 [38].

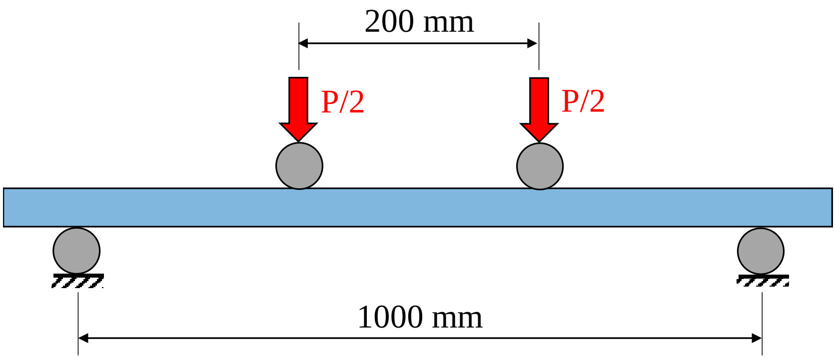


Figure 14. Four-point bending test proposed by the standard ISO 1288-3 [39].

The main issue with this approach is that, even if the strength of glass is accurately calculated with bending tests, this does not guarantee the safety of said element. The main reason for this is because glass is prone to accidental or spontaneous breakage [42], and therefore it may break, even if the adequate safety coefficients are chosen. Therefore, the design of glass requires a study of the resistance to impacts and other unconsidered causes, what Bos refers to as "damage sensitivity" in his PhD [43].

With respect to laminated glass, most of the mechanical tests are developed for automotive applications [44] or safety glazing [45], and mainly focus on the impact resistance. The standard ISO 3537 [46] includes metallic ball drop tests, and soft body impact tests for pedestrian safety. The standard ANSI Z26.1 [47] also contemplates metallic ball drop tests, as well as penetration and ballistic tests for bulletproof glass. Another type of tests performed to evaluate the impact resistance of laminated glass are the pendulum tests. For instance, the standard ISO 29584 [48] defines a soft body impact test to evaluate the impact resistance and breakage mode of safety glass. A pendulum test is also defined, in that case for flat glass, in the European norm ISO 12600 [49].

The international standard for laminated glass in buildings ISO 12543 evaluates the performance of laminated glass mainly based on the impact resistance, determined from a pendulum test [48], and durability to high temperature, humidity, and solar radiation. Durability tests are also contemplated in the American standard ANSI Z26.1 [47], in that case to humidity, high temperature and chemical resistance.

As a general conclusion, mechanical tests on laminated glass mainly focus on the impact resistance, while some standards propose tests to evaluate the flexural strength of monolithic glass. However, none of these standards focus on the post-breakage stage, which is an essential factor for structural elements, especially in brittle materials such as concrete or glass. The Guidance for Structural Design of Glass Components [50], developed in 2014 by the European Commission, aimed to achieve a new set of standards for the future development of a new Eurocode on structural glass.

1.2 PhD hypothesis

The main aim of this PhD is to come closer to a safe design of structural elements made of glass. The concept of safety is defined in this PhD by a series of key performance indicators, especially in terms of post-breakage strength, ductility, and stiffness.

This PhD is based on the assumption that it was possible to make safer laminated glass elements, especially in terms of post-breakage strength, stiffness and ductility, by using the right design parameters. Such design parameters include, but are not limited to, the type of glass, the number of glass sheets, the interlayer material, the bond between glass and interlayer, and the type of connection between the laminated glass structural element and other substrates.

In some cases, when comparing different designs, there may be a conflict between the pre- and the post-breakage performance, meaning that the strongest design is not necessarily the safest. When this happens, it is important to evaluate the benefits and drawbacks of each one. However, given the brittle nature of glass, the priority objective may generally be making safer laminated glass elements.

1.3 Objectives

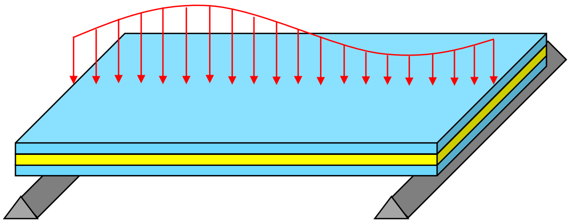
The main objective of this PhD is to contribute to the creation of safer laminated glass elements for structural applications. To do so, several secondary objectives are established. The first one consists on providing a better knowledge of the behaviour of laminated glass and the two materials it is made of: glass sheets and polymeric interlayers.

With respect to the interlayer material, several authors agree that it plays a key role in the pre-breakage performance [17,27,31] and post-breakage safety [24,26,29] of laminated glass elements. There is a wide variety of commercial interlayer materials developed for different applications [51,52]. In this PhD, extensive information about these interlayer materials is gathered for a more adequate material selection.

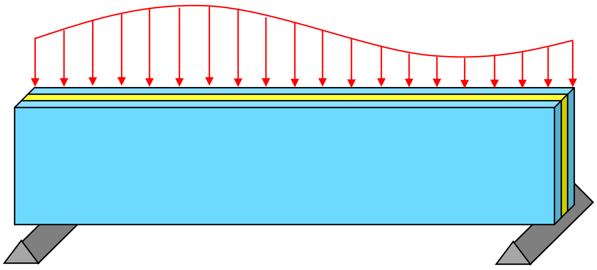
A study of the mechanical properties of polymeric interlayers should include tests on the polymeric films, but also on laminated glass specimens, because the autoclave process may affect the mechanical properties of the interlayer [32]. In addition to that, it is not only important how strong and stiff the interlayer may be, but also the quality of its adhesion with glass.

Interlayer materials in laminated glass are viscoelastic, and therefore their mechanical properties are time- and temperature-dependant [22,23]. As a consequence, a proper material characterization must take into account these two variables, so that the material selection can be made based on the expected load duration and working temperature range for each application. From dynamic mechanical analysis (DMA) it is possible to obtain the numerical models that express the properties of these materials as a function of both time and temperature [53].

The mechanical behaviour of laminated glass varies greatly depending on whether it works as a plate, with the load perpendicular to the surface (i.e., out-of-plane loading), or as a beam with a coplanar load (i.e., in-plane loading), as shown in Figure 15. So, another objective is to study, for both plates and beams, the deflection in the serviceability limit state (SLS), as well as the strength and breakage in the ultimate limit state (ULS). Given the time-dependant mechanical behaviour of the polymeric interlayer, this study should differentiate between the instantaneous, elastic response, and the long-term, viscoelastic response.



(a) Laminated glass plate (out-of-plane load)



(b) Laminated glass beam (in-plane load)

Figure 15. Bending load on a laminated glass plate (top) and a laminated glass beam (bottom).

When studying the in-plane bending performance of laminated glass beams, the main objective is to see what makes laminated glass beams stronger and safer, by analysing several design and material parameters. Some key performance indicators must be chosen in order to do this comparative study.

One of the most critical parts of laminated glass elements are the joints that connect them to other adjacent elements. That is because, in order to achieve a higher transparency in buildings, the market demands increasingly larger glass panels and smaller joints, which means that larger loads are concentrated on smaller surfaces [54]. This increases the risk of glass fracture caused by stress concentration. For that reason, another objective of this PhD is to collect information, classify, and compare different types of joints for laminated glass elements.

1.4 Thesis structure

The content of this PhD is divided in five chapters (Figure 16). Chapter one includes an introduction to the research topic, the PhD hypothesis and the main objectives sought to be attained. Chapter two includes a brief introduction to the methodology employed.

Chapter three presents the papers that constitute the PhD. Five of these papers have already been published in scientific journals (Q1), while the other three have been submitted. Papers 1 and 2 are review articles that present the state of the art of two key elements for the structural use of laminated glass in buildings: the polymeric interlayers and the types of connections. Papers 3 and 4 are experimental studies on polymeric interlayers not adhered to glass, studying the tensile properties, as well as the response under different strain rates, times under tension, ageing factors, and temperatures. Papers 5 and 6 study the bond between glass and interlayer, as well as the shear contribution of the interlayer on the mechanical properties of laminated glass. Finally, papers 7 and 8 present full-scale tests on laminated glass structural elements. The content and main results of each paper are briefly explained, together with its contribution to the state of the art and the objectives of the PhD. Chapter four includes a global discussion of the results. Chapter five includes the final conclusions, as well as suggestions for future work.

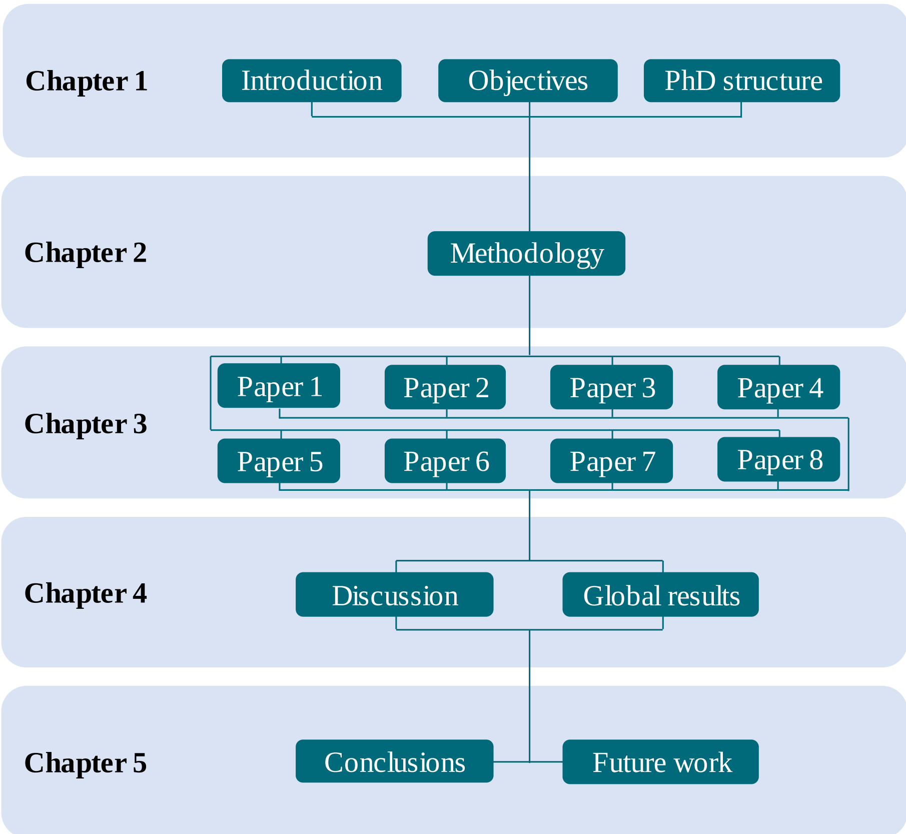


Figure 16. PhD structure.

Chapter 2

2. Methodology

As indicated in the objectives section, this PhD aims to study the mechanical properties of laminated glass, with a specific focus on the study of the interlayer materials that create a bond between glass plates. This study can be divided in three main groups: literature research, experimental testing, and simulation. The materials for the experimental tests were supplied by CRISTEC (Balaguer, Spain). They also did the manufacturing of the laminated glass specimens.

The literature research gave an idea of the current state of the art. It allowed to identify the main challenges of the structural use of glass in buildings. It also helped to find fields in which research could be expanded. It allowed to identify two elements that had high impact on the mechanical properties of loaded laminated glass elements.

One of them was the polymeric interlayer, which had a big impact on the pre-breakage strength and stiffness, and post-breakage safety of laminated glass elements. Most of the research found in the literature focused mainly on two interlayer materials: PVB and SentryGlas. However, there are many others that could provide better features for some applications. For that reason, another review was carried out collecting information about different interlayer materials, including the chemical structure, mechanical properties, durability, and recyclability [51].

The second important element for the performance of laminated glass structures were the joints that connect laminated glass elements to other substrates. In these joints, high stresses are concentrated in small regions, which could lead to glass breakage or at least cause large deflections. There are many different joint designs, some of them are better in terms of strength, while some others are better in terms of durability, aesthetics, cost, or stress distribution. Choosing the right type, size, and number of connections may be determining in order to optimize the overall performance of laminated glass elements.

For that reason, information about different joint designs was collected, and they were classified in groups and compared between them [54].

In addition to that, an experimental study was made with seven different commercial interlayer materials, including but not limited to SentryGlas and PVB [55]. This paper studied factors such as the tensile stiffness and strength, as well as the durability of said materials. This paper focuses on the study of interlayer materials. This means that the results, although useful and complete, were missing two key elements: the study of the adhesion between glass and interlayer, and the cohesiveness between glass sheets. In addition to these two factors, the study of polymeric films alone may be misleading because their mechanical properties may change after the autoclave process [32]. For that reason, subsequent studies were conducted with laminated glass specimens subjected to shearing [56] and bending.

The double-lap shear test and the three-point bending test were simulated using the finite element modelling software COMSOL Multiphysics. The main goal of these simulations was to obtain more accurate information about the stress distribution on the glass sheets, about the contribution of the interlayer, and to present hypothetical, untested scenarios once the simulation model had been validated experimentally.

The durability of the polymeric films and laminated glass was tested by means of accelerated ageing tests. It is hard to tell how accurately can accelerated ageing tests describe long-term exposure to real life weathering factors. It is even harder to determine the equivalent time of exposure in real life of an accelerated ageing test conducted in a laboratory. However, these tests also present some advantages: the most important one is that they allow to control the parameters and isolate one (or more) ageing factors (e.g., temperature, humidity, or solar radiation), in order to see how each of these affects separately the tested specimen or material. In addition to that, when performing comparative studies, as in this case, it is easier to establish identical conditions for all the specimens and prevent uncontrolled factors from affecting unequally the different specimens.

The contribution of the interlayer on the strength, bending stiffness, and post-breakage safety of laminated glass elements is different in horizontally placed elements (plates) and in vertically placed elements (beams). The post-breakage safety is of the utmost importance in laminated glass beams. For that reason, since laminated glass beams seem to be inherently brittle and unsafe, an experimental campaign was carried out aiming to identify design factors that would make laminated glass beams safer.

Another element that was scarcely considered in the initial study was the influence of the temperature and the load duration. The importance of these two parameters was highlighted in previous sections. For that reason, a new round of experimental tests was conducted on the same initial group of polymeric films, but this time taking into consideration these two parameters.

The influence of long-term loading and deflection recovery after load removal was also studied on a laminated glass slab, with three laminated glass plates, each with a different interlayer material, supported by two laminated glass beams. The two phases of the deflection of the slab (creep and recovery) were simulated using ABAQUS by means of the Effective Stiffness Concept (ESC). The viscoelastic properties of the interlayer were taken and adapted from the results of the DMA tests on polymeric films.

Tensile tests were conducted on interlayer materials without glass [55] because this is the easiest and most common type of test for polymeric films. In the case of laminated glass, two types of tests were conducted: shear tests [56] and bending tests. Bending tests give a better representation of the real-life mechanical behaviour of laminated glass, but in these tests it is harder to study the contribution of the interlayer than in shear tests, where the correlation between the response of the interlayer and the measured results is much easier to establish.

In this PhD, most of the experimental tests were comparative studies between different materials. In the case of mechanical tests, factors such as the temperature, humidity, or time of loading may affect the mechanical properties of the interlayer. For that reason, it is important to clearly identify all of these parameters and indicate them, in order to make it easier to reproduce the results. In addition to that, in order to avoid that the differences between materials are caused by variations in these parameters, it is important to ensure that they are the same for all materials, or otherwise specify it.

Chapter 3

3. Papers comprising this PhD

Figure 17 shows the papers comprising this thesis. The initial study of the state of the art (papers 1 and 2) made clear the importance of the contribution of the interlayer material in the mechanical behaviour of laminated glass. That led to the study of different commercial polymeric interlayers (papers 3 and 4), as well as its bond with glass in laminated glass elements (papers 5 and 6). The experimental testing on laminated glass specimens also allowed to study the breakage mode of glass, as well as the post-breakage behaviour of laminated glass elements. Finally, full scale laminated glass structural elements (laminated glass beams and slab) were tested (papers 7 and 8).

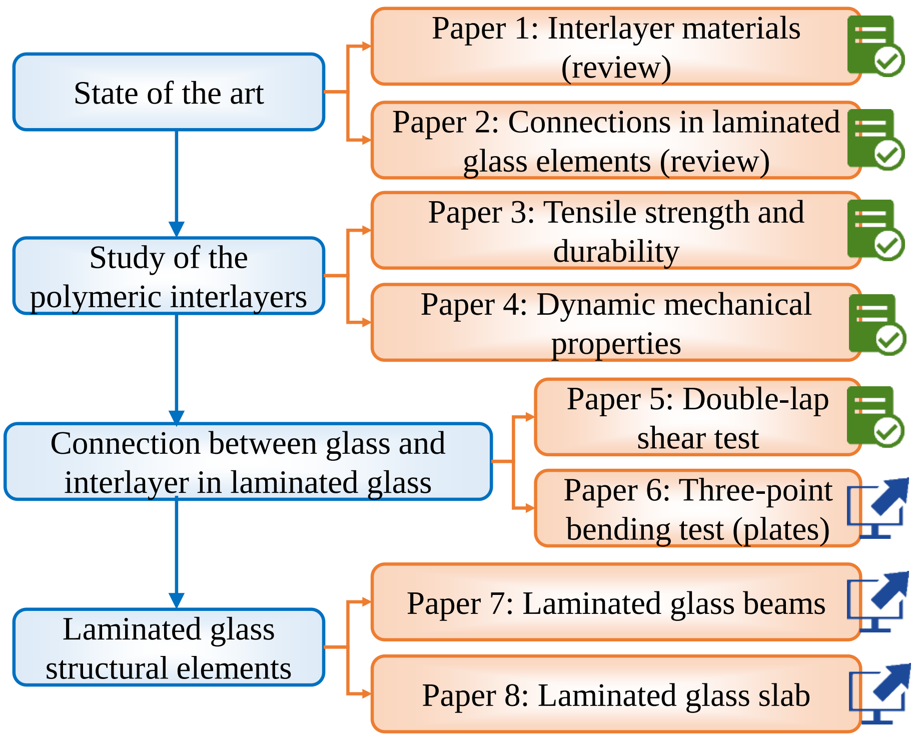


Figure 17. Papers comprising this PhD.

3.1. Paper 1: Polymeric interlayer materials for laminated glass: A review

3.1.1. Overview

This review provides information about several polymers used as interlayers for laminated glass, including but not limited to: chain structure, strength, ductility, stiffness, glass transition temperature, transparency, resistance to ageing effects, and recyclability. The interlayer material selection could be done based on some of these factors, and the importance of each of them may vary depending on its intended use. The interlayer materials studied in this review are some of the most commonly used ones, which can be classified in the following polymer groups: polyvinyl butyral (PVB), ionomers (e.g., SentryGlas), ethylene-vinyl acetate (EVA), also known as polyethylene-co-vinyl acetate, and thermoplastic polyurethane (TPU).

3.1.2. Contribution to the state-of-the-art

This review offers an unprecedented compilation of information about several polymers used as interlayer materials for laminated glass. By gathering the properties of different interlayers, it also provides a comparative study that may be useful for researchers and engineers.

The paper includes information about the methodology for the mechanical characterization of the listed interlayers, either as an independent film or as part of a laminated glass panel. The published results of mechanical tests on laminated glass panels aimed to evaluate mainly two aspects: the adhesion between glass and interlayer, with pull-out tests or peel tests, and the shear transfer capacity of the interlayer between confronted glass surfaces, with bending tests.

This part highlights the influence of loading time and working temperature on the mechanical response, since the interlayer materials are highly time- and temperature-dependent. Many tests, conducted on polymeric films and laminated glass specimens, allow obtaining the relaxation modulus as a function of time for static loading, E(t), and the complex modulus as a function of frequency for dynamic loading, E*(ω).

Since polymers are less durable and more sensitive to weathering factors such as humidity, solar radiation, and thermal cycles than glass, accelerated ageing tests on polymers and laminated glass are also abundant on the literature. However, since there is not a consensual standard for laminated glass. Instead, different authors follow different methodologies, based on various norms and standards. There are two main types of tests: the ones that try to simulate as accurately as possible the effect of long-term exposure to environmental factors, and the ones that try to isolate the effect of a single ageing factor (i.e. humidity, temperature, or solar radiation), in order to see how each factor affects separately the polymer and its bond with glass.

3.1.3. Contribution to the objectives of the PhD

Given the brittle nature of glass, combining it with a ductile material seemed to be the only feasible option in order to obtain safer structural elements made of glass. In fact, another common element in all the different approaches was the use of laminated glass, for all its already mentioned benefits when compared with monolithic glass.

Within the different studies of laminated glass there was another common point: the interlayer material governs the behaviour of laminated glass. Although the polymeric interlayer is much thinner, softer, and weaker than glass sheets, choosing one interlayer over another can more than double the bending stiffness of laminates glass plates [57] and the lateral stability of laminated glass beams [31], and provide a higher level of post-breakage load-bearing capacity [21,58].

Identifying the importance of polymeric interlayers led to the subsequent research on these polymers and its bond with laminated glass. In addition to that, collecting information about the chemical structure of the polymeric interlayers allowed to identify later, for example, how the level of plasticiser in PVB affected its glass transition temperature, how the percentage of vinyl acetate in EVA affected its stiffness, or why the exposure to humidity could lead in some cases to an adhesion loss between glass and interlayer.

3.1.4. Journal paper

The scientific contribution from this research study was published in the journal Construction and Building Materials in 2020.

Reference:

Martín M, Centelles X, Solé A, Barreneche C, Fernández AI, Cabeza LF. Polymeric interlayer materials for laminated glass: A review. Construction and Building Materials 230 (2020) 116897. https://doi.org/10.1016/j.conbuildmat.2019.116897

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Review

Polymeric interlayer materials for laminated glass: A review

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HIGHLIGHTS

- Different laminated glass interlayer materials (PVB, EVA, SGP, and TPU) are studied.
- The review provides a chemical overview and the main material characteristics.
- Interlayer characterization methods are reviewed and classified.
- Effects of ageing, mechanical properties, and recyclability are taken into account.
- The review focuses on laminated glass in the building sector.

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ABSTRACT

Laminated glass is obtained by bonding two or more glass layers using a polymeric interlayer. Compared to monolithic glass, laminated glass is beneficial in terms of post-breakage safety, security against break-ins, and acoustic insulation, among others. That is why laminated glass is being used for a wide variety of constructive solutions. Polymers such as PVB, ionomers, EVA and TPU are used as interlayer materials in laminated glass. This review aims to describe the most common polymeric interlayers, outline its characterization techniques, and give a general overview about the recyclability of the interlayers. There are two main properties used to characterize the interlayer materials: mechanical properties and resistance to ageing factors. Main mechanical tests found in the literature are summarized, and the properties studied in each of them are listed. Most experimental studies regarding ageing resistance consider mainly three weathering agents: humidity, UV radiation, and temperature.

3.2. Paper 2: Experimental results of mechanical, adhesive, and laminated connections for laminated glass elements – A review

3.2.1. Overview

The connections are an essential part of any structural system for a building project, and they have a big impact on its overall performance and cost. In addition to that, they are generally one of the most complex and challenging parts for the calculation, design, and assembly.

Connections are designed to join any structural or enclosure element to other adjacent elements. In the case of connections for laminated glass elements, these can be classified in three main groups: mechanical, adhesive, and laminated (Figure 18).

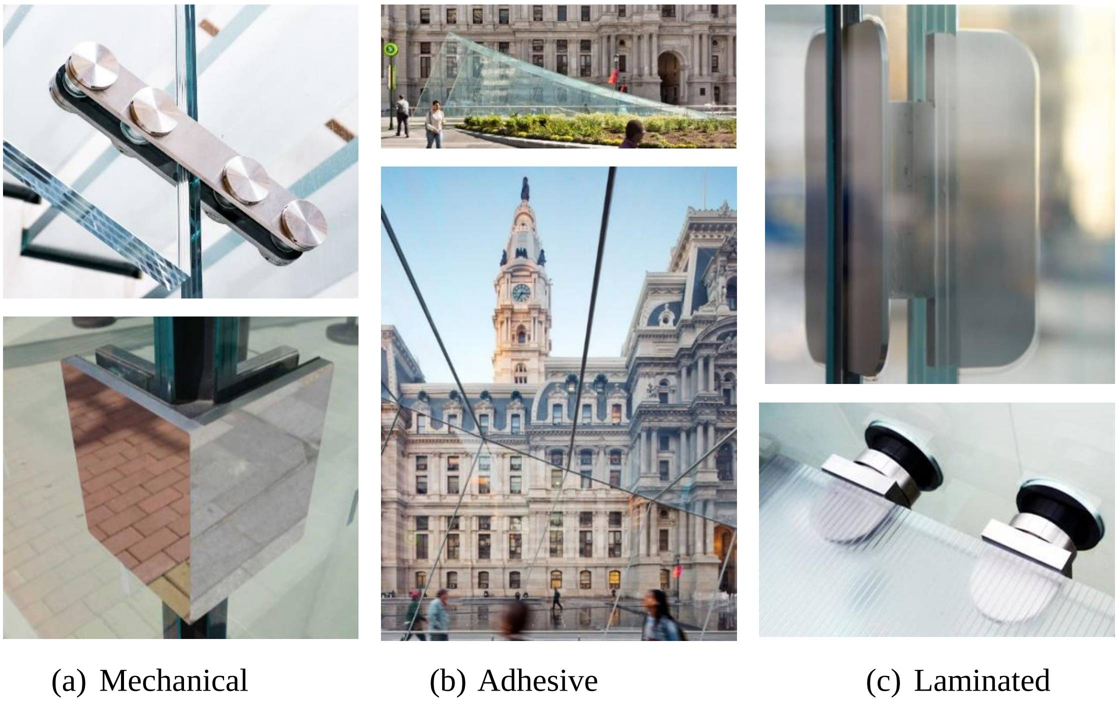

Figure 18. Examples of (a) mechanical, (b) adhesive, and (c) laminated connection in laminated glass elements [1].

Mechanical connections use metallic elements, and generally include an intermediate material, usually a polymer, to prevent direct contact between glass and metal, which could cause glass breakage due to stress concentration. External factors such as the load duration and the working temperature (within the typical temperature range in buildings) have little or no effect on the performance of mechanical connections.

Adhesive connections use adhesive materials, such as rubbers, silicones, or epoxies, in order to create the bond between the glass element and the supporting structure. This type of connections requires less manufacturing than bolted connections, and generally has a more homogeneous stress distribution along the bond region. Moreover, some adhesives are transparent, which can be highly desirable for some architectural applications. However, adhesive connections are less durable than mechanical connections, and their mechanical properties are more sensitive to external factors such as humidity and temperature.

In laminated connections, the joint is created with the same polymeric interlayer that bonds the glass sheets of laminated glass together. They have more or less the same advantages and disadvantages as the adhesive connections. For laminated connections, the most commonly used interlayer material is SentryGlas, because of its higher strength and stiffness, good adhesion to both glass and metals, and its relatively good performance under long-term loading and at higher temperatures. The demand of this type of connections is continuously increasing, especially for aesthetic reasons.

This paper presents the different types of connections, describes them and lists the main advantages and disadvantages of each group. For all types of connections, it presents the most commonly used mechanical tests found in the literature in order to compare or validate different designs or materials. Furthermore, for adhesive and laminated connections, it presents different ageing tests conducted to study the effect of weathering factors on the colour, adhesion, and strength of said connections.

The paper concluded that there is not a single solution that is the best for all cases. Instead, each option presents strengths and weaknesses, and the choice that is considered best will depend on several factors such as the required strength, the desired transparency, and the severity of the weathering conditions. It also highlighted that the most common cause of failure of bolted connections is glass breakage at the borehole region. In the case of adhesive and laminated connections, glass breakage becomes a less relevant risk, but the adhesive materials and polymeric interlayers are more sensitive to weathering factors, and its strength decreases with time of loading and temperature.

3.2.2. Contribution to the state-of-the-art

As mentioned in previous sections, glass is a brittle material, and glass breakage generally occurs due to stress concentrations in surface flaws, which leads to crack growth. As a consequence, the connections represent a region particularly prone to breakage, because high loads are transferred through small surfaces, leading to high stresses.

Most of the connections for laminated glass are opaque, and for that reason one of the aims is to make them as small as possible in order to minimize their visual impact and increase the overall transparency. The size of laminated glass elements is also continuously growing, in order to reduce the number of connections needed. These two modifications result in a progressively increasing load that must be transferred through increasingly smaller joints.

It is also mentioned in the introduction that there is no Eurocode for laminated glass, nor a consensual guide to study the mechanical response of laminated glass elements in buildings. This paper shows how the lack of reference standards leads to several different types of tests, although some of them are based on European or American standards. In that sense, this paper compares the different test methods, identifies which are the most commonly found in the literature, and shows the advantages and limitations of each of them.

3.2.3. Contribution to the objectives of the PhD

From the initial literature research, it was possible to see many common challenges in different research publications. The main concern, the most limiting factor when designing glass beams, was the brittle nature of glass.

Glass breakage is mainly caused by stress concentration, which leads to uncontrolled crack propagation. This represents an obstacle for the design and use of structural glass, and is especially determining in connections between a glass element and another substrate, because in said connections loads are transferred through smaller surfaces, leading to high stress concentrations. This particular case of connections for structural glass elements was present in many research articles, and for that reason one of the first tasks was to put together all that information in a review article [51].

3.2.4. Journal paper

The scientific contribution from this research study was published in the journal Engineering Structures in 2019.

Reference:

Centelles X, Castro JR, Cabeza LF. Experimental results of mechanical, adhesive, and laminated connections for laminated glass elements – A review. Engineering Structures 180 (2019) 192–204. https://doi.org/10.1016/j.engstruct.2018.11.029

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Review article

Experimental results of mechanical, adhesive, and laminated connections for laminated glass elements – A review

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ABSTRACT

In order to increase transparency in buildings, structural elements made of laminated glass are being developed. The recent technological improvements in terms of material research, fabrication processes, and construction techniques, are creating new design opportunities for laminated glass structural elements. For laminated glass, the post-breakage strength and safety are important because of the brittle nature of glass, especially in structural applications. The connection between elements is a critical part, because high loads are concentrated in small surfaces, leading to local peak stresses. In this review, different connection types for structural glass elements are presented, and their performance is evaluated. Most common connection types are mechanical, adhesive, and laminated. The main goal of this review is to compare the experimental results obtained from different types of connections, evaluating the type of test, the materials used, the pre- and post-breakage performance, the failure mode, and the influence of ageing factors and load duration.

3.3. Paper 3: Tensile test on interlayer materials for laminated glass under diverse ageing conditions and strain rates

3.3.1. Overview

Interlayer materials define the flexural behaviour of laminated glass, but these polymers experience degradation over time when exposed to severe environmental conditions. In addition to that, since they are viscoelastic, their mechanical properties depend, among other things, on the strain rate. The aim of this paper was to see if (and how) the strain rate and three different ageing factors (humidity, high temperature, and thermal cycles) affected separately the mechanical properties of the polymeric interlayer.

In order to conduct this research, seven commercial interlayer materials (PVB BG-R20, PVB ES, Saflex DG-41, SentryGlas, TPU, EVALAM 80, and EVASAFE) were chosen. Three groups of specimens were subjected to different accelerated ageing tests, and later to uniaxial tensile tests (Figure 19), all of them at the same strain rate. Three other groups of unaged specimens were subjected to tensile tests at three different strain rates.

Figure 19. Tensile test on a polymeric film.

3.3.2. Contribution to the state-of-the-art

This paper provides a comparative study between some of the most commonly used interlayer materials. The results include the glass transition temperature, obtained using the differential scanning calorimetry (DSC) technique, the mass gain over time due to water absorption during water immersion, and the influence of accelerated ageing tests and strain rate on the mechanical properties of the polymeric films.

From the tensile tests, the chosen performance indicators were the tensile strength, initial stiffness, and toughness. As indicated in previous sections, these parameters may affect the pre-breakage behaviour (bending stiffness, lateral stability), and post-breakage safety (breakage mode, strength, and ductility) of laminated glass elements.

The accelerated ageing tests can help to decide if a certain material is adequate for a specific application. By separating in the study the effect of humidity and temperature, the results can be extrapolated to different locations, depending on its climate, although varying the temperature range of the thermal cycles may affect the result.

This study must be complemented with studies of the polymer in laminated glass. The main reason is that the autoclave process may affect the mechanical and optical properties of the interlayer, but also because studying the interlayer alone neglects the importance of the bond between glass and interlayer.

3.3.3. Contribution to the objectives of the PhD

One of the main reasons why glass is used in outdoors applications, such as external glazing in buildings or car windshields, instead of other transparent, stiff polymers such as PC or PMMA, is because glass is highly durable against weathering factors such as humidity and solar radiation. It is able to preserve its optical and mechanical properties for years, even under adverse weather conditions. Instead, polymers are generally more prone to experience ageing when exposed to environmental conditions. In the case of polymeric interlayers for laminated glass, ageing could affect, among other things, the transparency of laminated glass, the mechanical properties of the interlayer, and the adhesion between glass and interlayer.

In order to study the effect of weathering factors on the optical and mechanical properties of different interlayer materials, seven different polymeric films were subjected to accelerated ageing tests. That included thermal cycles, water immersion, and isothermal tests. From these tests it was possible to measure the water absorption capacity of the specimens, and how this affected its transparency. In addition to that, the aged specimens were subjected to tensile tests until breakage and compared with unaged specimens. These results were collected and presented in Paper 3 [55].

3.3.4. Journal paper

The scientific contribution from this research study was published in the journal Construction and Building Materials in 2020.

Reference:

Centelles X, Martin M, Solé A, Castro JR; Cabeza LF. Tensile test on interlayer materials for laminated glass under diverse ageing conditions and strain rates. Construction and Building Materials 243 (2020) 118230. https://doi.org/10.1016/j.conbuildmat.2020.118230

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Tensile test on interlayer materials for laminated glass under diverse ageing conditions and strain rates

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HIGHLIGHTS

- A tensile test was performed on seven laminated glass interlayer materials.
- The mechanical properties of the materials were affected by the elongation rate.
- EVALAM, EVASAFE and TPU were the least affected by ageing factors.
- Water immersion led to water absorption and transparency loss for SentryGlas and PVB.
- Mechanical properties of SentryGlas and PVB dropped after water immersion.

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Ageing test

ABSTRACT

Laminated glass is obtained by bonding two or more glass layers with a polymeric interlayer. The coupling between glass layers depends on the shear stiffness of the interlayer. The mechanical and optical properties of the interlayer may be affected by weathering factors. Since interlayer materials are viscoelastic, the strain rate may also affect its stiffness and ultimate strength. In this paper, tensile tests are conducted on seven different polymeric films (PVB BG-R20, PVB DG-41, PVB ES, SentryGlas, EVASAFE, EVALAM 80, and TPU) at three different strain rates. The mechanical and optical properties of unaged specimens are compared with specimens exposed to thermal cycles, high temperatures, and moisture. The unaged specimens of PVB DG-41, PVB ES, and SentryGlas had the highest stiffness, EVALAM 80 and EVASAFE had the highest ductility, PVB and SentryGlas had the highest tensile strength, and EVALAM 80, EVASAFE, and TPU were less affected by ageing factors and strain rate.

3.4. Paper 4: Viscoelastic characterization of seven laminated glass interlayer materials from stationary tests

3.4.1. Overview

Unlike glass, whose mechanical properties are very stable during its service life in buildings, the mechanical properties of the polymeric interlayers are highly time- and temperature- dependant. For that reason, stationary tests were conducted on the seven interlayer materials previously tested in Paper 3. That allowed to do a viscoelastic characterization of these materials, and to express their mechanical response as a function of time and temperature.

The viscoelastic characterization was obtained by means of relaxation tests at different temperatures. After performing the tests, the relaxation master curves were obtained applying the time-temperature shifting with the Closed-Form-Shifting (CFS) algorithm presented by Gergesova et al. [59]. A generalized Maxwell model was the used to find an equation that could fit, by means of a Prony series, each relaxation master curve.

The Prony coefficients are enough to obtain the equation, and therefore the approximation for the experimental relaxation master curves. Said coefficients are provided in the paper. In addition to that, the Prony coefficients allow obtaining the master curves of the two components of the complex modulus $E^*(\omega)$: the storage modulus $E'(\omega)$ and the loss modulus $E''(\omega)$.

The storage and the loss modulus are essential parameters to model the dynamic behaviour of each of the seven presented polymers. The storage modulus indicates the capacity of a material to store and return elastic strain energy, whereas the loss modulus is associated to the strain energy that the material absorbs and then dissipates, mainly through heat. The ratio $\tan(\delta)=E''(\omega)/ E'(\omega)$ indicates the offset angle between the stress and the strain, and it also provides a measurement of the damping of the material.

3.4.2. Contribution to the state-of-the-art

Pelayo et al. [23] did a viscoelastic characterization of PVB, by performing dynamic and stationary tensile tests at different temperatures, using PVB films without glass, and then applied it to the bending of laminated glass [28]. Andreozzi et al. [22] did a viscoelastic characterization of PVB as well, but in that case they used laminated glass specimens and subjected the interlayer to dynamic torsion tests.

The fact that these and other authors focused on PVB is due to the fact that it is the most commonly used interlayer in several applications, including automotive and architectural [51]. However, some other interlayer materials have a higher transparency, stiffness, glass transition temperature, adhesion with other materials such as steel or polymers, resistance to weathering factors, etc. For that reason, the most adequate interlayer material may depend on its final application and it is wise to study the different options available on the market.

This paper does a viscoelastic characterization of seven different polymeric interlayers, from four different polymer families: PVB (PVB BG-R20, PVB ES, and Saflex DG-41), EVA (EVALAM 80 and EVASAFE), TPU, and SentryGlas. This allows to perform a comparative study between these materials, in terms of the glass transition temperature, the relaxation modulus $E(t)$, and the two components of the complex modulus $E^*(\omega)$: the storage modulus $E'(\omega)$, and the loss modulus $E''(\omega)$.

3.4.3. Contribution to the objectives of the PhD

The mechanical behaviour of the interlayer, as well as its contribution on the cohesiveness of laminated glass, were thoroughly studied in previous tests. However, the literature review gathered in Paper 1 [51] indicated that the mechanical properties of the interlayer were time- and temperature-dependant, and that was barely taken into consideration in previous papers from this PhD.

In this paper, the materials used are the same seven interlayers already tested in Paper 3 [55]. However, in Paper 3 the materials were subjected to uniaxial tensile test until breakage, at a constant elongation range. This allowed to know some material properties, such as the maximum deflection and stress, and the tensile stiffness, for some specific conditions in terms of load duration and temperature. By contrast, in this paper, the tests were carried out at different temperatures and taking into consideration the time under stress. This allowed to do a viscoelastic characterization of the interlayers, that is, to express the relaxation modulus of each material as a function of both time and temperature. From the tests at different temperatures, it was possible to apply the time-temperature superposition (TTS) and obtain the master curve for each material.

3.4.4. Journal paper

The scientific contribution from this research study was published in the journal Construction and Building Materials in 2021.

Reference:

Centelles X, Pelayo F, Fernández AI, Castro JR, Cabeza LF. Viscoelastic characterization of seven laminated glass interlayer materials from stationary tests. Construction and Building Materials 279 (2021) 122503. https://doi.org/10.1016/j.conbuildmat.2021.122503

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Viscoelastic characterization of seven laminated glass interlayer materials from static tests

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HIGHLIGHTS

- Stress relaxation tests were conducted on seven laminated glass interlayers.
- The master curves were obtained by using the t-T-P shifting (CFS) algorithm.
- The stiffness of all tested interlayers decreased over time and temperature.
- An equation to fit each relaxation master curve was represented by a Prony series.
- The storage and loss modulus were obtained by using interconversion methods.

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ABSTRACT

The mechanical behaviour of laminated glass is strongly affected by the polymeric interlayer placed between glass layers. In general, this interlayer is a viscoelastic material, and therefore it may experience creep and stress relaxation when subjected for an extended period to a constant stress or strain respectively. In this study, seven different commercial interlayer materials (EVALAM, EVASAFE, PVB BG-R20, Saflex DG-41, PVB ES, SentryGlas, and TPU) were evaluated with relaxation tests at different temperatures, in order to build the relaxation master curves through the time-temperature superposition principle. A generalized Maxwell model was chosen to describe the viscoelastic behaviour of the tested materials. This paper includes the coefficients of the Prony series that fit better the experimental results. This paper has two main goals. First, to present the Prony coefficients (e_i and τ_i), which can then be used to create numerical models that take into consideration the time and temperature-dependant behaviour of the interlayer. Second, to provide the two components of the complex modulus ($E^*(\omega)$) of each material, the storage modulus ($E'(\omega)$) and the loss modulus ($E''(\omega)$), which can be obtained from the relaxation modulus ($E(t)$) by using analytical interconversions.

3.5. Paper 5: Double-lap shear test on laminated glass specimens under diverse ageing conditions

3.5.1. Overview

As previously stated and widely supported by the literature, the shear behaviour of the interlayer material in laminated glass is a key factor for the bending stiffness of laminated glass elements [27], the lateral stability of laminated glass beams [31], the post-breakage safety of broken laminated glass [26], and the strength and ductility of laminated connections [54].

This paper aims to study the shear behaviour of laminated glass, as well as the effect of weathering factors on the strength of the interlayer and the bond between glass and interlayer. To do so, double-lap laminated glass specimens were designed, fabricated, and tested (Figure 20). Four different interlayer materials were chosen: PVB BG-R20, Saflex DG-41, SentryGlas, and EVASAFE. Four groups of specimens were subjected to accelerated ageing tests (thermal cycles, humidity, and UV radiation), and were compared with the unaged specimens.

3.5.2. Contribution to the state-of-the-art

Paper 3 [55] studied the most relevant mechanical of properties polymeric films in laminated glass. This paper represents another step ahead in that same direction. In this case, laminated glass specimens, manufactured by specialised professionals, are tested to study the connection between glass and interlayer and the overall mechanical performance. Special attention is paid to the interlayer, and to how external factors such as the autoclave process and the ageing factors affect its mechanical and optical properties.

Figure 20. Double-lap shear test.

This paper presents an innovative test setup, with a double-lap shear specimen to study the glass-to-glass connection, and without the necessity of bolts or clamps to fix the specimen to the universal testing equipment. The specimen design was based on other glass-to-steel or glass-to-GFRP double-lap shear tests found on the literature [60], and was adapted to create glass-to-glass double-lap shear specimens.

3.5.3. Contribution to the objectives of the PhD

After studying the tensile properties of different polymeric films used as interlayers, it was necessary to see how this applied to laminated glass. The results of the tensile tests presented in Paper 3 [55], although useful as a first approach, were only partially complete, because they did not take into consideration the effect of the autoclave process on the properties of the polymeric interlayer, nor the importance of the bond between glass and interlayer. It is presumable that the mechanical response of the interlayer changes after the autoclave process to create the bond between glass and interlayer [32].

Therefore, Paper 5 [56] followed a similar procedure as Paper 3 [55] in terms of performing accelerated ageing test followed by mechanical tests, but this time with laminated glass specimens instead of polymeric films. In addition to that, in this case, a group of specimens was exposed to the light of special lamps Osram Ultra Vitalux 300W E27, with a wavelength distribution similar to the solar radiation.

The same test was simulated using COMSOL Multiphysics in order to see the stress distribution in the glass sheets, the interlayer, and the bond region between glass and interlayer. Among other things, it allowed to see how the adhesion loss in one of the surfaces caused a load asymmetry, leading to higher bending moments in one of the glass sheets, and a subsequent stress peak that ended up causing glass breakage in some cases.

3.5.4. Journal paper

The scientific contribution from this research study was published in the journal Construction and Building Materials in 2020.

Reference:

Centelles X, Castro JR, Cabeza LF. Double-lap shear test on laminated glass specimens under diverse ageing conditions. Construction and Building Materials 249 (2020) 118784. https://doi.org/10.1016/j.conbuildmat.2020.118784

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Double-lap shear test on laminated glass specimens under diverse ageing conditions

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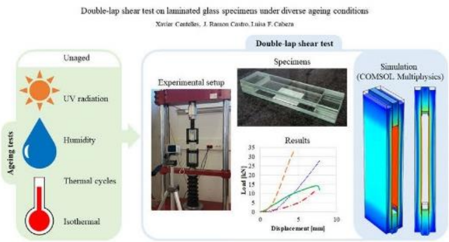
HIGHLIGHTS

- Laminated glass double-lap shear specimens with four interlayers were tested.
- The type of interlayer material affected the maximum load and breakage mode.
- Humidity and long-term UV radiation had a negative effect on some specimens.
- The strength either increased or remained unaffected by thermal cycles.
- The stress distribution was not homogeneous in the glass-interlayer interface.

GRAPHICAL ABSTRACT



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ABSTRACT

Laminated glass is a composite laminate obtained from combining two or more glass layers with a polymeric interlayer. The adhesion between glass and interlayer, as well as the shear strength and stiffness of the interlayer, are key factors to evaluate the cohesive behaviour of laminated glass. Glass is a very durable material, while polymeric interlayers can be deteriorated by exposure to weathering factors. A double-lap shear test was carried out on laminated glass specimens, with four different interlayer materials (PVB BG-R20, Saflex DG-41, SentryGlas, and EVASAFE), after different ageing tests (unaged, thermal cycles, humidity, and UV radiation). The material selection affected the shear behaviour of the bond between glass and interlayer, and so did the previous exposure to certain ageing factors. Since the polymeric interlayers are viscoelastic materials, and therefore its mechanical properties are time- and temperature-dependant, the results here presented should be complemented with dynamic and static tests at different temperatures.

3.6. Paper 6: Study of the pre- and post- breakage flexural behaviour of laminated glass with different interlayers at different deflection rates

3.6.1. Overview

The shearing stiffness of the laminated glass interlayer material may affect the pre- and post-breakage performance of laminated glass elements. In addition to that, the laminated glass interlayer materials are viscoelastic, which means, among other things, that their mechanical properties are time-dependant. As a consequence of that, the shear stiffness of the interlayer, and therefore the bending stiffness of laminated glass, may vary as a function of the strain rate.

In this paper, laminated glass plates with two glass sheets were subjected to bending (Figure 21) at a constant deflection rate until breakage of both glass sheets (Figure 22). There were four different interlayer materials (the same four tested in paper 5): PVB BG-R20, Saflex DG-41, EVASAFE, and SentryGlas. The bending tests were performed at three different deflection rates: 2 mm/min, 10 mm/min, and 50 mm/min. The main goal was to study the mechanical performance before glass breakage, as well as the breakage modes and post-breakage behaviour, and how these parameters were affected by the mechanical properties of the interlayer material and the deflection rate at which the specimens were bent.

The bending stiffness in the pre-breakage phase was measured by means of the effective stiffness concept (ESC), establishing an equivalence between each laminated glass plate and a monolithic panel with the same flexural behaviour in order to simplify the calculations. This also allowed to establish a correlation between the pre- and the post-breakage bending stiffness, where only one the top layer remained unbroken and was responsible of the overall bending stiffness.

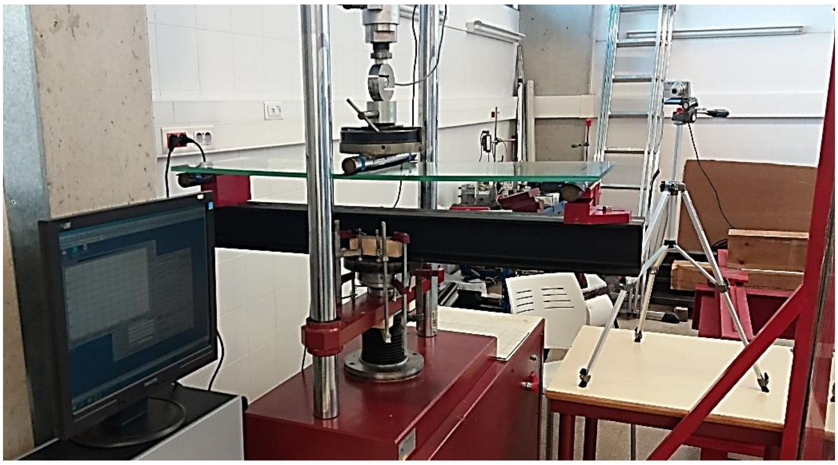


Figure 21. Three-point bending test on a laminated glass plate.

Figure 22. Broken laminated glass specimen after the three-point bending test.

From these tests it was observed that the stiffer the interlayer, the higher the cohesiveness between glass sheets, and therefore the higher the bending stiffness and strength. In addition to that, the cracked surface was higher in specimens with stiffer interlayers, presumably because a higher maximum load was reached, and therefore more elastic strain energy was dissipated through the cracks. There were no significant differences in the mechanical response between different deflection rates.

The same three-point bending test was simulated using COMSOL Multiphysics in order to see in more detail the deflection of the specimens, as well as the tensile and shearing stress distribution, along the length of the plate and in the cross section. The simulation also allowed to extrapolate the results to other interlayer stiffness values than the ones tested, and to see how the specimens approached the two theoretical limits: the monolithic limit for stiffer interlayers and the layered limit for softer interlayers.

3.6.2. Contribution to the state-of-the-art

One of the main problems of the structural use of laminated glass in buildings is that there is no Eurocode for structural glass [50], and some national standards suggest neglecting the favourable contribution of the interlayer [61]. As a consequence, laminated glass structures are usually oversized, leading to a higher material consumption, dead weight of the structure, and total cost. Finding an accurate calculation method and simulation software could lead to optimized yet safe laminated glass structures.

In this sense, this paper presents the mechanical of laminated glass plates under bending loads with four different interlayer materials. In addition to that, the same test is simulated with COMSOL Multiphysics. This allows to see the influence of the shear stiffness of the interlayer on the stress distribution and the bending stiffness of laminated glass beams. These results could contribute to create a more accurate calculation method for laminated glass plates by taking into consideration the favourable effect of the interlayer.

3.6.3. Contribution to the objectives of the PhD

The aim of this paper was to see how the mechanical properties of the different interlayers, previously tested in Paper 3 [55] before the autoclave and in Paper 5 [56] after, affected the pre- and post-breakage behaviour of laminated glass plates under out-of-plane bending. The results from Paper 3 [55] showed how the deflection rate affected the stiffness of the interlayer. That is why, in this case, bending tests were also conducted at different displacement rates, in order to see how it applied to larger laminated glass specimens.

The calculation was based on consolidated calculation theories typically used to evaluate the flexural behaviour of laminated plates [19,31,62]. The effective stiffness concept represents a simplified method to calculate the bending of laminated glass by switching from a composite laminate, with layers of different thickness and stiffness, to a monolithic element with the equivalent flexural behaviour.

In terms of pre-breakage behaviour, specimens with interlayer materials of different shear stiffness presented different values of bending stiffness, proving the correlation between these two factors. Another interesting result was that, according to Paper 3 [55], all tested polymeric interlayers had a nonlinear mechanical behaviour, and the nonlinearity was also present after the autoclave (Paper 5 [56]), but all the laminated glass specimens under bending tested in Paper 6 presented a linear behaviour until breakage. This could mean that the interlayer in the latter specimens performed only within the linear elastic range.

After breakage of both glass sheets, specimens with stiffer interlayers (SentryGlas and Saflex DG-41) were able to resist the weight of the broken glass, and a small additional load. On the other hand, specimens with softer interlayers (PVB BG-R20 and EVASAFE) fell from the supports, as they were unable to resist the weight of broken glass. The post-breakage load-bearing capacity can be an indicator of the structural safety of a laminated glass element.

3.6.4. Journal paper

The scientific contribution from the present research work was submitted to the journal Composite Structures in May 2020.

Reference:

Centelles X, Castro R, Cabeza LF. Three-point bending test on laminated glass panels with different interlayer materials under different deflection rates. Submitted to Engineering Structures, 2020.

3.7. Paper 7: Experimental study and comparison of different fully transparent laminated glass beam designs

3.7.1. Overview

In this paper, laminated glass beams, with vertically placed glass sheets, were subjected to a four-point bending test (Figure 23) with a separation of three meters between the two bottom supports and a cross section of 300x30 mm. The main goal of this paper was to evaluate how some design parameters, in particular the number of glass sheets, the type of glass, and the stiffness of the interlayer, affected the structural performance of the beams. To do so, five different beam designs were chosen, with the same external dimensions, and the only differences were found in the three previously mentioned parameters: number of glass sheets (three or five), type of glass (annealed or heat-strengthened), and interlayer material (PVB Clear or SentryGlas). The rest of the test parameters were the same for all specimens, including the vertical downwards displacement rate of 1 mm/min at the top supports. Three replicates of each design were tested, making a total of 15 tested beams.

Figure 23. Four-point bending test on laminated glass beams.

The structural performance was evaluated based on pre-breakage behaviour and post-breakage safety. The performance indicators chosen for the pre-breakage stage were the maximum pre-breakage strength and the bending stiffness. The performance indicators chosen for the post-breakage safety were redundancy (i.e., the difference between maximum pre- and post-breakage load) and breakage mode.

The results showed how specimens with three annealed glass sheets had a higher pre-breakage strength, whereas specimens with five annealed glass sheets had a higher redundancy and more progressive breakage. Using heat-strengthened glass instead of annealed glass did not significantly increase the maximum pre-breakage load, and instead it had a detrimental effect on the post-breakage safety, since the breakage was abrupt rather than progressive. The stiffness of the interlayer material had a negligible effect on the pre-breakage performance, but specimens with the stiffer interlayer (SentryGlas) had a higher redundancy and cracks concentrated in a smaller surface.

3.7.2. Contribution to the state-of-the-art

So far, researchers have identified that laminated glass beams require special attention in terms of post-breakage safety. Most of the solutions developed to create safer structural elements made of glass require reinforcement materials, mainly steel, in order to increase the bending strength and post-breakage safety [63]. Some other solutions are based on statically indeterminate beams: these can be completely constrained even after local glass fracture. This can be achieved, for example, by means of implementing sacrificial glass sheets [64] or redundant boundary conditions [65].

All these mentioned research articles were based on the assumption that laminated glass beams are unsafe and have an unpredictable behaviour, except when they are strongly oversized or combined with another reinforcement material. The paper here presented aims to prove that it is possible to create safe fully transparent elements, if the proper design parameters are chosen. Using more glass sheets, even if they are thinner, made of annealed glass, with stiffer interlayers, can lead to a more progressive breakage and a higher redundancy, that is to say, safer laminated glass beams. In fact, according to the obtained experimental results, in beams with these design parameters, initial fracture due to overload would not lead to total collapse.

3.7.3. Contribution to the objectives of the PhD

This paper is the first one of the PhD in which the laminated glass specimens are placed vertically and subjected to an in-plane bending load. The mechanical response of a composite laminate is completely different when the load is applied perpendicular to the surface of the layers, as in Paper 6, or coplanar to the layers, as in the case of laminated glass beams.

It is previously indicated in this PhD that one of its main objectives is to seek a safe design of structural elements made of glass. It is also repeatedly highlighted that glass is brittle and tends to have an abrupt, unexpected breakage. This paper tests several laminated glass beams, varying some design parameters, in order to determine if a certain combination of parameters makes laminated glass elements safer. The results in this sense are quite relevant, since the different design parameters led to significant differences in the overall performance. Using five glass sheets instead of three, a stiffer interlayer, and annealed glass instead of heat-strengthened glass led to a more progressive breakage and a higher redundancy, that is to say, safer laminated glass beams.

3.7.4. Journal paper

The scientific contribution from the present research work was submitted to the journal Composite Structures in March 2020.

Reference:

Centelles X, Castro JR, Cabeza LF. Experimental study and comparison of different fully transparent laminated glass beam designs. Submitted to Composite Structures, 2020.

3.8. Paper 8: Long-term loading and recovery of a laminated glass slab with three different interlayers

3.8.1. Overview

Some singular buildings have walkable floors made of laminated glass. In this paper, a laminated glass slab is built with three laminated glass plates supported on two laminated glass beams (Figure 24). Each of the laminated glass plates had a different interlayer material: PVB Clear, PVB ES, and SentryGlas. The laminated glass beams had a length of 3 m between supports, and the separation between beams was of 1.5 m. The laminated glass slab was subjected to a surface load, with a value of 3 kN/m^2, as proposed by the standard EN 1991-1-1 [66] for office or other public areas. The load was applied using water, in order to ensure that the surface load was homogeneous, with a wooden perimetral formwork, a plastic coating to prevent water leakage, and a plastic film on top to prevent water evaporation.

Figure 24. Laminated glass slab placed on a metallic structure with wooden lateral restraints.

The constant load was kept during four months. The deflection of each plate was measured, as well as the deflection of the beams (Figure 25), during the four months of loading, and during one month after removing the load in order to measure the recovery rate of each structural element.

Figure 25. Displacement sensors to measure the vertical deflection at the midspan of the plates and the beams.

The study also included a prediction of the deflection of the three different plates using the effective stiffness concept (ESC). Said analytical calculation was performed using MATLAB. Since the interlayer materials were considered viscoelastic, the effective stiffness was also time- and temperature-dependent. The models were subjected to the same boundary conditions as those of the experimental tests.

The results show how the deflection of the laminated glass plates increased over time due to the creep of the interlayer, whereas it remained almost constant in both laminated glass beams, since the contribution of the interlayer is almost negligible in the pre-breakage phase of laminated glass beams. The comparisons between the experimental results and the simulation showed a reasonable accuracy, especially in the laminated glass plates with PVB Clear and SentryGlas, whereas larger errors were encountered in the plate with PVB ES.

3.8.2. Contribution to the state-of-the-art

This paper presents an unprecedented study of the SLS of a laminated glass slab under long-term loading, using a real-scale experimental test setup of a laminated glass slab supported on two laminated glass beams. The experimental test included several innovative aspects, such as the large size of the laminated glass slab, the high surface load, and the long duration of the test. Another unprecedented aspect is the fact that the paper includes a study of the recovery stage after the removal of the load. The experimental results are then compared with an analytical prediction of all the stages of the test, including the deflection recovery after unloading.

Some authors had already studied the evolution of deflection over time (creep) of a laminated glass plate under a constant load [23], even doing a comparative study between different interlayer materials [27]. However, this paper presents an unprecedented test in terms of load amount (3 kN/m^2), loaded surface (3x1.5 m^2), and test duration (four months loaded and an additional month for recovery). The study of the deflection recovery after unloading is considered to be another innovative element, together with the fact that no other similar published work was found in which the load was applied using water.

These results, together with the simulation, show the importance of taking into consideration the contribution of the interlayer, since a stiff interlayer such as SentryGlas can more than double the bending stiffness and load-bearing capacity of laminated glass elements. However, this requires a proper material characterization, and knowledge on the most unfavourable working conditions in terms of load duration and working temperature. The simulation results show how the results of tensile tests on polymeric interlayers (without glass) can be used to simulate the flexural behaviour of laminated glass with a reasonable accuracy, although the autoclave conditions during the manufacturing process may affect the mechanical properties of these interlayers [32].

3.8.3. Contribution to the objectives of the PhD

The calculation of any structure or structural element requires to take into consideration three different aspects: equilibrium, resistance and stiffness. This paper focused on the study of the stiffness by measuring the deflection and its evolution over time. It is noteworthy that the stiffness could be studied because the other two aspects (equilibrium and resistance) were previously solved, for plates in Paper 6 and for beams in Paper 7.

Four of the interlayer materials tested at different constant deflection rates until breakage in Paper 3 [55] were later tested in Paper 6 as part of laminated glass plates, also at different constant deflection rates and until breakage. Following the same approach, three of the different polymeric interlayer materials subjected to stationary tests in Paper 4 are subjected to a long-term stationary test in laminated glass panels in this paper.

This paper collects most of the important results obtained during the course of this PhD, presented in the previous papers. After seeing how different interlayer materials had different shearing stiffness in Paper 5 [56], the influence of the shearing stiffness of the interlayer on the bending stiffness of laminated glass plates was confirmed in Paper 6. Paper 5 [56] also includes laminated glass plates with three different interlayer materials, and different mechanical responses are also observed. However, in this case, unlike in Paper 6, it is possible to see the evolution of the bending stiffness over time, since it is a long-term stationary test. The reduction of the bending stiffness is associated to the creep experienced by the interlayer materials, which was previously measured in Paper 4.

The deformational results obtained from this paper can be relevant for several different loading scenarios, from short- to long-term loading and unloading. The main scenario that is not considered in this test would be dynamic loading (e.g., wind and seismic load).

3.8.4. Journal paper

The scientific contribution from the present research work was submitted to the journal Composite Structures in June 2020.

Reference:

Centelles X, Pelayo F, Castro JR, Cabeza LF. Long-term loading and recovery of a laminated glass slab with three different interlayers. Submitted to Composite Structures, 2020.

Chapter 4

4. Global discussion of results

An initial literature research allowed to identify the importance of the interlayer in the overall performance of laminated glass. As a consequence, different interlayers were studied in this research. The experimental results presented in this PhD were carried out using up to seven different interlayers that belong to four different polymer groups: polyvinyl butyral (PVB), ionomer (e.g., SentryGlas), ethylene-vinyl acetate (EVA), and thermoplastic polyurethane (TPU).

All these interlayer materials presented a nonlinear behaviour under tensile stress, as well as a time- and temperature-dependant mechanical response. The stiffness of PVB and SentryGlas increased with higher deflections, whereas it progressively decreased in the case of TPU and EVA. When tensile tests were carried out at higher elongation rates, both maximum strength and initial stiffness increased.

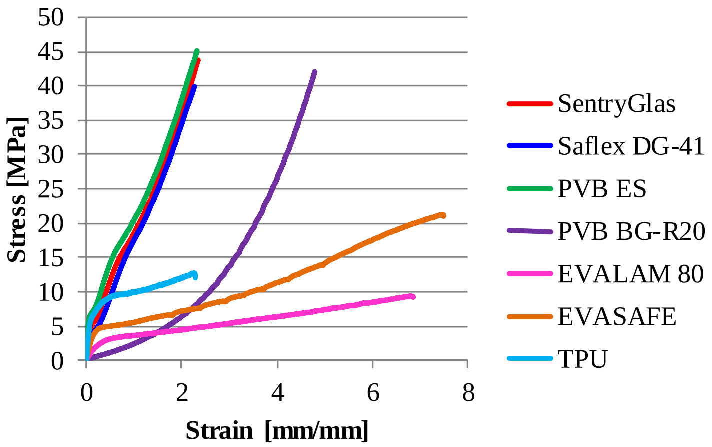


Figure 26. Stress-strain diagram with the results of the tensile tests for all the interlayer materials at the same strain rate (10 mm/min).

The glass transition temperature (T_g) was a determining factor when evaluating the viscoelastic behaviour of the interlayer materials in laminated glass. In stress relaxation tests, as temperature increased, the relaxation modulus decreased at a much higher rate in the region near the T_g. In dynamic tests, the ratio tan(δ)=E''/E' increased near T_g, meaning that the loss modulus, related to the viscous behaviour of the material, played a more predominant role compared to the storage modulus, related to the elastic behaviour.

From the dynamic tests it was possible to obtain the master curves of the seven tested polymers (Figure 27). These master curves could then be converted to mathematic expressions by means of the Prony series. The parameters of these expressions can be implemented in a finite element software in order to simulate the viscoelastic behaviour of these materials. That part allowed to complete the experimental study of the polymeric interlayers, as a previous step to the evaluation of the tense-deformational behaviour of laminated glass plates with the same previously tested interlayer materials.

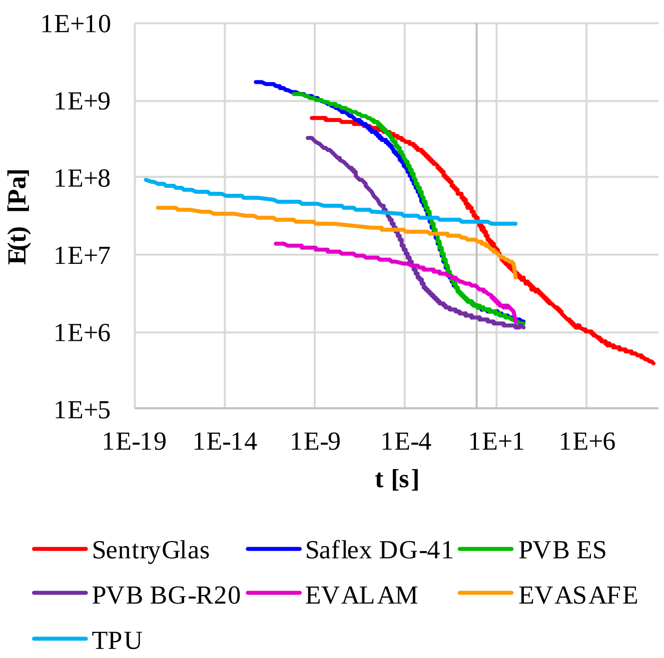


Figure 27. Relaxation mater curves of seven different polymeric interlayers obtained from DMA tests.

Exposure to ageing factors, such as humidity, thermal cycles, and UV radiation, could affect the mechanical properties of some of the interlayers, as well as their adhesion with glass. Exposure of laminated glass specimens to humidity or water immersion had an especially detrimental effect on SentryGlas and PVB interlayers, causing loss of transparency, water absorption, and a drop of strength and stiffness, in addition to adhesion loss between glass and interlayer. Thermal cycles did not significantly affect any of the tested interlayers. Exposure to UV radiation affected especially the laminated glass with EVASAFE, probably due to changes in the polymeric chain of EVA and the cross-linking between glass and interlayer.

(a) UV radiation tests (b) Temperature tests (c) Humidity tests

Figure 28. Setup of the different ageing tests.

Laminated glass plates under out-of-plane bending were tested. The specimens presented a behaviour highly dependent on the shear stiffness of the interlayer, both in the pre- and the post-breakage stages. The pre-breakage bending stiffness of a laminate, which was calculated using the Effective Stiffness Concept (ESC) [6,19], could experience up to a fivefold increase depending on the shear stiffness of the interlayer. The pre-breakage behaviour of the laminated glass plates was always between the two theoretical limits: the layered and the monolithic (Figure 29).

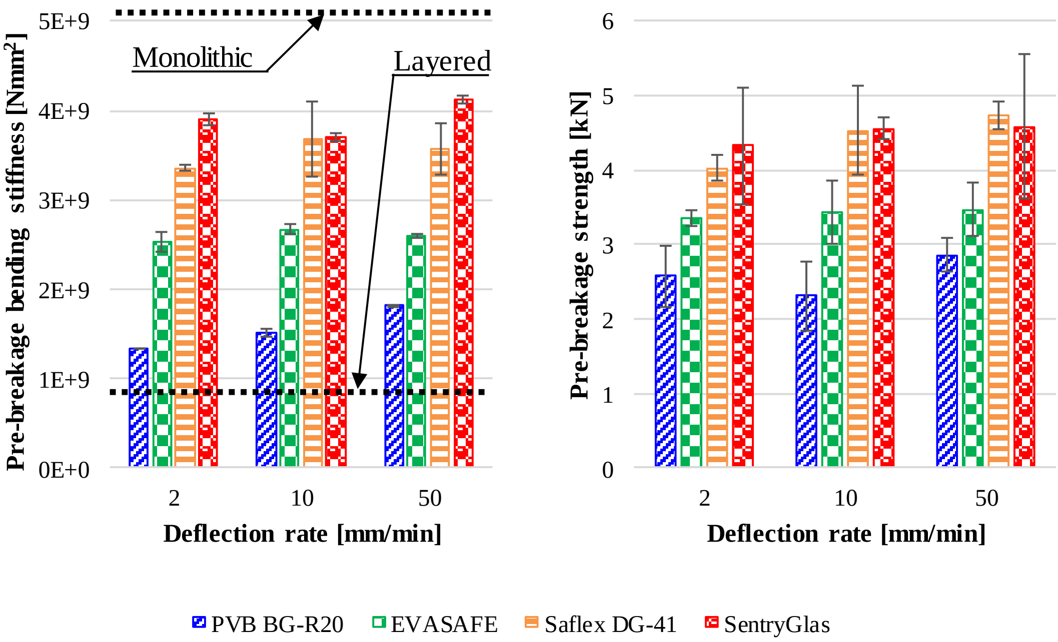
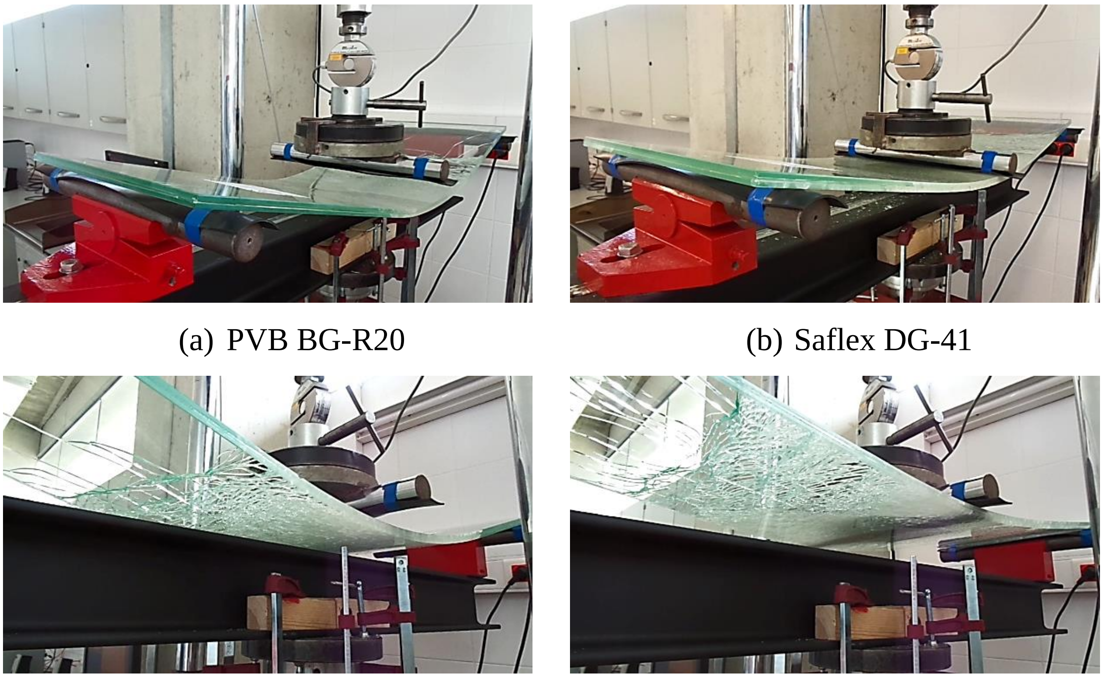


Figure 29. Column diagrams comparing the pre-breakage bending stiffness, calculated using the ESC, and the maximum load of the specimens with different interlayers.

For laminated glass specimens with two glass sheets, in case of breakage of a single glass sheet, the influence of the interlayer and the broken glass fragments bonded to the interlayer was not statistically significant. However, after breakage of the second glass layer, only specimens with stiffer interlayers (SentryGlas and Saflex DG-41) were able to resist de weight of broken glass shards, apart from a small but significant additional load (Figure 30).



(a) PVB BG-R20

(b) Saflex DG-41

(c) EVASAFE

(d) SentryGlas

Figure 30. Specimens after breakage of both glass layers with different interlayers.

When the laminated glass plates were subjected to long-term loading, their deflection progressively increased as a consequence of the creep experienced by the interlayer. The deflection of each plate was measured, and the readings were compared with the numerical predictions using the ESC in MATLAB. The results, presented in Figure 31, show a reasonable accuracy between the experimental results and the simulation model. The simulation was made using the data provided by the manufacturer for the interlayers [67], and was then applied to laminated glass plates using Effective Stiffness Concept (ESC).

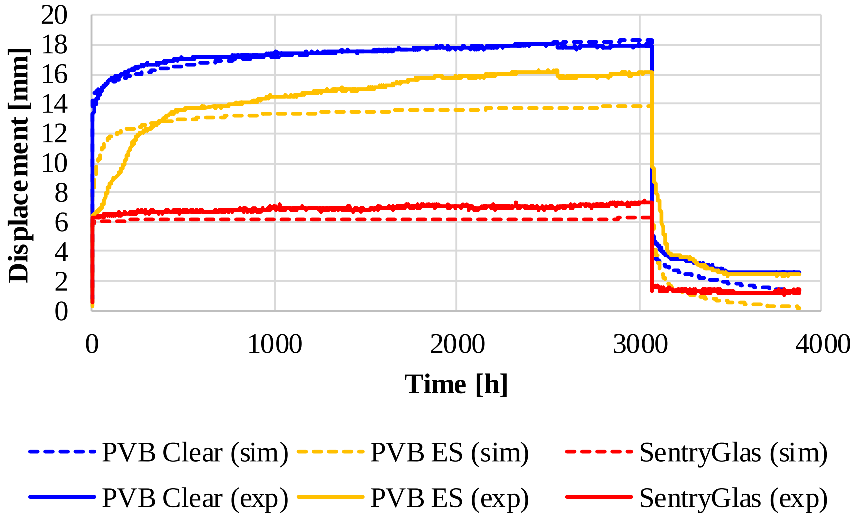


Figure 31. Creep and deflection recovery of three laminated glass plates under long-term loading. Comparison between the experimental results (exp) and the numerical predictions (sim).

In the case of laminated glass beams under in-plane bending, specimens with three thicker layers had a higher strength and bending stiffness than specimens with five thinner layers. However, the difference between both types of beams was relatively small, and specimens with five layers presented a very big advantage in terms of post-breakage strength, because they had a progressive breakage, with many small, evenly spaced cracks gradually forming in the central one-third before the total collapse (Figure 32), acting as an early warning system and providing a bigger safety margin.

(a) 3x10 mm (b) 5x6 mm

Figure 32. Comparison between the breakage mode of a laminated glass beam with 3 layers of 10 mm and another with 5 layers of 6 mm.

Chapter 5

5. Final conclusions

5.1. Conclusions

This PhD presents a review of the state of the art of laminated glass, focusing on the interlayer materials and the connections with other elements, given the importance of both of these aspects in the overall performance of load-bearing laminated glass elements. It also provides a thorough, detailed study of the mechanical properties of interlayer materials and laminated glass under several different loading scenarios, including the study of the effect of exposure to ageing factors. Finally, simulations using COMSOL Multiphysics and MATLAB allowed to extract more information from the experimental tests, to establish correlations between them, and to extrapolate the results to other untested scenarios.

The approach of this PhD on how to face the challenge that represents the application of laminated glass in structural applications started with the study of the polymeric interlayer, because there was a general agreement in the literature that it governed the behaviour of laminated glass. For that reason, published information about different interlayer materials was gathered in a review, and tensile and DMA tests were conducted on seven different commercial polymeric films.

The study of the interlayer was followed by the study of laminated glass, with a special interest on the contribution of the interlayer. To begin with, a double lap shear test was carried out on aged and unaged laminated glass specimens with different interlayers. The same test was then simulated using COMSOL Multiphysics, in order to more accurately evaluate the contribution of the interlayer, as well as the stress distribution on glass, interlayer, and the connection between both.

These tests were followed by bending tests, first on plates and later on life-size beams, focusing on the post-breakage safety, and trying to identify different design parameters, such as the type of glass, the number of layers, and the shear stiffness of the interlayer, that may lead to safer laminated glass structural elements.

For the last bending test, a long-term surface load was applied on a life-size laminated glass slab, with three laminated glass plates, each with a different interlayer, placed between two laminated glass beams. The load was removed after four months in order to evaluate the progressive deflection recovery. Simulations of the long-term bending tests with MATLAB were carried out using the viscoelastic properties of the interlayers provided by the manufacturers [67]. The bending performance was simplified using the Effective Stiffness Concept. The comparison between the simulation and the experimental test allowed to identify that there was a reasonable similarity between both, and therefore the information from the manufacturer may be adequate, in this case, for the calculation and design of structural elements made of glass.

It must be taken into consideration that higher discrepancies between the experimental results and the analytical prediction were found in the plate with PVB ES, which gives rise to re-examine the methodology. The test setup was identical for all three plates, but its complexity in terms of surface size, load magnitude, and test duration may have an impact on the overall accuracy of the test and the control over the measured parameters.

In some mechanical tests, a progressively increasing load or deflection was applied on the specimens until breakage (ULS), while in some others a constant load or deflection was applied, in order to study the effect of creep and stress relaxation respectively (SLS). For the study of laminated glass plates and beams, several performance indicators were evaluated, and the most significant ones could be identified. For the pre-breakage behaviour, the key performance indicators were the bending stiffness and pre-breakage strength. For the post-breakage safety, the most relevant factors were the redundancy, as already highlighted by Bos [43], and the breakage mode.

There are many different polymers used as interlayer materials for laminated glass. The best candidate may depend on the structural requirements and its final application. Out of the seven interlayer materials chosen to be studied, SentryGlas was the best candidate in terms of structural performance, because it presented the highest strength and stiffness, and was less sensitive to time and temperature variations than PVB. However, it was also more expensive, and therefore cheaper alternatives may be considered for less demanding applications. Under short-term loading and mild temperatures, PVB with a lower amount of plasticiser (e.g., PVB ES and Saflex DG-41) presented a similar behaviour to SentryGlas. EVA interlayers had lower mechanical properties, but they presented advantages in terms of manufacturing without need of the autoclave. Within the EVA group, EVASAFE bested EVALAM-80 in strength, stiffness, and ductility. Finally, TPU may be especially adequate in applications where glass sheets are bonded with stiff polymers (e.g., PC or PMMA), because of its very good adhesion to both glass and polymers.

The contribution of the interlayer was different in laminated glass beams. In that case, the shear stiffness of the interlayer did not have such a significant influence on the bending stiffness and maximum pre-breakage strength. Instead, it affected the lateral stability of the beams, as well as the shape of cracks in broken glass sheets. The key to safer laminated glass beams was in the glass rather than the interlayer. Using more glass sheets instead of thicker glass sheets, and using annealed glass instead of heat-strengthened glass, led to safer laminated glass beams, with a lower maximum strength but a more progressive breakage and a higher post-breakage strength.

The main conclusion of this thesis is that it is possible to create safe structural elements made of laminated glass if the right design parameters are chosen. For example, using stiffer interlayers has a beneficial effect on both pre- and post-breakage stages. However, in some cases, choosing the strongest material has a detrimental effect on the post-breakage safety, which is essential in laminated glass, because glass has a high risk of accidental breakage due to its brittleness. For instance, laminated glass beams with heat-strengthened glass instead of annealed glass have a higher maximum load-bearing capacity, but a much lower post-breakage strength.

To sum up, choosing the right interlayer material, type of glass, number of layers, and connection design may lead to safer laminated glass structural elements. However, there are many factors, such as the risk of impact, the service life temperature range, the load characteristics, and the exposure to ageing factors, which may affect the safety and performance of laminated glass structural elements. For that reason, it is essential to develop a new Eurocode in order to provide the common rules for a wider and safer use of structural glass in buildings.

5.2. Future work

This PhD includes a thorough study of the mechanical properties of laminated glass and the interlayer materials. It also includes some approaches to the study of the post-glass-breakage stage are presented, especially in terms of crack shape and density, as well as post-breakage strength and stiffness. However, information is missing in terms of glass breakage, which have been shown to be essential, given the brittle nature of glass.

Regardless of the safety coefficients chosen when calculating a structural element made of glass, it may still break due to unconsidered external factors and intrinsic surface flaws. These uncontrolled factors affect the toughness and the ultimate strength of glass. The unsafe and unpredictable mechanical behaviour of glass makes it essential to develop a standard that properly defines the strength of glass and its use for structural applications in buildings.

There are already Eurocodes for structures of concrete, steel, reinforced concrete, timber, masonry, and aluminium. If structures made of glass become a growing trend, it is only natural that, in the years to come, a new Eurocode for structural glass will be published.

Even at present, when it has been used in several singular buildings to create impressive glazed facades and walkable floors, laminated glass is still a material that does not transmit confidence to the users for its brittle behaviour. A deeper study of the material performance under different loading conditions, together with the development of new solutions that provide higher ductility and post-breakage safety to glazed elements, could reverse that situation.

Other research activities

Contributions to international conferences

The PhD candidate contributed to different international conferences:

1. **Centelles X**, Martin M, Solé A, Castro JR, Cabeza LF. Material research, design and testing of structural elements made of laminated glass. 10º Congreso Internacional de Ingeniería Temodinámica 2017, Lleida (Spain). Poster presentation.
2. **Centelles X**, Castro JR, Cabeza LF. Bending behaviour of laminated glass panels with different polymeric interlayers: experimental testing and simulation. Building Simulation 2019, Rome (Italy). Oral presentation.

International meetings and workshops

The PhD candidate assisted to international meetings and conferences:

1. Structural Glass – Technology and design, professional training course, CMM – Associação Portuguesa de Construção Metálica e Mista, Lisbon (Portugal).
2. Joint Meeting ECES-IAE-Annex 30 and Open workshop with Spanish Stakeholders EERA subprogramme on TES, 2017, Lleida (Spain).

Scientific exchange

The PhD candidate did a stay in Gijón (Spain) during the development of this PhD thesis, hosted by the University of Oviedo.

In this research stay, the candidate learnt the DMA test methodology and performed relaxation tests at different temperatures on several interlayer materials for laminated glass. He also learnt how to obtain the stationary (creep and stress relaxation) and dynamic (storage modulus and loss modulus) master curves of viscoelastic materials, as well as the mathematical expressions to simulate their mechanical behaviour.

Universidad de Oviedo
Universidá d'Uviéu
University of Oviedo

Other activities

Projects participation

- Nueva viga de vidrio multilaminado con función estructural. Centro para el Desarrollo Tecnológico Industrial (CDTI), Ministerio de Ciencia, Innovación y Universidades, IDI-20160588.
- Identificación de barreras y oportunidades sostenibles en los materiales y aplicaciones del almacenamiento de energía térmica (SOPPORTES). Ministerio de Ciencia e Innovación, ENE2015-64117-C5-1-R, 2016-2018.

Organizing committee participation

- INNOSTORAGE Third Training School - Experimental Apparatus for Measurement, 2016, Lleida (Spain)
- Eurotherm Seminar #112 – Advances in thermal energy storage, 2019, Lleida (Spain).

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