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.

Keywords

Laminated glass; adhesive connections; mechanical fittings; failure mode; experimental test

1. Introduction

The use of transparent elements in modern architecture is growing, aiming to ensure natural light in buildings, give a perception of larger indoor spaces, and bring occupants closer to nature. For this reason glass has become one of the main basic materials in buildings [1]. The growing use of glass has led to many advances in terms of material research (e.g. thermally strengthened glass and laminated glass), engineering improvements (e.g. larger glass panels and curved glass) and new construction techniques (e.g. laminated glass beams and glass-to-glass adhesive connections).

Glass is a brittle material without plastic deformation, which means that it is unable to absorb high amounts of energy in case of impact or to redistribute local peak stresses. Glass breakage happens in most of the cases due to the crack propagation from surface flaws that appear during some stages of the life cycle (i.e. manufacturing, machining, transport, assembly, and service life). That is why the real tensile strength of annealed glass (30-80 MPa) is much lower than the theoretical one (5000-8000 MPa) [2]. Therefore, its tensile strength is lower than the compressive strength, because cracks under tensile stress tend to open, unlike compressed ones. The tensile strength may be even lower with long-term loading because the exposition to water or humidity may cause stress corrosion and subcritical crack growth.

The improvement of glass structures is closely linked to the technological development of the connection systems. The main tasks of a joint in a glass structure are to provide a way to connect glass components to the rest of the structure, to adjust dimensional inaccuracies, to ensure that it behaves according to the theoretical model (e.g. roller bearing or rigid restraint), and to absorb shock waves to limit the damage propagation [3]. The brittle nature of glass makes it very challenging to use smaller connections, because smaller contact regions involve higher local stresses. In regions with geometrical singularities, such as edges, corners, or holes, glass breakage is more likely to happen due to an unexpected scenario, even with a proper connection design. If that unexpected breakage happens, it is important to prevent the sudden and total structural collapse, as well as the projection of sharp glass fragments. A “fail safe response” could be achieved if, after breakage, the structure maintained sufficient structural integrity and load bearing capacity, in order safely evacuate the occupants and replace the broken elements [4].

There are many different ways to connect laminated glass beams to other structural elements. These can be classified in mechanical, adhesive, and laminated connections. Mechanical connections can be either bolted or clamped. They make use of intermediate metallic elements to transfer loads. In glued joints, an adhesive material is placed between elements to keep them connected. In laminated connections, it is the interlayer material between glass layers the one used to create a bond between elements. In all three cases, it is important to prevent direct contact between glass and glass, steel, or other tough materials, because glass would be unable to deform plastically in order to increase the contact surface and therefore decrease the local stresses. In mechanical supports, direct contact is prevented by using an intermediate elastic material, which must be flexible enough to redistribute stress peaks, but have sufficient strength and stiffness to transfer loads without breaking [5]. In the case of adhesive connections, direct contact between stiff elements is prevented by the adhesive layer, whereas in the case of laminated connections it is the interlayer material the one that prevents it. The inclusion of soft intermediate materials reduces the bending stiffness of the connection, making it harder to create rigid connections.

Bolted connections have been proven to be a good solution for both steel and timber structures, but the brittle nature of glass makes that kind of connections less convenient for laminated glass elements: the small contact surface may lead to stress concentrations and crack propagation from the small flaws generated during the drilling process, leading to glass breakage [6]. On the other hand, adhesive and laminated connections have shown promising results since they require no drilling and there is no direct contact between glass and other stiff materials. They may be an innovative alternative to mechanical fixings, but there is still a lack of results for long term performance, which is essential, as it has been proven that load duration and degradation due to weathering factors have a big influence on the performance of the adhesives [7].

Bos [3] conducted a survey among structural glass engineers where he identified that the most common causes of premature failure were ignorance and negligence in manufacturing, transport, and construction. Joints are a critical part about the manufacturing and the construction stages, and a critical region where stress concentrations may appear in glass. It is important to be able to accurately predict the load at which the first crack appears, as well as the ultimate load, the fracture mode, and the load transfer mechanism of each element and the whole structural system.

The aim of this review is to list the most relevant connection designs for glass elements, in order to indicate their structural performance, auxiliary materials, safety in case of breakage, durability, and experimental tests carried out to validate them. The connections are separated in three main groups: mechanical, adhesive, and laminated fixings. In mechanical connections, metallic bolts or clamps are used to transfer loads between elements. Adhesive connections make use of adhesive materials to connect glass elements to other substrates, such as steel, aluminium, glass, timber, or other construction materials. In laminated connections, the interlayer material that keeps glass layers connected between them in laminated glass is also used to bond glass elements to other substrates.

2. Glass fixings: experimental research

The safety and the strength of innovative designs and materials for glass connections were experimentally tested by different authors. Table 1 shows different mechanical joint designs tested in the literature, Table 2 adhesive, and Table 3 laminated. The tables provide information about the materials used and the tests carried out.

Table 1. Experimental research on mechanical glass fixings.

Connection type	Main characteristics	Tests
Bolted [6,8-10]	- Requires glass cutting and drilling. - Load transfer: surface contact between the bolt and the glass borehole. - Requires glass thermal strengthening. - Failure generally caused by crack propagation from the surface flaws at the borehole region.	Double-lap shear [6,8-10]
Clamp [11]	- Glass cutting, drilling and thermal strengthening is not necessary. - Slip of the clamp, due to an insufficient pre-compression or stress relaxation, is a common cause of failure for in-plane loads.	Horizontal panel with four supported corners [11]
Friction-grip [12,13]	- Requires glass cutting and drilling. - Load transfer: shear load (friction) from bolt to exterior glass surfaces. - Requires glass thermal strengthening. - Failure due to slip of the pre-stressed bolt or glass breakage. - In case of glass breakage, the elastic strain energy release will be greater, and therefore the post-failure strength will be lower [3].	Double-lap shear [12] Three-point bending with a friction-grip joint at the midpoint between supports [13]

Table 2. Experimental research on adhesive glass fixings.

Substrates	Adhesive	Tests
Glass-to-glass [14,15]	Two-part epoxy resin [14] UV-curing acrylate Ritelok UV50 [15] UV-curing acrylate Conloc 685 [15]	Single-lap shear [14] Double-lap shear [15]
Glass-to-metal [15-18,20,21]	One-part polyurethane SikaFlex 265 [15] Two-part polyurethane SikaForce 7550 [15,20] Two-part acrylate SikaFast 5211 [15] Two-part acrylic Holdtite 3295 [20] UV-radiation cured acrylic Bohle 682-T [20]	Tensile (metallic point fixing on glass surface) [15,17] Double-lap shear [15,21] Shear (metallic point fixing

	Transparent structural silicone adhesive [16, 22] Two-part silicone Sikasil SG-500 [17] Two-part silicone Dow Corning DC993 [20] Two-part epoxy T9323 B/A [17] Two-part epoxy DP 490 [21] Two-part epoxy 2216 B/A [20] One-part MS-polymer Soundaseal 270 HS [17]	on glass surface) [15-17] Shear (metallic linear fixing on glass surface) [17] Horizontal panel with four supported corners [18] Single-lap shear [20]
Glass-to-timber [22,24]	One-part polyurethane Ködiglaze P [23] One-part polyurethane Prefere 6000 [22] Two-part acrylic SikaFast 5215 [22] Two-part acrylate SikaFast 5221 [24] One-part silicone Sikasil SG-20 [22] Two-part silicone Sikasil SG-500 [24] Two-part silicone Ködiglaze S [23] Two-part epoxy DP 490[24] Two-part epoxy Körapox 558 [23]	Tensile [22] Single-lap shear [22] Shear on a glass panel with a timber frame [23]
Glass-to-GFRP [14,25,26]	One-part polyurethane Sikaflex 265 [25] Two-part polyurethane Sikaforce 7710-L100 [25] Two-part epoxy resin [14,26] Two-part epoxy Sikadur-31 CF [25]	Pull-out [14] Single-lap shear [26] Double-lap shear [14,25]

Table 3. Experimental research on laminated glass fixings.

Substrates	Interlayer	Tests
Glass-to-glass [14]	PVB [14]	Two-lap shear [14]
Glass-to-steel [4,16,19,28,29]	SentryGlas [4,16,19,28,29]	Three-point bending [4] Pull-out [28,29] Shear (steel point fixing on glass surface) [16] Tensile (steel point fixing on glass surface) [19]

There are many different tests to evaluate the capacity of a connection to transfer shear and tensile loads (Figure 1). Shear tests are carried out to study the capacity of a connection to transfer shear stresses.

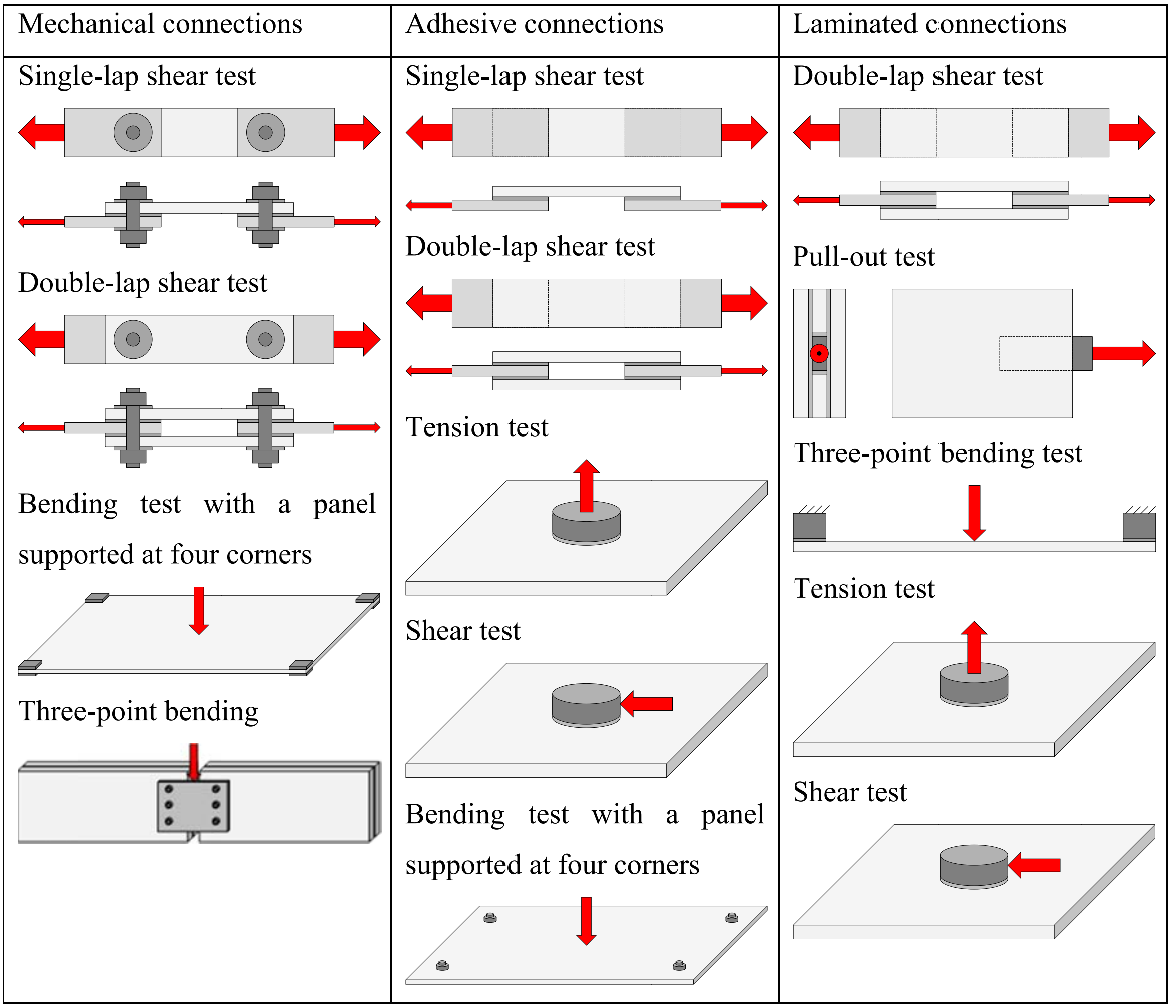


Figure 1. Sketch of the test setups for mechanical, adhesive, and laminated connections.

In the single-lap shear test, two plates are bonded together on their lateral surfaces and then subjected to a tensile or compressive load. The eccentricity between the adjacent surfaces usually leads to a bending moment on the lateral panels, and a combination of shear and tensile stress on the joint. In double-lap shear test specimens a symmetrical arrangement is implemented in order to prevent such combination of shear and tensile stress. However, in both tests, the misalignment between adjacent panels creates tensile loads and an uneven stress distribution at the bond region [12,14,15].

Tensile and shear tests can also be applied on point fixings. A metallic connector is bonded to a glass surface using an adhesive or an interlayer, and then it is subjected to a load, that can be either parallel to the glass surface (shear load) or normal to the surface (tensile load). For metallic reinforcements or embedded joints, pull-out tests are also carried out to find the strength needed to remove them from their original slot, as well as the deflection experienced before being pulled out.

In mechanical tests, special care is needed when glass is involved, because it is brittle and the effect of tensile or flexural stresses, as well as the local effect of glass-to-steel contact, could cause premature failure of glass. Therefore, when only one of the substrates was glass, the load was mainly applied on the other material (steel, GFRP, etc.) [6,9,15,20,26]. In glass-to-glass connections, compressive loadings were preferably carried out [15], and clamps with intermediate material were used to apply tensile loads [14].

3. Mechanical fittings

3.1. Bolted connections

3.1.1. Pin-loaded bolted connections

Bolted connections are a good solution for materials that allow plastic deformation such as steel and timber. This type of connection, however, is not the most efficient type for brittle materials, because high local stresses appear at the contact region between the fixing system and the glass borehole, where surface flaws are more likely to appear during the drilling process. Thermal pre-stressing of the drilled glass elements is needed to increase resistance and prevent premature breakage. The thermal strengthening has two beneficial effects: it increases the glass tensile strength and reduces the detrimental effect of surface cracks and flaws [8].

Depending on the degree of thermal strengthening, it is possible to obtain thermally tempered glass or heat strengthened glass, between which the main differences are the value of surface pre-stress and the breakage mode. Tempered glass has a higher pre-stress value, breaks into small blunt pieces and the initial cracking leads to total breakage, whereas heat strengthened glass has a lower pre-stress level and has a crack pattern similar to annealed glass. Tempered glass provides higher strength than heat strengthened glass, but laminated glass with tempered glass has a lower residual strength and a higher risk of pulling out of the point fixing in case of glass breakage, especially when soft interlayers are used [2]. All cutting and drilling for bolted fixings must be done before thermal strengthening. The stress distribution and the degree of toughening associated to the thermal strengthening process are factors that may affect the glass strength in the region of the bolt hole [10].

At the contact region between the glass borehole and the steel bolt, stress peaks may appear and cause glass failure. To prevent that, an intermediate material must be used. An adequate intermediate material should be soft enough to redistribute stresses at the contact region, resistant and stiff enough to transfer loads without breaking, and durable if exposed to environmental conditions [5]. The mechanical properties and thickness of the isolating material may affect the strength of bolted connections. There are other factors that may affect the load-bearing capacity of that type of connections: the closeness to fit (higher clearance leads to higher local stresses because of the smaller glass-to-bolt contact surface), the distance from the borehole to the edges [18], the glass surface quality, and the load characteristics (i.e. load duration, direction, eccentricity, etc.).

To et al. [9] carried out an experimental campaign aiming to determine the strength of bolted joints with tempered glass under in-plane loading. Between the steel bolt and the glass borehole, three concentric rings were placed: an inner cooper ring, an intermediate stainless steel ring, and an outer adhesive resin (mixture of epoxy resin and hardener) ring. The results showed that the crack initiated in the resin ring for excessive compressive stress (around 11 MPa) at the region in contact with the steel ring. The applied load kept increasing after failure of the resin, but the maximum stress on the glass grew faster than before because the resin became unable to redistribute stresses as effectively as before breakage. Glass failure started at the hole edge when a tensile stress of approximately 120 MPa was reached.

Watson et al. [10] carried out a tensile double-lap shear test similar to the one performed by To et al. [9]. Their goal was to determine the critical flaw size at which cracks propagate under a certain tensile load. For the studied cases, cracks usually originated at the borehole chamfer edge. The coaxial double ring test was found to underestimate the critical flaw size on glass bolted specimens, and therefore was unsuitable as a quality control measure of bolted glass components. The initial flaw sizes of annealed glass specimens were significantly larger than the ones of tempered glass. The authors associated that observation with the existence of a certain degree of crack healing, meaning that the fracture strength of specimens with induced flaws increased if no stress was applied over an extended period of time.

3.1.2. Countersunk fixings

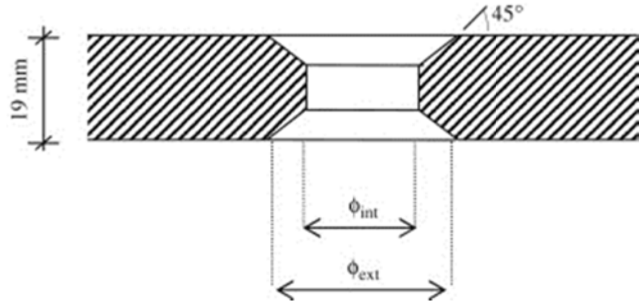
A countersunk fixing is one type of bolted fixing that uses conical holes and bolts in order to resist out-of plane loading and obtain flat external surfaces, without bolts projecting beyond it. For that kind of connections, the clearance between bolt and hole is smaller and limited, which means smaller dimensional tolerances are allowed [30]. Figure 2 shows the comparison between a protruded bolted fixing and a countersunk fixing.

(a) (c)

(b) (d)

Figure 2. Images of a glass structure (a,b) using protruded bolted fixings and another one (c,d) using countersunk fixings [31,32].

Bernard and Daudeville [8] evaluated through simulation and experimental testing different connection parameters to obtain the optimal design: borehole geometry (Figure 3), washer material (aluminium and PTFE), glass thermal strengthening degree (annealed and tempered glass), bolt preload level (between 0 Nm and 100 Nm), and friction coefficient between glass and washer (with or without lubrication).



Designation	Φ_{int} (mm)	Φ_{ext} (mm)
a1	38	40
a2	54	56
b1	24	40
b2	40	56
c1	30	40

Figure 3. Geometry of the different drill hole geometries tested by Bernard and Daudeville [8].

Glass thermal tempering was very effective to increase the load-bearing capacity of the connection, multiplying approximately by four the ultimate load. The lubrication of the contact between glass and washer and the use of PTFE washers were beneficial and increased the ultimate load on annealed glass specimens, but had a less conclusive effect on tempered glass. The bolt preload had a positive effect on the ultimate load because it locally increased the glass surface pre-compression, but the initial cracking led to instantaneous breakage (especially for annealed glass) due to the higher elastic strain energy release.

3.2. Clamp fixings

Isolated clamps replace linear supports in some applications in order to minimize the visual impact of the frames. They can be designed to simply hold the glass in place (out-of-plane loads) or to support structural elements (both out-of-plane and in-plane loads). A soft intermediate material, such as neoprene or rubber, can be used if the only goal is to hold the glass in place. When used to support in-plane loads, stronger gaskets are needed (e.g. aluminium sheets), in order to transfer shear loads but still eliminate peak stresses. For pre-stressed clamps, sometimes a stronger, stiffer interlayer material is used at the clamped region to prevent breakage or stress relaxation [5].

Feng et al. [11] tested the mechanical response of an individual panel supported at the four corners with steel clamps, and a 7x7 grid of glass panels, supported with steel tensors, connected with the same clamping system. The applied load was distributed and perpendicular to the surface. The clamping joint limited displacement and out-of-plane rotation. Warping and bending of the panels caused high tensile stresses; for that reason the use of fully tempered glass was recommended. The highest stresses were achieved at the corners, where the connections were placed.

3.3. Friction-grip bolted fixings

Friction-grip bolted fixings are typically used for elements undergoing in-plane loads. The typical design consists of two steel plates clamped together with a preloaded bolt that passes through the glass pane (Figure 4). The pre-stressing contact surfaces enable high friction forces to transmit shear stresses. The drill hole is oversized in order to prevent direct contact between bolt and glass. An intermediate material is included between the steel plates and the glass panel in order to distribute the bolt preload on a larger glass surface and provide friction against both glass and steel [30].

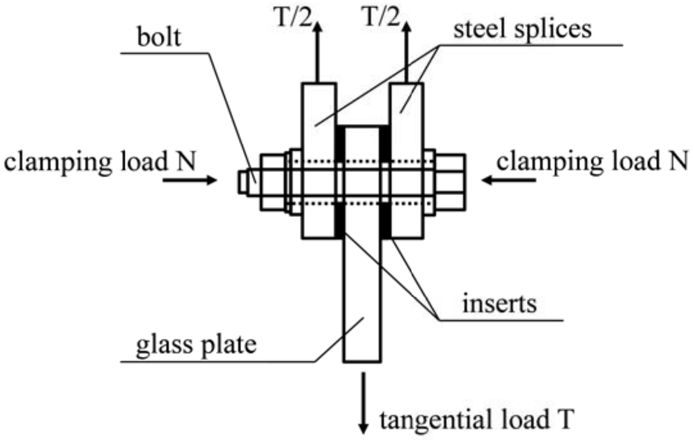
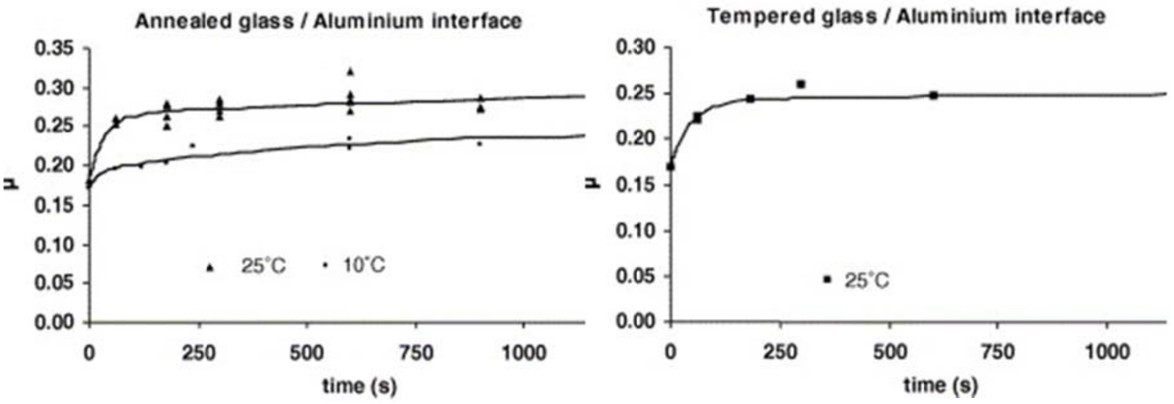


Figure 4. Design of a typical friction-grip bolted connection with a glass plate and two steel splices [12].

Panait et al. [12] carried out an experimental campaign where tempered glass plates with preloaded steel bolts were subjected to tensile double-lap shear tests. A stiff resin layer prevented direct contact between the glass borehole surface and the steel outer ring.

The joint failure started when there was sliding between glass and the aluminium inserts. The maximum static friction force depends on the bolt preload value and the friction coefficient between glass and aluminium. The authors identified that the friction coefficient between glass and an aluminium inset was time and temperature dependent, as displayed in Figure 5. The load-bearing capacity kept increasing until a crack perpendicular to the loading appeared on the glass borehole surface. From that point on, the principal stresses at the borehole surface significantly increased. Even though the resin ring cracked by compressive stress when sliding started, there was no direct contact between glass and steel.



(a) (b)

Figure 5. Diagrams expressing the friction coefficient between aluminium and (a) annealed glass or (b) tempered glass, for different temperatures and duration of the load application [12].

Campione et al. [13] studied the performance of friction-grip joints in a three-point bending test, where two parts of a halved glass beam were connected using steel angles and an intermediate steel plate (Figure 6). The authors evaluated the effect of the following parameters on the ultimate load and the breakage mode: bolt preload level, glass type (annealed, heat strengthened and fully tempered), interlayer material (PVB and PC), beam dimensions, and angle geometry.

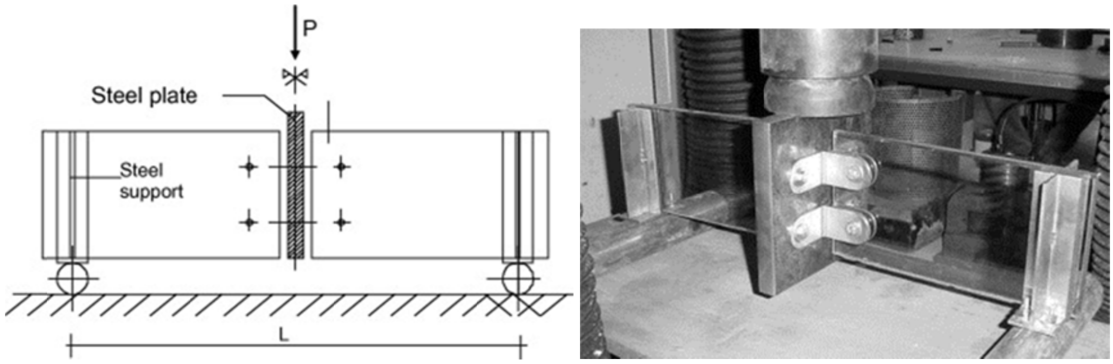


Figure 6. Test setup of the three-point bending test carried out by Campione et al. [13].

All specimens had a linear elastic behaviour, until the peak load was reached when the brittle failure started near the borehole edge. Fully tempered glass specimens had the highest load-bearing capacity, but lacked post-breakage strength, whereas annealed glass with PC specimens had the best remaining structural capacity. The bolt preload increased the strength and deflection at failure, but the preload value may decrease in long-term applications due to stress relaxation of the interlayer material or the polymeric insets. Specimens with PVB interlayer presented instantaneous failure after glass breakage.

4. Adhesive fixings

4.1. General overview

Adhesive connections are obtained from bonding a glass element to another substrate using an adhesive material. The adhesive materials commonly used in glass can be divided into four groups: epoxy resins, polyurethanes, acrylates, and silicones [12]. Epoxy and acrylic adhesives present higher strength and stiffness, while silicones and polyurethanes present, in general, higher ductility and resistance to weathering factors [15,20].

The main advantages of adhesive connections, compared to mechanical connections, are that they require no drilling and the load is spread more evenly, reducing local stresses. Other important advantages are that they allow to better adjust tolerances, damp vibrations, and improve visual appearance, since there are no connectors or other protruding elements. The main problems are that, in general terms, adhesive connections have lower strength than mechanical connections, and its performance is influenced by working temperature, weathering, and load duration.

Weathering includes exposure to thermal cycles, humidity, solar radiation, and biological attacks. It may lead to chemical and molecular changes in the structure of the adhesive material and its bonding with glass. It can cause a reduction of adhesion between adhesive and substrate, as well as an embrittlement and decrease of strength of the interlayer material [2]. In an experimental study for adhesive connections carried out by Lancker et al. [17], the authors identified a lack of quantitative data and reliability of the results regarding the accelerated ageing procedures to study the long-term effect of environmental factors on adhesive materials in buildings.

The adhesive material has to be strong and stiff enough to transfer the design loads for long periods of time without degrading. However, it must also be flexible to redistribute stresses, and to compensate dimensional tolerances and thermal expansions without breaking or causing the breakage of the glass elements. A progressive breakage is desirable; the failure of a connection must not result in a total and instantaneous collapse of the whole structure. There are some design considerations that may help reaching a safe breakage. For example, designing structures with alternative load paths, in order to redistribute loads in case of local breakage, and implementing secondary support structures with the sole purpose of preventing the collapse of the main glass structure [30].

The deformation of the interlayer material under long-term loading until collapse can be divided in three stages: stretching of the molecular chain (elastic, reversible), sliding of the molecular chain (creep, irreversible), and physical bonding loss until breakage [5]. Short-term loads are not very representative of the performance of an adhesive connection, because long-term loads usually lead to larger deflections and a decrease of strength [20].

The main types of failure for adhesive fixings are the following: cohesive failure at the adhesive, cohesive failure at the substrate, adhesion loss between adhesive and substrate, or a combination of these. Failure of the adhesive can be either ductile or brittle, depending on the mechanical properties of the cured adhesive and the working temperature.

4.2. Adhesive materials

The adequacy of a polymeric material to be used as an adhesive for a specific application depends on many factors such as loading requirements, working temperature range, chemical compatibility, thickness of the bonded area, weathering conditions, and curing process. The Table 4 of the European pre-normative document EUR 26439 EN [2] compares the performance of four different adhesive groups. According to that table, epoxy and polyurethane are stronger and stiffer for both short- and long-term loadings, whereas acrylate and silicone are more durable. Stiffer adhesives have higher capacity to transfer shear loads, whereas higher ductility allows the adhesive to redistribute stresses. Moreover, the ratings shown in that table are compared with the ones found in the literature along the present review.

Table 4. General comparison of different adhesive systems [2].

	Tension and shear strength	Stiffness	Ductility	Viscosity	Temperature resistance	Ageing behaviour	UV resistance	Transparency, colour
Epoxy resin	+ + +	+ + +	+	+ + +	+ +	+ +	+ +	+
Polyurethane	+ +	+ + +	+ +	+ +	+ +	+ +	+ +	+ +
Acrylate	+ +	+ +	+ +	+ +	+ +	+ + +	+ + +	+ + +
Silicone	+	+	+ + +	+	+ + +	+ + +	+ + +	+

In one-part component adhesives, the curing process is generally done by exposure to UV. In two-part component adhesives, the curing happens as a result of a chemical reaction when the two components are mixed. The curing process may be affected by the thickness of the material.

Some materials are especially formulated to cure for thin or thick sections, depending on its intended application. The thickness of the adhesive also affects its mechanical behaviour: thicker adhesive layers have a better capacity to redistribute stresses and to absorb shear strain caused by differential thermal expansion. However, thicker adhesives tend to have lower strength, especially for more rigid adhesives [15].

There are many other factors that may affect the mechanical response of an adhesive joint, but two of the more important ones are load duration and working temperature. Viscoelastic materials may suffer creep or stress relaxation when subjected to long-term loading, and its strength and stiffness may significantly decrease when working above the glass transition temperature.. Below the glass transition temperature the strength and stiffness of the adhesives increase, but performing at low temperatures may cause adhesion problems and brittle cohesive failure of the adhesive. The glass transition temperature can be different depending on the adhesive material, and it is important to know if it is below, within or above the working temperature range.

4.3. Glass-to-glass connections

Experimental results evaluating the performance of different adhesive materials for glass-to-glass connections were found in the literature. Machalická and Eliášová [15] performed a double-lap shear test with five different adhesives: one-component polyurethane (SikaFlex 265+Booster), two-component polyurethane (SikaForce 7550), two-component acrylate (SikaFast 5211), UV-adhesives (Ritelok UV50 and Conloc 685). Speranzini et al. [14] tested a transparent two-component epoxy and a light grey two-component epoxy with a single-lap shear test.

Machalická and Eliášová [15] studied the effect of glass surface treatment, artificial ageing, with a combination of ageing factors (temperature, UV radiation, and moisture), and thickness of the adhesive on strength and adhesion. These authors identified that there was an uneven stress distribution in the connection surface, with higher stresses at the edges. Other authors reached the same conclusion after performing experimental tests on adhesive or laminated connections [19,33]. A sandblasted glass surface improved the adhesion of acrylate adhesives. The joint strength decreased with the thickness of the adhesive, and the differences were greater for more rigid adhesives. After the accelerated ageing cycle, the shear strength values of the Conloc 685 UV-curing adhesive were reduced by about 40%. The Ritelok UV50 UV-curing adhesive was assessed as unsuitable for structural use because of serious deterioration of its mechanical properties due to higher relative humidity in the accelerated ageing cycle.

Both structural resins tested by Speranzini et al. [14] showed a good level of resistance. Failure in both cases was cohesive at the adhesive, and the glass remained intact because the resin did not penetrate the surface of the glass.

4.4. Glass-to-steel connections

The most common type of tests found in the literature, are peel tests [15,17,20], where a displacement perpendicular to the adhesive surface is imposed, and shear tests, that can be either double-lap shear [15], single-lap shear [20], pull-out [17,18], or shear tests where a load parallel to the adhesive surface with a certain eccentricity is applied [16,17].

Machalická and Eliášová [15] used for glass-to-steel connections the same adhesive materials that they used for glass-to-glass connections: one-component polyurethane (SikaFlex 265+Booster), two-component polyurethane (SikaForce 7550), two-component acrylate (SikaFast 5211), and UV-adhesives (Ritelok UV50 and Conloc 685). Van Lancker et al. [17] used a structural two-component epoxy (3M Scotch-Weld 9323 B/A) and a one-component MS polymer (Soudaseal 270 HS) for point-fixings, and a fast-curing two-component silicone (Sikasil SG-500) for linear fixings. Overend et al. [20] used a silicone (Dow Corning DC993), a two-component polyurethane (SikaForce 7550 L15), an epoxy (3M 2216B/A), a two-component acrylic (Holdtite 3295), and a UV-curing acrylic (Bohle 682-T).

Machalická and Eliášová [15] observed, for both tensile and shear tests, cohesive failure of the polyurethane adhesive. Cohesive failure of the adhesive provided higher ductility than glass failure and lower strength variability than adhesive failure. In the acrylate adhesive SikaFast 5211, cohesive failure of the adhesive was observed on sandblasted glass specimens, whereas a combination of adhesive and cohesive failure was observed in smooth glass specimens. Failure of the glass was also observed in some shear specimens. The adhesive thickness increase affected the mechanical properties of the connection: for thicker adhesives, maximum elongation increased, but the load-bearing capacity decreased. The differences were greater for more rigid adhesives.

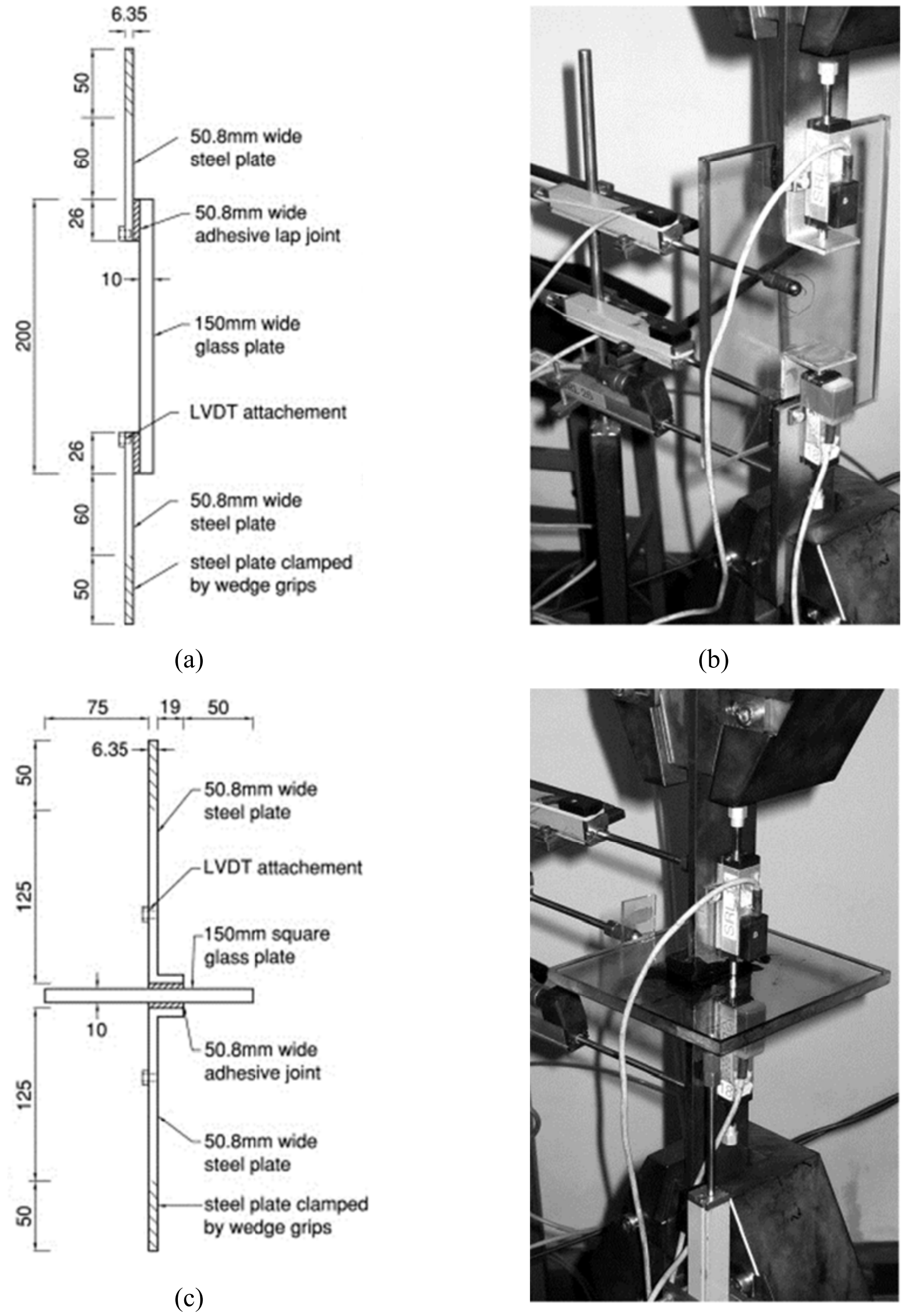
The same authors performed an artificial ageing test to simulate the effect of real weathering conditions. It consisted of nine ageing cycles, containing thermal cycles between -20 ºC and 80 ºC, combined with UV radiation and water shower at 20 ºC. The study concluded that no significant deterioration of the mechanical properties was observed on specimens with one-component polyurethane SikaFlex 265, two-component polyurethane SikaForce 7550, and two-component acrylate SikaFast 5211. However, the thermal cycles led to the formation of bubbles and cracks in the SikaFast 5211 adhesion surface, mainly because of the differences in the thermal expansion coefficients between adhesive and substrate. UV-curing adhesives are resistant to UV radiation, but the effect of moisture caused a 40% decrease of strength in Conloc 685, and Ritelok UV50 was established as unsuitable for structural applications because of the dramatic adhesion weakening.

Van Lancker et al. [17] tested three different adhesive materials, and each of them presented a different breakage mode. The breakage mode of the structural two-component epoxy (3M Scotch-Weld 9323 B/A) was either a combination of adhesive and cohesive failure, or a brittle cohesive failure of the glass. A more ductile behaviour was observed for the one-component MS polymer (Soudaseal 270 HS). For the unaged specimens with this adhesive, cohesive failure of the adhesive was observed. In the case of the fast-curing two-component silicone (Sikasil SG-500), a purely cohesive failure of the adhesive was observed.

Ageing tests were carried out by Van Lancker et al. [17], including three weeks of immersion in water at 58±3 ºC, two weeks of 100% relative humidity at 58±3 ºC, four weeks of thermal cycles between -10 ºC and 50 ºC, 265 hours of exposure to UV radiation at 45±5 ºC, or a combination of these. All the ageing factors, except for the thermal cycles, caused visual degradation to the two-component epoxy adhesive (3M Scotch-Weld 9323 B/A). Exposure to UV radiation also caused coloration of the one-component MS polymer Soudaseal 270 HS. No visual degradation was observed after ageing tests in the fast-curing two-component silicone (Sikasil SG-500) specimens. Water immersion caused the most significant decrease in strength and stiffness for all the tested adhesive materials. It also led to partial adhesive failure for one-component MS polymer (Soudaseal 270 HS) and fast-curing two-component silicone (Sikasil SG-500) specimens. Thermal cycling had a negligible effect on the mechanical properties of the 3M Scotch-Weld 9323 B/A and the Sikasil SG-500 specimens. In contrast, it led to a significant initial increase of strength and stiffness for Soudaseal 270 HS, due to cross-linking and reduction of internal stresses, followed by a decrease, caused by thermal degradation.

Dispersyn et al. [18] tested a horizontal panel under gravitational load, with six stainless steel point-fixings, and rubber adhesive disks under compressive loads between glass and steel. They tested and compared two types of connections: one allowed rotation and the other did not. The result was that higher stresses, due to more restricted boundary conditions, and smaller displacements, due to the fixed rotation, were reached with the fixed connection. Different distances from the connection to the edge and corners of the panels were also tested, resulting into lower stresses, lower deflections, and a more uniform stress distribution when the edge distance was maximal.

Overend et al. [20] studied the shear and tensile strength and stiffness of five different adhesive materials (silicone Dow Corning DC993, polyurethane SikaForce 7550L15, epoxy 3M 2216 B/A, two-component acrylic Holdtite 3295, UV-curing acrylic Bohle 682-T) performing two different tests: single-lap shear and T-peel (Figure 7).



(a) (b)

(c) (d)

Figure 7. Test sketch and set-up of (a,b) the single-lap shear test and (c,d) the T-peel test [20].

From the experimental results, Overend et al. [20] identified that cohesive failure of the adhesive was observed for silicone, two-component acrylic, UV-curing acrylic, and the single-lap shear test of the epoxy. Adhesion failure at the adhesive-steel interface was observed for polyurethane, and adhesion failure, partly at the adhesive-steel interface, partly at the adhesive-glass interface, was observed in the T-peel test of the epoxy. For short-duration loads, silicone was considered the best material for low strength/stiffness steel-glass joints. The two-component acrylic and the epoxy were considered the best materials for stronger/stiffer joints. Further research is needed for long-duration loading, cyclic loading, and ageing factors.

Santarsiero et al. [16] performed a shear test on a stainless steel connector bonded to a glass surface. Transparent structural silicone adhesive (TSSA) was chosen to create the bond. Shear tests were carried out at different temperatures between -20 ºC and 80 ºC, and displacement rates between 0.1 mm/min and 10 mm/min. The results show how the shear strength of the adhesion was sensitive to both working temperature and strain rate, but it proved to be much less sensitive to temperature variations than the other tested material: the ionomer interlayer SentryGlas. From -20 ºC to 80 ºC, the shear strength of TSSA decreased a 37%, whereas for SentryGlas it decreased a 98%. The shear strength of both TSSA and SentryGlas increased 30% from the test at 0.1 mm/min to the test at 10 mm/min. The failure mode of TSSA specimens is full cohesive at the adhesive.

Santarsiero et al. [19] also performed a tensile test on the same specimens and with the same deflection rates and temperatures described in [16]. TSSA specimens displayed an approximately bilinear behaviour until full cohesive failure of the adhesive. Very similar results were obtained at different strain rates. The geometry of the load-displacement curve is also similar for different temperatures, with the exception that failure at higher temperatures happens with lower tensile forces.

4.5. Connection of glass to other construction materials

4.5.1. Glass-to-aluminium connections

Zangenberg et al. [21] studied the adhesion between a triple-layered laminated glass panel with heat strengthened glass and PVB interlayer, and an aluminium (alloy type 6061-T6) embedded plate with sandblasted surface to increase adhesion. A two-component epoxy adhesive DP490 from 3M was used. Four different experimental tests were carried out: uniaxial tensile, double-lap shear, four-point bending, and in-plane shear. The epoxy adhesive DP490 had a linear elastic behaviour until reaching 2/3 of the ultimate stress. Both out-of-plane and in-plane tests showed a linear performance of the connection until breakage. For in-plane shear tests and long-term loads, breakage started in the glass, near the support area, rather than the connection. The adhesive material showed a dependency on load rate: long term loading caused larger deflections, plastic deformation and creep.

Machalická and Eliášová [15] performed a double-lap shear tests with glass connected to three different metals: steel S235, stainless steel 14301, and aluminium Al 6082. The authors concluded that the use of different metallic substrates did not have a decisive influence, because the crucial factor in the glued joints was the cohesive strength of the adhesive, not the substrate material. The adhesive material, the adhesive layer thickness, and the ageing process, had a more relevant influence on the overall behaviour of the joint. Other factors such as load duration were not taken into consideration in this study but may also have a relevant influence on the behaviour of the joint.

4.5.2. Glass-to-timber connections

Blyberg et al. [22] studied the tensile and shear resistance of the connection between a glass and wood. Three different adhesives were tested: the one-component moisture-curing silicone Sikasil SG-20, the two-component acrylate SikaFast 5215, and the one-component pressure-curing polyurethane Prefere 6000. When a load was applied on the specimens, the stress distribution was found to be non-uniform along the adhesive bond area. The difference between the maximum stress and the average stress was higher with stiffer adhesives and thinner adhesive layers. That is because, in these cases, the glass-adhesive or wood-adhesive interfaces experienced higher shear stresses, and therefore higher deflections, especially in the wood because of its lower stiffness.

From that experimentation carried out by Blyberg et al. [22], failure in silicone specimens happened mainly by a combination of cohesive failure of the adhesive and adhesive failure at the adhesive-timber interface. In the case of acrylate specimens, it happened by a combination of cohesive failure of the wood or the glass and adhesion to wood. Polyurethane specimens experienced mainly adhesive failure at the adhesive-glass interface and, in some cases, cohesive failure in glass.

Kozlowski et al. [23] designed a timber-glass composite beam using three different adhesives (epoxy 3M DP490, acrylate SikaFast 5221, and silicone Sikasil SG-500) to bond the central glass panel to the top and bottom timber flanges, and two different glass types (annealed and heat strengthened). The specimens were subjected to a four-point bending test. The load at first crack was similar for specimens with epoxy and acrylate adhesives, and lower for specimens with silicone adhesive. Similar results were obtained in terms of bending stiffness: it was similar for beams bonded with acrylate and epoxy adhesives, and lower for beams bonded with silicone adhesive. Using heat strengthened glass instead of annealed float glass led to an increase of strength of 50% in beams made using epoxy and acrylate adhesives, and 20% when using silicone adhesive. In all specimens, the maximal load was higher than the load at first crack, because the timber at the bottom flange limited crack propagation and provided a significant post-breakage load-bearing capacity to the beam.

Ber et al. [23] connected a glass panel to a timber frame using three different adhesives: a two-component silicone Ködiglaze S, a one-component polyurethane Ködiglaze P, and a two-component epoxy Körapox 558. A shear in-plane load was applied on the glass panel with a timber frame. The ultimate load of the specimens of the epoxy group was the highest, and fracture occurred in the glass panel and in the timber frame, but the bond line remained intact. The ultimate load of the specimens with silicon and polyurethane adhesives was less than half of the one in epoxy bonded specimens. Failure with silicon and polyurethane adhesives occurred at the timber frame, cohesive failure of the adhesive, or a combination of both.

4.5.3. Glass-to-GFRP connections

Valarinho et al. [25] studied the adhesion and shear transfer between glass and GFRP through double-lap shear tests. Three adhesive materials were tested and compared: elastic gap-filling polyurethane adhesive (Sikaflex 265), structural polyurethane adhesive (Sikaforce 7710-L100), and structural epoxy adhesive (Sikadur 31-cf). Specimens with Sikaforce and Sikadur presented similar values of strength and stiffness. In these specimens, failure occurred due to breakage of the glass panes, except for two specimens, which presented a premature adhesive failure in all interfaces due to an inadequate surface preparation. In contrast, all Sikaflex specimens had adhesion failure of the glass-adhesive interface, which had the lowest values of strength and stiffness. In a tensile test on the three adhesive materials, Sikaflex displayed the lowest tensile strength and highest deflection (over 30 times higher than Sikaforce and 300 times higher than Sikadur).

Speranzini et al. [14] performed a double-lap shear test and compared the performance of three structural resins (two-component epoxy) as adhesive materials. The authors identified that there was a peak of stress near the edges of the adhesion surface. The difference between the maximum stress, which led to failure of the adhesive, and the average stress, calculated as the applied force divided by the adhesion surface, was bigger in specimens with higher bond length.

This means that in specimens with higher bond length breakage occurred when the average stress was lower. However, despite the reduction of average stress, the maximum load increased with higher bond lengths, because the increase of the adhesive surface was greater than the decrease of average shear stress.

4.6. Discussion

Some of the experimental results obtained in the literature do not match with the ones from the European guidance EUR 26439 EN [2]. According to that standard, epoxy adhesives are stronger than polyurethane, which is as strong as acrylate, and stronger than silicone. Overend et al. [20] tested all these materials and their results were similar to these, except for the case of acrylic adhesives, which were the strongest.

In terms of transparency, according to the standard, epoxy adhesives and silicones have the lowest qualification in transparency. However, Speranzini et al. [14] tested three different epoxy resins, one of which was completely transparent and presented a good structural behaviour compared to the other two. Silicones can also be transparent, like the transparent structural silicon adhesive tested by Santarsiero et al. [34].

Standard EUR 26439 EN [2] gives to acrylates the highest rating in terms of ageing behaviour and UV-resistance, as well as an average value of temperature resistance. However, Machalická and Eliášová [15] tested three acrylates and all of them experienced severe degradation. In fact, one of them (UV-curing acrylate Ritelok UV50) was even considered unsuitable for structural applications because of its weakening and adhesion loss. By contrast, no deterioration of the mechanical properties was observed on polyurethane specimens, which have a lower rating than acrylics in the standard.

The differences between the European standard and some of the results found on the literature may be due to the fact that, each of the adhesives listed (epoxy resins, polyurethanes, acrylates and silicones), are in fact a broad range of materials and additives that may have a significant effect on the listed properties. For example, silicone is rated as the material with the lowest mechanical properties, and this is in line with the experimental results of Overend et al. [20],

However, the European guidance EUR 26439 EN [2] matches with the literature when it establishes that the most adequate adhesive material depends on its intended application. For that reason, the material selection must be made taking into consideration the loading characteristics, the exposure to weathering factors, and the aesthetical requirements, among other factors.

5. Laminated connections

5.1. General overview

In laminated connections, the interlayer material used to bond glass layers together to form laminated glass panels is the same one used to connect laminated glass elements to another substrate. The main advantages of this are that both transparency and adhesion to glass are guaranteed, as well as the capacity to transfer shear loads, since these are basic requirements for the interlayer material to be used in laminated glass.

Laminated connections are mainly used in connections working under shear stresses, such as embedded joints [35], segmented beams [36], or steel reinforcements [37]. However, the use of interlayer materials with higher tensile strength has led to the development of new laminated connections, where the interlayer material is subjected to tensile stress at the connection [4].

The main types of failure for laminated fixings are cohesive failure at the interlayer or the substrate, adhesion loss between interlayer and substrate, or a combination of these. Failure of the interlayer can be either ductile or brittle, depending on its mechanical properties and the working temperature. Most interlayer materials have a ductile behaviour at room temperature, but they can have a stiff and brittle behaviour when working below glass transition temperature.

5.2. Laminated connections materials

There are many different interlayer materials, such as polyvinyl butyral (PVB), ethylene-vinyl acetate (EVA), thermoplastic polyurethane (TPU), and ionomer. However, most of the literature focuses on PVB, which is the most used interlayer for all applications (automotive, glazing, etc.), and SentryGlas, which is an ionomer widely used for structural applications and safety glazing.

The mechanical properties of the interlayer material affect the mechanical behaviour of laminated glass. Serafinavičius et al. [38] made a flexural test on laminated glass specimens with three different interlayers (PVB, EVA, and SentryGlas), and calculated the maximum deflection and maximum tensile stress at the glass panels. Results clearly showed how stiffer interlayers contributed to a more cohesive behaviour of the composite laminate.

5.3. Glass-to-glass connections

Experimental results with different interlayer materials for laminated connections between glass elements were found in the literature. Biolzi et al. [27] performed a double-lap shear test with PVB as adhesive material at different temperatures with a sustained load for an extended period of time. Louter et al. [36] performed a flexural test on glass beams with overlapping glass segments and steel reinforcement.

Biolzi et al. [27] studied and compared the results obtained under different weathering conditions (temperature and relative humidity), with different load durations (from 6 to 40 days). The experimental results confirmed the high sensitivity of PVB to both temperature and load duration: PVB suffered creep in the whole temperature range considered (from -20 ^{o}C to 50 ^{o}C), and its shear modulus was negligible for most applications with long-term loads at temperatures above 30 ^{o}C.

Louter et al. [36] performed a flexural test on beams with overlapping glass segments and steel reinforcement. This system allows obtaining longer glass beams without needing intermediate (opaque) joints. A steel reinforcement was added to prevent failure by creep of the interlayer and to seek a progressive breakage. The results showed that crack initiated at the glass, where there was a seam and therefore the cross section was weakened. Total collapse happened due to the failure of the steel reinforcement.

Serafinavičius et al. [38] performed flexural tests on laminated glass panels using three different interlayer materials: PVB, EVA, and SentryGlas. The test was carried out at different temperatures with a sustained load. The bending stiffness of the panel was lower for softer interlayers (PVB), but it decreased when the temperature increased and when the load duration increased. That is because the interlayer materials are viscoelastic and therefore its mechanical properties are sensitive to these two factors.

5.4. Glass-to-steel connections

Among the literature reviewed, the most common interlayer material for glass-to-steel connections was SentryGlas [4,17, 18,19,22]. SentryGlas is a strong and stiff interlayer material that presents a good level of adhesion to both glass and steel. From the specimens with SentryGlas, it was concluded that the temperature and strain rate variations had important effects on the mechanical response of the connections [17,18,22]: the maximum load increased as the temperature decreased and/or the strain rate increased. In temperatures of 40 ºC and below, the specimens had a linear elastic response up to a brittle cohesive failure of the glass [18,19,22], whereas for temperatures of 50 ºC and above, the material had a plastic behaviour before breakage [18,19], combined with the formation of bubbles in the case of peel tests [22]. In terms of ageing, thermal cycling and humidity had a negative effect on the shear transfer capacity of the SG interlayer [17].

Royer-Carfagni and Silvestri [4] developed a connection design in which the interlayer ionoplast also acted as adhesive material for the connection with a metallic fixing. Besides transferring loads from the glass panel to the metallic fixing, the interlayer connection also prevented direct contact between glass and steel, which would cause premature failure for local peak stresses. The interlayer worked under tensile stress for any out-of plane bending load (Figure 8), both upwards and downwards.

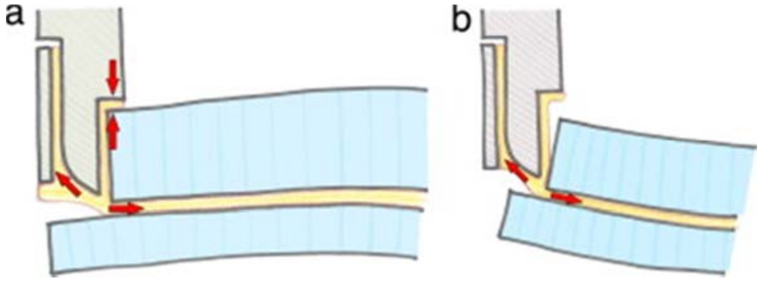


Figure 8. Load transfer from the glass panel to the steel fixing in a three-point bending test for: (a) an upwards bending, and (b) a downwards bending [4].

In that same study, the breakage of the unaged specimens started at the load application point of the glass, where the maximum bending moment was reached. After breakage of both glass plies, the interlayer remained attached to the metallic holder. In terms of mechanical properties, the accelerated ageing and test temperature only affected the tensile condition (downwards bending), because in the upwards bending the load was transferred through compression from glass to steel. The ageing test was divided into three levels: the first one consisted of exposure to xenon arc light for eight days at 63 ºC and two days at 74 ºC, the second one was thermal cycles between -30 ºC and 57 ºC, with a one hour soak at 30 ºC and 95% relative humidity during seven days, and the third one was a repetition of the second. A group of specimens was exposed to the first level only, another to the first and the second, and a last group to all three levels. For aged samples under cyclic loading, failure occurred due to the breakage of the interlayer at the connection region under tensile stress. Tests were carried out at different temperatures ranging from -20 ºC to 50 ºC. A higher peak load was reached with lower test temperatures, but at -20 ºC the breakage of the interlayer was brittle Exposure to UV radiation led to transparency loss, and bubbles and cracks formation in the damaged (exposed) interlayer.

From the studied ageing factors, exposure to temperature variations and humidity were found to be the ones with a higher negative impact on the mechanical properties, with a decrease of over 50% on the ultimate load. Exposure to UV radiation led to transparency loss.

Louter et al. [28] performed a pull-out test on a glass-to-steel laminated connection with SentryGlas interlayer. The tests were carried out at different temperatures, ranging from -20 ºC to 80 ºC. The pull-out strength kept decreasing as temperature increased. The most significant reduction happened above the glass transition temperature of the material, which is, according to the paper, of 55 ºC: the pull-out strength decreased 10% from -20 ºC to 23ºC, 49% from 23 ºC to 60 ºC, and 71% from 60 ºC to 80 ºC. In addition to that, the effect of thermal cycling and exposure to humidity were also tested. Thermal cycling test consisted of 150 cycles of 4 hours each between -20 ºC and 30 ºC. Humidity test consisted of the exposure in air at 50 ºC and 100% relative humidity during four weeks.

Santarsiero et al. [16] performed a shear test on a stainless steel connector bonded to a glass surface. SentryGlas was the interlayer material chosen to create the bond. Shear tests were carried out at different temperatures between -20 ºC and 80 ºC. The results show how the material was very sensitive to temperature changes, with a lower stiffness and maximum load at higher temperatures. The greatest strength and stiffness reductions appeared at high temperatures (larger than 23 ºC). The strength reduction from -20 ºC to 23 ºC was 30%, whereas from 23 ºC to 60 ºC it was 91%. The failure mode changed from adhesion failure in the glass-interlayer interface at low temperatures, to cohesive failure of the adhesive at high temperatures. Three different strain rates were tested (0.1 mm/min, 1 mm/min, and 10 mm/min), and the shear strength increased 30% from the test at 0.1 mm/min to the test at 10 mm/min.

With the same materials and test conditions as described in [16], Santarsiero et al. [19] also performed a tensile test. The mechanical response of the specimens was highly temperature-dependant, and it affected mainly the maximum load and the breakage mode. At 60 ºC maximum load was reduced up to 24% compared to -20 ºC. Between -20ºC and 40 ºC failure was a combination of cohesive failure at the interlayer and adhesion loss at the glass-interlayer surface. At higher temperatures, delamination started with the formation of bubbles, which led to strength decrease and adhesion loss.

5.5. Discussion

PVB and SentryGlas are the most used interlayer materials for laminated connections. SentryGlas is widely used in glass-to-steel connections because of its good adhesion to glass and steel. SentryGlas is stronger and stiffer than PVB, but its mechanical performance is significantly temperature-dependant. For that reason, laminated connections with SentryGlas may be a good option for indoor applications, where thermal fluctuations are much smaller.

6. Conclusions

Among the experimental tests used to evaluate and validate joint designs or adhesive materials, the most commonly used for mechanical fittings are: single-lap shear test, double-lap shear test, in-plane bending test, and out-of-plane bending test. For adhesive connections, the most common experimental tests are: single-lap shear test, double-lap shear test, tension test, and pull-out test.

The parameters considered more relevant to evaluate the performance of a connection for glass elements are its mechanical properties (strength, stiffness, and ductility), and how these are affected by long-term loading, high temperatures, and ageing factors such as UV radiation, humidity, or thermal cycles. Other factors such as the level of transparency, the additional manufacturing required, and the difficulty of the fabrication process must also be taken into account.

The main issue in the case of clamped joints was the in-plane resistance. Friction joints require a certain level of pre-compression to prevent slip of the glass panel, but an excessive pre-compression of the clamp could cause breakage of the glass, the interlayer material, or the inset that prevents direct glass-to-steel contact. In addition to that, in long term applications, the viscoelastic interlayer or the inset material could experience stress relaxation, leading to a reduction of the initial pre-compression of the joint. The stress relaxation issue could be mitigated with stiffer materials replacing the interlayer at the clamp region.

The most common cause of breakage in the case of bolted connections was crack propagation from initial flaws at the borehole surface. That issue made thermal strengthening essential for that type of connections. Bolted connections need more cutting and drilling than clamped or adhesive connections, and all cutting and drilling must be done before thermal strengthening. An option to prevent local peak stresses at the borehole surface is the implementation of pre-loaded bolts, but preloaded bolts are friction joints and therefore have similar problems to the ones displayed by clamped joints.

This research highlighted the importance of an adequate material selection. In the case of mechanical fittings, thermal strengthening of the glass was found to be essential in the case of bolted connections, to increase the tensile strength at the borehole surface. For friction-grip connections, the intermediate material that prevents direct glass-to-steel contact should be strong enough to transfer loads between the two connected elements, flexible enough to redistribute stresses, and provide a high level of friction with both glass and steel to prevent slip.

Adhesive connections solved the problem of local stresses and eliminated the need of glass cutting and drilling, but other problems arose regarding long term loading, working temperature, and ageing. Given the viscoelastic nature of the adhesive materials, they suffered stress relaxation and creep for long-term loads. A significant strength and stiffness reduction was identified at high temperatures, especially above the glass transition temperature [16]. Finally, ageing also affected the mechanical and optical properties of the adhesive. In most cases, ageing led to a decrease of strength, stiffness, adhesion, and transparency (the latter in the case of transparent adhesives only). When UV-curing or temperature-curing adhesives were used, if the curing process was incomplete, exposure to UV radiation and thermal cycles could improve the strength and adhesion of the joint. However, also in those cases an excessive exposure led to degradation of the adhesive material.

It would be desirable that adhesive connections provided a high shear load transfer capacity and that ageing factors, load duration and working temperature had little or no effect on its performance. For instance, Santarsiero et al. [16] performed the same mechanical test on adhesive connections with TSSA and laminated connections with SG, at different temperature ranges between -20 ºC and 80 ºC, and TSSA connections proved more resistant at high temperatures.

A cohesive failure of the adhesive is also the more adequate breakage mode in terms of safety, because it presents higher ductility than glass failure and lower variability than adhesion failure. The two-component adhesives tested by Machalická and Eliášová [15] presented a good level of resistance and cohesive failure of the adhesive under shear loading. The two-component polyurethane adhesive SikaForce 7550, the two-component acrylate SikaFast 5211, and the one-component polyurethane SikaFlex 265also presented a cohesive failure of the adhesive, and no deterioration of its mechanical properties was observed after oxposure to weathering factors.

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References

1. The Freedonia Group, World Flat Glass Industry Study with Forecasts for 2018 & 2023, Study #3212, Cleveland, OH, November (2014)
2. M. Feldmann, R. Kasper, et al., Guidance for European Structural Design of Glass Components Support to the implementation, harmonization and further development of the Eurocodes. Report EUR 26439 EN. Publications Office of the European Union, Luxembourgh, 2014, ISBN 978-92-79-35093-1 (pdf). doi: 10.2788/5523.
3. F. P. Bos, Safety Concepts in Structural Glass Engineering: Towards an Integrated Approach, PhD Thesis. Zutphen, the Netherlands (2009)
4. G. Royer-Carfagni, M. Silvestri, Fail-safe point fixing of structural glass. New advances, Engineering Structures 31 (2009) 1661-1676, doi:10.1016/j.engstruct.2009.02.050
5. M. Haldimann, A. Luible, M. Overend (2008). Structural Use of Glass. Zürich, Switzerland: IABSE-AIPC-IVBH
6. Q.D. To, Q.-C. He, M. Cossavella, K. Morcant, A. Panait, J. Yvonnet, The tempering of glass and the failure of tempered glass plates with pin-loaded joints: Modelling and simulation, Materials and Design 29 (2008) 943–951, doi:10.1016/j.matdes.2007.03.022
7. J. Watson, M. Overend, Q. Jin, W. Lai, Premature Failure in UV-Cured Adhesive Joints, Glass and façade technology research group, University of Cambridge.
8. F. Bernard, L. Daudeville, Point fixings in annealed and tempered glass structures: Modeling and optimization of bolted connections, Engineering Structures 31 (2009) 946-955, doi:10.1016/j.engstruct.2008.12.004
9. Q.D. To, Q.-C. He, M. Cossavella, K. Morcant, A. Panait, J. Yvonnet, Failure analysis of tempered glass structures with pin-loaded joints, Engineering Failure Analysis 14 (2007) 841–850, doi:10.1016/j.engfailanal.2006.11.020
10. J. Watson, J. Nielsen, M. Overend, A critical flaw size approach for predicting the strength of bolted glass connections, Engineering Structures 57 (2013) 87–99, http://dx.doi.org/10.1016/j.engstruct.2013.07.026
11. R.-Q. Feng, J.-H. Ye, Y. Wu, S.-Z. Shen, Mechanical Behavior of Glass Panels Supported by Clamping Joints in Cable Net Facades, International Journal of Steel Structures 12 (2012) 15-24, DOI 10.1007/s13296-012-1002-5
12. A. Panait, Q.-C. He, B. Bary, M. Cossavella, K. Morcant, A coupled experimental and numerical approach to the integrity of friction-grip connections in glass structures, Engineering Failure Analysis 14 (2007) 23–35, doi:10.1016/j.engfailanal.2006.01.001

13. G. Campione, S. Colajanni, G. Minafò, The use of steel angles for the connection of laminated glass beams: Experiments and modelling, Construction and Building Materials 29 (2012) 682–689, doi:10.1016/j.conbuildmat.2011.10.004
14. E. Speranzini, S. Agnetti, M. Corradi, Experimental analysis of adhesion phenomena in fibre-reinforced glass structures, Composites Part B 101 (2016) 155e166 http://dx.doi.org/10.1016/j.compositesb.2016.06.074
15. K. Machalická, M. Eliášová, Adhesive joints in glass structures: effects of various materials in the connection, thickness of the adhesive layer, and ageing, International Journal of Adhesion & Adhesives 72 (2017) 10–22, http://dx.doi.org/10.1016/j.ijadhadh.2016.09.007
16. M. Santarsiero, C. Louter, A. Nussbaumer, Laminated connections for structural glass applications under shear loading at different temperatures and strain rates, Construction and Building Materials 128 (2016) 214–237, http://dx.doi.org/10.1016/j.conbuildmat.2016.10.045
17. B. Van Lancker, J. Dispersyn, W. De Corte, J. Belis, Durability of adhesive glass-metal connections for structural applications, Engineering Structures 126 (2016) 237–251, http://dx.doi.org/10.1016/j.engstruct.2016.07.024
18. J. Dispersyn, J. Belis, J. De Jaegher, Influence of corner and edge distance of adhesive point-fixings for glass structures. Engineering Structures 105 (2015) 174–185, http://dx.doi.org/10.1016/j.engstruct.2015.09.037
19. M. Santarsiero, C. Louter, A. Nussbaumer, Laminated connections under tensile load at different temperatures and strain rates, International Journal of Adhesion and Adhesives 79 (2017) 23–49 http://dx.doi.org/10.1016/j.ijadhadh.2017.09.002
20. M. Overend, Q. Jin, J. Watson, The selection and performance of adhesives for a steel-glass connection, International Journal of Adhesion & Adhesives 31 (2011) 587–597, doi:10.1016/j.ijadhadh.2011.06.001
21. J. Zangenberg, S.H. Poulsen, A. Bagger, H. Stang, J.F. Olesen, Embedded adhesive connection for laminated glass plates, International Journal of Adhesion & Adhesives 34 (2012) 68–79, doi:10.1016/j.ijadhadh.2012.01.003
22. L. Blyberg, E. Serrano, B. Enquist, M. Sterley, Adhesive joints for structural timber/glass applications: Experimental testing and evaluation methods, International Journal of Adhesion & Adhesives 35 (2012) 76–87 doi:10.1016/j.ijadhadh.2012.02.008
23. B. Ber, M. Premrov, A. Štrukelj, M. Kuhta, Experimental investigations of timber–glass composite wall panels, Construction and Building Materials 66 (2014) 235–246, http://dx.doi.org/10.1016/j.conbuildmat.2014.05.044
24. M. Kozłowski, E. Serrano, B. Enquist, Experimental investigation on timber-glass composite I-beams, Challenging Glass 4 & COST Action TU0905 Final Conference (2014)

25. L. Valarinho, J.R. Correia, F.A. Branco, Experimental study on the flexural behaviour of multi-span transparent glass–GFRP composite beams, Construction and Building Materials 49 (2013) 1041–1053, http://dx.doi.org/10.1016/j.conbuildmat.2012.11.024
26. E. Speranzini, S. Agnetti, Flexural performance of hybrid beams made of glass and pultruded GFRP, Construction and Building Materials 94 (2015) 249–262, https://doi.org/10.1016/j.conbuildmat.2015.06.008
27. L. Biolzi, E. Cagnacci, M. Orlando, L. Piscitelli, G. Rosati, Long term response of glass–PVB double-lap joints, Composites: Part B 63 (2014) 41–49, http://dx.doi.org/10.1016/j.compositesb.2014.03.016
28. C. Louter, J. Belis, F. Veer, J.P. Lebet, Durability of SG-laminated reinforced glass beams: Effects of temperature, thermal cycling, humidity and load-duration, Construction and Building Materials 27 (2012) 280–292, doi:10.1016/j.conbuildmat.2011.07.046
29. M. Santarsiero, C. Bedon, C. Louter, Experimental and numerical analysis of thick embedded laminated glass connections, Composite Structures 188 (2018) 242–256, https://doi.org/10.1016/j.compstruct.2018.01.002
30. C. O'Regan (2015) Structural use of glass in buildings (Second edition). The institution of structural engineers. London, United Kingdom: The Institution of Structural Engineers
31. Eckersley O'Callaghan Engineers. Apple Sanlitun. Retrieved from: https://www.eocengineers.com/project/apple-sanlitun-175 (last visit 9 March 2018)
32. Eckersley O'Callaghan Engineers. Apple Soho. Retrieved from: https://www.eocengineers.com/project/apple-soho--110 (last visit 9 March 2018)
33. A.D.Crocombe, Global yielding as a failure criterion for bonded joints, International Journal of Adhesion and Adhesives 9 (1989) 145-153, https://doi.org/10.1016/0143-7496(89)90110-3
34. M. Santarsiero, C. Louter, A. Nussbaumer, A novel triaxial failure model for adhesive connections in structural glass applications, Engineering Structures 166 (2018) 195-211, https://doi.org/10.1016/j.engstruct.2018.03.058
35. C. Bedon, M. Santarsiero. Laminated glass beams with thick embedded connections – Numerical analysis of full-scale specimens during cracking regime. Composite Structures 195 (2018) 308–324, https://doi.org/10.1016/j.compstruct.2018.04.083
36. C. Louter, F. Veer. Experimental research on scale 1:4 models of an 18m reinforced glass beam, part I. Glass Performance Days (2007) 87-92,
37. C. Louter, J. Belis, F. Bos, D. Callewaert, F. Veer. Experimental investigation of the temperature effect on the structural response of SG-laminated reinforced glass beams. Engineering Structures 32 (2010) 1590–1599, https://doi.org/10.1016/j.engstruct.2010.02.007

38. T. Serafinavičius, J.P. Lebet, C. Louter, T. Lenkimas, A. Kuranovas, Long-term laminated glass four point bending test with PVB, EVA and SG interlayers at different temperatures, Procedia Engineering 57 (2013) 996 – 1004, doi: 10.1016/j.proeng.2013.04.126