# Load-Bearing Capacity of Two Transparent Adhesives for Glass Joint under Elevated Temperatures

**Jakub Mareš, Michal Rambousek, Yasmina Boutar, Martina Eliášová**

Department of Steel and Timber Structures, Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic, jakub.mares.3@fsv.cvut.cz

## Abstract

Glass, known for its transparency and widespread use in various building applications, is gaining prominence in load-bearing structural components. The distinctive combination of aesthetic appeal and structural potential is driving innovation in architectural and engineering design, thereby expanding the role of glass beyond its traditional applications. However, the brittle nature of glass presents a significant challenge, particularly with the design and implementation of joints in structural glass elements. This paper focuses on transparent adhesive-bonded joints in glass structures, with particular attention to the influence of elevated temperatures on adhesives and the shear load-bearing capacity of bonded joints. Furthermore, the effect of the wettability of floated glass on bonded joints is also discussed. Experimental research findings on transparent adhesive bonding are presented, featuring pilot tests on two adhesives, Loctite® EA 9455 and Epox® G300, each with distinct viscosities, applied to samples made of standard soda-lime-silica float glass. The shear tests were carried out at room temperature and elevated temperatures of 40 °C, 60 °C and 80 °C. The results demonstrate that the behaviour of bonded glass-glass assemblies is significantly altered in a narrow temperature range proximate to the adhesive glass transition temperatures. This research highlights the importance of selecting adhesives with suitable thermal and mechanical properties for load-bearing glass applications. Stiff adhesives, while offering higher initial strength, induce localized stress concentrations that raise the risk of glass failure. Conversely, ductile adhesives promote more uniform stress distribution but exhibit reduced load-bearing capacity at elevated temperatures. These insights are crucial for advancing the design of bonded transparent structural joints, particularly in high-temperature environments where balancing stress resilience and thermal stability is essential.

## Keywords

Float glass, Transparent adhesive, Elevated temperature, Wettability, Glass transition temperature, Brittle failure, Load-bearing capacity

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# 1. Introduction

The luxurious and transparent appearance of glass has captivated architects and artists for many centuries, making it an essential element in contemporary design and architecture. The industrialisation of the glass manufacturing process has made this originally expensive material more accessible and affordable, and its use has increased significantly in recent decades. It is only natural that glass is being incorporated not only as an aesthetic element but also as a structural material in load-bearing structures.

Glass is characterised by high compressive strength, which became a significant advantage in the 1930s when the first hollow glass bricks were developed. These glass bricks can be considered the earliest glass elements used as primary load-bearing components in construction. (Eskilson, 2018)

As architectural demands evolved and development advanced, engineers faced new challenges in utilising glass in more complex structural roles. Currently, it is possible to observe not only glass elements subjected to compression but also glass plates designed to withstand bending tension.

The tensile strength of glass is lower than its compressive strength, but more importantly, glass is almost perfectly brittle. Brittle materials are defined by an absence of plastic reserve. This implies that in the event of localised stress peaks arising within such materials, there is no localised plastic deformation to dissipate the stress. Instead, the material immediately begins to develop cracks, leading to failure without any warning. This inherent property of brittle materials poses a significant challenge when designing details and joints for load bearing glass structural elements. (Haldimann, Overend, & Luible, 2008)

## 1.1. Types of glass-to-glass joints and properties influencing load-bearing capacity of bonded joints

The most traditional glass-to-glass joints are those with mechanical fasteners. It is well documented that every fixing with a small contact surface is a potential point of stress peaks. Consequently, steel components such as bolts poses a risk of brittle fracture in the glass structure. It is therefore crucial to pay great attention to the design of mechanical glass joints to ensure the smooth stress distribution between the glass and steel components. For instance, a flexible rubber washer, is usually inserted between the glass and the steel components to reduce stress peaks. (Lavko & Kvočák, 2020)

The focus of this work is the second type of glass-to-glass connection, which is adhesive bonding. The mechanical and visual properties of these joints are strongly influenced by the properties of the adhesives used. Adhesives that remain transparent throughout the lifetime of the glass structures can provide a transparent and continuous view of the glass elements, unobstructed by any steel components. Furthermore, if an adhesive with high ductility is used, it can reduce stress peaks and distribute them along the entire length of the joint (Lavko & Kvočák, 2020).

However, the use of adhesives in load-bearing functions gives rise to a multitude of issues. The most significant of these appears to be the effect of temperature on the mechanical properties of joints. With an increase in temperature, the adhesive's stiffness decreases, and when the glass transition temperature of the adhesive is exceeded, the stiffness is significantly reduced. At the same time, the adhesive's strength is reduced. (Boutar , Eliášová, Tichá, & Zikmundová, 2023)

The prediction of the load-bearing capacity of the bonded joint depends on the estimated specific failure mode that occurs. If an adhesive with low ductility and high strength is used, the resulting stress peaks in the glass will cause failure of the joint to begin in the glass. In this case, the load-bearing capacity of the glass joint is dependent mainly on the glass characteristics. This type of failure is generally considered to be undesirable in load-bearing glass structures and is subject to the a number of influences. For a more detailed analysis, please refer to Haldiman et al. (Haldimann, Overend, & Luible, 2008)

In the event of failure in the adhesive layer, this is manifested through one of two mechanisms: cohesive failure or adhesive failure. In the case of cohesive failure, the fracture propagates through the bulk of the adhesive, resulting in the adhesive layer splitting into two distinct segments. In this scenario, it is not possible to observe the initial crack. The adhesive undergoes separation due to exceeding its intrinsic material strength. (Hasheminia, Park, Chun, Park, & Chang, 2019)

In contrast, adhesive failure occurs at the interface between the adhesive and the glass substrate. Here, the crack initiates at the free edge of the bond line and propagates along the adhesive-glass interface. This type of failure is characterised by a loss of adhesion, resulting in the separation of the adhesive layer from the glass surface. (Hasheminia, Park, Chun, Park, & Chang, 2019)

The adhesive strength of the interface between the adhesive and the glass depends primarily on the surface characteristics of the surfaces to be bonded. Such characteristics include the chemical composition of the glass, its wettability with regard to the adhesive, and its surface roughness, among other factors.

Good wetting of surfaces by adhesives is a prerequisite for the formation of strong adhesive bond. In addition, with better wettability of the adhesive on the adherend, the influence of the roughness of the adherend increases. It is clear that the adhesive with better wettability better fills all surface flaws of the glass and, as a consequence, increases the bonded area (*Fig. 1*). This means that if the adhesive has good wettability, the bond strength increases with the surface roughness. On the other hand, if the adhesive has poor wetting of the adherend, the influence of roughness on the bond strength is minimal or none. (Bouška, et al., 2015)

It is evident that the circumstances surrounding a failure may not always be readily apparent. In some cases, a combination of various failure modes may occur. For example, there may be cohesive adhesive failure, or an adhesive failure accompanied by glass failure. Consequently, these combinations should be considered as a third category of failure modes for glass-to-glass bonded joints.

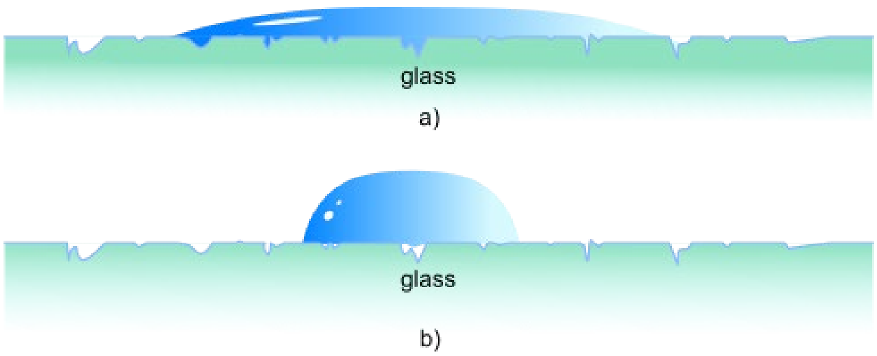



*Fig. 1: Glass surface wettability: a) better wettability and lower static contact angle b) worse wettability and bigger static contact angle.*

Different joining techniques have their advantages and disadvantages. The right combination of different types of joints can enhance their benefits and eliminate their problems (Silva & Öchsner, 2008). For this reason, hybrid joints have been developed. The most common type of hybrid joint is a combination of mechanical fasteners and adhesive (see *Fig. 2*). The adhesive provides smooth distribution of stress field and bolts increase the reliability of the structure at higher temperatures.

*Fig. 2: All glass construction with hybrid joints realised in Old Town Gate in Prague.*

## 2. Materials

Based on previous experiments, two adhesives were selected for further investigation: Loctite® EA 9455 and Epox® G300. Both adhesives are low-viscosity transparent epoxy resins, chosen for their good UV stability over the product lifetime.

Tensile and shear tests were carried out on these adhesives at room temperature and at elevated temperatures 40 °C, 60 °C, and 80 °C. Standard soda-lime-silica glass specimens with a bonded joint on the air-side of the glass plate were prepared for the shear tests.

The term air-side refers to the surface of the glass that was not in contact with the molten tin during the floating process. It is important to differentiate between the air and tin side because the floating process causes a different chemical composition on both surfaces. These surface chemical composition can affect the adhesive strength of the bonded joints. (Boutar , Eliášová, Tichá, & Zikmundová, 2023)

## 3. Tests

### 3.1. Tensile test of adhesives

Tensile tests of the adhesives were conducted on the test specimens, which are shown in *Fig. 3*. The specimens have a thickness of 2 mm and were subjected to uniform tensile load in accordance with the requirements of EN ISO 527. (EN ISO 527-2, 2012; EN ISO 527-1, 2019)

The test results are presented in *Fig. 4*, which illustrates the tensile diagrams with stress-strain relation for both adhesives at various temperatures. A discernible correlation between the mechanical properties and temperature is evident from the tensile diagrams. In addition, the Epox® G300 adhesive shows a significant change in Young's modulus between 40 and 60 °C. The glass transition temperature ($T_g$) of this adhesive was calculated to be approximately 58 °C, as determined from the maximum of loss factor function (tan(δ)). This indicates that when the temperature is altered from 40 to 60 °C, the adhesive transitions from a glassy state to a rubber state, resulting in a reduction in the stiffness of the adhesive.

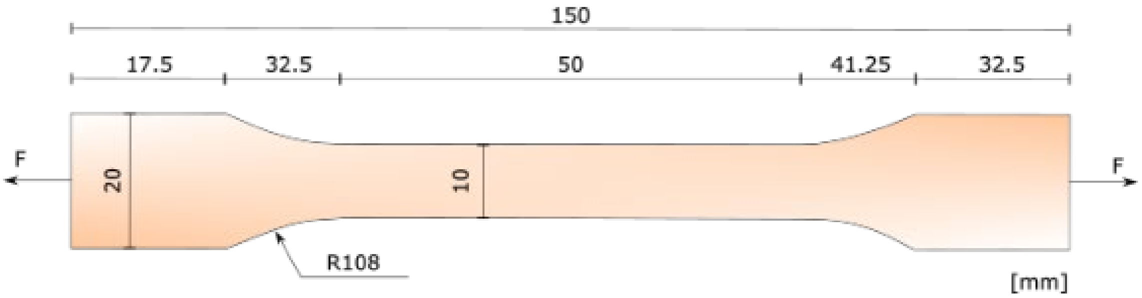
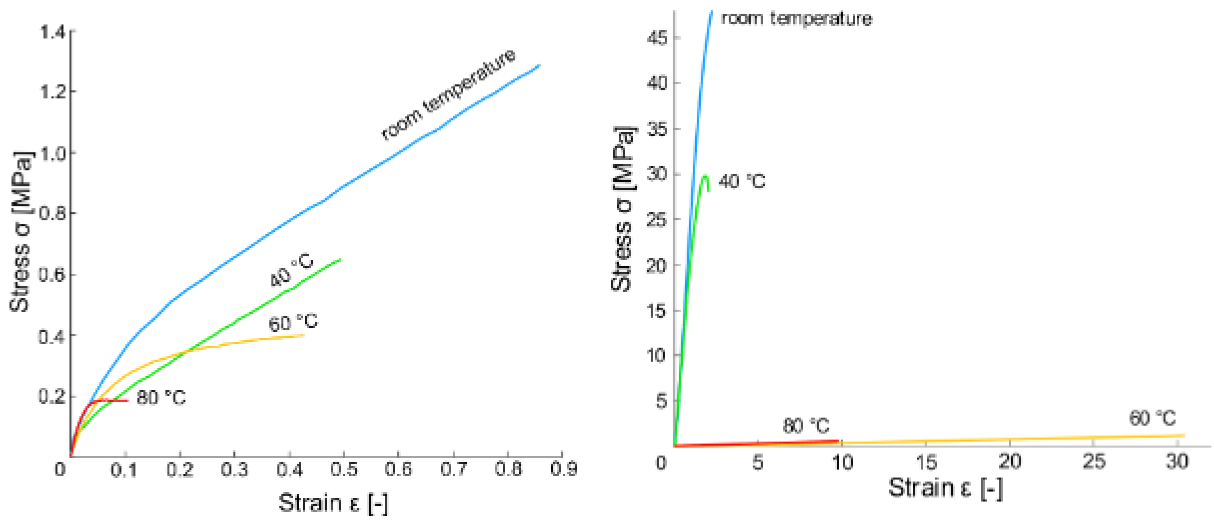



*Fig. 3:Testing specimen for tensile tests.*

*Table 1: Tensile tests results for Loctite® EA 9455 and Epox® G300 at various temperatures.*

| | Loctite® EA 9455 | | | EPOX® G300 | | |
|---|---|---|---|---|---|---|
| | Young's modulus [MPa] | Tensile strength [MPa] | Tensile failure strain [%] | Young's modulus [MPa] | Tensile strength [MPa] | Tensile failure strain [%] |
| RT | 6.63 ± 0.88 | 1.21 ± 0.14 | 85 ± 0.08 | 2375.73 ± 334.89 | 48.72 ± 1.92 | 2.31 ± 0.03 |
| 40 | 5.56 ± 0.23 | 0.68 ± 0.10 | 55 ± 0.09 | 2235.13 ± 243.62 | 30.45 ± 0.69 | 2.10 ± 0.12 |
| 60 | 4.25 ± 0.17 | 0.43 ± 0.06 | 46 ± 0.16 | 3.35 ± 0.03 | 1.01 ± 0.10 | 30.17 ± 1.02 |
| 80 | 4.17 ± 0.80 | 0.23 ± 0.06 | 12 ± 0.04 | 5.06 ± 0.38 | 0.45 ± 0.07 | 9.57 ± 0.60 |




a) b)

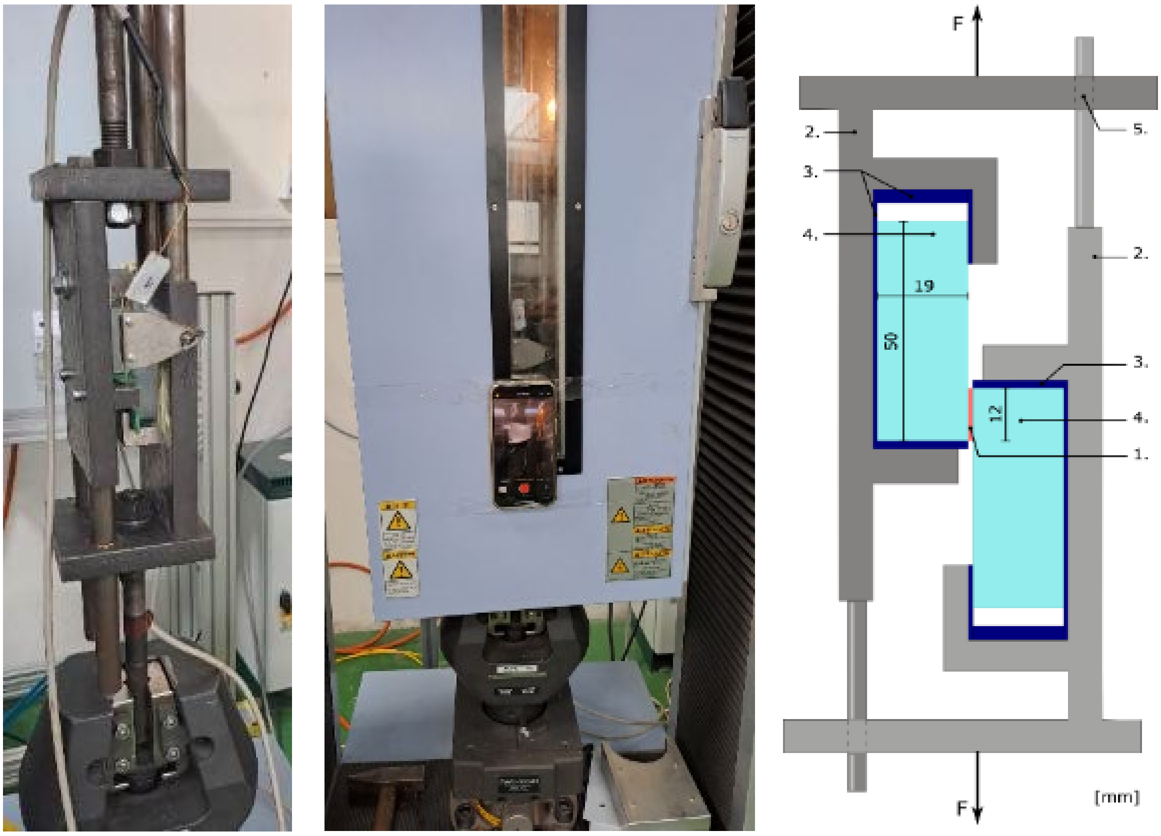
*Fig. 4: Stress- strain relation. a) Loctite® EA 9455 (Boutar , Eliášová, Tichá, & Zikmundová, 2023). b) EPOX® G300.*

Conversely, Loctite® EA 9455 has a glass transition temperature of 36 °C, and jump in Young's modulus between room temperature (around 23 °C (Boutar , Eliášová, Tichá, & Zikmundová, 2023)) and 40 °C is not so notable from tensile tests. This can be attributed to the fact that the room temperature is situated within the glass transition range of the Loctite® EA 9455 adhesive.

Table 1 presents the calculated average values and standard deviations obtained from the aforementioned tensile pilot test. It can be observed that the Young's modulus of the Epox® G300 adhesive is significantly higher at room temperature and 40 °C than that of the Loctite® EA 9455 adhesive. However, after exceeding the glass transition temperature of both adhesives, the values of the Young's modulus are comparable. A similar phenomenon can be observed at tensile strengths, but at maximal strains the values of the Epox® G300 adhesive are lower at each temperature.

### 3.2. Shear tests

The glass cubes, with dimensions of 50 × 50 × 19 mm, were bonded together on the air side with an overlap of 12 mm and with a thickness of 1 mm of the bonded interlayer. Shear tests were carried out on these specimens, as detailed in the test scheme shown in *Fig. 5*. The selection of this loading method was driven by the objective of limiting the tensile stress in the glass and enhancing the probability of failure of the bonded joint, not the glass cubes.

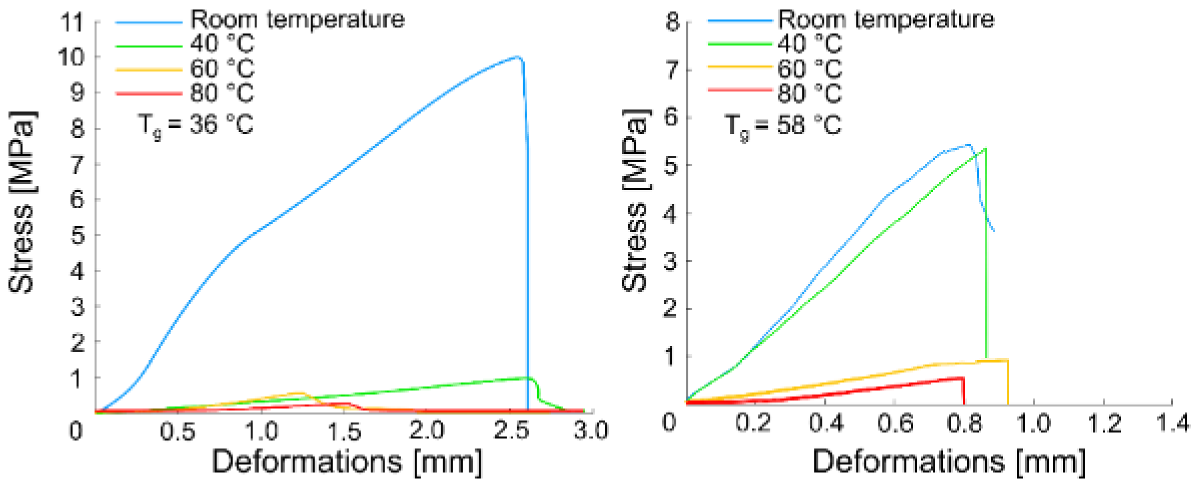



a) b) c)

*Fig. 5: Set-up for shear strength tests: a) Set up without a heat chamber b) Setup with a heat chamber c) Test scheme* (Boutar , Eliášová, Tichá, & Zikmundová, 2023)
*1. Adhesive with a thickness of 1 mm, 2. Steel fixator, 3. Elastic pads, 4. Glass specimens, 5. Slip connection.*

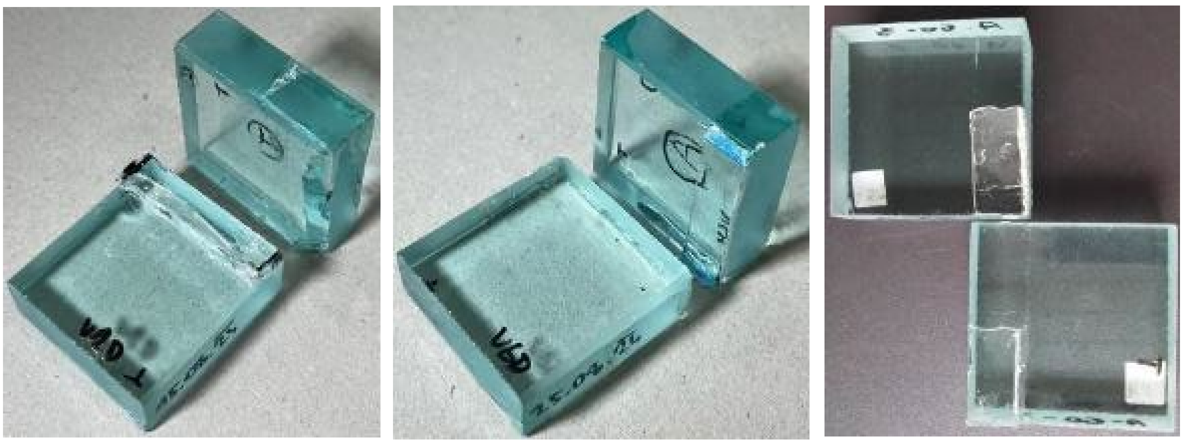
The results of the shear test are presented in Fig. 6 . These figures illustrate the relationship between stress and vertical displacement between glass cubes in the specimen at various temperatures.

Another important phenomenon that has been observed is that despite the higher tensile strength of Epox® G300, the joint with this adhesive achieves lower maximum stresses at room temperature than the joint with Loctite® EA 9455. To fully understand this property, it is necessary to observe the failure modes that occurred in shear tests (see *Fig. 7*). In the tests conducted with Loctite® EA 9455 adhesive, the failure mode observed was a combination of adhesive and cohesive failure of the adhesive (Combined failure), which occurred in all tested temperatures (Boutar , Eliášová, Tichá, & Zikmundová, 2023). In contrast, in tests with the Epox® G300 adhesive, a combination of cohesive glass failure and particular adhesive failure at the glass-adhesive interface was observed (Mixed failure) in six of the seven specimens tested at room temperature. At 40 °C, only two-thirds of the specimens reached the load capacity via the same combined failure mode and above the glass transition temperature, all specimens failed in a pure adhesive failure mode. The occurrence of glass failure in specimens treated with Epox® G300 at room temperature indicates the fact that stiffer adhesives are less effective at distributing stress peaks. This suggests that for a given load, greater stresses are transmitted through the glass in these specimens than in specimens bonded with Loctite® EA 9455, resulting in an earlier failure.




a) b)

*Fig. 6: Shear pilot tests a) results for Loctite® EA 9455 (Boutar , Eliášová, Tichá, & Zikmundová, 2023); b) Shear pilot tests results for Epox® G300.*



*a) b) c)*

*Fig. 7: Observed failure mods: a) Mixed failure; b) Adhesive failure; c) Combined failure (Boutar , Eliášová, Tichá, & Zikmundová, 2023).*

## 4. Conclusions

In order to accurate design and assessment of the adhesive bond, it is essential to correctly identify the critical failure mode of the joint. As evidenced by the tests results and information presented above, determining the most unfavourable failure mode is a challenging discipline. This is because it is influenced not only by the current boundary conditions, such as temperature, but also by the history of the specimen and its individual components. It is important to note that failure can occur not only within the bulk of the glass or adhesive, but also at the interface between them. Furthermore, the load-bearing capacity of a given failure mode may be improved by one parameter, while the same parameter may conversely worsen the load-bearing capacity of another failure mode. To illustrate, the roughness of the glass surface can enhance adhesion between the glass and the adhesive. On the other hand, surface defects represent the locations where stress peaks occur, leading to the deterioration of the load-bearing capacity of glass.

It is clear that the selection of the appropriate adhesive is of fundamental importance in the design of glass bonded joints. The pilot tests described in this paper were conducted with two low viscosity adhesives. The tensile tests of the adhesives themselves showed that there were significant differences in stiffness and strength. The higher strength and stiffness exhibited by Epox® G300 adhesive is accompanied by a lower strain at failure, which is indicative of its greater brittleness. As the shear tests subsequently showed, the higher stiffness and the occurrence of larger stress peaks can fully exploit the advantages of the higher adhesive strength, and a joint with a higher adhesive strength can achieve a lower load-bearing capacity due to a completely different failure mode.

The results of the tests conducted at different temperatures indicate that the frequency of failure in the adhesion mode increases with increasing temperature. This finding is consistent with the observed fact that adhesion loads are diminished at elevated temperatures (Blandini, 2005). Additionally, it has been demonstrated that temperature has a significant effect on the strength and stiffness of both the adhesive itself and the resulting joint. Furthermore, a reduction in the stiffness of Epox® G300 results in a better distribution of stress peaks, which ultimately leads to the cessation of failure in the glass at increasing temperatures.

The temperature dependence of the load-bearing capacity of bonded joints represents a significant limitation in terms of their potential applications. The test results demonstrate that when the glass transition temperature is exceeded, the load-bearing capacity of the joint is significantly reduced. Therefore, it is essential to ensure that the bonded joints are located in areas where this temperature is not exceeded. In glazed façade systems, the temperature can reach considerable heights, and temperature control can make servicing the system very expensive. Furthermore, it is unsuitable to utilise these adhesives in joints that are assessed for fire resistance without implementation of supplementary measures. The enhancement of the reliability of glass-bonded joints through integration with mechanical fasteners offers a potential resolution to this challenge.

Despite the continuing difficulty of engineering calculations for bonded glass joints, their transparent and continuous appearance provides motivation for further research and development in this field. The ability to reduce stress peaks in a brittle material such as glass could offer a decisive advantage over mechanical joints.

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