EXPERIMENTAL INVESTIGATION OF THE DURABILITY OF LOAD BEARING TIMBER-GLASS COMPOSITES UNDER THE EFFECTS OF ACCELERATED AGING

Halet Almila Arda Buyuktaskin,[1]* Mehmet Serkan Yatagan,[1] Gulseren Erol Soyoz,[1] Leyla Tanacan,[1] and Morvarid Dilmaghani[1]

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

ABSTRACT

Although timber was used extensively as a structural material for traditional buildings in Turkey in the past, usage of structural timber decreased significantly over time and timber has been largely replaced by other materials. As timber is a natural, durable and sustainable material, it would be desirable to re-introduce timber structural elements to contemporary construction in a form that is appealing to industry. Timber-glass composite structural elements are potentially a good candidate for this purpose. To that end, a series of tests were conducted on load-bearing timber-glass composites in order to understand the long–term structural performance of the composite material under atmospheric conditions; to decrease the recurring cost of repair and maintenance; and to minimize the exhaustion of raw materials and energy. In this paper, the first part of this experimental work is presented, which focuses on the durability of timber-glass composite under the effects of accelerated aging, carried out on small-sized timber-glass composite specimens. Accelerated aging effects were observed under wetting-drying, freezing-thawing, UV effects, resistance to acids and high temperature. The mechanical strength of the timber-glass composite specimens before and after the effect of accelerated aging was measured by adhesion and shear strength tests and a comparative analysis of the results was carried out. The results of the experiments indicate that timber-glass composite is suitable to be used under protection from environmental conditions.

KEYWORDS

load bearing timber-glass composites, adhesion test, shear test, durability test, aging

1. INTRODUCTION

The use of large-size glass glazing in conjunction with timber has significantly increased over the last decade as the physical characteristics of glass panels have been enhanced and proper integration of timber and glass has a positive impact on the energy efficiency of buildings. The structural utilization of timber-glass load-bearing composites, which are still in early stages of

1. Department of Architecture, Faculty of Architecture, Istanbul Technical University, Taskisla Campus, Taksim, 34437 Istanbul, Turkey
*Corresponding and main author: almila@itu.edu.tr (e-mail), +90 212 2931300 / 2284 (phone), +90 212 2514895 (fax)
ORCID ID: 0000-0003-3950-9018

adoption, is an innovative construction technique with a significant potential of applicability in architecture. Timber with its natural appearance and glass with its transparency can be an appealing combination for architects and occupants of modern buildings. Combined appropriately, timber and glass can form different types of composite elements, such as beams or shear walls that can be included in the load-bearing structural system of buildings. Nevertheless, lack of knowledge on load-bearing timber-glass components limits the potential of these materials' use in buildings.

Timber-glass composites can be utilized as a substitute for steel-glass composites, which have many areas of application such as new construction, additions to existing buildings, and retrofit of historical buildings. Timber-glass composites are one of the new generation of structural composite systems. In addition to the advantages of its constitutive materials, i.e. transparency of glass and natural characteristics of timber, timber-glass composites have further benefits for load-bearing systems, such as being lightweight and therefore enabling smaller timber cross-sections.

The main concerns regarding timber-glass composite are its long-term behavior due to aging and deformations. Due to this reason, a comprehensive investigation of advantages and drawbacks of timber-glass load bearing composites are critically important for potential adoption of this system in the construction industry.

The past twenty years have witnessed a number of research projects in the area of structural glass applications. Linear glass structures, such as beams, fins and pillars [1], as well as glass plates with in-plane and out-of-plane load bearing capacity have been investigated by various researchers [2, 3]. Past research has also focused on two-dimensional timber–glass structures. Several research studies on the combination of glass with timber can be found in the literature. For example, Nicklisch and Weller tested small-scale adhesively bonded timber-glass specimens that were exposed to different aging scenarios [4]. This experimental study evaluated the influence of several ageing scenarios on the strength of adhesives with intermediate and high stiffness. The mechanical strength was determined via tensile and shear tests. At the University of Maribor, experimental research on the analysis of load bearing timber-glass I-beams with silicone adhesive were performed by bending tests [5]. Cruz and Pequeno also studied I-beams with flanges of two separated timber parts [6]. Kozlowski et al. investigated the behavior of load bearing timber-glass composite shear walls and beams. The testing procedures involved various loading conditions: pure vertical load and different combinations of shear and vertical loading. The shear walls were tested to obtain failure mechanisms and buckling loads, while tests on beams were focused on stiffness properties and load bearing capacity [7]. A similar study was carried out by Premrov et al. who conducted an experimental study on racking resistance of prefabricated timber-glass wall elements. The study was on the lateral load bearing capacity of the timber-glass wall element with a two-sided glass sheathing glued to the outer side of the timber frame and a single glass pane placed in the center of the cross section [8].

Past experimental research has shown that the most important parameter to influence the load bearing capacity and stiffness of timber-glass composite elements is the connection between the timber frame and the glass pane [1–3]. The use of adhesives thus opens new possibilities, such as the ability to connect materials with different mechanical properties. By using adhesive joints, a higher bonding strength can be achieved at a lower cost in comparison to alternative methods, e.g. joints with mechanical connectors. One of the major advantages of adhesive joints is that the bonded elements are connected through full sections that are not weakened

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

by holes, and thus the loads are transferred homogeneously over the entire surface rather than a single point [9].

The adhesive that glues the glass to the timber to form a composite element is one of the main parts of the structural system which transfers the load from timber frame to glass panel. It must be sufficiently strong to counteract the transferred load and yet remain flexible enough to accommodate the movement due to differential thermal expansion. It should also perform the task of weather sealing the building against various high-stress environments. The adhesive must not stiffen and lose its elastic properties in extreme cold, or soften and lose its adhesion strength in heat, particularly on southern exposures in warm climates. Furthermore, the bond line that is exposed to full radiation of the sun, either directly (on the edges) or through the glass, must not deteriorate.

The research literature shows some examples of timber-glass bonding connections subjected to variable climate conditions. A study by Cruz and Pequeno [12] presents the results of shear tests on specimens made up of a glass plate fixed between two timber boards involving different types of adhesives. Tests performed under the influence of temperature led to the conclusion that there is a substantial increase of the load bearing capacity when temperature decreases to negative values of –10 °C, while it decreases with increasing temperature up to 40 °C. Another study by Nicklisch et al. [13] assess the aging stability of a silicone adhesive bond between timber and glass specimens exposed to different aging scenarios such as exposure to low or high temperatures and high or low humidity in order to consider the influence of environmental impacts on the adhesive performance. Some specimens were stored at humid conditions (+20 °C, 90% RH), while other specimens were stored at room temperature in combination with low relative humidity (+20 °C, 30% RH). The impact of aging on the strength was evaluated by the results of tensile loading tests. The results reveal a temperature dependent material behavior of the adhesive joint. Compared to the initial values (tensile tests on the specimens at room temperature), the tensile strength increases at a test temperature of –20 °C and decreases for the majority of tested materials at +80 °C. Nevertheless, extreme temperatures are not considered a highly critical impact. In another study by Nicklisch et al. [14], material properties of the adhesives were determined through mechanical testing of the small bonded timber-glass specimens under varying climatic conditions: room temperature, +80 °C, and –20 °C. The results of tension tests show that the fexible 2-component adhesive used in the experiments reveals strong temperature-dependent behavior. A temperature of 20 °C leads to a major increase in stiffness. The results of shear tests show a clear influence of temperature on the failure load. Among different types of adhesives, the stiff epoxies reached the highest shear strength of all tested adhesives at room temperature; the failure strength of specimens was lower when tested at –20 °C. At the same time the strength of all specimens comprised of adhesives with intermediate stiffness improved at low temperatures. Loss of adhesion to the glass occurs at high temperatures with both the epoxy series and flexible 2-component adhesive. Only the specimens with soft silicone adhesives showed cohesive failure of the adhesive in all conditions. A study by Blyberg [1] presents tests on the effect of moisture on the acrylate adhesive bond properties. Two specimen categories were kept in four different climates. The specimens of the first category were kept at 60, 85 and 98% relative humidity (RH) and thereafter taken out and tested. The specimens of the second category were first kept at 98% RH and then dried at 35% RH before testing. The shear strength of 4.65 MPa obtained for the specimens kept in 85% RH does not indicate any significant strength reduction compared to the specimens kept in 60%

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

RH having a shear strength of 4.90 MPa. But, for the specimens kept under higher relative humidity of 98%, their strength was reduced to 3.24 MPa. However, the adhesive bond was not largely affected by the higher relative humidity of 98% exposure after the specimens had been dried None of the specimens failed due to the cohesive failure in the adhesive. Instead, the failure occurred almost without exception in the interface between adhesive and timber. Therefore, it cannot be concluded that the smaller strength obtained for the 98% RH is caused by a reduced strength of the adhesive; it may equally well be due to the reduced strength of timber with high moisture content.

Both the geometry of the bonding line and the type of adhesive have a significant effect on the flexibility of the timber frame and the stress distribution in the glass panel [3]. Therefore, the following parameters influence the long-term performance of the composite under static and dynamic loads: type of adhesive, durability of adhesive, thickness and width of the glue line, and the specific material types of glass and timber. Several ways to attach the insulating glass unit onto the timber frame using adhesive bonding were studied and presented by Schober et al. [10]. In this work, a timber–glass panel consisting of a double insulating glass plate was circumferentially bonded to the timber coupling frame using acrylate and silicone adhesives, which in turn were attached to the main timber frame with self-tapping screws.

Appreciating the potential and aiming to satisfy the future promise of timber-glass composites, a European Research Project as part of the Woodwisdom-Net Research Program has just been completed. The interdisciplinary and international project consortium was formed as a collaboration of various universities, research institutions and industrial partners from Austria, Germany, Sweden, Turkey, Slovenia, Chile and Brazil. The project titled, Urban Wood and under the project acronym LBTGC (Load Bearing Timber-Glass Composite Structures), explored wood-based construction for multi-storey buildings using adhesive-bonded timber-glass composites as load bearing beams, columns, and stiffening panels. Experimental studies formed the leading part of the LBTGC research project, and various load-bearing timber-glass composite structural elements in different scales were tested under selected loading conditions.

As the timber-glass composites are expected to be used as load bearing elements at the façade of the buildings as well as the interior, their behaviour in different atmospheric conditions to withstand the rigors of wear, weathering and other disintegrative influences and their long-term durability are critical concerns when assessing their lifespan.

The objective of the research presented in this paper is to investigate the performance of timber-glass composites experimentally under the accelerated aging agents of atmosphere. This is achieved by monitoring the changes in the mechanical and physical properties of the composites before and after durability tests. A comparative analysis of the test results of small-size specimens were carried out according to the requirements of the standards mentioned in each section below.

These durability tests of the small-sized timber-glass composite specimens constitute the first phase of our experimental research. The method used for the tests also forms a preliminary framework for the analysis and evaluation of the second and third phases of our research, i.e. the testing of the long-term behavior of middle-sized specimens under different seasonal and climatic effects, and the lateral-load testing of full-scale timber-glass shear wall specimens, respectively. The test results obtained in the first phase of the research, which are described in this paper, provided useful guidance for the assembly of the structural elements and were utilized for the structural analysis of the full-scale specimens tested under monotonic and cyclic lateral loading.

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

2. METHODOLOGY

In this study, accelerated durability tests were carried out in order to observe the long-term load-bearing performance of corner joints, which play an important role in transferring loads from timber-glass composite elements designed as shear walls. Bonding details for the contact surface of the structural adhesive were calculated on the basis of both specified transferred loads and the glass width.

In the composite specimens, for a safer breakage performance, tempered glass with a thickness of 8 mm was used. The glass was cut to pre-determined specimen sizes prior to the tempering process, which does not change the surface characteristics of the glass. The adhesive was applied to the surface of the glass where it had contact with air.

Birch plywood was used as the timber part of the composite specimens. Birch plywood generally performs well in applications demanding high strength, rigidity and creep resistance. Eighteen mm thick birch plywood, appropriate to use in the protected external applications, was selected [15]. This type of plywood is in hazard class 2 BS EN 335-3, which can be used behind cladding or under roof coverings, and for interior situations where moisture conditions are above the hazard class 1 level [16]. It is also capable of resisting weather exposure for short periods of time. Plywood panels made of cross-bonded, 1.4-mm-thick veneers were sanded on both sides to achieve a smooth, hard and durable surface. According to BS EN 314-2 [17], each glue line of the plywood has to satisfy two criteria: the mean shear strength and the mean apparent cohesive wood failure for all bonding classes, as given in Table 1.

The adhesive type used in this study to bond the timber (plywood) and glass is two-component silicone, specifically produced for use in wood-glass composite units. It cures at room temperature and has low shrinkage of approximately 4% during vulcanization. It is non-corrosive, UV-resistant, and crack and notch resistant. Its high expansion-tension value guarantees high stability bonding and resistance to water and moisture. Some of the physical and mechanical properties of the silicone given by the manufacturer are listed in Table 2.

TABLE 1. Strength requirements for each glue line of Class 2 plywood (BS EN 314-2).

Mean shear strength f_v (N/mm^2)	Mean apparent cohesive wood failure w (%)
$0.2 \leq f_v < 0.4$	≥ 80
$0.4 \leq f_v < 0.6$	≥ 60
$0.6 \leq f_v < 1.0$	≥ 40
$1.0 \leq f_v$	no requirement

TABLE 2. Physical and mechanical properties of vulcanized silicone sealant (adhesive) [22].

Density at 23 °C	approximately 1.29 g/cm^3
Temperature resistance	–40 °C up to +150 °C
Tensile strength	approximately 2.9 N/mm^2
Tensile expansion	approximately 350%
Stress expansion modulus at 100%	approximately 1.0 N/mm^2

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

In order to determine the effect of durability tests on the timber-glass composite specimens, shear and tensile adhesion tests were performed before (laboratory conditions at 23 C°, 50% RH), and after the durability tests, i.e. wetting-drying, freezing-thawing, resistance to acids and weathering conditions, UV effects and resistance to high temperature. Any change in the weight and deformation of the specimens were also monitored and recorded [11].

2.1 Test methods

The uniaxial tensile adhesion tests were performed only after the freezing-thawing and wetting-drying durability tests. The number of specimens for each test setup is given in Table 3. The timber-glass shear specimens were tested in a single-lap configuration to determine the shear strength.

The shear test specimen was composed of birch plywood with the dimensions of 50 × 60 mm, and tempered glass with the dimensions of 50 × 50 mm. The length of the overlap between the plywood and glass, where the adhesive was applied, was 12 mm, and the thickness of adhesive was 3 mm (Figure 1). The glass and timber surfaces were cleaned with a dry cloth prior to the application of the adhesive. After the production, the specimens were cured in laboratory conditions at 23 °C and RH 50% for seven days. The shear tests were performed with a testing machine with a capacity of 100 kN and with a loading rate of 50 N/s. The specimens were gripped by metals in order to balance the load on the axis of the specimen, coplanar to the bonding surface. The failure loads and failure modes of each specimen were monitored and recorded.

An uniaxial tensile adhesion test was performed to determine the adhesive strength of the composite according to specifications given in BS EN 1348 [18]. Plywood pieces with the dimensions of 50 × 50 mm, were bonded on 450 × 450 mm glass plate by two-component silicone sealant (Figure 2). In the uniaxial tensile test, pull-off headings with 50 mm diameter were attached to the plywood. Tensile force at a rate of 250 ± 50 N/s was applied to the specimen via the pull-off heading (Figures 3 and 4). The maximum tensile forces at failure, and failure modes of each specimen were recorded and evaluated according to TS EN 12004 [19].

TABLE 3. The number of specimens for shear and uniaxial adhesion tests before and after the durability tests.

Test conditions	Number of shear test specimens	Number of adhesion test specimens
Laboratory conditions (23 C°, 50% RH)	6	6
Wetting-drying	6	6
Freezing-thawing	6	6
Resistance to acids (HCl)	3	—
Resistance to acids (SO_2)	3	—
UV effect	6	—
High Temperature	6	—

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

FIGURE 1. Dimensions of shear test specimen give in mm and schematic representation of the shear test apparatus.

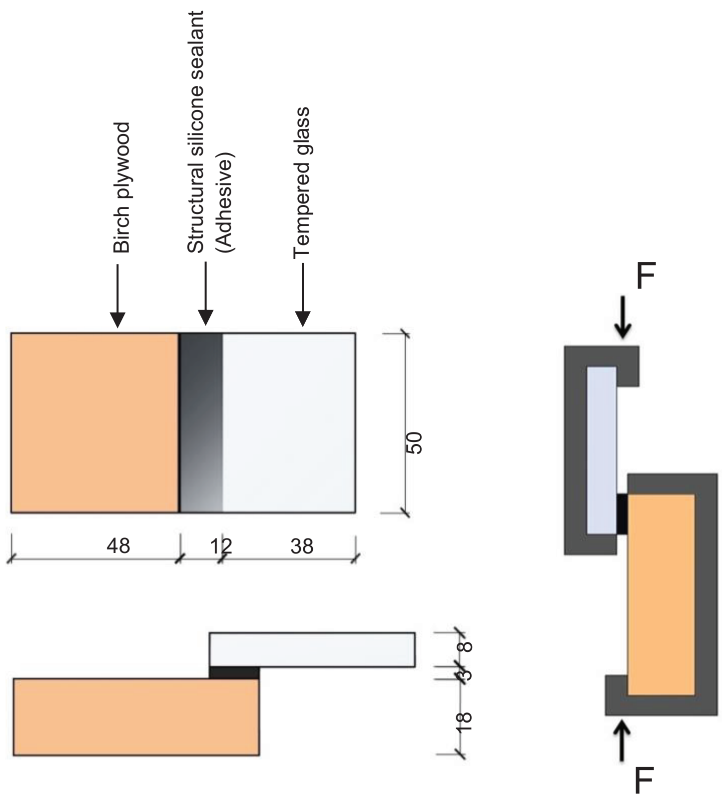
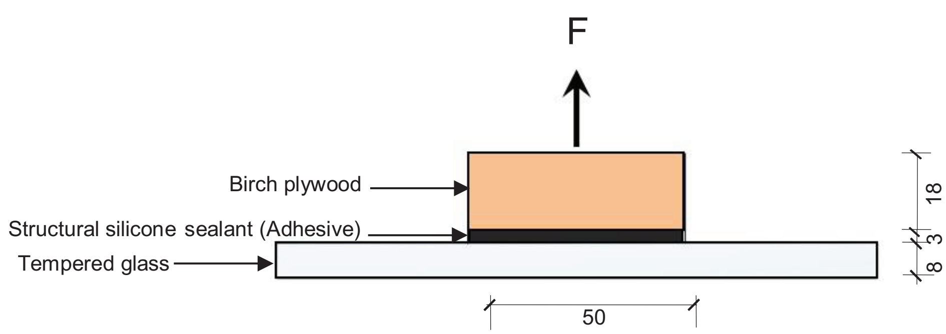


FIGURE 2. Dimensions of adhesion test specimens given in mm.



Wetting-drying, freezing-thawing and UV effect tests were performed in a 225-liter Espec climate chamber. The interior dimensions of the chamber were 750 × 500 × 600 mm and its temperature range were –20 °C to 100 °C. The maximum humidity of the chamber was 100% RH.

For the wetting-drying test, shear test specimens were immersed in 25 °C water for 18 hours and then dried at 50 °C for six hours at each cycle. Seven cycles were completed during the test procedure [16].

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

FIGURE 3. Production stages of adhesion test specimens.

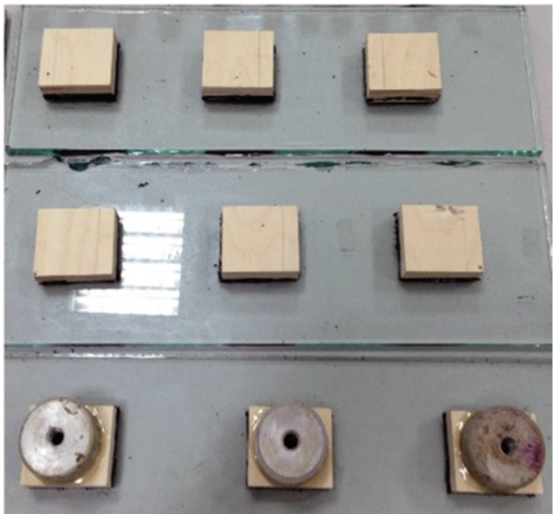


FIGURE 4. Test set-up of the uniaxial adhesion test.

FIGURE 5. The timber-glass specimens placed over the SO_2 concentration.

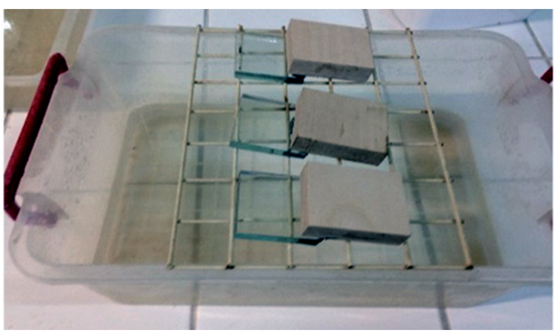
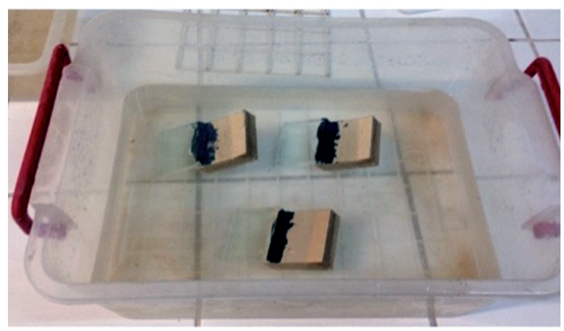


FIGURE 6. The timber-glass specimens in HCl concentration.



For the freezing-thawing test, shear test specimens were cured for 3 days under laboratory conditions at 23 °C and 50% RH. Each freeze-thaw cycle was performed with 18 hours of freezing at –20 °C and 6 hours of thawing at +25 °C; twenty-five cycles were completed during the test procedure [16].

The resistance of the composite to a combination of temperature, humidity and sulphur dioxide was determined by placing the test specimens in a container for 28 days with 5% sulphur dioxide (SO_2) concentration. Sulphurous acid (H_2SO_4) is a solution that contains between a mass fraction of 5% and 6% of sulphur dioxide in de-mineralized or de-ionized water. Three shear test specimens were held horizontally on a frame in the container, approximately 100 mm above the acid solution (Figure 5). The frames were designed in a way that they allowed the acidic vapor to move freely around the specimens. Containers were sealed with a lid. The temperature inside the container was kept at 20 ± 5 °C for the duration of the test. Reference specimens were kept in the desiccator. The specimens were removed from the containers and compared with the reference specimen after 7 and 28 days. Any visually observed changes such as changes in color, splitting, flaking or erosion were recorded.

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

The effect of acids in the atmosphere was measured by placing three timber-glass shear specimens into a water solution with 1% HCl (Figure 6). The specimens were removed from the solution on the 7th day. Their appearance was compared with the reference specimens with respect to their change in color and visual appearance.

The amount of solar radiation is one of the most important factors in the deterioration of polymer-based adhesives during exposure to weathering. The infrared radiation has no direct photochemical effect on the weathering of polymers (although it may affect the temperature of exposed specimens); however, UV wavelength radiation is photochemically active due to the degree of UV radiation exposure and duration. The level of degradation by UV light was evaluated by two methods: with the spectrophotometer measurements using the specifications given in UNI 11259 [20] and with visual examination. An UV effect test was performed to determine the level of degradation of the material after being exposed to ultraviolet light at 23 °C and 50% RH. The effect of sunlight was simulated by fluorescent UV lamps placed within the climate chamber (Figure 7). It should be noted that UV light represents roughly 5% of the sunlight which causes the most polymer degradation.

At the beginning of UV effect tests, timber-glass composite specimens were cured at 23 °C and 50% RH for 24 hours prior to the measurements of colorimetric coordinates of the specimens with the spectrophotometer. Then, the specimens were placed 75 cm below the 400 W UV lamp in the climate chamber and were exposed to UV light for 4 hours. The colorimetric coordinates of the specimens were measured again at the end of the 4 hours of exposure. The specimens were placed under a UV lamp for a further 22 hours and the colorimetric coordinates of the specimens were measured once again. The total duration of the test was 28 days. On the 28th day, the final colorimetric coordinates of the specimens were measured by spectrophotometer. Finally, the photocatalytic property of the material was calculated. As part of the visual investigation, changes in color of the specimens were monitored. The reference specimen was covered with aluminum foil and placed 75 cm below the 400 W UV lamp. After 28 days, any change of color in the specimens was recorded.

Timber-glass shear specimens were also tested to determine their behavior in high temperature according to DIN 4102-1 [21]. The proprietary specifications provided by the manufacturer indicate the temperature resistance of the vulcanized silicone sealant to be 150 °C [22]. After the shear specimens were weighed, they were exposed to 150 °C in the oven until

FIGURE 7. UV effect test in the climate chamber.

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

the thermal steady state had been reached. The soaking time at 150 °C was 30 minutes to keep the specimen in a steady state condition. Afterwards, all the specimens were maintained in the desiccator for slow cooling down and then weighed.

3. RESULTS AND DISCUSSION

3.1 The effect of durability on shear testing

The average values of shear strengths determined for the timber-glass specimens under laboratory conditions and after the aging tests are given in Table 4 together with the observed failure modes. Types of failure modes that were encountered in the tests are shown in Figure 8 (a, b, c, d, and e).

It is observed that the average value of shear strength for the timber-glass specimens tested under laboratory conditions is 0.91 N/mm^2.

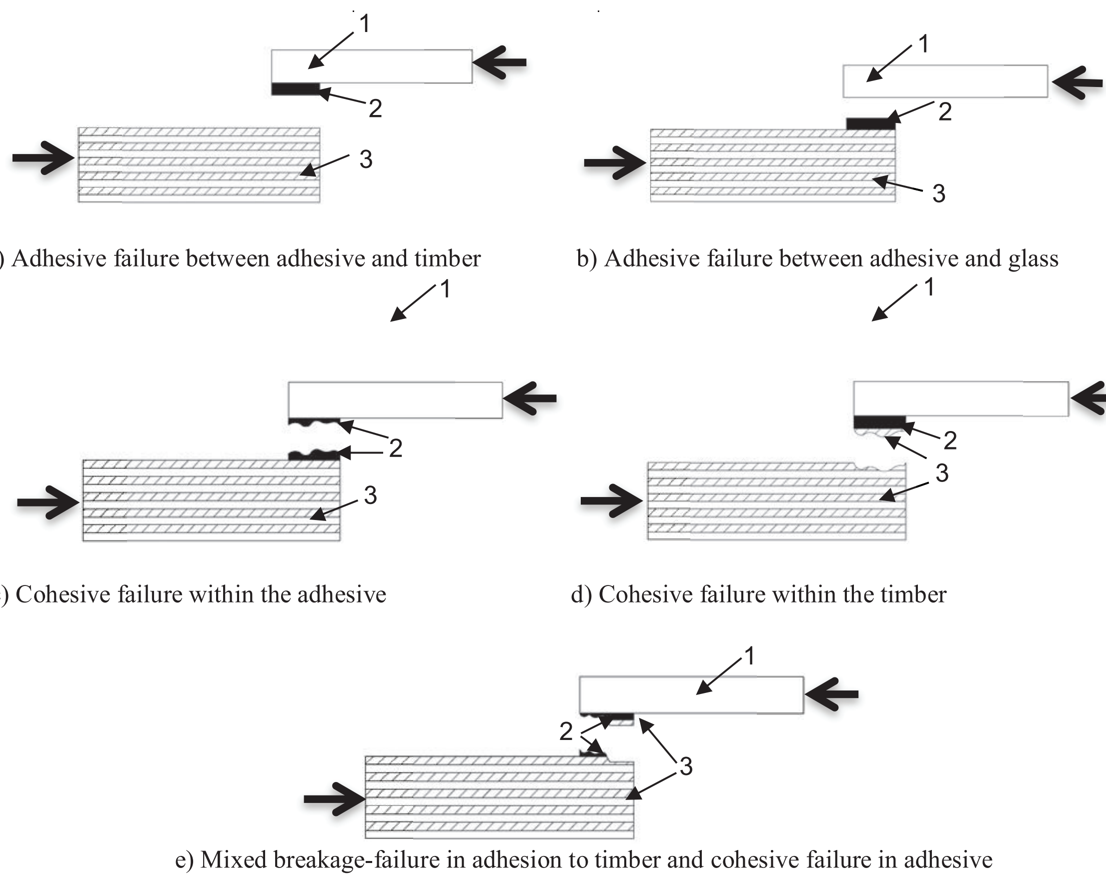
The average shear strength of the specimens directly in contact with HCl solution was 88% lower compared to the original average shear strength of 0.91 N/mm^2. Therefore, the acid test had the most adverse effect on the shear strength of the composite specimens. The failure mode of those specimens is cohesive within the adhesive, i.e. the structure of the adhesive totally degrades due to loss of intermolecular attraction between the molecules.

TABLE 4. Average shear test results before and after aging tests and failure modes.

Test conditions	Average shear strength N/mm^2	Failure modes
Laboratory conditions (23 °C, 50% RH)	0.91	Mixed breakage– Adhesive failure between adhesive and plywood and cohesive failure within adhesive
Wetting-drying	0.54	Mixed breakage– Adhesive failure between adhesive and plywood and cohesive failure within adhesive
Freezing-thawing	0.60	Cohesive failure within adhesive
Resistance to acids (HCl)	0.11	Cohesive failure within adhesive
Resistance to acids (SO_2)	0.43	Mixed breakage– Adhesive failure between adhesive and plywood and cohesive failure within adhesive
UV effect	0.51	Mixed breakage– Adhesive failure between adhesive and plywood and cohesive failure in adhesive
High temperature	0.49	Mixed breakage– Adhesive failure between adhesive and plywood and cohesive failure within adhesive

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

FIGURE 8. (a, b, c, d, e) Failure modes for timber-glass composites, Glass(1)-Adhesive(2)-Timber(3).



SO_2 effect simulates the polluted air which may react with rain to form sulfuric acid. The test results showed that SO_2 does not degrade the adhesive as much as HCl. In addition, no dimensional deformation or discoloring was detected in the specimens exposed to SO_2. The average shear strength of the specimens exposed to SO_2 decreased by 53% in comparison to the pre-test average shear strength of 0.91 N/mm^2. The failure mode was of a mixed type; cohesive within adhesive and adhesive failure between adhesive and plywood. This type of failure was observed after the application of other durability tests as well. All these degrading agents tend to break the bond between adhesive and plywood as well as intermolecular bonds of the adhesive.

Wetting-drying and freezing-thawing tests decreased the shear strength of the specimens approximately 60% with respect to the specimens tested in laboratory conditions. The freezing-thawing test had a higher aging effect on the adhesive bonding capacity compared to the wetting-drying test since the adhesive became brittle because of the freezing effect and lost its elasticity as well as its bonding capacity. Additionally, the top layer of the plywood absorbed water and this condition resulted in bonding failure between the plywood and the adhesive. Test results showed that there was no change in the weight of the specimens. However, the color of the plywood turned darker because of the water that settled in the surface layer of the plywood, deforming the structure by swelling and shrinkage.

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

TABLE 5. Average values of color variations (R at the forth hour, twenty-sixth and final day) of the specimens under UV effect.

	R_4 (%)	R_{26} (%)	R_{final} (%)
Timber-glass specimens	1.90	2.24	–1.62

Concentrated ultraviolet exposure decreased the average shear strength by 44% compared to the pre-test shear strength of 0.91 N/mm^2. The color of the plywood became darker and the color variation values differed from positive to negative (Table 5), which was consistent with observations by visual inspection. Mixed failure mode of loss of adhesion and cohesion of the adhesive seems to indicate that the adhesive may not have adequate residual shear capacity after aging under the UV effect.

As a previous study mentioned, in a research study by Nicklisch and Weller [4], the aging stability of two promising adhesives used to bond small-scale timber-glass specimens was evaluated. All specimens passed through a visual inspection after being exposed to different aging scenarios. This study revealed that an intermediate stiff adhesive composed of silane terminated polymer and epoxy resin exhibit a profound loss of strength and has discoloration after being exposed to UV-light. A two component epoxy provides a better UV-stability. The central part of the joint which is visible through the glass takes on a yellowish to brownish color. It also failed at the boundary to the glass side by near surface cohesive failure in adhesive. The stiffer adhesive exhibit even a full loss of adhesion on the glass surface. This observation indicates a strong influence of UV-radiation on the properties of the joint. Similar to our study, the failure pattern correlates strongly with the findings obtained by visual inspection and the assessment of the strength.

High temperature at 150 °C reduced the average shear strength of the composite by 46% compared to the original shear strength of 0.91 N/mm^2. At the end of the test, it was observed that the glass and timber parts of one of the specimens were separated from each other. The reason for this type of failure can be shrinkage of the timber and/or stiffening of the adhesive. On the other hand, the rest of the specimens showed mixed breakage failures resulting from adhesive failures between the adhesive and the plywood and cohesive failures within the adhesive. This result indicates that the composite must be used cautiously under relatively high temperatures.

3.2 Uniaxial tensile adhesion test

The results of the uniaxial tensile adhesion tests of timber-glass specimens tested under laboratory conditions and after the aging tests of wetting-drying and freezing-thawing are given in Table 6 together with the observed failure modes.

The average tensile adhesion strength of the specimens tested under laboratory conditions is 1.19 N/mm^2. Minimum adhesion tensile strength has to be higher than 0.5 N/mm^2 for reaction adhesives according to TS EN 12004 [19]. The adhesion tensile strengths of the specimens after wetting-drying and freezing-thawing tests decreased by 12% by 13% compared to the original adhesion tensile strength of 1.19 N/mm^2, respectively, both of which are higher than the minimum required value of 0.5 N/mm^2. The larger reduction in strength recorded after the wetting-drying test may be explained as a result of the low resistance of plywood to wet conditions. Thus, it is confirmed that this type of plywood is not suitable for use under direct contact

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

TABLE 6. Tensile adhesion test results before and after aging tests with failure modes.

Test conditions	Average tensile adhesion strength N/mm^2	Failure modes
Laboratory conditions (23 °C, 50% RH)	1.19	Cohesive failure in timber
Wetting-drying	0.93	Cohesive failure in timber
Freezing-thawing	1.04	Cohesive failure in timber

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

with water. As noted previously, Nicklisch et al. [13] performed a similar study that assessed the aging stability of a silicone adhesive bond between timber and glass specimens exposed to different aging scenarios. The tensile tests are used to evaluate the impact of aging on the strength. The results showed that high temperatures, wet conditions or a high moisture content in the timber adherend typically lead to a loss of strength and the increase of adhesive failure on the timber surface. Drying of the bonded specimens generally improves the joint performance.

In summary, all the observed failure modes are cohesive in the timber (Figures 9, 10 and 11). Plywood with its hygroscopic nature absorbs water, resulting in failure in the plywood part

FIGURE 9. Cohesive failure in timber of a specimen tested in laboratory conditions.

FIGURE 10. Cohesive failure in timber of a specimen tested after wetting-drying test.

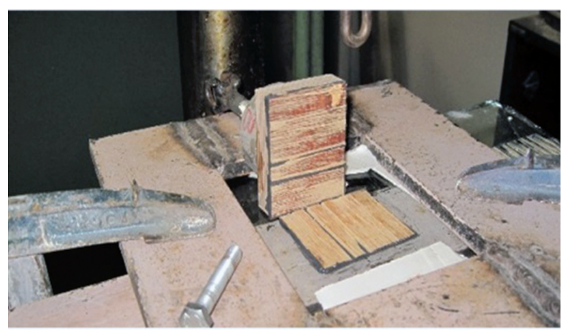
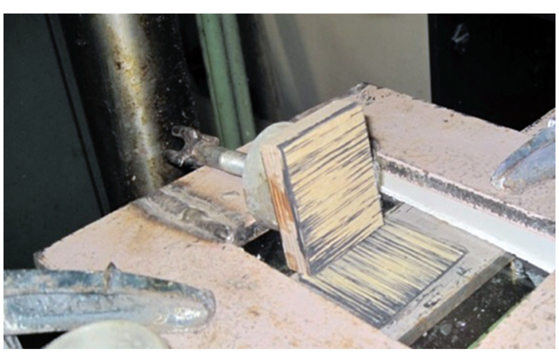


FIGURE 11. Cohesive failure in timber of a specimen tested after freezing-thawing test.



of the composite. After the freezing-thawing test, although the adhesive becomes brittle, the predominant mode of failure is again based on the weakness of the timber, which results in the breakage of the cohesive bonding structure of the timber.

4. CONCLUSIONS

The mechanical properties and durability of timber-glass composite elements were investigated experimentally and the following conclusions were drawn:

- Hydrochloric acid (HCl) and freezing-thawing are determined to be the most important aging agents that adversely affect the properties of adhesive under shear forces. The bonding capacity of the adhesive and the load-bearing capacity of the composite substantially decrease after aging tests compared to the specimens tested under laboratory conditions. As a result, it is recommended that the effects of acids, especially HCl, should be taken into account in the applications of timber-glass composites in industrial and urban zones.
- Adhesive tensile strength of the material is found to depend primarily on the cohesive forces in timber indicating that the silicone adhesive functions better than timber when exposed to aging (freezing-thawing and wetting-drying) agents. Hence, long-term timber behavior is the dominant determinant in the load bearing capacity of the composite.
- Since the adhesive must not stiffen and lose its elastic properties in extreme cold and/or must not soften and lose its adhesion strength in the heat, the freezing-thawing, UV and IR (infrared) effects should be taken into account when timber-glass composite is to be used at cold and particularly on the southern exposure of buildings in warm climates like Turkey.
- It is observed that the timber-glass composite is suitable to be used under protected environmental conditions. If the surface of the timber is protected from water contact, then water related failures of the composite can be prevented.
- Regarding the reduction in shear and adhesion strength of specimens after the durability tests, it is concluded that factors of safety should be introduced for structural design considering each aging condition. It is clear that more experimental work needs to be carried out to be able to propose a factor of safety to be used. Care should be taken in determining the factor of safety for timber-glass composites under HCI effect in particular, due to the significant shear strength loss under this condition.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Scientific and the Research Council of Turkey (TUBITAK) for funding the research project "Load Bearing Glass and Timber Composites" (project no:110O950) which is a part of the international research program WoodWisdom-Net. The authors would like to note that any assessments, statements and opinions presented in this paper solely belong to the authors and should not be in any way considered the official position of TUBITAK. Additionally, we would like to thank our collaborating industrial partners Trakya Cam Sanayi A.S., Turkish Timber Association, and Otto Chemie who were involved in this project.

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

REFERENCES

[1] Blyberg L.: Timber/glass adhesive bonds for structural applications. Licentiate thesis, Linnaeus University, Vaxjö, Sweden (2011)

[2] Močibob D.: Glass panel under shear loading—Use of glass envelopes in building stabilization. PhD, École polytechnique fédérale de Lausanne, Lausanne, Switzerland (2008)

[3] Huveners EMP.: Circumferentially adhesive bonded glass panes for bracing steel frames in facades. PhD, Eindhoven University of Technology, Eindhoven, Netherlands (2009)

[4] Nicklisch F.; Weller B.: Adhesive bonding of timber and glass in loadbearing façades—evaluation of the aging behaviour. World Conference on Timber Engineering, 22–25 August; Vienna, Austria (2016)

[5] Premrov M.; Zlatinek M.; Štrukelj A.: Experimental analysis of load bearing timber-glass I-beam. *Journal of Construction of Unique Buildings and Structures* (2014)

[6] Cruz P.; Pequeno J.: Timber-glass composite beams: Mechanical behaviour & architectural solutions. Challenging Glass Conference 1, 22,23 May 2008; Delft University of Technology, Netherlands (2008)

[7] Kozłowski M.; Dorn M.; Serrano E.: Experimental testing of load-bearing timber-glass composite shear walls and beams. *Journal of Wood Material Science & Engineering* (2016)

[8] Premrov M.; Ber B.; Štrukelj A.: Racking resistance of prefabricated timber-glass wall elements. *Journal of Applied Engineering Science* (2014)

[9] Habenicht G.: *Applied adhesive bonding: A practical guide for flawless results*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA (2009)

[10] Schober KP.; Leitl D.; Edl T.: Holz-glas-verbundkonstruktionen zur Gebäudeaussteifung. Magazin für den Holzbereich, Heft 1, Holzforschung Austria, Vienna, Austria (2006)

[11] Dilmaghani, M.: An Experimental Study On Small Sized Specimens Made of Load Bearing Timber Glass Composites, Master of Sc. Thesis (under the supervision of Asst. Prof. Dr. H. A. Arda Buyuktaskin), Istanbul Technical University, Istanbul, Turkey (2015)

[12] Cruz P.; Pequeno J.: Structural Timber-Glass Adhesive Bonding. Challenging Glass: Conference on Architectural and Structural Applications of Glass. Faculty of Architecture, Delft University of Technology (2008)

[13] Nicklisch F.; Giese-Hinz J.; Weller B.: Glued windows and timber-glass facades—performance of a silicone joint between glass and different types of wood. Engineered Transparency Conference. 20,21 September, Düsseldorf, Germany (2016)

[14] Nicklisch F.; Dorn M.; Weller B.; Serrano E.: Joint study on material properties of adhesives to be used in load-bearing timber-glass composite elements. Engineered Transparency Conference at glasstec. 21,22 October, Düsseldorf, Germany (2014)

[15] BS EN 636-2 'Plywood specifications'.

[16] BS EN 335-3 'Durability of wood and wood-based products'.

[17] BS EN 314-2 'Plywood bonding quality'.

[18] EN 1348: 2007 'Adhesives for tiles—Determination of tensile adhesion strength for cementitious adhesives'.

[19] TS EN 12004: 2007 'Adhesives for tiles—Requirements, evaluation of conformity, classification and designation'.

[20] UNI 11259: 2008 'Determination of the photocatalytic activity of hydraulic binders—Rodammina test method'.

[21] DIN 4102-1: 1998 'Fire behaviour of building materials and elements'.

[22] Ottocoll S 660 Technical Datasheet: Two-component silicone adhesive for timber-glass composite elements (2013)

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access

Downloaded from https://prime-pdf-watermark.prime-prod.pubfactory.com/ at 2025-08-29 via free access