Glass-rigid foam composite for innovative concrete sandwich elements

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Abstract
In building envelopes, sandwich elements with facings made of glass currently require either adhesives or mechanical connectors. The avoidance of any connectors seems to be favorable in terms of resource and energy savings both in production and in building envelopes. The present studies are part of the development of a glass-rigid foam-concrete sandwich element without additional adhesives and mechanical connectors. This paper reports on the structural bond behavior between polyurethane rigid foam and float glass with different surfaces with or without applying a bonding agent. Tensile bond and shear tests show, that a sandblasted toughened glass surface results in cohesive failure of the insulation layer. The two production-related surfaces of float glass are defined as atmosphere and tin side. Both surfaces offer an adhesive failure between the insulation layer and glass. Test specimens of glass and insulation layer without bonding agent show no significant differences between the atmosphere and the tin side. Overall, the test specimens with bonding agents achieve higher levels of adhesive tensile bond and shear strength. Light and electron microscopic studies of fractured surfaces show, that the bonding agent has a significant influence on the wetting and pore formation of the liquid polyurethane.

KEYWORDS
glass, polyurethane rigid foam, sandwich element, shear strength, tensile bond strength

1 | INTRODUCTION

1.1 | State of the art

Building envelopes with opaque glass as the final surface layer combine the requirements of design, durability, and weather protection in facade construction. Panes of opaque, colored, or coated glass suggest themselves as surface layers (Figure 1). Glass also offers the option to use solar power by integrating photovoltaics.

Typical applications in concrete constructions are sandwich wall elements, which comprise a load-bearing shell made of reinforced concrete, an insulation layer made of rigid foam, and a reinforced concrete facing shell fixed to the load-bearing shell by mechanical connectors. The sandwich wall element in Reference 4 combines the conventional build-up with a facing made of glass panes, which are joined to the reinforced concrete facing shell by polymer cement adhesive mortar (Figure 2A).

Lightweight steel-rigid foam sandwich panels, which use a direct bond between steel sheets and a core of polyurethane rigid foam as a proven method, are also often applied in building envelopes. In Reference 5, this structural member has been enhanced by using glass as an additional layer (Figure 2B). The steel-rigid foam sandwich panels are fitted with an additional layer of heat-strengthened glass which is adhered to the steel surface.
However, installing connectors or applying bonded joints are labor and cost-intensive. The technical innovation of the new glass-rigid foam-concrete sandwich element presented, provides load-bearing composite joints, which ensure load transfer only by structural adhesion between the individual layers with no additional adhesives or mechanical connectors for precast concrete sandwich elements. In Reference 9 and the present study, the technical feasibility of a glass-rigid foam sandwich element without adhesives and mechanical connectors is demonstrated by characterizing the composite behavior of glass and freshly applied polyurethane foam.

Furthermore, these first results show the general suitability for application as a facing layer with integrated insulation in sandwich elements with precast reinforced concrete load-bearing shells. In this context, the glass layer requires sufficient tensile bond and shear strength to the rigid foam for various loads, such as dead or wind loads. Therefore, the focus of the tests for the manufacturing process is primarily on the application of the rigid foam to the glass surface. Subsequent investigations include the determination of the tensile bond and shear strength in order to characterize the load-bearing behavior of the composite joint under tensile and shear stress. The mechanical tests are supplemented by microscopic analysis of the glass and rigid foam fractured surfaces.

### 1.3 | Bond between the glass and rigid foam

Due to its constant material properties and surface quality, the investigations of the bond between the glass and rigid foam are done on industrially produced float glass (FG) made from soda-lime-silicate glass with a characteristic flexural tensile strength $f_{g,kk}$ of 45 MPa, and a Young's modulus of 70 000 MPa. As a result of manufacturing in a float process, it has two different surfaces referred to as the atmosphere and tin sides. Sandblasting of one of the smooth sides of the float glass provides the third surface with higher roughness for the study. Thermally toughened glass as heat strengthened glass or toughened safety glass is initially not investigated during the course of this study since the flexural tensile strength of the glass is not relevant for the bond behavior.

Generally, the bond between two solids made by the adhesive is formed through adhesion and through micromechanical interlocking at the interface. The quality of the bond largely depends on the effective surface. Due to the high porosity of the rigid foam, the surface available for load transfer consists of the cut cell walls, the number, and thickness of which can be increased through the use of bonding agents. Increased surface roughness of materials results in an improved bond thanks to a larger contact area and the resulting improved interlocking of the joint partners. However, this requires the rigid foam to match the surface profile of the glass as good as possible. Otherwise, for instance, in the case of gas pockets included in...
recesses, the roughness has the opposite effect owing to the reduction of the structurally effective bonding surface.

Rigid foam insulation materials can be made from expanded polystyrene (EPS), extruded polystyrene (XPS), or foamed polyurethane (PUR). The direct application of expanded polystyrene to glass is only possible at considerable expense with production facilities in the form of an expander and requires the production of metal negative forms which must be integrated into an existing production process. After leaving the extruder, extruded polystyrene exists as a profile strand, the surface of which sets when it leaves the outlet and thus does not allow for a direct bond with the glass surface. By contrast, the process with foamed polyurethane offers a cost-effective and quick option for production, in which liquid polyurethane is applied to one side of the glass panes, sets into the rigid foam through the addition of pore inducers onto the glass surface, and allows for an adhesive bond. The following tests are therefore done with a polyurethane rigid foam.

2 | TEST OF THE COMPOSITE JOINT

2.1 | Production of the glass-polyurethane blanks

For the application of the polyurethane onto the glass surface, the glass panes are integrated into the common process for producing steel-rigid foam sandwich elements. In this process, the raw polyurethane mixture is foamed between two facing sheets made from steel. For the production of the glass-polyurethane test specimen, the glass panes run through the production line on the bottom steel cover plate of the sandwich elements and are coated with polyurethane from above via nozzles according to the representation in Figure 3. Prior spraying of the glass surface with the bonding agent made from methylene diphenyl diisocyanate (MDI) used for the steel-rigid foam sandwich elements is optionally possible. Curing of the liquid polyurethane then occurs within 8 to 12 minutes and requires a rapid outflow of the reaction and process heat. Thin panes of glass with a maximum nominal thickness of 5 mm, which first pass through the preheater in order to ensure the necessary adaptation of the polyurethane to the profile of the glass surface, are therefore used. The automated process with constant process parameters thus allows for the production of uniform test specimens with evenly spatially distributed properties and a homogeneous composite joint with no local faults such as air pockets or variable thickness.

2.2 | Tensile bond tests

2.2.1 | Test set-up and execution

Investigation of the tensile bond strength is done through a centric tensile test based on the test set-up in accordance with to determine the tensile strength of thermal insulation materials in construction. After curing, the test specimens for 48-hours the conditions during the tests are given with a temperature of +25°C and 55% relative humidity. The test program is listed in Table 1.

![Figure 3](image)

**Figure 3** Application of liquid polyurethane on glass surface

![Figure 4](image)

**Figure 4** Test set-up for tensile bond tests on glass-rigid-foam composites

| Glass surface                  | With bonding agent | Without bonding agent |
|-------------------------------|--------------------|-----------------------|
| Atmosphere side               | 5                  | 5                     |
| Tin side                      | 5                  | 5                     |
| Sandblasted side              | 5                  | 5                     |
Figure 4 shows the test set-up. The thickness of the polyurethane rigid foam on the glass pane is 40 mm. Test specimens with a 100 mm by 100 mm bonding surface are produced from the rigid foam. The glass pane is bonded with a carrier plate made from plywood and can therefore be braced against the testing machine. The tensile force is applied to the test specimen on the upper side via a steel plate which is screwed onto a plywood panel glued to the polyurethane rigid foam.

The load is applied displacement-controlled with a rate of 0.5 mm/min until fracture. Testing of the bond between polyurethane and the untreated surfaces of the atmosphere and tin side of the glass and the sandblasted surface is done in three series. The same surfaces, but treated with bonding agent before application of the polyurethane, are tested in three further series. The five test specimens for each one of six surfaces results in a total of 30 tests.

### 2.2.2 Results and analysis

Figure 5 shows the mean values and coefficients of variation for the tensile bond strength \( f_t \) from the five tests each in the individual series for the various glass surfaces. The error indicator marks the scatter range of the individual results with minimum and maximum values of the tensile bond strength. The mean value of the tensile strength of the polyurethane rigid foam \( f_{t,PUR} \) is 0.180 MPa.

The mean value of the tensile bond strengths without bonding agent is 0.018 MPa for the atmosphere side and 0.017 MPa for the tin side. With the bonding agent, the mean values increase to 0.026 MPa for the atmosphere side and 0.036 MPa for the tin side. A positive impact from the tin on the strength can only be seen with the use of a bonding agent. The tin side then has a tensile bond strength which is 38% higher in comparison with the atmosphere side. This difference can be assumed to be significant owing to the comparably low coefficients of variation in both cases.

A significant increase in the tensile bond strengths with mean values of 0.130 MPa without bonding agent and 0.176 MPa with bonding agent can be seen with sandblasting of the surface. The tensile bond strengths significantly exceed the minimum value of 0.080 MPa required in the European guidelines for thermal insulation composite systems. Using a bonding agent, thus achieve approximately the tensile strength of the polyurethane rigid foam. Overall, the use of a bonding agent on all glass surfaces results in higher tensile bond strengths. Additionally, there is less scattering in the individual values for the surfaces treated with a bonding agent.

The cause of failure for the two smooth surfaces is an adhesion failure between the glass and the polyurethane rigid foam in all tests. On the sandblasted surface without bonding agent, the polyurethane rigid foam detaches directly at the boundary layer with residue of a few particles in the depressions in the glass. A combined adhesion and cohesion failure should be assumed. The use of a bonding agent on the sandblasted surface results in a clear cohesion failure.
2.3 | Shear tests

2.3.1 | Test set-up and execution

Based on the test set-up for shear tests according to,18 a double-symmetric test specimen with two exterior 10 mm thick steel sheets is selected corresponding to the representation in Figure 6. To this end, two glass-polyurethane blanks are bonded to the free surface of the glass panes to form a test specimen. The dimensions of the cut rigid foam piece with a thickness of 20 mm are 200 mm in the direction of the force and 100 mm in the width. Installation of the test specimen into the test set-up is done after gluing the two outer surfaces of the rigid foam piece to the steel sheets. The two outer steel sheets are connected to the test machine without constraint by a bolt and a tension plate. The load is applied to the glass pane using a hollow steel profile arranged above the glass pane. Elastomer strips between the hollow steel profile and the glass pane should prevent the edge of the glass from breaking.

Two inductive displacement transducers measure the relative displacement between the steel sheets and the glass. The load is applied displacement-controlled with a rate of 0.5 mm/min until fracture. In analogy to the tensile bond tests, the smooth surfaces of the atmosphere and tin side and the sandblasted surface are each tested with and without a bonding agent. After curing, the test specimens for 48 hours the conditions during the tests are given with a temperature of +25°C and 55% relative humidity. The test program of the total of 30 tests is listed in Table 2.

2.3.2 | Results and analysis

Figure 7 shows the mean values and coefficients of variation for the shear strength \( f_s \) of each of the five tests of the individual series for the various glass surfaces as well as the mean value of the shear strength \( f_{s,PUR} \) of the polyurethane rigid foam at 0.188 MPa. The error indicator marks the scatter range of the individual results with minimum and maximum values of the shear strength.

For test specimens with the composite joint on the atmosphere side of glass the shear strength cannot be increased by using a bonding agent. At 0.101 MPa without bonding agent and 0.095 MPa with bonding agent, the mean values of the shear strengths are not significantly different. However, the significance of the results with bonding agent is reduced by the high coefficient of variation of 28.2%. Test specimens with a composite joint on the tin side of glass show increased shear strength due to the use of bonding agent, resulting in 89% of the shear strength \( f_{s,PUR} \) of the polyurethane rigid foam.

Similar to the tensile bond tests, the profiling of the glass surface using sandblasting results in improved bond behavior between the glass and the rigid foam. The mean value is 95% of the shear strength \( f_{s,PUR} \) of the polyurethane rigid foam without bonding agent, and 97% with bonding agent. A significant difference between the sandblasted surfaces with and without bonding agent cannot be determined since the load-bearing capacity of the composite joint is limited in both cases by reaching the material strength of the polyurethane rigid foam.

For the atmosphere and tin sides without bonding agent a predominantly adhesive failure is identified. However, isolated planar polyurethane rigid foam residues are found on the glass surface, which means that a partial cohesive failure can also be assumed. The percentage of residues on the glass surface is smaller on the atmosphere side than on the tin side. The surfaces of the tin side with bonding agent and the sandblasted surface with and without bonding agent indicate a cohesive failure in the rigid foam.

3 | MICROSCOPIC STUDY OF THE FRACTURED SURFACES

3.1 | Electron micrographs and image analysis

The quality of the bond depends on the chemical, geometric, and mechanical properties of the surfaces of the bonded parts, among other things.14 Analysis using scanning electron microscopy is used to study the surface structure of the polyurethane rigid foam. Computer-aided image analysis of the surfaces with regard to the number of pores and the pore area as well as the area of the effective cell walls
for the transmission of tensile and shearing forces is also done in order to demonstrate a possible connection between the bond strengths achieved and the surface structures of the polyurethane rigid foam in the composite joint.

Image analysis is carried out separately on the tensile bond test specimens that failed purely adhesively for the atmosphere side and the tin side in each instance with and without bonding agent. Owing to the cohesive failure in the polyurethane rigid foam, the sandblasted surfaces could not be analyzed. Figures 8 and 9 show images of the surfaces of the polyurethane rigid foam produced with the scanning electron microscope.

The results of the image analysis are summarized in Table 3. It is shown, that the bonding agent has a significant effect on the total pore surface and the number of pores in the composite joint. The surfaces with bonding agent have a higher wetting and therefore have a lower total number of pores and a larger effective remaining area for the transmission of tensile and shearing forces. No positive impact of the tin side without bonding agent can be seen in the image analysis. On the basis of the image analysis, a clear connection can be seen between the available bonding surface and the resulting bond strength and confirms the results of the tensile bond tests and the shear tests on the tin side. The mean value for the shear tests on the
FIGURE 9  Top: Polyurethane rigid foam debonded from the tin side without bonding agent, bottom: Polyurethane rigid foam debonded from the tin side with bonding agent; images on the left side are from the scanning electron microscope and the right side shows the associated contrast images.

TABLE 3  Results of image analysis for a typical image section

| Parameter          | Atmosphere side |             | Tin side                          |             |
|--------------------|-----------------|-------------|-----------------------------------|-------------|
|                    | Without bonding agent | With bonding agent | Without bonding agent | With bonding agent |
| Number of pores    | 82              | 141         | 66                               | 125         |
| Medium pore area   | 7216 μm²        | 2085 μm²    | 9323 μm²                         | 2142 μm²    |
| Total pore area    | 0.592 mm²       | 0.294 mm²   | 0.615 mm²                        | 0.268 mm²   |
| Image detail area  | 1.238 mm²       | 1.238 mm²   | 1.238 mm²                        | 1.238 mm²   |
| Remaining area     | 0.646 mm²       | 0.944 mm²   | 0.622 mm²                        | 0.970 mm²   |
| Pore fraction      | 47.8%           | 23.8%       | 49.7%                            | 21.6%       |
| Remaining area fraction | 52.2%          | 76.2%       | 50.3%                            | 78.4%       |
atmosphere sideshow a value which is 6% lower with bonding agent than without bonding agent. However, the coefficient of variation, at 28.2%, is relatively pronounced in comparison with the other results and shows a trend toward higher strengths in the individual results. It can therefore be assumed, that the connections from the image analysis with a higher number of test specimens also prove true for shear tests on the atmosphere side.

3.2 Element detection on the surfaces of the glass and polyurethane rigid foam

Detection of the elements present on the surfaces of the bonded parts is done in order to analyze the chemical effects of the bond. The method used allows for characterizing these elements on the surface by occurrence and frequency. The mass fractions of the selected elements on the glass surfaces are summarized in Table 4. On the tin side, there is a mass fraction of 1.06% of tin. No tin is found on the atmosphere side.

By detecting tin on the surface of the detached rigid foam, a possible chemical bond between tin and polyurethane or the bonding agent is to be tested. However, the results of the analysis indicate no traces of tin on the rigid foam surface. Table 5 shows the elements on the rigid foam surface detached from the atmosphere and tin sides by mass fraction. Methylene diphenyl diisocyanate (MDI) forms long-chain macromolecules with polyurethane at the temperature of +55°C used for manufacturing the glass-rigid foam blanks. As a result, in addition to the wetting of the glass surface, the bond improves due to the increased Van der Waals forces between the glass and the rigid foam. In accordance with Reference 11, more close-meshed interlinking of polymer macromolecules results in a higher carbon content and thus to greater molecular forces directly at the interface between the polymer and the component to be bonded. In accordance with Reference 11, tin has a catalytic effect in the formation of polymers and encourages bonding between rigid foam and glass by reducing the bonding energy required. As a result, a more close-meshed interlinking of the macromolecules occurs at the same process temperature. For instance, the use of the bonding agent results in a higher carbon content on the tin side with 78.83% than on the atmosphere side with 76.06%. The detection of higher carbon content on the rigid foam detached from the tin side suggests a closer meshed interlinking of the macromolecules and thus an increase in the Van der Waals forces responsible for bond. This results in higher strengths on the tin side.

| Table 4: Mass fractions of the elements detected on the two glass surfaces of the atmosphere and tin side |
| --- |
| **Element** | **Mass fraction** |
| **Atmosphere side** | **Tin side** |
| Oxygen (O) | 43.98% | 43.10% |
| Sodium (Na) | 12.25% | 12.00% |
| Magnesium (Mg) | 2.69% | 2.31% |
| Aluminum (Al) | 0.67% | 0.38% |
| Silicon (Si) | 33.54% | 33.78% |
| Calcium (Ca) | 6.87% | 7.37% |
| Tin (Sn) | 0.00% | 1.06% |

| Table 5: Mass fractions of the elements detected on the surfaces of the debonded polyurethane rigid foam |
| --- |
| **Element** | **Mass fraction** |
| **Atmosphere side** | **Tin side** |
| Carbon (C) | 76.06% | 78.83% |
| Oxygen (O) | 20.34% | 20.34% |
| Aluminum (Al) | 0.12% | 0.00% |
| Phosphorus (P) | 0.66% | 0.12% |
| Chlorine (Cl) | 2.81% | 0.71% |

**Figure 10** Fracture pattern of shear test on the atmosphere side of glass. Left: Polyurethane rigid foam on the glass surface without bonding agent. Right: Surface of the detached polyurethane rigid foam.
side in comparison with the atmosphere side and confirms the results of the tensile bond and shear tests.

3.3 Light micrographs of the fractured surfaces

The quality of the fractured surfaces of test specimens, which demonstrate extensive polyurethane rigid foam residue on the glass surface, indicates a combination of adhesive and cohesive failure and are therefore studied under light microscope. Figures 10 and 11 show the polyurethane rigid foam adhering to and detached from the glass surface with and without bonding agent after the shear test. The smooth glass surface without bonding agent has a thin layer of residue with large pores and thin cell walls. The analog surface with bonding agent has a thicker layer of residue with pores which are still closed. This correlates with the results from the preceding electron micrographs. The use of bonding agents results in less pore formation directly at the boundary with the glass. The pores in the fractured surface initially appear to be smaller but are actually just less cut.

FIGURE 11 Fracture pattern of shear test on the tin side of glass. Left: Polyurethane rigid foam on the glass surface without bonding agent. Right: Surface of the detached polyurethane rigid foam

FIGURE 12 Schematic illustration of different pore formation without and with bonding agent in the boundary layer between glass and polyurethane rigid foam

4 CONCLUSION AND OUTLOOK

The studies are aimed at the realization of a load-bearing composite joint between glass and polyurethane rigid foam without additional adhesives or mechanical connectors and its characterization through tensile bond and shear tests. To this end, polyurethane rigid foam is applied, with and without bonding agent, to the atmosphere and tin sides of smooth float glass surfaces and float glass surfaces produced through subsequent sandblasting. The use of a bonding agent results...
in higher tensile bond and shear strengths on all glass surfaces. Workable results are achieved for surfaces roughened through sandblasting which, in principle, allows for a composite joint with no additional connectors with and without bonding agent and which achieve the thresholds defined in Reference 11 for a thermal insulation composite system without mechanical attachment.

The positive impact of the profiled glass surface on the bond strength is demonstrated by light and electron microscopy. The use of methylene diphenyl disocyanate (MDI) as a bonding agent is likewise beneficial since this results in a larger effective bonding surface. The scattering of the bond strength of the surfaces treated with bonding agent is lower. This can be attributed to a more even formation of the pore structure in comparison with surfaces without a bonding agent. Here, the bonding agent significantly affects the geometry of the pores directly at the boundary between the two materials to be bonded, that is, glass and polyurethane rigid foam. If the polyurethane is applied without bonding agent, large, thin-walled pores occur which develop a smaller effective surface for the transmission of tensile and shearing forces. The use of bonding agents results in smaller pores with significantly more polyurethane between the cut pores and thus increases the effective bonding surface. The different pore structures are shown schematically in Figure 12. The thicker cell walls at the boundary result in a cohesive failure in the rigid foam and explain the higher tensile bond strengths in comparison to smooth surfaces with adhesive failure. The image analysis of the electron micrographs correlates very well with the results of the tensile bond and shear tests in this respect.

Figure 13 shows a prototype of the glass-rigid foam-concrete sandwich element with and without bonding agent between the glass and the polyurethane rigid foam. In a later application, the glass is not transparent but opaque due to coloration or coating. A definitive assessment of the behavior of the bond between glass and polyurethane rigid foam under climatic, chemical, and physical stress conditions, under mechanical strain from dynamic, cyclical, and permanent loads, and of the fire behavior requires further testing. Detailed review and parameter study on the bond of various types of rigid foam and concrete can be found in References 7 and 8.

ACKNOWLEDGMENTS
The results of this research are based on a joint venture between the Chair of Structural Design and the Chair of Structural Concrete. The project was financially supported by Universität Siegen. Special thanks go to the co-operation partners Karl Bachl GmbH & Co. KG from Röhrnbach, Germany, Fischer Profil GmbH from Netphen, Germany, and Weiss Chemie + Technik GmbH & Co. KG from Haiger, Germany for providing numerous test specimens and friendly support.

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How to cite this article: Weimar T, Hammer C, Leutbecher T, Metje K. Glass-rigid foam composite for innovative concrete sandwich elements. Civil Engineering Design. 2021;3:3–12. https://doi.org/10.1002/cend.202000010

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