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Experimental testing of load-bearing timber–glass composite shear walls and beams

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Abstract
The paper presents results from the experimental testing of load-bearing timber–glass composite shear walls and beams.

Shear wall specimens measuring 1200×2400 mm^2 manufactured with three adhesives of varying stiffness were tested. Twelve specimens with a single 10 mm thick glass pane and one specimen with an additional insulating glass unit were produced. The testing procedures involved various loading conditions: pure vertical load and different combinations of shear and vertical loading. The test results showed that the adhesive had only a minor influence on the buckling load which was the main failure mechanism.

240 mm high and 4800 mm long timber–glass beams manufactured with adhesives of different stiffness were tested. For the webs, two types of glass were used: annealed float and heat-strengthened glass, in both cases 8 mm thick panes were used. In total, 12 beams were tested in four-point bending until failure. Despite the considerable difference in adhesive stiffness, beam bending stiffness was similar. Concerning load-bearing capacity, the beams with heat-strengthened glass were approximately 50% stronger than the beams made using annealed float glass.

Keywords: *Structural glass, timber–glass composites, shear wall, beam, finite-element analysis.*

1. Introduction

In modern architecture glass is being used to an ever-increasing degree to create open spaces and to create indoor environments with natural light. Glass can also be used to create energy-efficient solutions, provided high-performance insulating glass units (IGUs) are used and the positioning of larger glass areas is based on relevant sun light considerations.

From a structural point of view, the increased use of glass in buildings provides a challenge to the structural engineer: glass façades or interior walls are not structural in the sense that they provide no stabilizing or load-bearing capacity for the building. The stabilizing capacity needed to handle horizontal loading (wind loads) must in such cases be managed by other structures than the façade itself. This adds to the complexity of the structure, it adds to the cost and it can also counteract the architects' intentions of lightness and transparency.

The intention of using timber–glass composite wall elements is to overcome this shortage by combining the façade requirements with a load-bearing structure. Timber–glass composites make use of the most favorable properties of timber and glass while avoiding their respective weaknesses. The advantageous properties include transparency, stiffness and strength for glass and the ductile nature of timber when used under compression. By combining these materials with suitable structural adhesives, brittleness – the main drawback of glass – can be avoided. Moreover, the use of bonded connections reduces unfavorable stress peaks in glass which are typical for mechanical connectors such as bolts.

First examples of timber–glass composites were presented in mid- and late 1990s (Stiell *et al.* 1996, Schmid *et al.* 1998) when the glass was glued onto wooden frames. The idea was primarily the use of glass in structural timber constructions as a load-bearing and stiffening element. More detailed research on actual load-bearing beams and shear walls was made by Hamm (2001). The research included an investigation of the load-bearing capacity

of timber–glass beam and plate elements bonded using a polyurethane adhesive.

Kreher (2004) dealt with timber–glass composite I-beams using glass as a web, which were deployed in a building project in Switzerland in 2002. The load-bearing mechanisms of timber–glass composite beams are as follows: in the uncracked state (referred to as *State I*), the glass web mainly carries the external loading and makes a larger contribution to the bending stiffness. In the cracked state (referred to as *State II*), cracks in the glass web occur but are stopped since the tensile forces are transferred to the wood flanges, thus bridging the crack. Hence the wooden flanges serve as reinforcement of the glass web and, if properly designed, contribute considerably to the ductility of the beam.

Various cross-sections for timber–glass beams were tested and compared by Cruz and Pequeno (2008). Serviceability Limit State (SLS) was there defined as the occurrence of the first crack while Ultimate Limit State (ULS) was defined by the reaching of final failure (where the load level might be below the maximum load level). With this approach, a high safety margin is reached.

Edl (2008) performed tests on small glass–timber specimens and tests on shear walls with silicone and acrylic adhesives, varying cross-sections and the mounting to the main structure. The shear walls were loaded pointwise (no vertical restraint on top), the vertical tension force being taken by steel anchors attached to the corner. Hochhauser (2011) studied, in a four-point bending test, a continuous glass web split into six individual glass panes which were connected with wooden elements using adhesives. In the system, the glass elements act as shear elements with compression diagonals (provided blocking elements are used in the corners).

Blyberg and Serrano (2011) and Blyberg *et al.* (2014) investigated composite beams and shear walls, in both cases with the timber flanges being made from two separate parts on either side of the glass pane (direct loading of the glass pane).

The studies presented herein relate to studies performed at Linnaeus University within the European WoodWisdom-Net research project *Load Bearing Timber Glass Composites* (LBTGC, 2012–2014). In contrast to most previous research described above, these studies were focused on using stiff adhesives for beams and shear walls (Kozłowski *et al.* 2014, Dorn *et al.* 2014a, 2014b). For reasons of comparison also flexible adhesives were used but to a lesser extent.

The aim of the paper is to show the capability of timber–glass composites and behavior under loading. Moreover, failure modes, influence of adhesives and glass type used (only for beams) are of interests.

2. Materials

2.1. Glass

Soda-lime silica glass (annealed glass) is the commonly used glass type in the building industry. It shows isotropic and almost perfectly elastic behavior until failure. Glass breaks in a highly brittle manner and does not show any plastic behavior, making it very susceptible to stress concentrations. The strength of glass depends on various parameters such as surface and edge quality, element size, duration of load, environmental conditions and the level of residual stress. The characteristic bending strength is typically 45 MPa, and characteristic stiffness typically 70 GPa.

The strength of glass can be improved by a tempering process, introducing residual compressive stresses at the surface by heat treatment followed by cooling, and hence reducing the risk of cracks forming under load. Depending on the level of the surface residual stress, heat-strengthened and fully tempered glass can be obtained. The fracture pattern of glass is highly dependent on the level of residual stress. Annealed float glass breaks into large fragments, while pre-stressing of glass results in a greater fragmentation. Characteristic bending strength of heat-strengthened and fully tempered glass is typically 70 MPa and 120 MPa, respectively. In the tests, float glass was used for shear walls while float glass and heat-strengthened glass were used for the beams.

2.2. Timber

Timber is a natural and the only truly renewable building material. It is environmentally friendly and in line with the principles of sustainable development. It shows a high strength-to-weight ratio, which in combination with a low thermal conductivity makes timber a good alternative to other building materials.

Timber presents highly anisotropic behavior due to the orientation of the wood fibers and the annual ring pattern. Therefore the mechanical properties are often assumed to be distinct along three perpendicular axes: parallel to the fibers, and normal and tangential to the annual rings. When subjected to compression, timber behaves in a rather ductile manner, while loaded in shear and tension the failure is brittle. Typically, modulus of elasticity of timber is 7–16 GPa along the grain and 0.23–0.53 GPa perpendicular to grain direction. Characteristic strength in fiber direction is typically 8–30 MPa in tension and 16–30 MPa in compression while the corresponding values across the fibers are 0.4–0.6 MPa and 2–3.2 MPa in tension and compression, respectively (EN 338).

For the timber–glass composite shear walls and beams presented here, Scots Pine (*Pinus Sylvestris*) was used for the timber parts. In the grading

process for this product, logs with suitable heartwood content, density and growth rings are selected by X-ray tomography and dried to 12% of moisture content and conditioned. Subsequently, all knots and defects detected are removed and the clear sections re-jointed. The material is mainly used for window manufacturing purposes and is therefore not graded for structural purposes.

2.3. Adhesives

Due to the brittle nature of glass and its susceptibility to stress concentrations, special considerations must be taken as regards connections. The continuous bond lines between timber and glass applied in the project reduce the occurrence of stress concentrations and spread the loads over large zones as compared to pointwise connectors.

All adhesives used in the research are dedicated for structural purposes. The main aim during selection of adhesives was to ensure good adhesion to wood and glass and to cover the full range of stiffness from low (1–3 MPa) to high stiffness (>1000 MPa). Table I presents adhesives used in the project and initial stiffness tested in standard conditions (20°C, 1 mm/min) studied in Dorn *et al.* (2014a). The epoxy adhesives 3M DP490 and Sika Dur 30 were of highest stiffness; in the mid-range regarding stiffness was the Sika Fast 5215, while Sika Sil SG 500 was the softest.

Before the application of the adhesives, the glass surfaces were cleaned with alcohol and dust was removed from the groves in the wood flanges with compressed air. Similarly, the glass surfaces for the shear walls were cleaned with alcohol. An additional foundation layer was applied to the inner surface of wood which should prevent leaking of wood extractives into the bond line.

3. Large-scale experimental testing

Within the project timber–glass shear walls and beams were investigated. The focus was on the studies on structural elements with stiff adhesives; the tests with the softer silicone adhesive were included for reference. 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.

3.1. Shear walls

Shear wall elements were manufactured using finger-jointed pine wood (non-structural finger joints) and annealed float glass. The dimensions of the shear walls are given in Figure 1. The timber frame cross-

Table I. Adhesives used in the project.

Adhesive	Chemical composition	Stiffness (MPa)	Usage
Sika Fast 5215	Two-component silicone adhesive, static mixer	76	B
Sika Sil SG 500	Two-component acrylic-based adhesive, static mixer	2.8	SW, B
3M DP490	Two-component epoxy resin, static mixer	1500	SW, B
Sika Dur 30	Two-component epoxy with granular filler material; manual mixing	4500	SW

Notes: SW, shear walls; B, beams.

section was 95×80 mm^2, and the glass pane thickness was 10 mm. One shear wall consisting of a 6 + 10 + 6 mm IGU was also manufactured. Three different adhesives were used, and in total twelve single pane specimens plus one IGU specimen were produced. The adhesives were: 3M DP490 (Epoxy) in six single pane specimens, Sika Sil SG 500 (Silicone) in four single pane specimens and Sika Dur 30 (Epoxy) in two single pane specimens and in the IGU specimen (Table II).

The shear walls were tested in a load frame allowing both horizontal and vertical loading to be applied. The principle is shown in Figure 2, which also shows the definition of a coordinate system with the xy-plane being parallel to the plane of the shear wall. The supports of the shear walls were designed such that displacements in the *x*- and *z*-directions and rotation about the *y*- and *z*-axes were prevented at the bottom while allowing rotation about the *x*-axis. The top support consisted of a stiff beam which in turn was placed on top of a guiding rail (Figure 2) that allowed displacement in the *x*-direction, rotation about the *x*- and *z*-axes (rotation about the *z*-axis is limited, though).

Loading was applied by separate actuators in the horizontal and vertical directions. Load cells were mounted in line with each of the actuators. In some of the tests a second load cell was mounted at the left end of the loading beam (Figure 2). The mounting of the shear wall in the frame was done by fixing the timber frame to the steel guides at the top and bottom by means of steel dowels. The reason for doing so was an attempt to introduce the horizontal loads in a more uniform matter along the length of the frame's width (as opposed to introducing the loads pointwise by compression in the corner regions). The dowels' ability to transfer vertical forces was thus limited (see Figure 3).

Apart from measuring the applied loads, displacements were also monitored. This was done using
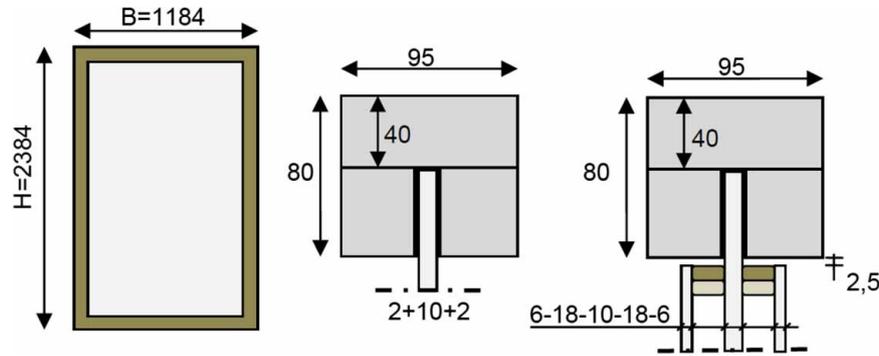
Figure 1. Geometry of shear wall specimens. Left: shear wall dimensions. Center: cross-section of timber frame–glass pane of single pane specimens. Right: cross-section of IGU specimen. Dimensions are approximate.

Table II. Overview of load cases and ultimate load levels for shear walls.

Adhesive	Type	Load case	Ultimate load (kN)	
			Horizontal	Vertical
3M DP490	Single pane	LC V	–	191.95
3M DP490[a]	Single pane	LC H	42.56	96.26
3M DP490 [a]	Single pane	LC HV20	57.09	139.23
3M DP490[a]	Single pane	LC HV50	40.58	101.65
3M DP490[a]	Single pane	LC HV20	55.69	152.69
3M DP490[a]	Single pane	LC HV50	43.89	134.26
Sika Sil SG 500	Single pane	LC V	–	182.28
Sika Sil SG 500 [b]	Single pane	LC H	106.84	89.36
Sika Sil SG 500	Single pane	LC HV25	48.15	144.30
Sika Sil SG 500	Single pane	LC HV60	47.89	139.36
Sika Dur 30	Single pane	LC V	–	175.38
Sika Dur 30	Single pane	LC H	55.96	110.65
Sika Dur 30[b]	IGU	LC H	84.95	122.49

[a]Tests with a second vertical load cell.
[b]Correction of the results to be explained in the text.

potentiometers as well as using a contact-free measurement system (Pontos, Gesellschaft für Optische Messtechnik mbH, Germany). This allows obtaining the 3D coordinates of markers on the shear wall (visible as white dots on black background in Figure 2) during the course of loading. The positions of the potentiometers and of the markers are depicted in Figure 4. The results from these measurements allowed determining the beginning of out-of-plane deformations (deformation in *z*-direction) which define the onset of buckling failure modes.

The test program consisted of three different load cases with the following loading sequences (see Table II for an overview):

Pure vertical loading (LC V): The specimens were loaded in displacement control by applying a vertical displacement to the top guides. No restriction on the horizontal displacement of the top rail was applied and thus only vertical force is introduced.

Pure horizontal loading (LC H): The top guide was prevented from moving in the vertical direction by locking the vertical actuator. Load was then introduced only horizontally (displacement control). Nevertheless, horizontal and vertical loads were introduced since vertical forces build up due to the restrained in-plane rotation of the shear wall by the top rail system.

Combined loading (LC HV20, LC HV50): At first, a pure vertical load was applied on displacement control while the horizontal displacement of the top rail was free. The target pre-load was 20–25% of the previously recorded ultimate load in pure vertical loading (according to LC V). The vertical actuator was then locked, and horizontal loading according to load case 2 was applied. In a similar way, a pre-load level with 50–60% of ultimate load in pure vertical load level was also used.

It should be mentioned that for shear walls using the silicone adhesive and the load cases involving shear, the test program could not be performed as intended. Reason for this is that the load application unit for horizontal loading could not apply higher deformations as approximately 80 mm (100 mm nominally). Since the shear walls with the silicone adhesive were comparably soft in response, the horizontal loading had to be stopped at the maximum but the tests were continued by applying additional vertical load until failure.

3.2. Beams

A total number of 12 beams of 240 mm high (*h*) were produced (Figure 5) using adhesives of different stiffness: Sika Sil SG 500, Sika Fast 5215 and 3M DP490. In comparison to the previous research (Blyberg and Serrano 2011, Blyberg *et al.* 2014), the length was increased to 4800 mm in the current study, also thinner glass (8 mm) was used. The web height was 190 mm and the web was made of annealed float and heat-strengthened glass. To
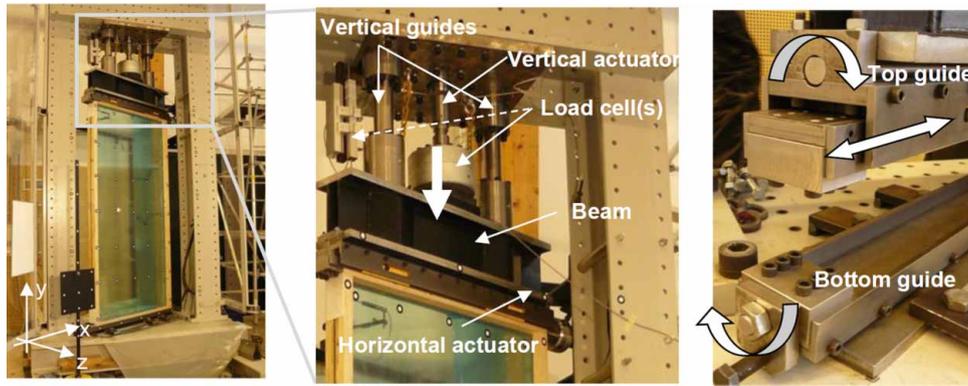
Figure 2. Load frame used in shear wall tests (left). Detail of the load introduction and distribution beam (center). Upper and lower guiding systems with degrees of freedom (right).
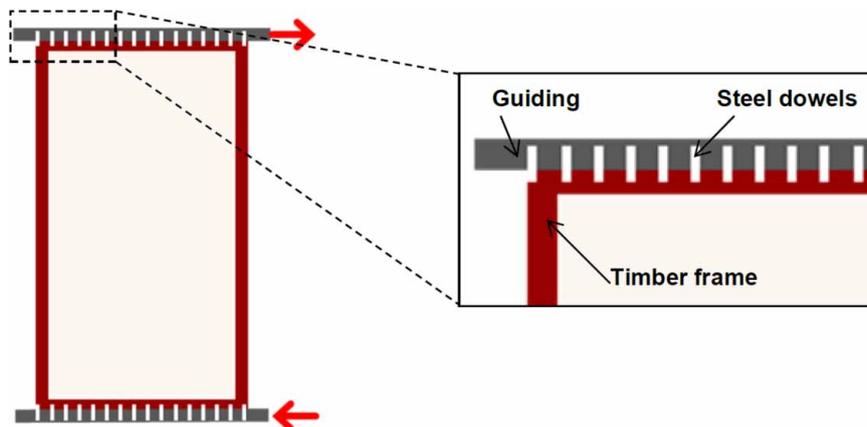

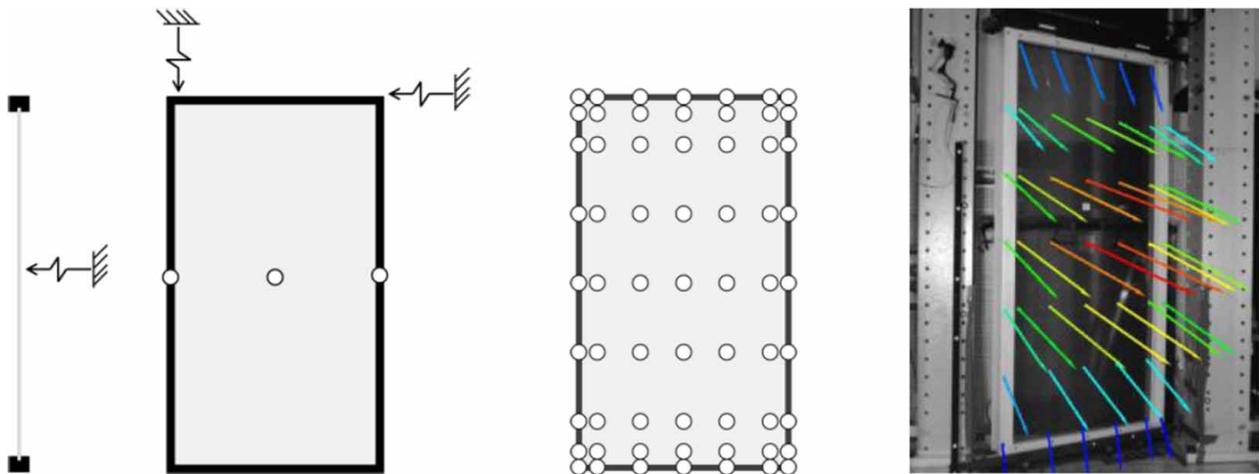Figure 3. Attachment of the timber frame by dowels.

Figure 4. Left: Potentiometer placement. Middle: Markers for pointwise tracking. Right: Deformation shape of a wall element in the buckling state under compression load (LC V).

avoid any influence of edge quality stemming from the cutting, all glass edges were polished (in case of heat-strengthened glass, edge treatment was done before the tempering process). Measurements of residual stresses from the tempering process (by a so-called SCALP-device) revealed an average compressive stress of -53.2 MPa at the surface and a tensile stress of 25.0 MPa in the center. The cross-sections of the timber flanges were 45×60 mm^2 and made of knot-free, finger-jointed Pine wood.
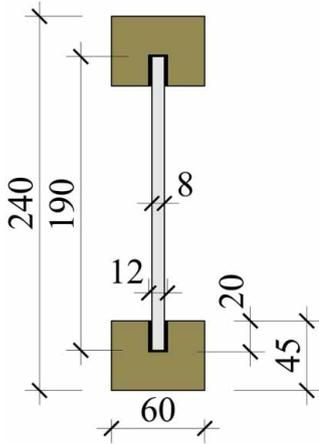
Figure 5. Cross-sectional dimensions of beams and flange.

In order to fit the glass web, a groove measuring $12 \times 20 \text{ mm}^2$ was milled in the flanges. Before manufacturing, the dynamic modulus of elasticity of the flanges was measured, averaging at 12.41 GPa. For the bond line connection, measuring $2 \times 20 \text{ mm}^2$ on both sides of the glass web, three different adhesives were used (Table I).

All beams were tested in four-point bending (Figure 6). The nominal distance between supports was 4320 mm ($18 \times h$) and the forces were introduced symmetrically at one-third of the beam span. To prevent lateral torsional buckling due to the high slenderness of the beams, two lateral supports, located close to the loading points, were provided. Apart from measuring the loading and global deformation of the beam (v_{global}), local deformation (v_{local}) over a length of 1200 mm ($5 \times h$) was also measured, in order to determine the beams' bending stiffness. A few specimens were also equipped with strain gauges to monitor the strain in the glass web and in the timber flanges, at various positions across the beam height.

4. Results

4.1. Shear walls

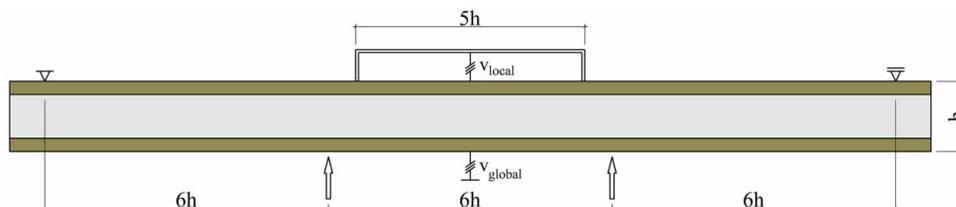The various combinations tested and the main test results in terms of ultimate load-bearing capacity

are reported in Table II. Figure 7 shows the individual test results in terms of measured horizontal and vertical loads at failure. It is to be noted that a quite limited number of specimens were available and thus only a limited number of repetitions were possible to perform. Thus rather the qualitative aspects than the quantitative aspects of the evaluation is the main focus.

The only failure mode observed was failure due to buckling of the wall elements under the external loading, irrespective of the adhesive used and the load case. No signs of premature glass failure, timber failure (fracture or plastic compressive behavior) or adhesive failure (e.g. by losing adhesion to wood or glass or by cohesion failure in the adhesive itself) were noticed during the tests. However, as explained below, a premature failure of the silicone specimens due to adhesive failure cannot be excluded.

Vertical loading (LC V): Specimens loaded in pure vertical load sustained a load of 184 kN (average of the three different adhesives). No direct influence of the adhesive stiffness was observed since the shear wall with the stiffest adhesive (Sika Dur 30) showed the lowest ultimate load and the shear wall with the
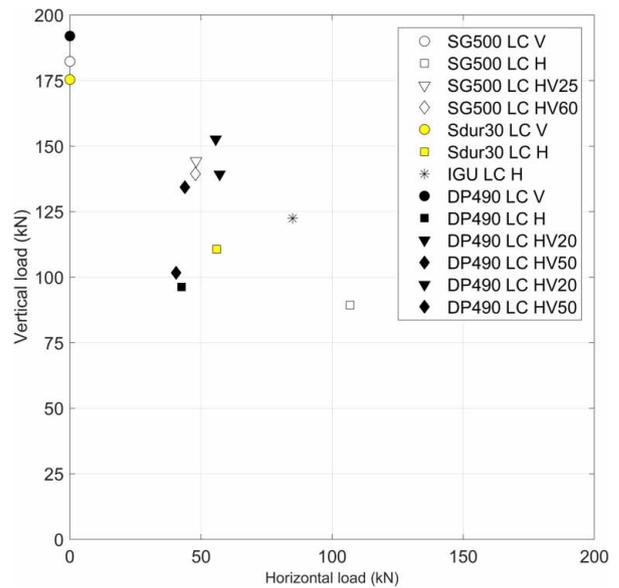

Figure 7. Ultimate loads for shear walls.

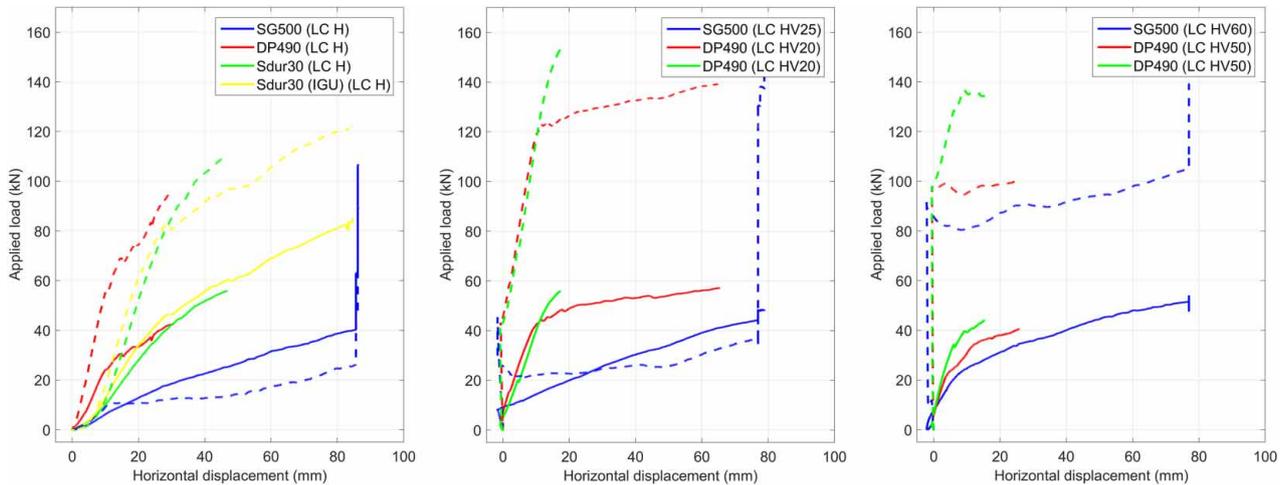Figure 6. Test set-up for testing timber–glass beams.

Figure 8. Load-displacement diagrams (horizontal force in full line, vertical force in dashed line) of the tested shear walls for load cases LC H (left), LC HV 2025 (center) and LC HV 5060 (right).

softest adhesive (Sika Sil SG 500) resulted in an intermediate ultimate load.

Horizontal loading (LC H): Under horizontal loading, global force equilibrium requires that vertical loads are introduced in order to prevent rotation of the element. This can be achieved by hold-downs in the corner regions (as is common in wall elements), or by preventing the vertical and rotational movement of the top of the shear wall (as was done in the tests by the top guide). The ratio between vertical and horizontal forces should be at least the same as the ratio of vertical to horizontal dimensions, i.e. 2:1 (see also the dashed gray line in Figure 7).

This is fulfilled for tests with adhesives 3M DP490 and Sika Dur 30, whereas it is not for adhesives Sika Sil SG 500. For the latter case, the vertical force is not increasing after about 10 mm horizontal displacement but remains approximately constant. For most of the test duration and also for the IGU (Sika Dur 30) a force ratio of 2:1 was achieved, but at around 45 kN horizontal load the curves change and the ratio becomes lower. This could possibly be explained by a premature failure of the silicone adhesive bond, although this was not observed during testing.

Combined loading (LC HV): A tendency that can be observed for the shear walls using the 3M DP490 adhesive is that the specimens for load case LC H (horizontal loading) sustain the lowest load (marker ■), followed by load case LC HV50 (marker ◆) and load case LC HV20 (marker ▼). A modest vertical pre-load therefore increases the load-bearing capacity significantly compared to pure horizontal loading while too high a pre-load is again lowering the capacity.

The shear walls with the soft silicone adhesive Sika Sil SG 500 showed similar results under combined load, but no influence on the load combination was

found. The shear wall specimen with the stiff adhesive Sika Dur 30 under pure horizontal load (LC H) showed a slightly higher bearing capacity compared to the specimen with the 3M DP490 adhesive.

Figure 8 shows the measured forces (vertical and horizontal) versus the horizontal displacement at the loading point for all specimens under horizontal load cases. The difference in stiffness is clearly seen comparing the shear walls made with the soft silicone adhesive to the ones made with the two stiffer epoxy adhesives. The latter show similar stiffness although the E-moduli of the two epoxy adhesives differ significantly.

Displacements at failure of the softer specimen are usually much higher than that for the stiffer specimens. The one exception from this is a specimen with 3M DP490 which shows rather large displacements. However, a change in the course of the diagram obviously hints to a strongly reduced
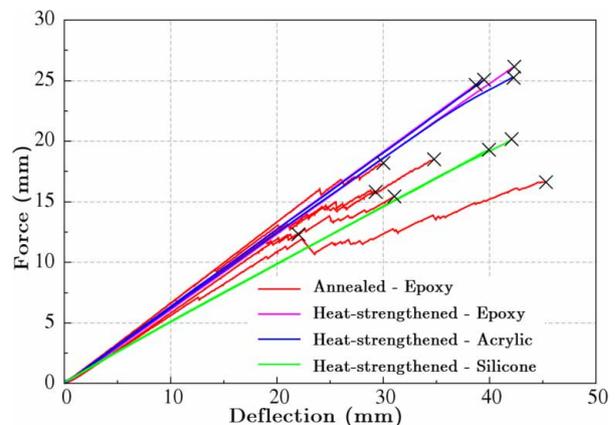

Figure 9. Load versus mid-span deflection plots for tested beams.

Table III. Experimental results of beams: failure loads and initial bending stiffness.

Glass	Adhesive	Experiments		
		Load at the first cracking (kN)	Maximal load (kN)	Initial bending stiffness (MNm^2)
Annealed float	3M DP490	11.6	16.4	0.893
Heat strengthened	3M DP490	25.2		
	Sika Fast 5215	25.5		0.907
	Sika Sil SG 500	19.8		0.720

stiffness (due to unknown reasons) which increases deformation until reaching the failure load level. Severe changes in the courses are also observed for specimens with the adhesive Sika Sil SG500 in all load cases; in LC HV25, the vertical pre-load drops as soon as horizontal loading starts and has not recovered; and in LC HV60, no additional vertical load is build up during the application of horizontal loads. Thus, the vertical loads are below the expected levels.
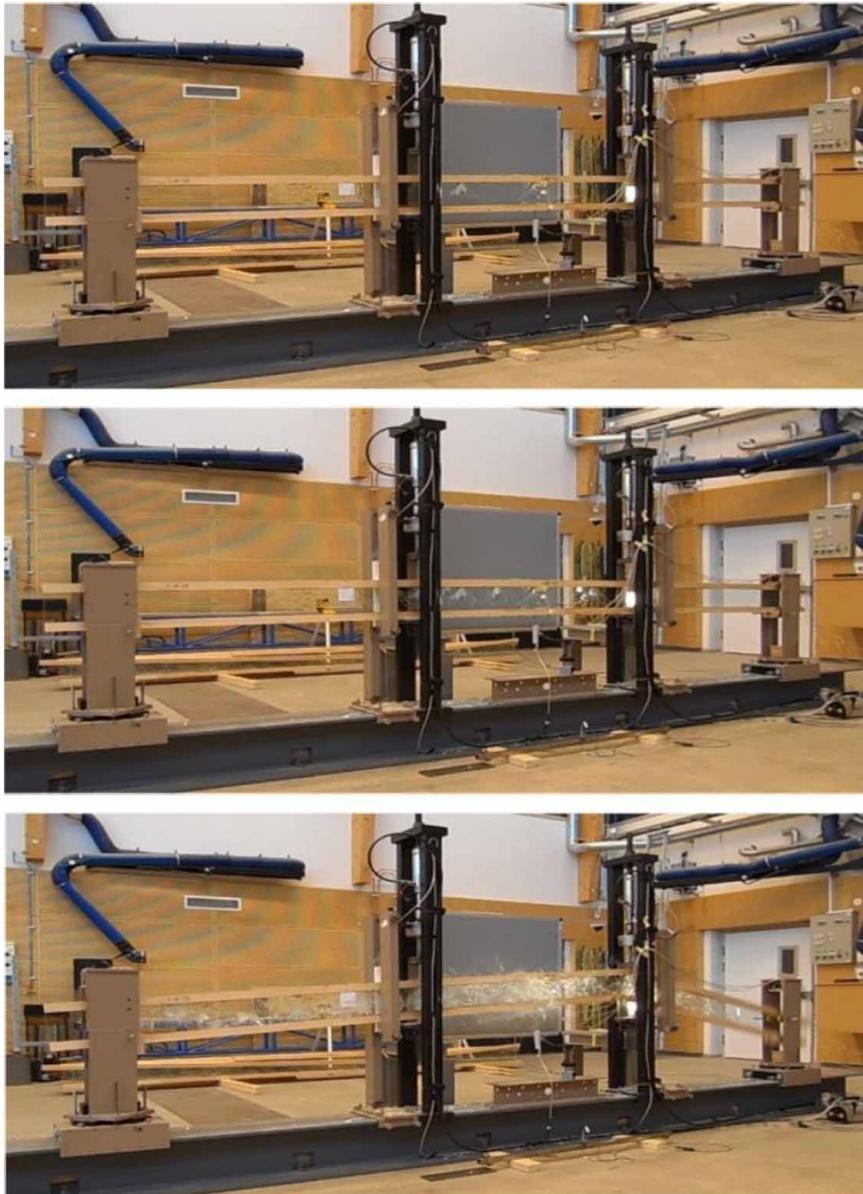

Figure 10. Progressive damage of timber–glass beam with annealed float glass.

Since the main difference between the shear walls was the use of different adhesives, the influence of their respective stiffness was of great interest. Differences were clearly observed for shear wall stiffness but to a lesser extent for failure load. This indicates that for this design, ultimate failure is not so much dependent on stiffness of the adhesives in particular, but rather on the strength of the glass and the buckling load of the shear wall. This is insofar surprising as other designs have shown a significant influence of the adhesive stiffness on the buckling load (Blyberg *et al.* 2014 experimentally and Neijbert 2013 numerically).

4.2. Beams

Figure 9 presents load-deformation curves for all beams. Clear differences in the behavior of beams using annealed or heat-strengthened glass could be observed. All beams with heat-strengthened glass showed linear behavior until failure which occurred at very similar displacements of approximately 40 mm, regardless of the adhesive used. Furthermore, the two repetitions for each adhesive showed good agreement. Hardly any differences neither in the load-deformation path nor in ultimate load (25.2 kN for epoxy and 25.5 kN for acrylic adhesives) could be seen for beams using acrylic and epoxy adhesives (Table III). The beams with silicone adhesive showed only approximately 20% lower ultimate strength than the beams using far stiffer adhesives.

The beams with float glass and epoxy adhesives exhibited progressive damage before final failure as can be seen in the increasing number of cracks before final failure (Figure 10). Initially, the load-deformation courses show good agreement with the beams using heat-strengthened glass since, until the first crack, the relationship between force and deflection was almost linear. With further cracks forming in the glass web, force drops occurred and a decrease in bending stiffness was observed (although the course is still linear between the drops). Even severely cracked webs maintained structural integrity and loads could continuously be raised. In all cases the final collapse was caused by a failure of the flange working in tension and an "explosive" failure of the compression zone of the glass web. The mean load at the first cracking was 11.6 kN while maximal load at failure was 16.4 kN (mean values of six specimens), which corresponds to an increase of approximately 50% of the load at the first cracking (Table III). The beams with heat-strengthened glass presented no post-breakage strength but failed at the occurrence of the first crack. However, due to the heat treatment of the glass, the beams could

sustain approximately 117% higher loads (at first crack) than the beams with float glass (comparing beams with the 3M DP490 adhesive). Comparing ultimate loads for those beams, an increase of approximately 54% was found.

5. Conclusions

The proof of concept and the great potential for timber–glass composites has clearly been shown in these two very different applications of shear wall elements and beams. The findings presented show that timber–glass composite elements may become alternatives to standard load-bearing structural components in buildings. In the following, some key findings are summarized and an outlook on future developments given.

5.1. Shear walls

Stiffness of the adhesive was clearly influencing racking stiffness of the wall elements but only to a certain level, and differences between stiff and very stiff adhesives could not be found. In terms of ultimate load levels, no clear distinction could be made.

All the tested shear walls failed due to buckling, regardless of load cases. This implies that load levels in the bond line, the wood frame and the glass pane were lower than the respective limit levels. This is in contrast to other studies on shear wall elements where different failure mechanisms were observed (usually at much lower load levels).

The shear walls exhibited very high load levels at failure, in vertical as well as horizontal load cases. This might allow using such shear walls not only as stiffening elements for horizontal loads but also for vertical load cases.

The concept of the U-shaped bond line seems to be promising. With this, the adhesive is confined on three sides and cannot be compressed that easily due to the high Poisson's ratios of the adhesives. This allows even for soft adhesives to exhibit high ultimate load levels in the composite.

The load introduction by a smeared approach could successfully be applied. In common tests scenarios, the loads are introduced only pointwise (usually in the corners) so that high forces are encountered. The presented approach is more relevant in terms of mimicking the final application within a structure where the wall element needs to be fixed continuously.

5.2. Beams

Regarding beam stiffness, no influence of the glass type is observed; the beams with annealed float and

heat-strengthened glass with epoxy adhesive exhibited identical bending stiffness (see Table III). This is expected since glass stiffness is not altered during the strengthening process.

The influence of the adhesive stiffness in the composite beam stiffness is surprisingly low considering the fact that the stiffness of acrylate and epoxy compared to silicone adhesive is approximately 100× and 1000× higher, respectively (see Table III). However, the adhesive used for bond line connections influences the bending stiffness of beams less than expected, mainly due to the fact that the glass web contributes most to the beam's overall bending stiffness. It is noted, that this may be only the case for this type of (bond line) geometry and the rather small timber flange area.

Regarding the failure pattern, the beams with float glass present multiple crack bundles before the final collapse, whereas the beams with heat-strengthened glass show sudden failure at the first cracking. This is also reflected in terms of load levels at failure where the beams with heat-strengthened glass present higher load levels compared to the beams with annealed float glass.

However, the increased ultimate load level for strengthened glass webs comes at the expense of ductility.

5.3. Further research

Although the proof of concept for the application of shear walls and beams could be demonstrated, the widespread use is not yet feasible. The use of glass as a structural, load-bearing component is currently strongly limited. Further advancements on timber–glass composites rely therefore on the development of reliable rules for structural glass and the possible use of single panes or mandatory use of laminated glass and the use of float or strengthened glass. A clear definition of the SLS and ULS is missing as well as the allowance of crack occurrence. This has direct consequences on possible ductility in timber–glass composites. Naturally, safety aspects have to be considered in anticipation of fire or vandalism. In a similar way, the use of adhesives under high and permanent loads is currently not allowed except for (structural) silicones loaded by very low stress levels. Also the long-term stability of the adhesives under varying climatic conditions over the full lifetime of the structure has to be guaranteed.

Practical aspects need to be solved which include the design of the cross-section with a closed or open bond line which both have advantages and disadvantages. This relates directly to requirements on thermal aspects and sound insulation. The connection to the main structure has yet to be

solved but techniques commonly known from timber engineering can be applied. In this context, design rules such as adequate ductility in the structure are to be considered (the shear walls do not show any ductility while some arguable ductility is present in the beams).

Investing in these research topics would open up possibilities for new structural and architectural concepts, but not least monetary limitations and the user perception need to be studied as well.

Disclosure statement

No potential conflict of interest was reported by the authors.

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