engineered transparency. International Conference at glasstec, Düsseldorf, Germany
21 and 22 October 2014

Design approaches for timber-glass beams

Michael DORN*, Marcin KOZŁOWSKI[a], Erik SERRANO[b]

* Linnaeus University, Department of Building and Energy Technology
S-351 95 Växjö
michael.dorn@lnu.se

[a] Silesian University of Technology, Department of Structural Engineering
Gliwice, Poland

[b] Linnaeus University, Department of Building and Energy Technology
Växjö, Sweden

Abstract

This paper relates to the mechanical performance of timber-glass composite beams, which take exceptional advantage of the combination of the materials involved. Beam bending tests were performed with beams made from float glass and heat-strengthened glass. Three different adhesive types were used: silicone, acrylate and epoxy. The test results show that, with a proper design, the timber is able to transfer load after glass failure and hence collapse is delayed and a ductile behavior can be obtained. The results from the tests were compared with an analytical method using the gamma-method and the agreement between the analytical method and the tests are shown to be excellent.

Keywords: timber-glass composite beams, design approach, numerical simulation, experiments, gamma-method

1 Introduction

Buildings of the future will be constituted of an intelligent and advanced combination of materials since the demands on the individual parts are ever increasing. Not only the structure as a whole but each individual part needs to be light-weight, load-bearing, transparent, cost-effective, energy-efficient, etc. – at the same time. This stems partly from architectural demands on unique structures but also on the construction companies and the future users. Simultaneously the need for energy efficiency and climate-friendly buildings is increasing. This will drive the application of timber for structural use further more and motivates innovative research and new concepts.

Timber structures usually comprise of elements of considerable dimensions while the structural part is often separated from the outer cladding, windows and façade. Hence an integrated approach is preferable and would allow for a considerable reduction of weight and increase of floor space.

The WoodWisdom-Net research project Load Bearing Timber Glass Composites (LBTGC, 2012-2014) is studying the combined use of timber and glass in structural elements. Within LBTGC large-scale structural elements (beams and shear walls) are developed and tested as well as show-case prototypes presented. This contribution describes work done at Linnaeus University (LNU) as part of the LBTGC project on timber-glass beams.

1.1 Concept of timber-glass composite beams

The hybrid timber-glass concept involves a single pane web made of glass and timber flanges bonded together with an adhesive (Figure 1).

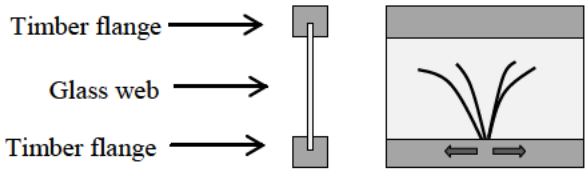

Figure 1: Schematic idea of the concept for timber-glass composite beams: cross-section of the hybrid beam (left), side-view of the beam with cracked glass web (right)

Even if the glass web fails, the glass shards are held in place by the timber flanges and the beam can still withstand loading. The bottom flange with the bond line adhesive connection acts as a bridge: the tensile forces that before failure were carried by the tensile zone of the web are now transferred by the timber flange. Therefore the concept prevents the brittle failure of the beam, provides ductility and offers a high post-breakage strength after possible glass failure (Figure 2). The post-breakage (residual) strength relates to an increased value of the load at final collapse of a beam in relation to the load at which an initial crack in the web occurs.

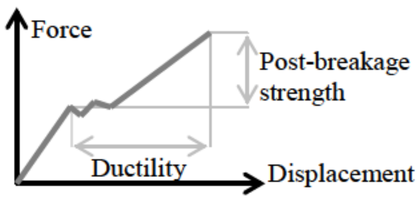

Figure 2: Force-displacement diagram presenting idea of ductility and post-breakage strength of timber-glass composite beams

The choices of the geometry as well as of the materials (adhesive stiffness, timber quality and glass type, respectively) have influence on the behaviour and the possible formation of usable ductility.

1.2 Previous work

Research on the combination of glass and timber started in the mid-1990s with the works of e.g. Stiell et al. [1] and Natterer et al. [2]. Hamm [3] and Kreher [4] investigated shear walls and composite beams which ended in the use of timber-glass composite beams in a hotel project in Switzerland (Kreher et al. [5]). Research was continued by studying the behaviour in experiments and theory by Blyberg et al. [6] as well as by Kozłowski et al. [7].

2 Materials

The use of glass and timber, combined with suitable structural adhesives, as a single structural elements has to deal with many different challenges, e.g. the (an-) isotropic material behavior regarding stiffness and strength or the time and temperature dependency.

The benefits of a combination lie in using the glass as the strong load-bearing part and the timber for easy mounting to the sub-structure and to prevent brittle failure of the element.

2.1 Glass

The glass used in the present project was annealed float glass or heat-strengthened glass. The stiffness is estimated at typically 70 GPa. Typical strength in bending is estimated at 45 MPa for annealed float glass and 70 MPa for heat-strengthened glass. Due to the tempering process, heat-strengthened glass usually fails with the occurrence of the first crack while the cracks may be locally contained for float glass.

2.2 Timber

The failure behavior of timber is typically brittle in tension and shear while it allows for substantial ductility in compression. Typical stiffness of softwood is 10-16 GPa in fiber and 0.5-1.0 GPa across fiber direction. Strength in fiber direction is typically 60-90 MPa in tension and 40-60 MPa in compression while it is approx. 3-6 MPa and 5-9 MPa across fiber direction, in tension and compression, respectively.

Graded pine wood was used in all tests. The grading process removes weak sections such as knots so that only clear wood remains. The wood is then finger-jointed which allows for longer bars. Wood and finger joints (adhesive) are not graded for structural purpose but used mainly for window manufacturing purposes.

2.3 Adhesives

The brittleness of glass makes it necessary to use wide-spread load transfer zones which reduce the occurrence of stress concentrations. Using structural adhesives along the edges of the glass panes takes this into account.

A large variety of adhesives is available with manifold of different characteristics. The chemical composition itself does not necessarily allow for a characterization regarding e.g. stiffness and strength, nevertheless silicones are usually regarded as the least stiff and strong while epoxies are the stiffest and strongest adhesives. The adhesives came in pre-packaged containers allowing an easy, quick and controlled mixing an application process.

The adhesives were selected to assure good adhesion and should cover the full range of stiffness from low (1-5 MPa) to high stiffness (> 1000 MPa). Hence the silicone Sika Sil SG500, the acrylate Sika Force 5215 and the epoxy 3M DP90 with an initial stiffness of approx. 2.8, 75 and 1500 MPa, respectively, were chosen.

Adhesives need to sustain also impacts over the life-span of the structure which are of non-mechanical nature but may affect durability, e.g. temperature differences, exposure to sunlight and moisture variation, and other environmental impacts. This investigation focused on the mechanical behavior and such environmental impacts were not studied.

3 Experiments

A set of twelve beams of 4800 mm length was produced and subsequently tested under four-point-bending (Kozłowski et al. [7]). Geometry (Figure 3) is similar to the tests by Blyberg et al. [6] with an 8 mm thick and 190 mm high glass web. The glass edges were polished to avoid influence of edge quality. Six webs consisted of annealed float glass and six webs of heat-strengthened glass (strengthening took place after edge treatment).

The bond-line was 2 mm in thickness and approx. 20 mm in width in all specimens. Thickness of the bond-line was secured by using rubber strips on both sides of the web at distances of approx. 400-500 mm. The flanges were of the knot-free, finger-jointed Pine wood mentioned above. The measured dynamic E-modulus was 12.41 GPa.

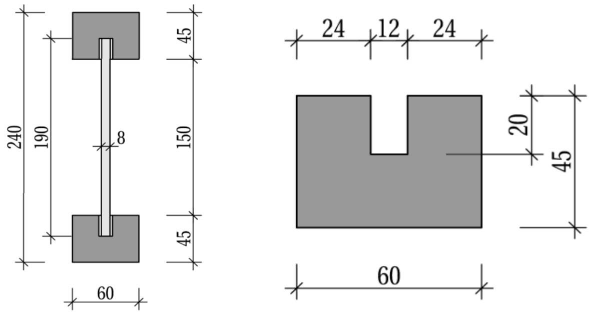

Figure 3: Cross-section of beams

The beams were manufactured directly at LNU by first washing the glass pane and applying tape to protect the glass web from excessive amount of adhesive. The adhesive was poured into the lower flange using pre-packaged containers and static mixers. The glass pane was set into the groove, fixed horizontally while applying pressure vertically. Remaining adhesive was removed and the specimen left for curing while being hold in place. The finished specimens were stored in the lab for approx. 70-80 days before testing.

To measure strain distribution across the beam depth, strain gauges were attached to the glass web in the tension and compression zone as well as on the timber flange in the tension zone in mid-span of the beam (four strain gauges per specimen).

Distance between the supports was 4320 mm while the loading points were mounted symmetrically at one-third of this span (Figure 4). Additional horizontal supports were used in order to prevent torsional buckling due to the high slenderness of the beams. Local deformation over a length of 5×beam height was measured to determine the bending stiffness of the beam more precisely.

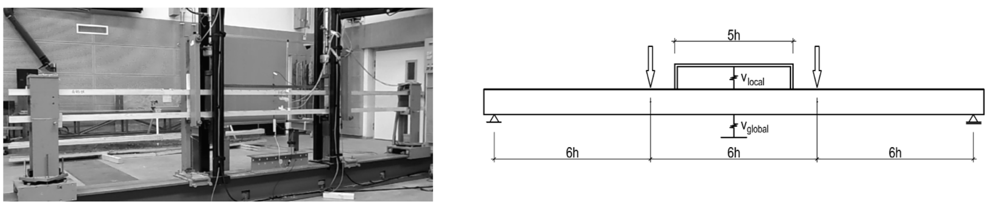

Figure 4: Loading scheme and testing machine

In the beams using the stiff adhesive 3M DP490 in combination with annealed float glass it was observed that stiffness is linear until the first crack appears. This was accompanied by a load drop and followed by a load increase at lower stiffness (Figure 5, E_AF beams). The cracking of the glass web did not lead to instant failure. Tension stresses are instead transferred via the adhesive into the tension chord – and back into the glass on the other side of the crack. This bridging effect has been observed before, e.g. in the tests by Blyberg et al. [6], and contributes to a certain ductility of the beams. Nevertheless, ductility (defined as the increase in deformation between the first crack and final collapse) is less compared to tests in Blyberg et al. [6], most likely due to the use of solid wood instead of LVL, the latter comprising a more controlled quality.

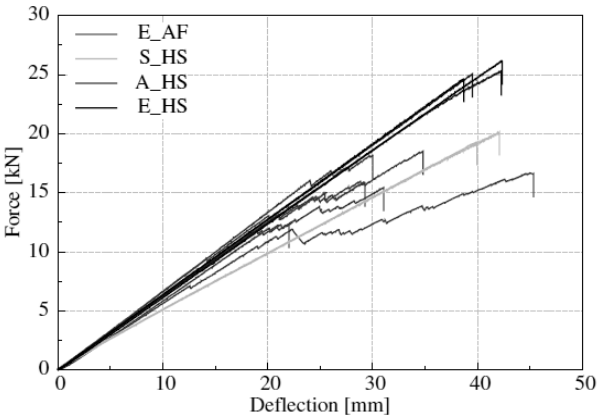

Figure 5: Load-deflection plots of beam tests using different adhesives and glass qualities

Beams with heat-strengthened glass do not show this ductile behavior but fail immediately (Figure 5, HS beams) at approx. identical deflection, irrespective of which adhesive is used. The load level was higher in the beams with 3M DP490 (E_HS beams) and Sika Fast 5215 (A_HS beams) adhesives of high and intermediate stiffness, respectively, as compared to the soft silicone adhesive Sika Sil SG500 (S_HS beams). Due to the pre-stressing of the glass, higher total loads and deformations were obtained compared to beams with annealed float glass (Table 1).

	Nr.	First crack [kN]	Max load [kN]	Adhesive
Annealed Float glass	E_AF01	9.4	19.5	3M DP490
	E_AF02	7.1	16.6	3M DP490
	E_AF03	12.0	15.5	3M DP490
	E_AF04	13.2	15.8	3M DP490
	E_AF05	11.9	12.5	3M DP490
	E_AF06	16.0	18.2	3M DP490
	Mean	11.6	16.4	
Heat Strengthened glass	A_HS01	25.1		Sika Fast 5215
	A_HS02	25.2		Sika Fast 5215
	Mean	25.2		
	E_HS01	26.2		3M DP490
	E_HS02	24.7		3M DP490
	Mean	25.5		
	S_HS01	20.2		Sika Sil SG500
	S_HS02	19.3		Sika Sil SG500
	Mean	19.8		

Table 1: Failure loads of beam tests

Glass quality obviously does not influence stiffness of the beams in the pre-cracked domain. Beams with Sika Fast 5215 and 3M DP490 show almost identical beam stiffness while the use of the softer Sika Sil SG500 leads to considerably lower beam stiffness. This allows concluding that the influence due to adhesive is limited by a threshold stiffness of the adhesive at which composite beam action is fully established.

Figure 5 shows that failure occurred almost at identical deflection for the beams with heat strengthened glass, regardless of the adhesive used. This could mean that glass tension stresses are reached on the tension side at this deflection which leads to immediate failure. The difference in load taken between the beams with soft silicone adhesive and the stiffer adhesives furthermore comes from insufficient composite action in the beams with silicone.

Load level and ultimate load in the beams with standard float glass is lower than with heat-strengthened glass. Still the failure mode is more ductile so that first cracks do not lead to a total collapse of the beam. This behavior is of course more favorable since failure is signalized by crack occurrence.

4 Analytical solutions

The gamma-method is used in timber engineering (Eurocode 5, [8]) to assess the load-bearing behavior of composite structures with compliant interfaces, typically nails or dowels, but has been successfully adapted for timber-glass composites (e.g. by Kreher [4]). The compliance is defined so that a value of $\gamma = 1$ means full composite action (no slip) while $\gamma = 0$ is identical to fully independently acting webs and flanges.

The analytically determined γ-values of the beams show that there is almost full composite action for the stiff and intermediate stiff adhesives with $\gamma = 0.999$ and $\gamma = 0.997$, respectively, while for the soft silicone $\gamma = 0.710$. Based on these γ-values the corresponding beam stiffness is 925, 923 and 752 kNm^2, respectively, which shows a good agreement to the experimentally determined stiffness (mean deviations were about 2-4 %).

Numerical investigations have confirmed the good agreement of this method.

5 Design of timber-glass beams

The proposed design of the beams, in particular the full coverage of the glass edge by single, continuous wood flanges, has shown to be reliable in the experiments. Estimation of stiffness by means of the gamma-method and the estimation of the occurrence of the first crack are in accordance with the test results. This can be regarded as a proof of concept which nevertheless has to be refined for final applications in structural applications. In particular, the following has to be investigated and decided on:

- Cost-efficiency: Although currently not competitive, architectural benefits may predominate and justify higher costs.
- Fire-safety: Apart from glass cracking, the adhesives are known to become very soft under high temperatures which will influence the behavior.
- Design-rules: Common design rules for different cross-sections, beam lengths, loading scenarios and loading conditions.
- Limit states: Definitions of the Serviceability (SLS) and Ultimate Limit State (ULS). Should SLS allow for cracks to appear?
- Safety: Resilience against willful damage and vandalism, also the exchange of damaged parts must be guaranteed.

- Glass quality and/or use of laminated webs: Glass quality mainly influences post-breakage, which also the choice of using single panes or laminated webs does.
- Glass as a load-bearing material: The use of glass as a load-bearing material and hence an integral part of a structure is restricted, mainly due to insufficient ductility. Composite structures might be a way to show the capabilities of glass.
- Long-term behavior: The consequences of creep and fatigue in the materials involved have to be fully understood and its interactions properly considered. In addition, environmental impacts, particularly on the adhesive, have to be considered (e.g. UV light and fungi).

6 Acknowledgements

This study is a part of the Wood Wisdom Net project “Load Bearing Timber Glass Composites” with partners from Austria, Sweden, Germany, Turkey, Slovenia, Chile, and Brazil. The financial support for the Swedish part of the project from VINNOVA - Swedish Governmental Agency for Innovation Systems - and the support from the industrial partners Stora Enso, SIKA Sverige AB, Södra Timber AB, Glasbranschföreningen and Pilkington Floatglas AB is gratefully acknowledged.

7 References

[1] Stiell, W.; Schmid, J.; Lieb, K.; Krause, H.: *Geklebte Glaselemente in Holztrag-werken. Abschlußbericht*. IRB Verlag, 1996.

[2] Natterer, J.; Kreher, K.; Natterer, J.: New joining techniques for modern architecture. Rosenheimer Fenstertage: Seminar.- Rosenheim, 2002, January 2002.

[3] Hamm, J.: *Tragverhalten von Holz und Holzwerkstoffen im statischen Verbund mit Glas*. PhD thesis, EPFL, 2000.

[4] Kreher, K.: *Tragverhalten und Bemessung von Holz-Glas-Verbundträgern unter Berücksichtigung der Eigenspannungen im Glas*. PhD thesis, EPFL, 2004.

[5] Kreher, K.; Natterer, J.; Natterer, J.: Timber-glass-composite girders for a hotel in Switzerland. *Structural Engineering International (IABSE)*, 14(2):149–151, 2004.

[6] Blyberg, L.; Serrano, E.: Timber/Glass adhesively bonded I-beams. In *Glass Performance Days 2011*, pages 451–456, 2011.

[7] Kozłowski, M.; Serrano, E.; Enquist, B.: Experimental investigation on timber-glass composite I-beams. In Louter, Bos, and Belis, editors, *Challenging Glass 4 & COST Action TU0905 Final Conference*. Taylor & Francis Group, 2014.

[8] DIN EN 1995-1-1. Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings, 12 2010.