Timber-Glass Composite Beams: Mechanical Behaviour & Architectural Solutions

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The structural utilization of timber-glass composite solutions is a daring constructive system, which although still in a very early stage, already presents an important potential of applicability in architecture. Natural lighting is a crucial factor in architectural conception, and one of the advantages of timber-glass composite beams lies precisely on the exploration of the capacities of lighting through structural elements. This means, first of all, it will allow benefiting from natural lighting in a way not much explored so far, creating light paths and improving spatial perceptions. On the other hand, the transparency of glass, associated with its structural employment, could achieve the most transcendent features of this material: magic and illusion.

Keywords: Glass, Timber, Architectural design, Lighting, Safety.

1. Introduction

1.1. Motivation

Part of this work centres on the results regarding safety and behavioural stability of the composite structure, particularly of laminated glass [1] [2] and respective structural connections. This is essential to the practical, safe and generalised implementation of an innovative and promising constructive system [3] [4] [5]. Also at a structural level, glass compression capacity and timber tension resistance can be exploited [6] [7], the same way that accumulated and tensile stresses must be avoided on glass surfaces. In this context, variations in the cross sections geometry of the beams are tackled. Such variations lead to greater or smaller stiffness and strength of the structural element.
This paper focuses on the analysis of the results obtained in laboratory with twenty beams and several variables. It also approaches the architectural applicability potential of this structural element in housing and urban solutions, specifically designed and developed with the main purpose of taking the best benefit from this construction solution.

2. Product: Timber-Glass Composite Beam

2.1. Concept and purpose

This solution serves the purpose of enhancing the values of a composite structural system [8] [9], in this case between elements which – according to what was concluded based on tests carried out – complement each other in their varied specificities. At a structural level, as well as at an architectural level, this product – Figure 1 – presents great advantages, not yet duly explored in the context of international architecture. Natural lighting, as a key element in architecture, is one of the main aspects to explore [10], as well as the volumetric expressiveness resulting from the structural assumption of an element with such characteristics as glass. Initially, there is the purpose of applying this product to evolving housing, firstly in only one floor, then in two floors. This would make it the first building with glass structure with more than one floor. Some variation is possible regarding the geometry of the cross section of the beams, thus allowing a greater or lesser stiffness and resistance of the structural element.

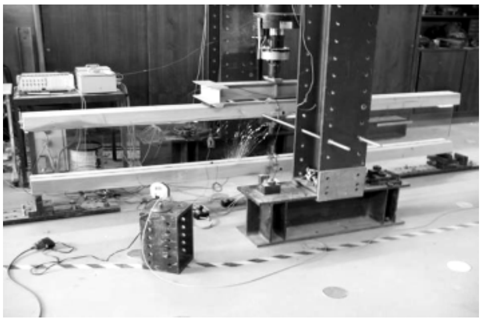

Figure 1a and b: Timber-glass composite beam.

2.2. Why a structural adhesive bonding?

This solution was adopted due to five main reasons:

- Ideal balance between strength and ductility, combining different materials;
- Uniform distribution of forces;
- Reduction of materials fragilization by avoiding drilling;
- Prevention of high peak stresses on glass surface;

2.3. Why glass in this composite structure?

For the three *Vitruvian* reasons:

- Aesthetics (*Venustas*) – architectural expressivity, transparency, magic and illusion and natural lighting;
- Functional (*Utilitas*) – thermal efficiency, sustainability and wood protection;
- Structural (*Firmitas*) – structural capacity, stiffness, strength and, new field not explored architecturally.

3. Architectural Solutions

3.1. Housing Model

This housing model aims at being the first building with more than one floor and a sustaining glass structure. The main intention is take full advantage of glass beams regarding the expressiveness of the building detached – Figure 2 –, or in urban model – Figure 3. On one hand, this is done by assuring the possibility of natural lighting in the intermediate space between both floors and consequent light entrances through the upstairs floor and/or downstairs ceiling; on the other hand, by enhancing the possibility of architectural expressiveness [11], mostly by making believe that the upper floor levitates and that, sustained by glass beams, seems to suspend in air – Figure 2b.

Figure 2a and b: Two floor housing model with timber-glass beams.

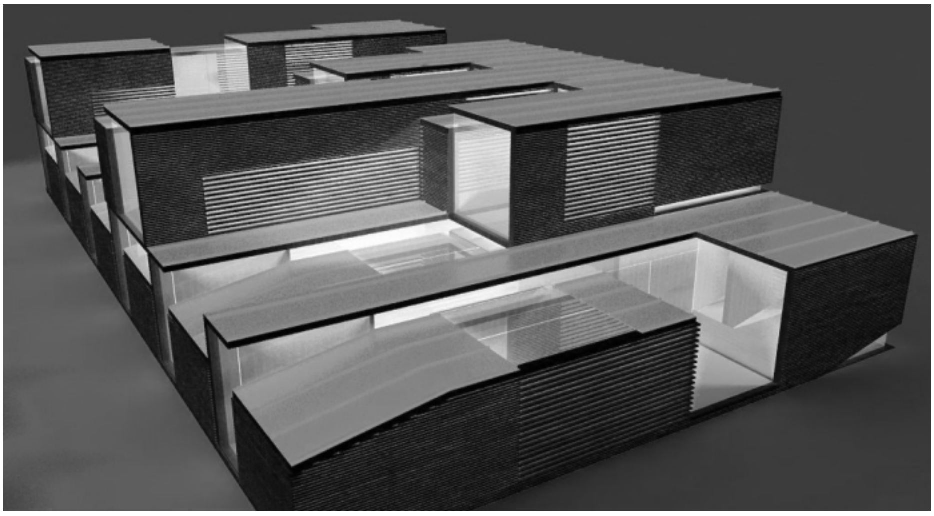

Figure 3: Urban modular solution – lighting through composite beams.

4. Experimental Studies

4.1. Laboratorial tests

In this set, twenty beams were tested – fifteen timber-glass composite beams, one glass beam and four timber beams – in sets of four point bending tests. All composite beams were 550 mm high, and consisted of 6.6.1 laminated glass 500 mm high, and *Pseudotsuga Menziessi* timber, with 100x70 mm^2 of cross section. The applied variables were four, as outlined on Table 1:

- Adhesive type – C (polymer); S (silicone) and Q (polyurethane reactive);
- Span – 650 mm; 1000 mm; 1700 mm and 3200 mm;
- Vertical support reinforce – with and without;
- Cross section – I section and rectangular (O) section.

Table 1: Tests performed – twenty specimens

Type section	I section							O section
Restraint	laterally restrained			laterally unrestrained				
Span [mm]	650	1000	1700	650	1000	1700	3200	3200
Laboratory Tests [•]								
Timber							•••• A	
Glass 6.6.1							• B	
C adhesive	•	•	•	•	•	•	•	
S adhesive	•	•	•				• C	• D
Q adhesive	•	•	•					

5. Results

5.1. Comparative analysis

Figure 4 presents a comparison between load-vertical displacement curves referring to four beams representative of what is intended to be analysed and demonstrated:

- A – Timber flanges with 3200 mm of span;
- B – All-glass beam with 3200 mm of span;
- C – Composite beam with I cross section, S adhesive and 3200 mm of span;
- D – Composite beam with rectangular section, S adhesive and 3200 mm span.

Analysing this dimension of beams – 3200 mm – leads to a direct and actual approach to the situation of constructive application, as the architectural design is based on this metrics, for questions related to prefabrication and transportability of the constructive elements. On the other hand, it enables a direct comparison between the capacities presented by the glass beam, the timber beam and the composite beam and easily concludes that the composite set works better than the sum of the components.

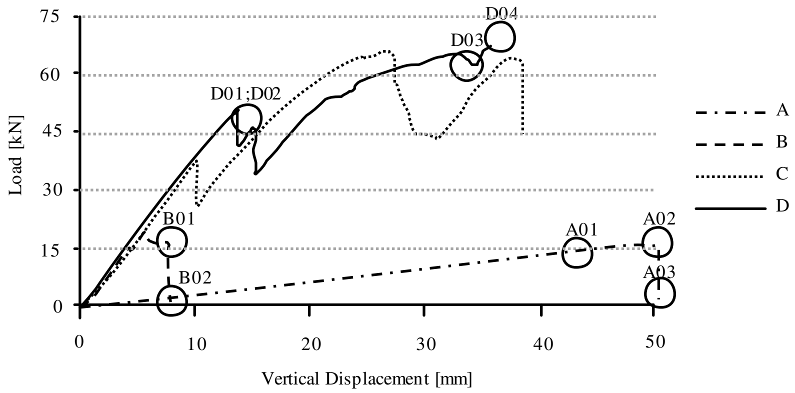

Figure 4: Load-vertical displacement curves of beams A, B, C and D (such legend in Table 1).

Beam A – consisting of timber flanges – presents a great capacity of deformation, as shown in Figure 5. Nevertheless, this characteristic spoils the load resistance capacity of this beam which, on average, does not bear more than 20 kN.

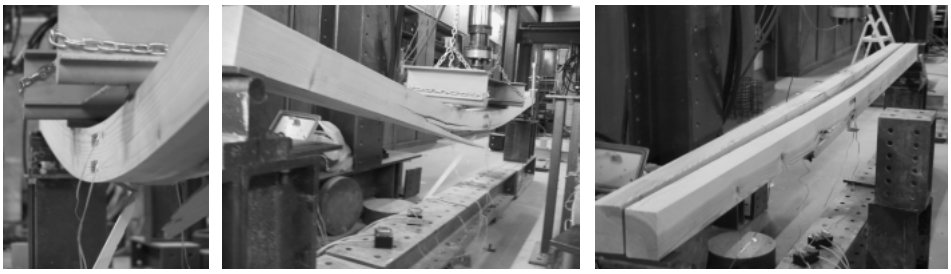

Figure 5a, b and c: Beam A – Tests on timber flanges in composite system. A01; A02; A03 in Figure 4.

As far as beam B – all-glass beam, Figure 6 – there is much more stiffness, as anticipated, but the brittleness presented by glass inhibits deformation from exceeding 5mm and the load bearing capacity from going further than 19 kN.

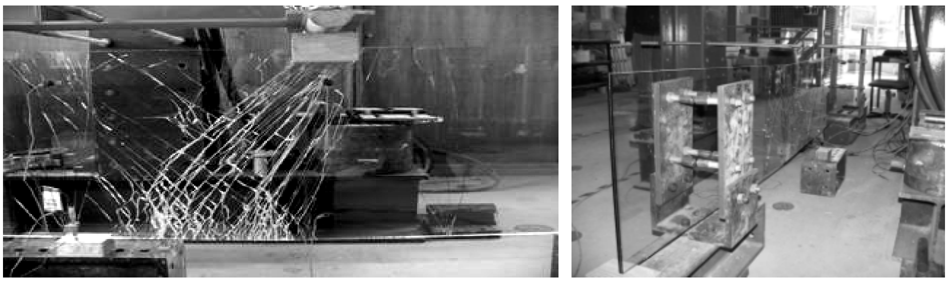

Figure 6a and b: Beam B – All-glass beam bending test. B01; B02 in Figure 4.

As regards beam B - timber-glass composite beam, rectangular cross section – highlight is given to the structural combination, which largely exceeds the sum of values individually presented by beams A and B. This beam has a corresponding load-displacement behaviour with much more incidences, resulting from the reaction capacity and stresses redistribution which characterizes this composite system. Figure 7a, 7b and 7c – point out on Figure 4 – represent some of those incidences. There is the sequential moment – Figure 7a and 7b – in which opposite glass plates crack, under a 50 kN load, at the area that is submitted to greater tensile stresses, causing a load redistribution that leads to a new increase in the strength. That load capacity reaches 67kN and from that moment on, the adhesive ends up collapsing at its lateral end – Figure 7c –, where it is subject to greater shear stress. Then, an interesting occurrence takes place. If properly used, that occurrence can function as an alternative safety system to the bonding connection. When in touch with its steel test supports, glass reacts in a resistance high peak that exceeds the maximum capacity previously mentioned. Only then does glass collapse, as shown in Figure 8. The design of architectural detail can envisage a system that benefits from that occurrence.

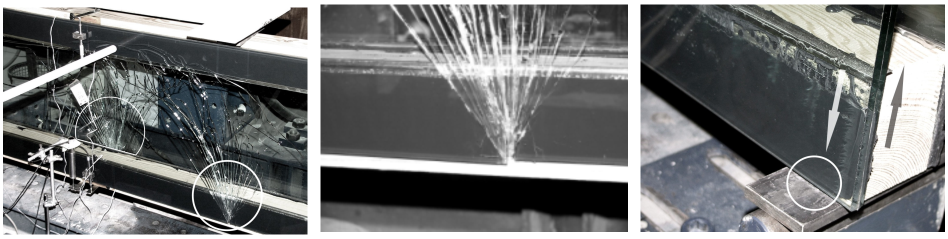

Figure 7a, b and c: Beam D – Composite beam, rectangular cross section. D01; D02; D03 in Figure 4.

Figure 8: Beam D – Composite timber-glass beam, rectangular cross section. D04 in Figure 4.

Despite the transversal section, beam C – composite timber-glass beam, I section –, presents a behavioural pattern very similar to the previous beam, though with less significant stiffness and several inferior values, which may be substantiated by the duplication of glass on beam C. However, it is also possible to observe the first cracking in the shape of an "*ear of wheat*" – Figure 9a – , the collapsing of the adhesive at the edge of the beam – Figure 9b –, and the increase of load resulting from the reaction of the glass plate on the support, which leads to the definitive collapse of the structure – Figure 9c.

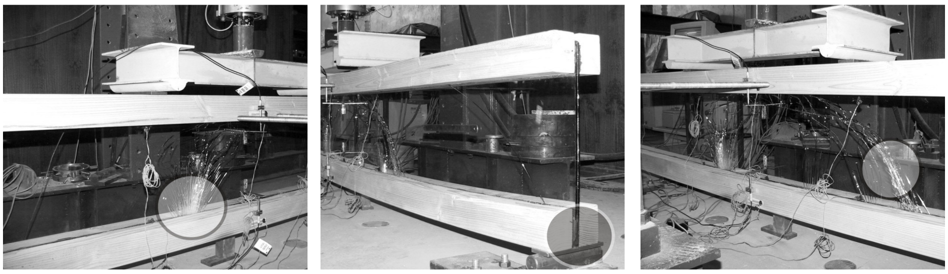

Figure 9a, b and c: Beam C – Composite timber-glass beam, I section. C01; C02; C03 in Figure 10.

5.2. Reference data

Table 2 and Table 3 illustrate some of the main values obtained in the tests performed, particularly concerning the first cracking and failure modes, respectively.
When attentively analysed, these values will result in a large set of conclusions that are not referred to within the scope of this paper.

Table 2: Results obtained in the tests performed, concerning to Serviceability Limit States

Type section				I section				O section
Restraint	laterally restrained			laterally unrestrained				
Span [mm]	650	1000	1700	650	1000	1700	3200	3200
				First Cracking Load / Serviceability Limit States				
Timber							-	
Glass 6.6.1							19 kN	
C adhesive; crack. mode	107 kN timber	101 kN timber	75 kN glass	88 kN glass	88 kN timber	59 kN glass	31 kN glass	
S adhesive; crack. mode	99 kN timber	22 kN glass	71 kN glass				35 kN glass	50 kN glass
Q adhesive; crack. mode	72 kN glass	69 kN glass	40 kN glass					
				First Cracking Vertical Displacement				
Timber							-	
Glass 6.6.1							5 mm	
C adhesive	24 mm	12 mm	10 mm	23 mm	18 mm	9 mm	7 mm	
S adhesive	13 mm	5 mm	12 mm				9 mm	13 mm
Q adhesive	5 mm	7 mm	5 mm					

In both Tables, the element of collapse is still identified, either in the case of the first crack or failure. This information leads to conclusions on the specific importance of every component in each case.

Table 3: Results obtained in the tests performed concerning to Ultimate Limit State

Type section	I section							O section
Restraint	laterally restrained			laterally unrestrained				
Span [mm]	650	1000	1700	650	1000	1700	3200	3200
				Failure Load / Ultimate Limit State				
Timber							20 kN*	
Glass 6.6.1							19 kN	
C adhesive; failure mode	130 kN timber	101 kN timber	96 kN glass*3	90 kN glass*2	97 kN glass*1	80 kN adhsv	55 kN glass*1	
S adhesive; failure mode	105 kN timber	86 kN timber	121 kN glass*3				65 kN adhsv	67 kN adhsv
Q adhesive; failure mode	96 kN timber	88 kN glass*1	48 kN timber					
				Failure Load Vertical Displacement				
Timber							100mm	
Glass 6.6.1							5 mm	
C adhesive	38 mm	12 mm	21 mm	25 mm	23 mm	18mm	13 mm	
S adhesive	17 mm	18 mm	50 mm				27 mm	35 mm
Q adhesive	9 mm	30 mm	30 mm					

* Average; *1 buckling; *2 buckling + adhesive; *3 shear stress

5.3. Safety

Guarantee of complete safety is a key necessity, without which it is not possible to reach the feasibility and implementation of this system. Figure 10, regarding beam C, confirms that this situation is properly assured, since the safety margin obtained is of about 85% in relation to the load capacity. Nonetheless, this value increases substantially as regards the vertical displacement.

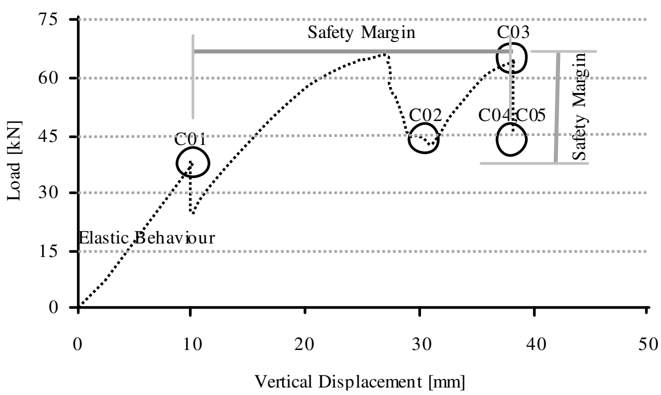

Figure 10: Load-Vertical Displacement curve of beam C (such legend in Table 1).

Figure 11a, b and c: Safety after maximum load. C04 (a); C05 (b) in Figure 10.

5.4. Why timber structurally combined with glass?

After analysing the test results, some important advantages for this type of composite structure were found:

- Ductility. With glass alone, no deformation of this level would be possible unless overloading point is achieved;
- Safety. It prevents brittle failure of the constructive system;
- Strength. The mechanical resistance capacity is enhanced;
- Evenly distribution of loadings due to the action of the structural bonding[12];
- Reinforcement of glass elements. Timber presents low variability in its longitudinal axis and this may play an important role in the lower flange;
- Lateral restraint of glass plate;
- Complementary characteristics, which gives meaning to composite behaviour. Glass is compression stress resistant; timber is tensile (in grain direction) stress resistant;
- Protection of the edges of glass, its most sensitive area;
- Possibility of creating a secondary structure for independent support.

6. Design and Detailing

One of the main purposes is to base part of the work on the design of solutions and details with a strong architectural component. As already mentioned in this paper, there is the possibility of using the high peak load capacity of glass after collapse of the adhesive. The integration of a metallic plate inside the timber structure, or a U profile, able to resist tension transmitted by the edge of the glass, will assure the redistribution of tension towards a larger timber surface.

Another example is correlated with the geometrical misalignment of glass in relation to the edge of the timber flanges – Figure 12a –, as to apply load on the surface of timber, thus protecting the edge of the glass plate from accumulated stresses.

One last example relates to the integration of wood flanges in a discrete restraint system, as to assure the stability of the structure. This is the solution to the buckling effect on glass in this context – Figure 12b and 12c.

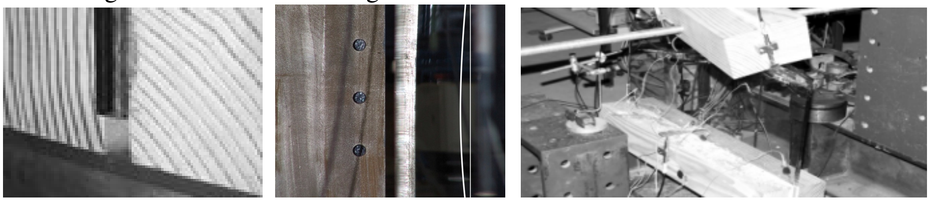

Figure 12a, b and c: Misaligned timber-glass geometry(a); buckling effect(b);laterally unrestrained beam(c)

7. Conclusions

In a generic analysis of the system, based in test results obtained, prominence is given to, among other aspects, the capacity of laminated glass to resist after first cracking, the less important influence of the heterogeneity of timber regarding the resistance of the specimens, and the effectiveness of the composite set.

Also worthy of attention is the fact that a discrete lateral restraint at the supports can be replaced by a continuous restraint of the upper flange, provided by the pavement.

Regarding the analysed adhesives, silicone adhesive is the most advisable, as it allows greater indexes of flexibility, thus assuring the needed structural mechanical resistance.

As demonstrated, the main characteristic of this composite system is that timber provides ductility and glass offers resistance and stiffness. These characteristics do not cancel themselves out. Instead, they are combined in a balanced behaviour.

8. Acknowledgements

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