Structural Timber-Glass Linear System: Characterization & Architectural Potentialities

José Manuel Pequeno [1,2], Paulo Jorge S. Cruz [2]
pequeno.jose@gmail.com
[1] dst domingos da silva teixeira, s.a. Rua de Pitancinhos, apartado 208, Palmeira, 4711-911 Braga, Portugal.
[2] ISISE, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal.

Keywords
1=Glass-Timber 2=Composite design 3=Architectural solutions
4=Structure 5=Lighting 6=Safety

Abstract

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 linear timber-glass composite elements – beams and columns – lies precisely on the exploration of the capacities of lighting through structural elements. This means it will allow benefiting from natural lighting in a way not much explored so far, creating light paths, improving spatial perceptions and achieving the most transcendent features of this material: magic and illusion.

Part of this presentation centres on the results that characterize the solution regarding safety and behavioural stability. This is essential to the practical, safe and generalised implementation of an innovative and promising technological system.

This presentation also focuses on the analysis of the results obtained in laboratory with more than twenty real-sized composite elements and several variables - variation in the cross sections geometry, adhesive type and lateral restrain. The final results and conclusions move towards the architectural applicability potential of this structural element in dwellings and urban solutions, designed to taking the best benefit from this technology.

Introduction and 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 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.

The present linear system comprises three components in the framework of the principles of sustainability: the economic viability of its implementation; the environmental compromise with recourse to solar systems; and the social and cultural support based on the constructive approach to nature and its renewable resources, which leads to the Forest Based Sector. Thus, the present system reinterprets, reinvents and recreates new horizons in the application of sustainable solutions. That is the spirit of its impact.

This constructive structural system fits in the market segment of sustainable construction, which will in short / medium term, become inevitable. Naturally, it is a segment which is broad and exponentially growing. The energetic component that the product includes will place it in a prominent position, which will represent an obvious asset.

This structural system was designed bearing in mind the preferable recourse to softwoods, that is, the ones grown throughout the European territory. Such principle is made feasible by the extraordinary input that glass and adhesive represent in terms of reinforcement of timber and the composite set. Tests and studies performed confirmed that even if hardwoods had been used, the behaviour of the system would not have substantially been improved, and this results in considerable wage reduction. Minimizing costs regarding production and implementation is of high importance. However it is also important to take into consideration that this system represents an enormous potential of applicability for European timber and glass markets.

The innovative Structural timber-glass composite linear system, tsquare, already patented - PT 104073 -, is illustrated in Figure 01. This product fits in a rand new generation of constructive systems. Such procedures of composite solutions present enough potential in order to become a booster in the economy of the glass sector, as they represent a new perspective and

Figure 1

tsquare system – structural timber-glass composite linear system. Total transparency.

attitude regarding such a primordial question as sustainability and its direct components: economic viability; social commitment and ecological protection and preservation.

Background of the tsquare system, as a glass linear structure

At the beginning of the 20th Century, a more open way of designing a house emerged, establishing an interior/exterior spatial relationship at this stage which was completely different from that which had existed up till then, thereby making a new field of conceptual relationships possible which opened up the way to the evolution of glass in architecture. From then until today, important innovations have arisen which have completely transformed glass industry and its field of application.

Glass which is tempered, laminated, coloured, with thermal and acoustic control, curved, U-profiled, photovoltaic, prismatic, bonded exterior glass or fastened exterior glass are just some of the types or variants of glass which currently constitute the state of the art of this material. Today, new possibilities are being looked at. However, in the specific context of the present invention, there is a matter of terminology which needs to be clarified and put into context: that which, as a rule, is currently called structural glass (exterior bonded system and glass fastening system), the solutions nowadays used. However, these solutions are merely self-sustaining and the glass does not have a function of resistance – and actually structural – to other elements, besides itself.

At present, whole structures solely made up of glass are becoming possible. However, the operation of this structural capacity in the glass is relatively recent, featuring as the main development means of this material – not only on its own, but also in composite systems. Resistant structural glass has mainly been deployed in linear elements as is the case of beams or columns. In the latter glass is tested on its own or in conjunction with other materials. Several examples are available such as the studies undertaken by De La Rochefocault and Manisse Olivier (when studying resistant elements in glass and their affixation system and connections – WO2006128887), by Seele GMBH & CO (when developing a metal-glass composite column for supporting building façade – DE102006044649), by Ulrich Knaack (also for the support and self-restraining of glass façades – DE19651444) by the Technological University of Delft (when strengthening glass beams with metal), by Michel Palumbo (when strengthening glass beams with carbon fibres and in other complementary safety studies – WO03023162), by the Technological University of Graz through Bernard Freytag (with concrete-glass composite beams), by the University of Dortmund in conjunction with RWTH Aachen (with mixed metal-glass beams), or finally EPFL of Lausanne by Julius Natterer and Klaus Kreher (with timber-glass composite beams).

However, it can thus be stated that a glass product was never truly developed in combination with timber in which both materials worked with the same structural importance. This is essentially because, in the context of timber-glass composite solutions, the problem of glass brittleness was never properly addressed. The timber-glass combination in the manner in which it is carried out in the composite linear system, both in geometrical terms as well as in terms of the semi-rigid adhesive bond, ensures a higher ductility, safety and autonomy index in terms of prefabrication as it is an autonomous, complete system.

Timber-glass composite structures – references and examples

The composite elements allow the best of the characteristics of two different materials to be brought together for a common purpose. In this case, in structural terms, the timber assumes good bending behaviour, being ductile to compression, whilst the glass presents a very positive result in terms of the compression force. Self-evidently, a composite structural solution shall manage to incorporate, contextualise and glean the potential of the advantages put forward, which can be observed in the results obtained from the tests of the present solution.

The main issue in the invention process is that timber and glass were very rarely bonded together in construction, all the less so in the truly structural sense. Timber-glass composite beams have already been referred to at the Hotel Palafitte in Lausanne in Switzerland by Klaus Kreher and Julius Natterer (which, as mentioned, incorporates a different logic at its origin and which was developed in the PhD thesis of the former "Traverhalten und Bemessung von Holz-Glas-Verbundträgern unter Berücksichtigung der Eigenspannungen im Glas").

At the HDW Info Pavilion, developed by the Wood-Glass studio of the Technological University of Helsinki by A. Lehto and T. Seppänen, the bonding system of timber and glass elements uses an acrylic bi-adhesive tape which seeks to ensure the positioning between the glass and the timber, but not allowing heavy structural loads.

Yoshiaki Amino, with the technical support of Jan Hamm, developed a family residence in Fuji in Japan where the outdoor shutters are made up of a wooden frame to which a glass sheet is stuck on the exterior. Contrarily to the usual door and window frame system, the glass pane ends up working as a timber protector. The

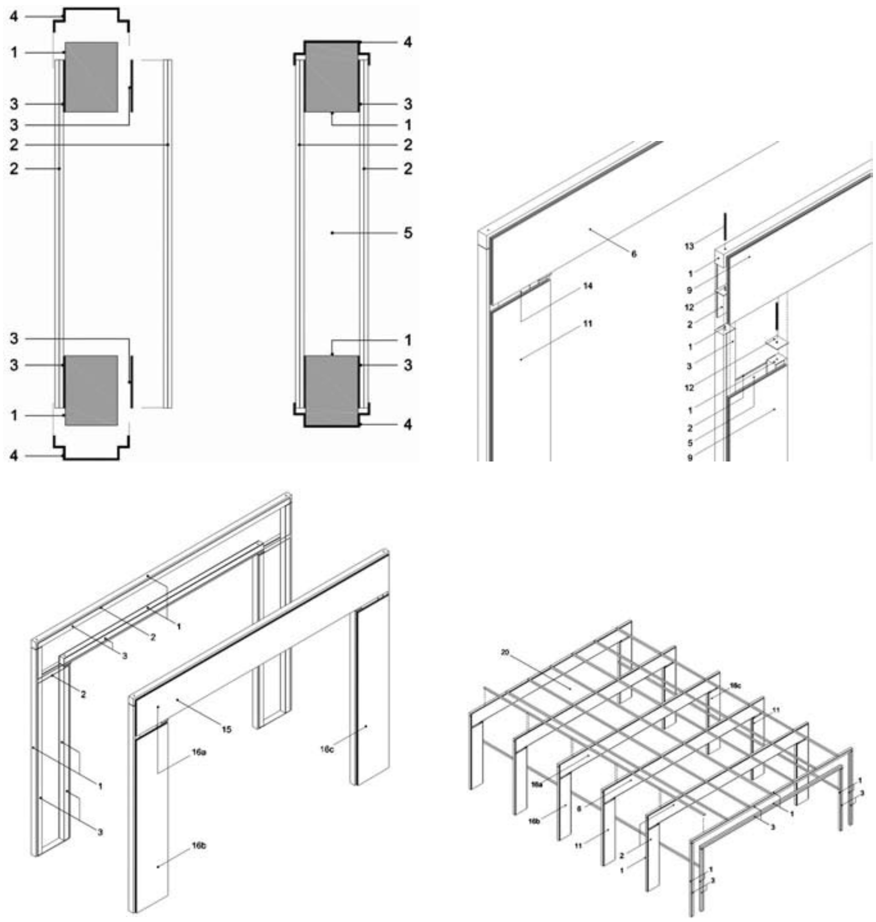
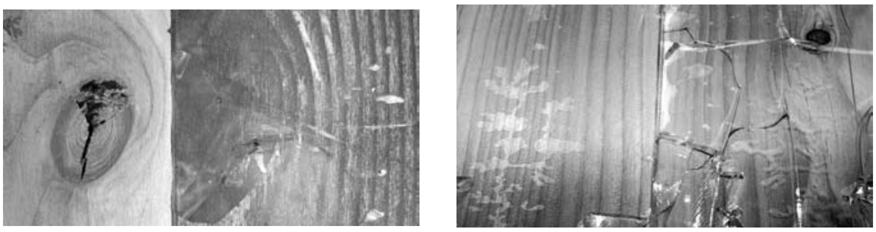


Figure 2a, 2b, 2c and 2d
System cross section and pieces and elements assembly

Figure 3

Consequences of timber tangential expansion on glass



Figures 4a and 4b

Different failure modes of the same adhesive, depending on primers application.

thesis - "Tragverhalten von Holz und Holzwerkstoffen im statischen Verbund mit Glas" – and the research work by Jan Hamm at the EPFL in Lausanne, not only refers to timber-glass composite beams, but also allows the results of some experiments to be observed using a rectangular glass pane stuck onto two timber battens situated on the two largest sides of the perimeter of the glass surface. The timber-glass frames of IBois – "Cadres Composites en Bois et Verre" -, from EPFL in Lausanne, carried out by Yves Weinand, are endowed with a structural use of self-restraining a laminar structure deploying these frames.

Finally, the Walch Window 04 uses the adhesive bonding system as the central element in the union between the timber and the exterior glass that protects it, slightly similar to that which occurs with the Amino project which has already been mentioned herein. However, the glass does not exercise any structural function in this case

Recapitulating, it can be concluded that the main challenge in terms of a composite timber-glass solution involves getting the most out of the expressive capacity and structural design of the materials, making up for the apparent natural deficiency of the glass in this regard and channeling the strains to which it is subjected to its compression capacity and avoiding the occasional, concentrated tensions on its surfaces. It is in this regard that the bondings are particularly important and this is why it was one of the main aspects of the research underlying the present system by means of the adhesive structural bonding, contrarily to the most common mechanical unions which would not solve the problem described above.

In this case, the challenge is the fact that the adhesive combines resistance and flexibility in view of the basic differences between glass (fragile) and timber (ductile under compression) which allows an even distribution of forces, the reduction in the fragility of the glass preventing boreholes and occasional tensions on the glass surfaces. Present solution was developed with the purpose and need for complementary and biunivocal structural operation between the materials involved.

Structural adhesive bonding system

The results obtained in laboratorial tests gave way to conclusions on various important aspects, such as strength and relative timber-glass displacement; timber deformation and its consequences; failure modes; variations due to surface treatments and primers utilization; glass type influence and also safety precautions that must be assured. Based the analysis of results, it is possible to identify three distinct groups in the context of strength and relative displacement:

- Adhesives highly resistant and insufficiently flexible;
- Highly flexible adhesives, yet insufficiently resistant;
- Adhesives that balance both key factors in this research: strength and ductility.

The greater the loading endured by the adhesive, the greater the strength to which both timber and glass will be submitted. A comparison between rigid adhesives – two-component acrylic –, shows that longitudinal deformation of timber is higher than timber-glass relative displacement. This fact brings consequences to the specimen behaviour. Longitudinal deformation of timber has repercussions in its tangential expansion. This represents precisely the occurrence that must be minimised, as it is responsible for the application of tensile stress on the glass surface directly in contact with timber, as shown in Figure 3. Even a highly resistant adhesive – tolerating stresses up to 15/20 MPa – under certain circumstances, easily fail due to the particular characteristics of the materials under study. Limiting the tangential dimension of timber in contact with glass surely represents a valid solution for this situation.

Different failure modes were observed depending on the type of adhesive and variables implemented. It was possible to conclude that surface treatment has a decisive influence in the adhesive bonding failure. In Figures 4, relating to the same product – a two-component acrylic – it is possible to observe two different types of collapses, through timber adhesion – primers applied – and through glass adhesion – without primers –, respectively.

Tempered glass, though more resistant to superficial stresses than laminated glass, presents two considerable and decisive disadvantages, such are brittle behaviour and an irregular surface. With some products – such as bi-component acrylic tape - , the difference is of less than half the effectiveness, due to the incapacity for compensating superficial imprecision.

Tests performed under the influence of temperature – Figure 5 – led to the conclusion that this factor will not hinder the accomplishment of the structural bonding system under analysis. Though there is a substantial increase of the loading capacity when temperature decreases to negative values of -10ºC, there is also the confirmation that the decrease occurring while temperature rises up to 40ºC is not worthy of note.

Regarding water saturation over long periods – Figure 6 –, there is a considerable loss of capacity at the level of the structural bonding and the elasticity of adhesives itself. This constituted an extreme test, based on circumstances that will not actually take place. However, it shows that it is important to bear in mind this question. The solution must ponder having control over the phenomenon of humidity

Figure 5

Temperature tests

Figure 6

Water saturation tests

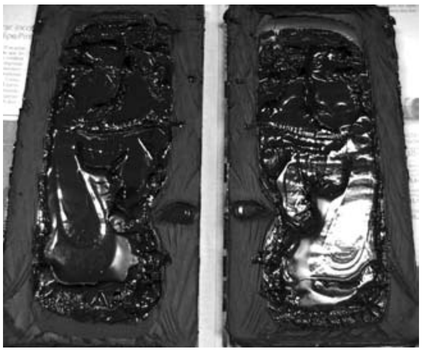


Figure 7
Glass-glass structural bonding

Type section	I section							box 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	•	•	•					

Table 1
Tests performed – twenty specimens

migration on the interface with wood, with recourse to the employment of specific primers.

Especially due to the utilization of glass, solar radiation is a decisive aspect when choosing the adhesive, not only for functional and structural reasons – UV resistance –, but also for aesthetic reasons. Silicone is the product that best responds to this type of necessities.

It is necessary to devote special attention to the glass-glass structural bonding, due to its imperviousness to air. This aspect may hinder the process of drying of the adhesive and consequent loss of capacity of the bonding system – Figure 7. In the case of timber-glass structural bonding, this issue is minimized by the porosity of timber.

Safety is a crucial and indispensable aspect. It implies deformability or ductility criteria, instead of brittle characteristics, which are unable to absorb tensions, usually much resistant but easy to suddenly and unexpectedly collapse.

The behaviour of the structural elements in periods ranging from the first cracking to the maximum loading resistance, and from this to collapse, is of essential importance.

The bonding solution pointed out in the present research can be a practical system regarding the structural use of several timber-glass composite elements. Depending on the geometry of the composite cross section, the specific mechanical characteristics of its components and the loading involved, it may be necessary to apply a more rigid or ductile adhesive.

The results obtained, concerning strength and ductility, demonstrate a wide range of mechanical behaviours - from extremely rigid to significantly ductile – and support the feasibility of this solution to the applications envisaged. Its main purpose should be the practical, safe and generalised implementation of innovative, daring and promising constructive systems.

Experimental studies – 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 box section.

Figure 8 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

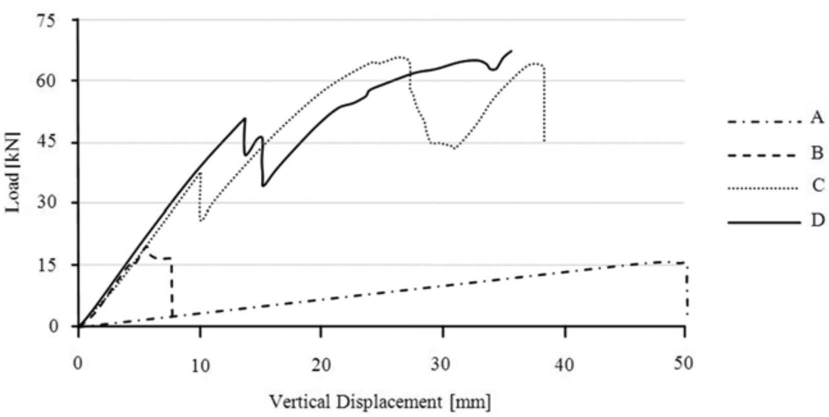


Figure 8
Load-vertical displacement curves of beams A, B, C and D (such legend in Table 1).

Type section	I section							Box 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	**90 kN** glass	**97 kN** glass	**80 kN** adhsv	**55 kN** glass	
S adhesive; failure mode	**105 kN** timber	**86 kN** timber	**121 kN** glass				**65 kN** adhsv	**67 kN** adhsv
Q adhesive; failure mode	**96 kN** timber	**88 kN** glass	**48 kN** timber					

Table 2
Results obtained in the tests performed concerning to Ultimate Limit State

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.

Table 2 illustrates some of the main values obtained in the tests performed, particularly concerning the failure modes.

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

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. Actually, 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 9 –, 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 10.

Tourist model – T3 unit, transportable tourist tower

The conception of this architectural design of housing and torusit model, essential in an early stage in the development of this work will, afterwards allow to face the characterization of the mechanical properties of the tested solutions with

Figure 9
Misaligned timber-glass geometry

guarantee of its future applicability. As far as the model itself is concerned – besides the already mentioned characteristics –, several types have been developed, ranging from studios up to five bedroom houses, either with vertical distribution – transportable tourist tower. Then, several implantation models have been developed, either as semi-detached houses and blocks. In a second phase, the structural solution was optimized, based on the search for tectonics and a contemporary architectural system construction. This goal led to the materialization of the tourist model – Figure 11.

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.

Figure 10
laterally unrestrained beam

Acknowledgements

A grateful acknowledgement is due to FCT, Fundação para a Ciência e a Tecnologia for the PhD grant with the reference SFRH/BDE/15538/2005, conceded to José Pequeno. DST, S.A., is also gratefully acknowledged for the commitment and support. Lastly, a thankful acknowledgment is also due to the significant support and effort of the laboratory staff at the Civil Engineering Department of University of Minho, mainly Mr. Marco Jorge e Mr. António Matos, whose collaboration was essential.

References

[1] Louter, Christian, Adhesively Bonded Reinforced Glass Beams, In: HERON, Vol. 52, No. 1/2, Delft University of Technology, the Netherlands, 2007.
[2] Palumbo, Michel, A New Roof for the XIIIth Century "Loggia de Vicari" (Arquà Petrarca -PD – Italy) Based on Structural Glass Trusse: a Case Study, Glass Processing Days, Tampere, Finland, 2005.
[3] Kreher, K.; Natterer, J.; Natterer, J.: "Timber-Glass Composite Girders for a Hotel, Switzerland", SEI, Vol.14, No. 2, 2004.
[4] Kreher, K., Traverhalten und Bemessung von Holz-Glas-Verbundträgern unter Berücksichtigung der Eigenspannungen im Glas, PhD Thesis Nr. 2999, IBOIS/EPFL, Lausanne, Switzerland, 2004.
[5] Weinand, Y.; Haasis, M., Cadres Composites en Bois et Verre, IBOIS/EPFL, Lausanne, Switzld, 2007.
[6] Hamm, J.: "Development of Timber-Glass Prefabricated Structural Elements", in Innovative Wooden Structures and Bridges, 2001, pp 119-124.
[7] Lehto, A.; Seppänen, T., HDW Info Pavilion HUT, Wood-Glass 2004-05", In: PUU, Finland, 2004.
[8] Freytag, B.,Glass-Concrete Composite Technology, In:SEI, Vol. 14, No. 2, IABSE, Zurich, Swtzl, 2004.
[9] Wurm, Jan, Columns, Glass Fins and Beams, In: Glass Structures. Design and Construction of Self-Supporting Skins, Birkhäuser, Basel, Switzerland, 2007.
[10] Baeza, A. C., A Ideia Construída, Edição Caleidoscópio, 2004.

Figure 11
T3, transportable tourist tower