Timber spatial trusses using hollow bars

Räumliche Holzkonstrukturen mit Hohlkastenelementen

Structures spatiales avec des éléments en caisson
en bois

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1. Introduction

Timber is an excellent material for use in high-span roof structures thanks to its great mechanical properties and low specific weight. In comparative terms, we can define the efficiency of a material in connection with any type of mechanical load as the quotient between its strength and its specific weight. Well, it is easy to verify that glued laminated timber and LVL outdo the performance of steel, which is normally used in building, in terms of tensile stress, compressive stress and bending stress. Its behaviour is particularly favourable in the case of short-term loads which are precisely what condition the dimensions of light roof structures the most.
1906 is a key year in the historical development of timber constructions. That year, Otto Hetzer submitted his patent to replace the mechanical means of connecting planks to one another by a casein adhesive. This allowed timber to be freed from its limitations in terms of form and dimensions set by the tree trunks they are obtained from. It likewise paves the way for new timber derived materials to appear. We might say that from that moment and onwards, the development of timber as a structural material truly began.
On the other hand, spatial trusses constitute one of the most significant typologies of the 20th century, because they are efficient when it comes to building long-span roofs. The trusses owe their efficiency to a combination of several factors: great strength and stiffness; lightness, thanks to the structure materialising itself in a triangular bar system; high hyperestaticity, which provides a great strain redistribution capacity.
The tetrahedral structure for a kite designed by Alexander Graham Bell in 1907, probably constitutes the first proposal for a spatial truss. During the more than one hundred years which have passed since then, countless structures featuring greatly diverse geometry have been built. An enormous development encompassing this field, ranging from node design or hoisting systems and on-site construction to the most diverse aspects of numerical control, has taken place.
In conclusion, a material as efficient as glued laminated timber and a high-performing structural typology like spatial trusses, both begin to develop during the first decade of the 20th century. However, they have, surprisingly enough, not been used together to a great extent. Those few examples which have been built have all occurred after 1985. The double-layer and double-curve spatial truss designed by Japanese architect Hamura Dohei Toh for the Oguni Dome constitute one of the most outstanding examples.

2. Hollow bars

There are historical records clearly showing that solid timber tubular section elements were used as early as the 13th century. They were perforated solid timber pipes for water supply.
Nature also provides us with natural hollow bars, such as bamboo. The extraordinary mechanical features of this material and the efficiency of a tubular shape make bamboo an ideal solution for bar constructions. Although there are numerous examples of constructions made of bamboo, it has virtually never been used to build spatial trusses. In this respect, only the proposals made by K Ghavami and L.E. Moreira of the Pontificia University of Brazil are worth mentioning.
The use of cardboard pipes when constructing bar structures has recently developed greatly. The works carried out by Japanese architect Shigeru Ban, constitute outstanding examples of the possibilities of this material, the most well-known example being the extraordinary Japanese Pavilion at the Hannover Expo in 2000. However, nor have cardboard tubes come to be greatly applied in the field of spatial trusses.

Figure 1: Hollow bars

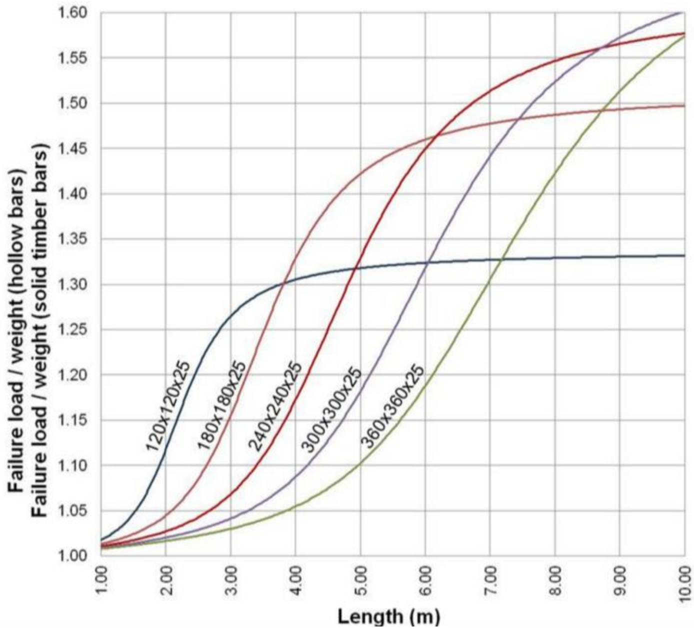

Figure 2: Comparative performance: hollow bars versus solid section bars

Figure 3: Compression test

Figure 4: Buckling

It is evident that using tubular section bars represents a particularly appropriate solution for constructing spatial trusses. This is so because we can get very long and light pieces featuring highly efficient compressive strength. At the same time, the tubular pieces are easy to manufacture employing glued laminated timber or LVL for the lateral sides (Figure 1). Figure 2 shows the increased compressive strength performance when comparing hollow bars to solid ones. Figures 3 and 4 show the high strength of this type of pieces obtained experimentally. Those figures correspond to the tests with 3340 mm long pieces with a 125 mm wide and a 25 mm thick cross section. The bars were made of glued laminated picea abies (Norway spruce) timber, strength class GL28h. The critical buckling load in the test run reached an average value of 190 kN for an weight of the bars of no more than 0.14 kN, meaning an optimal use of the material.

One of the main issues concerning timber spatial trusses is that of joining the bars together. The efficiency of a timber truss solution depends, to a great extent, on how efficiently the load on the bars is transmitted to the node. Thanks to adhesives having developed, especially the resin epoxy ones, it is easy to join bars together using threaded steel rods inserted in timber. This is a highly efficient system which is particularly appropriate to be used in building timber bar spatial trusses. Joining them together with glued bars gives great stiffness and strength and, in addition to this, they can easily be designed as ductile joints.
Our research team has carried out a lot of work, not only theoretical, but experimental as well, on this type of joints using a wide variety of timbers.
With the objective of enhancing the features of this type of joints, our team has developed a system which improves the anchorage of the bars. It is about creating a bulb or internally expanding the drill which is filled with epoxy adhesive. The expansion reduces the concentration of tensions at the end of the anchorage and significantly improves the joint's load capacity, thereby allowing shorter anchorages to be used. Figures 5 and 6 show the failure modes that occurred during the experimental trials with adhesive-bulb anchorages.
Joints employing glued-in rods and adhesive-bulb anchorage systems are easy to use in combination with tubular timber bars. The ends of the hollow bars are finished with solid high-density hardwood plugs, which serve a triple purpose: they serve as a pattern for gluing the lateral sides of the hollow bars; they are used for anchoring the glued threaded steel rods with adhesive epoxy; finally, they prevent fire from reaching the inside of the tube, which makes it more resistant in case of fire.

Figure 5: Adhesive bulbs to improve the axial strength of steel threaded bars glued in timber

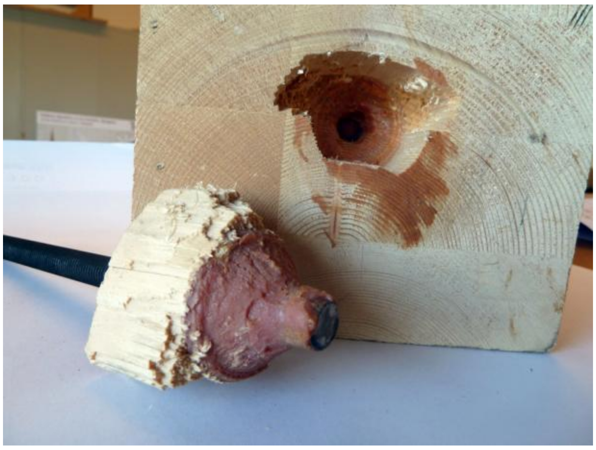

Figure 6: Adhesive bulbs to improve the axial strength of steel threaded bars glued in timber

3. Timber spatial trusses using hollow bars

Being asked by the University of La Coruña to design and build a sport centre, gave us the opportunity to construct a spatial truss employing stackable semiocthedrical modules made of hollow glued laminated timber bars.
The project basically consisted in designing the closure and the roof of some already existing facilities.
The closure of the space was performed by means of a 24-centimetre-thick brick wall holding up the roof structure. Said wall reaches a height of more than 10 m and needs to withstand the gravity loads transmitted by the roof as well as the wind actions. The wall begins in the foundation and it reproduces the plan design of the roof structure modules. The crown of the wall follows a straight plan on which the spatial truss is supported. The plan at wall's base and crown produces hyperbolic paraboloids which characterise the image of the façades. This way, we manage to unite an interesting aesthetical effect with a desirable construction easiness and rationality (ruled surfaces) as well as great structural efficiency.

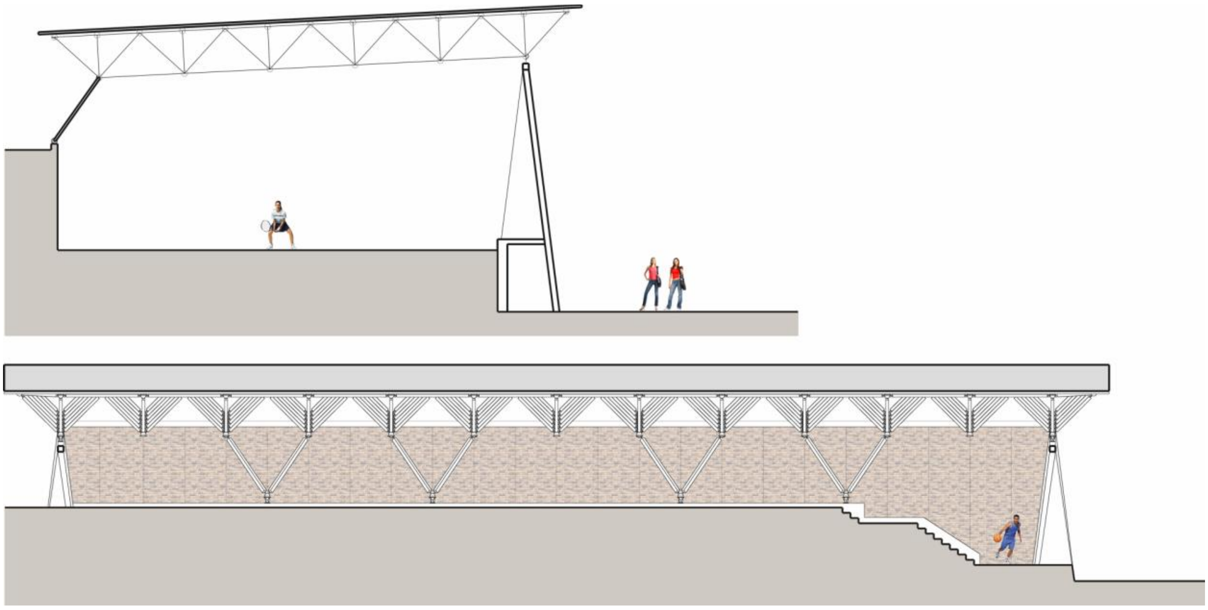

Figure 7: Sections

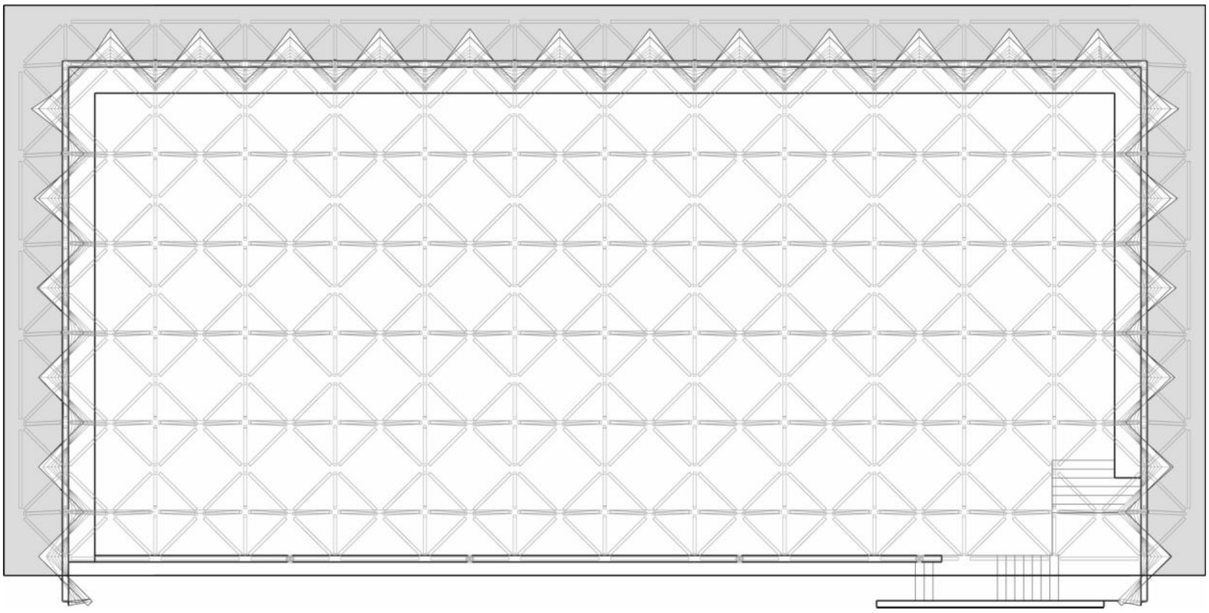

Figure 8: Plan

Figure 9: View of the brick walls

Figure 10: View of the brick walls

Figure 11: View of the brick walls

The roof structure is made up of a timber spatial truss which is held up by the bearing brick wall on three of its sides; on the fourth side, the structure is held up by v-shaped timber supports connected to the already existing concrete wall. The weight of the structure is 8.98 Kg/m^2, if we consider the wood only, and of 14.43 Kg/m^2 if we take the repercussions of the ironworks and metal connections into account.
The spatial truss is composed of semi-octahedral stackable modules which are placed 45º with respect to the truss's edges. This geometrical arrangement is due to aesthetical reasons and so as to be consistent with design of the brick wall. The studies also clearly showed that this arrangement was the one that lead to a lower number of stackable modules of different dimensions, which favoured the idea of modular construction. The total number of modules amounts to 78. The modules are 2.45 m long and 1.73 m high and they are made of hollow laminated spruce timber bars, strength class GL28h. The bars employed have a hollow 125 mm wide cross section and they are 25 mm thick. Only the V-shaped supports and their immediate diagonals have different dimensions, being 150 mm wide and 30 mm thick. The structure is completed by the bars in the lower layer which link together the vertexes of the modules, which are 346 cm away from one another.
The bars are joined together by means of a sphere-cap-shaped node made of cast steel. The design of the node comes from a double requirement: joining together the bars which make up each module; and joining the modules together to one another. The bars are linked together with the metal node by means of a threaded bar made of 8.8-quality steel with a 24-mm diameter. The rod is glued into a piece of solid high-density hardwood by means of two-component epoxy resin (Sikadur 52).
Figure 12 shows the dimensions of the semi-octahedral stackable piles. In figure 13, the details of the lower and upper nodes are shown in detail.
Finally, figures 14 to 24 show different aspects of how the truss's modules were assembled as well as pictures of what the completed construction looks like.

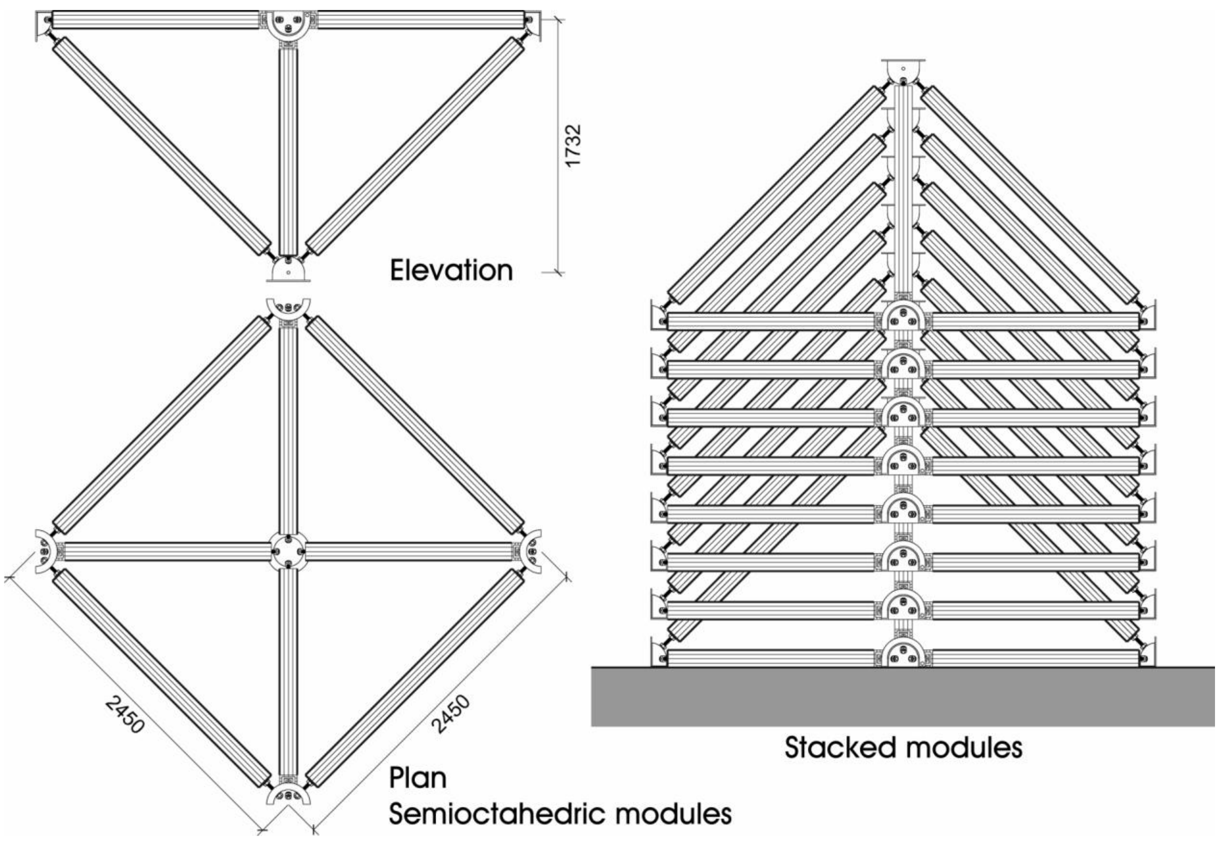

Figure 12: Stackable modules

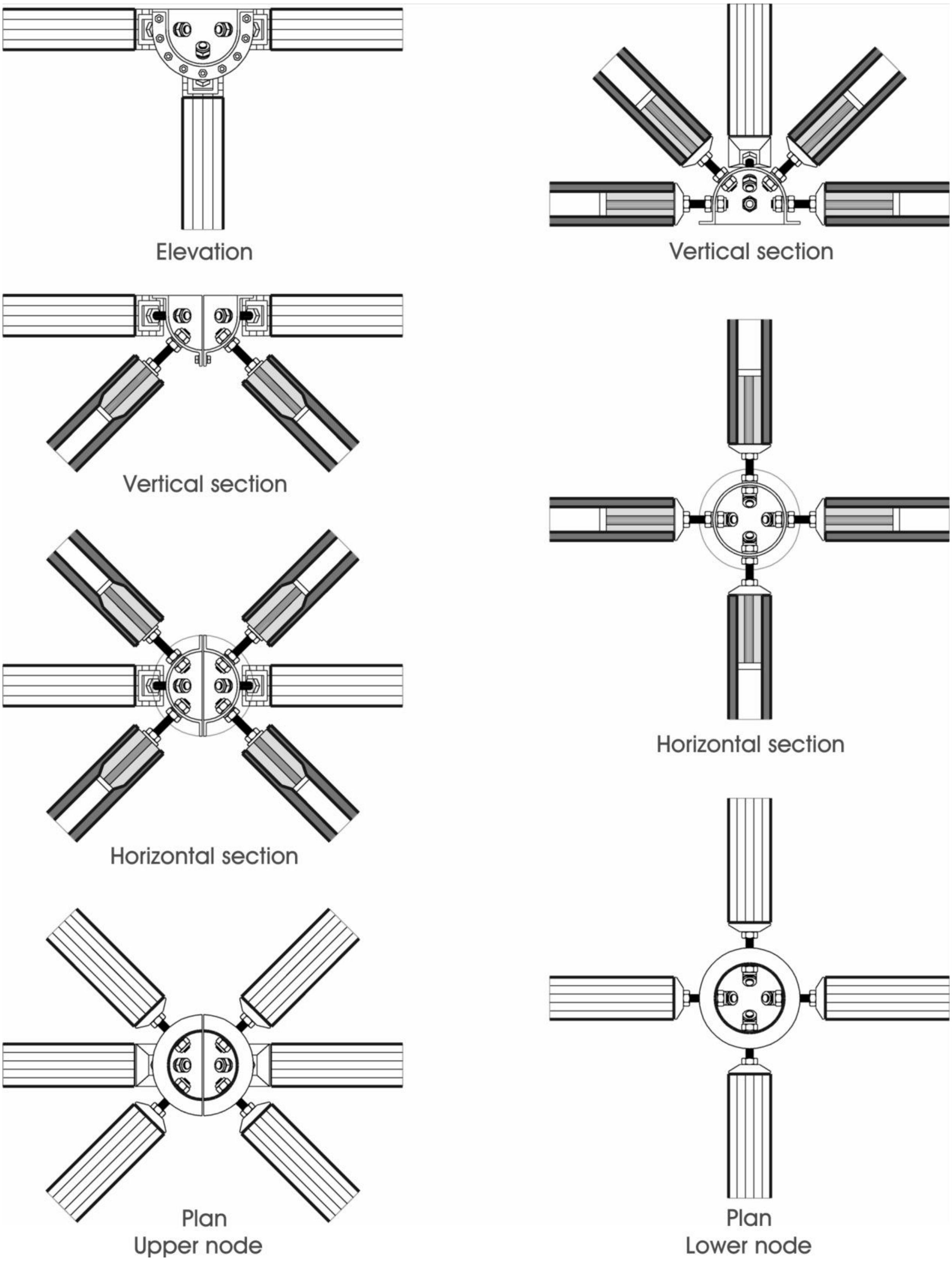

Figure 13: Nodes

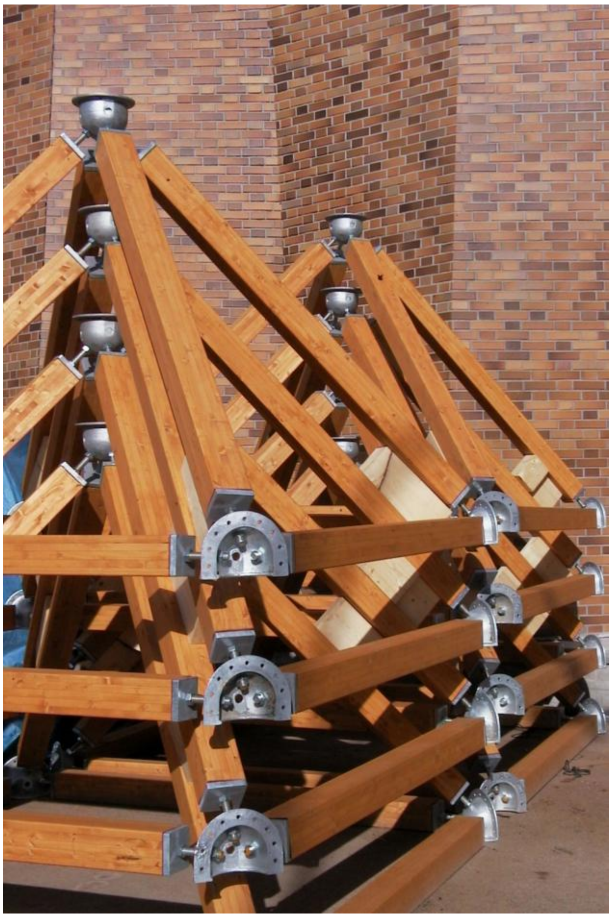

Figure 14: Stackable modules

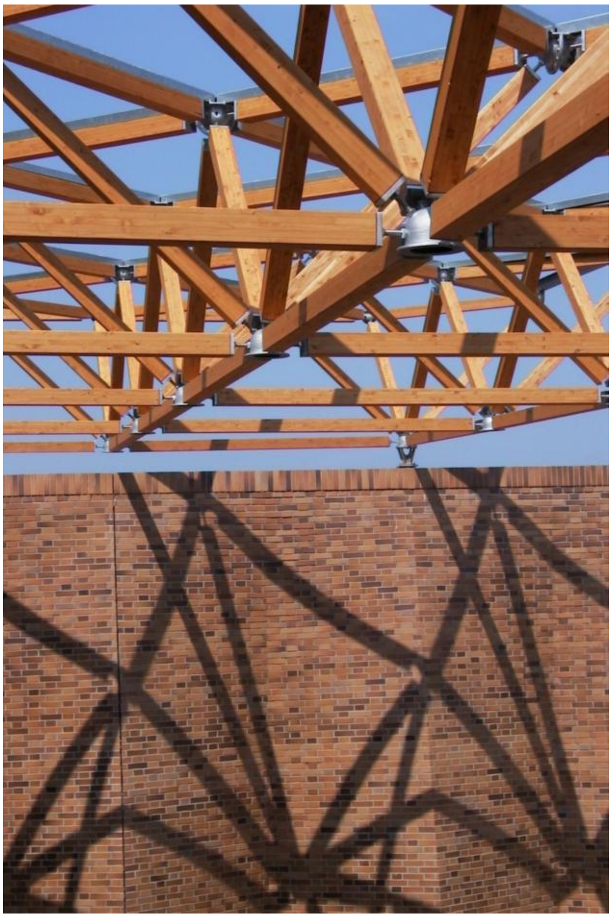

Figure 15: View of the timber spatial truss

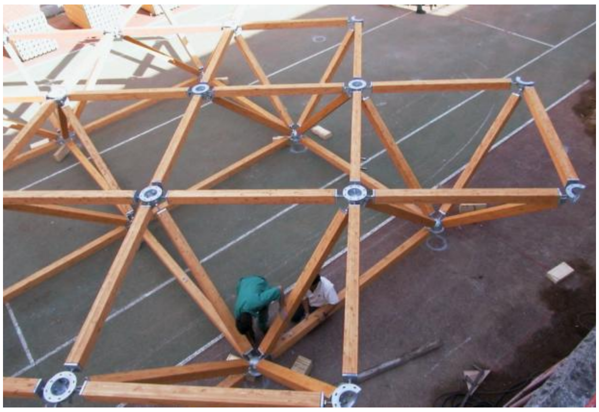

Figure 16: Assembly process of modules

Figure 17: View of a upper layer node

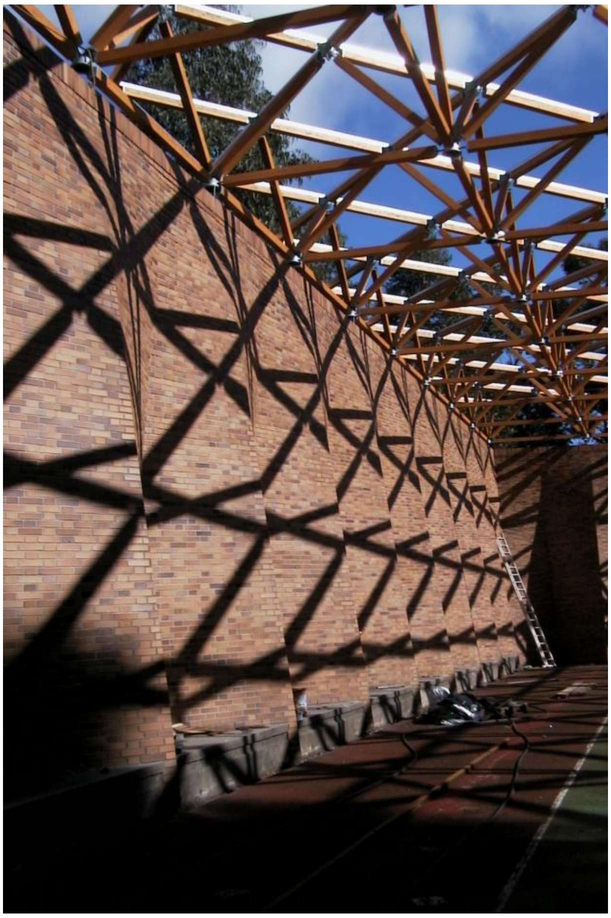

Figure 18: Internal view of the building

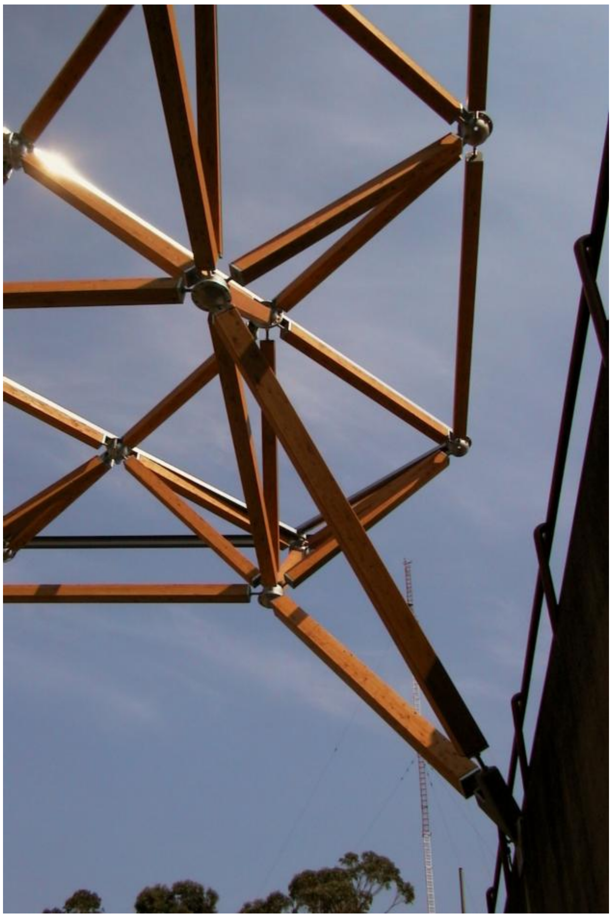

Figure 19: View of the timber spatial truss

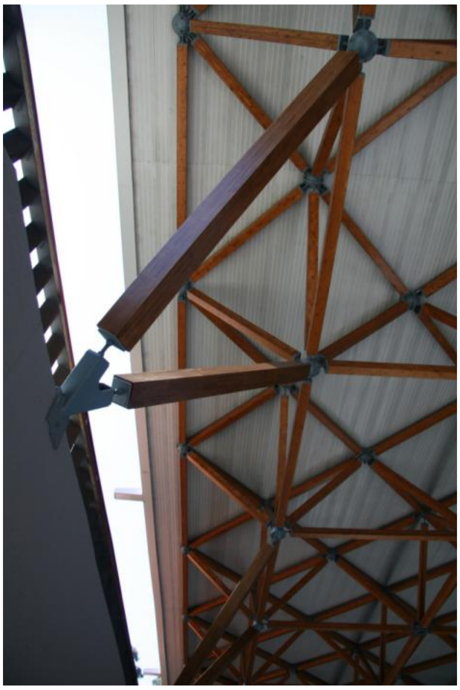

Figure 20: View of the timber spatial truss

Figure 21: View of the timber spatial truss

Figure 22: External view of the building

Figure 23: External view of the building

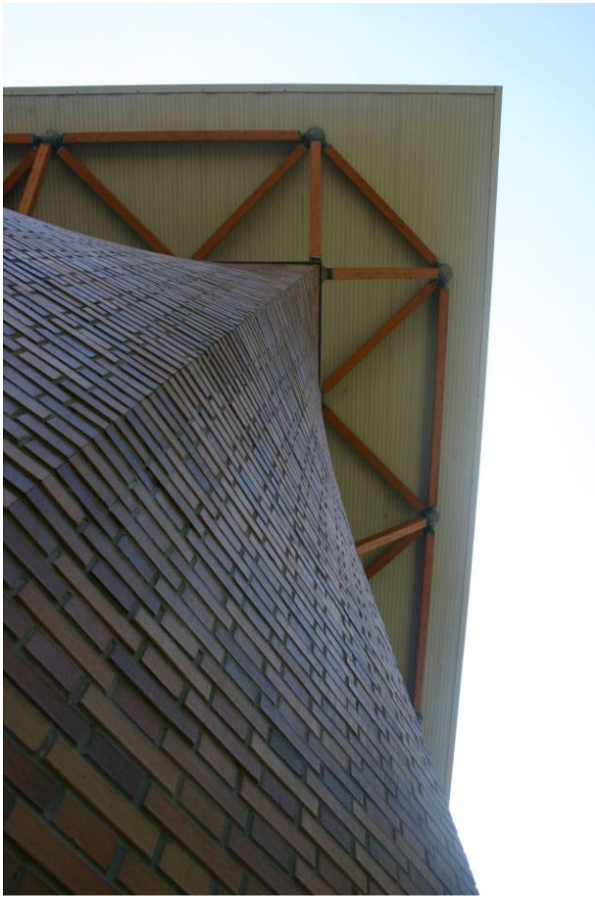

Figure 24: External view of the building

4. Conclusions

Spatial trusses using hollow bars made of glued laminated timber or LVL constitute a highly efficient solution for building long-span or medium long-span roofs. This efficiency occurs as a result of the joint use of two elements that are especially appropriate for light long-span structures: timber and the spatial truss as a structural typology. Glued laminated timber or LVL contribute to the efficiency of the structure as a whole by providing high-quality mechanical properties with low specific weight. As for the spatial truss, it contributes with a structural typology providing high-quality structural features which unite low weight, high hyperestacicity and great stiffness.

Using spatial trusses designed with an appropriate geometrical configuration permits building a modular construction with elements which, in addition, may be stacked. All of this redounds positively to the manufacturing, storage and assembly process.

Using glued timber or LVL hollow bars is especially appropriate for the spatial truss typology. In addition to being a truly simple manufacturing process, very long and light pieces can be designed and only be slightly punished by buckling. This allows recurring to larger modules, thereby decreasing the number of nodes in the structure, lowering the cost and creating a greater open space.

Employing joints with glued rods and a bulb system, constitutes an ideal system for use in the building of timber-bar spatial structures.

The glued-bar joints make it easy to join any type of truss typology and geometrical layout to the node. Moreover, high-strength and rigid hidden joints with ductile behaviour are achieved.