TÉCNICO LISBOA

Glued Laminated Timber Structural Design

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Extended Abstract

Jury

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Introduction

Timber was one of the first materials to be used by mankind. It was easy to obtain, to work with and presented capacity for a wide range of possibilities. But with the introduction of steel and concrete in current constructions, timber use started to decay, as it couldn't keep competitive against these new materials. The introduction of mass produced glued laminated timber (glulam), by Otto Hetzler (1), came to change this building material's advantages. It became a competitive solution.

But doubts and misbeliefs were raised, concerning timber's durability and fire safety, although they were inaccurate (2).Timber structures, in Portugal, never gained relevance. This led to a loss of specialized engineers in timber design, making the author's goal to learn how to correctly design timber structures.

State of the art

Production

The production of glulam is actually an industrialized and code regulated process, using synthetic adhesives, such as polyurethane and phenol-based compounds. It uses the finger-joint technique to assemble end-to-end boards to create laminations and then the laminations are all bonded together using a proper adhesive. This adhesive is chosen according to the service class of the member. There are three service classes according to Eurocode 5, as presented in Table 1.

Table 1 – Service classes

Service class	Environmental conditions
Service class 1	A moisture content in materials corresponding to a temperature of 20ºC and the relative humidity of the surrounding air only exceeding 65% for a few weeks per year. The average moisture content in most softwoods will not exceed 12%.
Service class 2	A moisture content in materials corresponding to a temperature of 20ºC and the relative humidity of the surrounding air only exceeding 80% for a few weeks per year. The average moisture content in most softwoods will not exceed 20%.
Service class 3	Climatic conditions leading to higher moisture contents than in service class 2.

Durability

This service classes will also be used for choosing the right preservative treatment in accordance with EN 460 (3), unless timber's species have adequate natural durability, in accordance with EN 350-2 (4). The preservative treatment is used to avoid the attack by biological agents as xylophage insects or molds. This agents reduce the bearing capacity of timber, by reducing the actual strength of wood fibers or, by reducing the effective section area or a combination of both.

As it can be seen in the service classes, the moisture content has a main role in wood's durability, but it's also important for the dimensional stability, because the wood swells with the increase of moisture. So when designing timber structures, the detailing have to accommodate this size variation in members. This moisture content variation is mainly due to the seasonal effect in air humidity, but also due to exposure to direct sunlight.

Structural behavior

Timber is a material with capacity to withstand both tension and compression stresses, but the structural behavior of timber is dependent to its fiber direction and defect presence. Meaning that, a piece of timber with a tension applied in direction of fibers, clear of defects, is more resistant than other, of the same species and in similar environmental conditions, with the force applied perpendicularly to the direction of fibers and/or with defects. This behavior is due to timber's anisotropic arrangement of fibers. The bearing capacity is also dependent on moisture content and load duration.

The Eurocode 5 brings the partial coefficient method to the design of timber structures, this method translates the anisotropy of timber in angle dependent coefficients, simplifying structural detailing. This structural detailing has two parts: the Service Limit States, which verifies the quality of service of the future construction, and the Ultimate Limit States, that check the structural safety. Timber connections are also covered by the Eurocode 5, which divides it in two groups, the glued joints and the connections with mechanical fasteners. For the last ones, its used the Johansen's theory for the determination of the load-carrying capacity of a connection. The carved connections are calculated as a typical shear force.

The behavior of timber exposed to fire is mostly time and size dependent, meaning that a timber member will resist more time the bigger the section, due to reduced specific surface and the good insulation capacity of carbonized timber. So for timber's fire design its usually verified by checking if the partial section not burned, after a specified period, still has the capacity to support the applied charges.

The second part of Eurocode 5, a bridge specific code, besides mentioning particular values to the security partial coefficients, also gives some constructive guidelines to be respected such as: the great importance of water draining, avoiding still water with an imposed inclination to all pieces in the bridge, the assurance that all members are ventilated and clearance to timber's dimensional variation.

Case study

To apply all the knowledge gathered, was chosen an initial design of a road bridge, afterwards was made a cost comparison between timber and reinforced concrete solutions. To make a connection with a real possibility, the bridge would be designed to replace an existing one. The bridge to be replaced has a length of 110m and 4m wide and crosses over the Sorraia river.

For the external actions on the bridge and service conditions, the Eurocodes 0 and 1 where used. The traffic load was simulated according to Load Model 1, using the α_i coefficients unitary. This Model complies two simultaneous systems, a tandem system with two axles of 300 kN each and a uniformly distributed loads system having a weight of 9 kN/m^2.

Was considered that members covered are in accordance to Service Class 2 and all other parts belong to Service Class 3.

Was chosen for the structural timber glulam GL 28h, with specifications in accordance to EN 1194 (5).

During the design a beam supported deck solution was selected as structural system. Given the length to cross, was chosen three span alternatives: 15m, 13.75m and 10m, all simply supported solutions. To estimate the remaining dead loads was design an initial cross-section of the bridge, according to Figure 1.

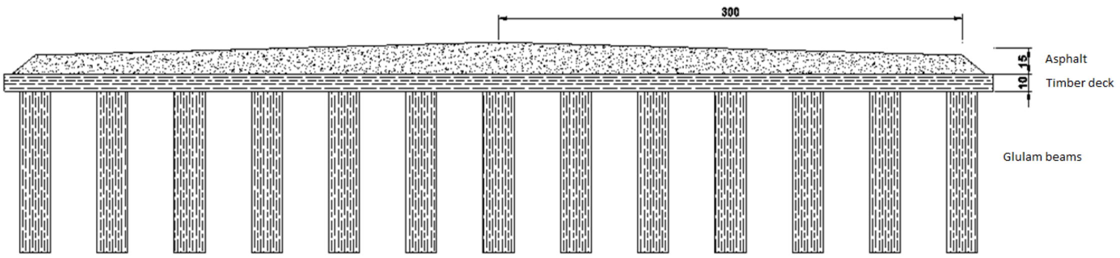

Figure 1 – Initial cross-section

In the deck, for the dispersal of concentrated loads, was considered the use of a cross laminated timber panel, with a half of the bridge width, 3.25m, and on top of that would be applied a layer of asphalt, 15 cm thick, to also contribute to dispersal of charges and to improve the grip for the vehicles.

A summary of all solutions is in Table 2.

Table 2 – Summary of solutions

Solution	Spans m	Number of spans	Traffic loads	
			$M_{Sd,max}$	$V_{Sd,max}$
1	15 (10)	6 (2)	$4744\ kNm$	$1305\ kN$
2	13.75	8	$4327\ kNm$	$1280\ kN$
3	10	11	$2775\ kNm$	$1170\ kN$

All calculations were made using *FTool*, version 2.12, a dimensional analysis software.

The ULS's Load of short duration and the SLS's long term deflection were picked as pre-design criteria.

After an iterative process, the following cross-sections were obtained for the three solutions, with a spacing between beams of $0.50\ m$, Table 3 :

Table 3 – Solutions' cross-sections

Solution	Width of cross-section	Height of cross-section
1	$0.30\ m$	$1.12\ m$
2	$0.20\ m$	$1.20\ m$
3	$0.20\ m$	$0.92\ m$

From the three solutions number 3 was elected, for the following reasons:

- The beams use less glulam volume, less 45% than solution 1 and less 23% than solution 2;
- The biggest members will have a length of approx. 10m, which transports are road legal, and will not need special permits;
- The cross laminated panels are produced only to a maximum of 10 m, so this solution will dismiss the creation of joint in the middle of span;
- All the members will be lighter and easier to maneuver, making possible the use of lighter and cheaper elevation equipment.

Comparison between timber uses in the solutions, Figure 2:

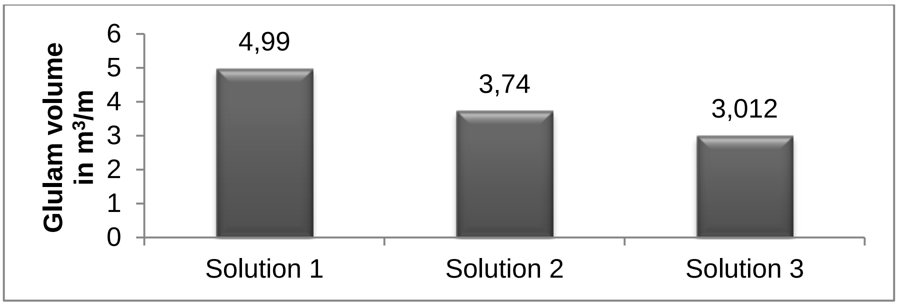

Figure 2 – Glulam volume usage

After careful design to the various Service and Ultimate limit states, was reached the conclusion that pre-design criteria, of long term deflection was most conditioning, so the section required remained the same. But in order to be easier to work between the beams and improve fire safety, the spacing was changed to $1.0\ m$, so the beam has now double the width, $0.40\ m$.

The support connections were designed to use a thin plate, $5\ mm$ thick, in each side of the beam, bolted through and through by 4 rows of 3 M22 8.8 bolts as showed in Figure 3. This connection is supported on a hinge, standing on a rubber base over the concrete support. This solution accommodates timber's dimensional variation and deflection movements without imposing more stress to the connection.

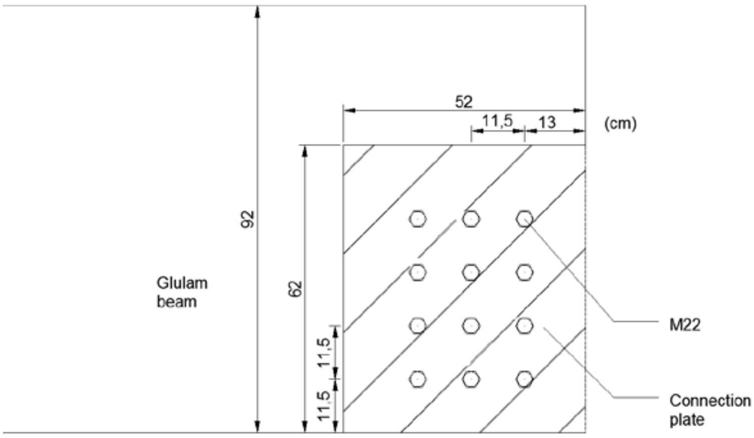

Figure 3 – End beam connection

The spacing between bolts complies with the minimum requirements of Eurocode 5, which were $90\ mm$ between bolts and $150\ mm$ for the space between the top of the beam and the higher rows of bolts.

Cleared the structural detailing, is now given special importance to constructive detailing, to enhance structure's durability. Two particular cases are worth mentioning:

- A protective cladding in outer beams, Figure 5. This protection function in two ways, one by covering the beam from rain and direct sunlight and two by working with a micro-ventilation process to keep timber's moisture content and temperature less variable;
- The use of connectors, for the rail guard posts, which offer the geometry necessary for correct ventilation of all members, Figure 4.

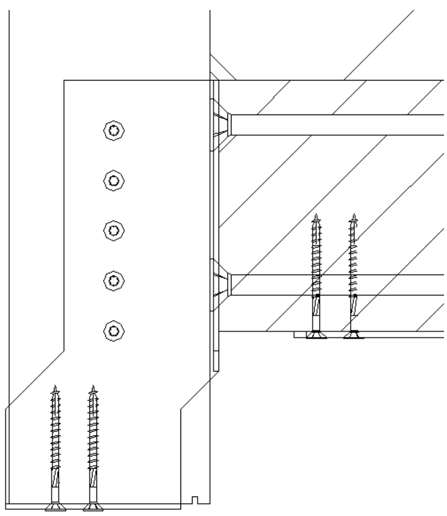

Figure 4 – Rail guard connection

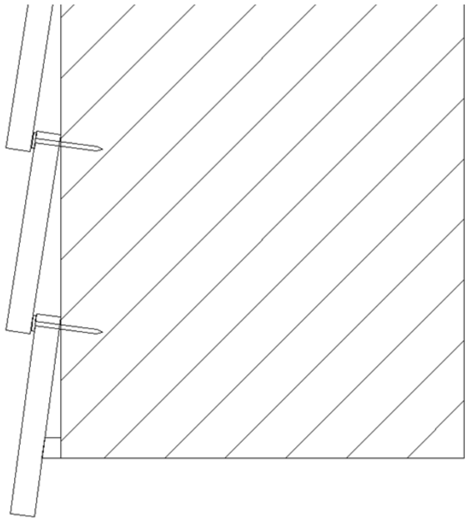

Figure 5 – Protective cladding

Several other general constructive rules were established such as: the use of timber in compliance to Service Class 3; for all connections most be used Fe/Zn 25c, a zinc protected steel; the adhesives used in all timber-based materials should belong to class I, according to EN 301 (6); should be applied a sealant coat to the top surface of the deck.

Costs

For the case study, it was considered that the timber deck could be an cost competitive option. So it was tested against an alternative in reinforced concrete. Was found that, for the same live load, the concrete estimated deck has approximately 4.5 times more weight than the timber deck solution. This means that the loads transmitted to the foundations, by the timber solution, are, according to the evaluation made, 46% of ones from the concrete solution, Table 4.

Table 4 - Timber / Concrete comparison

Load \ Solution	Reinforced concrete	Timber	Timber/Concrete comparison
$\boldsymbol{V_{Sd,G}}$	$1128\ kN$	$196.8\ kN$	17.45%
$\boldsymbol{V_{Sd,Q}}$	$585\ kN$	$585\ kN$	100%
$\boldsymbol{V_{Sd}}$	$1712\ kN$	$781.8\ kN$	45.64%

Given the unknown soil conditions, 15 m deep pile was used, with 4 piles by support and in the margins that number is raised to 8 piles. The estimated costs for Table 5 and Table 6 are based in the unitary values from the software Cype, except the cost of timber which was provided by the company Bernardino & Mendes.

Table 5 – Costs for timber solution

Parcel	Description	Unitary cost	Units	Total cost
Piles	55 cm diameter in reinforced concrete	245.5€/m	$(9 \times 4 + 2 \times 4) \times 15 = 780\ m$	191.482,20 €
Pile caps / columns	Margins	243.23€/m^3	$67.2\ m^3$	53.121,43 €
	Middle	243.23€/m^3	$151.2\ m^3$	
Timber Deck	Beams and CrossLam deck	1080€/m^3	$331.32\ m^3$	357.825,60 €
Steel connectors for supports	Steel connectors in Fe/Zn 25c	5.07€/kg	$5720\ kg$	29017 €
			Total	631.446,79 €

As for the concrete solution the costs are in Table 6.

Table 6 – Costs for reinforced concrete solution

Parcel	Description	Unitary cost	Units	Total cost
Piles	55 cm diameter in reinforced concrete	245.5€/m	$1560\ m$	382.964,40 €
Pile caps / columns	Margins	243.23€/m^3	$134.4\ m^3$	53.121,43 €
	Middle	243.23€/m^3	$302.4\ m^3$	
Concrete Deck	Reinforced concrete	250.00€/m^3	$660\ m^3$	165.000,00 €
Steel connectors for supports	Steel connectors in Fe/Zn 25c	5.07€/kg	$2860\ kg$	14.508,00 €
			Total	668.716,04 €

The difference in total costs is small, when compared to estimation errors. To give a perspective on the weight of each parcel on total cost, Figure 6 and Figure 7.

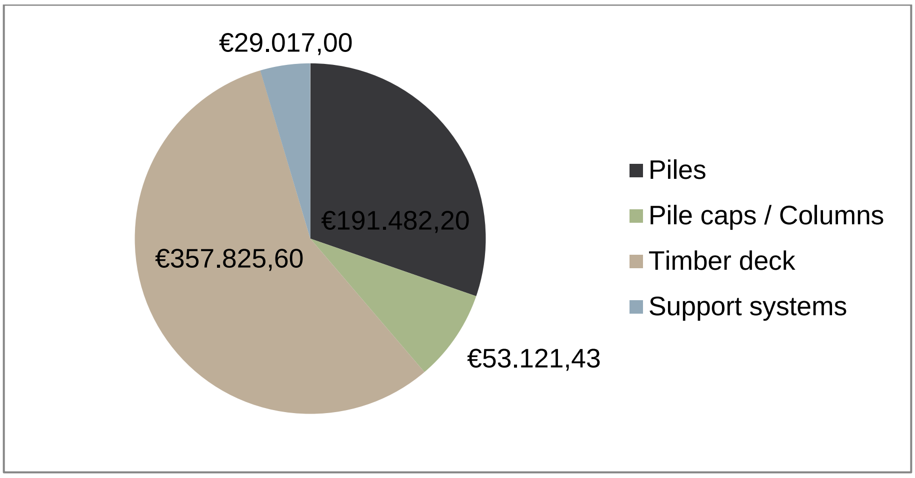

Figure 6 – Costs for timber solution

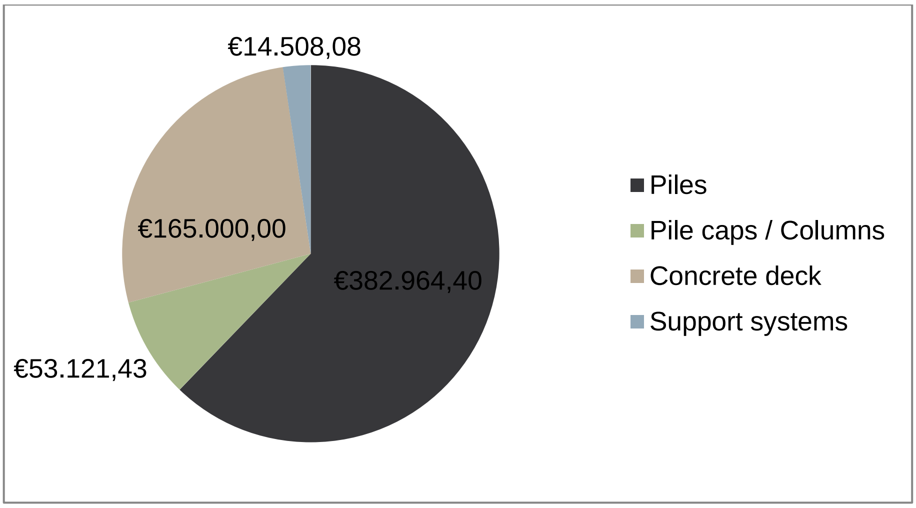

Figure 7 – Costs for concrete solution

It's observed from these graphics that, even if the totals are similar, the proportion between partial costs aren't.

In timber's solution great percentage of cost was due to the timber deck, while in concrete's solution the foundations were the most expensive parcel.

Conclusions

This work was focused on author's formation in timber's design, specializing on glued laminated timber. Has been approached timber's mechanical behavior remarked by its anisotropy and good capacity to withstand booth tension and compression. The manufacturing process was also described and a visit an actual glulam factory as taken place.

The durability and strategies to improve it were discussed. Such as the design method, provided by EN 335 (7), EN 350 (8) (4), EN 460 (3) and the EN 1995-1.1 (Eurocode 5) (9), based on criteria as moisture, wood species and temperature to evaluate the need for preservative treatment.

Its presented the Eurocode 5 and its design verifications to Service and Ultimate limit states. Design to fire protection and connections also was approached.

For the case study, a timber bridge was chosen, with a beam supported deck solution as structural system. This project defines a replacement option for an end-of-life concrete bridge. The timber bridge loading was defined according to the Eurocode 1 part 2 (10) to support full traffic weight. Special attention was given to structure detailing, concerning water drain, member ventilation and direct sunlight protection.

The cost comparison performed, between the timber bridge and a reinforced concrete alternative revealed that the proposed bridge is cost competitive. Evaluating the partial costs, was concluded that even with the timber deck being more expensive, the extra cost its compensated with cheaper foundations.

So the glued laminated timber showed objective and subjective advantages as its competitive cost and performance, its environmental friendly qualities inherited from solid timber or as its aesthetics and good blend with the surroundings.

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