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Case study

Comparative analysis of the reinforcement of a traditional wood floor in collective housing. In depth development with cross laminated timber and concrete

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ABSTRACT

The restoration of heritage buildings deserves innovative and sustainable solutions that prioritize reinforcement versus substitution. When considering materials to undertake the actions, wood and its derivatives such as cross-laminated timber (CLT) are an interesting option. The aim of this study is to conduct a comparative analysis of two constructive systems from a structural point of view. Both are mixed systems: concrete-wood and CLT-wood. The reference floor structure proposed to simulate a real situation is searched among the typology of existing floors described in different treaties from XVIII and XIX Centuries.

After comparing the samples in terms of deformation, in fire situation, and considering the influence by load increases on the building foundations, the lightness of the mixed solution wood-CLT offers advantages as it makes the state of permanent loads very similar to the original state of loads of the building.

1. Introduction

The growing development that problems related to rehabilitation of wooden floor structures, presents actions with various constructive solutions, and while the choice frequently responds to purely economic reasons, nowadays the possible historical and artistic value of the building on which the action is undertaken, should be considered. This can justify, despite being more expensive, opting or reinforcement versus substitution. Furthermore, there is an increasing sensibility towards the problem of reversible and less invasive techniques of restoration [1].

When such situations are faced, among causes which usually require to choose the type of measures to be adopted, they are wood degradation (loss of resistant section), change of use of the building (increase in service loads), functional reasons (deformations, vibrations), or the need to adapt to recent regulations (fire protection, soundproofing, etc.)

In any case, the generalized criterion of the designer during the 20th century when choosing the material to be used has been to prefer using concrete and steel rather than wood itself, usually considered as a more archaic and less practical or reliable material.

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In this type of construction it is increasingly common that changes in use are proposed, so the need to strengthen their wood slabs is faced, even being in good condition, to increase its loading capacity, and in turn increase their rigidity, as is frequently exceed the allowable maximum deformation for certain loads.

The increasing demands on security make that these floor structures should also perform functions that were not considered priority at their time of construction, like the ability to function as a rigid diaphragm in its plane, the vertical elements linked to it, in solidarity, so that they have a box behavior, allowing to absorb horizontal actions, and the ability to redistribute the gravitational loads between the different linear elements that compose it, so if one of them is overloaded, it can work together with the adjacent.

One of the most frequent reinforcement solutions applied to date has been the placement of a slab of lightly reinforced concrete on the existing slab previously cleared. But new lines of research are providing innovative and sustainable solutions that make wood and its derivatives currently an option to take into account when deciding the material to be used in such situations, as in the case of cross laminated timber.

In order to assist the process of decision-making in the design phase, a comparative analysis will be carried out from a structural point of view, for both building systems, to thus be able to assess which, with equality of benefits, presents more advantages and better qualities.

A case study is proposed to use it as a parameter of comparison, in a framework very close to what could be a real situation, although understanding that it is not a generalization.

2. Bases for the selection of the reference floor structure. The case study

The framework in which the analysis is located is the need for a reinforcement by change of use from housing to office, in a reference slab in good condition, located in the first floor of a building type of collective housing between party walls, with development in depth of the Madrid of the XIX Century.

The variety of existing slabs complicates the choice of what might be called a reference slab. It is a complex situation that has taken place in other practical research seeking a type, with the object of achieving practicality and application in decision making, both economic and design [2].

The documents found to date are not accurate, and in this typology lumber and parts form demolition used to be reused, so the dimensions of the elements are not very homogeneous. For this study, in order to simplify calculations, sections are made to the same sample. To be able to narrow the typology of existing floors, the base has been the following documents:

- The “Treaty on urban ordinances in Madrid”, from Teodoro de Árdemans in 1791 [3], since in it there are references to the scantlings used in the floor structures of the XVIII and XIX Centuries and, though the dimensions are based in anthropomorphic measures, in the “Law of Equalization of weights and measures” throughout the Kingdom, enacted by Carlos IV in 1801, there are already established equivalencies between the old measures and the new metric.
- Treaties and Construction Manuals, managed by architects and site managers for centuries, that collect guidelines of the constructive system with timber framework that has governed for centuries, allowing us to understand the principles used by those in their design and dimensioning. While in Spain there is little documentation of timber construction prior to the XVII Century, it's known that the wooden structures that were made at the time were calculated mostly applying rules from French technical texts. In Benito de Blais Treaty, “Elements of mathematics” of 1783 [4], the teachings of the major Gallic texts of the time are gathered.
- The “Treaty of masonry” of 1827 of Villanueva [5], that describes the types and construction processes of the beam filling that are often found, doing a very descriptive review of system and process.

2.1. Determination of span, squareness and beam fill

- In his treaty Árdemans contemplates a series of rules that relate the length of the floor structure with the scantlings to be used and that is summarized in the following:
- For small spans, of up to 3.60 m, a wood of a ten (8.70 × 12.18 cm), either a “sexma” and eighth beam (10.44 × 13.93 cm).
- In medium spans of up to 4.10 a wood of an eight (12.18 × 15.67 cm) was used, and up to 4.50 m were solved with a wood of six (20 × 13.93 cm).

Table 1
Joists dimensioning following Bails.

Span (Feet/m)	Squareness(Inches/cm)
15/4.5	5 × 7/13 × 18
15–18/4.5–5.4	6 × 8/15 × 20
18–21/5.4–6.3	7 × 9/18 × 23
21–28/6.3–8.4	8 × 11/20 × 28

- In the largest spans up to 5.74 m a "sexma" wood or beam of forth and "sexma" or joist of twenty second (20.89 × 13.93 cm) was used.

For his part, Benito de Blais recommended not to use joists over 18 ft, whose section is determined by its length (tightness) and the weight it supports (Table 1).

As separation between parts, it advises to use 1.25 times the beam width. The total edge of the floor structure, function of the weight and surface to be covered is estimated in 14″ in conventional housing. In terms of the types to be used, it describes as general case the perpendicular beam filling to walls.

Villanueva establishes that the beam fillings usually found are generally based on the fill between joists with gypsum as binder of different materials, and that the most common systems are:

- Hollow bricks of gypsum, with separations between joists of 1.5 feet (=1 elbow = 41.80 cm), 2 feet (56 cm) and even 3 feet (83 cm), thought as he describes, in the 19th century the frequent was to use one separation that was slightly larger than the thickness of the beam. This type of floor structure has been called "hollow by solid", using for this the wood of sixth or joist each 22, the wood at eight and the wood at ten or "alfargía". They were built by form working the future hollow brick with the "camón" or "galápago", placed on the notches or slats deliberately nailed on the lower sides of the joist.

The filling consisted of a mixture of plaster and rubble from the works, to make up the joists on their upper side (Fig. 1).

- Ceramic jars, with full filling of gypsum. The jars were placed between the joists, stuck between them, and tend to have irregular conical shape, of about 15 cm in diameter at the top and 12 cm diameter at the bottom. They are usually placed with about 25 cm of separation, butted. This requires about 0.003 m^3 volume (Fig. 2).
- Filling of massif, with a mixture of plaster and rubble (pieces of brick, plaster, etc.) to alleviate possible padding. When fillings are rubble and the technique hollow by massif " . . . the timbers tangle and weave with sieves, and regularly tend to be a distance one from another of the thickness of one of them, so sift is to cross in the middle of the spans. The cited materials of gypsum and the less heavy rubble are thrown on the boards between the sieves, mixed and locked with each other, forging up the soil, and below the ceiling is made" . . . (Fig. 3).
- Ceramic timbrel vault, which used to be of simple partitioned. Its use was appropriate for separations of beams between 3 and 4 times the thickness of the wood. On the notches the timbrel vaults were made with artisan brick using gypsum, and on top it was filled with plaster and rubble to level the joist, topped with the suspended ceiling, often made with a wooden slat finished with plaster.

2.2. Test samples geometry

A first classification of the most representative floor structures, depending on the maximum span length, and corresponding to a joist squareness, as Ardemans and Benito de Blais established in their treaties, is associated with the four types of beam more frequent that can be find as Villanueva determines, giving as a result the appearance of 16 samples; four of each maximum span and corresponding section (Table 2).

Each sample is named with a prefix (M), a letter and a color, which depends on the maximum length of the floor structure, and corresponds to the established joist section. In addition, it is accompanied by a number and shaded with a color range, depending on the types of beam filling (Fig. 4).

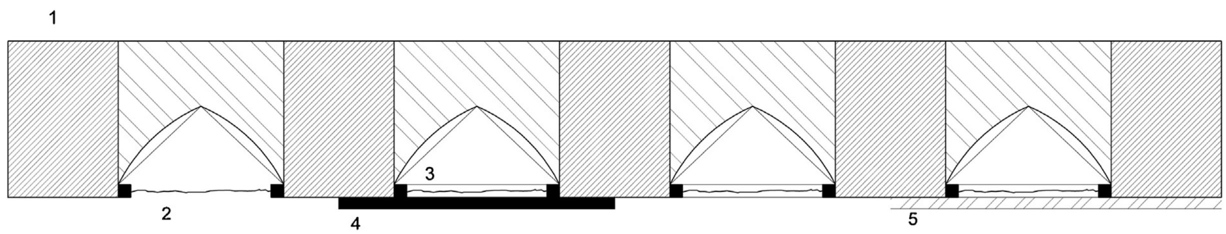


Fig. 1. Slab section with plaster beam filling.
1. Piece of wood.
2. Esparto grass net.
3. Gypsum filling mixed with esparto grass on board.
4. Formwork board.
5. White plaster.

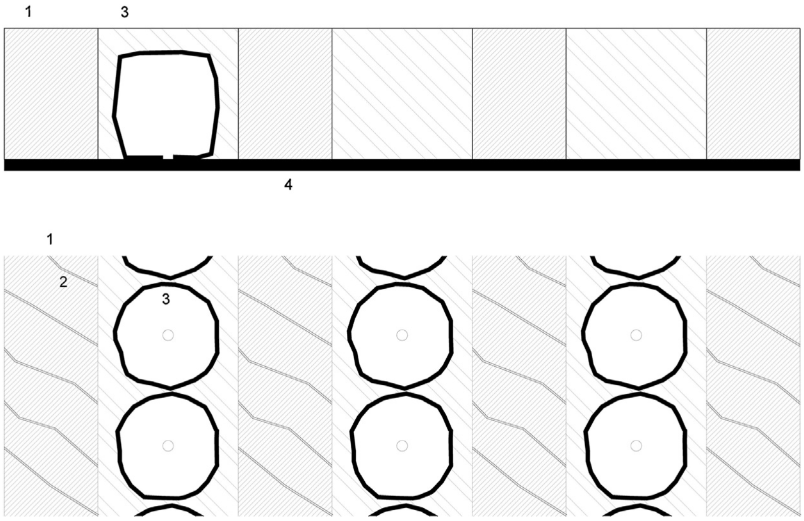


Fig. 2. Floor structure with ceramic pots beam fillings.
1. Piece of wood.
2. Esparto grass net.
3. Ceramic jar.
4. Provisional splint or white plaster.

2.3. The resistance class of the found wood

The strength class will be determined through the appropriate mix of species and quality, being the latter the most complicated work, as parts to rate are not normally fully accessible. Although the species is difficult to determine and a micro test sample will have to be analyzed to focus the issue, being the pinaster (Pinus pinaster), Scots pine (Pinus sylvestris) and Black pine (Pinus nigra) the species of broader presence in this type of work and that for a same quality, they have similar mechanical properties, we establish that, in this case, scots pine is the species used in joists [6].

Considering that in a real case we will have to make the analysis and relevant tests to establish geometrical and resistance reference values, and correct them with a coefficient of reduction depending on its apparent state in our theoretical case, we establish that the reference floor joist is solid wood, sawn, Scots pine (Pinus sylvestris), resistance class C18 (Table 3).

3. Description of the proposed reinforcement systems

This analysis focuses on the comparison of two construction systems used in the reinforcement of the reference floor structure: a reinforced concrete floor slab and a cross-laminated wood board.

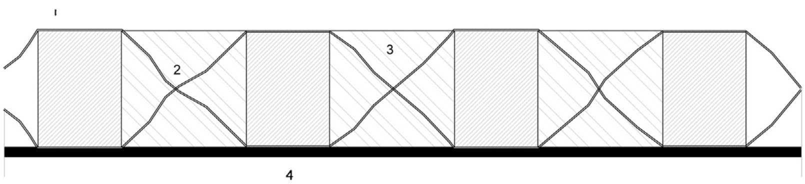


Fig. 3. Floor structure with massif beam filling.
1.- Piece of wood.
2.- Crossed esparto grass that ensures the filling.
3.- Rubble filling mixed with gypsum to plane with pieces of wood.
4.- Provisional splint 3/4 boards pinned to wood pieces. It is scrolled once the filling is done.

Table 2
Samples.

SAMPLE	L m	b cm	h cm	Type
A1	3,60	8,70	12,18	Plaster vault
A2				Ceramic jar
A3				Massif filling
A4				Timbrel vaulta
B1	4,10	12,18	15,67	Plaster vault
B2				Ceramic jar
B3				Massif filling
B4				Timbrel vault
C1	4,50	13,00	18,00	Plaster vault
C2				Ceramic jar
C3				Massif filling
C4				Timbrel vault
D1	5,40	15,00	20,00	Plaster vault
D2				Ceramic jaro
D3				Massif filling
D4				Timbrel vault

In both cases we will consider that:

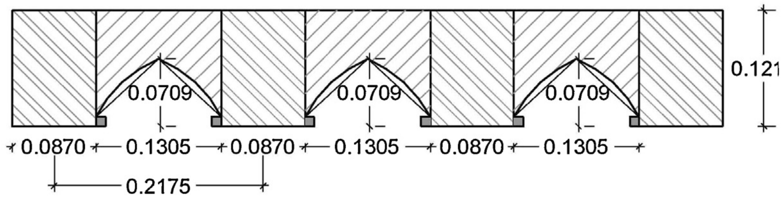
- Foundation and the original vertical wooden framework, continue taking their load bearing function, although we will finally make an approximation of possible reinforcements to be performed by the load increase.
- Reinforcement arises unloading the weights of fillings and floors, and service overload, while the reinforcement works are executed.
- The original floor structure remains in use, even when its situation is partially degraded.
- The action plan will be held from the upper part of the existing slab, which has an upper floorboard of 2 cm, of the same wood, and that is in good condition, so it stays.
- The reinforcement will join the joists, using metal connections lag screws type.
- In this case, the remaining deformation will not be taken into account for calculating purposes, but will be considered for the execution, making a series of recommendations to address the implementation on site of the two systems.

3.1. Mixed system concrete – wood

This constructive practice gives the whole ensemble of greater strength and rigidity, and it has been widely used, not very rightly, without any kind of union between both materials, so both parties worked independently from each other, barely improving their structural features. In these conditions, moreover, concrete increases the weight of the system in a very significant way in floor slabs with important different levels, and not infrequently, showing even worse results than before the intervention.

The solution is based on the incorporation of a thin slab of reinforced concrete on top of the existing slab, combining both systems together, through a suitable connection system. The objective is to achieve that concrete, or most of it, works under compression, which increases the resistant edge of the slab, and all the mechanical characteristics that determine its behavior to deflection, although in doing so concrete – wood connectors need to be capable of absorbing the longitudinal shear stress that are generate on the surface of contact between both materials, what allows understanding the floor

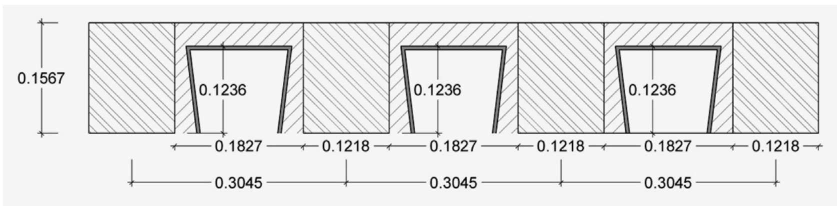
SAMPLE	PRA1			
L m	b Cm	h cm	Type	Separation cm
3,60	8,70	12,18	Gypsum vault	21.75



DISTRIBUTED LOADS

PERMANENT				VARIABLE
Wood kN/m	Beam filling kN/m^2	Partitioning kN/m2	Total kN/m2	Use kN/m2
	0,5688	1,0000	1,5688	2,00
LINEAR LOADS				
0,0403	0,1237	0,2175	0,3815	0,4350

SAMPLE	PRB2			
L m	b cm	h cm	Type	Separation cm
4,10	12,18	15,67	Ceramic jar	30,45



DISTRIBUTED LOADS

PERMANENT				VARIABLE
Wood kN/m	Beam filling kN/m^2	Partitioning kN/m2	Total kN/m2	Use kN/m2
	0,4984	1,0000	1,4984	2,00
LINEAR LOADS				
0,0725	0,1518	0,3045	0,5288	0,6090

Fig. 4. Example of sample sheet.

Table 3
Mechanical characteristics of wood C18 (CTE DB-SEM, 2006).

Scots pine	$f_{m,k}$ Bending Stregth	$f_{v,k}$ Shear Strength	$f_{c,90\ k}$ Perpendicular Compression Strength	$f_{h,d}$ Crush Resistance	$E0_{,med}$ Modulus of elasticity parallel	ρ_{med} Average density
C18	18 N/mm2	2,5 N/mm2	3.4 N/mm2	16 N/mm2	9 kN/mm^2	3.80 kN/m3

structure as a set of mixed beams of concrete – wood, whose T section considerably improves the behavior of the ensemble [8].

The connectors which ensure the two materials working together, are critical elements of the solution and there are different types: continuous, isolated, anchored with resin or mechanically, etc., although it is preferable to opt for those specifically developed for the concrete-wood union, since the manufacturer usually provides a sufficiently tried and tested own calculation system. However, any connector type is valid, provided it meets the mechanical requirements previously exposed [9], as the lag bolts or wood screws.

These consist of a shaft with an area threaded tip (rope) and a smooth stretch (shank), (Fig. 5). The shape of the head can be lenticular, round, countersunk and hexagonal. They work facing lateral loads (shear) and unlike nails, they have a high resistance capacity against extraction forces.

In this case, the thickness of the layer of HA25 reinforced concrete will be from 5 to 8 cml, according to calculation (Table 4) with a mesh of 5 20.20, to constitute the joint section of wood and concrete and achieve the increase of inertia. To solve the beam-reinforcement connection, we will place two self tapping screws 8/100 DIN571, quality steel 10.9, at each joist, inclined 45°, with pre-drill, and protruding 2.7 cm of the same. In addition, a waterproof breathable layer between wood and concrete will be placed to prevent the passage of moisture.

The connection to the wall will be solved through perforations, armed with corrugated steel bar glued every 30 cm with ⌀ 16 mm, 90 cm long curved 45°, inserted 40 cm in the framework wall, in a 30 mm diameter hole, around the perimeter of the floor structure and every 50 cm, received with epoxi-resin mortar of 1600 kg/m^3 density (Fig. 6).

From the implementation point of view, the remnant deflection tends to be a problem, as it is usually endeavored to level the compression layer on its upper side, resulting in higher thicknesses in the center of the span, that is to say, overweight in the more committed area. Possible solutions are, either maintain a constant thickness and then leveled with an underlayment of flooring or use a light filling as a basis of flooring (e.g. a dry slab) (Fig. 7).

The execution procedure follows these steps:

- Demolition of the false ceilings if they exist.
- Shoring of the slab with upper girders and lower cross sleepers in the center of the span, coined and nailed to joists.
- Lifted of flooring and fillings, to discover the joists on their upper side.
- Setting of the shoring.
- Evaluation of the joists, execution of possible replacements and partial repairs and application of fungicide treatments to wood.
- Installation of waterproofing sheet.
- Fixation of the connectors sealing the sheet encounter.
- Execution of holes in the perimeter, at the level of the compression layer walls, for connecting reinforcement and walls. Placement of corrugated bars and sealing of holes with epoxi formulated mortar.
- Leveling of the slab with lightweight material (expanded dry clay or lightly bound with cement).
- Placement of mesh and connection with the reinforcement of perimeter walls.
- Concreting with low dosages of water/cement ratio, allowing the pumping.
- Once reached the minimum resistance, de-shoring.

This solution has the disadvantage of significantly increasing the inherent weight, 25.0 kN/m^3, what in wood is particularly unfavorable, being more penalized the permanent loads respect overloads, in addition to these high loads transmitted to the rest of the structure, with its corresponding conditions. It is a non-reversible or reversible solution with a high cost.

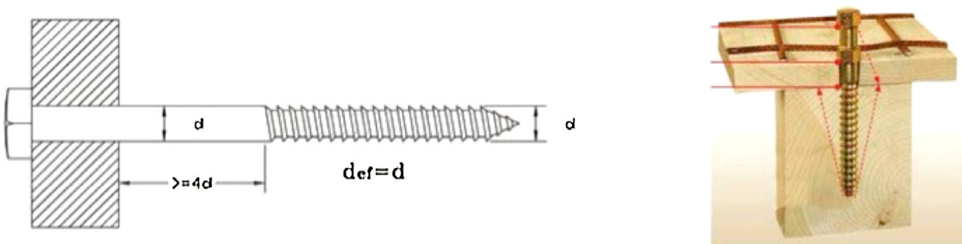


Fig. 5. Lag screws connectors.

Table 4
Concrete technical data.

Concrete technical data HA25	
Concrete type	HA25/P/20/IIa
Modulus of elasticity	2,000 kN/cm^2
Weight	25.0 kN/m^3
Specific heat. (cp)	1000 J/(kg*K)
Res.water vapor (μ)	80
Behavior against fire	REI-30
Insulation	
Thermal cond. (λ):	2.50 W/(m*K)
to airborne noise	30 dB
to impact noise	24 dB
Thermal global insulation(U) of the system	1.70 (W/m2 K)

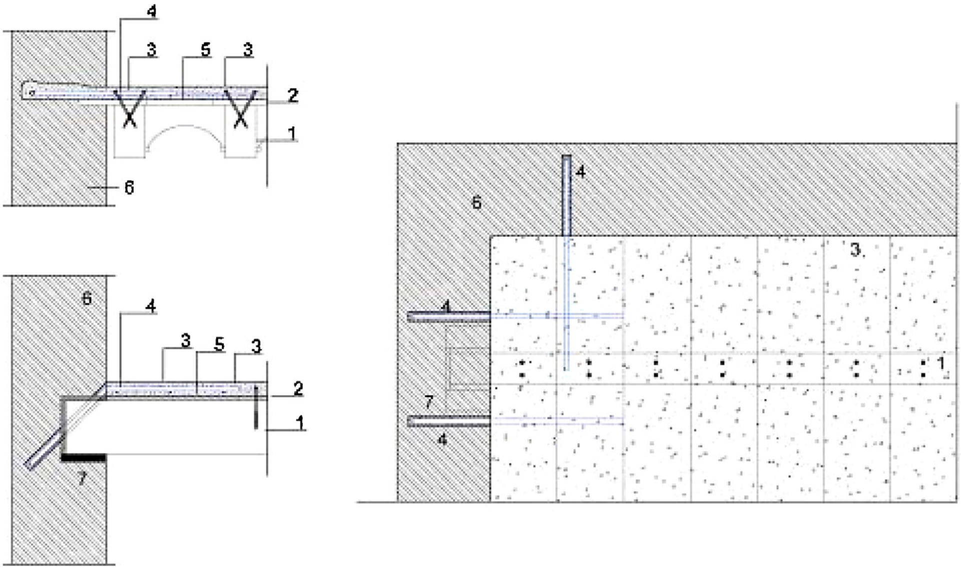


Fig. 6. Standard constructive section of concrete reinforcement.

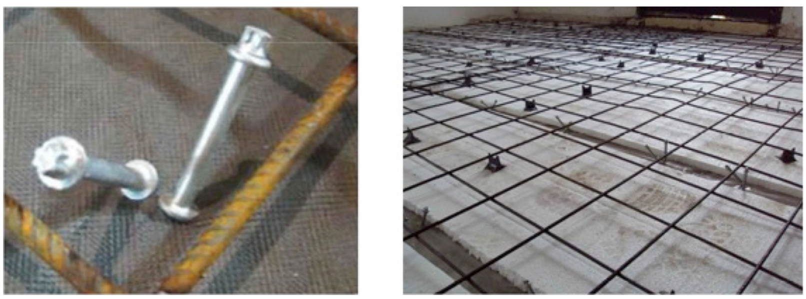


Fig. 7. Assembly.

Source: Aitim

Table 5
CLT Technical data.

CLT board technical data	
Type of wood	C24
Modulus of Elasticity	1.000 kN/cm^2.
Weight	5,0 kN/m^3
Specific heat. (cp)	1600 J/(kg*K)
Res.water vapor (μ)	25 a 50
Behavior against fire	B-s2, d0
V.carboniz:	0,67 mm/min.(1cara)
Insulation	
Thermal cond. (λ):	0.13 W/(m*K)
to airborne noise	30 dB
to impact noise	24 dB
Thermal global insulation (U) of the system	1.08 (W/m2 K

3.2. Mixed system CLT – wood

The system is aimed at maintaining as far as possible the structural system of the existing building, installing a steel deck solution among the existing wooden beams and cross-laminated timber panels, to keep the original image and ensure the bracing of the property in the rehabilitation phase.

Using CLT panels, the process of material production and the installation on the slab reinforcement is industrialized, starting with the thorough previous study of the zone of action, then drawn in computer format, the most suitable cutting according to structural requirements, room size and intended installation process. This graphic information is sent to the factory, where the panels are custom cut through fully computerized mechanization systems, apart from applying the corresponding fungicide and insecticide treatments by spraying also at the factory [10].

In our case, a panel of 6–7.8 cm. cross laminated timber will be used, depending on needs, with 3 layers of red spruce boards visually classified in class heavy duty C-24 according to EN 338, or according to DIN 4074 S10 and a board width of 0.98 m. (Table 5) to achieve a correct standard width modulation (2.95 m) and length of each room span. The used glue for the manufacture is a PUR 100% free of volatile compounds, approved according to EN 301 for interior load-bearing elements [11].

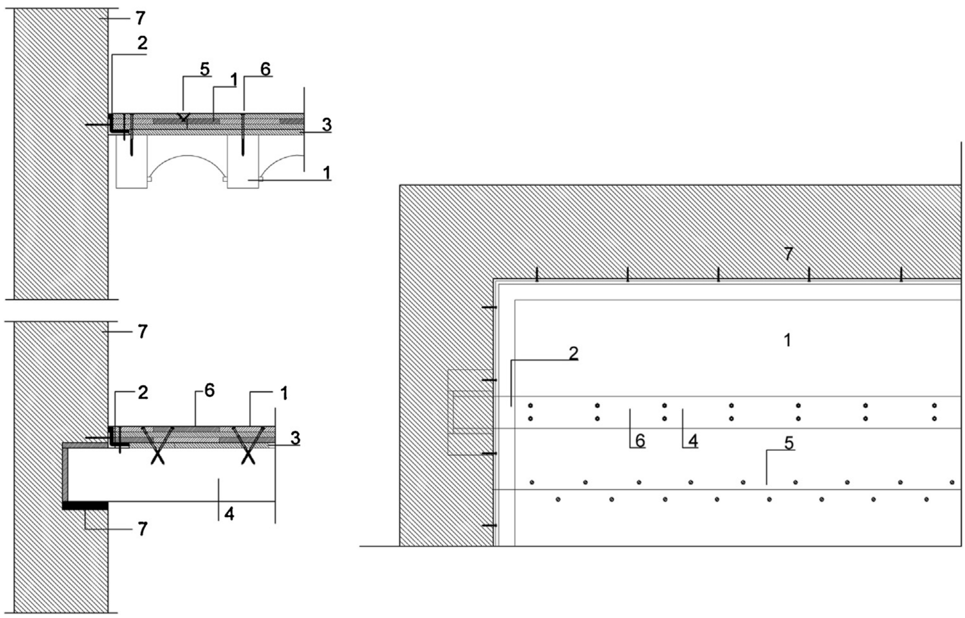


Fig. 8. Standard constructive section reinforcement with CLT.

Fig. 9. Assembly.

Source: Aitim.

Half lap joint on wood panels, and connections between them using self tapping lag screws with rounded flathead bichromated 6/50 DIN571, steel quality 10.9 each 100 cm each placed at an angle of 45°. Attachment to the existing "solivos" with the same type of self tapping lag screws, dimension 8/100, inclined, which solve the joint between both elements. The connection to the wall is solved with the embedment of existing beams and brackets 40.100.10 each meter, anchored to the wall through Hilti studs (chemical anchor HIT-MM Plus M8 and HASEM120 rod), staggered and bolted to the board through self-drilling bolt SFS WS-T fC71 each 60 cm, to finally fill the profiles in the perimeter wall with resin mortar (Fig. 8).

The panels are transported form the factory to the site with a self-propelled crane, and are lifted horizontally from the truck to the outdoor passage for its location in the worksite (Fig. 9).

From the point of view of their application, the remnant curvature represents again a drawback when it comes to having to define the horizontal plane for connecting the panel with the existing joists evenly. Although the board is designed for the most unfavorable deformation, the solution is to vary the thickness of each board on the basis of the existing deflection, to get the flatness on its upper side. For calculation purposes a constant board thickness has been considered.

The enforcement procedure follows these steps:

- Demolition of the false ceilings if they exist.
- Shoring of the slab with upper and lower sleeper cross in the center of the span, coined and nailed to the joists.
- Lifted of the floor and fillers, to discover the joists on their upper side.
- Setting of the shoring.
- Evaluation of the joists, execution of possible replacements and partial repairs and application of fungicide treatments to wood.
- Lifting of the floor structure, having previously established at the factory the modulation and thicknesses to solve the remaining deflections. Boards will reach the sitework in series, according to the established assembly.
- Placement of LD profile in the entire perimeter screwed into the walls with chemical dowels and stuck with fluid mortar.

Fig. 10. Assembly.

Source: Aitim.

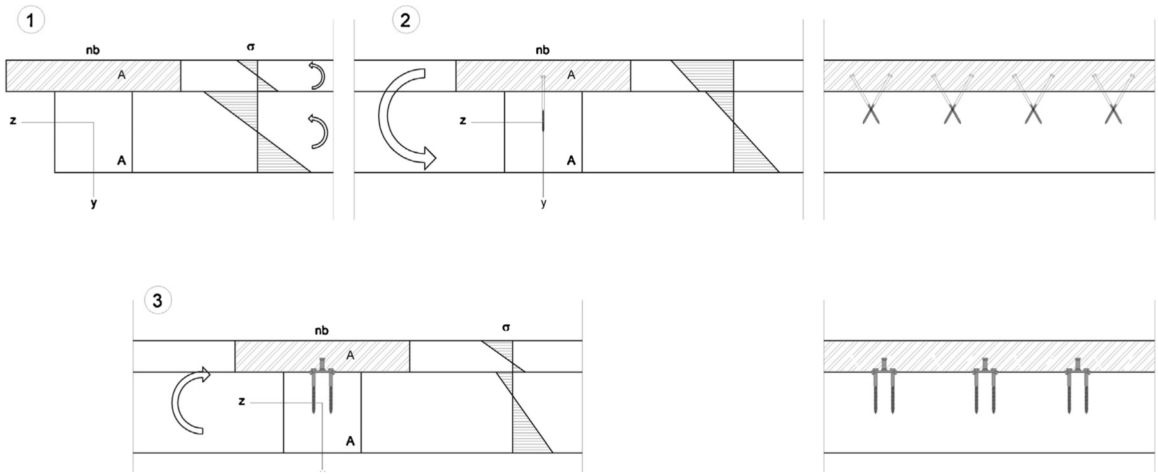


Fig. 11. Calculation methodology for mixed floor slabs.
1. Without connection
2. Total connection
3. Semi-rigid connection

- Lifting and placement of panels on wooden beams. One inconvenient is to move the prefabricated panels within the interior of the building, still needed a series of auxiliary means to allow to move, turn, lift and place panels of important dimensions and weights in a simple way and without relevant human physical effort.
- Mechanical fixing of the panels together, joists and LD profile on the perimeter.
- Unshoring.

It is a lightweight and reversible solution, with an increase in weight of 5.0 kN/m3, which is assumed easily by the existing structure. It has the disadvantage of having to define the horizontal plan to connect in a uniform way the panel with the existing beams, because of the remnant deflection. The system load transfer is immediate (Fig. 10).

4. Calculation methodology: homogeneous section

The so-called mixed beam, combine into a single element or piece two materials and technologies reaching a unique model, which takes into account the overlapping of both materials. The mechanical behavior lies in the effectiveness of the connection between the two materials, which is done based on elements such as screws, nails, pins, etc., usually discontinuously.

The applicable specific current legislation [7,12], contemplates the possibility of calculating mixed floor slabs considering either a total connection between the two materials (tensile connectors) or a semi-rigid connection (shear connectors) between the two (Fig. 11).

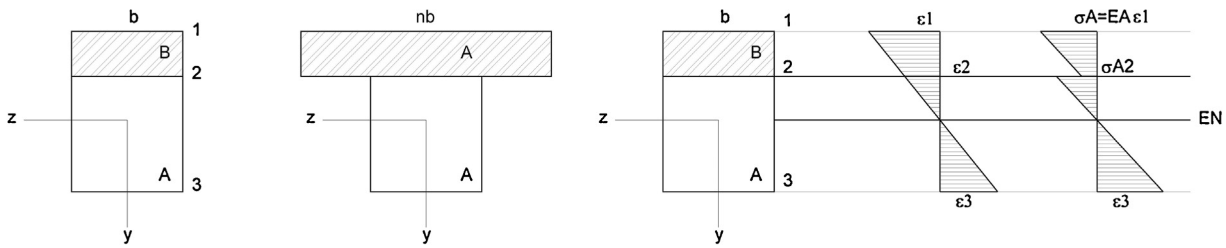


Fig. 12. Transformed section and stresses at the section.

The DB CTE-SE-M [7] sets that, provided that the system will allow the formation of a tight connecting rod with tilt rod mechanism forming angles between 40° and 60° with the plane of contact, and for parts whose span is less than 12 m, the sliding of the union can be set aside, and perform the analysis with the total cross section through the classical theory of strength of materials. In this case it can be ensured that the depletion by bending failure occurs first on the mixed section and then the bending failure by relative slipping between the two partial sections [13].

To dispense of the sliding of the union and to consider a total connection between beam and reinforcement, lag screws should be placed inclined, since this situation provides them much greater rigidity than when placing them orthogonally to the parts they connect.

As the object of this research is the comparative study of two reinforcement systems that use two different materials, the rigid connection option will be applied, and the general calculation of the slab will be made using the theory of the homogenized section. Basically, the approach to determine how the two materials work together is carried out considering the unification of the two into one homogeneous, one of them turning into inertias or equivalent sections to the other and thus be able to apply the formulas of the elastic, strain or efforts together and at the same time for the mixed material. Furthermore, the theory of bending can be directly applied to mixed beams, since it is assumed that the material is homogeneous and deformations and efforts vary proportionally with the depth of the neutral axis, although it is only valid for materials within the elastic range (Fig. 12).

The firs step is to transform the cross section of a composite beam in an equivalent of a beam made of a single material. Then the beam is usually analyzed by bending, and finally, efforts in the transformed section are converted to the original beam. The behavior to bending of the joint section of the wood and the reinforcement depends on the rigidity of the

Table 6
Reinforcement sections by sample and system.

SAMPLE		REINFORCEMENT THICKNESS (cm)	
		CLT	HA25
RE	A1	6.00	6.00
RE	A2	6.00	6.00
RE	A3	6.00	6.00
RE	A4	7.80	8.00
RE	B1	6.00	5.00
RE	B2	6.00	5.00
RE	B3	6.00	5.00
RE	B4	6.00	6.00
RE	C1	6.00	5.00
RE	C2	6.00	5.00
RE	C3	6.00	5.00
RE	C4	6.00	5.00
RE	D1	6.00	5,00
RE	D2	6.00	5,00
RE	D3	6.00	5,00
RE	D4	7.80	7,00

Table 7
Load increment by reinforcement.

	1 FLOOR			FOUNDATION		
kN/m	PR	RE CLT	RE HA25	PR	RE CLT	RE HA25
A1	3,16	3,70	5,75	12,63	14,79	23,00
A2	2,75	3,29	5,34	10,98	13,14	21,35
A3	3,81	4,35	6,40	15,25	17,41	25,61
A4	3,16	3,70	5,75	12,65	14,81	23,02
B1	4,02	4,63	6,97	16,06	18,52	27,87
B2	3,56	4,17	6,51	14,24	16,70	26,05
B3	4,99	5,61	7,95	19,98	22,44	31,78
B4	4,05	4,66	7,00	16,18	18,64	27,99
C1	4,81	5,48	8,05	19,23	21,93	32,19
C2	4,29	4,96	7,53	17,15	19,85	30,11
C3	5,96	6,64	9,20	23,86	26,56	36,82
C4	4,89	5,56	8,13	19,54	22,24	32,50
D1	6,06	6,87	9,94	24,22	27,46	39,77
D2	5,33	6,14	9,22	21,32	24,56	36,87
D3	7,65	8,46	11,54	30,61	33,85	46,16
D4	6,13	6,94	10,02	24,54	27,78	40,09

connector, which varies according to the type used and its relationship with wood and reinforcement. It is most commonly that the two materials are in contact, the connector is applied to shear efforts, and if they are inclined between 45 and 60°, they also work to axial forces. In this case, considering a total connection between reinforcement and beam, the cross sections remain flat, before and after deformation, because bending happens to reinforcement and wood.

The deflection of the two parts of the mixed section is the same, and the behavior of the section is considered elastic. It must be considered that the connection between the parties has to be to the section full capacity, under the criteria of flexural strength [14].

Equally and as the CTE-BD-SE-M [7] determines, the sizing of lag bolts that operate at traction is proposed considering the axial load. Tensile strength and shear of the lag screws will be obtained from the document CTE-DB-SE-A [15], and the minimum distances have been determined by the rule of screws perpendicular to the longitudinal axis [16].

5. Comparative structural analysis of the two systems

Inevitably, solutions respond to regulatory requirements determined by the change of established use, in particular structural and fire, where fire stability must be guaranteed during 60 min for administrative use, with their corresponding overloads.

A Service Class 1 and Class of Use 1 are established, not taking into account the CTE-DB-HE [17] and the CTE-DB-HR [18], to understand that they are not enforceable. In terms of the limitation of the relative deflection, it will be verified only that it does not surpass in L/300, all the shares acting.

By adopting load considerations settled in the CTE-DB-AE [19], it is determined that:

- It will only be taken into account the actions of a persistent or temporary situation.
- Permanent actions in initial position will be increased, the own weights of the considered reinforcement, which characteristic value Gk will get its value half deducted from the nominal dimensions, and certain specific weight from Tables 6 and 7 (5.0 kN/mN for HA25).
- The own weight of masonry is considered with a load of 1.0 kN/m2 of built surface.
- For the service overloads it will be established that an area with tables and chairs in administrative use, increasing the initial with a total of 3 kN/m2 by 1 kN/m2.
- Local tests of load-bearing capacity are performed, whereas a concentrated load acting at any point in the area, and independently of the evenly distributed overload, of 2 kN.
- Other variables such as wind, thermal actions or snow are not taken into consideration.
- It is established that the flooring after the reinforcement is a laminated wood flooring, so its own weight is despicable.

5.1. The initial situation

The analysis of the results of the initial situations shows, regardless of the covered span, that they are the samples made with beam fillings, lighter the ones which behave in a less demanding way in all of the observed variables; M2 floor structures with ceramic jar as beam fillings, and M1, beam fillings made with “galápagos”, which in the end are the ones with less permanent load.

The shear stresses of all samples are negligible, and its remarkable the good behavior that the system generally has in a situation of fire, mainly because the joists are exposed only on one side. No sample meets the required requirements of deformation, so it is clear that the main problem of this system is the excessive deflection, justified by the low modulus of elasticity that wood has.

5.2. Calculation model

From the practical experimentation, the number of possible variables is so high that the organization of a representative test campaign of each possible case is unfeasible because of its complexity and cost.

The present comparative study has allowed to elaborate spreadsheets that facilitate the sizing and comparative analysis of the two considered solutions. A first sheet called Geometry of samples contains the tabs for the samples (Fig. 13), linked to summary tables of loads distribution, which are the basis for each of the sample worksheets (Fig. 14).

These are named as the sample, and in them the reinforcements on each section are verified. They contain a first section of data entry, wherein are introduced: the denomination of the sample, the strength class, the class of service, the use of the area, the working element (isolated or interconnected) and the regulatory requirements for deflection and fire resistance demanded. The option to select different data to Strength class C18, Class of service 1, to modify the use of the area, the operation of the element and limitation of deflection and fire resistance is left, to carry out the study of behavior of different elements in different situations.

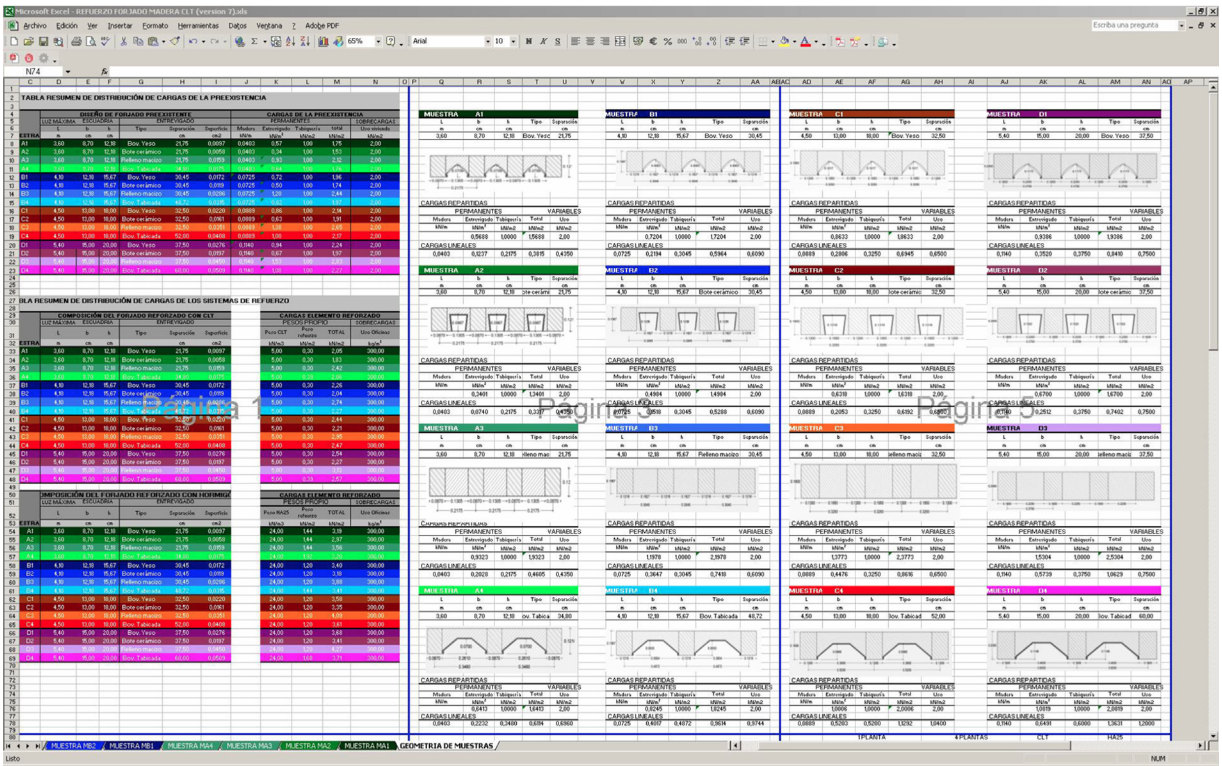


Fig. 13. Sample geometry spreadsheet.

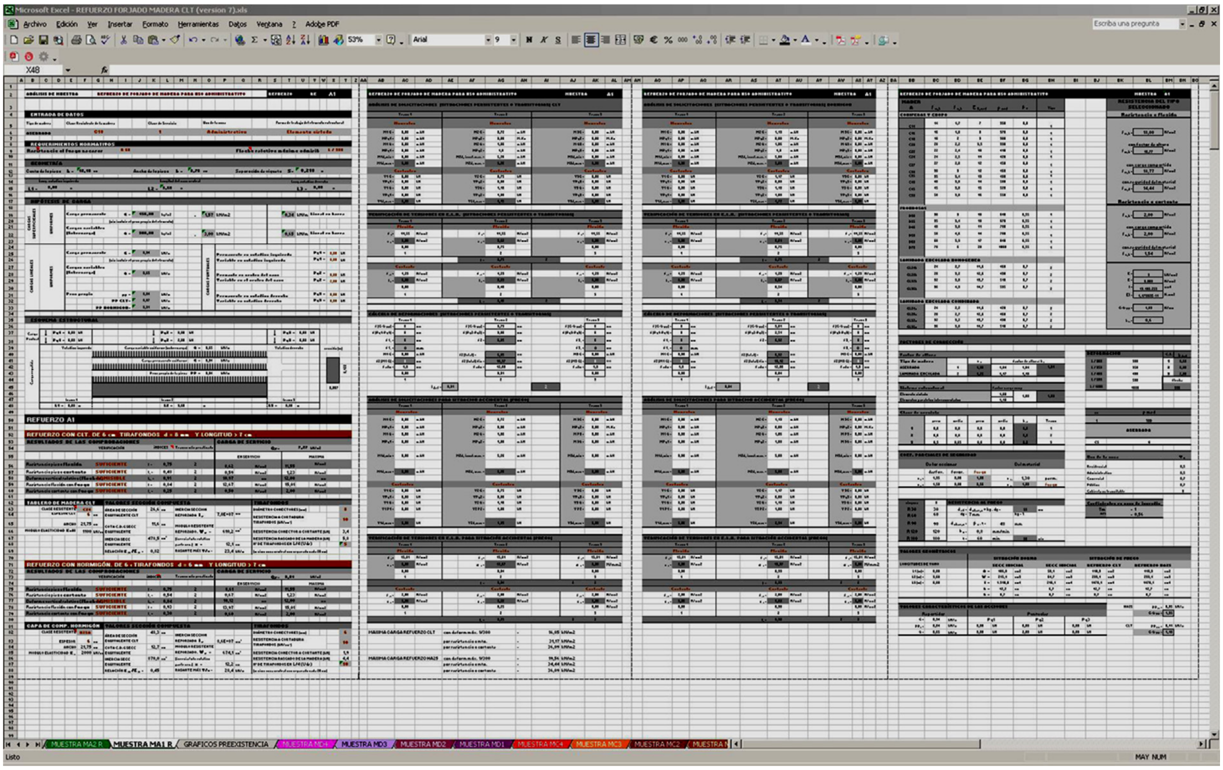


Fig. 14. MA1 R sample sheet.

After entering the name of the item, the program automatically generates the geometry sample, and applying the rest of data, hypothesis of load and structural scheme, that the sheet recovers from the geometry of samples. There is the option of introducing cantilever elements, which, once established, are reflected in the structural scheme, in order to study the variable. The values for calculating the properties of the joist with which the tensions are compared, are obtained by dividing the characteristic values of the Resistant class chosen, by the partial safety coefficients and coefficients of simultaneity that the CTE-DB-SE-M [7] assigns for each situation, taking into account also the correction factors corresponding to each design situation. For the verification of the reinforcements, the type of reinforcement (in this case, HA25 and C24 for CLT) is introduced and its thickness, transformed the program data of the cross section for the composite beam, in the equivalent of a beam just wood, as determined in the calculation methodology. The option to increase the reinforcement sections is left in case that any requirement is not met for a particular sample. It is important to mention that the CLT thicknesses are the ones that can be found on the market. The testing of structural safety against fire is made according to the method laid down in annex SI-E of the basic document CTE-DB- SI [20], which evaluates the mechanical behavior of a "reduced section" whose dimensions depend on the duration of the fire and the characteristics of the material, applying the partial coefficients that correspond to an extraordinary situation.

In the verification of the vertical deformation of beams (deflection), the application only analyses the total deflection check, omitting two of the three checks recommended by the technical code, since the final intent of this study is to conduct a comparative analysis of two constructive systems, the total deformation produced by all loads is considered enough guidance.

For dimensioning the lag screws, diameter and shear resistance provided by the manufacturer must be introduced. Once done that, the necessary number of them is generated (Fig. 15). Finally, a third type of sheet is incorporated, named Graphics reinforcement M, where are represented in graphical format, and on separated sheets the comparative study of the results obtained in each situation, of all the samples. Graphics are conformed by the maximum span of maximum stresses in section by bending and shear, the deformations by maximum deflection and the maximum stresses in section by bending in situation of fire. In addition, a study of the use of the material for each situation is performed (Fig. 16).

REINFORCEMENT A1

CLT REINFORCEMENT 6 cm — LAG SCREWS d = 8 mm & LENGHT > 7 cm

CHECKS RESULTS	VERIFICATION	INDEXES		Section more penalised	SERVICE LOAD ON SERVICE		MAXIMA	
					Qs= 7,27 kN/m2			
Piece resistance bending	ENOUGH	I_m =	0,75	2	8,62	N/mm2	11,55	N/mm2
Piece resistance shear	ENOUGH	I_v =	0,48	2	0,59	N/mm2	1,23	N/mm2
Relative vertical deformation (deflection)	ADMISSIBLE	I_{def} =	0,91	2	10,97	mm	12,00	mm
Bending resistance with fire	ENOUGH	$I_{m,fi}$ =	0,84	2	12,67	N/mm2	15,01	N/mm2
Shear resistance with fire	ENOUGH	$I_{v,fi}$ =	0,25	2	0,50	N/mm2	2,00	N/mm2

CLT WOOD BOARD

RESISTANCE CLASS	C24	
CLT THICKNESS	6	cm
WIDTH	21,75	cm
ELASTICITY MODULUS Eclt	1100	kN/cm²

COMPOUND SECTION VALUES

EQUIVALENT CLT SECTION AREA	26,6	cm	INERTIA REINFORCED SECTION I_r	7,0E+07	mm⁴
COTA C.D.G SECC EQUIVALENTE	11,6	cm	RESISTANCE MODULUS. W_r =	610,2	cm³
INERCIA SECC EQUIVALENTE	478,5	cm⁴	(inertia/mto estatic sec. part) z =	12,1	cm
RELACIÓN E_m/E_c =	0,82		MÁX LEVEL V/z=	23,4	kN/m

LAG SCREWS

CONNECTORS DIAMETER (mm)	8
LAG SCREWS SHEAR RESISTANCE (kN/cm²)	10
CONNECTOR SHEAR RESISTANCE (kN)	3,4
WOOD SHEAR RESISTANCE (kN)	5,8
Nº LAG SCREWS ON L/4 (Units)	5
(min central zone one separated each 20 cm)	

CONCRETE REINFORCEMENT. OF 6 cm — LAG SCREWS d = 8 mm & LENGHT > 7 cm

CHECKS RESULTS	VERIFICATION	INDEXES		Section more penalised	SERVICE LOADS ON SERVICE		MAXIMA	
					Qs= 8,81 kN/m2			
Piece resistance bending	ENOUGH	I_m =	0,75	2	8,61	N/mm2	11,55	N/mm2
Piece resistance shear	ENOUGH	I_v =	0,54	2	0,67	N/mm2	1,23	N/mm2
Relative vertical deformation (deflection)	ADMISSIBLE	I_{def} =	0,84	2	10,12	mm	12,00	mm
Bending resistance with fire	ENOUGH	$I_{m,fi}$ =	0,93	2	13,97	N/mm2	15,01	N/mm2
Shear resistance with fire	ENOUGH	$I_{v,fi}$ =	0,30	2	0,60	N/mm2	2,00	N/mm2

CONCRETE COMPRESSION LAYER

RESISTANCE CLASS	H25A	
THICKNESS	6	cm
WIDTH	21,75	cm
ELASTICITY MODULUS E_c	2000	kN/cm²

COMPOUND SECTION VALUES

AREA OF EQUIVALENT SECTION CLT	48,3	cm	INERTIA REINFORCED SECTION I_r	8,6E+07	mm⁴
DIMENSION C.D.G EQUIVALENT SECC	12,7	cm	RESISTANCE MODULUS. W_r =	674,1	cm³
INERTIA EQUIVALENT SECC	870,0	cm⁴	(inertia/mto estatic sec. part) z =	12,2	cm
RELATION E_m/E_c =	0,45		MÁX LEVEL V/z=	28,4	kN/m

LAG SCREWS

CONNECTORS DIAMETER (mm)	8
LAG SCREWS SHEAR RESISTANCE (kN/cm²)	10
CONNECTOR SHEAR RESISTANCE (kN)	3,4
WOOD SHEAR RESISTANCE (kN)	5,8
Nº LAG SCREWS ON L/4 (Units)	6
(min central zone one separated each 20 cm)	

Fig. 15. MA1 R sample sheet. Verifications.

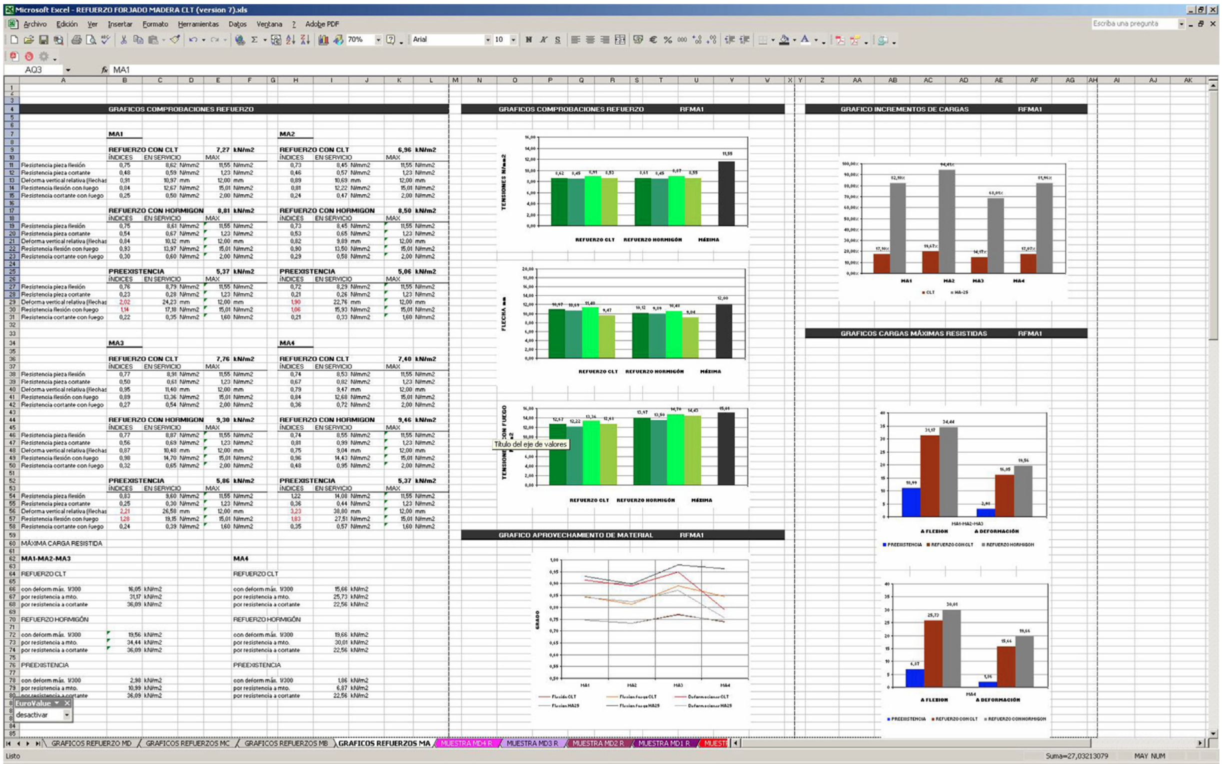
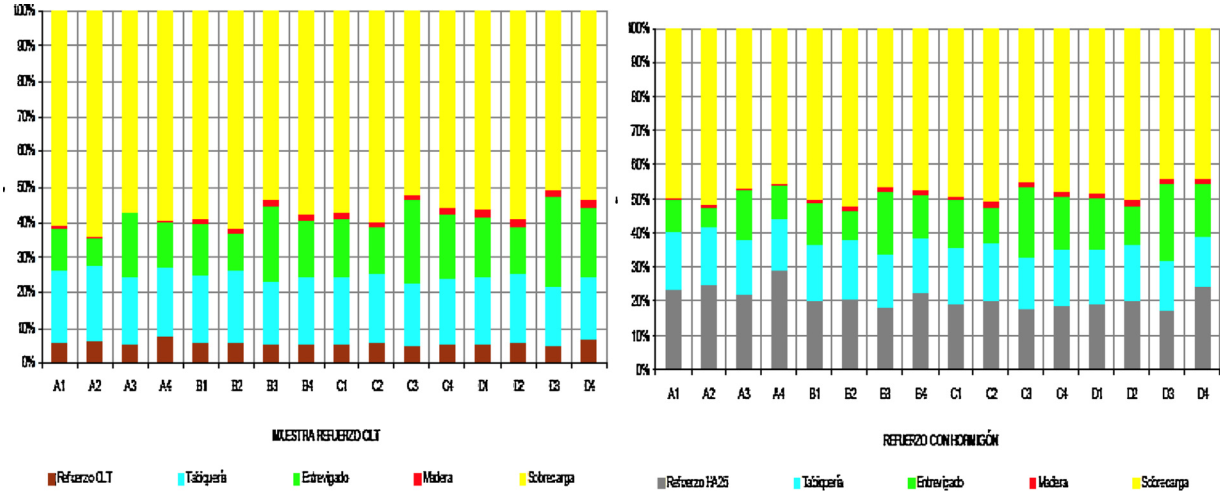
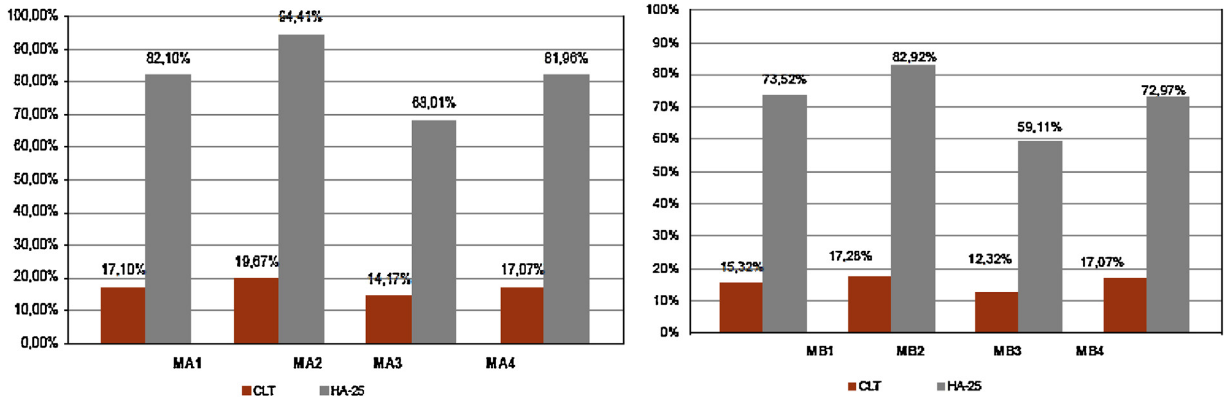


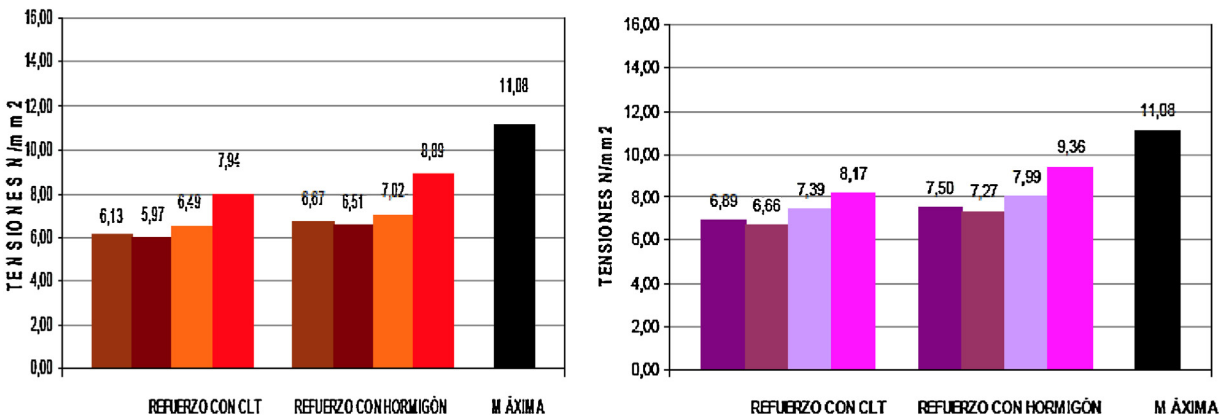
Fig. 16. MA reinforcement graphics sheet.



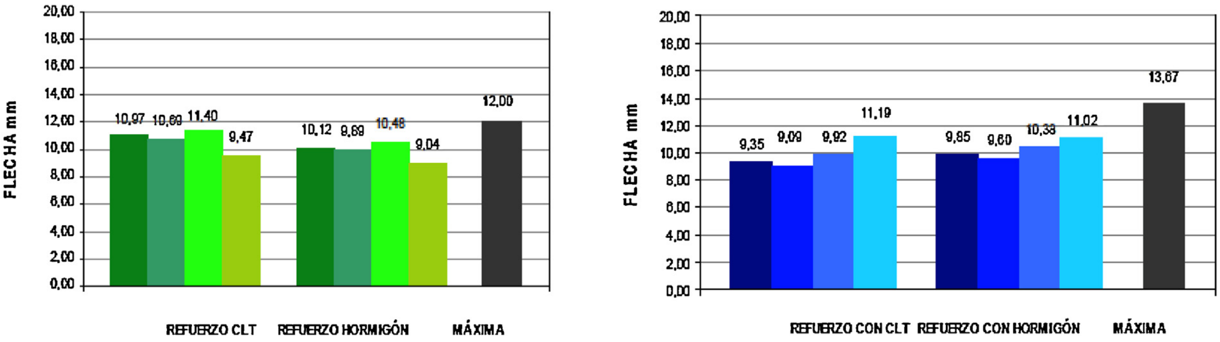
Graphic 1. Load distribution on reinforced section.



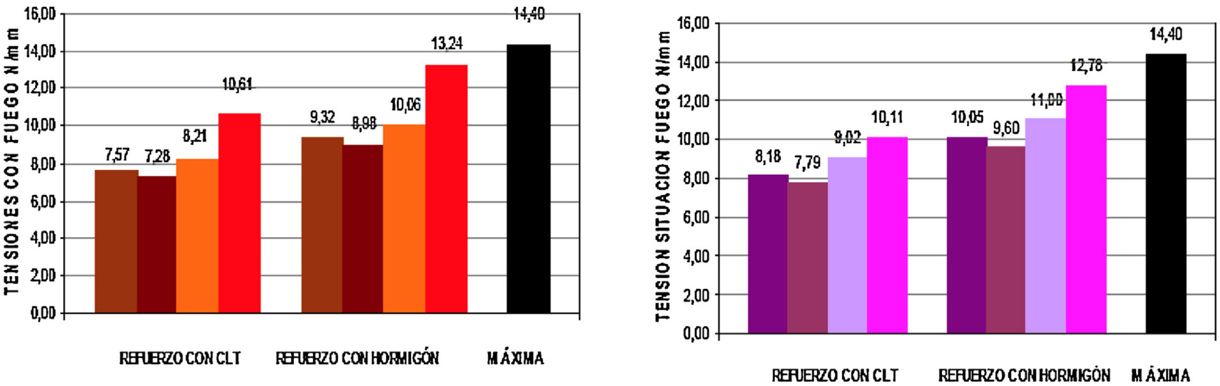
Graphic 2. Increase by own weight. Samples: MA and MB.



Graphic 3. Bending stresses on reinforcements. Samples: MC and MD.



Graphic 4. Deformations. Samples: MA and MB.



Graphic 5. Stresses in fire situation. Samples: MC and MD.

6. Results

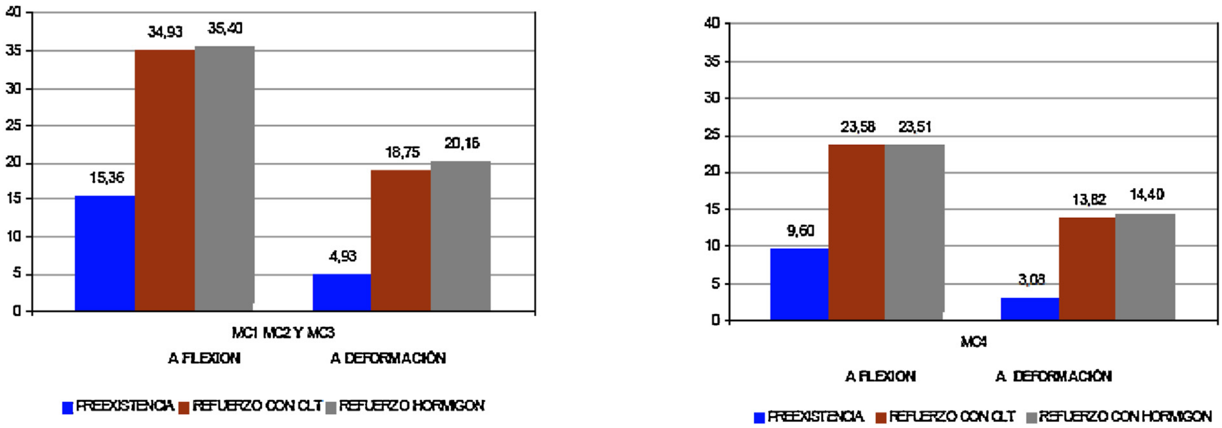
As it can be seen in Table 6, to comply with the established requirements, all the MA samples should strengthen them with 6 cm, regardless of the system, excluding the MA4, that has to be reinforced with a CLT board of 7.8 cm or with 8.00 cm of concrete. For the samples MB, MC and MD it is enough to reinforce them with a 6 cm. CLT board, or with 5 cm of concrete, to comply with the requirements, except the MD4 that needs 7.00 cm of concrete or a 7.8 cm. CLT board.

In the case of reinforcement with CLT, the variable loads pose greater proportion with respect to the total than the permanents. However, in the case of reinforcement with HA25, it is widespread the proportion of permanent to be greater than the variables. This is because the weight of the system made with CLT is far lower than that made with HA25 (Graphic 1).

In the system made with concrete, the weights of the partitions become equal with the reinforcements; in the system with CLT are more important the beam filling weights. Considering the samples by maximum spans, the increase of own weights on the pre-existence of each system is significantly higher in the concrete, regardless of the thickness used for reinforcement, being greater the more lighter the beam filling of the pre-existence is in both cases (samples M2, beam filling of ceramic pot) (Graphic 2).

The shear tensions of the reinforced sections are negligible. It is generalized that, the least demanding of almost all the samples, in terms of stress, is the one made with beam filling of ceramic pot [5], and the one that approximates most to the admitted is the one with timbrel vault beam filling, except the MA4, that has the lower wood section (and spans minor than 3.60 m), because that has been strengthened with greater thickness both in concrete and CLT (Graphic 3).

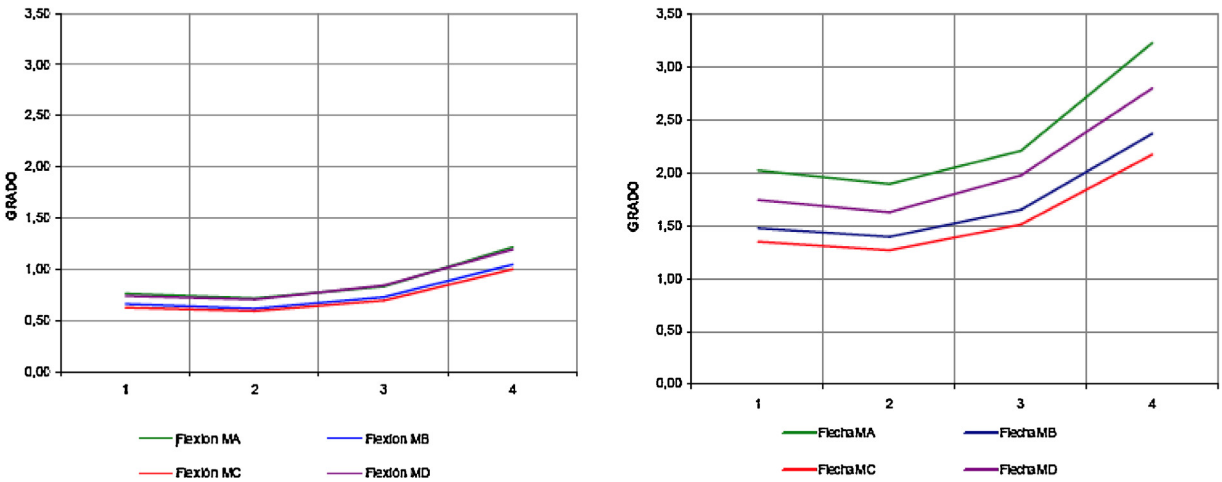
In terms of deflection, taking into account that none of the samples met the requirements proposed in the initial situation, reinforced sections are kept bellow the required maximum deflection, but to do so, the totality of the MA and the M4D samples have required more amount of material in the two proposed systems. Only the M4B has needed to increase only the section of the reinforcement of HA25.



Graphic 6. Maximum loads admitted. Sample: MC.

Once again the sample made with beam filling of ceramic pot [2] the least demanding of almost all samples in terms of deformations, and the MA4 the less deformed by its greater reinforcement. However, in the MD samples, deformations are approaching more the admitted that elsewhere, especially in the reinforcement with concrete. It is generalized that sections reinforced with HA25 deforms more than those made with cross-laminated, except the MA sample (Graphic 4).

In fire situation, all samples behave within the admitted, and have been reduced to not exceed the admissible, even though all of the MA are to the limit, by being the edge of the pre-existing joist very small. However, the higher sections, MC and MD, behave much better, producing tensions far below the requirements. It is noteworthy that sections with CLT reach lower tension values than the sections reinforced with concrete in this situation of fire (Graphic 5).



Graphic 7. Degree of material usage. Bending and deflection.

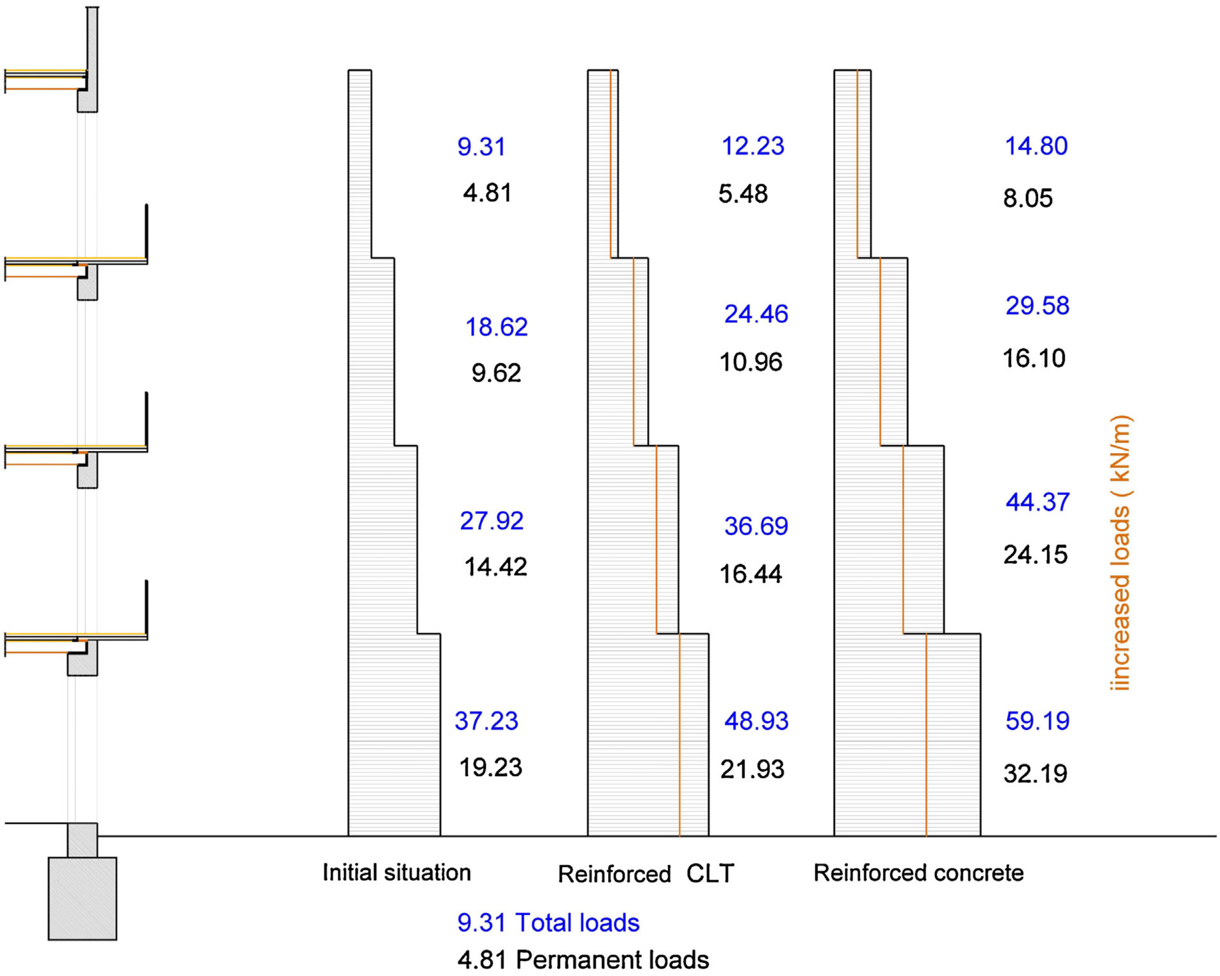


Fig. 17. Load increment scheme. MC1 sample.

7. Conclusions

The increase in maximum loads supported by the two systems with respect to the initial situation is considerable, and in both cases they are very similar, variations to exist below the 0.5 kN/m2 in almost all samples, in limitation both of tension and deflection (Graphic 6).

It has to be taken into account that the difference between what the reinforced concrete section supports, and what endures the one reinforced with CLT, does not exceed the difference between the own weights of the reinforcements, which shows that much of the one made with concrete is intended to support itself.

The behavior of reinforcements in a fire situation is acceptable, due primarily to the joists are exposed only on one side, with which to remove the beam filling to lighten the own weights, can become counterproductive, as it would penalize in excess the response of the element at fire situation, increasing ηf reduction factor.

Due to the weak response in terms of deflection in the initial situation of all the samples, generally it is more important to increase the inertia of its resistant module section. Therefore, increasing the total depth of the element (solution more productive than increasing the width), it would be possible to achieve the values of inertia in the section that will allow to achieve joist meeting the demanded requirements (Graphic 7). For the purposes of deflection, permanent charges penalize rather than variables, with what at first, when selecting the reinforcement system to increase the edge of the section, and limit as far as possible the deformation, it should be aimed to use a system as light as possible.

The analysis of the possible disorders in foundations by the load increases in such buildings, lead to uncertainties that will have to be taken into account in the decision-making process prior to the action on the floor, especially if to this it is added the rigor of the emerging regulations (Table 7).

In a first approach, if it is established that the mean strength of the land that is considered in Madrid is 2 kg/cm2 (20 T/m2), in the initial status, for the spans that are handled and four floors and roofing, ditches should have a width of 1 m, as a minimum, when the widths that are normally found are smaller [21].

The solution made with CLT makes compatible to the original structural walls of the building to continue assuming their load-bearing function, thanks to the lightness of the new floors, which makes the state of permanent loads very similar to the original state of loads of the building. However, reinforcing with the system made with concrete, it will be feasible to have the need to reinforce to say the least the affected foundation, especially if it is necessary to act on several floors of the building, since in this case, the values of the loads in this area grow exponentially (Fig. 17).

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