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Design of a prototype for the doors of the organ of the Cathedral of Tarragona

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Abstract

A real project motivated this article about analyzing, checking and designing a prototype for the stretcher of the doors of the Organ of the Cathedral of Tarragona. But its shorter length gives it more freedom to get theoretical conclusions, having no information and details from a longer analysis and new details founded during future site works. The main topic developed in this article the structural design of the old doors of the Organ, which have to be placed again in their original position. But as in other historical projects, is always a good beginning to research similar cases that can give further information. That's why some cases were compared sharing same static conditions in order to find advantages to design a better structure using as less material as possible. Some static values were checked and compared, maintaining advantageous standards while doing the changes that were proved as positive to improve the new design of the doors.

Keywords

Prototype; doors; organ; wood; stress design; Cathedral of Tarragona; restoration.

Introduction

At the beginning of last march we hoisted up a great dimensions cross in the interior of the church of Santa Maria del Mar of Barcelona (fig. 1). It was a complicated and stressful project because the cross - made of bronze and weighting 10 kN – had to be sustained by the existing ceiling vaults of the presbytery. Although the calculations and inspections were overwhelmingly positive and enough guaranties could be made to continue the project forward, nobody was able to breathe a sigh of relief until the cross was completely suspended from the central cable, hanging a span from the ground for a few seconds.

All along the months that the project went on -of which we made the technical supervision- all the members of the team thought that it was a strange commission, but at the same time the most extraordinary that we will ever be part of. To our surprise, few days later, we received the commission from Archdiocese of Tarragona to participate in the renovation-restoration of the doors of the Organ of the Cathedral (fig. 2) in a multidisciplinary team directed by Centre de Restauració de Béns Mobles de Catalunya – CRBMC. Our Job would be to test or design the structural elements of the doors and to ensure the viability of the suspension.

The doors. Antecedents

Our enthusiasm to start was immense, especially by the fact that it was not any ordinary building and that the intervention was not only a simple examination of an existing element but a collaboration with a team to return the doors to the great Organ, improving, if possible, the existing structural system if any risk is detected.

The doors of the Organ – from XVI century - are painted canvases of large format fixed on wooden structural frames with hinges that could be closed or opened to leave it visible, situated in the central nave of the Cathedral of Tarragona. There was a liturgical and very symbolic tradition that in the Lenten season the Organ would be closed, coinciding with its silence, until after the resurrection Sunday, when it was opened and played again.

The doors were removed some years ago, in order to renovate the interior of the cathedral and the pipe organ, and no documentation was kept. Until the beginning of the intervention they were left lent over a wall until the moment that it was decided to restore and place them in their original position. The state of the wood is very poor, regardless no decision would be made about the intervention until it is possible a deeply analysis. But this fact has motivated this study, based on a real case and situation, even if the conclusions may not be used at the real project and intervention (fig. 28).

The doors. Current state

The doors consist of rectangular perimeter frames - base of 4.6 m and height of 7.0 m – with a system of posts and diagonals that give it structural rigidity. On both interior and exterior faces are located the painted fabric, nailed to the frame and which would probably have a structural function besides the picturesque one. The doors are mounted on the furniture of the Organ via wrought iron hinges (5 each door) that enter more than 1.5 m inside of the frame.



Figure 1.
Hoisting up the Santa Maria del Mar Cross.

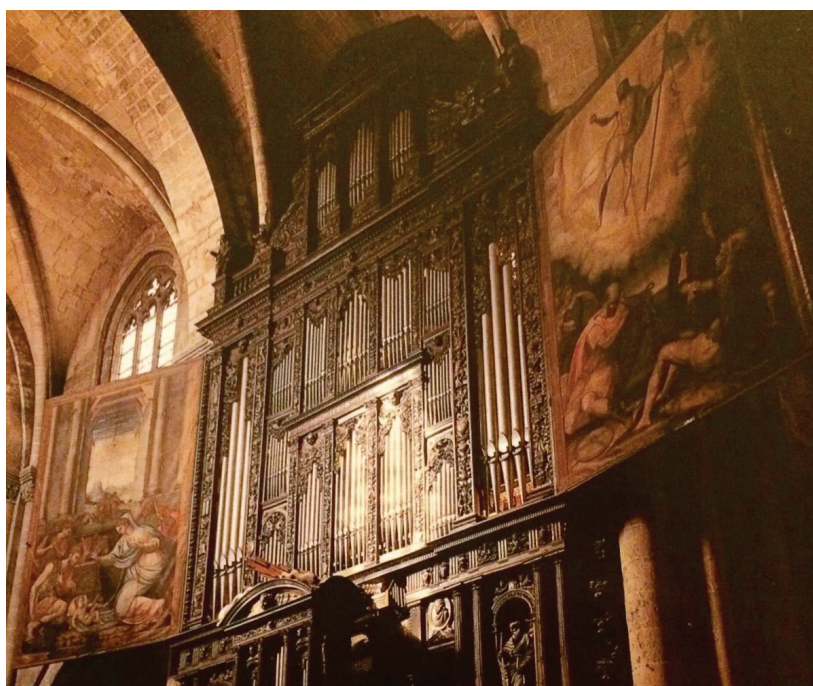


Figure 2.
The doors of the Organ of the Cathedral of Tarragona.



Figure 3.

The pipe organ without the doors



Figure 4.

The pipe organ without the doors.



Figure 5.

The supporting scaffolding of one of the frames.



Figure 6.

The supporting scaffolding of one of the frames.



Figure 7.

The state in which the doors were found.



Figure 8.
The scaffolds as a door support.

One of the facts we gathered in the displacement of the first door to the provisional scaffolds was the weight of each element. Its weight, 2.16 kN, included the linden wood structure, the fittings and joints of the 5 hinges, the two canvases (interior and exterior) and thousands of nails with wide heads by which are fastened to the frame. This information is very important since, first of all, it enables us to know the maximum forces on supports of the anchors of the hinges (vertically as much horizontally) and in second place it gives us an approximation of the weight of two canvases, about 70 m² each frame. The first exercise consists of subtracting from the total weight of 2.16 kN, the weight of the wooden structure and the fitting of wrought iron. The resulting value would be the weight, more or less precise, of the canvases and the fastening nails. This weight will be practically the same one that the new frames should support.

One objective which we have focused on and planned for from the beginning was to try to not alter the system technically, ensuring to copy the pre-existences and to add the minimum of modifications for improving substantially its behaviour. A clear example is the selection of the type of wood: Linden wood on the existing frames. This is a sort of wood of large and straight spans, but soft and with sap rich in minerals and nutrients, which make it very vulnerable to degrading agents and with little durability. It is proposed for the new prototype American or Canadian cedar, which is resistant to decomposition but not so easily degradable by Xylophagous insects.

The choice of the wood is still an open decision. Aluminium frames and hybrid aluminium-wood frames are common but options that we discard for now, and the first tests are being done with C18 type wood (conifer with resistance of 18 N/mm² under normal stresses) and density of 4.20 kN/m³.

Other important elements to consider and to have in mind are the five hinges which fix the frames to the organ. They are made of wrought iron, are 150 cm long and weight 1.2 kN each (6.0 kN in total, by no means negligible).

With all these weights and subtracting them of the total, we have around 0.5 kN for each canvases of 35 m². It is important to consider this weight, first for being a permanent load, which are the type that cause greater deformation in wooden structures, and second for its non-uniform disposition, because it has a greater percentage at the superior part of the stretcher and almost zero at the inferior part.

One of the wonders of the doors is its system of opening and closure. It is a manual mechanism operated by a handle - situated on the inferior bench of the organ - which rotates a roller (image 11) joined by the two heads of a continuous cable which, according to the direction of rotation, opens or closes the frames. An ingenious system of pulleys and bearings (image 12) which has been repaired and enhanced in diverse recent proceedings, with some changes in the materials but maintaining the same initial essence, and which use is now intended to be recovered. This is a good new, but an additional constraint added to the assembly which has to be taken into account since it has not been used in many years.



Figure 9.
Inferior hinge of the frame.



Figure 10.
Image of the bad condition of the frame.



Figure 11.

Inferior roller of manual operation for opening and closing.



Figure 12.

Arm with bearings which pushes or pulls the doors.

The doors. Technical inspections

The structural verifications are focused on two aspects, primarily: the verification of the anchoring of the hinges to the fixed furniture of the organ, and the dimensioning of the frame structure. Indirectly they lead to diverse non-structural decisions which are also important and linked to the structural behaviour of frames: the stress on the canvases and the possible creases of the doors, the bad functioning of the closing and opening system due to the excessive deformation, the vibration or the instabilities due to the movement and the excessive slenderness, the fitting of the doors inside the furniture of the organ... are some of the examples. From here the actions and the decisions have to be taken collectively, following multidisciplinary criteria, since one issue affects diverse and very specific fields and none of the members of the team controls transversally in its totality. This is what makes this project a very exciting challenge and at the same of a great exigency for all those involved.

The existing frame is a light structure, orthogonal, modulated and orderly with a perimeter rectangular framework, two vertical posts and three interior horizontal elements, in addition of two diagonals. All of them are 4x12 cm, linden wood in a very bad conservation state. This reduced thickness makes the slenderness more extreme, with elements with base of 4cm and height of 700cm in the transversal direction, the movement direction.

The details of the joint and intersections between the bars are unknown, because until this moment, the paintings of canvases have been restored on the old frames to avoid folding them during the weeks that the project of designing and assembling of the frames lasts. This has limited the analysis of the structure of the frames.

By palpating and in backlighting the geometries and the dimensions has been extracted to elaborate a sketch of the image (fig. 14) which has been the base of its analysis, and which we will consider an approximation from which we can start the analysis. In despite of its geometrical proximity, it will never be enough similar to the real behaviour of the system, because we don't know the typology of the joints, its rigidity and the participation of the canvases and the hinges among other things.

A first analysis of the deformation and stresses behaviour has been done with the program WINEVA, chosen for its clarity and easiness of data input, foreseeing the realization of different families of models to be able to compare the results.

Technically the values which has been chosen as notable, starting with the distribution and the direction of the reaction on the furniture of the organ (fig. 15) or the instantaneous maximum deformation of (0.8 mm – fig. 17) are the maximum compression in absolute value (2.35 kN – fig. 16), the maximum stress under compression (0.49 N/mm²) and the maximum value of horizontal reaction. Furthermore, these are the moments and maximum shear forces (which help to know if there is an over-solicited element) although a priori they don't affect the global behaviour of the frames in a notable way (fig. 18 and fig. 19).

Other results have been analyzed, but these are the values that are chosen as a reference with the intention of reducing the maximum values, without increasing the inherent weight (the major permanent load of the system).



Figure 13.
Image of initial state of the first frame.

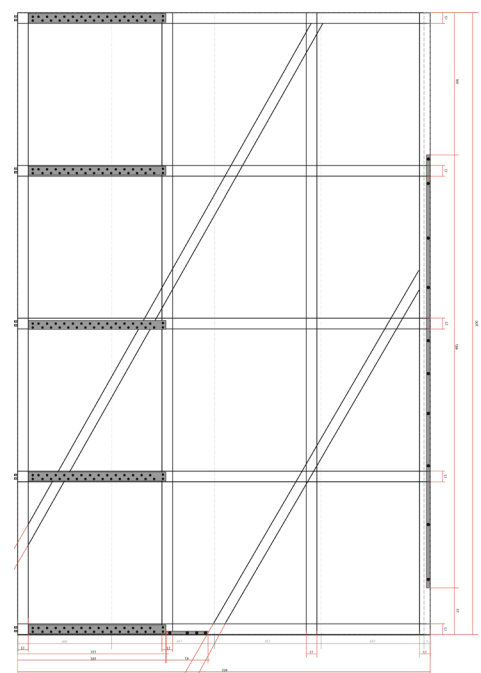


Figure 14.
Initial sketch done by the restorers.

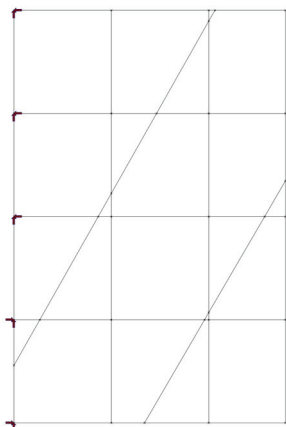


Figure 15.
Reactions of the frame.

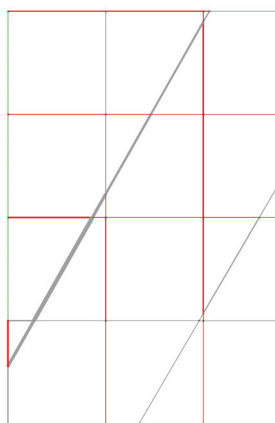


Figure 16.
Diagrams of the frame.

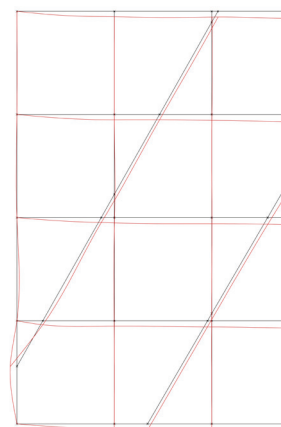


Figure 17.
Deformation of the frame.

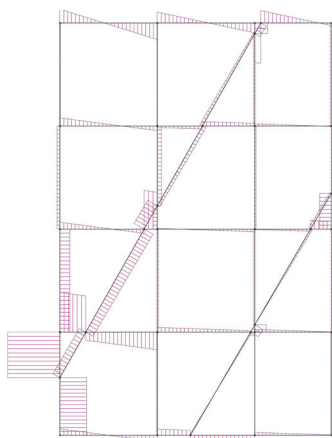


Figure 18.
Diagram of shear forces of the frame.

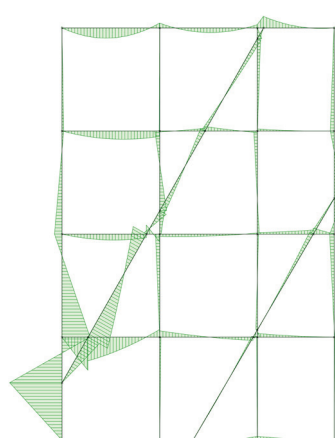


Figure 19.
Diagram of bending moments of
the frame.

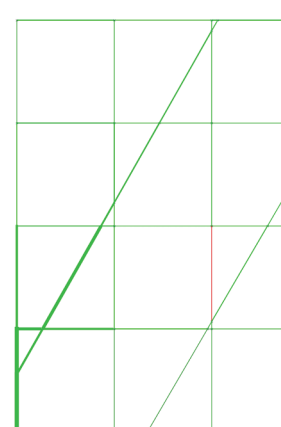


Figure 20.
Diagram of maximum global
stresses of the frame.

Analyzing more particularly the previous images, it can be seen that the point of rotation of the frames is situated between the third and fourth hinge, encountering the maximum reaction in the fourth hinge, a position near the diagonal with the maximum of compression. The disposition of these encounters between the bars seems little accurate, since it ends up causing the maximum of shear forces and bending moments, which accumulate the maximum stresses (fig. 20) in the bars not considered as principals.

An effect that will be favourable but has not been taken in consideration in this phase of analysis is the structural effect of the hinges in the left part of the frame on a resistant level. It has been taken in account, logically, their inherent weights, but the horizontal elements which they are anchored have been considered of sole wooden material.

The collaboration of the canvases as a structural element is unclear, although certainly they come under load and deform, they are tensed and help to maintain the geometry and distribute the stresses accumulated in the intersections of the wooden elements. Due to its conservation state, stiffening and tearing of some the extremes, no structural function is envisioned in the new design of the frames for the canvases, although they are a limiting condition, since if they deformation of the frame is excessive they will be tensed, something that cannot be permitted.

The doors. Similar cases

After some days of research, three cases of elements has been chosen that are considered to have similar structural characteristics - of loading and supports – to the case study.

The three cases are of doors, or doors of altarpieces of diverse dimensions, but with similarities that permit us to analyse with same criteria as in the actual frame of the doors of the organ of Tarragona and to see if they have some logic in structural design that could be used in the new design in order to improve the actual conditions.

The three cases considered are:

1. A solid wooden door located in the abbey of Saint Pierre de Moissac (Occitanie, France). This is a secondary door of the premises, solid, wooden with a very clear disposition of posts and diagonals, and the inferior part has a double thickness (fig. 21). It has been considered for trebling the compressed diagonal, and duplicating the superior horizontal tensed element, with the idea of distributing the stresses in different parallel bars. It disposes of two hinges.
2. The doors of the major altarpiece of Church of San Miguel Arcángel d'Ibdes (Calatayud, Zaragoza). This is one of the closer case and more similar which has been found. Constructed in 1556, they dispose of minor density of structural elements (fig. 22). Their restoration by IPCE (Instituto de Patrimonio Cultural de España) has been finalized in March of 2017.
3. The doors of major altarpiece of the church of San Pablo (Zaragoza). In the same manner of the one from Ibdes, it is one of the closer and more similar cases that has been found. Constructed in 1524, its structure of diagonals disordered inside of a frame with certain modulation is notable (fig. 23). They were restored some years ago by IPCE (Instituto de Patrimonio Cultural de España), reproducing the same original frame.

The prototype. Structural analysis. Comparative cases

Once the cases for comparison are chosen, it is needed to homogenize some of the particular properties, like the dimensions, the applied loads or the number of the supporting hinges, among other things. This is a first phase of adjustment in which specific data of original case is lost for approximating toward the case study, to be able to compare some parameters and results from a more objective point (fig. 24).

Thereby, the dimensions of the frame and wooden elements were adapted to the doors of Tarragona, and the weight of the canvases and the hinges were unified (elements that are thought to be preserved). A geometrical adaption which still has not been done in this first phase is adopting the geometry to the exact position of the five hinges of Tarragona, since its position is linked, usually, to the position of the horizontal inferior elements. Modifying the position of the five supports, would alter excessively the models to be comparable. The objective is to compare the real behaviour with dimension and similar loads, but without adapting fully the bars to the fixed points of another case which would make them loose essence. This will be undertaken in the second phase.

The first verification that has been done, before a more profound analysis, is the comparison of the inherent weight of the 4 models. Being a permanent load, in a displacement with variations of humidity (equal to a class 2) the weight is needed to be more similar between the models, in the way that the one that has more density of interior bars, these would be of minor section. The resistant characteristics, the density of the wood and the dimensions of the frameworks of the frames are the same in the four models.

On the subject of the joints, and looking to unify criteria, the exterior frame is articulated to the four extremes and so are the bars that reach it. It has to be taken in account that the frame of Tarragona has only 4 cm of thickness, and that the intersections imply a major weakness of the element, in the way that the links between the elements that are not straight come close to the behaviour of a pure articulation. In a more advanced phase it is intended to adopt the geometry so there would not be intersection of more than two bars, which would make the link impossible.

Also, the values of the horizontal reaction on the hinges have been compared, to estimate the points and the values of maximum solicitation. The Tension-Compression values of reaction are not representative in our case, since they produce the same effect on the furniture of the organ, by being doors that could be opened up to 180°.

The next result table compares different parameters, where the maximum value of each row of results with the four compared models is indicated with bold font.

In the table (fig. 25), it is verified that the model of the existing frame of Tarragona is the one that accumulates the most maximum values, being of notice is the instantaneous deformation for the relation of the behaviour with the patrimonial canvases (about the double of the one in second place); the one with maximum stress under compression, which could provoke instabilities (approximately the double of the most favourable one); the one with maximum stress for the bending moment, which gives us an idea of the effectiveness of the design (four times bigger than the minimum value) or the maximum horizontal reaction, which demonstrates the effectiveness of the distribution of the loads on the supports (it accumulates the maximum value of compression and almost the maximum of tension).



Figure 21.
The door of Moissac.



Figure 22.
Placing the doors for dimensional verification. San Pablo.



Figure 23.
The doors of altarpieces of Ibdes (Zaragonés 2017).

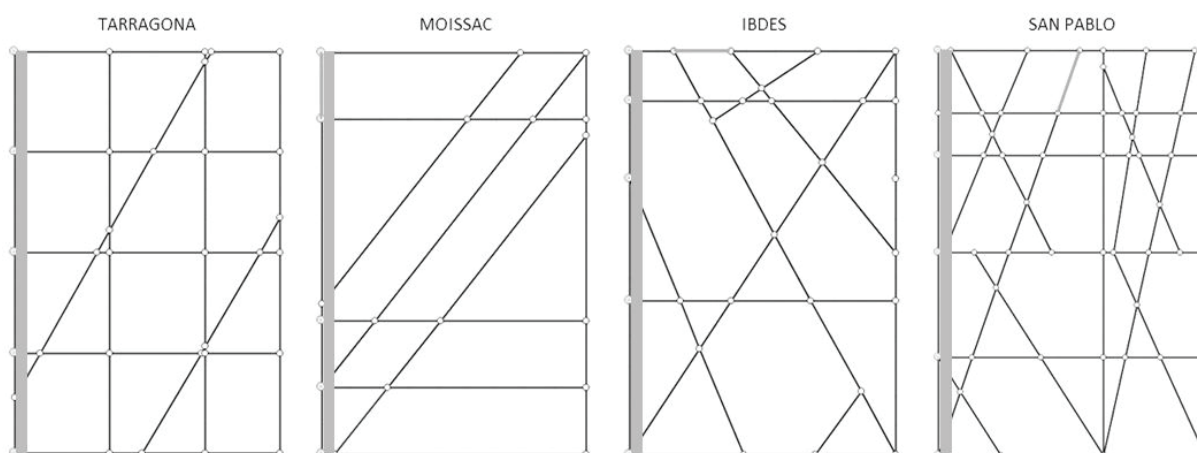


Figure 24.

Initial models (with real adapted geometry) which has been compared in the first phase.

		TARRAGONA	MOISSAC	IBDES	SAN PABLO
LOADS - kg	<i>Ihn. Weight</i>	124,20	113,10	122,90	130,20
	<i>Hinges</i>	48,80	50,10	39,00	48,80
	<i>Canvas fabric</i>	97,80	97,80	97,80	97,90
	<i>Total</i>	270,80	261,00	259,70	276,90
MAX. DEFORMATION - mm	<i>Instantaneous</i>	1,20	0,30	0,50	0,60
MAX. AXIL - kg	<i>Compression</i>	235,00	128,00	190,00	165,00
	<i>Tension</i>	88,00	92,00	88,00	70,00
MAX. SHEAR FORCE - kg		53,00	29,00	12,00	41,00
MAX. BEN. MOMENT - kg-cm		2.610,00	1.660,00	600,00	780,00
MAX STRESS - kg/cm²	<i>Compression</i>	4,90	2,67	3,96	3,44
	<i>Tension</i>	1,83	1,92	1,83	1,75
	<i>Shear forces</i>	1,10	0,60	0,25	0,85
	<i>Bend. Moment</i>	54,38	34,58	12,50	16,25
REACTIONS - kg		<i>HORIZ</i>	<i>HORIZ</i>	<i>HORIZ</i>	<i>HORIZ</i>
	<i>Hinge 1</i>	-50,50	-93,80	-64,70	-47,40
	<i>Hinge 2</i>	-23,30	-2,20	4,50	-8,20
	<i>Hinge 3</i>	-90,60	32,60	-15,30	-38,10
	<i>Hinge 4</i>	133,70	61,20	-17,50	-25,50
	<i>Hinge 5</i>	30,80	2,20	93,00	119,20

Figure 25.

Table of results of phase I.

Furthermore, if we analyze globally the results table, we would see the minor forces and stresses under compression, thus also less prone to suffer instabilities, and the minimum value of deformation in the 'Moissac' model. However, this model accumulates some high bending moments and, although the reactions are more homogeneous, it has room for improvement.

The two other models are the intermediate results with regard to the previous ones, highlighting the minimum of stresses of shear forces and the bending moment of the 'Ibdes' model, that indicate a more pure axial behaviour, or the fact that the design of the 'San Pablo' model with many bars with reduced section does not stand out for an excess of deformation or of stress. This last one is the only of the four cases with superior hinges under tension, with the point of rotation between the fourth and the fifth hinge.

The prototype. New frame. Initial proposal

The proposal of the new frame design has never been a closed question. The project of renovation-restoration from the beginning evolves as more information is gathered. To show respect for the encountered pre-existences and understanding that they have been resisting for some hundred years, it was deemed adequate not to dismiss maintaining the existing geometry although being of new construction and in all case seek to improve it, so it was included in this comparative study.

After the first analysis and verifying that the design of Tarragona is improvable concerning the geometry, and that the strategy of using the minimum of material is very favourable for the reduction of the permanent loads, it seems adequate to us to study variations in its geometry to improve its structural behaviour.

In this sense, the first phase of the analysis will be of great utility for facing the new design. It seems clear that the fact of disposing of diagonals in the compressed direction is a good option. It is helpful that they are compressed because the links will be easier to execute and elements or joining materials would not be required and furthermore because as they are more than one unit, it will divide and reduce stresses that could provoke an instability of the bar in question.

According to these commentaries, some first models are proposed (fig. 26), adapting the geometry to the position of the five hinges that require to keep the 5 horizontal bars of the Tarragon model, but some diagonals are introduced like the style of the 'Moissac' Model.

Analyzing, with the same criteria as on the first phase, the numerical results of the first models of this second phase, there has been proposed some variations, step by step, in order to be able to verify the effectiveness or not of each new proposal. In this phase, the weight of the canvases and the hinges are the same, and so is their position in the model. What is different is the inherent weight of each model (according to if it has more bars or not, since the dimensioning of the bars that are repeated are always the same, with occasional exception).

In the next results table (fig. 27) the parameters are compared like in the first phase, the maximum values are indicated with bold font:

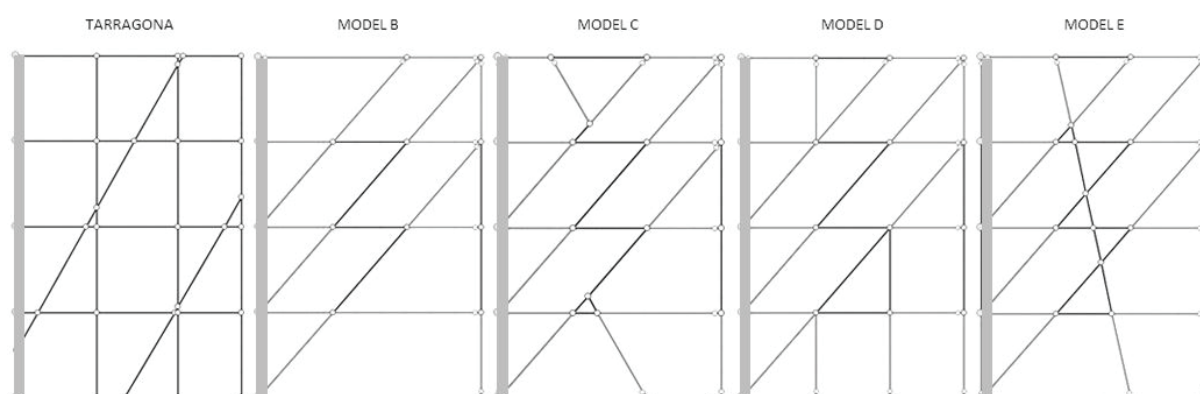


Figure 26.
Comparing geometries of the analyzed models.

		TARRAGONA	MODEL B	MODEL C	MODEL D	MODEL E
LOADS - kg	<i>Inn. Weight</i>	124,20	110,20	115,00	117,20	1.26
	<i>Hinges</i>	48,80	48,80	48,80	48,80	0.49
	<i>Canvas fabric</i>	97,90	97,90	97,90	97,90	0.98
	<i>Total</i>	270,90	256,90	261,70	263,90	2.72
MAX. DEFORMATION - mm	<i>Instantaneous</i>	1,20	0,20	0,20	0,20	0,20
MAX. AXIL - kg	<i>Compression</i>	235,00	84,00	99,00	93,00	0.92
	<i>Tension</i>	88,00	62,00	79,00	69,00	0.79
MAX. SHEAR FORCE - kg		53,00	27,00	29,00	17,00	0.16
MAX. BEN. MOMENT -kg-cm		2610,00	1320,00	770,00	360,00	0.04
MAX. STRESS kg/cm2	<i>Compression</i>	4,90	1,75	2,06	1,94	19.17
	<i>Tension</i>	1,83	1,29	1,65	1,44	16.46
	<i>Shear forces</i>	1,10	0,56	0,60	0,35	3.33
	<i>Bend.Moment</i>	54,38	27,50	16,04	7,50	0.83
REACTIONS - kg		<i>HORIZ</i>	<i>HORIZ</i>	<i>HORIZ</i>	<i>HORIZ</i>	<i>HORIZ</i>
	<i>Hinge 1</i>	-50,50	-61,80	-39,60	-46,60	-0.40
	<i>Hinge 2</i>	-23,30	-46,50	-79,00	-68,90	-0.79
	<i>Hinge 3</i>	-90,60	33,70	40,50	33,50	0.16
	<i>Hinge 4</i>	133,70	26,40	16,20	24,40	0.53
	<i>Hinge 5</i>	30,80	48,20	61,90	57,50	0.50

Figure 27.
Table of results of phase 2.

According to this comparison, it is observed, at first sight, that the original model (Tarragona) accumulates the maximum values, notably – in a negative sense – being the one that weights the most, but with the worst design possible, as the value of maximum instantaneous deformation demonstrates (6 times superior to others); the one with the maximum stress under compression, which could provoke instabilities (force of more than double of the most favourable one); the one with the maximum stress of the bending moment, since it gives us an idea of the effectiveness of the design (more than seven times greater than the minimum value) or the maximum horizontal reaction, which demonstrates the effectiveness of distribution of the load on the supports (accumulates the maximum value so compression and tension).

The first model evolving as a result of merging the models 'Tarragona' and 'Moissac' (Model 'B') show very favourable results, since almost in all the parameters it achieves minimum values in comparison, notably minor stress under compression among all analyzed models and a more uniform distribution of reaction. It has a greater stress state in comparison with other models like shear force and bending moments – without being worrisome values – the design is still improvable.

Analyzing this model in detail, it is observed that the values of greater bending moment and shear force are concentrated in the horizontal superior and inferior bars, due to the inherent weight, of the hinges and canvases. It is decided to give more supports to these bars with vertical posts and diagonals of minor section (Models 'C', 'D' and 'E').



Figure 28.

Image in real magnitude of the furniture of the organ captured by drone (Octocam-maps).



Figure 29.

Team gathered with the topographer.

Conclusion

The bad condition of the wood of the frames implies, unfortunately, that it is necessary to substitute the totality of the bearing structure of the canvases. This fact opens the door for a deep and accurate analysis of the pre-existence and to use new technologies for structural analysis to improve its functionality and to be able to apply 'science and research' in a project of patrimonial renovation-restoration of first order, as is this case.

Our first objective and main concern was to keep the canvases under stress and without creases, thus we had to find a design of frame that would limit greatly the deformation, to avoid that the patrimonial canvases could suffer deformations or excessive stresses, which would mean its potential degradation.

To be able to evolve and improve the design, some parameters have been set in comparison, like the dimensions of the frames, joints and loads. The same process of standardization has been done with the quantity, dimensions and positions of the interior bars, which have been also modified along the process.

The weight and other factors of the models have been homogenized to not disfavour or favour some over others. The presence of the hinges that could contribute in an increase of rigidity on the first part of the horizontal bar with which is connected has not been simulated.

The control of inherent weight, of the stresses under compression, which could result in instabilities and over stresses, and of the shear force and bending moment have resulted in an evolution of the design on the parts with most concentration of stresses. When these parameters have been stabilized, a more uniform distribution has been verified with lower values in the points of support. As a way of simplifying the process and the results, the coefficients of increasing of load were not applied, neither those which affect the deferred deformation or the characteristic resistance of the wood. Being coefficients that affect the same values in each model, they have not been considered in this comparative analysis, and they will be applied in the verifications of the final model, before its construction.

Once to the point of valuing the models, according to the results of the comparison realized, the keys to the good design for a frame of characteristics of the case study are the optimization of each of the bars, making them function at the best possible way (particularly and combined) without adding unnecessary inherent weight.

About the numerical results of the comparisons, especially of the phase 2, the best models for the purpose of results are 'D' and 'E', with minimum variations between them. Probably, valid now, might be a constructive reason to tip the balance towards the model 'E', for not having intersections of more than two bars. Its final definitive selection is discussed with all the team, especially with carpenter, in a date posterior to the closing of this article. What is described in this document is methodological procedure of looking for the optimize form on a theoretical level according to constraints of the construction work.

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