Characterization and Evaluation of the Conservation Status and Safety of the Monastery of *Nª Senhora do Desterro*

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October 2015

Abstract: The main purpose of this project goes through the characterization and the evaluation of conservation and safety status of the east wing of the Monastery of *Nª Senhora do Desterro*. It is a historical monument that was a subject to several changes, which might have caused a negative impact on the structural safety. Given the uncertainty associated with the lack of plants or historical documents of the building, the study starts with the process of the constructive and structural characterization, based on the characteristics of old buildings (*pré-pombalino*) and the inspection work performed in the building. Taking such heed on this initial face is essential to synthesize all the changes in each element and to get a clear notion of their conservation status. Since this is a masonry building and it wasn't possible to provide direct test that would allow getting the mechanical properties of the materials, there was a need to develop a research study in order to exceed this problem. A critical study follows, in order to define carefully all the regulatory parameters required for the safety verification. So it was necessary to elaborate analytical calculation models that would allow getting a correct simulation of the behaviour of the building, under the actions it may be subjected. Thanks to its validations it was possible to produce different sensitivity analysis, according to the structural changes made through the ages, enable to obtain the less interventional strengthening and rehabilitation proposal, which would also providence the best structural performance.

Keywords: Characteristics of Historical Building; Masonry; Safety Verification; Rehabilitation and Strengthening of Structures

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1. Introduction

The rehabilitation and conservation of old buildings is a laborious work that requires an extra care, given the difficulty of defining the seismic vulnerability as well as the lack of information that still exists for this type of buildings down in current legislation. Given that and the fact that there may not exist sufficient historical documents, it's common to be necessary to implement the structure inspection. This work should be complemented with campaigns and prospecting rehearsals to ensure that there's the necessary knowledge of the resistance and deformability of the materials. Since the analytical modeling of that behavior implies previous knowledge of this data.

We are faced with a very different world of building that the regulation ignores, with emphasis on design of new buildings. Despite these difficulties, this work will certainly provide huge improvements, ensuring a more effective structural behavior during an earthquake as well as the preservation of the architectural patrimony of the country. In generality is necessary, and bring an important added value to the rehabilitation process, to use with caution, sensitivity and common sense all available knowledge of the different involved areas of the project.

2. Historical Evolution

The monastery in the study is located in *Anjos*, center of Lisbon, started being built in 1591 by the *Bernardos* brothers of Cistercian Order. The authorship of the project belongs to *Baltazar Álvarez*, considered one of the greatest figures of Portuguese arts in the context of the modern period [1]. Despite the sobriety be the model idea of Cistercian architecture, being guaranteed a certain order in their monasteries, it doesn't apply in this one, and the fact that the first floor plans of this wing that exist are from 1807, and which just contain the third and part of the second floors, it turns this characterization more complicated. However, thanks to the existing partnership between companies involved in the current project (since the business of structures and engineering projects, architects, historians and the business responsible for future occupation of the building), it was possible to get more easily the most interesting conclusion.

It is known that different intervention to what the old monastery was subjected began in 1750, which last occupation was destined to a hospital, a role that it kept until 2007. It might had been during this last occupation, which lasted 150 years, that the structure of the monastery started to suffer significant changes, given their functional requirements. Throughout this protect only the changes that occurred in the east wing will be considered, since it's the body that contains the highest numbers of original structural elements.

3. Main Characteristics of the East Wing of the Monastery

3.1. Constructive Characterization

Given the large number of changes that had occurred, an analysis separating element to element and floor to floor will be done, in order to simplify the understanding.

<u>Foundations</u>: The inspection tests executed didn't allow taking certainties of the type of construction. However, after consulting the geological map of Lisbon [2], it was observed, that the monastery is founded on rocks. And so it should be a typical case of a direct foundation.

<u>Exterior Resistant Elements</u>: In general these are elements from rubble masonry with large thicknesses, having 2,2 meters on the first floor and decreasing to 1,5 meters on the fourth floor. These large thicknesses are justified by the resistance of the material that forms these, because the masonry doesn't present a good resistance to traction forces. In addition, there is one of the exterior façades, which may be a gravity wall at the level of the first two floors. It is grounded on one of the sides thereby increasing the resistance load of these elements. That's why they have larger thicknesses in the first floors. The visible damages over these elements are referring to the opening of

the holes with considerable dimensions. These damages reduce the load capacity of the walls, which might jeopardize their safety.

Interior Resistant Elements: Concerning damages these types of elements don't present great problems, however it is noticable that there are elements whose original constitutions were quite modified. For simplicity these were rated by four different groups of columns, where: A – stonemasonry; B – unreinforced concrete; C – rubble masonry; D – brick masonry. In a summarized manner elements categorized as A and C are original from the monastery, the others ones are referring to columns that have their original properties quite modified or even nonexistent. In the first floor the modified elements are from the groups B and C, and in the second floor they are from the groups C and D, on this floor also exist a couple of elements from the group A. In the case of the third floor all the columns are original and belong to the group C. Finally in the fourth floor there are no interior resistant elements.

The analysis also includes a north body. On the 1st and 2nd levels, of the interior there are 3 columns of stonemasonry, which suffered a significant reduction of its section. This is a consequence of having opted to place an intermediate floor in this body, that originally had double height ceilings.

Pavements: Overall the construction technique inside the monastery is relative to arches and vaults, since this is the solution used for the ceilings of 1st, 2nd and 3rd floors. Some of these vaults show damage in their bases or, in some cases, were demolished or do not exist, and were replaced with a voided slab (as those were old vertical access between floors). On the 4th floor, where the original ceiling took the place of the old roof of the monastery, there is a voided slab of pre-stained beams. This slab unloads on concrete trusses, with high dimension.

Roof: Since there must have been needed to add an activity to the fifth floor, during the time that this building operated as a hospital, there had also been a need to build a new roof. This one is higher and wider than the original. Its structures are composed by beams of unreinforced concrete and trusses (according to the free span). These elements are blocking with pre-stressed concrete beams with smaller dimensions. The roof covering is underpinned on these last ones, constituted with ceramic tiles.

3.2. Structural Characterization

After producing an exhaustive study that has as its main aim to represent the original structure plants of the monastery, the plants presented bellow resulted (Figures 1, 2, 3 and 4). These represent the actual structural characteristics of the different floors of the east wing, all the elements that are presented in yellow are related to structural elements, which were demolished, and the red ones are related to the elements that had been constructed with many different techniques.

This is the simplest and most effective way of representing the structural characteristics of the study wing, making it possible to realize the importance of each element as well as the changes that these have suffered.

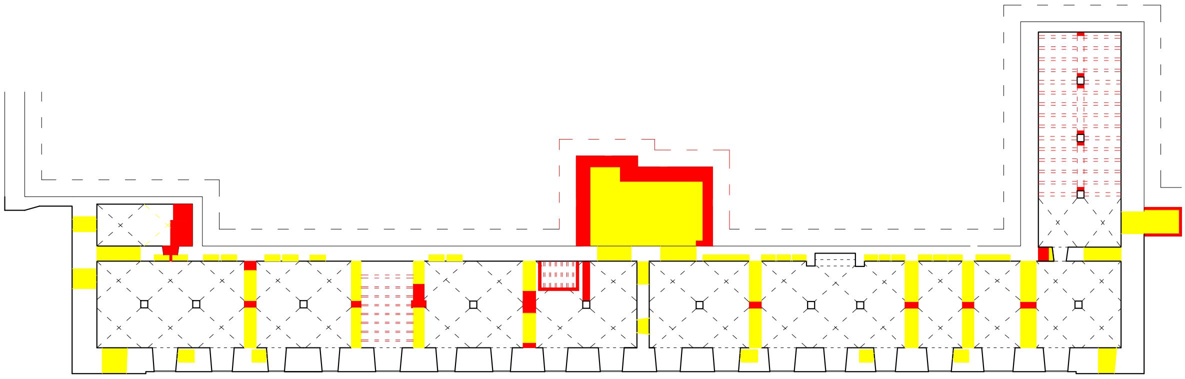

Figure 1 – Plant with the structural changes that occurred on the first floor.

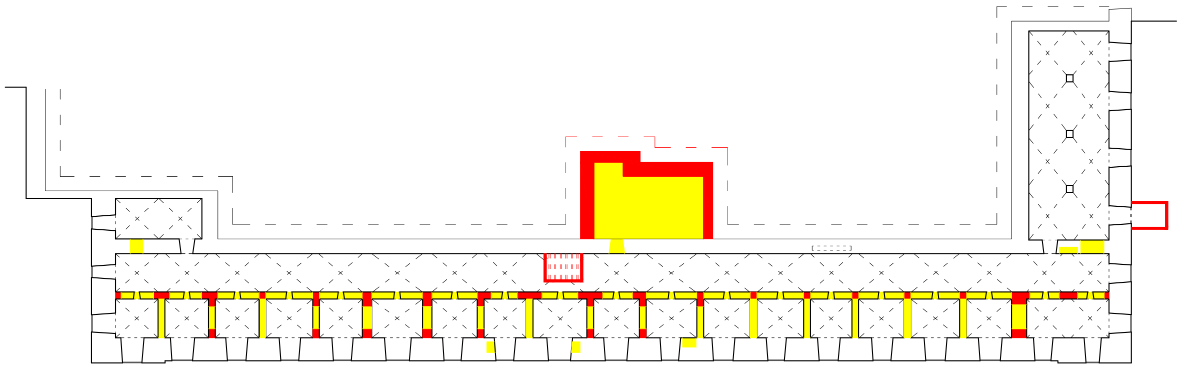

Figure 2 – Plant with the structural changes that occurred on the second floor.

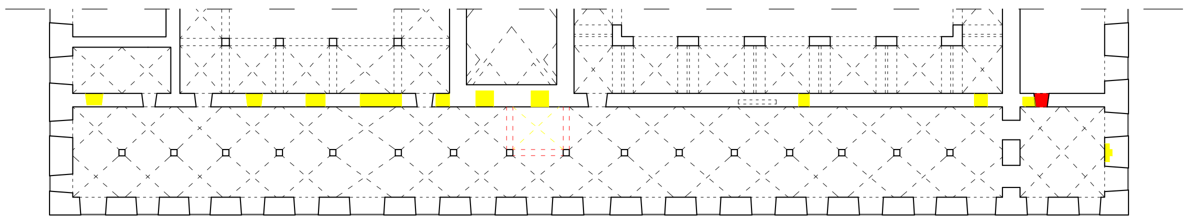

Figure 3 - Plant with the structural changes that occurred on the third floor.

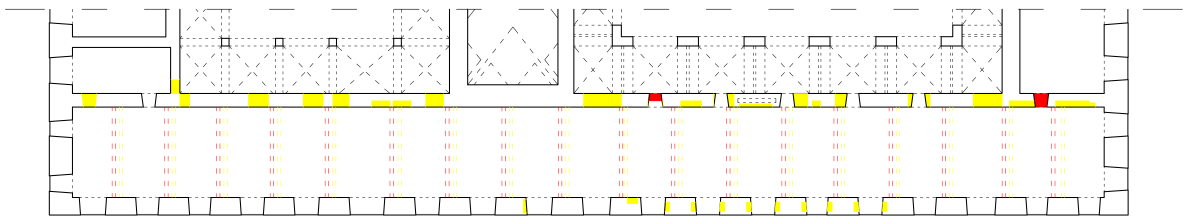

Figure 4 - Plant with the structural changes that occurred on the third floor.

3.3. Mechanical Characterization of the Materials

It's not possible to evaluate the safety level of a structure without the knowledge of the tensile strength of its material. As noted previously this is a masonry building that can briefly be evaluated given two principal groups of materials, where: 1 – elements in stone masonry and 2 – elements in rubble masonry. On account of being a material that doesn't have its mechanical characteristics well defined, it was necessary to elaborate detailed studies on how to classify these best. The masonry is made of heterogeneous, discontinuous and anisotropic material, and there is always a great uncertainty associated with the type of behaviour that this material would contain, especially in old buildings. Therefore it's necessary to define the parameters of deformability and strength comprising from this material. In summary there are two different ways to determine these properties through direct methods (with the realization of *in-situ* and laboratory test) or indirect methods (determine the characteristics thru empirical formulas, forced *a priori* knowledge of the basic components). Since in this project there weren't made *in-situ* tests to determine the resistance values, those are based on the bibliographical references consulted with instances similar to the case of study. (Like the case of [3], [4], [5] and [6]).

4. Regulation Framework

After consulting the regulation, Eurocode (EC), it was possible to check that there still many limitations exist, concerning the safety verification on the historical building, especially masonries. Who is focusing their study on new building projects. It was also observed that the Italian regulation presents somewhat more realistic view of classification of those type of buildings, given confidence factors that can improve the mechanical material proprieties. However, given the uncertainty that still exists, the seismic action will be just set EC8. For such action it was considered that the building belongs to an important class type II as seen it is located in Lisbon, what makes it belong to the zones 1.3 (for the seismic action type 1) and 2.3 (for the seismic action type 2). As damping coefficient value, it was considered equal to 5% and the behaviour factor was considered equal to 1,5. Thus having all the unknown parameters of design spectrum for elastic analysis, it is already apparent that less rigid buildings (with the first mode of vibration period higher than 30 seconds) the seismic action conditioning is of type 1. Relatively to the resistance properties of the principal materials, the values assumed are:

Table 1 – Safety Ultimate Values (strength and deformability of materials)

Material Type	Mechanical Properties Considered						
	γ (kN/m^3)	E (MPa)	G (MPa)	v	$\sigma_{compression}$ (MPa)	$\sigma_{traction}$ (MPa)	τ_{shear} (MPa)
Stone Masonry	22	1 000	200	0,2	1,2	0,1	0,1
Rubble Masonry	19	700	150	0,2	0,9	0,1	0,1

5. Conservation and Safety State

In order to verify the safety of the building it was necessary to elaborate analytical calculation models, which contributed to the conclusions about its behaviour under the effects of several actions. Given the particularity of the shape of the structure of the present wing, it was possible to obtain its global behaviour through two different models. The first one (Figure 5) was the simplest, only constituted with “frame” elements, which varies between thickness and height according to the floor it belongs to. This represents one of the elements situated between spans along the exterior east façade. The long longitudinal length makes its tension not to vary much, making plausible its realization of this simple model. The second model (Figure 6) refers to the general behaviour of the east wing. For this modulation all the resistant elements were taken into account, such as: exterior resistant elements modelled by “shell” elements of masonry rubber, the internal columns by “frames” elements considering the different materials, and sections along the wing and the pavements by “shells” elements. At this initial phase it was necessary only to consider the locking effect made by the vaults, all over the floors.

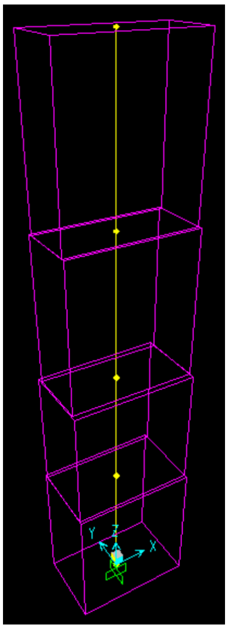

Figure 5 – Frame Model.

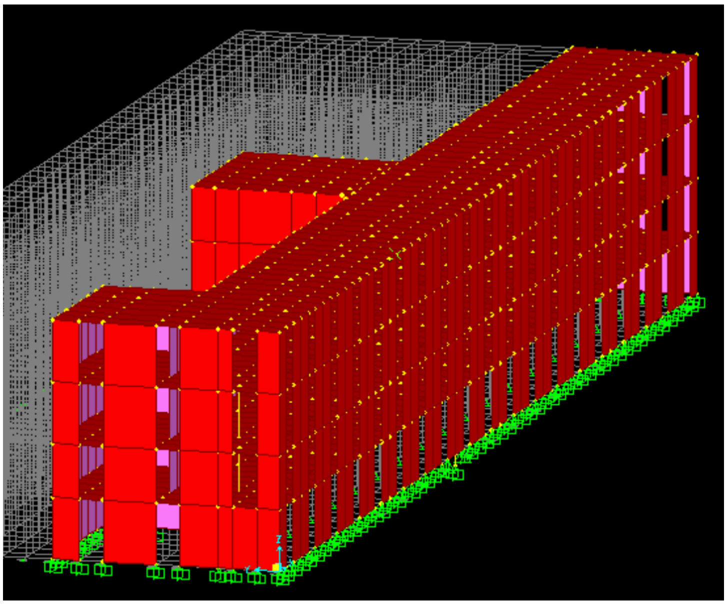

Figure 6 – General Model.

The validation of the models was performed confirming that the values of stresses and displacements meet the expectations, and also by checking if over the different modes of vibrations of the building the sum of participation of the masses would be higher than 90%. It was also verified that, despite the differences, the models had presented very similar results.

The safety verification for a dynamic analysis was confirmed by the calculation of the tensile stress in the base of the element in the study, worst-case scenario. The value of tension obtained rounded the 0,90 MPa, much higher than the maximum permissible (0,10 MPa). These values derive from the constraint seismic combination, for this case it corresponds to the action type 1 in the transverse direction of the wing (Y direction in the models).

Concerning the safety verification for the static analysis, it was confirmed through the compression stress in some of the vertical elements present in the east wing. 6 different cases were analyzed: A.1 corresponds to the stress value at the base of the exterior element that was previously under analysis; A.2 is similar to the previous case, but the element contains a reduced section, corresponding to the worst demolition made inside it; B.1 corresponds to the maximum stress value at the base of a stonemasonry column (inside the wing); B.2 corresponds to the maximum stress value at the base of a masonry rubber column (inside the wing); C.1 corresponds to the stress value at the base of the stonemasonry columns in the north body (first and second floors); C.2 corresponds to the stress value in the middle of the same stonemasonry column as the previous case. The cases B.1, B.2, C.1 and C.2 exceed a bit the admissible stress limit.

Lastly the influence of certain parameters was analyzed, checking the changes which had occurred in the models. The first analysis was the variation of the imposed loads on the building. It was found that this isn't a parameter with an importance to the safety verification of this type of masonry building. The second, and last, analysis was referent to consider a reduction of the modulus of elasticity. Given the deformation values applied on the top of the models, it was acceptable to consider a reduction of 50% of the initial amounts of modulus of elasticity.

6. Proposed Intervention Plan

6.1. Impact Assessments of the Demolitions Made Over the Years

With an goal to improve the actual performance of the wing during an earthquake, and in order to get an intervention plan that respects the history and architecture of the monument, different sensitivity models of study were elaborated. They were meant to realize the impact in case of a demolition of the interior walls, the compartmentalizing elements in the original structure of the first and second floors. For that purpose 3 different models were created, taking advance of the previous general model: the 1st is regarding the reconstruction of the original walls along the first floor, in the transverse direction (as may be seen in the Figure 1, in yellow); the 2nd is regarding the reconstruction of the original walls in the transverse direction along the second floor (yellow elements over the smaller length on the wing plant, Figure 2); and the 3rd modulation is similar to the previous reconstruction over the second floor, but refers to the original wall along the longitudinal direction of the wing (yellow elements in the Figure 2 along the greater wing length).

Thanks to these studies, it was achieved with more certainty that the reconstruction of the walls along the first floor upgrades the greatest wing behaviour with an improvement around 38% of the actual performance. As for the cases of the second floors, it's better to opt for the reconstruction of the walls across the transverse direction. However, the wing performance improvement is around 6%. Before presenting the final proposal, a model that takes into account the original behaviour of the wing was also elaborated, with the reintroduction of all the aforementioned walls. The results of those are the baseline values of the final proposal.

6.2. Final Proposal

Based on the previously acquired knowledge, the final proposal requires the reconstruction of the following elements, represented in yellow in Figures 7 and 8, along the first and second floors:

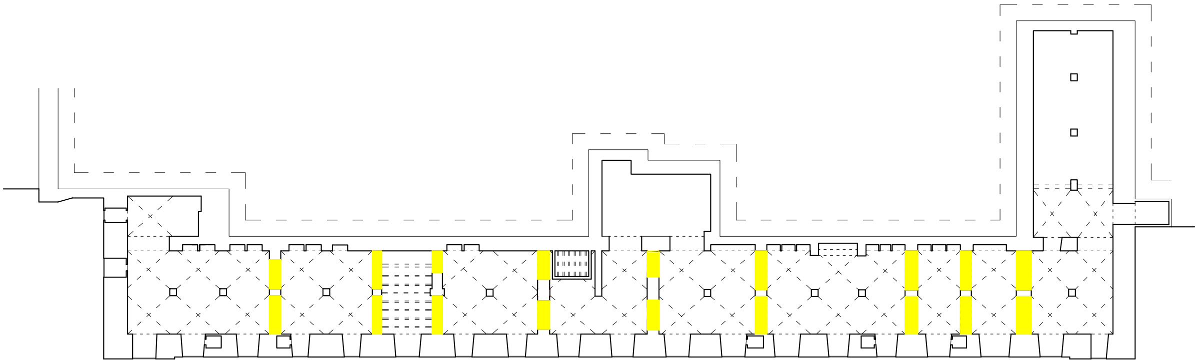

Figure 7 – Plant of the final proposal in the first floor.

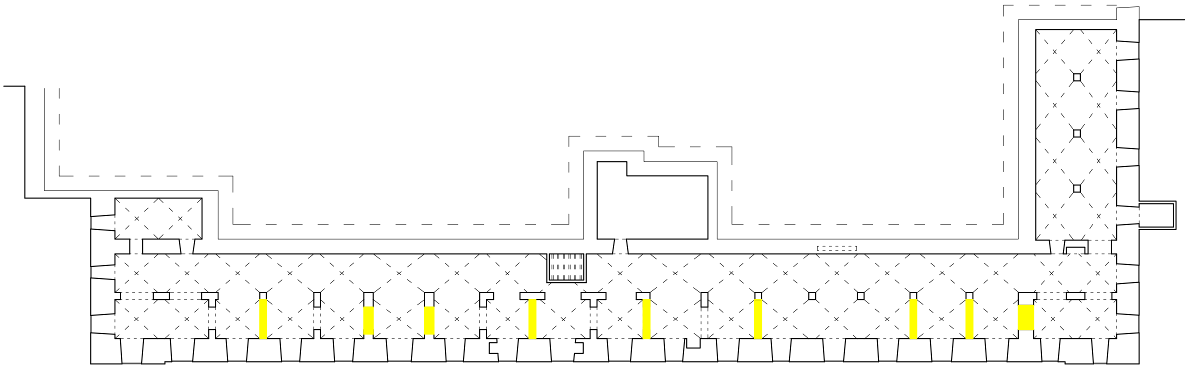

Figure 8 – Plant of the final proposal in the second floor.

Thereby achievement secures an intervention with quite similar results, to those obtained in the original model, requiring half of the walls reconstructed area. The results obtained for this final proposal are represented in Table 2.

Table 2 – Values obtained in the Final Proposal.

Final Proposal	
N (kN)	2576,1
M (kN.m)	1944,8
e (m)	0,75
σ_C (MPa)	0,66
V (kN)	617,6
τ (MPa)	0,12

In this last model it was admitted the possibility of cracking. Given that the resistance of the normal stress of the elements it's calculated based on simplified method, who despises the traction resistance of the masonry elements. As verifiable, the compressive stress value is below the safety limit. However, it is also necessary to calculate the shear stress along the east façade. The resulting value still a slightly higher that the limit, but the regulation allows to considering the redistribution of shear forces over the elements. In this way is possible to affirm that the final proposal ensures the safety verification of the wing for the seismic action.

This way, the final proposal is based on the reconstruction of the walls, listed previously, together with some precautions that are extremely important to ensure. Without them the reconstruction of the walls to rehabilitate and to strengthen them in order to achieve the global security of the wing would not be very effective. It's therefore necessary not only to ensure the reconstruction of the base of some vaults, but also to proceeded with the cracks or visible damage fill as well as to check if the consolidation of the resistant material is correctly done (especially in the base of the arch). At the level of the exterior walls and other changes, which would appear over the characterization work, should be performed a reconstruction of more damaged areas as well as reparation of the cracks, always ensuring that the transmission of forces between resistant elements are properly performed. Regarding the technical reconstruction of the walls, presented in the final proposal, the construction through a traditional technique should be preferred, i.e., rubber masonry wall (connected with hydrated lime). The connection of these new walls to the existing elements should be ensured through local rock bolting.

7. Conclusions

To deal with old buildings is, in the first place, to show willingness to understand a historical reality in movement [7], since all of them exist associated to an identity that should always be regarded with respect throughout any type of intervention. In case of the building under analysis, during the period of the project it has became clear that none of those cares were regarded. That has become evident after verifying the existence of several changes in this wing, where no coherence exists between the adopted techniques or by being careful to maintain the architectural image of this historical building.

One of the principal added values of this project is related to the exhaustive characterization work of the east wing, together with information sharing of that happened easily among all the companies from different areas, involved in the future project of occupation of this building. Due to this it was possible to reach appropriate conclusions about the original structure of the monastery (unfortunately it wasn't possible to find any original plants), to understand better the type of changes that had occurred, as well as their purpose, and also to be able to identify the conservation status of each element.

Concerning a fact that couldn't be carried out in any test, that is to be able to characterize the mechanical properties of the materials, turned out to be the first major constraint of this project. Since there was no margin of certainty that would have allowed taking a different approach along the regulation framework, eventually it has been a less restrictive analysis into count.

However, it is believe that the exhaustive, clear and careful way how all this project was elaborated would be enough to guarantee that, despite of the limitations of this type of works, quite real values along the models have been achieved. As well as all the essential care, which must be taken into account throughout the presentation of the final proposal of intervention, was presented. In case of the type of construction technique, cares between resistant elements must be provided. Also the options of possible reinforcement forms on the structural damage were presented throughout this project.

After completing this project it was possible to conclude, that the complexity, the history and the successive bad interventions related to this building make it unfeasible to present only one solution. However, this relativity should be studied, so that fair and duly substantiated measures could be taken, always respecting the historical value of the monument.

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