## PONENCIAS

# Sustainable interventions: Rehabilitation of old timber structures with traditional materials

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## ABSTRACT

The intervention in built heritage is a way of preserving cultural identity. Therefore, it demands special care and sensibility. In particular, the rehabilitation of old buildings concerns not only façades, but all the structural elements, namely floors, roofs, and inside walls, as part of a more global and consistent heritage. However, most of the interventions on old buildings consist in the substitution of the structural elements instead of their rehabilitation. This situation results mostly of a lack of knowledge and understanding of the existing materials and (or) of the rehabilitation/strengthening techniques.
In general, the preservation of the structural elements results in benefits, not only in terms of heritage preservation, but also in the minimization of the interventions and their impact. However, even when this strategy is followed, the rehabilitation/strengthening techniques using traditional materials has been often ignored and substituted by techniques which use modern materials, frequently expensive and sometimes with doubtful efficiency. This situation is particularly common in old timber structures, namely roofs and floors, which exist all over the World, in some cases with many centuries. Therefore, an effort should be done to invert this situation i.e., to show the community that it is possible to preserve timber structures and, at the same time, to use traditional materials and techniques, leading to more sustained actions.
In order to promote sustainable interventions, contributing to a real maintenance of the built heritage and respecting the International charts and ICOMOS (International Council on Monuments and Sites) recommendations, NCREP (1) (Nucleus for the Conservation and Rehabilitation of Buildings and Built Heritage, a team within FEUP - Faculty of Engineering of the University of Porto) have been participating in many rehabilitation projects, analyzing the state of conservation of buildings and designing rehabilitation solutions, in particular using traditional materials, like wood and steel. The present paper will focus NCREP experience in the intervention of old timber structures, namely at Rodrigues de Freitas school, Valadares Palace, and Valongo and Corpus Christi churches.

## 1. INTRODUCTION

Most of the buildings built till the beginning of the XX century in Portugal is made of masonry, mainly stone (exterior and some interior walls), and timber elements (floors, roofs, ceilings, interior and some exterior walls). If properly connected, these elements promote a good global behaviour: the masonry walls support the floor beams and roof trusses which, on the other hand, act as horizontal braces, inducing a more uniform distribution of stiffness and loading throughout the structure. Thus, if properly designed and in good conditions, these systems constitute efficient structures.

This type of construction is disseminated all over the country and represents most of our built heritage, justifying the increasing interest on its preservation as memory of culture and identity. Unfortunately, most of it is degraded and abandoned, demanding urgent intervention. However, the intervention on old built heritage is not a consensual issue and may result on less conservative approaches. In particular, substituting structural elements instead of rehabilitating it has been a widespread policy that results mainly from the lack of knowledge on the materials and on the techniques and their efficiency. In general, direct intervention on the elements, avoiding substitutions, not only results on heritage preservation, but also on the minimization of the necessary actions and their impact. Though, even when this option is considered, the intervener often prefers new materials, specially polymers and composites, sometimes with higher costs and not always with proved efficiency, instead of traditional materials.

In this field, and particularly for old timber structures, NCREP's option has been mostly oriented to techniques using traditional materials, like wood and steel. These techniques, consisting, for instance, in the addition of timber elements and steel plates, have been applied in the rehabilitation of old buildings with very good results. Some examples will be analysed in this paper, namely: Rodrigues de Freitas School (Porto, beginning of XX century), Valadares Palace (Lisbon, reconstructed after the 1755 earthquake), Valongo Church (Valongo, XIX century) and Corpus Christi Church (Vila Nova de Gaia, XVII century).

At the same time, and in order to support the interventions, a campaign of laboratorial tests is being performed in old timber beams, not only to understand the mechanical behaviour of these elements, but also to assess the performance of techniques involving the use of traditional materials, analysing their efficiency, field of application, and evaluating advantages and disadvantages in comparison to other techniques. The tests are being done in LESE (Laboratory for Earthquake and Structural Engineering) of FEUP, in timber beams removed from old building's floors that, for a number of different reasons, would be demolished. The results obtained will be shared with the scientific community at the end of the campaign and will, hopefully, contribute to more sustained interventions and in accordance to international charters and recommendations.

## 2. INTERVENTIONS IN OLD TIMBER STRUCTURES USING TRADITIONAL MATERIALS

### The structural intervention

The need for the intervention on timber structures is usually related to the existence of damages or alterations of use with load increase. Between the most common damages, one can refer the natural ones (knots, splits, etc.) and those resulting from biotic attacks (insects and fungi) and from incorrect constructive details or structural interventions. These causes not always originate the collapse of the structural elements or structures, but are often associated to their deficient behaviour, with high levels of vibrations and deformations. Consequently, in order to ensure the safety and, at the same time, the

proper performance of the structures, it is necessary to intervene in the damaged structural elements through rehabilitation actions.
The decision about the type of intervention should be taken only after a rigorous and careful survey of the structure (3). According to the results obtained in the survey and to the circumstances of each situation, the intervention on a particular element or structure can take two different ways: **Rehabilitation** or **Substitution**. **Rehabilitation** can be seen as the natural solution that allows the maintenance of the element or the structure. This option may involve a strengthening action, particularly when the original structures are improperly designed or when changes of use (with higher loads) are expected, demanding a higher strength. In a limit situation, the intervention can consist in the **Substitution** of the element or structure, a solution that should be carefully analysed taking into account the percentage and intensity of the damage.

## The choice of rehabilitation techniques

The rehabilitation of timber structures can be done using different techniques, with pros and cons concerning effectiveness, compatibility, intrusiveness, etc. Some of them imply the use of traditional materials, such as wood and steel, and others involve the use of more innovative materials, namely composites (e.g. epoxy, FRPs…). The selection of the best technique must take into consideration the particularities of the construction, namely the existence of constructive elements with particular interest, e.g. ceilings with decorative elements, or the increase of load or any collateral effect to the walls, for instance. Besides of that, when choosing the techniques and materials to use, there are, among others, two criteria linked to heritage protection that should be respected: **Compatibility** and **Reversibility**.
**Compatibility** is linked to the physical and chemical interaction between the existing structure and the intervention solution. In particular, the elements, materials and (or) techniques implemented shouldn't react with those of the existing structure or introduce higher stiffness in localized structural areas. This criterion avoids the introduction of new damage in the structure through the intervention. A good example of that are the glued or very rigid connections in timber elements that may induce concentration of stresses in the interface area, i.e. the occurrence of new damage. **Reversibility** is linked to the will that the interventions be substitutable so that they can give place to more efficient and (or) protective interventions in the future. Generally speaking, the less intrusive solutions are often the more reversible ones.
The effort taken by NCREP in the use and development of techniques with traditional material, as wood and steel, is related to the above mentioned factors. If correctly analysed and applied, these techniques can be an excellent solution to rehabilitation interventions in old timber structures. As (4) refers, the intervention shall be done through a detailed analysis of the techniques and the technologies which were originally used in the construction.

## Techniques with traditional materials

There are many different ways of using traditional rehabilitation techniques in old timber structures, namely: (A) the fixation of timber pieces or thin steel plates, with varied configurations, to the sides of the element (the mostly used by NCREP in the interventions, as it can be seen in point 3.); (B) the introduction of thin steel plates in the interior of the element; (C) the installation of steel belts around the element; (D) the installation of new structural elements (timber or steel) parallel to the existents, among others (5).
To increase knowledge on the efficiency of these techniques in order to give useful information to designers and constructors about the suitability of each technique to solve specific situations, NCREP is developing a laboratorial testing campaign (see point 4.). As a matter of fact, the information related to

research on rehabilitation techniques on old timber structures using traditional materials is quite limited. For instance, in the case of traditional carpentry joints, despite of being widely used, the number of studies on their mechanical performance and on possible strengthening techniques is scarce. With few exceptions, research on timber joints has been oriented towards new engineering configurations. Simultaneously, only few studies were developed in elements subjected mainly to bending; some authors performed bending tests in beams reinforced with steel elements, but reaching contradictory results. The majority of the studies was done in elements with high axial or shear forces. Strengthening techniques on floors to improve the diaphragm behaviour have also been analysed, proving experimentally its efficiency, but advising that further refinement is still needed for the technology to be applied in the construction practice (6). Concerning the connections between timber structures (roof, walls and floors) and masonry walls, although it is usually appointed as a key-element to the overall behaviour of a building (7), in particular under seismic events, no significant efforts have been spent on their study.

## 3. INTERVENTIONS WITH TIMBER AND STEEL ELEMENTS

### Introduction

The use of **timber elements** in the rehabilitation of old timber structures is a very common solution. However, in these interventions it's important to have timber elements of the same wood species and with similar characteristics: density, strength and stiffness, to those of the original structure. (8) refers the convenience of using old timber elements, with the drying process completed, and the importance of having compatible moisture contents between new and old elements to avoid physical incompatibilities. When it's not possible to obtain similar wood, timber elements retrieved from the demolition of old buildings can be used or, as alternative, the new elements, already dry, can be previously placed in the constructions where they will be installed to acquire a moisture content in equilibrium with the construction environment.

On the other hand, solutions with **steel elements** are commonly used in interventions on old timber structures, particularly on timber floors, leading to an increase of strength and stiffness. Even though, when using these elements, two questions should be analysed: the compatibility with the timber elements (the behaviour of wood and steel is considerably different) and the fire resistance of the metallic elements. In fact, timber structures support temperatures for which steel structures would have already failed. Therefore, to avoid the steel elements to become the weakest point of the strengthened structure it's important to improvement their fire resistance, which can be done through physical barriers or fire retardant products. Simultaneously, steel elements should be protected against corrosion.

The following sections describe four rehabilitation interventions of NCREP on old timber structures: the first two using mainly timber elements and the other two using mainly steel elements.

### Rodrigues de Freitas School, Porto

The survey of the structures of Rodrigues de Freitas School evidenced a precarious state of conservation of the timber roofs, involving an area of about 4000m$^2$. The choice of the type of intervention was carefully analysed; the global substitution was an option, although the preferred solution was, since the beginning, the rehabilitation with localized substitution of structural elements. A detailed study on the existing structural elements was performed by NCREP to define the "philosophy" of the intervention, namely the "approval" and "rejection" criteria, allowing estimating the areas where rehabilitation and substitutions were expected (9). This study confirmed that the rehabilitation was the best option and the following techniques were recommended:

### a) Addition of new elements to the sides of the damaged elements

This operation consisted in the fixation of new timber pieces on both sides of the damaged structural elements, with M16 stainless steel threaded rods with hexagonal nut and broad-brimmed washers (to increase the tension distribution), endowing it of an higher inertia, Fig. 1 and Fig. 2. The new timber pieces had physical and mechanical characteristics similar to the *in situ* elements and were treated against biotic attacks; the steel rods were submitted to a treatment to increase their fire resistance.

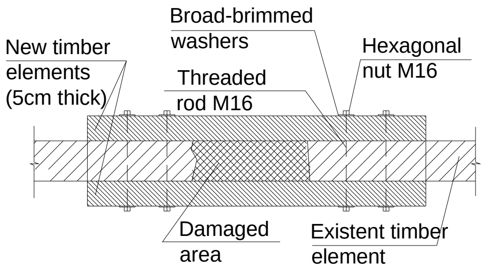


Fig. 1 – Strengthening of the damaged structural elements with timber pieces.

Fig. 2 – Strengthening of a damaged tie beam with timber pieces.

### b) Introduction of bracing elements

The introduction of new timber bracing elements was suggested to reduce the length of the compressed elements (rafters and struts), decreasing the possibility of buckling. These new bracing elements were installed in both sides of the reinforced element and adequately screwed to the battens or to the ridges, Fig. 3 and Fig. 4.

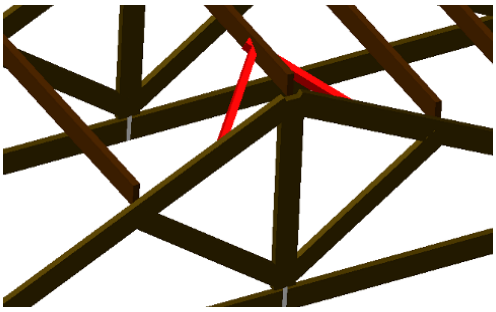

Fig. 3 – Introduction of bracings to reduce the buckling length of the compressed elements (rafters).

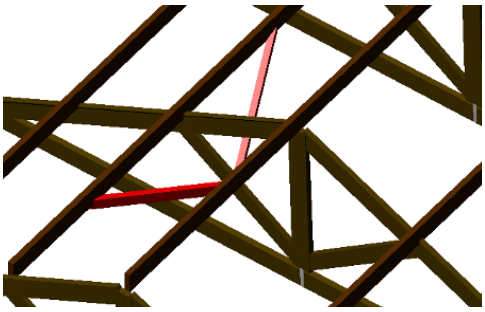

Fig. 4 – Introduction of bracings to reduce the buckling length of the compressed elements (struts).

### c) Partial substitution of the structural elements

In certain situations it was necessary to substitute (globally or partially) the damaged elements by new ones. While in the case of the struts and ridges it was considered convenient to substitute the complete length of the element, in the case of rafters and tie-beams it was possible to substitute only a part of it, with the connection between the new and the existent being done with new timber pieces in each side of the elements, fixed with M16 threaded rods and screws, Fig. 5 and Fig. 6.

## PONENCIAS

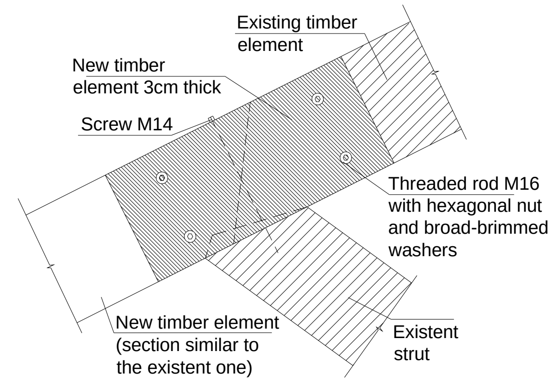

Fig. 5 – Substitution of a part of a structural element.


Fig. 6– Substitution of a part of secondary tie beam.

### Valadares Palace, Lisbon

The intervention in Valadares Palace concerned the rehabilitation of the vaulted ceilings, supported by timber beams with a length of approximately 8,0m. After the survey of these beams with the non destructive equipment called Resistograph, it was possible to conclude about the intense degradation of the beams supports due to biotic attacks: insects and fungi. It was also noticed a considerable deflection at the mid-span of the beams (about 20,0cm), caused by the load of a heavy support system of a lamp located at the top of the main stairs (10). Therefore it was recommended a local intervention to rehabilitate the beams supports and a global intervention to correct the beams deformations.

#### a) Supports rehabilitation

The rehabilitation of the timber beams supports was performed through the fixation (with screws), to their sides, of new timber elements. These new elements, made of the same wood species of the *in situ* elements, created the new support of the damaged beams in the walls. Afterwards the new elements were connected to a mudsill installed at the top of the wall, to guarantee the global behaviour of the building and their correct connection to the stone masonry wall, Fig. 7 and Fig. 8. The damaged extremities of the beams were cut and the remaining wood was treated against biotic attacks, Fig. 9.


Fig. 7 – Strengthening of the damaged structural elements with timber elements.


Fig. 8 – Strengthening of the damaged structural elements with timber pieces and a steel bracket.


Fig. 9 – Cut of the damaged parts of the beams.

A metallic bracket (L150x15) was also fixed to the masonry wall through threaded rods (crossing the whole thickness of the wall) to improve the beams supports and to contribute to the wall strengthening, particularly in out of plan actions, in an intervention oriented to the seismic protection of the building, Fig. 10. All the new timber elements were previously treated in autoclave with an anti-biotic product. On the other hand, all the steel elements were submitted to a treatment to increase fire resistance and to protect against corrosion. The structural design of the fasteners respected the recommendations of Eurocode 5 (11).

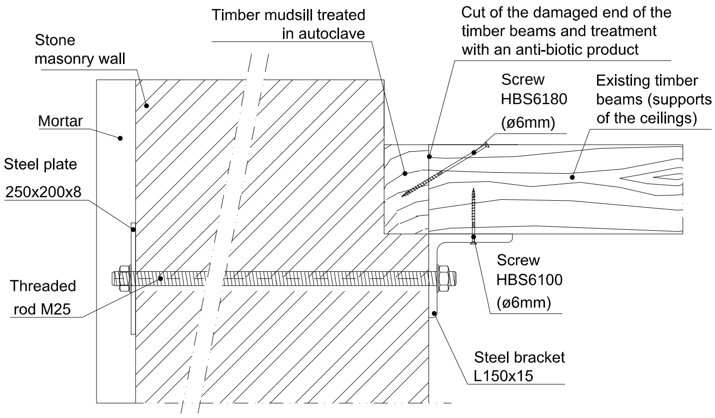


Fig. 10 – Strengthening of the damaged structural elements with timber pieces and a steel bracket.

**b) Deformation correction**

After the rehabilitation of the supports and the removal of the heavy load of the lamp from the mid-span of the beams, the existing deflection was removed throughout a system of steel cables. Before the restoration of the plasters, the ceiling support was also improved with the use of small threaded rods fixed to the timber beams, Fig. 11 and Fig. 12.

Fig. 11 – Improvement of the ceiling's support with the use of threaded rods.

Fig. 12 – Ceiling after the correction of the deformation and restoration of the plaster.

## Valongo Church, Valongo

The tests performed with the Resistograph in the timber structural elements of the roof of Valongo Church confirmed the deep degradation of some of the tie beams of the trusses, with losses of the transversal section exceeding, in some cases, 50%. Some other structural problems were also observed in the trusses, namely the fact that some hangers were loading the tie beams, the existence of deficient connections between structural elements, the intense degradation of the rafters and ridges supports in the masonry walls and the deformation of the steel elements that perform the connection between the tie beams and the walls (12). Since the substitution of the roof structure wasn't an option, not only by its patrimonial value, but also because of the technical difficulty and costs associated to an intervention of that type, the solution consisted in localized structural interventions, as it is described in the following points.

# PONENCIAS

### a) Tie beams support rehabilitation

The supports of the tie-beams were rehabilitated with steel plates, 6mm thick, in both sides of the element, through threaded rods (Φ10mm), up to a distance of 1,0m from the wall to guarantee the connection to the sound part of the wood, Fig. 13. The steel plates were introduced in existent openings at the masonry walls, the damaged parts of the wood were removed and the sound parts were treated against biotic attacks and separated from the sealing material with a lead sheet.

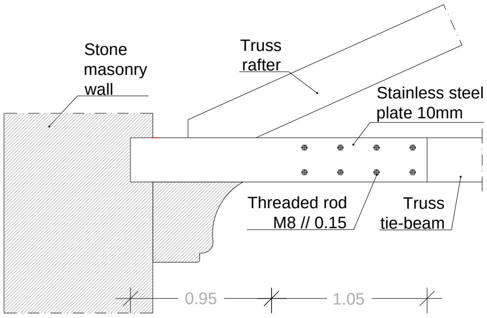

Fig. 13 – Strengthening of a support of a tie beam with steel plates and threaded rods.

### b) Repositioning of the connections between structural elements

The connections between the trusses elements were reinforced with steel plates, traditionally used in the construction of timber trusses, Fig. 14.


Fig. 14 – Use of traditional steel elements to improve the connection between timber elements.

### c) Improvement of the connections between rafters and tie-beams

Stretched steel cables connecting the rafters of the trusses were placed to avoid the rafters to slide on the top of the tie beams. These cables act as tie-beams and contribute to the proper functioning of the trusses, Fig. 15.


Fig. 15 – Introduction of stretched steel cables to connect rafters of trusses.

## PONENCIAS

**d) Rehabilitation of the connections between rafters/ridges and walls**

The connections of the rafters and ridges to the masonry walls were reinforced with steel plates and threaded rods, solution similar to the one used with the tie beams, Fig. 16.



Fig. 16 – Strengthening of the supports of rafters/ridges and the masonry walls.

### Corpus Christi church, Vila Nova de Gaia

The survey performed in Corpus Christi church evidenced the intense degradation of the timber roofs (Upper Choir and Apse), as the result of biotic attacks (13).

In the Upper Choir’s roof it was observed the warping of some trusses tie beams and rafters and the rupture of some other structural elements. The rehabilitation of the roof involved some particularities, not linked to the direct intervention on the structural elements, but due to the constraints associated to the existence of a wooden ceiling with painted coffers connected to the trusses, Fig. 17. This ceiling, with high patrimonial value, was restored *in situ* in order to avoid its deterioration, fact that obliged the structural intervention to be developed by the upper side of the ceiling. The care needed to avoid damaging the coffers implied some additional precautions, such as the protection with geotextiles and the maintenance of temporary struts to support the ceiling.

The intervention in the roof consisted in the strengthening of the structural elements showing insufficient transversal section, mainly in the supports, through the introduction of steel plates connected to the sides and, in some cases, to the bottom of the elements through threaded rods, and fixed to the masonry walls, Fig. 18 and Fig. 19. The connections between the support beams and the ceilings were reinforced with new timber elements, in order to avoid the ceiling to deform. In very specific situations, new timber structural elements were introduced to substitute the damaged ones, Fig. 20.

Fig. 17 – Existent wooden ceiling with painted coffers.

Fig. 18 – Strengthening of the supports of ceiling beams with steel plates and threaded rods.

Fig. 19 – Strengthening of the supports of tie beams with steel plates and threaded rods.

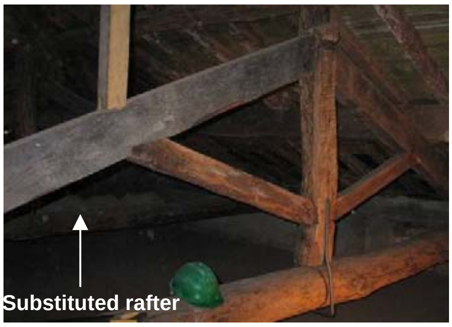


Fig. 20 – Substitution of a rafter by a new element.

In the case of the Apse timber roof, exclusively constituted by rafters and with intense degradation, it was observed the cracking of the subjacent vaulted ceiling. As these cracks could be stabilized through an efficient bracing of the support masonry walls, it was decided to create a new and stiffer timber roof, Fig. 21 and Fig. 22. This new roof was identical to the old one, but with reinforced connections between structural elements by means of traditional carpentry joints and steel elements, Fig. 23, which contributed to an increase of the trusses stiffness and, consequently, to the improvement of the walls structural behaviour. Additionally, the connection between the rafters, and the mudsill and between this one and the walls, were reinforced to mobilize the global structural behaviour of the building.

Fig. 21 – Original roof of the Apse.

Fig. 22 – New timber roof of the Apse.

Fig. 23 – Steel elements introduced to increase the stiffness of the roof

## 4. LABORATORIAL TESTS IN REAL SIZE SPECIMENS

In order to support the options taken in old buildings interventions, a campaign of laboratorial tests in old timber beams is being performed. This campaign aims not only understanding the mechanical behaviour of the elements, but also assessing the performance of rehabilitation techniques involving the use of traditional materials, such as wood and steel, attesting its efficiency, its field of application and evaluating advantages and disadvantages in comparison to other techniques. The campaign focus mainly on the experimental assessment of techniques applied to full-scale timber structures retrieved from old buildings in Portugal. The tests are carried out according to (2), with the application of a series of cycles of increasing displacement to the beams up to a level of displacement beyond the maximum peak load, Fig. 24. Displacement transducers and a load cell measure the beam global and local deformation and the applied load.

The beams, with average diameters and spans of about 0,20 and 4,0m respectively, were tested first in their actual state to assess the original mechanical characteristics, stiffness, strength and failure modes. Afterwards, according to the failure mode, different rehabilitation techniques using traditional materials will be applied, namely the link of new timber elements to the existing ones through wood dowels, screws and traditional joints and the use of internal or external steel connectors/plates/belts. Then, the beams will be tested again, following the same set-up and loading conditions of the first test. The comparison of the results will give a good measure of the techniques efficiency. The choice of the intervention procedure will depend on the conservation state and on the behaviour of the element during the test prior to the intervention.

The behaviour of the original beams (first test) was linear elastic until a fragile rupture, which had place at half-span, near knots or other defects situated in the tensioned side, showing their strong effect in the structural behaviour of the timber elements, in particular in the bending strength. This rupture happened for values close to 40,0kN and for half-span displacements of 60,0mm, Fig. 24. Afterwards, the beams responded with a small "plastic plateau" until higher displacements (about 90,0mm), followed by a second sudden rupture and a gradual decrease of strength. The loading and unloading cycles were applied to the beams after the first rupture until maximum displacements of about 130,0mm. The final residual displacements were of 70,0mm. The average mechanical properties of the beams were calculated according to EC5 (11) and are in the range of expected values: modulus of elasticity, $E_{m,g}$ = 7,5GPa and bending strength, $f_m$ = 36,2MPa. The result of the modulus of elasticity was close to the values obtained in an *in situ* load test performed on beams of the same timber floor (5).

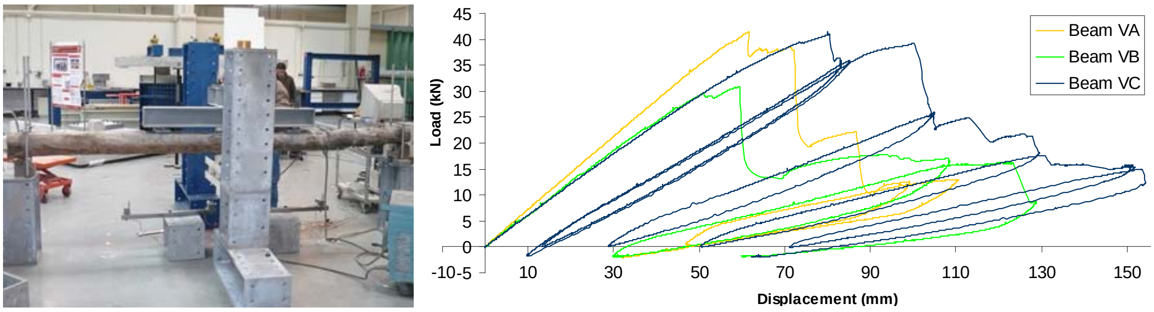

Fig. 24 – Tests on timber specimens according to (2) – Setup and Load *vs* displacement diagrams.

The testing campaign will allow the assessment of the mechanical characteristics and behaviour of real structures, in particular: the bending stiffness, strength and failure modes of the beams. It will be shown that timber structures can be rehabilitated using traditional materials at low cost, sustaining the no need for replacement under partial damage conditions. Hopefully, the tests will confirm that these techniques can be applied with success, allowing more compatible interventions, in better agreement with international charts and recommendations.

## 5. CONCLUSIONS

In general, the preservation of the structural elements results in benefits, not only in terms of built heritage preservation, but also in minimization of the interventions and their impact. Even though, when this strategy is followed, the implementation of traditional rehabilitation techniques has been commonly passed over by techniques which use modern materials, frequently expensive and with doubtful efficiency. This situation is particularly common in old timber structures, namely roofs and floors, which exist all over the World, in some cases with many centuries. Therefore, an effort should be done to change this situation i.e., to show the community that it is possible to preserve timber structures and, at the same time, to use traditional materials and techniques, leading to more sustained interventions.

In this field, NCREP's option has been mostly oriented to techniques using traditional materials, such as wood and steel. These techniques consist, for instance, in the addition of new timber elements and steel plates, and have been applied in the rehabilitation of old buildings with very good results. Some examples are described in this paper, namely with Rodrigues de Freitas School, Valadares Palace, and Valongo and Corpus Christi Churches. At the same time, a campaign of laboratorial tests is being performed in old timber beams to assess the performance of techniques involving the use of traditional materials, evaluating advantages and disadvantages in comparison to other techniques. The tests are being done in LESE in timber beams removed from old building's floors that, for a number of different reasons, would be demolished. The results obtained will be shared with the scientific community in the end of the campaign, and will hopefully contribute to more sustainable interventions and in accordance to international charters and recommendations.

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