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CONSTRUCTION AND BUILDING PERFORMANCE

BUILDING AND DESIGN TECHNOLOGIES

CULTURAL HERITAGE SUSTAINABILITY RESTORATION: A QUANTITATIVE METHOD FOR THE REVERSIBILITY ASSESSMENT OF INTERVENTIONS ON HISTORICAL TIMBER FLOOR

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Abstract

Restoration technology has different characteristics from mechanical, chemical, and industrial technologies. In fact, it concerns objects recognised as cultural heritage as evidence of historical, cultural, aesthetic values, which the intervention has to preserve. The observation of the damages caused by wrong restoration interventions has led to the formulation of guidelines to limit the risks of such interventions. One of the basic principles of these guidelines is reversibility: since degradation is an inevitable process, construction works will likely require restoration and functional adaptation over time. The historical timber floor is the technology system that embodies and tells the history of a building in a more reliable way: it is the most evident testimony of the technological-cultural-economic characteristics that have conditioned the design and construction of a given building in history.

In accordance with the need to preserve these historical testimonies, the study aimed to develop an innovative method for the quantitative evaluation of reversibility in the restoration and static consolidation of timber floors. The method aims to evaluate the most reversible intervention, i.e., more sustainable in terms of future revision and modification.

Keywords

Sustainable refurbishment, Reversibility, Timber floors, Historical buildings, Cultural heritage.

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1. INTRODUCTION

One of the main objectives of modern restoration is to preserve the historical structure and material consistency of the historical artefact, restoring its cultural values and leaving the legibility of the historical stratification unaltered [1]. When the restoration intervention involves the consolidation of structural parts, in order to allow a less invasive approach, the Code of Cultural Heritage and Landscape [2], at art. 29, paragraph 4, establishes that the restoration can be limited to a structural improvement, for the properties located in areas declared at seismic risk, without necessarily having to comply with the regulatory parameters imposed for the anti-seismic adaptation. The Technical Standards for Construction [3] also point out that historic buildings cannot be adapted entirely at the expense of the loss of priceless historical and architectural values. In addition to the loss of aesthetic values, there is also the risk of distorting the original static scheme. The designed techniques should, if possible, correspond to the original ones, and the integrated parts should be distinguishable from the pre-existing ones.

It is possible to affirm that the reversibility exists when the methodological approach foresees interventions conceived in a regime of constraint that guarantees easy disassembling operations of the system: adding, integrating, supporting, tying, strapping, pulling, and pushing can be considered reversible actions. On the contrary, replacing, injecting, glueing, and demolishing are irreversible actions.

By taking the concept to the extreme, it can be deduced that only the strut represents the true paradigm of reversible structural intervention, together with the tie rod [4].

The tie rod and the strut are simple solutions, almost always easy to implement, visible, and thus maintainable, effective, removable, retractable (in the sense of controllable and adjustable in their effectiveness), in a word: reversible [5–7].

Camillo Boito (1836-1914), promoter of philological restoration, emphasises the need to respect the history, i.e. the successive formal stratifications induced by the various ages [8]: "[…] Restoration must, therefore, be characterised by a distinction between original and added parts […]", because "the better the restoration is carried out, the more the lie becomes insidious and the deceit triumphs" (opposing Viollet le Duc's stylistic restoration). Boito's thought, which hopes for additions clearly distinguishable from the original parts, seems to subtend the need for reversible interventions.

The 1972 Italian Restoration Charter [9] states in art. 4 that "[…] restoration means any intervention aimed at maintaining efficiency, facilitate reading and transmit to the future the works and objects […]". Art. 7 of the same document also allows, for restoration work, the execution of "[…] additions of accessory parts in static function or reintegration of small parts historically ascertained implemented according to the cases or determining in a clear way the periphery of the additions or adopting differentiated material even if tuned, clearly distinguishable to the naked eye […]". Article 8 recommends that "[…] any intervention on the work […] must be carried out in such a way and with such techniques and materials as to be able to give confidence that in the future it will not make impossible a new possible intervention of preservation or restoration […]".

Therefore, starting from the need to preserve timber systems (floors, roofs, etc.), the research aimed to develop a method to evaluate the reversibility of the interventions that, from time to time, are necessary to preserve the integrity in order to adapt the system to changing functional needs.

2. STATE OF THE ART

A large part of the architectural wood heritage consists of the roofs and floors of historic load-bearing masonry buildings. Blaha et al. (2018) [10] report an example of the cultural stratification of timber roof structures in the Czech Republic. The authors studied the case of a building in Prague, where an Italic Baroque roof replaced the original Gothic roof (by architect Martino Allio, in the year 1685). The comparison between the typologies of the pre-existing Gothic roof and the new Italian Baroque roof led to interesting results in comparison with Czech Baroque typologies. Bertolini Cestari and Marzi (2018) [11] propose a multidisciplinary analysis of the problems related to the conservation of the cultural heritage of timber roofs. The authors analyse ten case studies in northern Italy.

Mosoarka and Keller (2018) [12] present a new procedure for the assessment of historical timber roof structures. The methodology is based on a multidisciplinary approach that aims to regulate future interventions based on a priority list, besides assessing the cost-effective condition.

Kunecký et al. (2018) [13] highlight the appropriateness of using "all-wood" scarf joints in renovation interventions (e.g., replacing excessively degraded scarves with elements of new material) of historic timber structures in Central Europe. They analyse the performance of scarf joints in terms of stiffness and the possible alterations in force distribution within the whole structural system.

Lima et al. (2018) [14] analyse consolidation solutions to improve timber elements' flexural stiffness. They test three solutions (based on steel plates, steel reinforcement, and steel cables) as an alternative to the pre-stressed cable technique.

In the last decade, composite solutions, wood-on-wood, have been studied to improve the external performance of the timber deck. Other studies investigate the consolidation of timber floors with cross-laminated timber (CLT), fixed to the beams to create a composite structure. Roensmaens et al. (2018) [15] present a variant of the CLT consolidation technique: the flexural stiffness of the floor is maximised by inserting a layer of wood blocks between the CLT slab and the existing joists. Unuk et al. (2019) [16] propose an improvement of the reinforcement technique with cross-laminated timber (CLT) panels. The use of a glass strip as additional reinforcement is discussed and evaluated with a practical example. The proposed approach allows the use of thinner CLT panels, thus achieving a significant increase in the load-bearing capacity of the timber floor.

The Conference "Principles For The Preservation Of Historic Timber Structures" [17] defined the primary objectives of preserving and protecting historical authenticity and integrity of cultural heritage. According to the results of this agreement, any intervention should be based on appropriate studies and assessments, respecting the aesthetic and historical values as well as the physical integrity of the structure:

a) be carried out by traditional means;
b) be reversible, if technically possible;
c) be such that it does not impede future conservation work;
d) be such that it does not hinder the possibility of subsequent access to the original structure;
e) for historical timber structures, the criterion of minimum intervention should be preferred.

At the 11th World Conference on Timber Engineering 2010, WCTE, Gubana A. [18] presented experimental tests on transverse timber beams with composite sections. The author shows that cross-laminated timber panels are generally used to construct walls and floors of new timber houses, but they also have interesting mechanical properties for the reinforcement of old timber floors in restoration works.

Riggio et al. (2012) [19] present the reinforcement and stiffening of traditional timber floors with the addition of timber boards and dry connections. In situ tests were performed on the structural elements, and the results were compared with those obtained in the laboratory on a disassembled element. The two test campaigns showed a good agreement of results. In particular, an increase of more than four times the effective flexural stiffness was obtained after repair in both cases.

From state of the art, it emerged that the reversibility of the restoration intervention is a concept that is becoming more and more important and attentive today in the scientific panorama and debate of the sector.

This research, therefore, starting from this assumption, intends to evaluate, through a quantitative approach, the reversibility factor of restoration interventions based on the initial requirements:

– necessity (understood as the need to adapt the historic building to new laws or functions);
– quantity (understood as the minimum amount of original material to be removed);
– compatibility and durability (a reversible intervention can be rethought and remodelled over time);
– low invasiveness and recognisability (a reversible intervention is minimally invasive and definitely recognisable);
– lightness (a reversible intervention can be designed with techniques that minimise the addition of material to the existing object).

3. TOOLS AND METHODS

This study aims to quantify the reversibility factor of consolidation work on timber floors. This approach, which can be extended to any concept, could be useful, for example, for predicting future maintenance interventions.

– Technique including removal of original material (S01)
– Technique without removal of original material (S02)

The methodology is divided into the following phases:

3.1. PHASE 1 (PHASE COMMON TO BOTH SCENARIOS S01 – S02)

Definition of the categories of intervention, according to the aims and objectives:

- intervention to support the beam (SB)
- intervention on the beam element (B)
- anti-seismic improvement intervention (AS)
- biological restoration intervention (BIO)

3.2. PHASE 2 (PHASE COMMON TO BOTH SCENARIOS S01 – S02)

The intervention techniques on timber floors are defined for each of the categories mentioned in phase 1, as shown in the summary table below (Fig. 1).

3.3. PHASE 3 (SCENARIO S01)

The method was calibrated on the basis of an intervention to replace the head of the beam with a timber pros-thesis (SB_1).

Sub-phase "0" is the initial state, corresponding to the state of the structure before the intervention. Sub-phase "1" corresponds to the preparation phase before the intervention. Sub-phase "2" corresponds to the finished intervention. Sub-stage "3" corresponds to the dismantling of the prosthesis. Sub-phase "4" corresponds to the re-operation in the same way as sub-phase 2.

Reversible can be considered any contemporary restoration intervention, both "conservative" and "aesthetic", which can be removed (for alterations or other reasons) without damaging the original (IRR - Rome Restoration Institute). Therefore, for the determination of the reversibility factor (RF), four parameters have been identified as significant for research, as their variation affects the outcome of the evaluation of this factor (RF). However, it is believed that this application can be generalised and extended to other contexts, using the expression:

$$RF = \sum pi\ Ri$$

Where Ri represents the contribution of each of the four parameters to the reversibility of the analysed technique.

This quantitative approach aims to require the designer to think, right from the initial design phase, about how to "disassemble" the intervention, being able to estimate the degree of permanent and irreversible alteration that the intervention itself will bring the timber artefact.

In this way, the evaluation of the most appropriate intervention technique (concerning the degree of reversibility desired) can be carried out objectively.

For the quantification of the reversibility factor, for the purposes of this method, an equation with 4 parameters was considered:

category of intervention	cause of the instability	goal	intervention technique
SB 01	structural and/or biological degradation	recovery and improvement of load-bearing capacity (compared to vertical loads)	replacement of the beam head with wooden prosthesis
SB 02	structural and/or biological degradation	recovery and improvement of load-bearing capacity (compared to vertical loads)	restoration of the beam head with epoxy resin
SB 03	structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	new supports with metal cantilever
SB 04	structural and/or biological degradation	restoration and improvement of bearing capacity (compared to vertical loads)	new supports with metal shoe
B 01	structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	integration of tie rods and metal struts
B 02	structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	increase of the resistant section by affixing metal profiles to the top surface
B 03	structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	increase of the resistant section by affixing metal profiles to the top surface
B 04	structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	confinement of bars of fiber-reinforced polymeric material to the intrados wooden beams
AS 01	regulatory adjustment	improved response to actions in the plan	affixing of a new planking, crossed, on the pre-existing one
AS 02	regulatory adjustment	improved response to actions in the plan	circling, with metal angles
AS 03	regulatory adjustment	improved response to actions in the plan	anchoring the beams to the masonry with tie rods and steel plates
AS 04	regulatory adjustment	improved response to actions in the plan	bracing by means of steel tie rods and ties, at the floor soffit
AS 05	regulatory adjustment	improved response to actions in the plan	bracing in fiber-reinforced composite material, at the soffit soffit intrados
AS 06	regulatory adjustment	improved response to actions in the plan	reinforced concrete slab at the extrados, anchored to the masonry with perimeter bond beam
AS 07	regulatory adjustment	improved response to actions in the plan	multidirectional sliding supports (energy dissipators) at the beam heads
AS 08	regulatory adjustment	improved response to actions in the plan	bracing by means of lattice girders or stays
BIO 01	biological (prevalent) and/or structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	recovery beams with fiberglass gratings
BIO 02	biological (prevalent) and/or structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	integration of load-bearing elements with glulam beam or steel plate
BIO 03	biological (prevalent) and/or structural degradation	restoration and improvement of bearing capacity (compared to vertical loads)	resistant section increase through the combination of woodworking elements

Fig. 1. *Non-exhaustive list of intervention categories as a reference for the development of the methodology.*

$$\text{RF (reversibility factor)} = \frac{(R1 + R2 + R3 + R4)}{4}$$

where:

- R1 (R_volumetric) is calculated considering an intervention of integrating the timber prosthesis and simulating a hypothetical subsequent replacement of the same. R1, therefore, measures the volumetric loss of material when the prosthesis is disassembled (step 3) and the timber element is returned to step 1 before restoration. The R1 value is the ratio between the residual volume, measured after the removal of the prosthesis, and the initial original volume, before the first restoration (V residual / V original). The original volume is the volume of the prosthesis applied in the first surgery, while the residual volume is the volume of the prosthesis, minus the non-recoverable material, following the removal of the joints. The value of R1, considering all possible cases, is a value between 0 and 1.
- R2 (R_mechanical) is the ratio between the measurement of the performance of the timber beam after the second intervention (sub-phase 4) and that measured during the first intervention (sub-phase 2). In the theoretical case, the slope of the load-displacement curve was taken as the basis for the methodological development. The value of R2 lies between 0 and 1.
- R3 (R_aesthetetic), measures the number of wood element surfaces irreversibly affected by the intervention. This coefficient is derived from the ratio S residual / S original, where S_res represents the aesthetically relevant surface of the original element after removing the prosthesis (sub-step 3), and S_original is assimilated to the initial, starting surface before the restoration intervention. The value of R3, in light of all possible cases, varies between 0 and 1.
- R4 (R_feasibility) mainly penalises the intervention techniques from the extrados of the floor, which would involve the partial or total alteration of the overlying floor, and therefore the compromise of the latter, if of particular value. A technique from the intrados, on the contrary, presents, theoretically, a higher level of feasibility, as it could be feasible even without the removal (even temporary) of components of the system and without altering any works or frescoes existing on the intrados. For what has been argued above, the coefficient R4 is considered variable (between 0 and 1) for interventions at the extrados, if the adopted technique foresees, or not, the removal of the floor above. On the contrary, it is considered invariant, that is always equal to 1, in case of intervention at the intrados.

Calculation of the reversibility factor (RF).

Samples similar to those in the previous table were taken. The actual restoration was then simulated (step 2), and the prosthesis was dismantled (step 3).

In order for the disassembly (step 3) to take place correctly, it is necessary to:

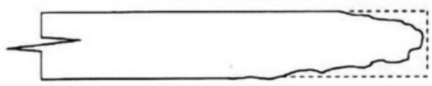
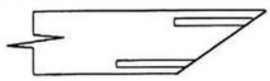
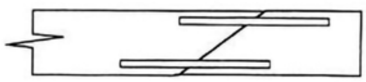
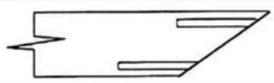
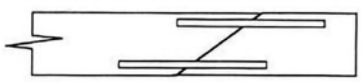
sub-phase	phase description	corresponding graphic scheme
0	status at the initial time	
1	preparation for the intervention: the beam is machined to accommodate the prosthesis	
2	realization of the consolidation intervention, through the assembly of wooden prosthesis anchored to the pre-existing part through the encroachment of fiber-glass bars sealed with epoxy resin	
3	removal of the prosthesis, to prepare the beam for the next surgery	
4	re-execution of the intervention referred to in step 2, with the same modalities	

Fig. 2. *Framework of the intervention methodology for the assessment of scenario S01.*

<table>
<tr><td colspan="12">Quantification of R1 parameter</td></tr>
<tr><td rowspan="3">test</td><td rowspan="3">breaking</td><td colspan="3">size of the break-ins related to subphase 1 (cm)</td><td colspan="3">size of the break-ins related to subphase 3 (cm)</td><td rowspan="3">breaking volume, subphase 3 (cm3)</td><td rowspan="3">breaking volume, subphase 1 (cm3)</td><td rowspan="3">difference (cm3)</td><td rowspan="3">average value (cm3)</td></tr>
<tr></tr>
<tr><td>b</td><td>h</td><td>z</td><td>b</td><td>h</td><td>z</td></tr>
<tr><td rowspan="4">1</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td rowspan="4"></td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="12">Quantification of R2 parameter</td></tr>
<tr><td>test</td><td></td><td>elastic module (MPa)</td><td>slope zone "1" (intervention side)</td><td>difference %</td><td colspan="2">slope zone "3" (side of the beam opposite the intervention)</td><td>difference %</td><td colspan="2">σ
rafters breakage</td><td colspan="2">σ
media breaking</td></tr>
<tr><td rowspan="2">1</td><td>1° intervention</td><td></td><td></td><td rowspan="2"></td><td colspan="2"></td><td rowspan="2"></td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="4"></td></tr>
<tr><td>2° intervention</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td rowspan="2">2</td><td>1° intervention</td><td></td><td></td><td rowspan="2"></td><td colspan="2"></td><td rowspan="2"></td><td colspan="2" rowspan="2"></td></tr>
<tr><td>2° intervention</td><td></td><td></td><td colspan="2"></td></tr>
</table>

Fig. 3. *Scheme for the quantification of R1 and R2 parameters.*

- add and cut the internal metal bars that were affixed during the first procedure (step 2);
- open the breakouts and extract the bars by removing as little wood as possible from the beam.

The table shows the method for calculating R1, derived from the ratio between the final volume (following removal of the prosthesis – sub-phase 3) and the initial volume (sub-phase 1).

In virtue of the previous considerations, the parameter R2 acquires the following value:

R2 = P2nd intervention / P1st intervention

where

- P1st corresponds to the average of the measured slope values for the two specimens after the first intervention;
- P2nd corresponds to the average of the measured slope values for the two specimens after the second intervention.
- R3 parameter evaluation: This parameter is significant when the beam surfaces are particularly aesthetically pleasing. To quantify this parameter, it is necessary to estimate the original presumed aesthetically significant surface of the element and the original residual surface after removing the prosthesis.
- R4 parameter evaluation: To estimate this parameter, it is necessary to evaluate the possibility of performing the intervention from the intrados, and in any case, without having to remove the upper floor.

3.4. PHASE 3 (SCENARIO S02)

The methodological scenario related to minimally invasive interventions, i.e., that do not involve the removal of the original material or at least a minimum part, is equally articulated through the quantification of the 4 parameters taken as reference for the methodology:

- R1 (volumetric incidence): results from the difference between the initial volume, the timber element, and the volume removed as a result of the intervention.
- R2 (mechanical incidence): results from the pre/post intervention structural check.
- R3 (aesthetic incidence): results from the surface of the original element, which is hidden as a result of consolidation.
- R4 (feasibility incidence): results from the evaluation of the difficulty of the intervention, i.e. if it requires additional works (such as the removal of the pavement and the concrete screed at the extrados).

3.5. PHASE 4 (PHASE COMMON TO BOTH SCENARIOS S01 – S02)

For each intervention technique, evaluate the reversibility factor (RF).

The following thresholds have been assumed for weight/judgement assignment:

RF threshold values

Intervention :			
volumetric contribution	mechanical contribution	aesthetic contribution	feasibility contribution
V_{origin} =	Quantification of the alteration between pre and post-intervention values	S_{origin} =	Evaluation of the difficulty of the intervention (e.g.: if it requires the removal of the floor, etc.)
Biologically degraded volume =		Busy surface for through-hole drilling =	
Volume of holes , cuts, etc. =			
V_{res}=		S_{res} =	
R_1 =	R_2 =	R_3 =	R_4 =

Fig. 4. *Summary diagram for quantifying the reversibility factor.*

- for 0% < "RF" < 80% low reversibility factor
- for 81% < "RF" < 90% average reversibility factor
- for 91% < "RF" < 100% high reversibility factor

4. APPLYING THE MODEL TO CASE STUDIES

4.1. INTERVENTION SB_1: REPLACEMENT OF THE BEAM HEAD WITH AN ANCHORED PROSTHESIS WITH CONFINED BARS

The intervention adopted for the elimination of biological degradation was the replacement of the beam heads. Below is shown the graphic scheme and the significant dimensional data related to the intervention, resulting from the design graphs (Figs. 1 and 2).

Dimensional data:
– beam: length = 560 cm; section = 24x16 cm
– dimensions of each perforation = 22x3,8x1,6 cm
– prosthesis : average length (at sight) = 52 cm

R1 and R2 parameter evaluation.

The factor R1 is obtained from the estimation of the final volume that would be obtained once the prosthesis is removed (step 3) and the estimate of the initial volume on which the operation is performed (step 1).

The volume of the bundle after sub-phase 3 is estimated by the volumetric difference made up by the difference in the volume of the breakthroughs, which in sub-phase 3 are obviously greater than those in sub-phase 1.

The factor R2 derives from the ratio between the mechanical characteristics, considered as a reference after a 1st and after a second intervention (sub-phases 2 – 4). In the specific case analysed, the slope of the load-displacement curve assessed near the connection between the prosthesis and the rest of the beam was taken as the reference for mechanical characteristics.

The table shows the mechanical characteristics measured on two specimens: there is no substantial variation between the values obtained for the beam after the first and second intervention, both in terms of elastic modulus and slope, in the zone "3", while there was a difference of about 30% less in the beam between the first and second intervention. This difference is probably due to an inaccurate replacement of the prosthesis in the second intervention: this is also demonstrated by the fact that the second joist, after a more accurate positioning, showed practically the same slope values.

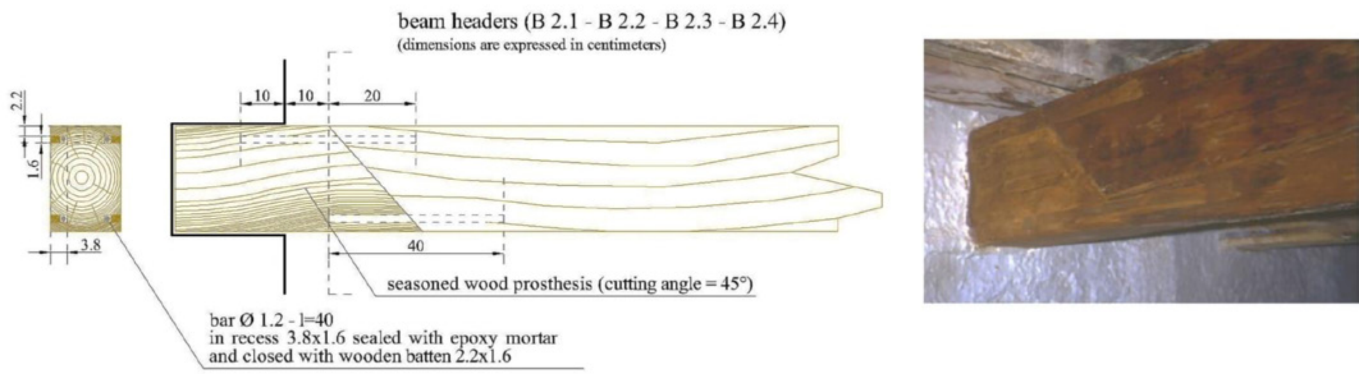

Fig. 5. *Graphic scheme of the intervention (on the left) / Post-intervention photo (on the right).*

Quantification of R1 parameter											
test	breaking	size of the break-ins related to subphase 1 (cm)			size of the break-ins related to subphase 3 (cm)			breaking volume, subphase 3 (cm3)	breaking volume, subphase 1 (cm3)	difference (cm3)	average value (cm3)
		b	h	z	b	h	z				
1	1	19	2,2	4	19,6	2,9	4,1	233	167	66	69,3
	2	19,5	2,2	4	19,8	2,8	4,2	233	172	61	
	3	18,5	2,2	4	19	3,2	4	243	163	80	
	4	19,5	2,2	4	19,2	3	4,2	242	172	70	
2	1	18,5	2,2	4	18,5	2,9	4,2	225	163	62	71
	2	21,2	2,2	4	21	3,2	4,2	282	187	95	
	3	20	2,2	4	20	3	4	240	176	64	
	4	18	2,2	4	18	3	4,1	221	158	63	

Quantification of R2 parameter								
test		elastic module (MPa)	slope zone "1" (intervention side)	difference %	slope zone "3" (side of the beam opposite the intervention)	difference %	σ rafters breakage	σ media breaking
1	1° intervention	19223	171713	-32	250247	9,6	24,40	25,44
	2° intervention	17339	116701		274267			
2	1° intervention	21503	142678	-7,1	230127	9,9	26,49	
	2° intervention	20707	132456		252952			

Fig. 6. *Development of calculations related to the quantification of parameters R1 and R2 for intervention SB_1.*

Under the above considerations, the R2 parameter acquires the following value:

$$R2 = P2nd\ intervention / P1st\ intervention$$

Therefore it is obtained:

$$R2 = \frac{124578}{157195} = 0,79$$

R3 parameter evaluation: This parameter is significant when the beam surfaces are particularly aesthetically pleasing. To quantify this parameter, it is necessary to estimate the original presumed aesthetically significant surface of the element and the original residual surface after removing the prosthesis.

R4 parameter evaluation: To estimate this parameter, it is necessary to evaluate the possibility of performing the intervention from the intrados, and in any case, without having to remove the upper floor.

4.2. INTERVENTION AS_4: ANTI-SEISMIC IMPROVEMENT THROUGH BRACING WITH TIE RODS AND PERIMETER RIMS, WITH METAL ELEMENTS, ON THE CEILING

The intervention consists of applying diagonal metallic tie-rods on the ceiling connected to the masonry corners. The connection to the timber beams is made employing "U" shaped metal ties (Fig. 7), and the intervention may be carried out both on the intrados and extrados of the timber deck. In this case, assuming that the floor above cannot be removed, it is considered to be carried out at the intrados.

The dimensional parameters considered for the purposes of quantifying the reversibility factor are:

Dimensional data:
- n°5 beams: length = 630 cm;
- beam section = 25x25 cm

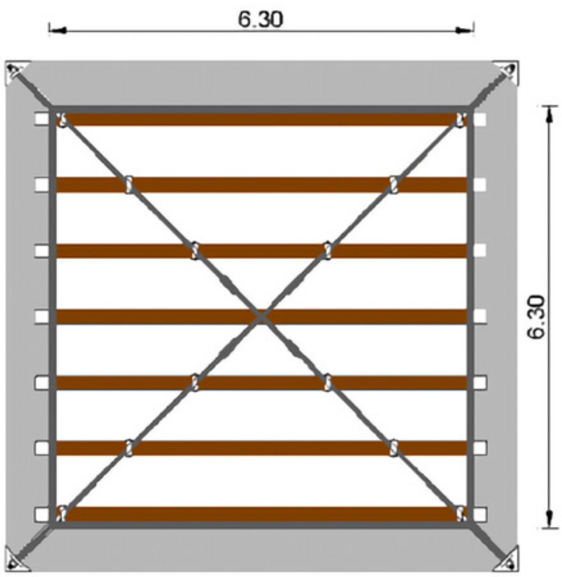

Fig. 7. *Scheme of the intervention AS_4.*

4.3. INTERVENTION AS_5: ANTI-SEISMIC IMPROVEMENT INTERVENTION, WITH PLATING OF THE DECK, THROUGH FRP CROSSED BANDS, EXECUTED AT THE EXTRADOS

This technique involves the stiffening of the timber deck, in its plane, through the application of FRP crossbands. Given the particular procedure, the technique requires the realisation of the intervention from the extrados of the floor and then requires the preventive disassembly of the floor above (Fig. 8).

The essential phases of the intervention are:

- removal of the walkable floor, at the extrados, where possible, after numbering the pieces for subsequent correct repositioning;
- application of bands of FRP fabric, roll type, of the appropriate length.

After installing the FRP reinforcements, second planking is applied to the extrados, orthogonal to the existing one, to improve the consolidation of the whole package (sandwich effect).

The assessment of the reversibility factor is based on the consideration that the FRP strips are removable by heat since the incipient melting temperature of the resin does not compromise the integrity and stability of the wood structure.

The resulting values are shown in figure 10, at row: AS_5 intervention.

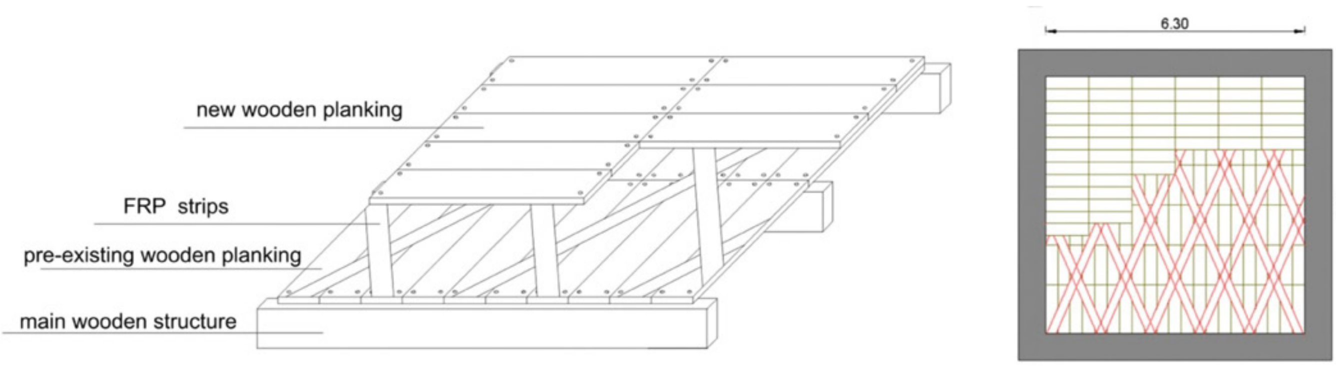

Fig. 8. *Scheme of the intervention AS_5 (axonometric view/top view). (Image source: "Guidelines for the Design and Construction of Externally Bonded FRP System for Strengthening Existing Structures" [20])*

4.4. INTERVENTION BIO_3: IMPROVEMENT OF THE BEAM'S BENDING STIFFNESS BY THE JUXTAPOSITION OF LATERAL SUPPORTS

The intervention was carried out by attaching new timber beams to the existing beams, connected using nails (Fig. 9). For the calculation of R1, the volume constituted by the removal of the nail was considered irrelevant. Therefore, only the removal of biologically degraded parts was taken into account. As far as the R2 coefficient is concerned, no relevant differences in mechanical performance were evaluated once one of the new beams was removed and then reapplied in the same way.

Fig. 9. *Photo of the intervention BIO_3.*

5. RESULTS AND DISCUSSIONS

The results of applying the method to the 4 sample interventions are:

- Intervention SB_1

The results obtained give an average "RF" (reversibility factor) value of 0.91. The reversibility is therefore equal to 91%.

Intervention SB_1: replacement of the beam head with an anchored prosthesis with confined bars			
volumetric contribution	mechanical contribution	aesthetic contribution	feasibility contribution
V_{origin} = 215 dm^3	calculated as shown above	S_{origin} = 4,00 m^2	the technique does not require intervention from the extrados
Prosthetic volume = 20,736 dm^3		Burglary surface = 0,014 m^2	
Burglary volume (increase of burglaries between 2nd and 1st intervention) = 0,036 dm^3		Visible surface of the prosthesis = 0,176 m^2	
V_{res} = 194 dm^3		S_{res} = 3,81 m^2	
R_1 = 0,90	R_2 = 0,79	R_3 = 0,95	R_4 = 1
Intervention AS_4 : anti-seismic improvement by means of bracing with tie rods and perimeter rims, with metal elements, on the ceiling			
volumetric contribution	mechanical contribution	aesthetic contribution	feasibility contribution
V_{origin} = 1575 dm^3	Unaltered values (between 1st and 2nd intervention)	S_{origin} = 33,00 m^2	the technique does not require intervention from the extrados
Biologically degraded volume = 20,00 dm^3		Busy surface for through-hole drilling = 0,034 m^2	
Volume of tie anchorage pin holes to the beams = 11,30 dm^3			
V_{res} = 1544,00 dm^3		S_{res} = 32,96 m^2	
R_1 = 0,98	R_2 = 1,00	R_3 = 0,99	R_4 = 1
Intervention AS_5: anti-seismic improvement intervention, with plating of the deck, by means of FRP crossed bands, executed at the extrados			
volumetric contribution	mechanical contribution	aesthetic contribution	feasibility contribution
V_{origin} = 4740 dm^3	unchanged values (between 1st and 2nd intervention)	S_{origin} = 40,00 m^2	the technique requires the removal of the upper floor
Volume removals after the 1st intervention = 0,00 dm^3		Surface of the elements removed to carry out the 2nd intervention (it is considered the restoration of 30% of the pre-existing planking) = 6,00 m^2	
Volume removals to perform the 2nd operation = 0,00 dm^3		S_{res} = 34,00 m^2	
V_{res} = 4740 dm^3			
R_1 = 1,00	R_2 = 1,00	R_3 = 0,85	R_4 = 0
Intervention BIO_3: improvement of the bending stiffness of the beam by juxtaposition of lateral supports			
volumetric contribution	mechanical contribution	aesthetic contribution	feasibility contribution
V_{origin} = 215 dm^3		S_{origin} = 4,00 m^2	the technique does not require intervention from the extrados
Biologically degraded volume = 4,00 dm^3	unaltered value	Surface removed after 1st intervention = 0,00 m^2	
V_{res} = 211 dm^3	(between the 1st and 2nd intervention)	S_{res} = 4,00 m^2	
R_1 = 0,98	R_2 = 1,00	R_3 = 1,00	R_4 = 1

Fig. 10. *Results on the calculation of the reversibility factor (RF) about the 4 case studies.*

– Intervention AS_4

The results obtained give an average "RF" value of 0.99. This results in a degree of reversibility of 99%.

– Intervention AS_5

The results obtained give an average value of "RF" of 0.71. The reversibility is therefore equal to 71%.

– Intervention BIO_3

The above table shows that the average value of "RF" is 0.99. Therefore, the intervention presents a high index of reversibility (99%).

From the results obtained above, it can be noted that the best behaviours, in terms of reversibility of the intervention, were obtained with the interventions:

– AS_4 (bracing, at the intrados, with tie rods and perimeter rims with metal elements)
– BIO_3 (improvement of the bending stiffness of the beam by the juxtaposition of lateral supports)

6. CONCLUSIONS

The study aimed to offer a new contribution to quantify the reversibility factor of a consolidation intervention on timber floors according to four parameters:

– volumetric contribution (R1)
– mechanical contribution (R2)
– aesthetic contribution (R3)
– feasibility contribution (R4)

The need to adopt a reversible approach in interventions on timber floors arises for many reasons:

1) the timber floor or roof, as historical, cultural, and constructive testimony, constitutes an architectural asset to be handed down to posterity and, consequently, to be preserved as much as possible in its integrity, its original typological characteristics, and its constructive peculiarities;
2) the concept of reversibility is combined with that of "sustainability": restoring the status quo ante makes the architectural artefact flexible to possible future re-adaptation and re-utilisation imposed by the continuous socio-cultural-normative evolution, but at the same time guarantees the permanence of the artefact itself;
3) to intervene permanently and definitively would mean precluding any kind of future intervention, in contrast with one of the basic principles of sustainability;
4) a consolidation intervention could soon turn out to be deficient with respect to the expected performance

due to the coming into play of variables that have occurred after the intervention has been carried out or, mistakenly, which were not considered at all in the design phase. The reasons that determine future interventions can be traced back to:

a) new disturbance pathologies;
b) entry into force of new regulations;
c) change of use of the building.

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