AXIOLOGICAL APPROACH TO STRENGTHENING OF TIMBER LOAD BEARING FLOOR STRUCTURES

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ABSTRACT

Timber load bearing floor structures of Italian historical constructions are complex systems made of girders, joists, subfloor, and completing components (lath to cover planking joints, small boards to cover the link between joists and girders, etc.). These floors are placed in and connected with the load bearing walls, thus constituting a more complex structural system. The need of strengthening of timber load bearing floors could issue from: timber decay (due to insects, fungi, fire, or creep), increase in loads, changes in safety and serviceability standards. Actual cases show countless states with regard to: building techniques; material state of preservation; size of the gap between required and provided performances; aesthetical, historical and material interest of ceiling and flooring.

In the light of contemporary architectural preservation theories, several values must be considered while choosing from among the conceivable systems for the strengthening of timber floors: aesthetical quality; signs of usage; technological features; material characteristics. Other needs must also be evaluated along with those values: the requirement to assure physical and aesthetical fruition of the building; the need to respect the original technological conception of the structure; the compatibility of the strengthening solutions with the existing structure, the possibility to remove it, and maintain it in efficiency; moreover the added elements should be clearly recognisable as contemporary.

This paper aims to single out the primary values to be considered, and to assess the most common strengthening solutions with regard to these aspects and to the actual state of the floor structure.

Keywords: Timber floor structures, Preservation, Strengthening, Italy

1. BETWEEN VALUES AND DATA: SOME ASPECTS OF CONSERVATION

1.1. Alois Riegls’s theory of values

At the beginning of 20th century Alois Riegls proposed to study monuments with reference to multiple values, often in conflict [1]. Although one century of historiographical studies lead to consider outdated some of the principles underlying the text (as Riegls’s evolutionist view of history), Riegls’s theory of values provides a logical method that can still be used for the analysis of cultural and artistic heritage that needs conservation.

In Der Moderne Denkmalkultus Riegls identifies two main categories of values: memory values and present-day values.

1.2. Memory values

The category of memory values encompasses:
- The intentional commemorative value, i.e. the potentiality of the monument to convey the message for the transfer of which it was created.
- The historical value, which point out the aptitude of the monument to represent a precise moment in the history of development of creative skills of craftsmen or artists.
- The age value, that is the capability of the monument to witness the set of natural phenomena that have led to its evolution from the original state to its present condition.

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1.3. Present-day values
The category of present-day values encompasses:
- The use value, which measure the functionality and safety of the monument in the use both as common building and as a museum of itself.
- The art value, subdivided in:
  - The newness value, that descend from formal integrity and unharmed polychromy.
  - The relative art value, which promote the aesthetic appreciation of the monument in relation with original and contemporary Kunstwollen.

1.4. Further considerations on the theory of values
After Alois Riegl, many other theoreticians have studied restoration as a intervention that must reconcile the contrast between the various values of cultural properties. For example Cesare Brandi defined restoration as “the methodological moment of the recognition of work of art in its physical concreteness and in its dual historical and aesthetical polarity, for the transfer to future” [2], thus he implicitly outlined two fundamental values: the historical and the aesthetical one. Brandi’s theory was elaborated for works of art, and it stated the clear prevalence of aesthetic instance against the historical one.
Recently some researchers also developed procedures and algorithms to analyze the conflict between values in the conservation and strengthening of cultural heritage from a quantitative point of view [3]. Contemporary theoreticians of conservation elaborated a new approach to the study of values; Amedeo Bellini affirm that «to restore an object […] is an indicative act of the recognizing of a value and of the will to maintain the possibility to experience it in the future», but he opposes to the use of the judgment of historical and aesthetic value as a tool for restoration works. Bellini affirms also that the basis for the conservation works should be found in a technical and ethical judgement, the first related to the contemporary culture, the second with the limited economic resources that can be devoted to conservation [4]. Moreover Paolo Torsello affirms that the idea of “value” must be substituted by the idea of “datum”: «The concept of value implies involvement and judgment, thus choice, possession, preference, privilege, but also exclusion, denial, rejection and so on; the one of datum involves detachment, suspension, deferment», and the datum «stands as a virtually inexhaustible source of knowledge, as an ever new start […] of processes of interpretation». Therefore we have no right to alter the data on the basis of a judgment that is always and inescapably relative, preventing subsequent reinterpretations [5].

1.5. Timber floors: several issues to be considered
Contemporary historiography extended its studies from great events and works of art, to every day history and material culture [6]. In the light of these new approach to the historical studies, several values/data must be considered, all of them must be seen in an historical point of view: aesthetical quality (of the bottom face of the timber frame, of the flooring and of the ceiling in case there is one); signs of usage; technological features (original structural conception and its change over time; signs of original manufacturing and of successive works; choice of materials; etc.); material characteristics (interest of the materials in itself and as a document of natural history; signs of aging; etc.). While choosing from among the conceivable solutions for the strengthening of timber floors, other needs must be evaluated along with those issues: the requirement to assure physical and aesthetical fruition of the floor and of the whole building; the need to respect the original technological conception of the structure; the opportuneness that strengthening solutions don’t contribute to decay or damage of the existing structure (compatibility), that they can be removed or substituted with little damage to the existing structure (reversibility), and maintained in efficiency (durability); in addition strengthening solutions should not disguise themselves as part of the existing structures, but they must openly declare their being contemporary (recognisability).

2. TIMBER LOAD BEARING FLOOR STRUCTURES OF ITALIAN TRADITION

2.1. General features
Before talking about strengthening of timber load bearing floor structures, we must set out how these building elements are. Timber load bearing floor structures of Italian historical constructions are complex systems made of girders, joists, subfloor, and completing components. These floors are placed in and connected with the load bearing walls, thus constituting a more complex structural system [7, 8].
2.2. Principal load bearing elements
The principal load bearing elements of these structures are the girders and the joists that constitute a horizontal frame whose complexity depends on various circumstances. Usually floors have:
- One way structure, made only by joists parallel to the shorter side of the room used for spans up to 3–4 m.
- Two way structure, made by one or more bearer parallel to the shorter side of the room, 2–3 m distant from each other, and joists perpendicular to them.
More complex frames (such as the Serlio floors) and floors with three tiers of beams are very unusual.

2.3. Subfloor and floor
Above the timber frame the subfloor is usually made of timber boards or thin bricks. Traditionally the subfloor supports a rubble screed that serves as a basis for the flooring; however many historical floors have already been refurbished by removing the original rubble screed and substituting it with a modern cement screed.

2.4. Complementary elements
There is a wide range of complementary elements; we have more and more elements that serve functional and aesthetic purposes, going from simple to more complex and refined floors. In this short introduction we will deal only with the more common ones, that play a considerable functional role, but analysing real cases we must consider all of them, while becoming aware of the values of a floor.
The first of these complementary elements are the joint laths; when the subfloor are made of timber boards, usually laths are used to sealed from below the planking joints to prevent the downfall of powder from the rubble screed (Fig. 2). The other important complementary elements are the so-called bussole: small boards utilized to close the space above the girder and between the ends of the joists, and prevent dust and dirt to settle (Fig. 1).
Sometimes in the 19th and 20th centuries timber floors were hidden from view by adding a ceiling, often decorated with paintings.

2.5. Role of the beams in the structural system
In the structural system made of the walls and the timber floors, girders and joists have also a role in connecting opposing walls acting as tie beams. Usually this role is carried out only due to the friction between the ends of the beams and the supporting walls. Sometimes, usually in areas where architects and master builders were aware of seismic hazard, the beams are anchored in the walls with a wrought iron strap ending with a pole or a plate [7].

3. THE REASONS FOR STRENGTHENING

3.1. Why we need to strengthen?
While talking about strengthening, first of all we need to point out why we do it. The need of strengthening could issue from: material decay or damage, increase in loads, changes of safety and serviceability standards.

3.2. Material decay
Timber ageing does not lead to a significant progressive loss of structural performance: in optimal environmental conditions structural timber elements maintain their load bearing capacity over time [9, 10]. The exposure to light, rain and air leads to a superficial degradation of wood. UV light causes a photodegradation of lignin and the products of degradation could be solubilised and washed away; wind contributes to superficial erosion by mechanical action [11, 12].
Wood is, however, a material of biological origin, thus in natural environment it tends to complete its life cycle with a progressive deterioration and a complete destruction by saprophytes: detritivores and decomposer. The principal saprophytes of wood are xilophagous insects and fungi.
If we exclude termites and few other species, wood-boring insects causes little structural damage, while fungi can quite rapidly lead a structure to collapse. Luckily most of the saprophytes fungi of wood needs a timber moisture content exceeding 18–20% to carry out an attack; thus it is sufficient to protect wood from water in all of its forms (air humidity, capillary water present in walls, rainwater or pipeline leakages, etc.) to eliminate most of the risks of significant biological degradation [9, 11, 13].

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Even if quite small, long-duration loads bring a progressive increase in deformations due to creep, that can cause the damaging of flooring, partitions, or equipments [7].

3.3. Material damage

The loss of strength of structural timber elements could also be due to damages caused by high temperature, fire or excessive loads that have occurred at any time in the history of the structure. Temperature below 100°C lead to a reversible loss of moisture in the wood. Between 100°C and about 200-250°C pyrolysis takes place: it causes the distillation of wood with the emission of gases due to the degradation of the lignin. At temperature of about 200-250°C the reaction becomes exothermic and the combustion of the external part of timber starts, while the inner part remains unaltered [12]. We can find timber elements exteriorly damaged by pyrolysis or fire that keep much of their original load bearing capacity [14].

Excessive loads and unexpected or anomalous load conditions may have acted on the structure in the past damaging its bearing elements, that are now unable to bear ordinary loads due to fractures. It is however necessary to be careful not to confuse physiological shrinkage cracks with fracture due to excessive stress: the mere presence of shrinkage cracks almost never indicate a loss of bearing capacity of timber elements [15].

3.4. Increase in loads

Loads could increase due to refurbishment works or to change of use. Refurbishment works could lead to the growth of non-structural permanent weights (new screeds, floorings, ceilings, partition walls, equipments, etc.), while change of use could increase imposed actions.

3.5. Changes of safety and serviceability standards

The carpenters and architects of the past based their projects on empirical evaluations of the loads acting on a structural elements or system and of its strength. Modern building regulations provide the careful calculation of self weight and specify imposed loads, furthermore the recent Italian building code [16] imposes seismic assessment of buildings all over Italian national territory. In seismic structural models for buildings, floors act as rigid diaphragms to divide seismic actions on vertical load bearing elements. Italian building code demands to assess existing building while doing restoration or refurbishment works. Moreover building codes define serviceability standards and request limitations of deformations and of vibrations. The reasons for these limitations are related to damaging of non-structural elements (flooring, partitions, equipments, etc.), and to human discomfort (annoying effects of sloping floors and footstep-induced vibrations).

4. THE METHODS FOR STRENGTHENING

4.1. Overall considerations about structural models

The carpenters and architects of the past based their projects on empirical evaluations of the overall behaviour of the building. The first structural models (almost until the beginning of 20th century) were not able to consider the structural system of a building as a whole, thus they decomposed building into simple parts (a wall, a pillar, a beam, a truss, etc.), often losing sight of the overall behaviour. Modern engineering elaborated new complex structural models based on the structural conception of new steel or reinforced concrete frame structure. Subsequently models for modern conceived and designed masonry structure were elaborated; however these model were not able to interpret the real structural behaviour of traditional buildings. This misunderstanding lead in the past to profound alterations of this heritage, due to the need to adapt the existing buildings to the abstract models [17].

Nowadays we must critically evaluate the structural models conceived for modern structures; eventually we must refuse them, and elaborate or choose other models more suitable to understand the real behaviour of the structure.

4.2. Passive and active strengthening systems

Strengthening systems can be classified into two categories: passive systems and active systems:

- Passive strengthening systems start contributing to the load bearing and to the overall resistance of the existing structure when its deformations are increased by external loads.
Active strengthening systems involve the introduction of internal forces in the system made of strengthened and strengthenener structures. This ensures an immediate efficiency of the strengthening, and the possibility of eliminating, at least in part, the existing deflections.

When possible active strengthening systems must be preferred to the passive ones because they do not require a further increase of deformations (and hence of stresses) in the existing structure to carry out their effectiveness.

When using tie-rods, active strengthening can be easily obtained by means of screw nuts, while in the other cases a different approach must be followed: a simple way to obtain an active strengthening is to reverse the deflection of the beam by means of telescopic props, and then apply the reinforcing systems.

4.3. A rational classification of strengthening systems for timber floors

The wide variety of strengthening systems for timber floors requests us to make a rational classification of them.

A first distinction must be made between systems that enhance only flexural strength and stiffness, and the one that increase also the in-plane stiffness of the floor. The former ones don’t alter the overall behaviour of the structure, while the second ones transform the floor into a rigid or semi-rigid diaphragm, giving the building a box-like behaviour, and the opportunity of this change must be carefully evaluated.

Dealing with the systems to improve flexural behaviour, we will follow and revise the governing approach proposed by Franco Laner [9].

The linear equations for determining the maximum bending moment (1), bending stress (2) and deflection (3) in a rectangular beam under simple bending are:

\[ M = \alpha \cdot q \cdot \ell^2 \]  
\[ \sigma = \frac{M}{W} = \frac{6 \cdot M}{b \cdot h^2} \]  
\[ f = \beta \cdot \frac{q \cdot \ell^4}{E \cdot J} = \beta \cdot \frac{q \cdot \ell^4 \cdot 12}{E \cdot b \cdot h^3} \]

where: \( \alpha \) and \( \beta \) = two coefficients depending from the restraints, \( q \) = the linear span load acting on the beam, \( \ell = \) the length of the beam, \( W = \) the section modulus, \( J = \) the moment of inertia, \( b = \) the width of the section of the beam, \( h = \) the height of the section of the beam, \( E = \) the modulus of elasticity.

A reduction of stresses is necessary to enhance the safety, while a decrease of deflection reveal an improvement of serviceability. In both cases we can act on many issues, individually or in a combined way: the loads, the restraints, the length of the beam, the modulus of elasticity, the dimension and shape of the beam. We can also enhance the safety increasing the unit bending strength of the material, or adding new materials that have a higher unit strength.

In the light of these considerations, we can now analyze the various strategies for the strengthening of a timber floor.

4.3.1. Reduction of the loads

The simplest method is the reduction of the estimated loads. This strategy can be pursued by decreasing (or not increasing) the non-structural permanent weights or by limiting imposed actions.

It is very difficult to obtain a considerable reduction of permanent weight, because almost always the self-weight of timber floors is quite low, and the screed is the only part that can be removed and substituted with a lighter one [14]; at best a reduction of only 0,5 kN/m² can be obtained against works for a complete renovation of floorings.

Both limiting the imposed actions and not increasing the permanent weights provide strong restrictions on the use. Therefore this solution can be used only when the timber beams keep a good load bearing capacity, and the floor demand the maximum degree of conservation, both of the flooring and of the ceiling, thus preventing the pursuing of other strategies.

An alternative solution to reduce the loads is the addition of further beams supporting a part of the load before borne by the existing beams [9, 18].
4.3.2. Action on restraints and length of the beam

The second strategy acts on the changing of restraints and of length of the beam. A simple increasing of the degree of restraint could be obtained making a better connection with the walls. This involves the partial demolition and reconstruction of the masonry portion around the supports of the beam; to obtain a higher degree of restraint is necessary to fix the end of the beam in the masonry, thus impeding timber ventilation and probably promoting decay.

Better results can be obtained by a simultaneous modification of restraints and length: operating at the end of the beam or near the midspan.

The operations on the end of the beams can be implemented by adding a supporting corbel or a beam adherent to the wall:

- The addition of a corbel implies a broad demolition of the masonry, an evident change in the floor appearance, and it could be mistaken for an pre-existing element if made of timber; given the high invasiveness, corbels could be used only for girders and not for joists [8, 9, 19].
- The application of a supporting beam adherent to the wall (the so-called dormiente) is suitable for the strengthening of joists, is minimally invasive because it could be fixed to the wall by a small number of anchorages; even if realised in timber these beams could be immediately recognisable thanks to the bolts used for anchorage [8, 9, 18].

For intervention near to the midspan we have many alternatives:

- To operate from above, hanging the beams to an upper structure. This solution is suitable to the case in which: there is, or it can be realized an upper structure that is capable of supporting the floor; it is allowed to partially occupy the upper storey with the tie rod; the flooring can be pierced for passing the tie-rod. All these conditions rarely occur together, so this solution is not easily exploitable [9].
- To insert one or more crosspiece beam. We can use this system when the transversal span of the floor is not excessive, otherwise the crossbeams would need to be too big. Furthermore the insertion of crosspiece in the walls implies a broad demolition of the masonry [9].
- To reinforce the girders with a system of struts and tie-rods (Fig. 1). One or two vertical struts could be placed below each girder, pushed up by a bent tie-rod to provide one or two intermediate support, creating a kind of overturned king or queen-post truss [7, 9, 14, 18, 19]. In this system the steel tie-rod is anchored by the mean of screw nuts, thus allowing to adjust its tension; the possibility to regulate the tension of the tie rod ensures an immediate efficiency (active strengthening) and the possibility of periodic maintenance of the system [9].

![Consolidation of a girder with a system of a vertical strut and bent tie-rod (E. Zamperini 2009). The tension in the tie-rod has been regulated by a torque wrench, immediately imposing the right collaboration with the existing beam. The choice of this system was suggested by the inaccessibility of the upper floor.](image)

- To place a couple of struts for each girder to create one (if the struts converge to the same point) or two intermediate supports [9, 14]. If the struts are made of timber, their section must be quite big and they will severely interfere with the physical and aesthetical fruition of the room. Thus this method of strengthening is suitable only for principal beams in rough rooms in which the alteration of the aesthetic has little importance. The strengthen structure can be lightened with the employment of steel, this makes also the work fully recognisable, extending the possibility of using this solution [18].
4.3.3. Actions on the cross section of the beam

The actions on the cross section of the beam are the sum of the works finalised to modify individually or in a combined way: the modulus of elasticity and the unit strength of the materials constituting the section, the shape and dimensions of the beam.

These strategies can be pursued in various ways:

- Trying to increase the stiffness and the strength of the existing timber by injecting resin inside it [20]; this procedure profoundly and irreversibly alters the original material and moreover there are strong doubts about its effectiveness [19].

- Replacing the portions of degraded wood with newly added materials (new timber, glulam, epoxy conglomerate) fixed to the existing beam by glued rod (steel or fibreglass), steel plates, bolts, or pegs. This operation implies an unrecoverable loss of the original materials and it is therefore strongly criticised by more conservative technicians. Furthermore if the added material is a resin conglomerate, it has a completely different rheology from the rest of the beam, and it is likely to disconnect from it due to moisture variations and differential shrinkage [14, 19].

- Enhancing the stiffness and strength of existing cross section by inserting and gluing materials with higher modulus of elasticity and strength. The new materials could be: glulam elements [8], fibreglass rods [14], steel rods [19], steel plates [14], L or T steel sections [14, 18], plate or rods of GFRP and CFRP [21]. All these solutions involve the loss of a part of the original material; in addition if the housings for these elements are made from above (thus requiring the dismantling of the flooring) the appearance of the beam remains unchanged, otherwise these grooves also disfigure the original appearance of the beam.

- Enhancing the stiffness and strength of the beam by making it collaborate with other added elements. These could be: solid timber boards (Fig. 2) or wood based panels; timber or glulam beams; steel plates or beams; pultruded FRP elements [23]; FRP tapes; a reinforced concrete slab [24]. The addition could be done: in the upper part, in the lower part, or on the sides of the existing beam.

![Fig. 2 Strengthening of a timber floor with timber elements (E. Zamperini 2009). On the left: the timber floor after the reinforcement. On the right: section of the girder before (above) and after (below) the strengthening. After the dismantling of the flooring and of the rubble screed, the deflection of the beam was reversed using telescopic props. Subsequently the board above the girder was removed and a series of portions of beam were forced into the space between the joists and fixed with screws to the girder. After that, the original board was put back in place, and another thick board was fixed with screws to the added partitioned beam. Other thick boards were placed orthogonally to the existing planking, one above each joist, and fixed with screws. Finally the telescopic props were released and the strengthening system immediately started to carry out its effectiveness.](image)

If the addition is made on the sides of the existing beam, old and new elements act in parallel, each supporting a portion of the load proportional to its own stiffness; the same behaviour is obtained if the addition is positioned above or below the beam, but is not connected to it.

However the best solution is to make the new elements work together with the beam, fixing the former ones to the other by means of shear connections to prevent mutual sliding. This connection can be pursued with: glues, nails, screws, glued rods, bolts, pegs, indentations, special connectors (in particular for the connection with reinforced concrete) [9].

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Operating from above imposes the irreversible dismantling or damaging of the flooring, but allows to limit or avoid the visual impact; operating from below or on the sides can allow a minor impact on material conservation, but it could lead to a total change of the appearance.

Special considerations could be done about two strengthening solutions that present similar behaviour, increasing also the in-plane stiffness of the floor: the use of timber boards or wood based panels and of reinforced concrete slabs. Increasing the thickness of the floor of the same quantity, the former can provide a greater net increase in carrying capacity, due to the limited weight of the added parts, but involves some problems that have made the system still not very common: the need to put side by side many panels, making behaviour along the joint uncertain; the lack of adaptability to irregular rooms; the difficult connection to the walls. Reinforced concrete slabs have the advantage of great adaptability to irregular plans and to deflected planking, but it requires a careful study of the connections to the masonry, and implies a considerable load increase on the walls, which can be only partially limited by using lightweight structural concrete. Furthermore over time creep and shrinkage of concrete can lead to a migration of stresses from the slab to the timber beam.

4.4. Thermal behaviour of the strengthened structure

While evaluating a strengthening system it is very important to study the thermal behaviour of the strengthened structure: if added elements have a coefficient of thermal expansion different from the one of timber (for example if the added elements are made of steel), the behaviour of the strengthened structure will vary depending on the temperature of the room. Thus in areas (e.g. attics) exposed to strong temperature changes, systems that use more than one material should be studied carefully.

5. CONCLUSIONS

Timber load bearing floor structures of Italian historical constructions are complex systems that show countless states with regard to: aesthetical, historical and material interest; building techniques; material state of preservation; size of the gap between required and provided performances; the requirement to assure physical and aesthetical fruition.

The choice among the possible strategies for strengthening, and – defined a strategy – among the various systems must start from the knowledge of those states and it must respect the principles of conservation: need to preserve the original technological conception of the structure and opportuneness that the adopted solutions don't contribute to decay or damage of the structure (compatibility); necessity that added elements can be maintained in efficiency (durability) and removed or substituted with little damage to the existing structure (reversibility); in addition strengthening solutions should not disguise themselves as part of the existing structures, but they must openly declare their being contemporary (recognisability).

However, within the limits related to conservation, it is important to uphold the right to formal autonomy for the project of technical and functional additions, because this seems the only way to pursue quality in what we add to the built palimpsest. In fact, although distant from the existing “text” in terms of style and morphology and even if complicating its the interpretation, only high-quality architectural elements can enrich the complex built context [24].

REFERENCES