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SEISMIC STRENGTHENING OF TRADITIONAL TIMBER STRUCTURES

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SUMMARY

Among the many issues related to the seismic strengthening of timber structures, this work focuses on the cyclic behavior of reinforced carpentry joints, the upgrading of properties of decayed or otherwise insufficient timber elements, and the strengthening of timber slabs, discussing the results of an experimental and numerical research program. Experimental tests and numerical analyses of strengthened full scale trusses have shown that an appreciable seismic response in the post elastic range may be obtained.

INTRODUCTION

In the seismic strengthening of existing buildings, often timber structures and substructures, like slabs or roof trusses, are removed and substituted with new materials and typologies. In some cases, negative consequences of this approach, up to structural collapse due to increased loads or other incompatibilities, have been observed for earthquakes that occurred after the intervention. Indeed, the lack of quantitative information on the effectiveness of strengthening techniques and the uncertainties in the effects of new rehabilitation proposals have often discouraged from preserving the original timber structures. Besides the important structural consequences and the possibly higher costs that may derive from substitution, replacing structures completely may not even be allowed when the building to be seismically strengthened is a historic one or a monument. In this last case, a requirement of conservation is usually issued by the Authorities concerned.

At present, also the cultural heritage embedded in more common buildings and building aggregates is being more and more recognized and sought as a value. In a perspective of conservation, however, many aspects concerning strengthening techniques have to be clarified, e.g. Larsen [1], Piazza [2]. The variety of situations of structural inadequacy or degradation that the professionals in charge of the strengthening design meet, the innovative use of traditional materials and the introduction of new ones, the need for the more traditional techniques themselves -often relying on empirical bases- to be validated and brought within an engineered framework, the recent proposals for new, more stringent seismic requirements in

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building codes, evidence the complexity of this field and indicate the questions to be answered in order to formalize design rules that may be confidently used in practice.

Among the many issues related to the seismic strengthening of timber structures, this work focuses particularly on three subjects, referring on the results of a research program on the rehabilitation and strengthening of timber elements and connections that has been followed for several years and is still in progress at the University of Trento, Italy. Namely, the cyclic behavior of reinforced carpentry joints, the upgrading of properties of decayed or otherwise insufficient timber elements, and the strengthening of timber floor slabs have been studied in various steps of the research program and are discussed here.

NEEDS IN REHABILITATION AND STRENGTHENING

Several types of carpenter joints may be found at the connection of different elements in old timber structures. Here, reference is made particularly to those found in trusses, because this is the timber structure that recurs most frequently, being commonly used to support roofs of masonry buildings.

Carpenter joints that may be found in these buildings may or may not have metal connectors, depending on their period of construction. In any case, the connector has no role in the service-load carrying action, but is generally present with the purpose of maintaining the assemblage of the node under possible adverse circumstances. In the seismic upgrading of these joints, in line with their original conception, metal connectors have to be renewed or applied, in order to ensure functioning of the connection also in the situation of reduced compression that may occur during an earthquake. The primary research needs for these connections are

- to investigate their mechanical characteristics, as the level of stiffness at rotation and the cyclic post-elastic behavior for different methods of reinforcement;
- to develop simple models of these semi-rigid joints, including the obtained cyclic behavior, that may be used within the analysis of complete structures.

At times, however, the elements converging into a joint may present a high degree of decay, often due to the local environmental conditions. In these cases, partial substitution or reconstruction of the element is required prior to the reinforcing of the connection.

A similar situation may occur as well at different locations along the elements. These cases may be summarized in a need for local material integration, or restoration of structural continuity.

When the problem is not in the local section degradation, but in the inadequacy of the original mechanical characteristics at responding to new needs, general reinforcement must be provided, aiming at upgrading the mechanical characteristics of the element.

As to timber floor slabs, interventions for seismic strengthening usually involve increasing their stiffness and tightening their link to vertical walls. The type of intervention depends on the level of stiffness required. The common case of stiffness upgrading to obtain a collaborating horizontal diaphragm has been considered and will be reported here.

In order to have practical significance, knowledge of the obtainable behavior based on experimental and numerical studies must always be confronted with the expected characteristics and response generally expected of structures in seismic areas, that are formalized in the recommendations and requirements of codes for buildings and structures in seismic regions. This point is discussed in the following section.

CODIFIED REQUIREMENTS

The principles underlying building codes and regulations are representative of the engineering knowledge in the particular sector considered and may be a reference also for subjects that are not treated in detail in the code specifications. Codes and regulations for buildings in seismic areas generally deal only with new timber structures and, possibly, with fairly recent, i.e. engineered structures to be strengthened or repaired. More traditional construction is not specifically considered. In countries of old constructional tradition, however, the latter represents the largest fraction of cases needing consideration. Basic principles expressed for new construction may then serve as guidelines for these cases as well. The Eurocode 8 [3], for instance, devotes a section to the design of new timber structures, but its most recent draft has eliminated the chapter related to the strengthening of old and damaged ones. Design of new structures may then become a source of indications for the strengthening of the old ones.

For new timber structures, the Eurocode 8 considers two kinds of behavior, recognizing either structures with dissipation capability, at various levels, or structures with low dissipation capability. This category has been upgraded in the last version of the code, whereas the former version indicated "non dissipating structures" in its place. Now, some albeit limited amount of ductility is always recognized to the timber structure and will have to be provided through design.

According to the code, dissipation occurs exclusively in the joints, while the timber elements are always to be considered -and maintained- in the elastic range. According to the same code, the properties of the dissipation zones must be determined experimentally. This indication is valuable also in the case of existing structures, where the presence of non engineered connections often poses problems even on their functioning mechanism in the static range, as long as experimentation can be on models and does not require destructive testing.

Again in the same chapter, it is stated that only joints and connection devices that may supply appropriate low cycle fatigue behavior may be used for dissipative zones, while the large glued joints are not considered dissipative.

As to carpentry joints, they may be used in new structures only if they are capable of satisfactory dissipation.

If these rules are considered as guidelines for the case of strengthening, in the reinforcing of carpentry joints attention is to be exercised in order to obtain a ductile behavior, while interventions that may lead to excessive stiffness and fragility must be ruled out in these areas.

Another fundamental need stems from the requirement of accurate modeling of the structure for numerical analysis, that must be performed in the condition prior and posterior to the proposed intervention. When the strengthening -and the modeling- concerns the dissipative zones, an accurate description of the post-elastic behavior may be required.

CAPACITY AND POST-ELASTIC BEHAVIOR OF JOINTS

The research program on timber joints

The research program that is briefly described here aimed at deepening the knowledge of the behavior of timber joints that recur more frequently in existing buildings, with the objectives described above.

The program included a campaign for collecting data on joint types, frequency, dimensions, conditions, materials and loading conditions. The survey was carried out visiting several constructions and collecting information for the different types of joints. This served as the basis for selecting and sizing the joints to be studied in detail.

The most significant and frequent connection has resulted to be the birdsmouth joint, that occurs in different configurations within traditional trusses, as in figure 1. The selected joint has been studied alternating numerical and experimental phases. A series of preliminary numerical analyses of the joint by the finite element method has been carried out and has been the basis for setting up experimentation. Experimental tests were both monotonic and cyclic. The test setup is shown in figure 2. The tested joints were built from softwood (*Picea Abies Karst*) that had been recovered from dismantled beams of old buildings. Full-scale samples were used.

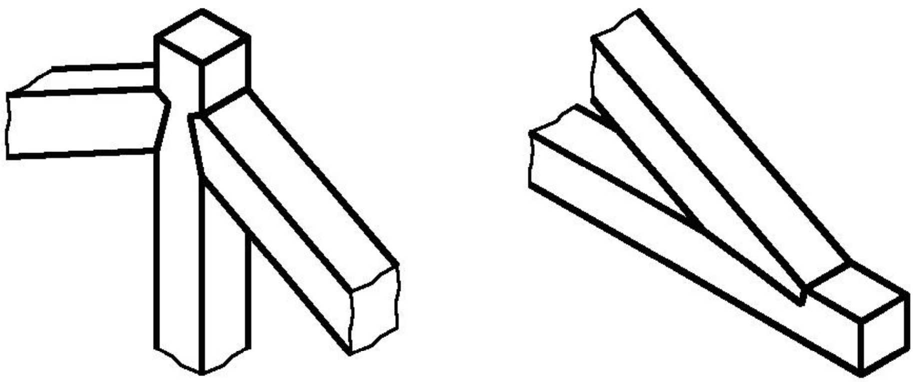

Figure 1. Typical locations of the birdsmouth joint in a timber roof truss

Although the number of samples has been quite large, amounting to some tens, one main role of experimentation has been that of calibrating numerical models of the nodal area for subsequent finite element analyses. By these, it was possible to carry out a parametric study providing results for values of the geometric proportions, of friction, of loads etc. Parameter values considered were regularly sequenced within ranges significant from a constructional point of view, according to the indications of the initial survey. In this way, a series of results that could be a reference for several real situations has been produced.

Connections have been studied both in the original configuration, without reinforcement, and in the presence of various types of metal connectors, representing different possible reinforcing solutions (the insertion of bolts, placing of steel stirrups on the connection sides, use of a steel binding strip) inspired from traditional devices, reinterpreted according to current practice. The behavior of the connection, represented in terms of moment versus rotation, has been described as a function of the geometric dimensions, of the compression in the rafter -an important parameter considering that the connection relies on friction-, of the angle between the connected elements, and others. Detailed results have been discussed in Parisi [4].

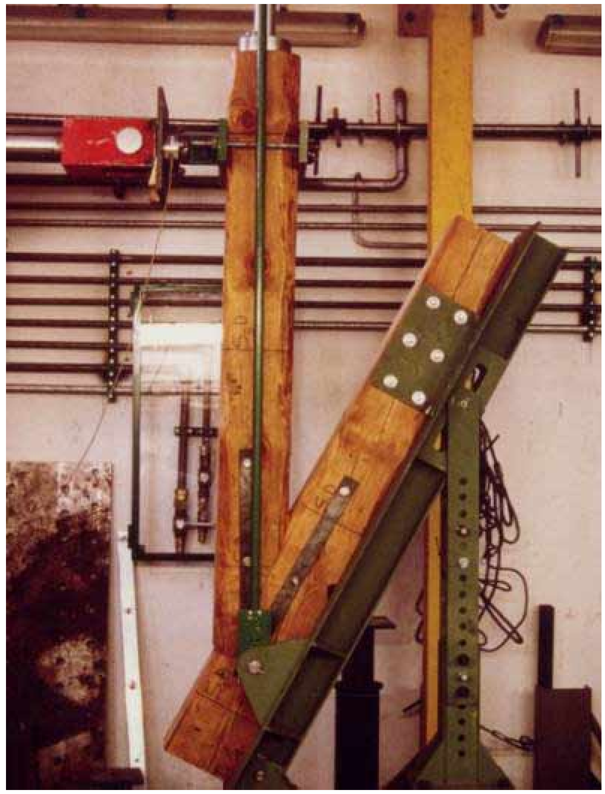

Figure 2. Apparatus for monotonic and cyclic tests on the birdsmouth joints

Although these functions have been derived numerically, experimentation has been fundamental for studying the post-elastic behavior, monotonic and cyclic, for comparing the effectiveness of the different types of reinforcement, particularly at the ultimate state, and for highlighting critical situations that could neither be recognized nor corrected otherwise.

As to the cyclic behavior, this can be developed, and thus tested, only in the presence of metal connectors, because in seismic conditions an unreinforced friction joint could disconnect or decrease its capacity, should compression be reduced, even if instantaneously. Therefore, in old roof-supporting structures carpenter joints must be completed with metal connectors that ensure continuity of behavior and maintenance of contact. The cyclic behavior curves that were obtained with the various types of metal connectors have common characteristics: the curve shown in figure 3 belongs to a joint reinforced with a single bolt. For element dimensions of 200×200 mm, the diameter of the bolt was 20 mm snug fitted, and that of the washer was 60 mm. The behavior is quite stable, at least for a few cycles. Subsequently, a pinching phenomenon takes over, which restricts the central part of the cycle, indicating that sliding occurs.

Pinching develops because of plastic embedding near the bolt. During reloading, after sliding has ended and the facing elements are in contact again, the joint re-acquires stiffness. Sliding increases in subsequent cycles, until the area of the cycles is drastically reduced, implying very low energy dissipation. Generally, the number of stable cycles that must be followed for the structure to endure the seismic action is not very high, and the behavior of the joint seems to be compatible with a reasonable seismic response. This may be noted in the results of some numerical analyses carried out with seismic excitation on trusses containing this kind of joints.

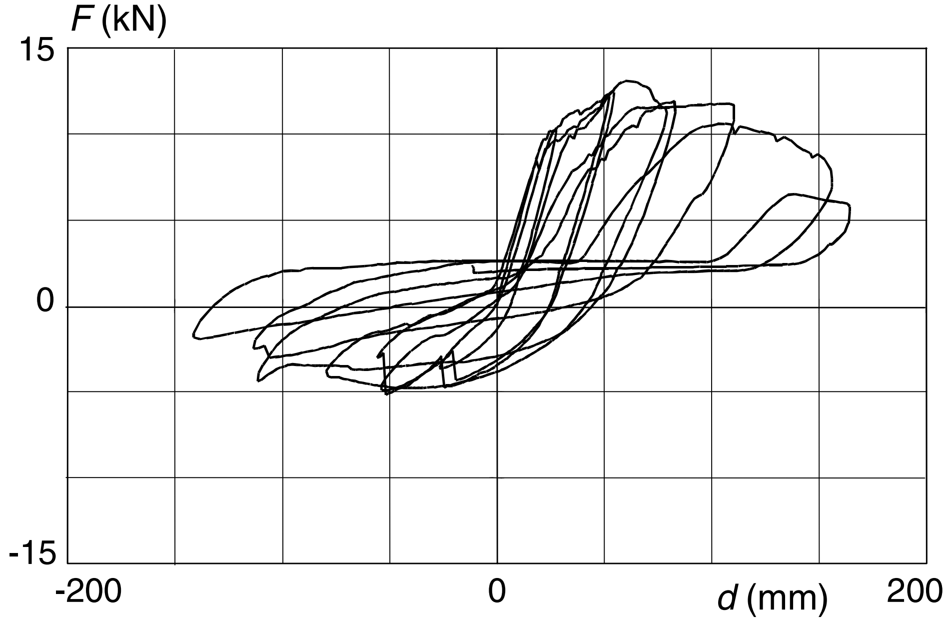

Figure 3. Cyclic test on a birdsmouth joint reinforced with one bolt (200x200 mm elements, 30° skew angle, 1.5 MPa compressive stress)

Comparative behavior of the reinforced joints

The types of reinforcement were actually revisiting traditional modalities of intervention that practice has developed for a long time, and that needed to be evaluated with modern criteria.

Connections reinforced with a single bolt behave initially, in the elastic branch, like the unreinforced connection. When the unreinforced connection would start sliding, the bolt takes over and, by bending, produces a further pseudo-hardening branch in the moment versus rotation diagram. Timber undergoes a permanent deformation perpendicular to fibers, where it is compressed by the washer. Compression by the bolt is in the direction parallel to fibers, where the material, that is grossly orthotropic, has much higher mechanical properties. The behavior of the joint reinforced with a bolt is altogether unmodified with respect to the original for service conditions and is improved in the post-elastic range, reaching an appreciable ductility level and good capacity of dissipation. The pinching that takes over with cycles has been discussed above. When the phenomenon becomes very extended, the reinforced connection continues to maintain contact, even if with large displacements. Failure generally occurs for local fracture in correspondence of a node.

Also the use of side stirrups does not stiffen the initial behavior of the joint. However, the elastic phase extends significantly. This device does not permit sliding between contact surfaces and is very little deformable. As a result, the energy dissipation is low. For cyclic loading, a permanent separation of the surfaces occurs after the load is inverted. Consequently, the stirrup takes over completely in carrying the loads, functioning according to a different conception with regard to the original connection. At this point, the behavior is completely based on the metal devices and is unreliable, because of the possibility of brittle fracture where the two prongs of the stirrup are welded. For these reasons, use of this kind of reinforcement device should be ruled out.

The third device was inspired by an old constructional tradition that used to bind a metal ribbon around the joint. In the modern interpretation, tension in the single-layer metal binding can be re-calibrated when needed. The behavior is intermediate between the two above, without the excessive stiffening of the stirrups and with a post-elastic behavior similar to the case of the bolt, but with more limited deformations; no separation of the contact surfaces occurs.

The case of bolts had a particular meaning in this research: it has been intended as an evaluation of this kind of reinforcement for itself, but also aims at comparing the effect of interventions that involve lower or higher stiffening of the connection. Often, strengthening of joints that originally offered a low degree of continuity, like those under study, is performed by techniques that involve a strong increase of stiffness, sometimes eliminating completely the possibility of movement, as in the example of figure 4.

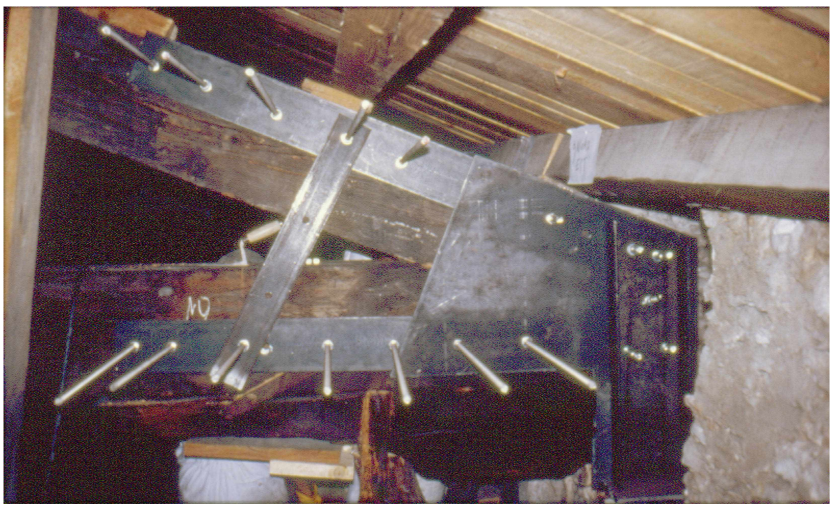

Figure 4. Overstiffening of the node of a roof truss, originally connected by a semi-rigid joint

Different connections reinforced with bolts have been tested. Reinforcement consisted of a single bolt, or two bolts of smaller diameter, in two different layouts. The comparison of the single bolt case with the two smaller bolts placed longitudinally along the joint has shown that the latter, that stiffened extensively the connection, almost eliminating its rotational capacity as in a mechanical locking of elements, was far less satisfactory than the former modality, being quite incapable of withstanding cyclic loading. In these conditions, a brittle behavior is easily triggered.

A second comparison was made within the single bolt case and the two bolts placed transversally to the joint. A more diffused stress state in timber, the higher reliability of the connection, and maintenance of the rotational capacity have shown this last to be the best alternative.

Lastly, experimentation had shown that in the toe area at the end of the chord, especially if the skew angle is low and consequently the shear force high, shear failure occurs along a horizontal plane. This fact has suggested reinforcing the toe area, as well as the tip of the rafter, with regularly distributed metal screws inserted in pre-drilled holes, as shown in figure 5. By this intervention this mode of failure has been eliminated in subsequent tests. In the Authors' opinion this is a strong indication for practical application.

Figure 5. Simple and efficient reinforcement of the chord toe area, by means of metal screws

A synthetic model of the joint

The second objective of this work was that of formulating simple numerical models of the semi-rigid connection that could be used in the analysis of entire structures. In a finite element framework, a suitable rotational spring model has been formulated and implemented, in Parisi [5]. These springs, to which the converging timber elements are connected, introduce in the structural model the local cyclic behavior of the semi-rigid joint. By defining the corresponding parameters, the desired behavior, like that obtained from experimentation, may be defined. It must be remarked that in friction joints the ultimate moment is a function of the level of compressive stress in the contact zone and, thus, of the axial force in the rafter. This effect, which is important in seismic analysis, has been also included in the modeling. The element has been tested and successfully used in the analysis of several roof trusses, as reported in a later section.

RESTORING CONTINUITY

Methods for strengthening timber elements depend on the type of problem, on the element, and on the objective to be reached. Yet, all are generally based on the collaboration between timber and other materials, as metals, fibers, or concrete. These methods may be classified into two basic groups. A first group is based on the addition of material embedded in the wood, supplying the mechanical characteristics missing in the original element, either because of degradation, or because of inadequate original design, as often occurs, for instance, in seismic strengthening to comply to new code requirements.

A second methodology is based on collaboration between new elements introduced alongside those to be strengthened, giving place to a mixed or composite system. This approach is particularly successful in the strengthening of floor beams, and as such will be described in a later section.

Strengthening with embedded materials

The approach adopted in some new types of connections that are now available particularly in modern glulam construction is interesting also in the field of repair and strengthening of existing structures, especially when these need locally high stiffness and strength in order to meet more severe code requirements, as shown in Piazza [6].

These connections utilize glued-in steel elements (bars or plates), completely hidden inside the timber, and occur in two basic types: those with steel bars glued-in parallel-to-the-grain and subject to tensile forces and those with glued-in bars perpendicular to the grain, subject to shear forces, del Senno [7].

This approach presents some unquestionable advantages when adopted in existing structures to improve mechanical properties or restore continuity: a high connection stiffness without significant settling, the possibility of ductile design through yielding of steel elements, even if in the presence of glue-based adherence, protection of glue and steel elements from fire, being these elements embedded in the timber.

A non-structural but not secondary advantage is that the aspect results unmodified, again because of embedding. On the other hand, some structural and general inconveniences exist. Among the first, the above mentioned timber-glue-steel connection which may give an elastic-brittle contribution to the global behavior; from a general point of view, the difficulties of assembling and glueing on site, and the consequent costs must be acknowledged.

In the strengthening for seismic action, this application of embedded reinforcement is generally not to be seen as an intervention for upgrading the existing traditional joints, but as a method for restoring continuity within an element when a part needs being substituted or two parts reconnected. As such, it may also be adopted to impose continuity between old and new material when part of an element is damaged or reduced due to decay, as in figure 6. Indeed, when wood in a structural element is severely decayed or damaged, material integration with wood or with etherogeneous materials has to be performed. Substitution of the decayed part with epoxy resins, epoxy-beton prostheses, or the like, are to be avoided because they induce brittle behavior. Decay of wooden material is very often concentrated at the ends of floor timber beams or at the ends of the wooden structures of the roof, at the connection with masonry walls, where local microclimate facilitates attack by microorganisms. Consequently, only a small decayed portion of the wooden element must be replaced with new material, usually a wooden piece, if possible of similar species and age.

Figure 6. Material integration with wood prosthesis

The addition of elements applied externally to the original one for its entire length in order to restore or increment its mechanical properties is often a simple and economic solution if realized in wood or wood products, but is generally not acceptable aesthetically.

Figures 7 and 8 show the behavior of a beam with embedded steel bars: it presents a marked difference from the usual elastic-brittle behavior of timber in bending. The reinforcement was designed to increase the bending stiffness of about 30 %, which was verified by testing.

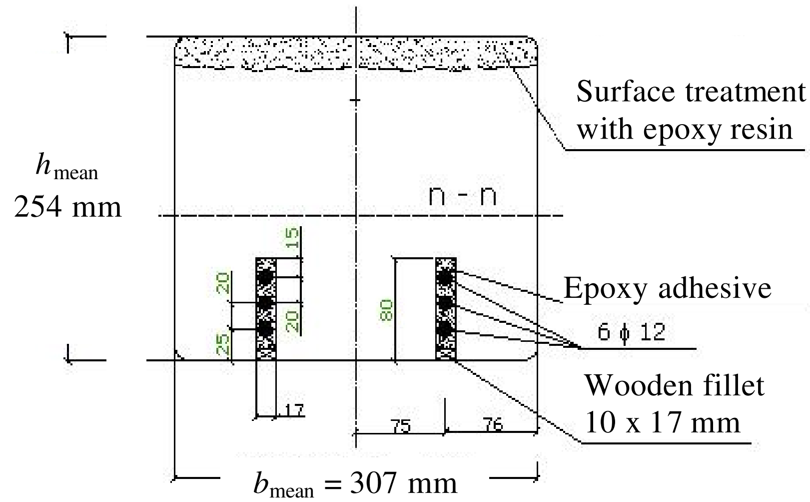

Figure 7. Cross section of a timber beam reinforced with embedded steel bars

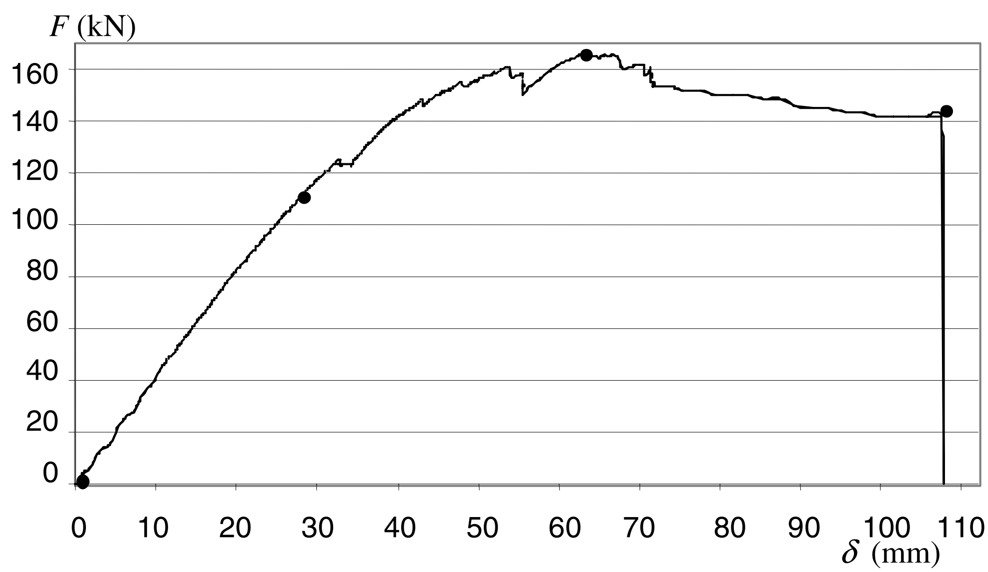

Figure 8. Mechanical behavior in bending of the steel - reinforced timber beam (applied load versus mid-span deflection)

The embedding of new materials for strengthening or restoring continuity still poses a series of problems of mechanical and non-mechanical type. It is currently a lively topic for timber research. One such question is if and to what extent the presence of glue in these multi-material connections may induce a brittle or partially brittle behavior. Timber elements, that are not considered dissipative, may be less sensitive to a reduced extension of the post-elastic range. Nevertheless, an acceptable level of ductility must be ensured, which makes this issue an interesting area for research.

IMPROVING MECHANICAL PROPERTIES OF TIMBER FLOORS

Frequently, seismic strengthening requires upgrading the mechanical properties of timber floor structures. Different solutions may be proposed, according to the desired level of capacity, as well as to other conditioning factors, like the quality of the masonry of the walls connected to the slab, or specific needs to preserve the original slab itself. In common cases, however, for timber beams belonging to a floor structure presenting limited material decay, the use of a composite system is one of the most effective strengthening methods, as in Ballerini [8]. Composite structures associate elements of a different material to the existing timber beams. In the floor case, the etherogeneous element is a slab. In a perspective of conservation of the structural system, this approach is particularly interesting, as the existing timber elements maintain their own static function.

The use of a concrete slab linked to the timber beams with adequate connectors (Figure 9) is particularly effective in seismic upgrading, because it links the masonry walls and, additionally, provides an incombustible element between different stories, as discussed in Piazza [9].

Figure 9. Glued-in steel connectors used for timber-based composite structures

Altogether, improvement of the floor strength and stiffness, greater capability of the slab to redistribute the applied vertical loads, and a horizontal diaphragm effect, are the main benefits expected from the realization of these mixed systems. Theoretical and experimental investigations have been carried out since the late seventies in order to characterize and compare different techniques, with particular attention to the connectors system: among others, the mixed timber-concrete solution with steel ribbed-bar connectors epoxy-glued into the wood, and the mixed timber-timber solution, with different wooden slabs (plywood, boards, etc.) and various connectors have been investigated in Piazza [6].

For comparative tests carried out at the University of Trento on full-scale floor models with span length of 5 m and beams with sections of width and height of approximately 150×200 mm, differing for slab type, connectors adopted, and for the timber beams, an increase of 3 to 5 times of the original timber beams has been reported in the composite structure at service load, depending on the methodology adopted, as discussed in Parisi [10]. Tests have shown that, as expected, the timber-concrete composite structure offered the highest mechanical characteristics, both at service and ultimate state. Other combinations, however, improved properties very satisfactorily, offering a viable range of alternatives, that may be suitable also to different requirements. In all cases, the key to positive behavior was an efficient system of connectors.

EXAMPLES ON FULL SIZE STRUCTURES

The most recent part of the timber research described here has addressed rehabilitation and testing of full scale structures, on the basis of results obtained for single elements and for connections (figure 10). The trusses that have been strengthened and tested in the program had been recovered from demolition in buildings where substitution of the roof structure was being performed. The trusses have been dismantled and later reconstructed in the laboratory. This has permitted to test techniques for local rehabilitation in damaged or decayed elements, to evaluate the effectiveness of joint strengthening on the global behavior of the structure, and has given a base for calibrating the results of numerical modeling of full structures, in which the previously developed models of joints had been included.

Figure 10. Experimental tests on the full scale model of a 25 m queen-post truss (Laboratory of the University of Trento)

In a first step, two trusses with a 14 meter span were salvaged. In the second, a large truss, measuring about 25 meters in span, which was originally part of the roof structure of a theater, had been eliminated when the building was remodeled and was recovered for testing. The trusses were subjected to various rehabilitation interventions, as in Parisi [11], that included reintegration of decayed chord ends and rafters, realization of connections restoring continuity in the chords, which in the latter case had been split in the operation of dismantling, and reinforcement at the chord toe, where the rafter is inserted, by a distribution of steel screws. As mentioned above, this intervention had proven to be particularly effective in avoiding brittle shear failure.

The trusses were remounted and tested under symmetric and anti-symmetric loads in monotonic and in all-positive cyclic modes. Testing was performed with loads much above the service level, but still in the elastic range, as previously verified by numerical analysis. Experimentation highlighted some aspects of the local behavior of the truss, mainly concerning contact, that could not be foreseen otherwise. The most interesting result is, however, in the good match between experimental and analytical results for the trusses under these load programs, which confirmed the validity of the semi-rigid model that had been developed on single joints for the analysis of complete structures.

Seismic analysis of these types of trusses with integration in the time domain and making use of the nonlinear cyclic spring elements have yielded behavior factors of about 3, an appreciable value, showing that appropriate strengthening may bring these old structures to significant levels of seismic response.

CONCLUSIONS

For new timber structures, the current seismic codes require that the timber elements remain elastic, while dissipation will occur entirely in the joints. General requirements for existing structures to be strengthened are for ensuring sufficient post-elastic behavior, in terms of displacements and dissipation capacity. In friction joints, contact must be ensured also under adverse loading conditions. In the strengthening of existing structures, caution is to be exerted in order to avoid causes of brittleness in the dissipating zones. Additionally, numerical models that may accurately include the behavior of the structural elements in structural analysis need to be used. From the research presented here, that includes experimental and numerical phases on traditional joints and entire structures and extends to new connection concepts to be used in repairing of damaged parts, it appeared that favorable results may be obtained in the seismic strengthening of traditional timber structures. The use of non invasive or drastic techniques has ensured, for the range of cases tested, good levels of response in terms of behavior factor, with a reliable behavior of the joints, without recurring to substantial modifications of the original structural conception.

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