CZECH TECHNICAL UNIVERSITY IN PRAGUE

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New Materials for the Rehabilitation of Cultural Heritage

by

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Summary

In this lecture some of the most recent intervention techniques for strengthening the cultural heritage constructions are presented and discussed. Many historical buildings are located in seismic active areas so that it is mandatory to define novel techniques that allow to increase the seismic capacity by respecting the requirements of the conservation.

In the last decade the interest of composite materials for the restoration and rehabilitation of ancient masonry buildings was continuosly increased. In particular textile strips of carbon or glass fibers were considered to provide aids for the masonry in those zones subjected to tensile stresses. The fibers are embedded in situ in thermosetting resins. Other composite products concern FRP meshes that are used to reinforce a mortar coating applied on both masonry surfaces. Moreover stainless steel thin strips or strands are also used in particular techniques easy to be applied and that do not modify appreciably the actual seismic response of the structure.

Different techniques for confining masonry columns so to increase the compression capacity and the ductility are presented. They concern the realization of hoops with FRP strips, with stainless steel thin strips and with stainless steel strands. The last one may be used also for exposed columns (not plastered) because the strands can be hidden with the mortar joint repointing.

For increasing the in-plane shear resistance of masonry walls four strengthening techniques are discussed: two uses FRP composites and two uses stainless steel devices. The application of FRP strips on the masonry surface through adequate adhesives provides good in-plane shear performances, even though the lack of confinement may be crucial for multi-leaf masonries. The realization of a mortar coating reinforced with FRP meshes on both masonry surfaces allowed to increase considerably both the shear capacity and the ductility of the wall. Moreover, the transversal connectors provide good confinement to the masonry so that the technique is effective also for multi-leaf masonries. A strengthening method is based on the use of stainless steel thin strips that provide both the needed transversal confinement and the ties necessary to form a truss system for increasing the in-plane shear resistance. Finally a strengthening technique is made with a grid of stainless steel strands (or FRP wires) disposed on both surfaces of the masonry and connected together through steel elements. Good transversal confinement is provided and the shear resisrance is significantly increased.

For out-of-plane flexure of the masonry the techniques with good confinement may guarantee good performances, even though further experimental studies are needed to support the theoretical results.

Souhrn

V přednášce jsou prezentovány a diskutovány některé z nejnovějších přístupů a technik zesilování kulturně historických konstrukcí. Mnoho historických budov se nachází v seismicky aktivní oblasti, takže je nutno vytvořit nové techniky, které umožní zvýšit jejich odolnost proti seizmicitě při respektování požadavků konzervace.

V minulém desetiletí zájem o použití kompozitních materiálů pro restaurování a obnovu starých zděných budov značně vzrostl. Zejména textilní pásky z uhlíkových nebo skleněných vláken byly používány pro vytužení zdiva v zónách vystavených tahovým napětím. Vlákna jsou uložena v pryskyřici. Ostatní kompozitní produkty obsahují FRP sítě, které slouží k vyztužení maltového krytí na obou površích zdiva. V některých případech jsou navíc použity tenké proužky nebo prameny z nerezové oceli, které výrazně nemění seismickou odezvu konstrukce.

Jsou prezentovány různé způsoby stažení zděných sloupů, čímž se dosáhne zvýšení tlakové únosnosti a duktility. Jde o opásání použitím FRP, obsahující tenké pásky z nerezové oceli a s nerezovými prameny. Tento postup může být použit také pro exponované sloupy, protože vlákna mohou být skryta maltou.

Pro zvýšení smykové odolnosti zděných stěn v jejich vlastní rovině jsou diskutovány čtyři techniky: dvě za použití FRP kompozitů a dvě za použití prvků z nerezové oceli. Použití pásů FRP na povrchu zdiva prostřednictvím vhodných lepidel je účinné pro požadovanou smykovou odolnost ve vlastní rovině, přestože nedostatečné sepětí může mít zásadní význam pro vrstvené zdivo. Použití malty vyztužené FRP sítí na obou površích zdiva umožňuje značně zvýšit jak smykovou únosnost tak i duktilitu zdi. Kromě toho, příčné konektory poskytují dobré upevnění do zdiva tak, že technika je účinná i pro vrstvené zdivo. Metody založené na použití tenkých proužků z nerezové oceli poskytují jak potřebné příčné sepětí, tak i vazby pro vytvoření příhradového systému pro zvýšení únosnosti ve smyku v rovině. Další způsob zesílení je založen na vytvoření roštu z prvků z nerezové oceli (z FRP nebo drátů) umístěných při obou površích zdiva a propojených ocelovými prvky. Při vhodně zvoleném příčném provázání dojde k významnému zvýšení smykové odolnosti.

Všechny tyto postupy poskytují dobrou míru provázání a mohou zaručit pro ohyb z roviny zdiva dobré působení, i když k potvrzení teoretických výsledků jsou potřebné další experimentální studie.

Keywords

Masonry constructions, ancient buildings, cultural heritage, earthquake engineering, strengthening techniques, composite materials, shear loads.

Klíčová slova

Zděné stavby, historické budovy, kulturní dědictví, seismické inženýrství, metody zesilování, kompozitní materiály, smykové účinky.

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1 Introduction

A lot of historical constructions belonging to the architectural cultural heritage are present all over the world: buildings, bridges, monuments, etc. These constructions are subjected to structural degradation due to ageing of the component materials, to chemical and/or biological attack, to increased service loads, to foundation settlements and to extreme environmental actions, as earthquakes or floods. So that, many historical constructions need interventions to preserve their structural effectiveness, which may concern local repairing or global retrofitting. In particular the constructions located in seismic prone areas need to be strengthened so to make them able to resist seismic actions, that were not considered originally in the design. But any intervention requests a previous good knowledge of the actual state of the construction: materials degradation, connection effectiveness, etc.

Damage assessment for historical masonry buildings is often a complex issue due to difficulties into defining specific categories and identifying geometry and materials. The historical heritage constructions have been subjected to several events over the time that may have altered their original “unicum” imprinting. This amplify the uncertainty about geometry, materials, interaction with other constructions, etc, and means that the evaluation of the structural behavior has to be approached through an assessment of the current condition of the structure and its history in terms of material properties, construction techniques, structural details, crack pattern, damage map, material decay.

The variability of parameters as well as masonry texture, degree and quality of connections, typology of component elements (i.e. disposition and dimension of blocks), mechanical properties of materials constituting the masonry assembly (i.e. stone blocks, bricks, mortar) can considerably influence the structural behavior. Furthermore, the original mechanical properties of materials, already variable because dependent on the geological history of the carved stones, can be often modified by age and environmental effects. This implies the need of detailed inspections and monitoring of materials decay.

Experimental in situ inquires and measures [1], better performed by the utilization of modern non-destructive tests [2], can solve most of the uncertainties related to a multidisciplinary knowledge of the examined building and can be useful also to calibrate finite element models that describe the static and dynamic behavior in the linear field. The evaluation of stress levels for static loads by experimental tests in situ becomes a useful instrument to calibrate the mechanical properties of the constituent materials (elastic modulus, strength), also by using simple mono-dimensional finite element models.

Moreover it is important considering that the historical masonry buildings were built on the basis of traditional rules, far from the current design standards.

Only a well assessed diagnosis of the building can be the basis to perform safety evaluation and to plan interventions compatible with minimum impact requirements.

The Charter of Venice [3] and, more recently, the Charter of Krakow [4] give comprehensive guidelines for the modem restoration of artistically relevant structures and may be considered as the reference documents in the field. The basic principles are as follows: the interventions should have respect for the original materials; required replacements need to be harmoniously integrated with the whole, but easily identified and additions are acceptable only if their influences on the other parts of the monument and/or its surroundings are negligible. In other words, the minimum destruction theorem applies. Moreover, any supplementary system should also be designed to be reversible: all the added components should be removable, leaving the structure as it was and allowing applications of new techniques with greater effectiveness. Also, because the typical life of such structures is much longer than that of ordinary buildings, common repair materials will most likely not have the necessary lasting durability.

These working hypotheses are now widely accepted and regulated, especially in countries where these kinds of structures are a significant fraction of the built heritage. However, achieving seismic performance by interventions that respect the structural system and, at the same time, remain completely removable is often hardly possible. This issue is why the listed principles are intended, in general, as asymptotic concepts, meaning that they are targets not fully achievable by common technology. One can easily recognize that retrofit based on steel and reinforced concrete, which have been and are essential for structural restoration fitting common buildings, may not be suitable for structures belonging to the architectural and artistic heritage. Thus, innovative methods can be used to achieve the same or better performances than traditional approaches, while respecting the discussed principles. In Italy a fundamental document on the application of the seismic prescriptions and code requirements specifically for the architectural and historical heritage is available; this is a reference, key document in the field [5].

Interesting theoretical and experimental confirmations are available concerning the effectiveness of these methods on buildings (e.g. [6-15]). Research studies are in progress concerning the intervention materials and techniques on masonry bridges.

2 Masonry types

The historical buildings are made with very different types of masonry; however they may be distinguished mainly in (Fig. 1): a) almost regular stone blocks, b) solid brick masonry with lime mortar, c) roughly squared stone blocks with different dimensions, d) roughly squared stone blocks with some layers of solid bricks, e) almost rounded stone blocks with different dimensions, f) stonework made with cobblestones. In most of masonries the elements are assembled with a lime mortar having very scarce mechanical characteristics. Moreover the masonries a), c), e) and f) are normally formed by many vertical layers (multi-leaf masonry) or by two layers with infill made with pebbles and very poor lime mortar.

The masonry in some cases is exposed (not plastered) and in other cases has the surface covered with a lime plaster. In the former case the surface of blocks and the mortar of the joints are more damaged by environmental chemical or physical actions than in the latter. Moreover, exposed masonries are frequently subjected to biological attack with the formation of weeds and lichens in the mortar joints reducing considerably the mechanical characteristics of the masonry.

The masonries subjected to seismic excitation tend to collapse in different ways: axial force, in-plane shear, out-of-plane flexure. The first type of collapse may occur in the case of columns, slender masonry piers or when the vertical component of the seismic action is important, as occurred in the earthquake of L'Aquila, Italy. In this case, in fact, the cyclic vertical stresses in the mortar joints caused the damage of the mortar with its transformation in granular material (debonding of sand grains), leading the masonry to its break up, with particular concern in case of multi-leaf walls (Fig. 2). The in-plane shear may occur by sliding or by diagonal cracking; both collapse mechanism may occur because of the scarce tensile resistance of the masonry. The out-of-plane flexure collapse may occur due to the excitation of the masonry in the direction perpendicular to its plane; such a collapse is frequent in buildings with the walls not connected to stiff floors (wall overturning, vertical flexure) or in case of multi leaf walls (Fig. 2).

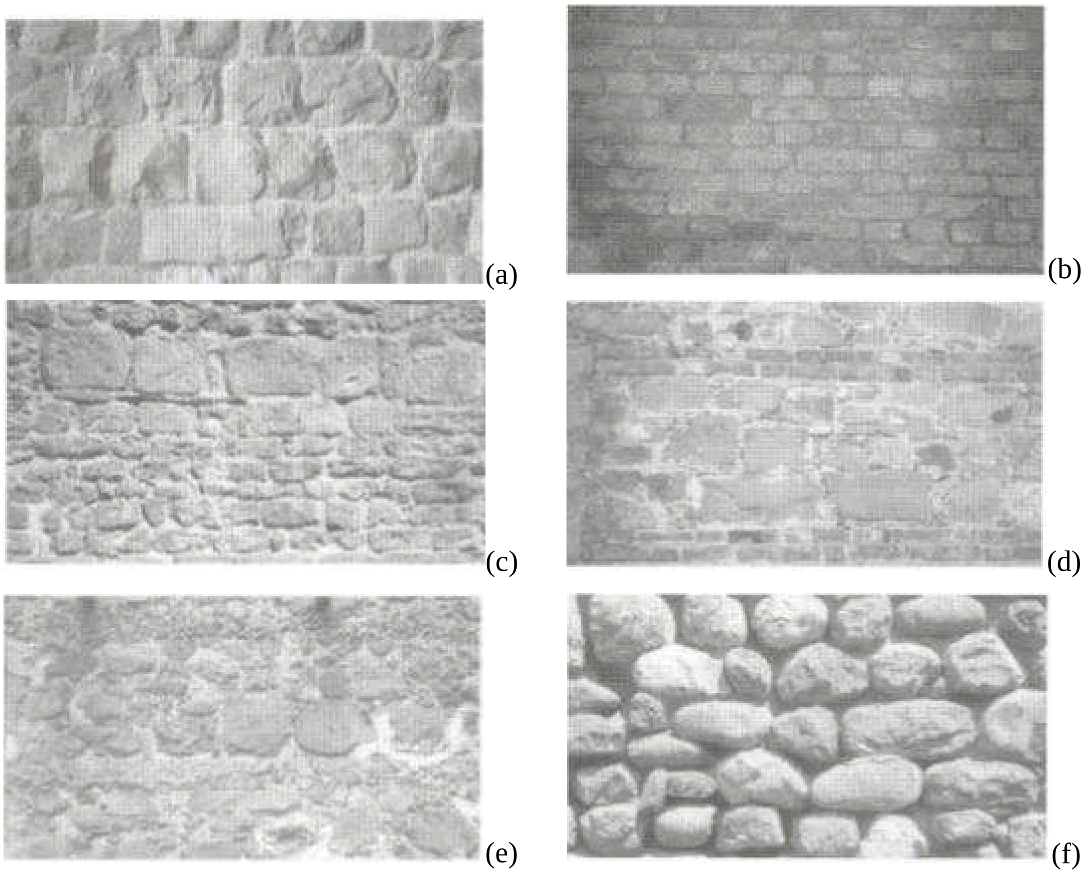


Figure 1 – Types of masonries: a) almost regular stone blocks, b) solid brick masonry, c) roughly squared stone blocks with different dimensions, d) roughly squared stone blocks with some layers of solid bricks, e) almost rounded stone blocks with different dimensions, f) masonry with cobblestones.

The last earthquakes occurred in Italy (Umbria-Marche 1997, Molise 2002, L'Aquila 2009) evidenced the low resistance of the buildings that did not have an effective connection among perpendicular walls and among walls and floors (structural integrity). Actually for such buildings, the most reasonable way to improve their resistance would be the substitution of the walls, but this it is unproposable for buildings belonging to the cultural heritage. It is then necessary to increase the resistance of these masonries through the use of materials and techniques that allow conserving the existing masonries with the respect of low invasiveness, high reversibility and high durability.

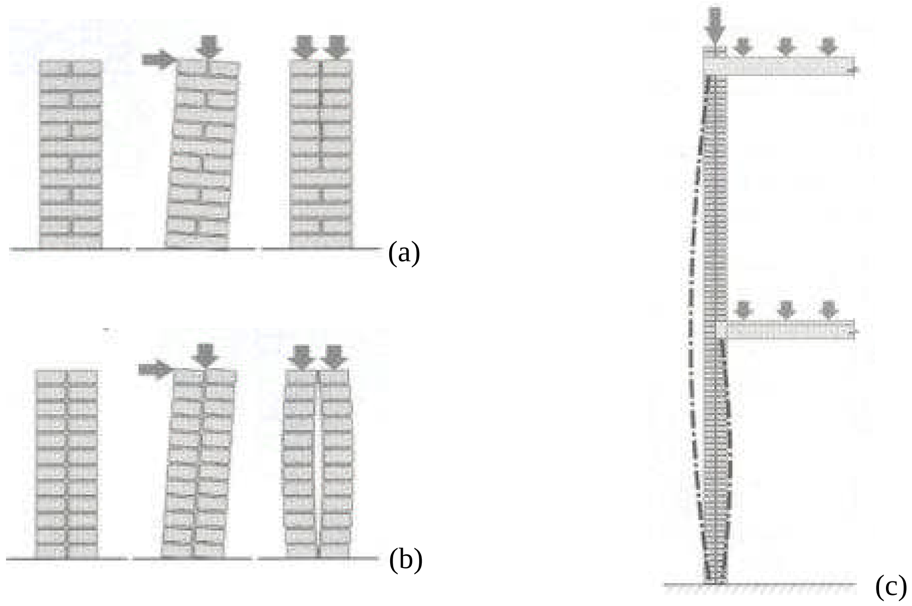


Figure 2 – Behavior of single and multi-leaf masonries under loading: a) one leaf masonry, b) two leaf masonry, c) two leaf masonry in a multi-floor building.

3 Materials for strengthening masonries

As stated above, most of the masonries of the historical buildings, with particular concern to stoneworks and to multi leaf masonries, are characterized by very poor mechanical characteristics therefore the collapse occurs with the breakup of the masonry. Moreover masonry elements subjected to relevant axial forces, as columns, may also collapse due to the cyclic degradation of the mortar during seismic vertical excitation.

Effective strengthening techniques are necessary to avoid local collapses of the masonry structure increasing the strength capacity of the material. For such a goal different materials have been studied in the last decade. In particular FRP (Fiber Reinforced Polymers) composites and special stainless steel strands or strips.

3.1 Composites

FRP composites started to be used for strengthening existing buildings around 20 years ago in USA and Japan, and mainly to strengthen reinforced concrete structures. After the Umbria-Marche earthquake (1997), in Italy was devoted particular attention to the use of composites to strengthen and repair masonry buildings because of their lightness, that do not increase the seismic masses, and their capacity to improve the masonry behavior without modifying considerably the response.

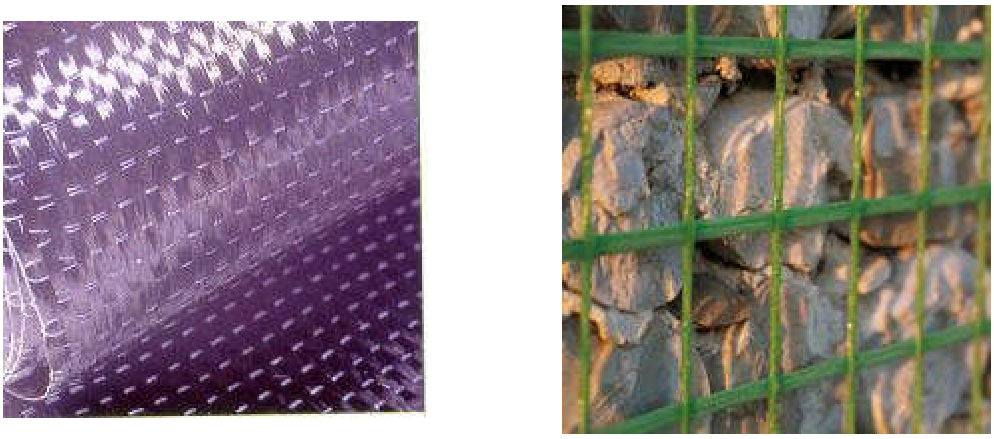
Moreover the Monuments and Fine Arts Services changed their point of view allowing the use of FRP, because they recognized the high performances of these new materials as well as the low invasiveness of the application (external application through adhesives). In fact, in 1998 FRP were used to consolidate the vaults of the St. Francis Basilica in Assisi, Italy. After that intervention many researches and studies were carried out to evaluate the potentiality of these new materials for strengthening masonry walls, vaults and floors.

However, designers did not use these materials, even though interested in, until 2008 because no codes were available to provide validated calculation procedures. In Italy the National Research Council proposed some rules [16], which were assimilated in the new Italian Code [17], concerning the design of interventions for strengthening structures using FRP.

Three Different types of fibers are normally used: carbon, aramid (kevlar 49) and glass. The mechanical characteristics are reported in Table 1. Carbon fibers have a significantly greater Young modulus than the other fibers, up to three times greater. The cost of carbon fibers is the highest and that of the glass is the lowest; an intermediate cost have the aramid fibers. In the restoration of masonry buildings only carbon and glass fibers are used. The lightly greater characteristics of aramid fibers with respect to glass fibers do not compensate the higher cost.

Tab. 1 - Mechanical characteristics of different fibers.

Material	Density (g/cm^3)	Tensile Strength (MPa)	Young Modulus (GPa)	Ultimate deformation (%)
Carbon	2.00	2400-5700	290-400	1.5-2.0
Kevlar 49	1.44	2400-4500	62-142	1.5-4.5
Glass	2.55	2000-4500	72-87	4.5-5.0



(a) (b)

Figure 3 – Unidirectional carbon fibers strip (a), glass fibers composite mesh (b).

Two applications of fiber composites are normally used to strengthen existing masonries: strips of fibers (Fig. 3a) bonded on the masonry surface through epoxy resin and a mortar coating reinforced with a GFRP grid (Fig. 3b).

In the first solution, textile strips of fibers are connected on site to existing masonry using special adhesives (wet lay-up system), characterized by durable behavior and possibly reversible nature, which are required for the application of any material/technique on cultural heritage assets. A unique self-adhesive material that, unlike conventional adhesives, maintains a high degree of rigidity at the “adhesive” state while possessing the ability to easily de-bond upon heating has been recently developed. Glass fiber reinforced polymers (GFRP) or carbon fiber reinforced polymers (CFRP) are considered as efficient solutions for reinforcing existing masonry elements.

The second strengthening solution consists of the use of lime-mortar coating reinforced with new generation FRP materials connected to masonry by means of mechanical devices (precured system). The durability requirement is a critical point of the strengthening technique. The lime (calcium hydroxide) present in the mortar is extremely aggressive and severely attacks both the surface and molecular structure of conventional E-glass fibers. The E-glass rapidly loses its ability to sustain loads because the alkali in the mortar corrodes the fibers. In these applications, to guarantee durability of the intervention, it is necessary to use alkali-resistant AR-glass fibers specifically designed for use in concrete and mortars and sufficiently stable in the aggressive lime environment (usually pH>12). The AR-glass fibers are obtained by adding zirconium oxide to the glass in a percentage greater than 16%. Extended studies on the performance of the materials (e.g. [18]) allowed the definition of a standard for AR-glass fibers [19]. The addition of zirconium causes a significant increase in the cost of the material (almost double).

Actually, the polymeric matrix (epoxy vinyl-ester) could protect the E-glass fibers so as to avoid their corrosion due to alkali, but the porosity of the matrix might not guarantee an adequate protection of fibers.

3.2 Stainless steel strands or strips

Different new strengthening techniques for masonry walls are based on the use of stainless steel either in small diameter strands or in thin strips. The small diameter strands, normally 1.0 mm, are produced for aeronautic uses and the steel is characterized by a tensile strength equal to 1550-1600 MPa. The high resistance is needed to compensate the small diameter that is requested to bend the strand without difficulties. The strands are arranged in order to confine the masonry and to prevent its break up. For the same purpose thin stainless strips (0.8x20 mm) may also be used. The steel characteristics are very different with respect to those of the strands: the yielding stress is 250-300 MPa and the tensile strength is 600-700 MPa; the maximum elongation at rupture is at least 40%.

4 Strengthening techniques

Various novel strengthening techniques for masonry buildings are proposed in the last decade, which makes use of composite materials or stainless steel (section 3). These techniques provide different effectiveness for the various stresses that interest the masonry elements. So that, in the follow, there are discussed separately the techniques that are effective for the elements subjected to the most common loading conditions: compression, in-plane shear and out-of-plane bending.

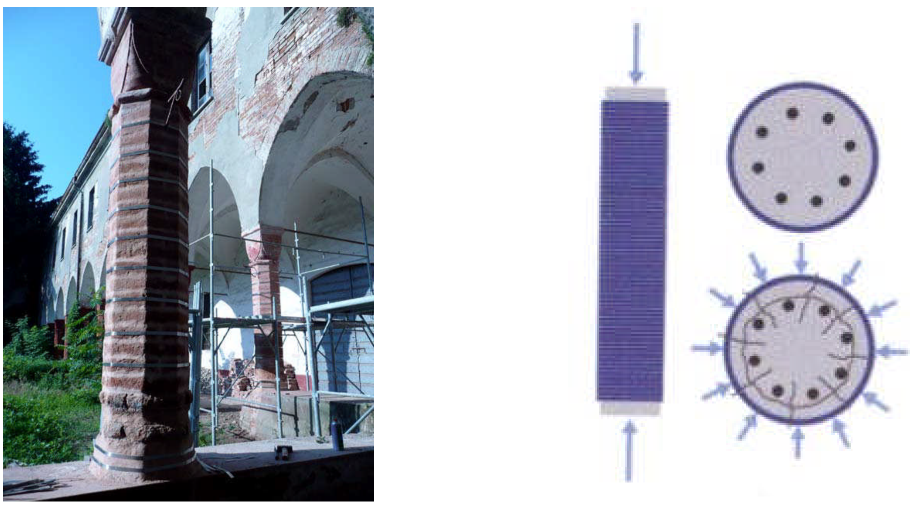
4.1 Compression

As well known, the masonry columns subjected to compression reach their ultimate limit state by the formation of vertical cracks. This occurs because the component materials, bricks (or stone blocks) and mortar, have a different deformability. In fact, as the load increases the transversal deformation of the mortar is greater than that of the brick, but due to the strain compatibility at mortar-brick interface the mortar is transversally compressed and the bricks are subjected to horizontal tensile stresses that cause the formation of vertical cracks. In order to postpone the crack formation it is significantly effective the application of hoops that contrast the lateral expansion of the column and consequently the tensile stresses in the bricks.

Many examples of such confining technique may be found in past strengthening interventions in brick and stone masonry columns by using steel rings. But these interventions are frequently excessively invasive from a conservation point of view, so that other strengthening types were proposed in recent times.

4.1.1 CAM system hoop

One technique consists in the application of thin stainless steel strips (CAM system [6]) that hoops the column at a relatively close spacing (Fig. 4a). The strips (normally 0.75x18 mm) are prestressed so they provide a transversal stress to the material improving the effectiveness of the hoop (triaxial behavior – Fig. 4b). As can be clearly understood, this technique is very easy to apply but its invasiveness is not significantly different to that of old steel rings. However, differently to old steel rings, if the columns are plastered it is possible to hidden the strips under the new plaster, due to their small dimensions. Obviously, the lower the hoop spacing is, the higher the effectiveness of the system is.



(a) (b)

Figure 4 – Column confinement: (a) with stainless steel strips (CAM system [6]), (b) effectiveness of prestressed hoops.

4.1.2 FRP strip confinement

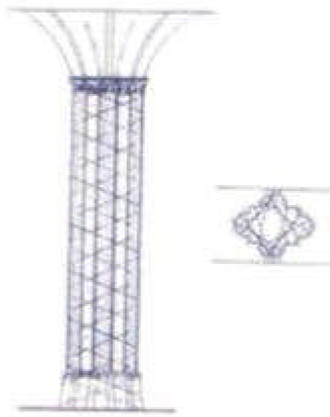
Another effective technique consists in the application of FRP (carbon or glass fibers) strips to confine completely the column (Fig. 5a). The tape of fibers is wrapped to the column with continuity; it may also be prestressed if apposite tools are used for the application. The effectiveness is guaranteed because the lateral confinement is continuous. One shortcoming of this technique is that do not allow the transpiration of the column and then chemical or physical damage of the masonry may occur as a consequence.

4.1.3 Injected bars

An internal confinement consists in the application of steel or GFRP rods inserted in holes crossing the column in all directions and injected with cement grout or epoxy resin (Fig. 5b). This intervention is mechanically effective, as demonstrated by many researchers, has low invasiveness because it is completely hidden inside the column but it is low reversible; in fact it is not easy to be removed in the future to substitute it with more effective techniques that may become available with future research.

Sometimes, when the column has large dimensions, this technique is applied in conjunction with FRP strip confinement so to improve the confining effect.

(a)



(b)

Figure 5 – Column confinement: (a) with CFRP strips, (b) with injected GFRP bars.

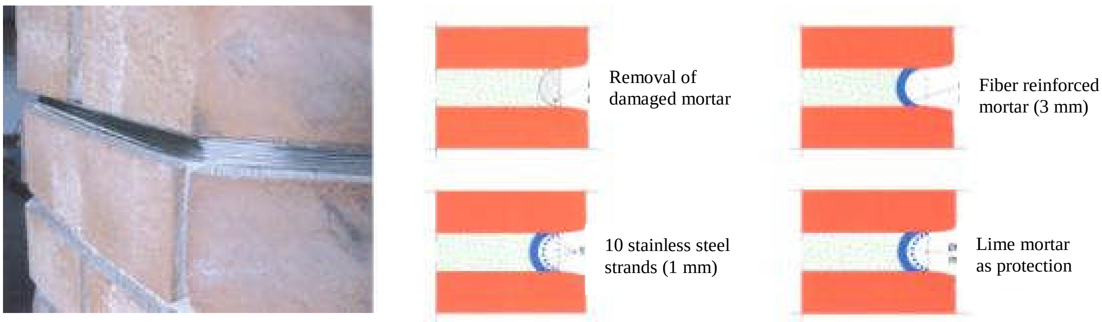
4.1.4 Stainless steel hoop confinement

An innovative confining technique was recently proposed by Jurina [20]. It consists in the application of small diameter stainless steel strands (1.0 mm) so to provide hoops to the column in correspondence of mortar joints (Fig. 6). As stated above, the lime mortars of ancient buildings has a greater deformability with respect to that of the bricks or stone blocks so that the application of a ring that prestresses radially the mortar joint increases significantly the capacity of the column. The technique has very low invasiveness and it is fully reversible.

An experimental investigation was recently carried out [20], in which columns with and without the application of strands were tested. Octagonal columns were considered with 520 mm diameter and 1200 mm height. The application of 10 strands (1.0 mm) in correspondence of each mortar joint evidenced that the column capacity was almost doubled (Tab. 2). In case of strands in alternate joints the column capacity increase was approximately 50%. The maximum vertical displacement increased considerably in confined columns. In Fig. 7 the samples near collapse are shown. In the unconfined sample the significant vertical cracks are evident; cracks are more diffused in confined samples.

Table 2 – Results of tests on confined columns with stainless steel strands [20]

Strand location	Column capacity (kN)		Max vertical displacement (mm)	
	Sample 1	Sample 2	Sample 1	Sample 2
None	756.6	824.8	14.66	29.60
Alternate joints	1274.9	1161.7	48.97	46.20
Every joint	1636.7	1454.2	60.79	61.28



(a) (b)

Figure 6 – Column confinement with stainless steel strands: (a) view, (b) application.

Figure 7 – Columns at the end of the test: (left) plain column, (center) strands in alternate joints, (right) strands in all mortar joints.

4.2 In-plane shear

The seismic resistance of a masonry building, if local mechanisms are prevented, depends on the in-plane shear resistance of masonry. The elements subjected to shear are the piers and the spandrels. The shear resistance of ancient masonries is normally very low so that frequently it is necessary to make interventions to strengthen them.

Some of the techniques used in the past, based on the use of very stiff reinforced concrete elements, cause significant changes in the response of the structure to seismic excitation and frequently lead to dangerous consequences. Moreover they cannot be used for cultural heritage. In the last 10-15 years, some strengthening techniques based on new materials were proposed and tested.

4.2.1 FRP strips

One of these techniques consists in the application through adequate adhesives of FRP strips on the surface of the masonry (Fig. 8). This technique is used since two decades to strengthen existing reinforced concrete structures. In particular, the surface of the wall needs to be regularized so to allow for a good adhesion of the strips. It is necessary to remove all the damaged parts of blocks and mortar, and then apply a high bond mortar to provide an adequate surface on which the strips may be applied. The strips of fibers, carbon or glass fibers, are fixed to the surface of the wall through epoxy resin.

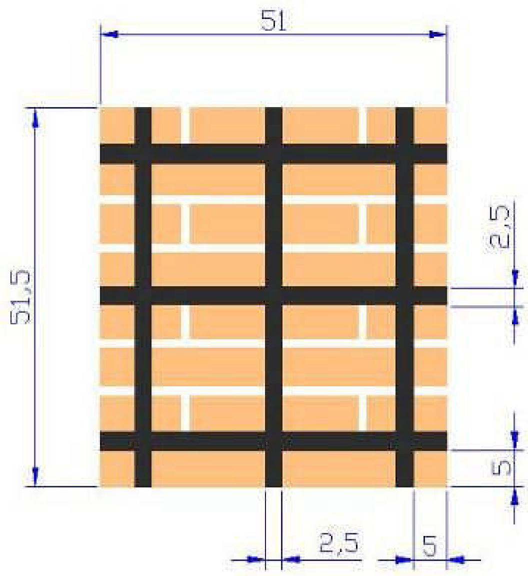


Figure 8 – View of the reinforcing technique based on FRP strips.

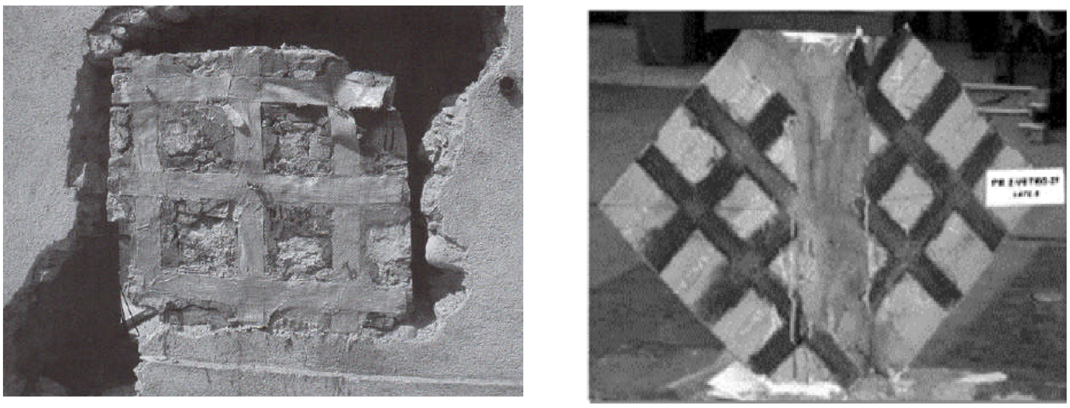
This technique has two main shortcomings: frequent debonding of strips and lack of confinement of the masonry. To avoid debonding it is frequently necessary to use mechanical connections of strips, especially when the surface of the wall is greatly damaged by environmental action. Instead, the lack of confinement is very critical in multi-leaf masonries. If there are voids among masonry layers, it is possible to add the grout injection technique, otherwise mechanical connections passing through the wall have to be used. The grout injected permits the saturation of cavities allowing for a homogenization of the masonry behavior. But, provided that the voids may be scattered, it is important that the mechanical characteristics of the grout be not too strong with respect to those of existing masonry otherwise significant stiffness variations may be found in the injected masonry. Different types of mechanical transversal connections (diatones) may be used to join masonry layers (bolted steel ties, injected steel or FRP rods, reinforced concrete studs, etc.).

When the masonries are subjected to important vertical seismic excitation that may cause significant mortar damage, it is important that the external masonry layers do not buckle, so that a good connection is requested among masonry layers.

Some researchers carried out diagonal compression tests on existing masonries reinforced with GFRP strips applied on both sides of the specimen (e.g. [8]). The results evidenced that a stone masonry with a shear resistance before strengthening of about 0.042 MPa, after strengthening reached a resistance almost three times as much. The masonry was one leaf. No debonding of the GFRP strips were registered (Fig. 9a). Some other researchers carried out diagonal compression tests on new masonries reinforced on one or both surfaces with GFRP and CFRP strips (e.g. [12]). The shear resistance of unreinforced specimens was very high (0.80 MPa). The results evidenced negligible increases of resistance in case of single face reinforced while an increase ranging from 50% to 75% was noted in specimens reinforced on both faces. In many specimens the debonding of the strips occurred (Fig. 9b).

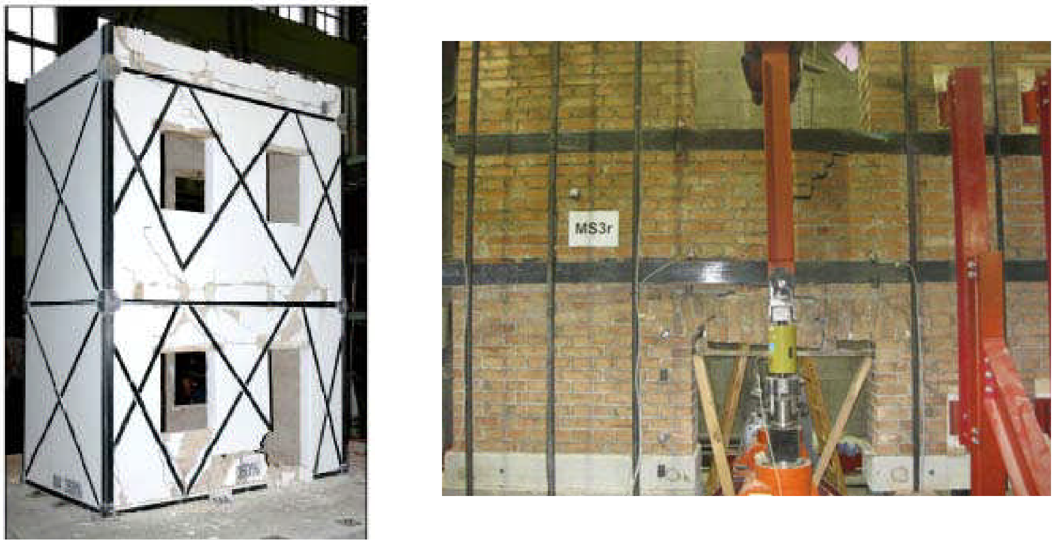
Some applications of such a technique may be evidenced in Fig. 10. In particular in Fig. 10a it is shown the experimental model (1:4 scale) of a building with the piers strengthened with diagonal CFRP strips; the model was tested at the ZAG Laboratory in Ljubljana, Slovenia. In Fig. 10b it is shown the experimental model (real scale) of a spandrel beam subjected to shear loads; the spandrel was strengthened with parallel CFRP strips and was tested at the Laboratory of Materials and Structures of the University of Trieste, Italy.

The technique is low invasive (application on the surface) and high reversible (removal without damaging the masonry) but it is not applicable on decorated or painted walls. The plaster has to be partially removed for the intervention and then replaced.



(a) (b)

Figure 9 – Experimental tests on specimens strengthened with FRP strips: (a) existing stone masonry [8], (b) new masonry [12].



(a) (b)

Figure 10 – Examples of application of CFRP strips: (a) building model tested at the ZAG laboratory, (b) masonry spandrel beam tested at the University of Trieste.

As stated above, to design the strengthening intervention it is necessary to evaluate through experimental tests, preferably in situ, the mechanical characteristics of strengthened masonry and to use these values in the structural analysis of the building. The debonding of the strip strongly depends on the surface of the wall; frequently considerable parts of the brick or stone are removed with the strip (rip-off failure).

Actually some rules and analytical relations are available in the Recommendations CNR-DT 200/2004 [16]. The first important aspect to be considered is the resistance to debonding that depends on the tensile resistance of the masonry f_{tm}, the specific fracture energy of the bond between FRP and masonry Γ_F and the characteristics of the composite (E_f Young Modulus, t_f thickness of the strip) through the relationship

$$f_{fd} = \frac{1}{\gamma_{f,d} \cdot \sqrt{\gamma_M}} \cdot \sqrt{\frac{2 \cdot E_f \cdot \Gamma_F}{t_f}}\,, \qquad (1)$$

$\gamma_{f,d}$ is a safety coefficient for bond (for masonry equal to 1.5) and γ_M is the safety factor for masonry. The fracture energy is given by the equation

$$\Gamma_F = 0.015 \cdot \sqrt{f_{mk} \cdot f_{tm}}\,, \qquad (2)$$

with f_{mk} compressive resistance of the masonry.

The optimal anchorage length is the minimum length needed to transfer the most bonding stress and is equal to

$$l_e = \sqrt{\frac{E_f \cdot t_f}{2 \cdot f_{tm}}}\,. \qquad (3)$$

If the anchorage length is less than that calculated with Eq. (3), the resistance to debonding is

$$f_{fd,rid} = f_{fd} \cdot \frac{l_b}{l_e} \cdot \left(2 - \frac{l_b}{l_e}\right), \tag{4}$$

with l_b the actual anchorage length.

The shear resistance of masonry elements may be assessed using the following relationship

$$V_{Rd} = \min\{V_{Rdm} + V_{Rdf}, V_{Rd\max}\}. \tag{5}$$

If the strips are disposed horizontally, the first terms of Eq. (5) are determined according to the truss scheme (Fig. 11)

$$V_{Rdm} = \frac{1}{\gamma_{Rd}} \cdot d \cdot t \cdot f_{vd}, \tag{6}$$

$$V_{Rdf} = \frac{1}{\gamma_{Rd}} \cdot \frac{0.6 \cdot d \cdot A_{fw} \cdot f_{sd}}{p_f}, \tag{7}$$

where, γ_{Rd} is the safety factor (equal to 1.2), d is the distance from the center of the reinforcement for flexion and the compression edge, t is the wall thickness, f_{vd} is the design shear strength of the unreinforced masonry, A_{fw} is the area of the horizontal FRP strip, p_f is the spacing of the horizontal reinforcement, f_{sd} is the minimum between the debonding resistance and the tensile resistance of the FRP strip.

The maximum shear resistance of the masonry for the collapse at compression of the diagonal struts of the resisting truss is

$$V_{Rd\max} = 0.3 \cdot d \cdot t \cdot f_{md}^{h}, \tag{8}$$

where f_{md}^{h} is the compressive resistance of masonry in the horizontal direction, namely parallel to the mortar joints (normally assumed equal to 0.5 f_{md}).

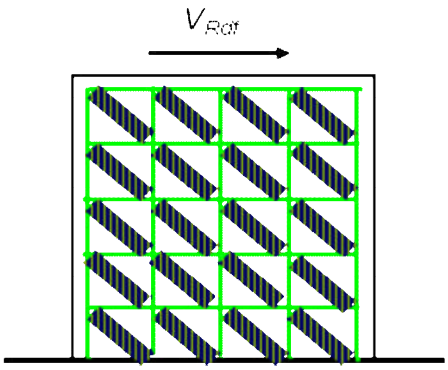


Figure 11 – Truss scheme for assessing the shear resistance increase due to FRP strips.

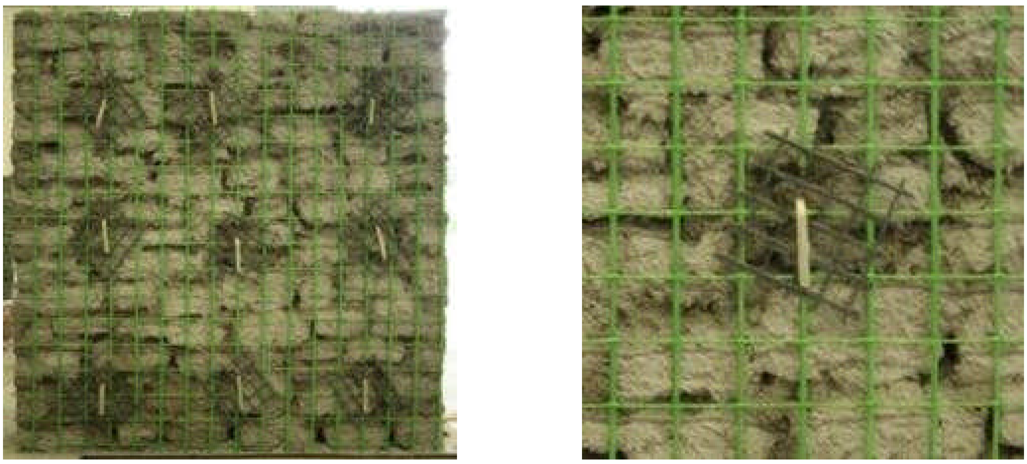
4.2.2 Mortar coating reinforced with GFRP mesh

Another strengthening technique concerns the application of a GFRP mesh on both faces of the masonry wall and embedded in a mortar coat. The GFRP mesh is formed with long fibers of glass that are covered with a thermosetting resin (vinyl ester epoxy and benzoyl peroxide as catalyst); the composite wires are weaved to form the mesh by twisting the resin impregnated transversal fibres across the longitudinal wires.

The application procedure of the strengthening technique concerns the following phases: a) removal of the existing plaster and the mortar from the joints between elements, 10-15 mm deep, on both wall faces, b) application of a layer of cement scratch coat, c) execution of passing through holes, 25 mm diameter, to allow for connectors insertion, d) application of the GFRP mesh on both faces, e) insertion of L-shaped GFRP connectors (8x12 mm) and injection of thixotropic epoxy resin inside the holes to fix the connectors, f) application of the new coating made with lime and cement mortar (30 mm thickness). The L-shaped connectors are lap spliced inside the hole; 6 connectors per square meter are provided.

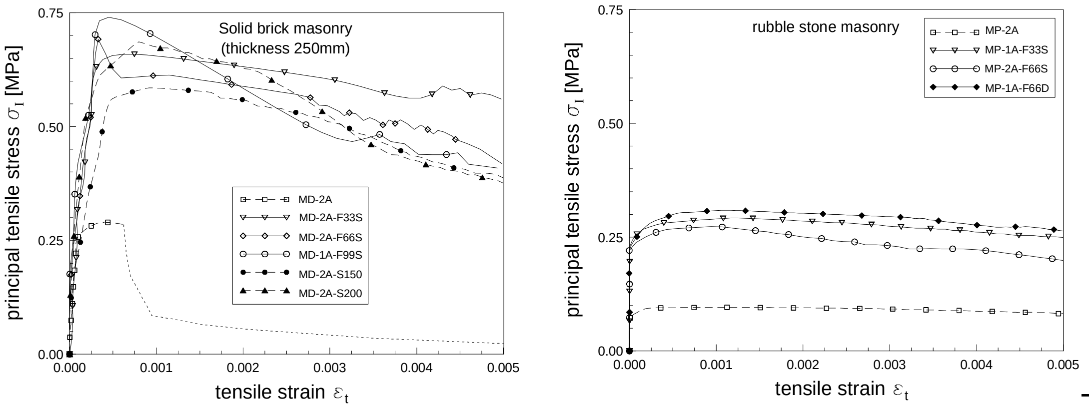
In Fig. 12a an example of application of the GFRP mesh on the masonry is displayed; in Fig. 12b the detail of the connector is evidenced.

A broad experimental investigation was carried out by the author on different types of masonries: solid brick, two leaf brick with scarce infill, stonework [15]. Numerous diagonal compression tests were executed considering also different types of mesh. The results evidenced that the increase in shear resistance was due to the confining effect of the coating on the masonry and to the shear resistance of the coating. The confining effect was more pronounced on stone masonries. After the crack formation the shear resistance of unreinforced specimens drop down very quickly, whereas it remained constant (stoneworks) or decreased very slowly (others) at the displacement increase up to significant value of the diagonal displacement. Some curves expressing the equivalent principal tensile stress as a function of the tensile strain evidence such a behavior: in Fig. 13a the curves refer to solid brick masonry 250 mm thick and in Fig. 13b the curves refer to rubble stone masonry.



(a) (b)

Figure 12 – Strengthening technique details: (a) GFRP mesh application [15], (b) detail of the GFRP connector.



(a) (b)

Figure 13 – Principal tensile stress-tensile strain curves: (a) solid brick masonry (250 mm), (b) rubble stone masonry [15].

The technique may be considered low invasive for the masonry structure but needs the plaster removal and substitution. Also for reversibility the technique removal requires also the plaster removal. But many cultural heritage constructions require the plaster substitution.

For using this technique, it is necessary to carry out at least one diagonal compressive test per each different type of masonry present in the building so to quantify the actual shear resistance and stiffness. Simple analytical relationships may allow assessing these values and then avoid carrying out specific experimental tests.

On the basis of experimental studies it was possible to define a relationship that assesses the equivalent tensile strength $f_{t,calc}$. The relationship considers the tensile strength of the reinforcement $f_{t,int}$ and that of the plain masonry $f_{t,m}$. The last one was increased with the coefficient β to take into consideration the confining effect provided by the coating to the plain masonry. The relationship is

$$f_{t,calc} = \beta \cdot f_{t,m} + 2 \cdot \left(f_{t,\text{int}} \cdot \frac{t_{\text{int}}}{t_m} + \frac{EA_r \cdot \bar{\varepsilon}}{t_m \cdot p} \right) \tag{9}$$

where t_m is the thickness of the masonry, t_{int} is the coating thickness, p is the grid dimension of the mesh and EA_r is the axial stiffness of a wire of the mesh. The parameter $\bar{\varepsilon}$ represents the deformation of the mortar in the uncracked condition corresponding to a tensile stress equal to the tensile strength of the coating mortar $f_{t,int}$; this parameter is obtained using the relationship

$$\bar{\varepsilon} = \frac{f_{t,\text{int}}}{E_{\text{int}}} . \tag{10}$$

E_{int} is the elastic modulus of the coating mortar. In Eq. (9) the first term represents the resistance of the plain masonry, the second term represents the coating resistance. Inside the parenthesis the first term represents the coating mortar contribution and the second represents the GFRP mesh contribution. This term is due to the compatibility of the mesh with the coating mortar (Fig. 14).

The values of coefficient β may be assumed equal to 1.5 for stonework, and equal to 1.3 for brickworks. After crack formation it is necessary to check that the reinforced coating be able to support a tensile force at least equal to 60% of the peak value, so as to avoid significant softening branches after the crack formation.

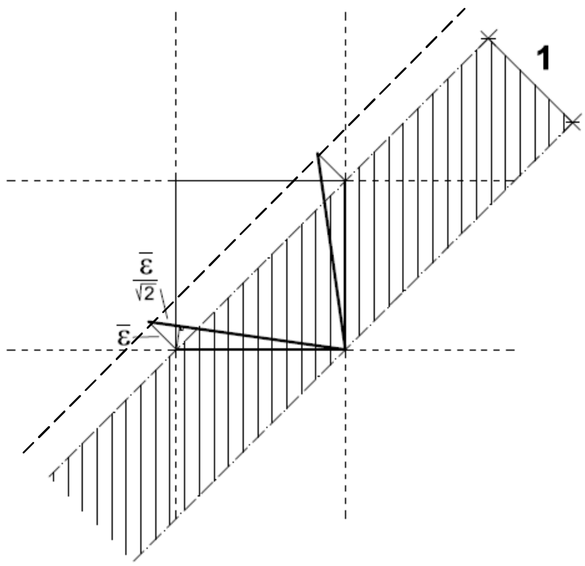


Figure 14 – Deformation of mesh wires due to the diagonal deformation of the coating mortar in correspondence of the tensile strength in the coating mortar [15]

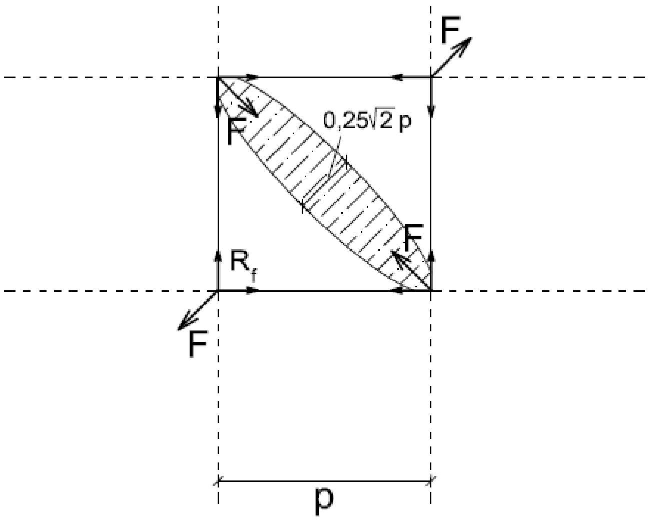


Figure 15 – Simplified strut-and-tie scheme that simulates the stresses in one grid of the GFRP mesh embedded in the coating.

In the scheme of Fig. 15, it was assumed an equivalent strut with a width equal to 0.25 the diagonal length ($\sqrt{2} \cdot p$) to represent the mortar effect. By imposing that the force F that causes the compression collapse of the strut or the tension collapse of the GFRP wire be equal to the 60% of the maximum one that caused the cracking it was possible to determine the minimum thickness of the coating to be used in order that the mortar strut would not fail for an equivalent tensile stress lower than 60% of the maximum one, as

$$t_{\text{int}} = 1.2 \cdot \frac{f_{t,calc} \cdot t_m}{f_{c,\text{int}}}. \tag{11}$$

Similarly, the minimum resistance of the GFRP wire of the mesh, for a certain grid dimension *p*, may be evaluated with the relationship

$$\frac{R_f}{p} = 0.3 \cdot f_{t,calc} \cdot t_m, \tag{12}$$

where $f_{c,int}$ is the compressive strength of the coating mortar.

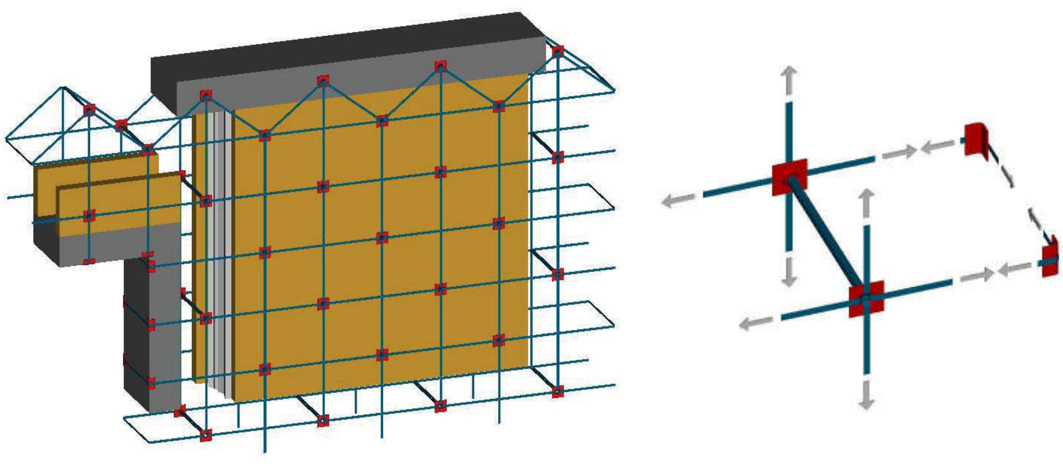
The equivalent shear modulus of the strengthened masonry G_{calc} may be assessed with the relationship

$$G_{calc} = \xi \cdot G_m + 2 \cdot \left(G_{\text{int}} \cdot \frac{t_{\text{int}}}{t_m} \right), \tag{13}$$

where G_m is the shear modulus of unreinforced masonry, G_{int} is the shear modulus of coating mortar. The coefficient ξ may be assumed equal to the coefficient β.

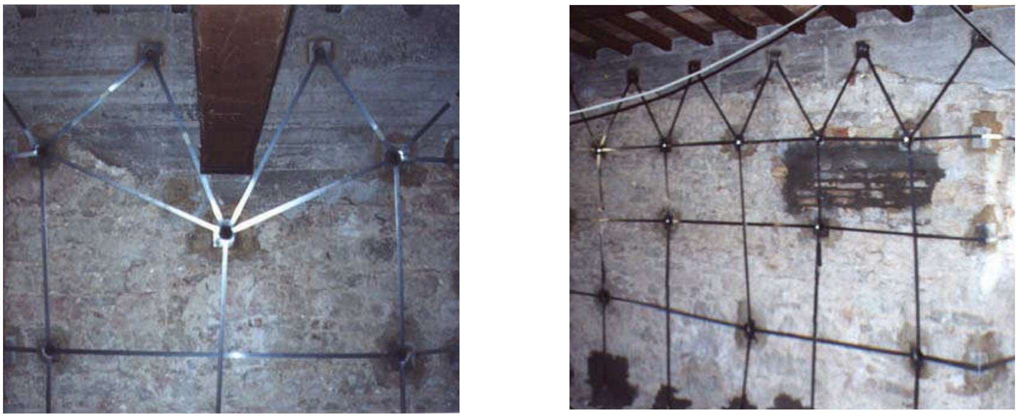
4.2.3 CAM system

Ancient masonry structures are often characterized by irregular or multi-layer masonry walls, with lack of transverse connections. The need for compacting them to improve their mechanical characteristics suggests the idea of using a three-dimensional system of tying. The CAM system [6], Active Ties for Masonries, is based on such idea. Ties are made of stainless steel thin strips (0.8x20 mm) and are pretensioned, so that a light beneficial precompression state is applied to masonry. Special connection elements permit to realize a continuous horizontal and vertical tie system, so that the shear and bending in-plane and out-of-plane strengths of single panels and entire walls are improved. The main characteristics of the CAM system are illustrated in Fig. 16, whereas in Fig. 17 two examples of applications are shown.



(a) (b)

Figure 16 – CAM system: (a) arrangement of the tie system, (b) detail of one node of the grid.



(a) (b)

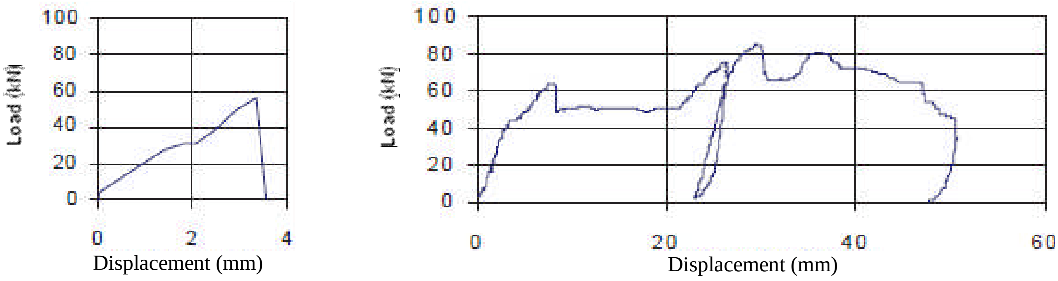
Figure 17 – Application of CAM system: (a,b) two examples of strengthened masonry.

The distance between holes is normally equal to 1000-1500 mm, depending on masonry characteristics. A specific tool is used for pretensioning the steel strips.

Some diagonal compressive tests allowed evidencing the effectiveness of this system [6]. The summary of the tests shows an appreciable increase in shear resistance and a considerable increase in ductility. In fact, the resistance increase was 15% in one case and 50% in the other case. The maximum displacement of strengthened specimens was almost one order of magnitude greater than that of unreinforced specimens (Fig. 18).

For applications it is necessary to carry out some diagonal compression in situ test to assess the mechanical characteristics to be assumed in the structural analysis. In the design of the reinforcement it is possible to use the relationships available for reinforced masonries.

The technique has the same shortcomings of the reinforced coating technique, so that it cannot be used in buildings with frescos or decorations on the walls.



(a) (b)

Figure 18 – Results of the diagonal compression tests: (a) unstrengthened specimen, (b) specimen strengthened with CAM system.

4.2.4 "Reticolatus"

Also the "reticolatus" technique, which consists in the use of FRP wires or stainless steel strands that are organized as a net, is effective to strengthen masonry buildings. The wires or strands, in correspondence of the intersections are connected to the wall through stainless steel elements passing through the wall and connected to the wires or strands of the other wall surface (Fig. 19). The wire or strands are allocated in the mortar joints. Firstly the detached mortar parts have to be removed and the joints have to be cleaned; then the first part of the reponting of joints has to be done using fiber reinforced mortar. The wires or strands are allocated in the joints and then the passing through connectors need to be applied. Finally the last part of the repointing may be applied. At the end the masonry is tied with a three-dimensional grid of strands.

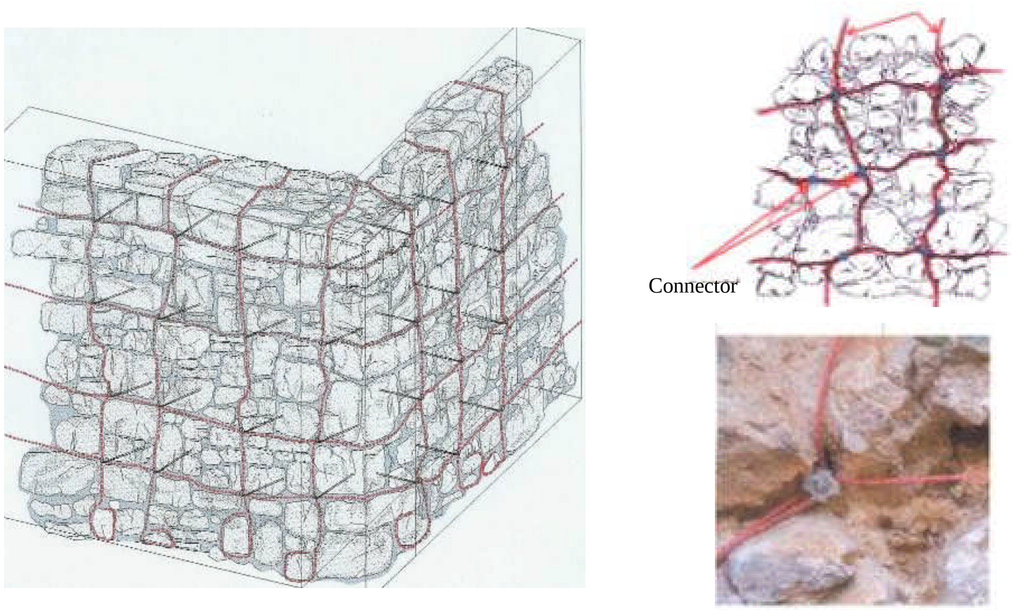


Figure 19 – Masonry strengthening technique with a net of GFRP wires or stainless steel strands: axonometric view and details.

Some diagonal compressive tests were carried out to evidence the increase in shear resistance and in ductility [7]. Three specimens were considered: unstrengthened stone masonry (A), deep repointed masonry (B) and masonry strengthened with the described technique (C). The results are graphically represented in Fig. 20, where the shear force against the shear drift is plotted. The summary of the results is reported in Table 3.

The curve (C) shows a shear resistance almost three times as much as that of curve (A). Good is also the ductility. This technique is adequate for exposed masonries (not plastered), in fact the strands and the transversal connectors may be hidden with the final repointing. The technique was developed to allow interventions on the many unplastered constructions present in the historical centers of European cities.

The design of the intervention may be carried out considering the relationships used for reinforced masonries. An experimental verification is however necessary.

Table 3 – Results of diagonal compression tests (reticolatus technique).

Type of strengthening	Ident.	Shear strength (MPa)	Shear modulus (MPa)
Unreinforced	A	0.029	541

Deep repointing	B	0.039	---
"Reticolatus" technique	C	0.063	653

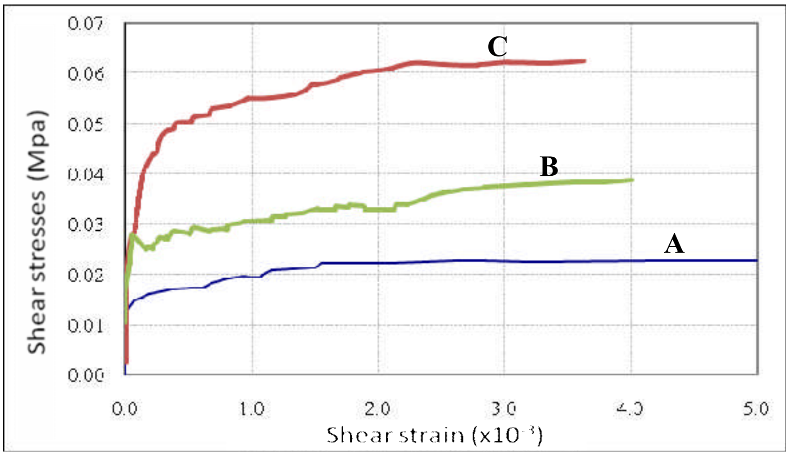


Fig. 20– Shear stresses against shear strain for unreinforced, repointed and strengthened with "reticolatus" masonries.

4.3 Out-of-plane flexure

The masonries disposed perpendicular to the seismic action are subjected to out-of-plane flexure. To avoid relevant flexural stresses in these masonries it is important that they be correctly connected to the floors and that the floors be adequately stiff in their plane, so to provide an effective horizontal restraint for the masonries. Nevertheless, in case of multi-leaf masonries, the out-of-plane flexural collapse may precede the collapse of shear walls, causing a significant reduction of the seismic capacity of the building.

Then, in case of multi-leaf masonries it is necessary to provide adequate interventions that avoid the separation of masonry layers. Such a goal may be reached by using strengthening techniques that link together the masonry layers. So that all the techniques that confine the original masonry are effective: mortar coating reinforced with GFRP mesh, CAM system, "reticolatus". Not adequate are the techniques that strengthen the masonry only on its surface (FRP strips or glued meshes). These techniques may be adequate to support out-of-plane flexure in multi-leaf masonries or two-leaf masonries with poor infill only if transversal connectors among layers (diatones) are provided. In some cases, instead of the transversal connectors, the injection of a grout of lime and pozzolan to fill the cavities inside the masonry is used. The grout links together the masonry layers avoiding their separation and consequently the masonry break up.

Very limited experimental investigations were carried out to study the effectiveness of the presented strengthening techniques in case of out-of-plane flexure. Only few numerical and analytical studies evidenced the effectiveness of the methods.

5 Concluding remaks

In this lecture some new materials and novel techniques for strengthening cultural heritage constructions in order to improve their performance under gravitational and environmental actions are presented and discussed. In particular, provided that many constructions are lacated in seismic prone areas, the techniques have to provide them effective improvements in the structural response, but they have also to satisfy the needs of the conservation: low invasiveness, high reversibility and high durability.

In the last decade a great attention was given to FRP composites as interesting materials for structural strenthening of ancient masonry buildings. The most used composites regards carbon fibers (CFRP) and glass fibers (GFRP) dispersed in thermosetting resin applied in the factory (precured system) or in the field (wet lay-up system). The first system concerns FRP meshes and the second system concerns fiber strips that are embedded in the polymeric matrix on field. Besides the composites are on interest also strands and/or strips of stainless steel.

For members subjected to compression (columns) the novel strengtheneng techniques consist in confining systems provided with FRP strips, stainless steel thin strips or strands. The hoops made with FRP strips may be continuous and provide a considerable compression capacity increase in circular columns. The shortcomings concern the lack of transpiration of masonry and the impossibility to apply on exposed (not plastered) columns. The hoops made with thin strips of stainless steel (CAM system) may be lightly prestressed. The greater the hoop spacing is, the lower the effectiveness is. The intervention is adequate for plastered columns.

The technique that applies small diameter stainless steel strands in the mortar joints evidences good effectiveness if the application is made in every mortar joint or in alternate joints. The intervention may be done also in exposed columns, the strands are hidden with the repointing.

For members subjected to in-plane shear two techniques are based on FRP composites and two on stainless steel thin strips or strands. The strengthening with FRP strips provide significant shear capacity increase even though great care is needed to prepare the surface for applying the strips; the debonding of strips frequently anticipate the tensile rupture of strips. The technique may be applied only on buildings that have to be plastered. For multi-leaf masonries the collapse may occur due to the buckling of outer masonry layers, due to the lack of confinement of the method. The strengthening with a mortar coating reinforced with FRP meshes is significantly effective and provides also a good confinement so that it is adequate for multi-leaf masonries too. The intervention may be applied to masonries in which the plaster may be sustituted.

The strengthening technique based on the application of thin stainless steel strips provides a good confinement to the masonry as well as a increases considerably the ductility under shear stresses. It is applicable only in cases where the plaster may be substituted. Finally the strenthening technique named “reticolatus” consists in two nets made with stainless steel strands applied on both surfaces of the masonry and connected one another with connectors passing through the masonry. Such a system increases both the shear resistance and the ductility of the wall. Provided that the strands are located in the mortar joints, the intervention may be completely hidden with the repointing.

The techniques that confine the masonry are effective also for out-of-plane flexure. In this case not enough experimental investigations have been carried out and so further research is needed.

6 References

[1] Binda L., Saisi A., Tiraboschi C., 2000 *Investigation procedures for the diagnosis of historic masonries,* Construction and Building Materials, Vol. 14, 199-233.

[2] Uomoto T., 2000, *Non-Destructive Testing in Civil Engineering, Elsevier Science, ISBN-10: 0080437176*.

[3] ICOMOS, 1964, *International Charters for the Conservation and Restoration of Monuments and Sites.* II International Congress of Architects and Technicians of Historic Monuments, The Venice Charter.

[4] ICOMOS, 2000, *International Conference on Conservation "Krakow 2000": Principles for Conservation and Restoration of Built Heritage, Paris, Charter of Krakow.*

[5] DPCM 12/10/2007, *Direttiva del Presidente del Consiglio dei Ministri per la Valutazione e la riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni,* Gazzetta Ufficiale della Repubblica Italiana n. 24, 29/01/2008.

[6] Dolce M., Nigro D., Ponzo F.C., Marnetto R., 2001. *Strengthening of masonry structures: the CAM System of Active Ties for Masonries*, X Congresso Nazionale "L'Ingegneria Sismica in Italia", Potenza-Matera, 9-13 Sept. 2001.

[7] Borri A., Corradi M., Giannantoni A., Speranzini E., 2009. *Strengthening of historical masonry structures*, Recupero e Conservazione, Ed. De Lettera.

[8] Corradi M., Borri A., Vignoli A., 2008, *Experimental evaluation of in-plane shear behavior of masonry walls retrofitted using conventional and innovative methods*, Journal of the British Masonry Society "Masonry International", Vol. 21, 1, 29-42.

[9] Valluzzi, M. R., Garbin, E., Dalla Benetta, M., Modena, C., *Experimental assessment and modelling of in-plane behaviour of timber floors.* Proceedings SAHC, Bath 2008, *Structural Analysis of Historic Construction* – D'Ayala & Fodde (eds), CRC Press, 2008.

[10] Gattesco, N., Macorini, L., *High reversibility technique for in-plane stiffening of wooden floors*. Proceedings SAHC, Bath 2008, *Structural Analysis of Historic Construction* – D'Ayala & Fodde (eds), CRC Press, 2008.

[11] Gattesco, N., Clemente, I., Macorini, L. & Noè S.: *Experimental investigation on the behaviour of spandrels in ancient masonry buildings*. 14th World Conference on Earthquake Engineering, October 12-17, 2008, Beijing, China.

[12] Valluzzi, M.R.; Tinazzi, D; and Modena, C.: *Shear behaviour of masonry panels strengthened by FRP laminates*, Construction and Building Materials, Elservier, (16), 409-416, 2002.

[13] Triantafillou, T.C.: *Strengthening of masonry structures using epoxy-bonded FRP laminates*, Journal of Composite Construction ASCE, 2(2), 96-104, 1998.

[14] Aiello, M.A.; Micelli, F.; Valente, L.; *Masonry confinement by using composite reinforcement*, Proc. 4th International Conference on Conceptual Approach to Structural Desing, Venice, 2007.

[15] Gattesco, N., Dudine, A., *Effectiveness of a masonry strengthening technique made with a GFRP-mesh reinforced mortar coating*, Proc. 8th International Masonry Conference, Dresden, 2010.

[16] CNR-DT 200/2004, *Istruzioni per la progettazione, l'esecuzione ed il controllo di interventi di consolidamento statico mediante l'utilizzo di compositi fibrorinforzati*, Consiglio Nazionale delle Ricerche, Roma.

[17] D.M. 14/01/2008, Italian Code, *Nuove Norme Tecniche per le Costruzioni*.

[18] Tannos F.E., Saadatmanesh H. (1999), *Durability of AR-glass fiber reinforced plastic bars*, Journal of composites for constructions, 3(1), 12-19;

[19] ASTM C1666/C1666M-08 *Standard Specification for Alkali Resistant (AR) Glass Fiber for GFRC and Fiber Reinforced Concrete and Cement*;

[20] Jurina L., 2010, *Techniche di cerchiatura di colonne in muratura*, Structural, Ed. De Lettera, n. 164, 38-49.

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Other titles:

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2002-present	Member of the Evaluation Board of research projects subjected to grant in Czech Republic, GACR (Grant Agency of the Czech Republic)
2002-present	Member of the Evaluation Board of research projects subjected to grant in Italy, Ministry of Education, University and Research (MIUR)
2002-present	President of the Structural Committee of the Professional Engineer Association of the Province of Udine, Italy.
2000-present	Member of the Technical Consulting Board of the Court of Justice in Udine, Italy.
1994-present	Member of the Inspection Board of the Friuli Venezia Giulia Region for Engineering structures built in seismic zones
1983-present	Member of the Professional Engineer Association of the Province of Udine, Italy,
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Professional career :

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Jul. 1983 – up to now.

Consulting engineer; besides the academic activity various structural designs of concrete and steel buildings, or special constructions, were carried out as self-governing professional engineer.

Jul. 1986 – Oct. 2001.

Assistant Professor; entrusted to research in the field of Structural Engineering and to take lectures and/or exercises in courses belonging to the same field; Department of Civil Engineering, University of Udine, Italy.

Jul. 1986 – Oct. 2001, (except from March 1989 to May 1990).

Laboratory expert supervisor; as Assistant Professor was also entrusted to supervise the development both in equipment and services of the Laboratory for Testing Materials and Structures of the Department of Civil Engineering, University of Udine, Italy.

Jun. 1992 – Jul. 1992.

Visiting Scholar; involved in study and research on steel-concrete composite structures at the University of Warwick, Coventry, UK, invited by Prof. R.P. Johnson.

March 1989 - May 1990.

Visiting Scholar; involved in research on nonlinear analysis of concrete structures at the University of Waterloo, Waterloo, Ontario (Canada), invited by prof. M. Z. Cohn.

May 1989.

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Jul. 1985 - Jun. 1986

Laboratory expert technician; entrusted to start and manage the activity of the Laboratory for Testing Materials and Structures of the Institute of Theoretical and Applied Mechanics. One year contract with the University of Udine, Italy.

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Research associate; Institute of Theoretical and Applied Mechanics of the University of Udine, involved in research on concrete structures under the direction of prof. Giandomenico Toniolo (full professor of Structural Design).

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Research fellow; Institute of Theoretical and Applied Mechanics of the University of Udine – involved in research on the nonlinear behavior of concrete structures under the direction of prof. Giandomenico Toniolo.

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Award; won a one year fellowship offered by the Industrial Association of the Province of Udine; spent in carrying out research at the Institute of Theoretical and Applied Mechanics of the University of Udine.

Research activity :

The research interests of the applicant are in the following fields:

- Theoretical and numerical modeling of structural behavior
- Structural analysis

- Nonlinear analysis of structures (concrete, composite, etc.)
- Fatigue in steel concrete composite bridges
- Time-dependent behavior of concrete structures
- Testing methods in civil engineering
- Monitoring of structures
- Diagnostics of structures.
- Mechanical joints in timber structures.
- Strengthening of ancient wooden floors.
- Rehabilitation techniques for existing masonry structures
- Durability of concrete structures
- Earthquake engineering

The research is normally carried out with the purpose of understanding the local or global structural behavior through specific experimental investigations, which allowed setting up numerical and/or analytical models able to simulate the actual behavior.
Specifically in the research activity the following projects may be evidenced:

1. steel-concrete composite structures: cyclic loads, nonlinear behavior, diagnostics;
2. strengthening and stiffening of wooden floors and masonry walls to improve the resistance of ancient masonry buildings to earthquakes;
3. experimental and numerical investigation on the behavior of mechanical joints in glued laminated timber structures;
4. nonlinear analysis of concrete structures concerning both normal and high performance concrete;
5. effects of creep on the behavior of concrete structures;

Research projects granted by Public Institutions.

The applicant partecipated in the following research projects either as coordinator or as member of the research group.

- “Innovative techniques and numerical models for the design of reinforced and prestressed concrete structures”. Coordinated by Prof. Pier Giorgio Malerba. Project financed by the Italian Ministry of University and Research (MIUR) – 1995.
- “Resisting mechanisms, cracking, damage and corrosion in NSC and HSC structures”. Coordinated by Prof. Pier Giorgio Malerba. Project financed by the Italian Ministry of University and Research (MIUR) – 1996.
- “HSC Benefits on durability behavior of reinforced and prestressed concrete elements made with high strength concrete”. Coordinated by Prof. Pier Giorgio Malerba. Project financed by the Italian Ministry of University and Research (MIUR) – 1997.
- “Providing new didactic tools to teach structural analysis according to the new university schedules”. Coordinated by Prof. Pier Giorgio Malerba. Financed by the Friuli Venezia Giulia Region, Italy – 2000.
- “Durability and reliability analyses on reinforced and prestressed concrete structures with or without damage”. Coordinated by Prof. Pier Giorgio Malerba/Prof. Gaetano Russo. Project financed by the Italian Ministry of University and Research (MIUR) – 2000.
- “Innovative connection techniques for timber members: experimental investigation to define connection characterized by effectiveness even with cyclic loads, easyness to apply and good esthetic aspect”. Coordinated by the applicant. Financed by the Friuli Venezia Giulia Region, the firm Stratex S.p.A., Sutrio, Udine and the enterprise Plus s.r.l., Cassacco, Udine – 2002.
- “Inverse problems in structural diagnostics: general aspects and applications”. Coordinated by Prof. Antonino Morassi. Project financed by the Italian Ministry of University and Research (MIUR) – 2003.

- "Assessment and reduction of the seismic vulnerability of masonry buildings". Coordinated locally by the applicant. National coordinators Proff. Sergio Lagomarsino and Guido Magenes. Financed by the European Community and the National Department of the Civil Protection – 2005-2007 RELUIS.
- "Study of high reversibility techniques for strengthening and stiffening of wooden floors of ancient buildings". Involved five Italian Universities: Bologna, Napoli I, Napoli II, Trento, Trieste. The Unit of Trieste was coordinated by the applicant. Project financed by the Italian Ministry of University and Research (MIUR) – 2006.
- "Analysis of the seismic scenarios concerning the educational buildings aimed to the definition of an intervention priority so to reduce the seismic risk". Structural group coordinated by the applicant. Involved in the project the Universities of Trieste, Udine and the Experimental Geophisic Observatory of Trieste (OGS) – 2008-2010. (ASSESS Project), financed by the Friuli Venezia Giulia Italian Region.
- "Study of new intervention techniques to improve the seismic resistance of the ancient buildings of the Province of Trieste by using innovative materials". Coordinated by Prof. Claudio Amadio. Financed by the Province of Trieste – 2009-2010.
- "Assessment of the seismic vulnerability of masonry buildings, historical centers, cultural heritage". Coordinated locally by the applicant. National coordinators Proff. Sergio Lagomarsino, Claudio Modena and Guido Magenes. Financed by the European Community and the National Department of the Civil Protection – 2010-2012 RELUIS.
- "Innovation in codes and technology concerning seismic engineering. Timber structures.". Coordinated locally by the applicant. National coordinator Prof. Paolo Zanon. Financed by the European Community and the National Department of the Civil Protection – 2010-2012 RELUIS.

Requests of financing research projects proposals to Public Institutions in progress.

The financing of the following project proposals were requested to public institutions:

- "Study of innovative solutions for shear walls of sustainable timber constructions. Experimental investigations and numerical simulations". Involves six Italian Universities: Brescia, Napoli, Sassari, Trento, Trieste, Udine. The project leader for the Unit of Trieste is the Applicant. Grant requested to the Italian Ministry of University and Research (MIUR) – 2010.
- "Compatible Materials and Techniques for Protecting Historical Masonry Bridges MATEMA". Seventh Framework Program Proposal by five Universities (Imperial College London UK, CTU Prague CZ, Salerno IT, Trieste IT, Bremen D), two research centers (ZAG Ljubliana SLO, EMPA Zurich CH), six enterprises (FibreNet Udine IT, Maurer Soehne Engineering D, Boviar S.r.l. IT, SM7 a.s. CZ, S&P Clever Reinforcement CH, MaterialTeknic am bau CH). The project leader for the Unit of Trieste is the Applicant. (November 2010).

International cooperations

- Prof. Miha Z. Cohn, University of Waterloo, Ontario, Canada. Cooperation in research on the moment redistribution on reinforced concrete frames. 15 months visiting professor at the University of Waterloo (1989-1990).
- Prof. R.P. Johnson, University of Warwick, Coventry, UK. Cooperation in research on the cyclic behavior of steel-concrete composite structures. Two months visisting scholar at the University of Warwick (1992).
- Prof. Miha Tomazevic, ZAG Ljubljana, SLO. Member of the Lecturers Board of the Master Program in Earthquake Engineering of the University of Trieste.

- Prof. Miha Tomazevic and Dr. Marjana Lutman, ZAG Ljubljana, SLO. Cooperation in a pending across border Italy-Slovenia research project dealing with the development of new strategies to assess the structural vulnerability of ancient masonry buildings located in seismic prone areas.
- Prof. Vladimir Kristek, Prof. Alena Kohoutkova, Dr. Lukas Vrablik, Czech Technical University of Prague, CZ. Cooperation in a pending FP7 EU Research Project proposal dealing with “Compatible Materials and Techniques for Protecting Historical Masonry Bridges – MATEMA”. In 2007 it was signed a research agreement between the Department of Concrete and Masonry Structures of the CTU Prague and the Department of Civil and Environmental Engineering of the University of Trieste. Moreover, Prof. Kristek was invited to take short courses and seminars at the Faculty of Engineering at the University of Trieste.
- Prof. Bassam Izzuddin, Dr. Macorini, Imperial College London, UK. Cooperation in a pending FP7 EU Research Project proposal dealing with “Compatible Materials and Techniques for Protecting Historical Masonry Bridges – MATEMA”.
- Prof. Lucio Colombi Ciacchi, University of Bremen, D. Cooperation in a pending FP7 EU Research Project proposal dealing with “Compatible Materials and Techniques for Protecting Historical Masonry Bridges – MATEMA”.

Industrial partners supporting research projects

- Stratex S.p.a., via Peschiera, 3/5, Sutrio, Udine, Italy – Industry of Glued Laminated Timber Structures – Financed various research projects aimed to study the behavior of joints in timber structures. (Research projects 2002-2004, 2010-2011 financed by Stratex and the Region Friuli Venezia-Giulia).
- Euroholz s.r.l., via Divisione Julia, Villa Santina, Udine, Italy – Industry of Glued Laminated Timber Structures – Financed various research projects aimed to study the behavior of joints in timber structures.
- Plus S.r.l., viale Udine, 8, Cassacco, Udine, Italy. – Building enterprise of timber dwellings – (Research project 2002-2004 financed by Plus and the Region Friuli Venezia-Giulia aimed to study the behavior of wooden panels when subjected to shear).
- Cimolai Costruzioni Metalliche, viale Venezia, Pordenone, Italy – Industry of Steel Structures – Partly financed research on steel-concrete shear connection.
- Precast S.p.a., via Martiri della Libertà, 12, Sedegliano, Udine. – Agreement for a study concerning the non-destructive testing techniques for concrete structures (2006).
- Spav Prefabbricati S.p.a., via Spilimbergo, 231, Martignacco, Udine, Italy – Industry of Prefabricated Concrete Structures – Financed a research project on the study of multistorey buildings subjected to earthquake (2006-2008).
- Fibre Net s.r.l., via Zanussi, 311, Udine, Italy – Industry of Glass Fibre Polymeric Products – Financed a research project aimed to study the effectiveness of a strengthening technique for existing masonry walls by using GFRP meshes (2008 – in progress).
- MEP S.p.a., via Leonardo Da Vinci, 20, Reana del Roiale, Udine, Italy – Industry producing electronic wire bending machines – It is in progress an agreement for studying an adequate shape for stirrups in reinforced concrete elements that can optimize the time of production and installation.

Consulting activity, technical or architectural realizations

Some of the most interesting studies or projects are in the following summarized:

- City-hall of Mortegliano, Udine (Italy), 5000 m^3, building made with reinforced concrete, steel and glue-laminated timber. Architectural plan, structural project and in field supervision (1987).

- Polycentric reinforced concrete gallery (~2000 m, highway Valcellina, Pordenone, Italy), Edil-Strade S.p.A., Castrocaro Terme, Forlì (Italy). Structural analysis (1988).
- Industrial buildings (~10000 m^3), firm Bozzi Meccanica S.p.A., via D'Orment, Buttrio, Udine (Italy). Diagnostics and rehabilitation design of concrete structures damaged by steel corrosion because of concrete carbonation (1993).
- Industrial building in structural steel (~10000 m^3), chair firm TOP SEDIA S.p.A., Manzano, Udine (Italy). Structural analysis and design (1995).
- Cylindrical steel silos for cement (36 m^3) sustained by 4 columns, O.R.U. Officine Riunite Udine S.p.A. Structural analysis and design optimization (1996).
- Polycentric gallery (approx. 3.0 m diameter) made with corrugated steel sheet to be used in quarries of crushed stones, OREB Sistemi Industriali S.r.l., Udine. Structural analysis and design optimization (1997).
- Steel industrial plant to produce precast concrete elements in Seoul (South Corea), O.R.U. Officine Riunite Udine S.p.A. Consulting on the design of structures using Eurocodes 3 and 8 (1997).
- Square steel silos for aggregates (850 m^3) made with rib stiffened plate elements and sustained by a lattice structure, close to Santiago (Cile), O.R.U. Officine Riunite Udine S.p.A. Stress analysis, considering the whorst loading conditions including seismic actions, and design optimization (1998).
- Exhibition pavilions (60x96 m each) of the New Rimini Fair, EuroHolz S.r.l., Villa Santina, Udine (Italy). Consulting on the structural modeling of the roof (grid timber vault) with concern to global and local stability (2000).
- Ancient water-mill with masonry structure, wooden floors and timber roof (~3000 m^3) (considered by the Monuments and Fine Arts Service, Udine), Molaro Iginio, Mereto di Tomba, Udine. Mechanical study for seismic strengthening using low invasive and high reversible techniques (2002).
- Building for the offices of Friuli Venezia Giulia Region in Udine, concrete and steel structures (~70000 m^3). Structural inspector (2005-2007).
- Ancient residential building with masonry walls and wooden floors (~15000 m^3), condominio "Lazzaretto Vecchio 10", Trieste. Steel strenthening system to allow removal of some internal walls. Structural design and in field supervision (2005-2007).
- Concrete residential building (~70000 m^3), condominio "Messaggerie", via Marangoni, Udine. Consulting for diagnostics and rehabilitation design of concrete structures damaged by steel corrosion because of concrete carbonation (2006).
- Concrete bell tower (113 m tall), Mortegliano. Consulting for diagnostics and rehabilitation design of concrete structures damaged by steel corrosion because of concrete carbonation (2007).
- Primary school building (~7000 m^3), Mortegliano, Udine. Assessment of structural safety (2010).
- Building of the airport of Trieste. Consulting on the assessment of structural safety (2010).
- Industrial building in structural steel (~28000 m^3), firm CAMILOT Erminio S.a.s., Ronchis, Udine (Italy). Structural analysis and design (2010).
- **Five** technical advices to the Court of Justice of Udine concerning structural malfunction of buildings (since 2000).
- **Six** expert opinions concerning structural problems of various masonry or concrete buildings involved in justice proceedings (since 1999).
- Member of the International Technical Commission entrusted to study adequate structural rehabilitation techniques for Charles Bridge in Prague (since 2010).

Publications

11 papers in International Journal with “Impact Factor”, 4 papers in International Journal with “review board”, 10 papers in Italian Journals or scientific series with “review board”, 1 book, 9 parts of books, 27 papers in the proceedings of International Conferences, 38 papers in the proceedings of Italian Conferences, 10 scientific reports, 17 reports of specialistic courses, 11 reports to technical studies, 9 reports of seminars. 103 international citations of main papers, h-index 4.

Selected publications

1. GATTESCO N., "Analytical Modeling of the Nonlinear Behavior of Composite Beams with Deformable Connection", Journal of Constructional Steel Research, Vol. 52, No. 2, Nov. 1999, pp. 195-218.
2. GATTESCO N., BERNARDI D., "Influence of Reinforcement Stresses on the Durability of HPC Members Subjected to Marine Environments", Journal iiC – L’Industria Italiana del Cemento, n. 788, Jun. 2003, pp. 512-521.
3. GATTESCO N., GIURIANI E., “A Test Proposal for Fatigue Experimental Studies on Stud Shear Connectors”, Proc. of the Symposium on Connections between Steel and Concrete, 9-12 Sept. 2001, Stuttgart, Germany.
4. GATTESCO N., TOFFOLO I., “Experimental Study on Multiple-Bolt Tension Joints”, Materials and Structures, RILEM, Vol. 37, n. 266, 2004, pp. 129-138.
5. GATTESCO N., PITACCO I., “Analysis of the Cyclic Behavior of Shear Connections in Steel-Concrete Composite Bridge Beams due to Moving Loads”, Proc. Of the 2nd International Conference on Steel and Composite Structures, ICSCS’04, 2-4 Sept. 2004, Seoul, Korea.
6. GATTESCO N., GUBANA A., “Performance of glued-in joints of timber members”, 9th World Conference on Timber Engineering, WCTE 2006, August 6-10, 2006, Portland, Oregon, USA.
7. GATTESCO N., “Experimental study on the structural efficiency of L-shaped p.c. beams in multi-storey prefabricated buildings”, European Journal of Environmental and Civil Engineering, Vol. 13/6, June 2009, Cachan Cedex, France.
8. GATTESCO N., MACORINI L., “Novel Engineering Techniques to Improve the In-plane Stiffness of Wooden Floors”, Proc. Int. Conf. on Protection of Historical Buildings, Prohitech 09, 21-24 June 2009, Rome, Italy.
9. GATTESCO N., MACORINI L., FRAGIACOMO M., “Moment Redistribution in Continuous Steel-Concrete Composite Beams with Compact Cross Section”, Journal of Structural Engineering, ASCE, Vol. 136, No. 2, Feb. 2010, pp. 193-202.
10. GATTESCO N., MACORINI L., CLEMENTE I., NOE’ S., “Shear resistance of spandrels in brick-masonry buildings”, Proc. 8th Int. Masonry Conference, 04-07 July 2010, Dresden, Germany.