PROBLEMS OF EXISTING MASONRY BUILDINGS AND COLLECTION OF STRENGHTENING TECHNIQUES AVAILABLE WITH DESCRIPTION OF THE APPLICATION

TECHNICAL REPORT

DEFINITION OF ADVANTAGES AND DISADVANTAGES OF TRADITIONAL AND MODERN STRENGTHENING TECHNIQUES, IN TERMS OF PERFORMANCE AND EXECUTION

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1 The CONSTRAIN Project

CONSTRAIN in an acronym of the original title “Research and dissemination of innovative strategies for seismic protection of masonry structures” (in Italian: CONdivisione e applicazione di STRAategie INnovative per la protezione sismica di edifici in muratura). It is an Interreg European project of Slovenia and Italy. The project has six partners, three from Italy and three from Slovenia: University of Trieste (leading partner), Fibre Net s.p.a., Veneziani Restauri Construzioni srl, University of Ljubljana, IGMAT d.d., and Kolektor CPG d.o.o.

The objective of the CONSTRAIN project are the definition, sharing and application of innovative strategies for seismic protection of existing masonry buildings. Most of the project involves cross-border cooperation and dissemination of results in the Program area and beyond.

The project is based on the synergy of skills in the field of production (of 4 private companies) and research (2 research institutions) to promote innovation in the field of interventions for structural strengthening, and to spread the acquired knowledge, experience and know-how quickly into practice. Fast transfer into practice will increase competitiveness of the construction sector.

The Program area for the project includes 5 Italian provinces (Trieste, Udine, Pordenone, Gorizia and Venice) and 5 Slovenian statistical regions (Primorsko-notranjska, Osrednjeslovenska, Gorenjska, Obalno-kraška and Goriška) as shown in Fig. 1.

More information about the project can be found at the project web page:

URL: *https://www.ita-slo.eu/it/constrain*

Fig. 1: The Program area[1].

[1] https://www.ita-slo.eu/it/programma/area-programma

2 Seismic hazard and buildings in the Program area

Based on the 2013 Euro-Mediterranean Seismic Hazard Model (ESHM13)[2], seismic hazard in the Program area is moderate to high (Fig. 2). The memory of many recent earthquakes in the broader region is still present in people's minds. The 1976 Friuli earthquake especially caused massive damages on both sides of the border.

One reason for high risk and a lot of earthquake damage is the high proportion of (old) masonry buildings in the building stock. The safety of people, structures and its contents during earthquakes is thus a serious concern of general public and government officials in the Program area.

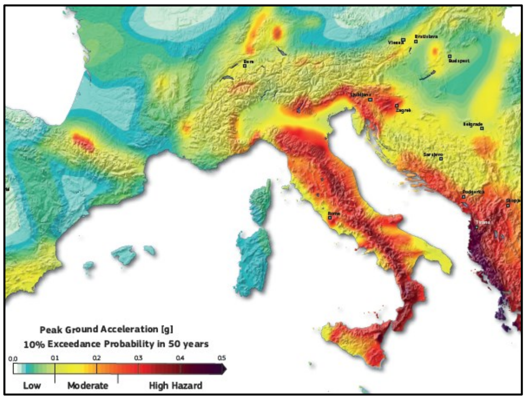


Fig. 2: ESHM13 seismic hazard map.

Building registries show that about 57% of the residential buildings in the 5 Italian provinces and about 50% in the 5 Slovenian statistical regions included in the Program area are made of masonry. Most of them (about 70%) were built before the 1980s.

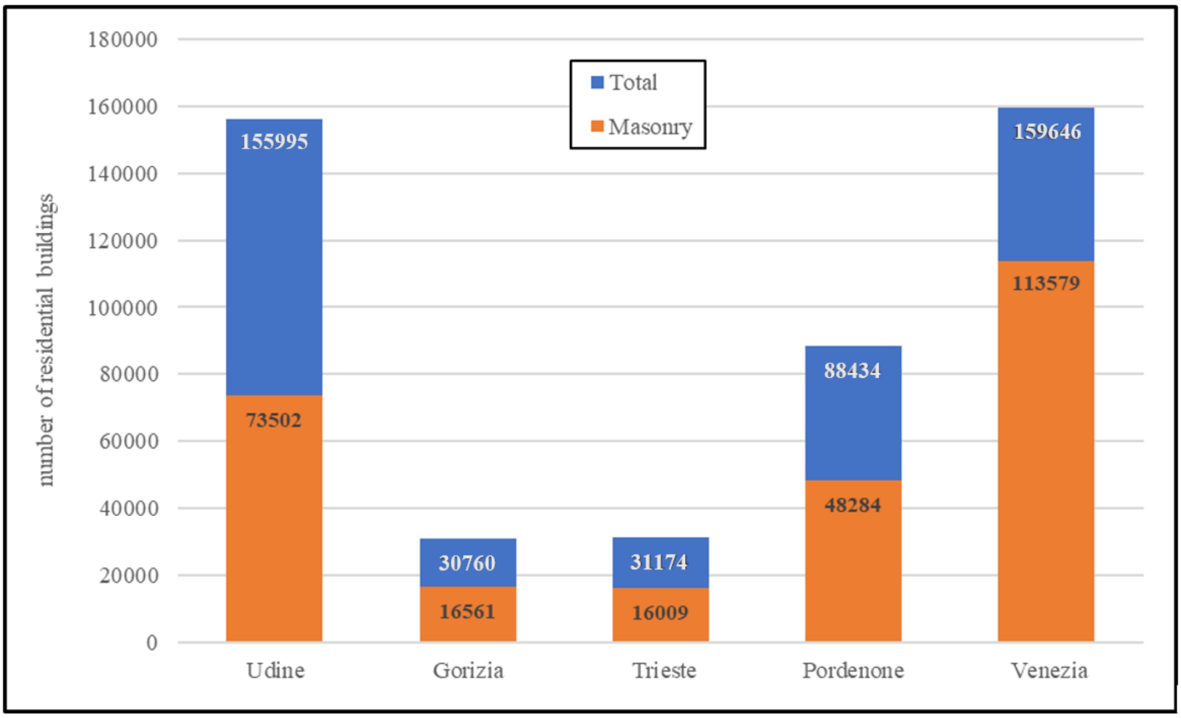


Fig. 3: Number of old masonry residential/total buildings in Italian provinces (ISTAT).

[2] http://www.efehr.org/en/Documentation/specific-hazard-models/europe/overview (Consulted in: 14.10.2021)

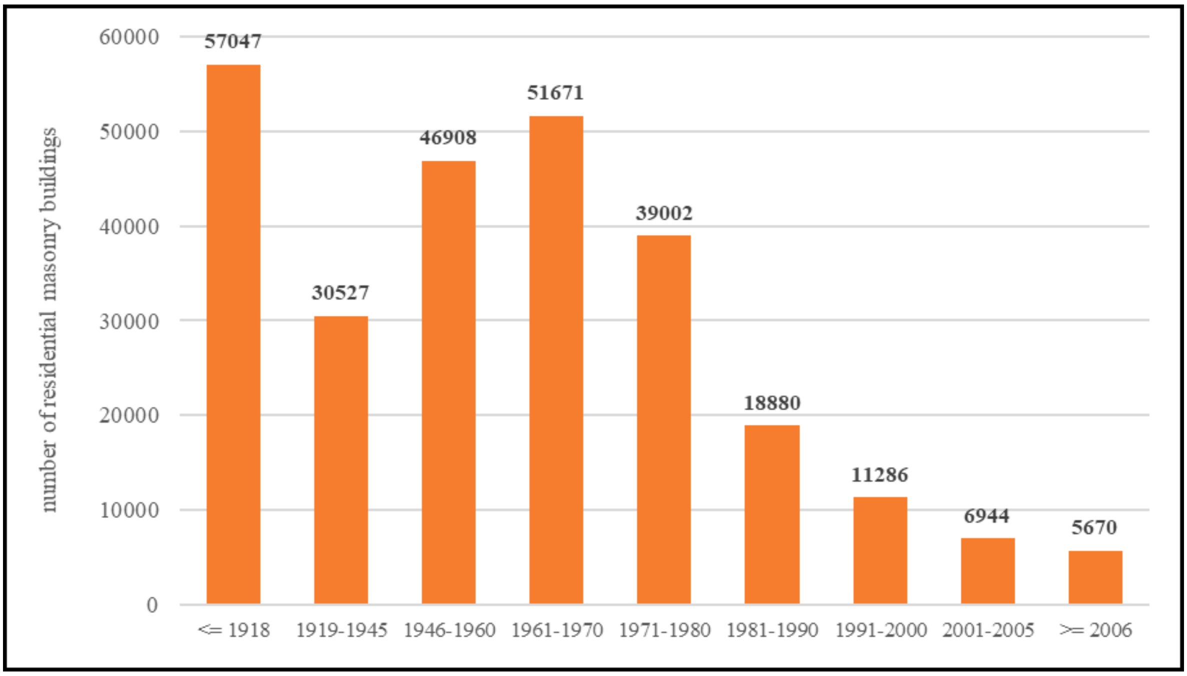


Fig. 4: Number of residential masonry buildings in Trieste, Udine, Pordenone, Gorizia and Venice (ISTAT).

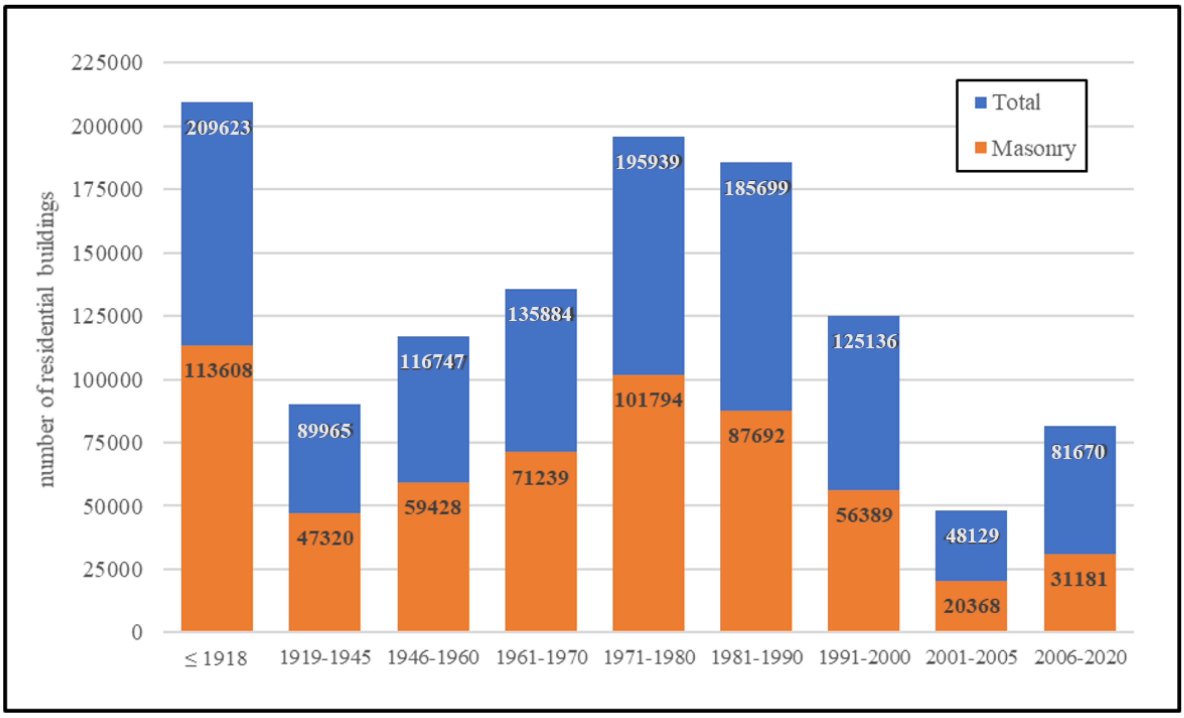


Fig. 5: Residential buildings in Slovenia by age and type (GURS).

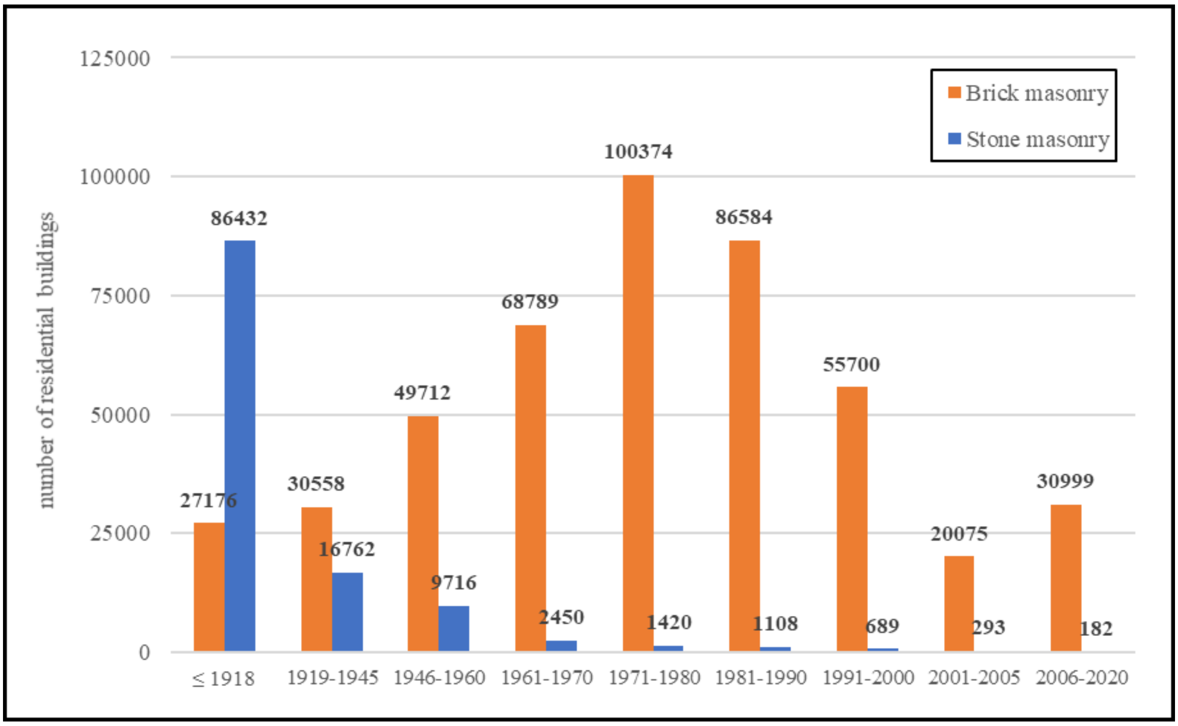


Fig. 6: Residential buildings in Slovenia by age and masonry type (GURS).

As the graphs above show, the majority of the existing masonry buildings in the Program area are made with un-reinforced solid bricks or stone masonry, and most of them were built before any engineering methods of design were developed. In the past there was also no or very poor knowledge of earthquakes and seismic effects on structures. In Slovenia, for example, the first seismic codes were introduced in 1963. In addition to lack of design methods, seismic loads were also very poorly understood in the early days of seismic design. An analysis of seismic forces in different codes through time (Fajfar, 2017) shows that these loads have increased substantially from the first codes until the Eurocodes we use today. Additionally, the strength and quality of used materials in the past was often quite poor. Old masonry structures are thus very likely to have insufficient resistance to earthquakes of expected (which is used in design) intensity. This requires that some form of strengthening of old masonry structures is usually necessary.

In many cases, old buildings need repair and strengthening for reasons other than improving seismic resistance. Such reasons are deterioration of materials, damage caused by the settlement of foundations or accidents. Interventions are often required also when existing buildings are modernised with different functional requirements such as larger windows and new doors. This is especially the case for old structures in city centres where old buildings are often protected as heritage.

Old masonry is a material with many variations and local characteristics. Nevertheless, three main categories of masonry can be defined that are typical in the Program area (Fig. 7):

- Stone masonry buildings, both rubblestone and cobblestones (typical in traditional buildings of mountain/karst or river areas), with typical thickness 400-450 mm (+100÷150 mm every 2 storeys). In most cases, stone walls are multiple-wythe walls (two or more partially connected or not at all connected wythes);
- Solid brick masonry buildings (typical in traditional buildings of plain and coastal areas), with typical thickness 250-380 mm (+120 mm every 2 storeys). Sometimes, such walls are made with double wythes, which are adjacent but not connected or with a cavity in between;
- Hollow brick masonry buildings (age of construction mainly after 1950), with typical thickness 250-380 mm (+120 mm every 2 storeys). For this type also, there are single and double-wythe walls with a cavity between wythes.

(a) (b) (c)

Fig. 7: Masonry typologies in the Program area: stone (a), solid bricks (b) and hollow bricks (c).

3 Typical deficiencies in existing masonry structures

As mentioned in the previous section, the response of existing (old, non-engineered) masonry structures to earthquakes can be insufficient. However, even after strong earthquakes some constructions remain undamaged. Studying post-earthquake damage has shown that there are several typical deficiencies, which lead to poor performance:

- Inadequate connection between structural elements and lack of box-like structural behaviour;
- Inadequate structural layout of walls (in floor plan and in elevation);
- Inadequate strength of masonry;
- Foundation/soil related problems.

Old buildings in which the *connections between structural elements are not strong* enough do not respond well to seismic loads and tend to lose integrity during earthquakes – cracks develop at connections and the building separates into several individual elements, each of which have to resist earthquake loads on its own. In this case, the resistance depends on the weakest element and failure occurs when the weakest element fails. This can happen very soon, at quite low earthquake intensity. In contrast, if the connections between elements are good, all walls work together in resisting earthquake loads. The behaviour of the structure in the latter case, in which all elements are well connected, is sometimes called box-like behaviour. Such buildings can resist much higher earthquake intensities.

This concept is illustrated in Fig. 8. In the left image (Fig. 8a), the connection between walls is poor. This causes the left wall to separate from the rest of the structure and collapse for out-of-plane overturning. The floor structures in this case are also weak (i.e. not stiff enough) and can't support the walls in out-of-plane direction.

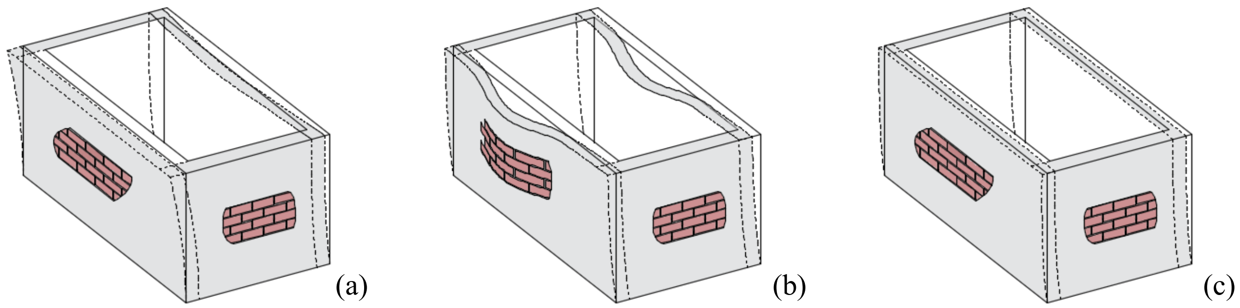


Fig. 8: Response of structures with different strength of connections: a) poor connection between walls and weak floor structure, b) proper connection between walls but weak floor structure and c) proper connection between walls and strong floor structure.

The case when connections between walls are strong, but the floor structure is too flexible is shown in Fig. 8b. Such case is problematic for two reasons: firstly, the floors do not provide sufficient support to the walls in the out-of-plane direction, then, the flexible floor is not able to distribute seismic forces among shear walls. Due to these problems, some walls can be overloaded and fail too early. This can potentially lead to cascading failures of other walls as well.

Finally, Fig. 8c shows a proper box-like behaviour of a structure. The connections between walls and between floor structures are strong enough so that the integrity of the structure is not jeopardized. The seismic excitation is faced by all the elements of the structure.

Ensuring proper connections between elements is the first priority when planning a strengthening intervention to improve seismic behaviour of old masonry constructions.

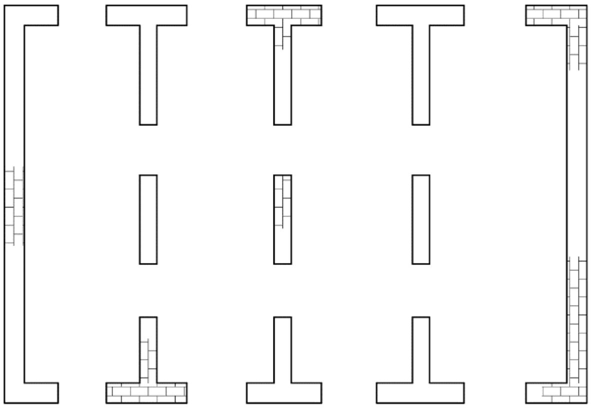
Typically damage due to loss of integrity of structures leads to complete collapse. The buildings in Fig. 9 show typical severe damages, which lead to loss of integrity of the structure.


(a)

(b)

Fig. 9: Loss of structural integrity: a) separation of perimeter walls (Montenegro, 1979), b) insufficient connection to floor structures (Borgo, 2016).

Buildings with *inadequate structural layout* perform poorly during earthquakes and are at high risk of damage or collapse. Typical for such buildings are uneven distribution of resisting elements in both perpendicular directions, and/or in elevation. Poor distribution of walls in plan is schematically shown in Fig. 10. Such structure is reasonably strong in vertical direction, but very weak in horizontal direction. Such deficiencies are usually reduced by adding load-bearing walls in horizontal (weaker) direction.


(a)

(b)

Fig. 10: a) uneven distribution of resisting elements in perpendicular directions, b) Collapse in one direction (Neftgork, Russia 1995)

Irregularity in elevation in masonry buildings most often arises from large openings at the ground floor. Usually, these openings were originally smaller and at a later time were enlarged when business requested to exhibit products (shop window). The result is a structure characterized with a soft storey, a concept known to perform very poorly during earthquakes. The capacity of a building with a soft storey to dissipate seismic energy is much more reduced and such structures can fail catastrophically (Fig. 11).

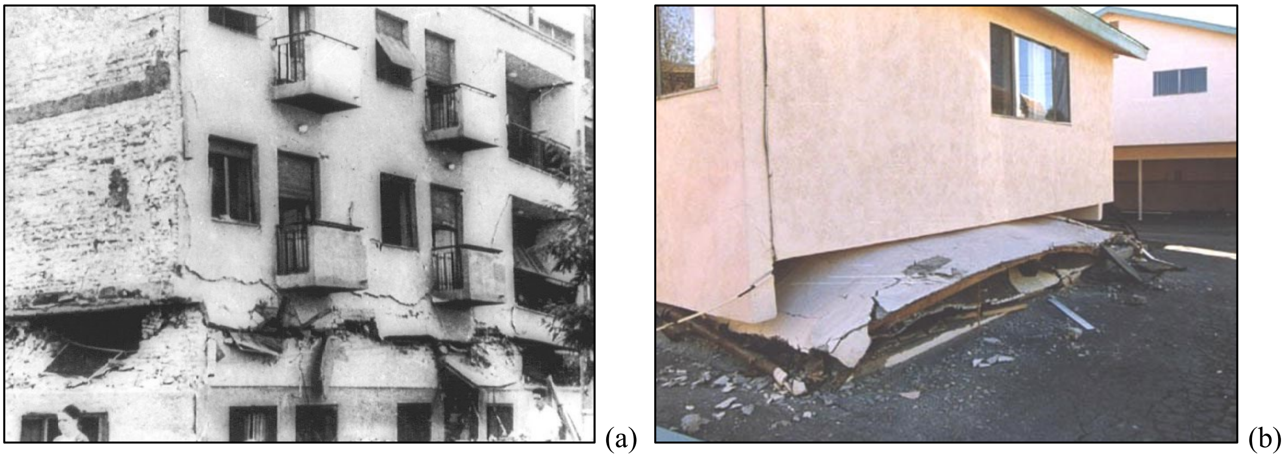


Fig. 11: Failure of soft storey: a) (Skopje,1963), b) (Neftgork, 1994)[3].

If the vertical structure is properly connected with ties and floors, the building can still fail if the *masonry has insufficient strength*. Unreinforced stone or brick masonry is a composite material with relatively high compressive strength, relatively low shear strength and negligible tensile resistance. This characterizes the behaviour of masonry, which is good for resisting gravity loads, but vulnerable to both in-plane and out-of-plane horizontal loads. Due to its mass, the masonry is quite resilient to wind loads.

The in-plane failure mechanism of old masonry is usually one of the following three: diagonal cracking, sliding shear failure and compression-bending failure (Fig. 12).

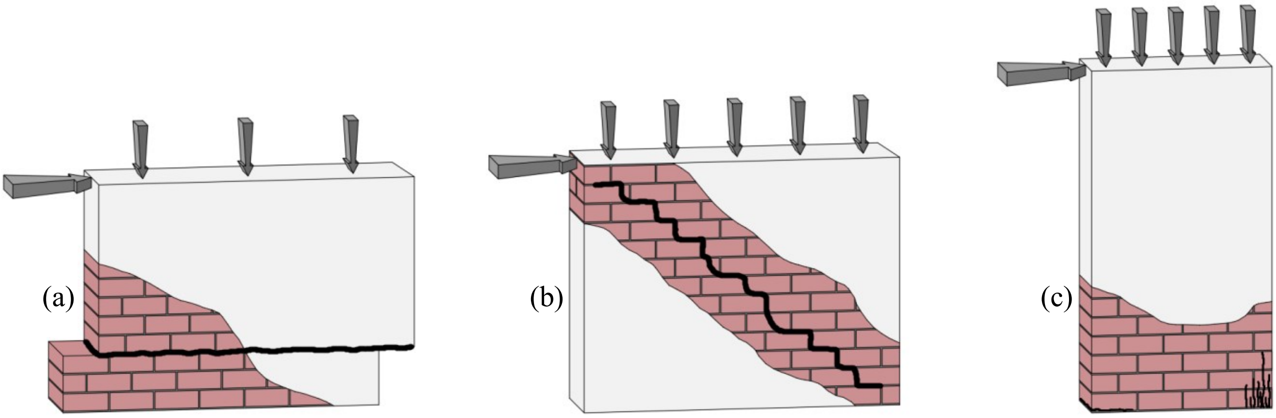


Fig. 12: Failure mechanism of masonry.

The above-mentioned failure mechanisms for ancient masonry are well established and confirmed by post-earthquake damage observations. For newer types of masonry, literature sometimes mentions rocking as the fourth failure mechanism, but this is a response not failure mechanism, because the ultimate failure is normally bending failure with toe-crushing. In old masonry found in the Program area, diagonal shear failure is the most common failure mechanism observed after earthquakes. Typical diagonal cracking damage is shown in Fig. 13 and Fig. 14.

The strength of masonry can be increased by applying different types of reinforced coatings. There are many possibilities, which are discussed in detail afterwards.

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[3] https://www.ladbs.org/services/core-services/plan-check-permit/plan-check-permit-special-assistance/mandatory-retrofit-programs/soft-story-retrofit-program (Consulted in: 15.10.2021)

Fig. 13: Diagonal shear damage (Umbria, 1997)

Fig. 14: Typical diagonal shear damage in piers of ground storey (Budva, 1997)

Walls made up of several unconnected wythes can often be found in historical buildings of the Program area. The damage mechanisms of such walls are characterised by the detachment or separation of wythes (Fig. 15 and Fig. 16) and such walls perform poorly to in-plane and out-of-plane loads.

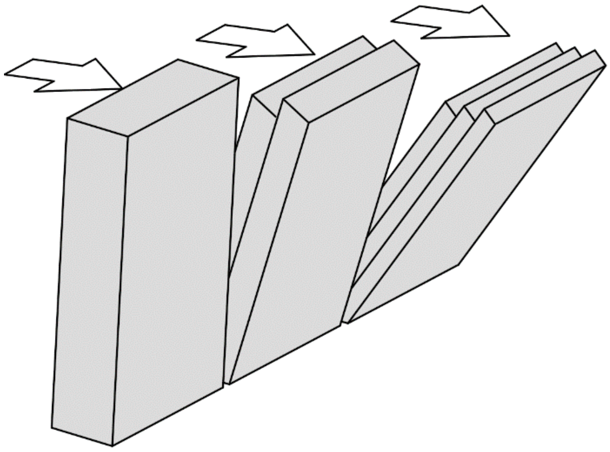


Fig. 15: Out-of-plane behaviour of a single-leaf wall and a multi-wythe wall

Fig. 16. Out-of-plane failure of a two-wythe wall (Borgo, 2016).

To obtain a monolithic behaviour, one must improve the transversal connection between wythes. This can be done by adding ties between wythes (so called artificial diatones) and/or by grout injections into the cavities between the wythes of stone walls.

Finally, even if the masonry building has structural integrity and proper distribution of strong walls, *the ground under the building can still fail*. The building in Fig. 17 sank about a meter into the soil that liquefied due to the dynamic excitation, because of its properties. That could happen also in case of landslides (as shown in Fig. 18). There are many vulnerabilities to consider.

Fig. 17: Building sank 1m into liquefied soil.

Fig. 18: Buildings cannot resist landslides (Arquata, 2016).

4 Guidelines for planning structural strengthening

Once an examination and/or numerical calculations have shown that a building requires strengthening, a proper plan of strengthening should be prepared. Such a plan addresses all of the typical deficiencies listed in the previous section. The intervention measures can be classified into four categories:

a) Measures for tying the walls, and for anchoring and stiffening the floors (improving structural integrity);
b) Measures for balancing the structural layout by lowering the distance between the in-plane centre of mass and the centre of rigidity of the building (improving regularity and structural layout of the structure);
c) Measures for strengthening masonry walls;
d) Measures for repairing/strengthening of foundations.

4.1 Improving structural integrity

If the considered building does not have ties connecting all walls at the level of floor structures, the providing of ties *should be the first step of any strengthening intervention*. It is relatively easy to find out if ties exist in a building or not. The anchors of wall ties are frequently visible on the façade (Fig. 19a), otherwise they can be located by metal a detector or a geo-radar (Fig. 19b).

Fig. 19: Anchors of steel ties on the façade (a), iron tie from XVII century house in Ljubljana (from Tomaževič, 2009) (b).

The other measure to improve structural integrity is stiffening of the floors. This can be achieved by replacing the wooden floor with a RC one, but this is just one possibility. In practice, there are many ways to strengthen wooden floors without replacing them. When stiffening the floors, it is very important to install anchors which tie the walls and the floors together.

4.2 Improving layout *of structural walls*

Measures for improving structural layouts usually consist of adding new walls. For large structures, the new walls are often RC walls with new foundations (Fig. 20). It is also possible to add new walls or close some openings in existing walls. The aim of these interventions is to achieve a similar amount of masonry (walls) in both perpendicular directions, and to have a layout of walls in which the centre of mass and centre of rigidity (in a floor) are as close as possible.

Fig. 20: Adding walls to an existing structure[4].

4.3 *Strengthening of masonry*

Knowing and classifying the quality of masonry of an existing building is one of the most important aspects of understanding its mechanical behaviour and seismic response.

Unlike reinforced concrete structures, in which the mechanical properties of the material have little variability, in masonry structures variations may be considerable. The variations can be in shape and dimensions of the load bearing masonry walls, the mechanical properties of mortar, the wythe connections, the vertical and horizontal joint characteristics, the type of texture and many others.

Another important aspect is the variety of construction techniques that have been developed and used in different geographical areas over the history. Each one has different performance and critical aspects, making it impossible to standardize the strengthening without a study of each individual case.

When choosing strengthening materials and technology, it is important to have experimental verification of the chosen strengthening system. The latter must be effective, simple and economically feasible. In the case of historical buildings, it must also fulfil the basic requirements of restoration and conservation of cultural monuments.

Experimental tests show that the strengthening of masonry can be very effective, but also that inappropriate strengthening does not improve seismic performance at all. The correct choice is therefore very important and can only be based on previous experiments and verifications.

[4] https://db.world-housing.net/static/data/100050/100271_017_08.jpg (Consulted in: 15.10.2021).

4.4 Strengthening of foundations

Post-earthquake inspections show that previously damaged foundations are rarely the main cause for earthquake damage and collapse. Nevertheless, old masonry structures often lack proper foundations, but have degraded foundation due to old age or have previous damage from (uneven) settlements. These foundations have to be strengthened or repaired to prevent damage progress. Strengthening by additional RC elements (Fig. 21) is very important for improving integrity of the structure and box-like behaviour.

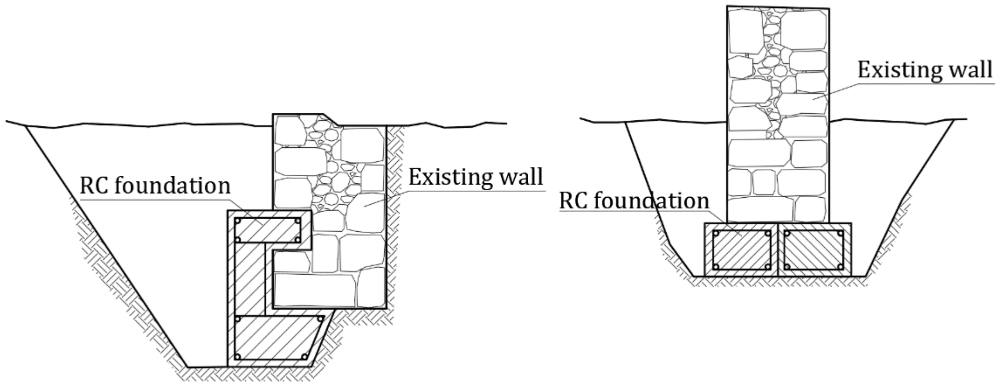


Fig. 21: Strengthening foundations by adding reinforced concrete (from Tomaževič, 2009).

5 Improving structural integrity of existing masonry constructions

5.1 *Tying walls*

The application procedure is detailed in APPENIDX A.

5.1.1 *Traditional horizontal steel ties*

The traditional approach of tying walls together is to use steel ties and to anchor them using steel plates (Fig. 22). Ties are usually provided for each wall and are usually installed in specially cut grooves. The location of the ties in height is as close as possible to the floors. In practice this is usually just beneath the floors. The diameter of the steel ties is normally 16-20 mm, but is determined by calculation (a tie must be at least as strong as the wall it ties). Ties are installed for all walls (perimeter and inner walls), as it can be clearly seen in Fig. 23. The ties are usually lightly prestressed by tightening the nuts with a wrench. This very effective technique is in use in Slovenia since late 70s.

Fig. 22: Ties and steel anchor plates at the corner.

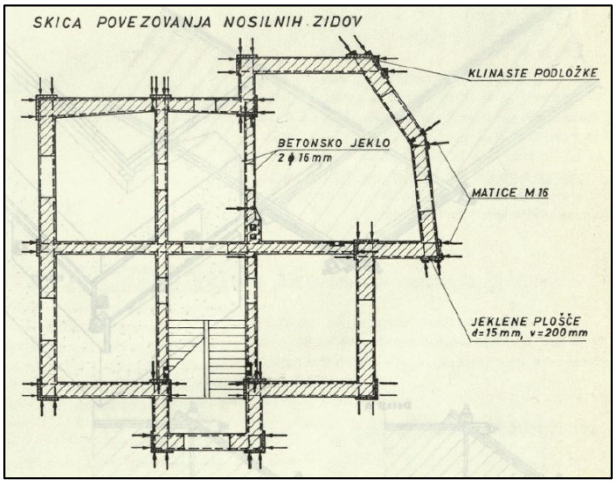


Fig. 23: Placement of steel ties (Vugrinec, 1977)

Normally, two ties per wall are placed symmetrically (Fig. 23) and these types of applications are recommended. For small buildings and thin walls only one tie per wall may be sufficient. Such a tie should be placed at the side of the wall and not through the center of the multi-wythe wall.

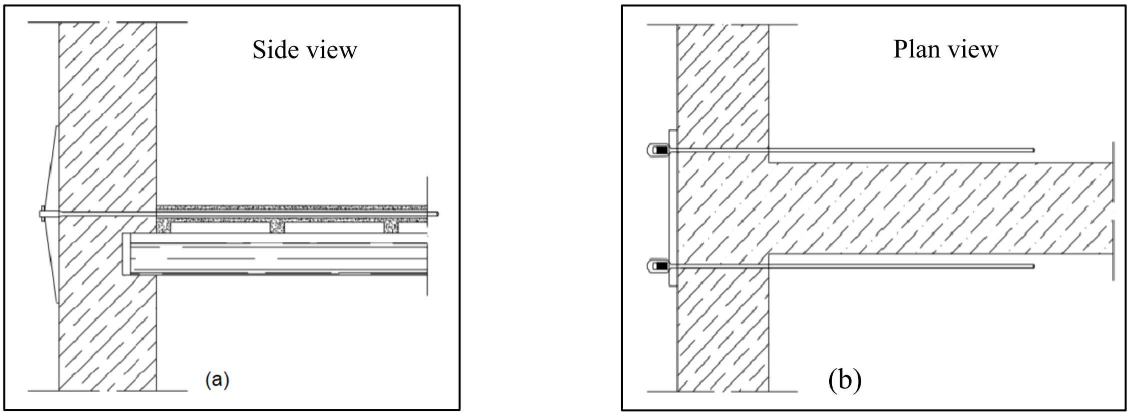


Fig. 24: Side view of a steel tie above timber joists (they are more often installed under joists) (a), and plan view of tie rods of an inner wall (b) (ReLUIS 2011)

The ties can also be prestressed by post tensioning to prevent (or delay) cracking during earthquake and to prevent rocking response in spandrels (see Fig. 25). Although, too much prestressing can have negative effects, especially in the case of multi-wythe walls and walls with poor mechanical properties.

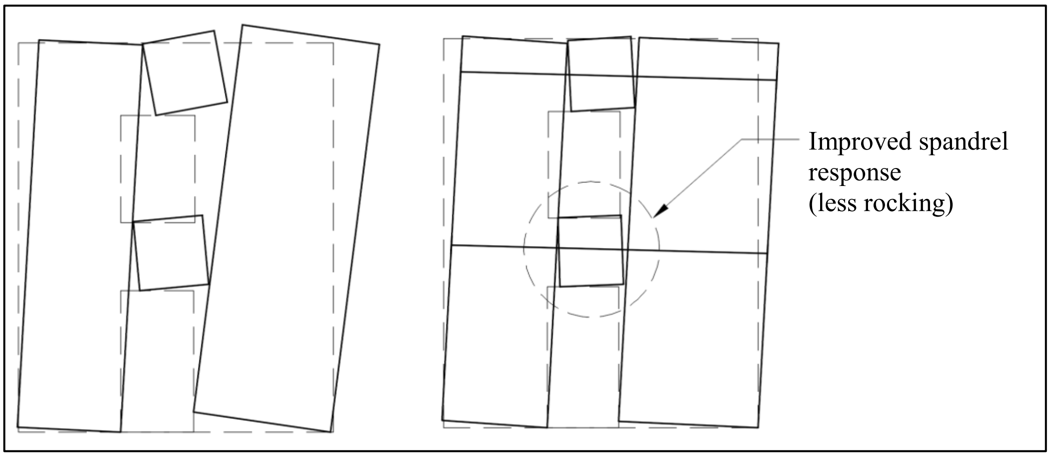


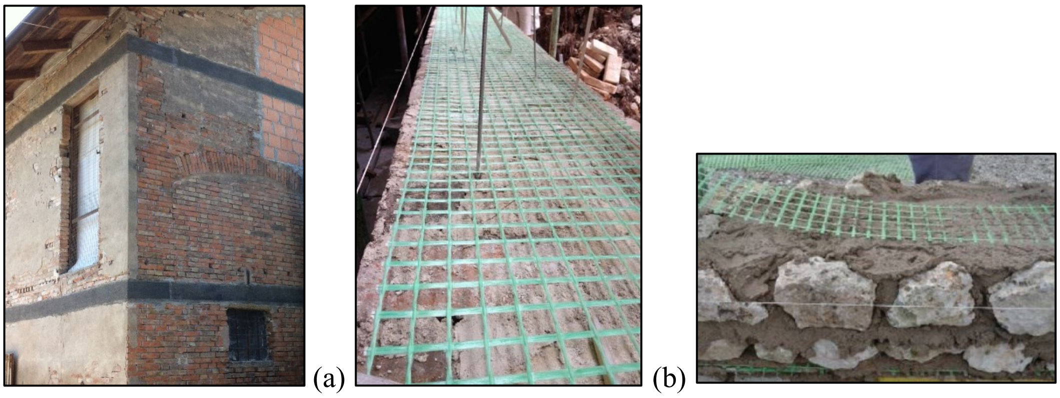
Fig. 25: Rocking of spandrels (left) is limited by ties (right).

In case prestressing is used, larger than normal anchor heads are used. Prestressing can also be achieved by heating the steel ties until the calculated elongation is reached and then anchoring the ties. The other option is to tighten the nuts until the calculated elongation. The calculations must consider prestress losses and a rigorous check of stress in masonry.

5.1.2 Ties made from FRP materials

Since the traditional steel ties are a very invasive technique, new methods to tie the building are under development. The main advantage of the new methods is that they are less invasive, cleaner and faster to install. The inconvenience for the residents, which is often the main deterring factor, is reduced. The new ties should be similarly effective at tying the building and ensuring a box-like behaviour, though this needs further verification. Experimental verification of efficiency of such ties is one of the topics of the CONSTRAIN project. The new ties are usually made of FRP (fibre reinforced polymer) materials, due to their availability, ease of use, and less invasive application. Typically, the used materials are CFRP (carbon fibre reinforced polymer) and GFRP (glass fibre reinforced polymer).

The new ties at floor levels can be installed only at the outer side of the perimeter walls (Fig. 26, left). A particularly interesting construction of a top horizontal tie in a stone masonry wall is where a GFRP mesh is inserted into the wall. Such application is interesting from a cultural protection point of view, as the constructed tie is invisible. The effect of such a tie will be tested within the project CONSTRAIN.



(a) (b) (c)

Fig. 26: CFRP ties at floor levels (a), GFRP top tie in a brick (b) and a stone masonry wall (c).

5.1.3 Increasing strength and stiffness of floors

In most cases, the floor structures of existing masonry buildings requiring strengthening are made of timber. The composition of such floors from bottom to top is: ceiling, wooden joists, deck boarding, sand for sound and fire insulation, and flooring. These floors are normally too flexible in their plane to distribute seismic loads to masonry walls and they need to be strengthened and stiffened. Often, such floors are also too weak/flexible when subject to vertical loads, and strengthening is required also to increase their load bearing capacity. There are several techniques available for strengthening the floors to vertical and horizontal loads.

5.1.4 Strengthening wooden floors with steel strips and/or additional boarding

A simple method for strengthening existing wooden floors, which preserves existing joists, is by adding an additional layer of deck boards orthogonal to the existing layer (Fig. 33). The new layer of boarding can be on top of the old one, or below the joists.

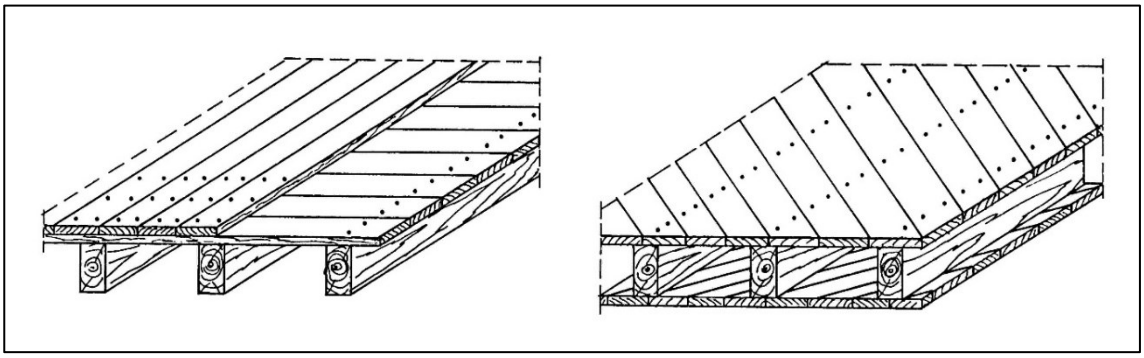


Fig. 27: Strengthening floors by an additional layer of boarding (from Tomaževič, 2009)

Alternatively, or additionally, the floor can be strengthened by diagonally placed steel strips (Fig. 28). The strips must be anchored into walls. Anchoring is usually done with steel anchors and steel angular elements (Fig. 29).

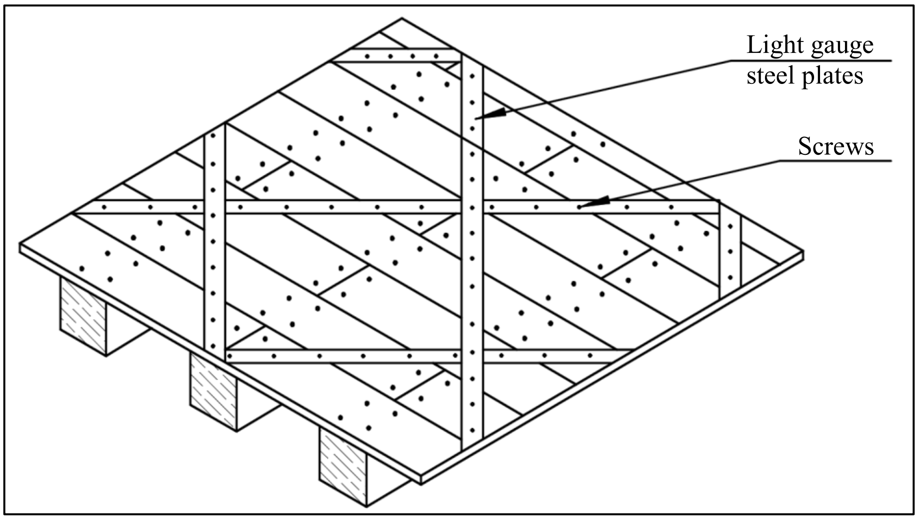


Fig. 28: Diagonal steel ties technique (Gattesco and Macorini, 2006; Piazza, 2008, Tomaževič, 2009).

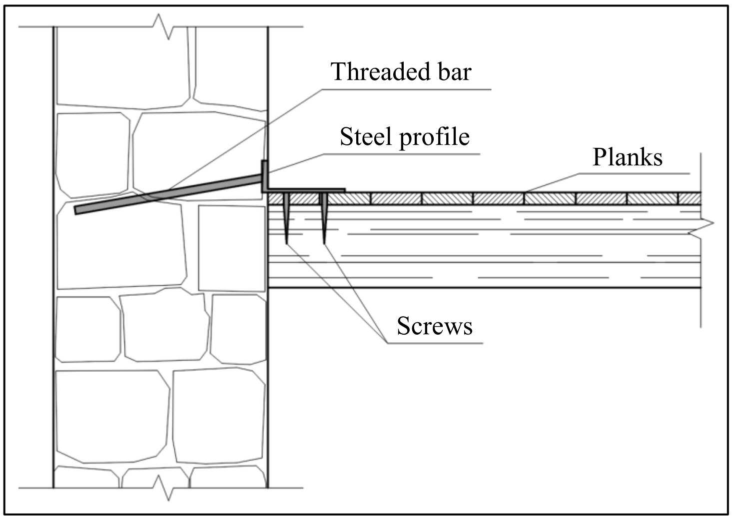


Fig. 29: Anchoring wooden floors into walls (Gattesco and Macorini, 2006; Piazza, 2008).

Advantages of the presented methods are:

- Simple and inexpensive;
- Suitable also for minor buildings;
- The mass of the building remains unchanged;
- Intervention is minimally invasive for the structure and reversible.

Disadvantages:

- The effect of strengthened floors depends on the anchors, which should be properly designed and carefully installed;
- The in-plane stiffness is not as high as that attained with a concrete slab solution.

5.1.5 Replacing or strengthening existing floors with a concrete slab

Most wooden floors in historical buildings have too low stiffness in their plane to properly distribute seismic loads to all walls. The integrity and box-like behaviour of the structure with such floors are poor. Furthermore, the floors are often excessively deformable under service loads, and may have excessive deformations due to creep under long-term loads. The stiffness in vertical direction is required also to avoid excessive vibrations and noise of people walking. To alleviate these problems, existing floors are often strengthened or replaced entirely by concrete slabs.

When the entire floor structure is removed and replaced by a concrete slab, special attention should be given to slab-wall contact. The slab should be placed at least 15 cm deep into a specially cut groove. Additionally, the slab should be strongly anchored into the walls by steel anchors (Fig. 30) or RC dowels (Fig. 31). The anchoring is especially critical in case of multi-leaf walls, and special attention should be given to connecting the outer wythes with the slab.

Although RC slab is a modern floor structure, which is very good for service loads and diaphragm action, its weight and strength can be problematic for walls of poor quality despite strong anchoring.

Strengths:

- Good service load performance
- Effective diaphragm action

Weaknesses:

- Relatively difficult to build and expensive
- Increases the mass of the structure
- Not accepted by the Cultural Heritage Protection

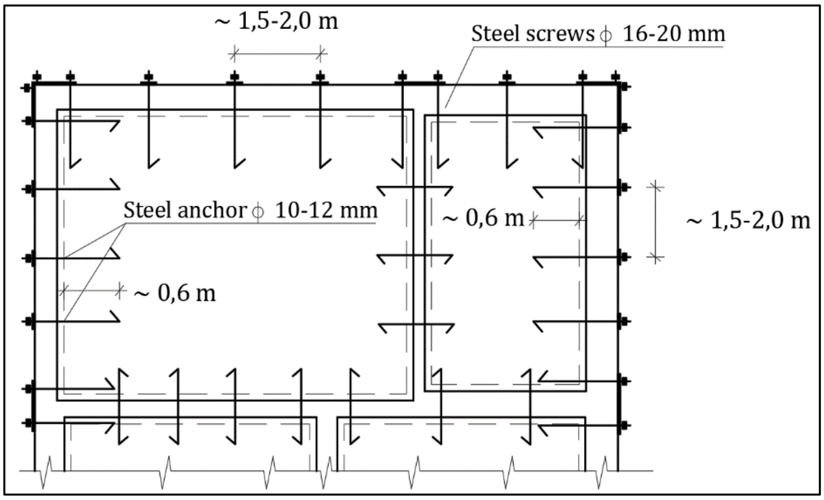


Fig. 30: Anchoring RC slab to walls by steel anchors (Tomaževič, 2009).

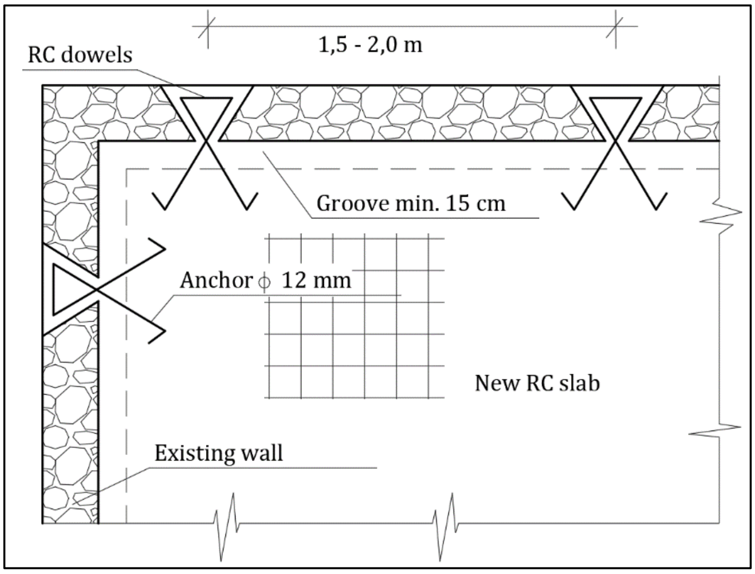


Fig. 31: Anchoring RC slab to walls by RC dowels (Tomaževič, 2009).

An alternative to complete replacement is removing the sand on the floors and replacing it with a thin (4 - 5 cm) concrete slab that works together with the beam as a composite system (Fig. 32). This technology is simple and inexpensive, and thus particularly suitable for small buildings. Furthermore, when properly connected to the walls, it provides the structure with a resisting floor diaphragm, which improves box-like behaviour and integrity. The gain in stiffness and strength of the wooden floors depends entirely on the efficiency of the connection between the concrete slab and the wooden beams. This connection is usually made through special connectors, of which several types are available on the market. Some examples are stud connectors fixed to the wood with epoxy resin, gang nail plates, common and high strength nails, and screws,

It is important to note that a temporary support should be used when casting the concrete slab as the slab cannot be considered effective until the concrete has hardened.

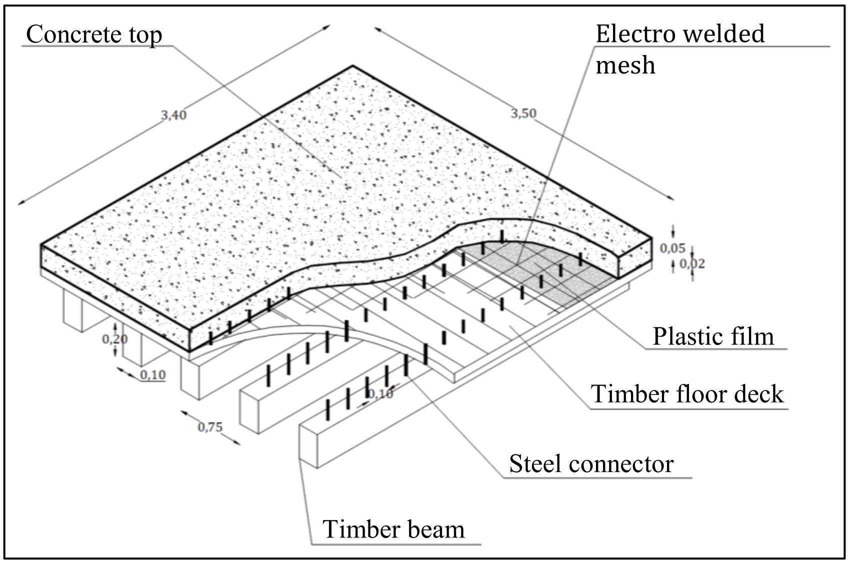


Fig. 32: Composite concrete slab - wooden floor system (Santos, 2015).

Strengths:

- Simple and inexpensive, and particularly suitable for small buildings;
- Acts as rigid floor diaphragm when properly connected to walls;

Weaknesses:

- Increases of the mass of the building;
- Frequently refused by the Cultural Heritage Protection due to high invasiveness and low "reversibility";
- Requires design of studs

5.1.6 Strengthening timber floors for service loads by FRP or steel strips

Wooden beams can be strengthened by using FRP or steel strips on the lower surface of the beams. Many layouts of the strips can be used. FRP strips can be glued to the beam by epoxy resin, and steel strips can be glued or nailed to the beam. The possible layouts are shown in Fig. 33 and Fig. 34. It is important to prop the beams before applying the strengthening. The propping can also be used to repair sagging (Fig. 35).

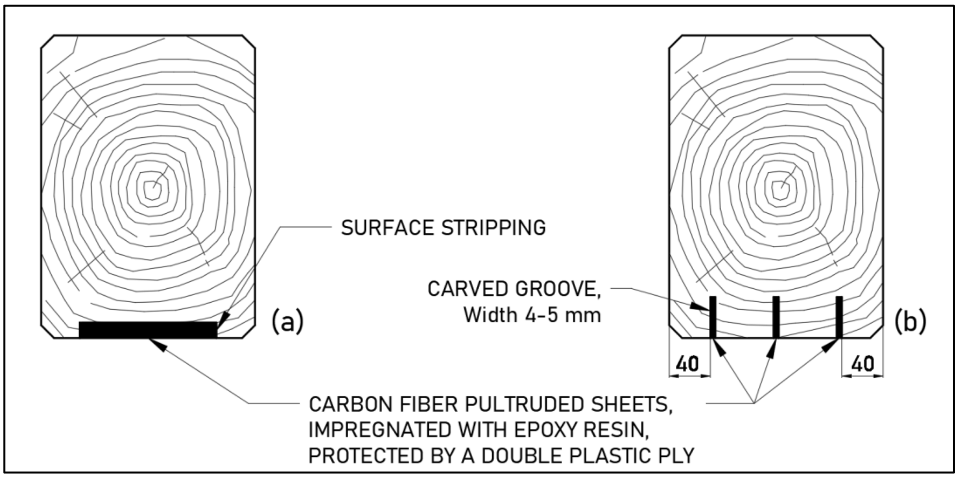


Fig. 33: Wooden beam strengthened by a single carbon fibre strip (a), and by three vertically placed strips (b).

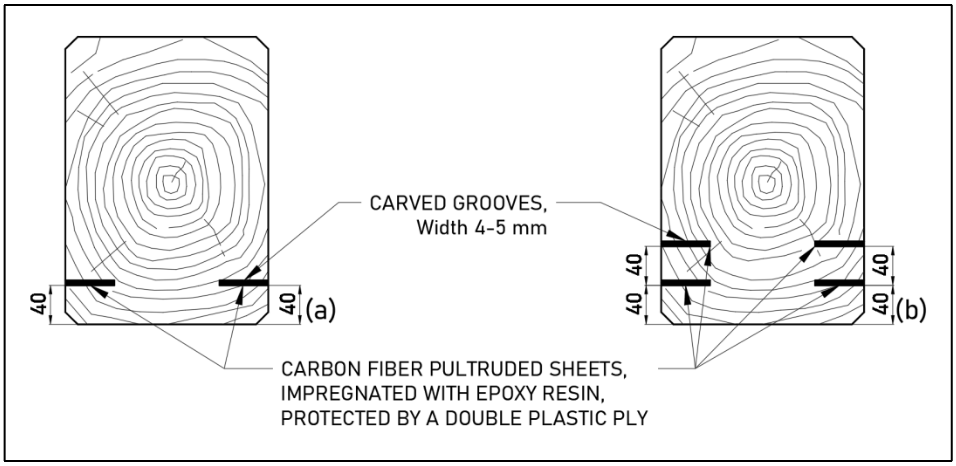


Fig. 34: Wooden beam strengthened by horizontally placed strips.

Fig. 35: Propped ceiling joists strengthened by carbon fibre strips.

6 Strengthening of masonry walls

Even when a masonry structure is placed on a good soil with sound foundations, has good structural layout and solid structural integrity, it can still damage and collapse during an earthquake if the masonry is not strong enough. This is illustrated in Fig. 36, which shows two nearly identical buildings placed only meters apart. The building made of solid bricks and weak lime mortar damaged severely (Fig. 36, left) during an earthquake whereas the building built from hollow clay blocks and strong mortar did not damage at all (Fig. 36, right). This shows the importance of strength and quality of the masonry material.

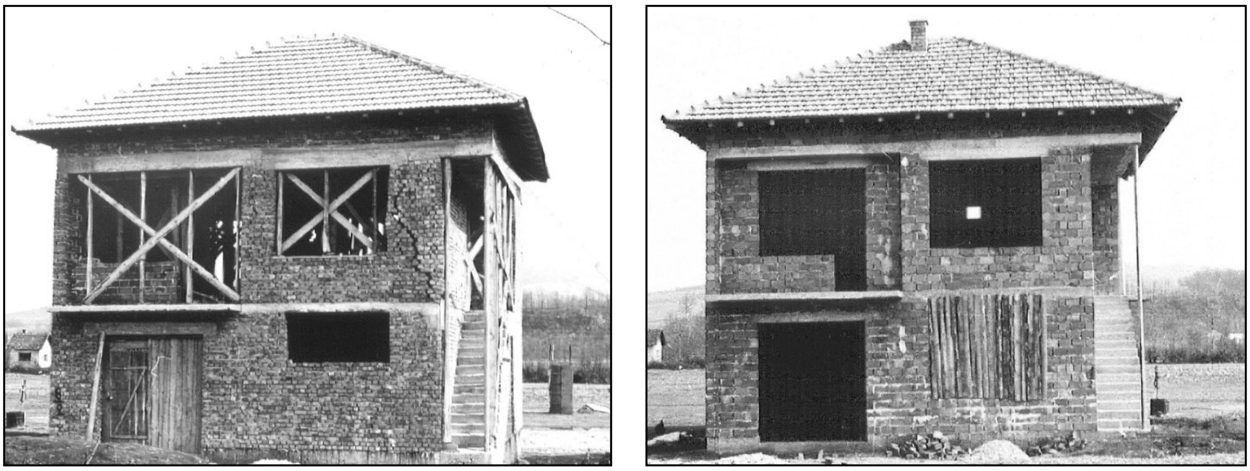
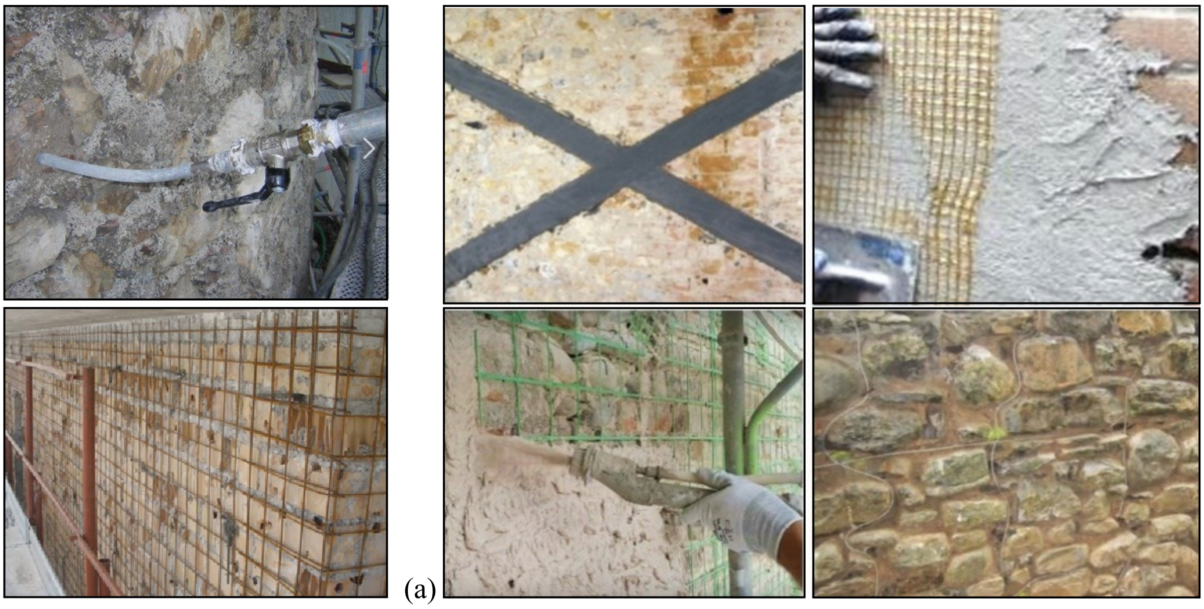


Fig. 36: Two nearly identical structures after earthquake. Building from solid bricks and poor mortar on the left damaged, whereas building from hollow clay blocks and good mortar did not. Shot after Banja Luka 1969 earthquake. Photos courtesy of prof. Tomaževič.

The strength of existing masonry varies a lot, and experimental tests are usually required to estimate it with precision. Generally speaking, stone masonry will normally be quite weak, especially if there are voids between the wythes. Stone masonry is therefore quite often strengthened. Strength of old brick masonry varies a lot and depends on the quality of bricks, mortar and workmanship, but in this case too, strengthening is often used. The decision on whether to use strengthening or not depends on the calculation of the seismic resistance of a structure. Due to high demand of current building codes, strengthening is very frequently required.

The strengthening techniques can be divided into two main categories: traditional and modern. The main distinction between the categories is in the used materials. Traditional techniques rely heavily on steel and concrete, whereas modern techniques use a lot of FRP technologies and modern reinforced mortars. The traditional techniques are tested and efficient, but their use requires large and invasive interventions as well as to temporarily move out, all of which is very inconvenient for residents. Modern technologies are cleaner and faster, and should be similarly effective. However, modern techniques should be verified experimentally before they are used in practice. Not all FRP based strengthening works.

Traditional and modern methods for strengthening are shown in Fig. 37. Typical representative technologies will be analysed later on.



(a) (b)

Fig. 37: Strengthening of existing masonry performances. Traditional grouting and RC coating (a). Modern techniques (b) Clockwise from top left: CFRP glued strips, Fibre Reinforced Cementitious Matrix (FRCM), repointing with steel strands and preformed GFRP mesh embedded in lime mortar.

6.1 Traditional intervention techniques

The application procedure is detailed in APPENIDX A.

6.1.1 Grout injections

The process of grout injections consists of the injection through flexible plastic pipes with a nozzle, of a highly fluid, high strength binder mixture, with a low water to binder ratio. Before injections of the joints among the bricks or stones, cracks and discontinuities have to be sealed. To avoid leakage, the injection has to be provided slowly and at low pressure. The injections are performed in several lifts. A lift is completed when the grout appears in the pipes of the next lift (Fig. 38). Indicative consumption of grout is between 50 and 150 $\mathrm{kg/m^3}$, but varies greatly with the type of masonry. The density of pipes for injections in practice is shown in Fig. 39.

The injection mixture is designed to have the following characteristics:

- high fluidity with low water to binder ratio;
- mechanical, physical and chemical characteristics comparable to those of the masonry structure, allowing a homogeneous and isotropic structural behaviour;
- low content of water-soluble salts;
- high breathability;
- high penetration power for filling of small cracks or cavities;
- absence of segregation in the mixture during injection;
- chemical compatibility with the materials used in historic buildings;
- reduced hydraulic shrinkage.

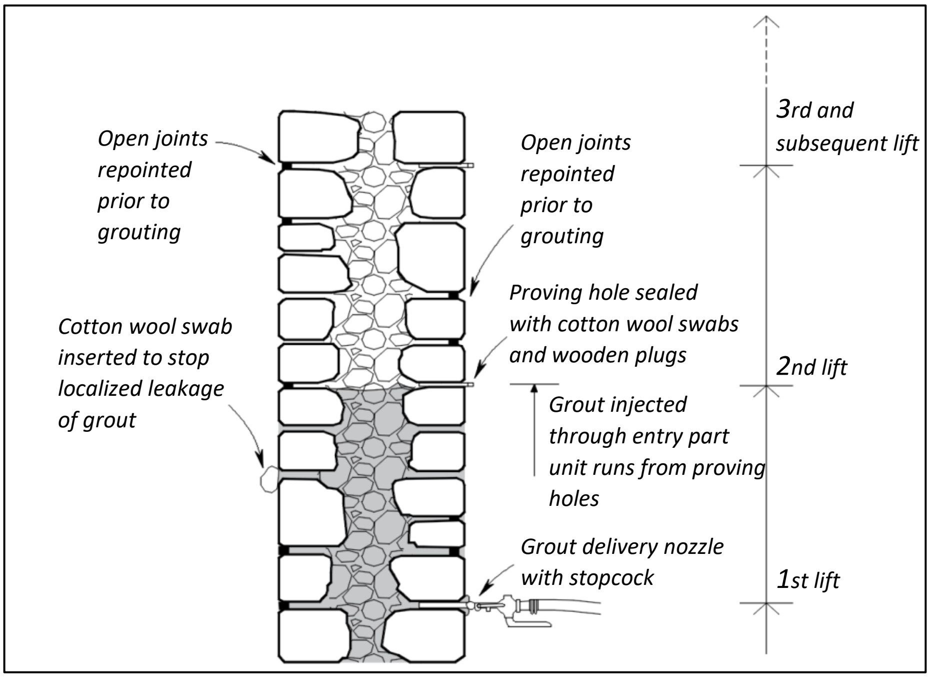


Fig. 38: The basic grouting method for filling the voids is illustrated here. (Iain McCaig, reproduced from English Heritage's Practical Building Conservation: Stone, 2012)

Fig. 39: Injecting stone masonry in practice[5].

The grouting injection technique has been widely used to effectively strengthen double-wythe stone masonry buildings after many earthquakes (e.g. North-East Italy—Friuli 1976, South Italy-Irpinia 1980, Central Italy—Marche-Umbria 1997, Slovenia 2000–2004, etc.). The method cannot be used on masonry without voids. *(Gattesco et al. 2015)*

Strengths:

- The filling of voids leads to a significant increase in the strength;
- Very effective for walls with widespread presence of voids, like rubble stone and cracked walls;
- It retains the appearance and thickness of the wall;

[5] https://deloindom.delo.si/uploads/thumbnails/2856/850/deloindom_djvu_26541_julij.jpg (Consulted in: 15.9.2021).

Weaknesses:

- Very expensive;
- Invasive and irreversible.

6.1.2 Reinforced cement coating

This strengthening technique consists of coating the wall with a steel reinforced cement or concrete layer (Fig. 40). The coating is applied to both sides of the wall and is usually reinforced by an ordinary steel welded mesh. Steel anchors (4-6 pc/m^2) through the wall connect steel meshes on both sides. The thickness of the coating depends on the technology and material. If cement mortar is used, the thickness can be as low as about 3 cm on each side, whereas if shotcrete is used, the thickness can be up to 6-8 cm. Before the application of the coating, the old plaster is removed, the surface is cleaned, and some mortar from the joints is removed to a depth of 10-15 mm.

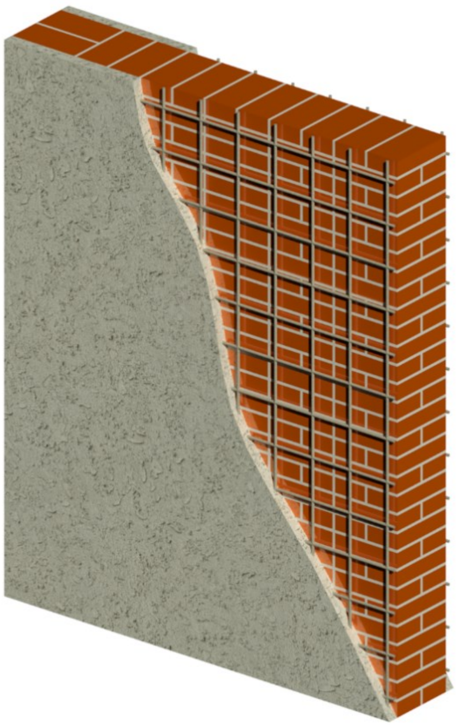


Fig. 40: Representation of a reinforced-cement coating

Strengths:

- Increase in stiffness, ductility and resistance to both shear and bending of the masonry;
- Very effective.

Weaknesses:

- Expensive, time consuming and invasive;
- Poor corrosion protection of the reinforcement (corrosion was observed after 10-15 years from the application);
- Increase of wall thickness and change of the appearance.
- Not applicable to buildings of cultural heritage.

6.1.3 *Artificial diatons (connections between wythes)*

Even in old multi-wythe stone masonry walls, the wythes are sometimes connected by stones. These (larger) stones are placed transversally in the wall and are called diatons. Presence of such stones importantly influences the mechanical properties of the wall. If no or too few diatons were used in construction, new artificial diatons need to be applied. Their purpose is the same of the original diatons, to strengthen and improve seismic performance of multi-wythe walls. The effect of diatons is also to distribute the loads to both wythes, prevent buckling of each individual wythe, and improve out-of-plane resistance of walls.

The artificial diatons consist of stainless-steel bars enclosed in a mesh fabric sleeve, which contains the special grout that is injected after the diaton in inserted into the wall. The first step of the procedure is to drill a hole through the wall, insert the diaton and inject the sleeve with grout. An artificial diaton is shown in Fig. 41. The head of the diaton after installation is shown in Fig. 42a, while Fig. 42b shows the fabric mesh for grout and how it expands to fill the area between the stones.

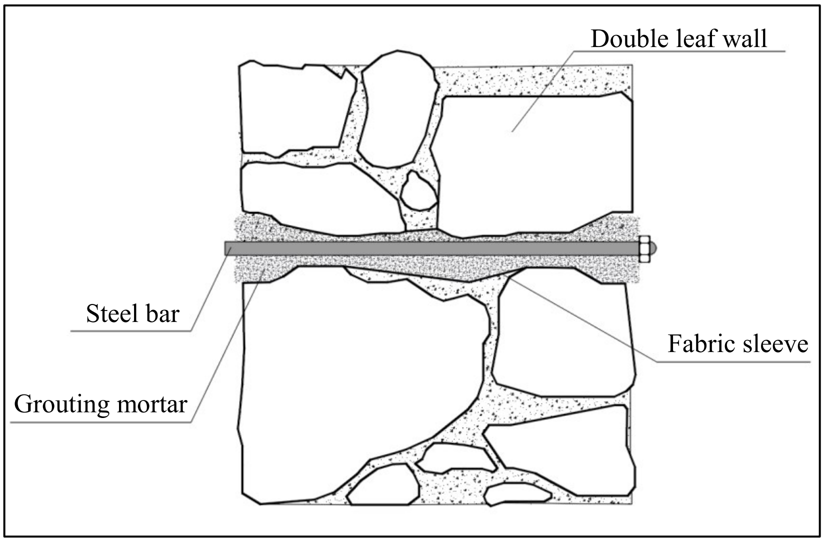


Fig. 41: Schematic view of an artificial diaton.

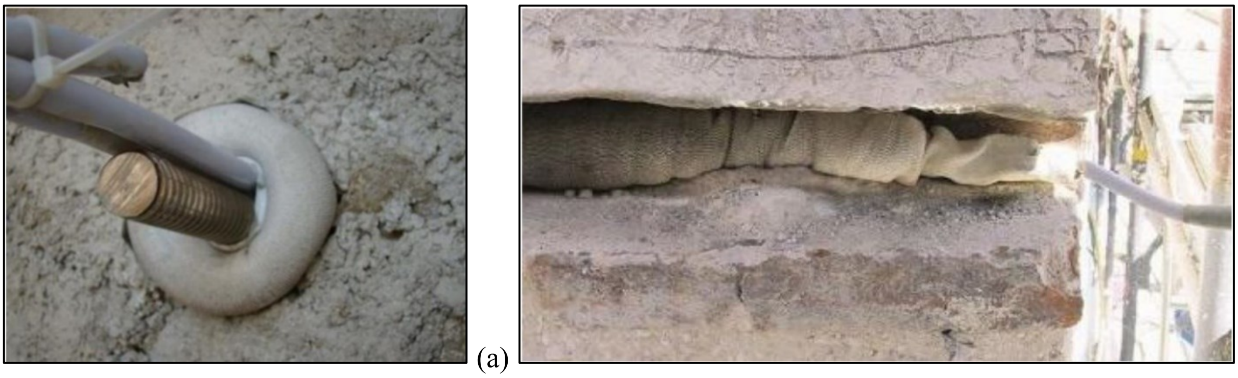

(a) (b)

Fig. 42: Visible part of the artificial diaton after installation[6] *(a), side view of the inserted diaton (b).*

Strengths:

- When high density of diatons is used, the wall can be treated as monolithic;
- Improved stress distribution between wall wythes;
- Increased resistance to vertical loads;

[6] https://www.bossong.com/consolidamento/diatoni-diatonos.html (Consulted in: 6.4.2021)

- No increase in wall thicknesses; can be hidden under a plaster layer.

Weaknesses:

- Invasive and irreversible;
- Expensive;
- Ineffective in cobblestone masonry walls (due to a low interlocking effect between stones).

6.1.4 Intervention techniques based on FRP materials

The FRP materials are usually very strong in tension (the actual strength depends on the type of fibres) and are used to assume the role of a tensile reinforcement. These tensile elements are bonded to masonry and form a composite material with improved seismic behaviour.

Many modern methods of strengthening based on the use of FRP materials exist. The fibres in FRPs that are used for strengthening masonry are typically either carbon, glass, or aramid. The FRP reinforcing products are available in different forms: solid strips (lamellae), bars, meshes with different spacing (usually bi-directional), and fabrics (usually uni-directional). Finally, the bonding to the masonry can be with either epoxy resin glue, or inorganic matrix.

The FRPs can also be used for reinforcing coatings, which cover the entire surface of the wall. Alternatively, FRPs can be placed locally in the areas of the wall with the highest tensions. For surface applications it is more suitable to use mesh or fabric, whereas for local applications it is more suitable to use strips or bars. Strips and bars are bonded externally to the surface of the wall or placed in specially cut grooves (this technique is called near surface mounted reinforcement).

The layout of the applied FRPs can be quite different. Strips are often glued in a diagonal pattern, meshes can be applied on one or on both sides, etc. The engineer's task is to define the most suitable solution for the considered structure. It should be noted, that some applications are very effective, whereas some combinations of masonry and FRP strengthening don't work at all. Especially critical is the bond between the FRPs and the masonry. If the bond is weak or if it fails, the effect of FRPs rapidly diminishes.

In this section, we will analyse the most commonly used methods and evaluate their strengths and weaknesses.

Externally bonded FRPs

Bonding strips are very effective at carrying tensile stresses. Therefore, they are usually placed locally and only where high concentration of tensions is expected. In arches, they may be applied at the intrados, whereas in vaults they are usually applied either at the intrados or at the extrados (Fig. 43). In masonry walls, the layout is usually diagonal (Fig. 44). Diagonal direction corresponds with the principal tensile stresses in shear walls and is thus a logical choice. In case flexural response is expected, vertical strips at the sides of the wall are a better choice. Especially in the case of vertical strips, special care must be taken to anchor them properly.

Fig. 43: Externally bonded FRP strips in arches (left) and vaults (right).

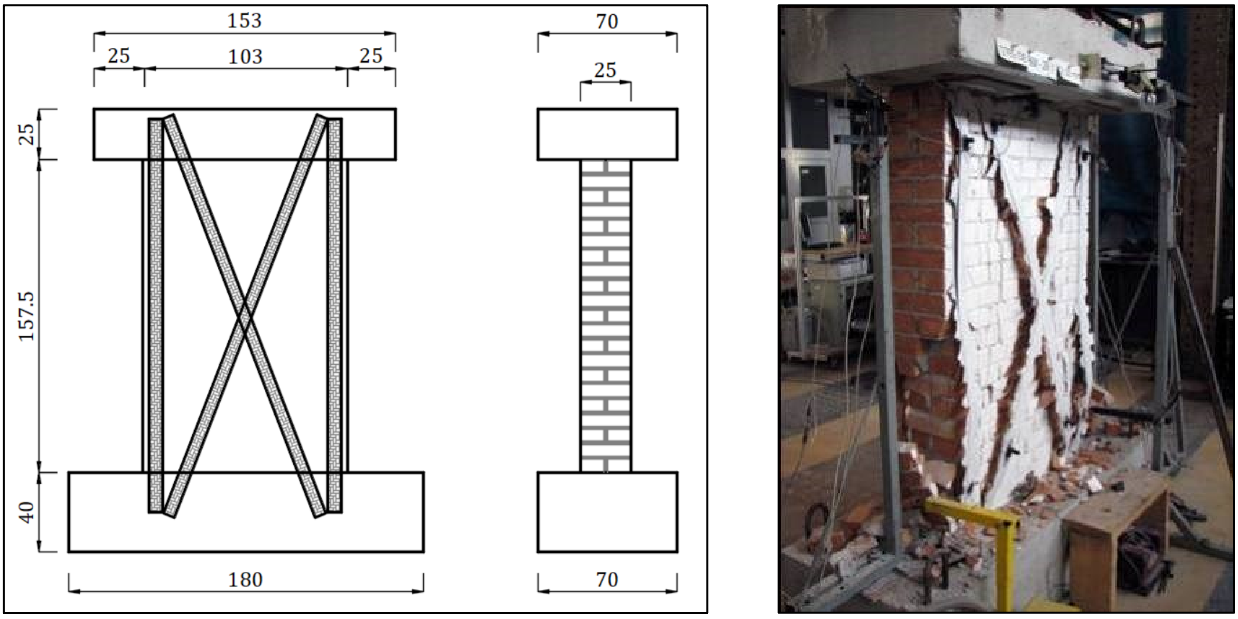


Fig. 44: Strengthening walls with FRP strips (Gams et al. 2017)

Prior to gluing the strips to masonry by epoxy glue, the surface of the masonry needs to be appositely prepared. Usually this involves sandblasting and using a primer to strengthen the surface. Nevertheless, some tests show that bond can fail and that such procedure is not sufficient. If the wall shrinks due to compression, the strips are likely to buckle out of plane and lose the bond with the wall. Since additional compressive stresses causing shrinkage are common during earthquakes, the application to walls may not be the most appropriate.

Advantages:

- Increase in mechanical characteristics of the strengthened member without changing dynamic properties of the structure (mass and stiffness remain the same);
- Easy and clean installation without loss of usable space;
- Minimal invasiveness and disturbance of occupants;
- Cost-effective.

Disadvantages:

- The use of EB (Externally Bonded) FRP can alter the aesthetic of masonry walls;

- Not suitable when shrinkage due to compressive loads is expected

Near surface mounted FRPs

Near surface mounted FRPs are essentially the same as externally bonded FRPs, except that they are installed into grooves. This is schematically shown in Fig. 45. As in the case of externally bonded FRPs, they are placed locally at places with the highest tensions. The products most suitable for such application are FRP bars and strips in combination with epoxy resin.

Advantages of near surface mounted FRPs over externally bonded FRPs:

- higher debonding protection;
- protection from the environment;
- minimal impact upon the aesthetics of the structure;
- reduced construction time, and minimal invasiveness.

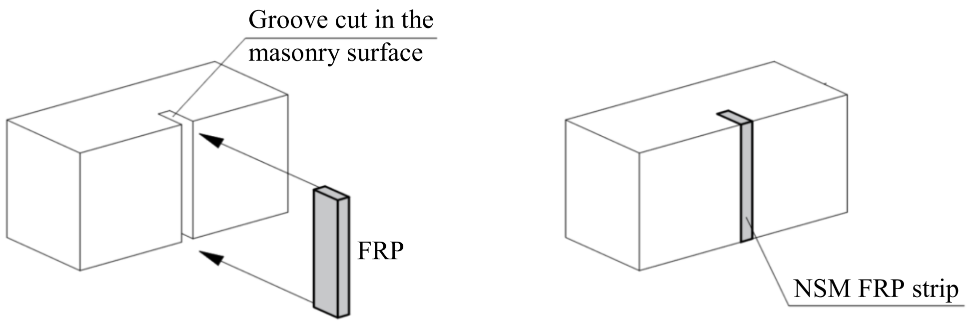


Fig. 45: Schematic representation of NSM FRP strip (Petersen, 2009).

6.1.5 Reinforced coatings with composite materials

When the FRPs had started to be used to strengthen masonry, FRPs were often glued to walls by epoxy resin. However, tests soon revealed that the incompatibility between a very strong epoxy resin compared to weak historic masonry caused problems. The key problem was that the difference between materials causes large stress concentrations at the bond and it tended to fail at quite low loads. Typically, the failure starts with the peeling off of a thin layer of masonry, as shown in Fig. 46, left. The improvement in seismic performance of such strengthening technique, shown in Fig. 46 right, does not justify its cost.

Coatings based on mortar (inorganic) matrix are much more compatible with masonry. The compatibility reduces the problem of debonding, but does not solve it, thus anchors are still used (Fig. 47). Better performance of mortar-based coatings compared to epoxy-based ones has been proven in many tests and the first are nowadays the most common type of fibre reinforced coatings.

A fibre reinforced mortar coating consists of an FRP product, usually in the form of a mesh, which is placed into a 30-40 mm thick mortar layer. FRPs are most commonly glass fibres due to their availability and low cost, and the mortar is usually a special mix designed for the strengthening application. The mortar must have an adequate workability for applications on vertical wall surfaces in a 20 mm thick layer without deforming before setting. The mortar used for strengthening nowadays is usually quite strong. It should be noted that glass fibres are exposed to alkali corrosion in the mortar. Glass fibre products for strengthening that can be in contact with mortar must therefore be alkali resistant. Products without such protection are unsuitable and can completely corrode within a few years.

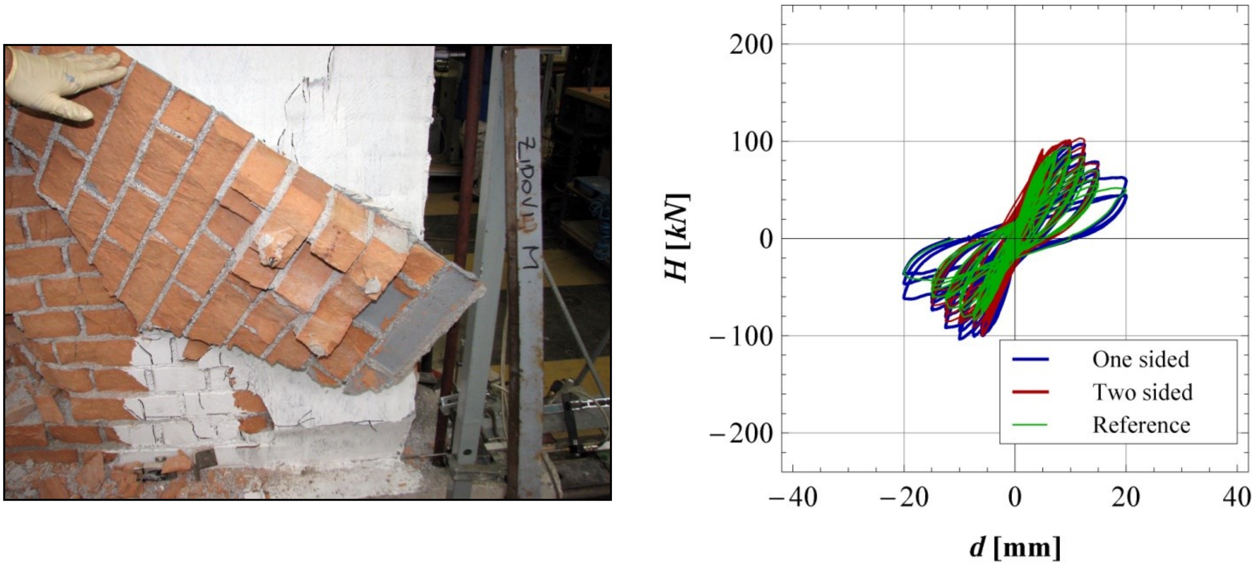


Fig. 46: Peeling off of type of debonding between coating with an epoxy matrix, left. Hysteretic response of walls with one sided and two sided GRPF reinforced coating in epoxy matrix, right (Gams et al. 2017).

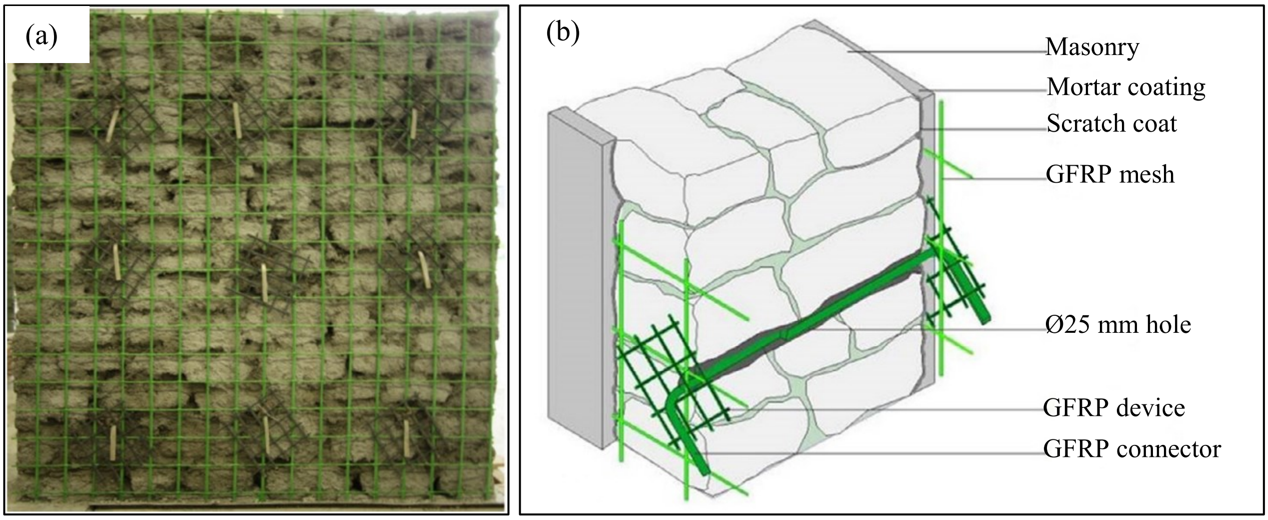


Fig. 47: GFRP mesh reinforced cementitious mortar coating on a stone wall. Application (a) and scheme(b) (Gattesco et al. 2015 & 2017)

In literature, mortar coatings reinforced with FRP meshes are commonly called CRM (Composite Reinforced Mortar) or Fibre Reinforced Cementitious Matrix (FCRM). All of these designations refer to the essentially same type of strengthening.

Application of FRP based coatings to stone and brick masonry walls has been studied by many researchers. An extensive study on strengthening stone masonry by prof. Tomaževič et al. (2015) was performed in the Program area with local materials and workmanship and is thus very relevant for this report and for the CONSTRAIN project. The results of the study showed that seismic response of stone masonry walls can be substantially improved, especially in terms of strength. It also highlighted the importance of connecting the wythes, and showed that problems with coating to masonry bond are less pronounced in stone masonry than in brick masonry. The study and the results will be discussed in detail later on.

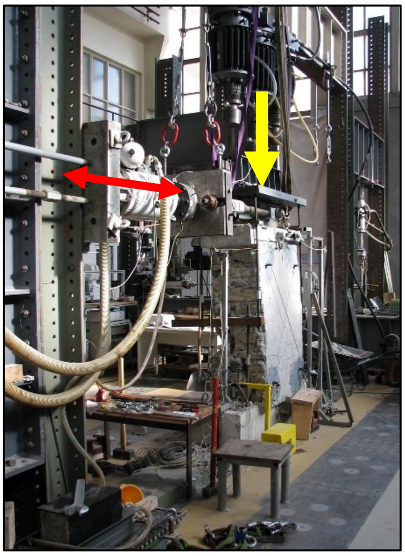
The extensive study on FRP based coatings on brick masonry by Gams et al. (2017) was also performed in the Program area with local materials and workmanship and will for this reason be thoroughly analysed. This study showed that the coating to masonry bond problems is a major issue for brick masonry walls. Some FRP reinforced mortar coatings debonded entirely when the walls were subject to simulated seismic loads. In some cases, the coating provided large increases in strength and ductility, but only if the coatings were strong and properly anchored to the masonry.

Finally, an extensive study on how to strengthen hollow block masonry was performed by Triller et al. (2019). They used masonry, typical for the Program area from the post world war II reconstruction period, and the study is therefore of particular interest. The investigated type of strengthening consisted in wrapping existing walls with GFRP reinforced mortar coatings. The experiments were performed on walls and on a full scale three storey pilot building, similarly to what is planned in the CONSTRAIN project.

6.1.6 Seismic behaviour of stone masonry strengthened by FRP reinforced coatings

In this section we present a summary of the test campaign by Tomaževič et al. (2015), which deals with the strengthening of stone masonry with FRP reinforced coatings and uses local stone masonry typical of the Program area. The topics addressed, like one-sided or two-sided coating application, are very relevant for the CONSTRAIN project and importantly influenced the strengthening solutions developed within it.

During the test campaign, 12 stone masonry walls with dimensions 1500/1000/500 mm (height/length/thickness) were tested in a shear-compression test configuration (Fig. 49), which simulate a masonry pier in a structure during an earthquake. The walls were constructed with stones, obtained from a demolished house in the region of Posočje. The stones, up to 30 cm in size, have been laid in lime mortar with a small amount of cement added to accelerate hardening. The walls were built by an experienced mason, familiar with the construction of traditional stone masonry. It is believed that this way, the laboratory constructed specimens that adequately represented three-leaf stone masonry, typical for the region. As determined by laboratory tests, the stone was a characteristic lime-stone from the area, with an average compressive strength of 220 MPa, whereas the average compressive strength of mortar was 3.3 MPa. The compressive strength of walls was 1.26 MPa and the modulus of elasticity was 470 MPa. Two walls were tested in the reference state to evaluate the effect of strengthening, while the rest were strengthened.



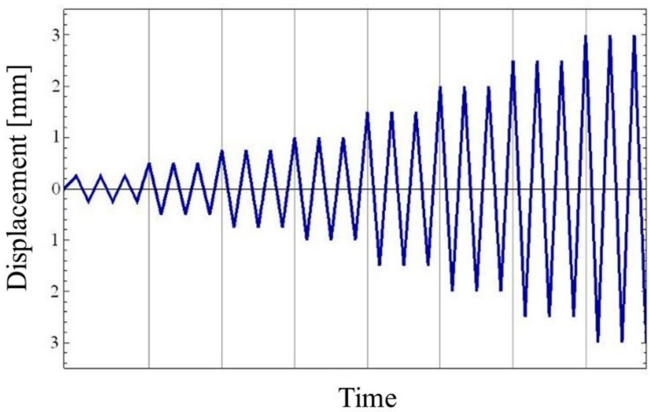


Fig. 48: Test setup for shear-compression tests. Red arrow shows imposed displacements and yellow arrow shows compressive force (left), simulation of seismic loads (right).

The walls were strengthened with a GFRP reinforced mortar coating. The first step of the strengthening process was the levelling of the stone wall surface. A substantial amount of mortar was used for this because the surface was uneven and with deep joints. After this stage, a structural bi-directional GFRP mesh (tensile strength 70 kN/m) was placed on the level surface and covered with about 2 cm thick layer of mortar. Carbon fibre anchors were used to connect the coating to the wall. The anchors were immersed in epoxy resin and inserted into pre-drilled holes.

The first set of walls was strengthened only on one side. The coatings were anchored to the wall at the corners as shown in Fig. 49. During the test, the wall developed shear damage in the form of diagonal cracks (Fig. 50a, b). The wall wythes split and separated at the middle surface (Fig. 50c) and the side without the coating disintegrated (Fig. 50a). Despite the severe damage the unreinforced side of the wall, its strength was increased about two times. Displacement capacity, on the other hand, was not improved at all. This can clearly be seen from the hysteretic response of the wall shown in Fig. 51, which shows the (shear) resistance as a function of lateral displacement at the top of the wall.

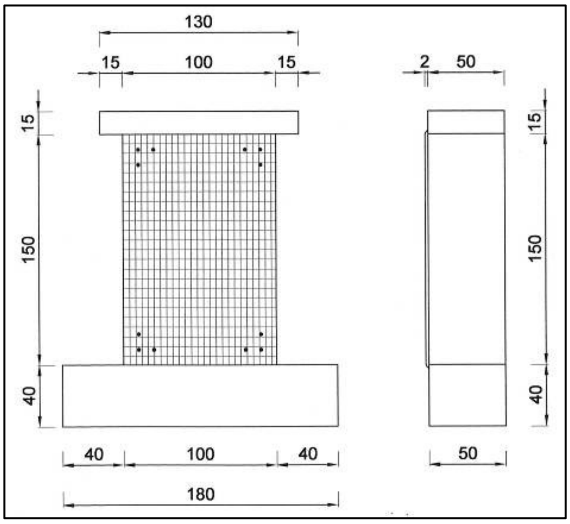


Fig. 49: Stone masonry wall strengthened only on one side by GFRP reinforced mortar coating, anchored to the wall at the corners.

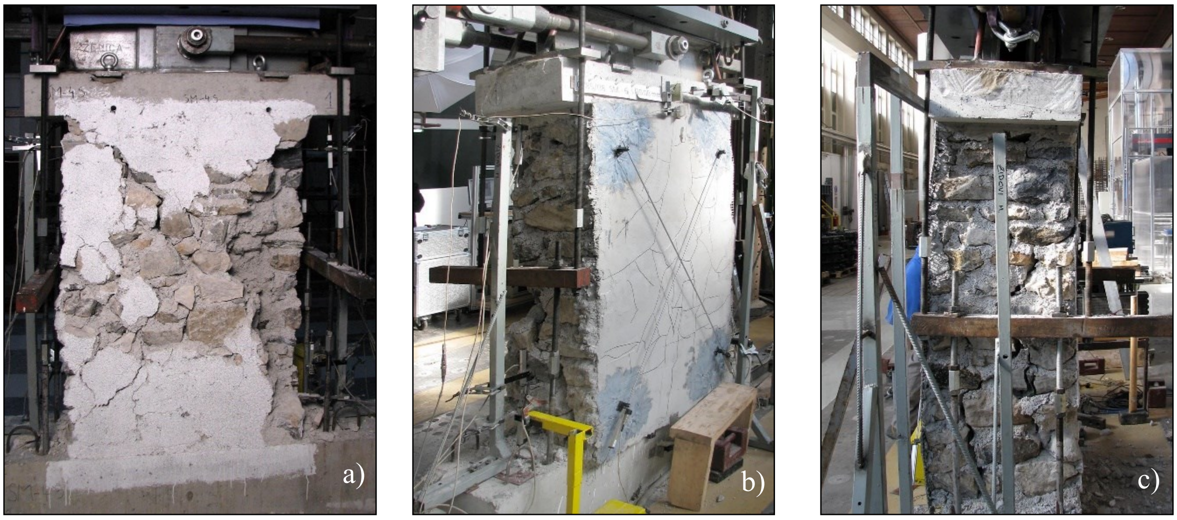


Fig. 50: Stone wall with coating on one side during test. Disintegration of the side without the coating (a), small damage on the side with the coating (b) and splitting of the wall due to lack of diatones (c).

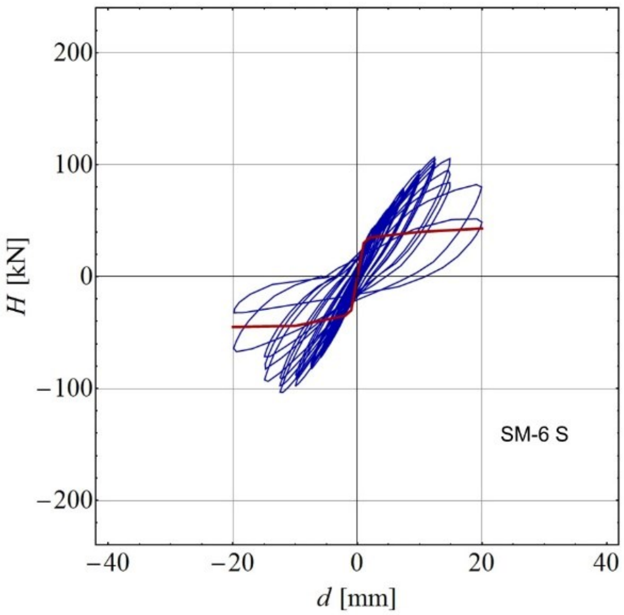


Fig. 51: Hysteretic response of stone masonry wall with one side GFRP reinforced mortar coating. Blue line shows the response of the strengthened wall and the red line indicates the resistance envelope of the reference wall.

The test showed:

- Connection of wythes by diatons is crucial if one-sided coatings are used
- The coating to masonry bond in stone masonry is sufficient (no problems observed)
- Strong mortar coating is very effective for stone masonry walls
- One-sided coatings on stone masonry can double the shear resistance

The other set of walls analysed are walls strengthened on both sides. The same type of strengthening was used (GRFP mesh reinforced mortar coating), except that in this case, the coating is applied to both sides and is not anchored. The layout of the coating is shown in Fig. 52.

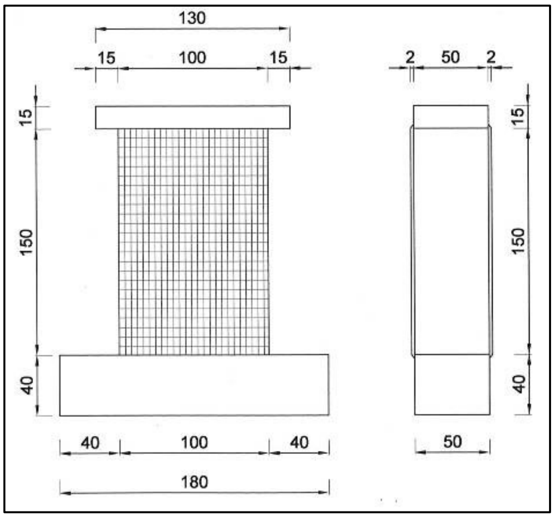


Fig. 52: Stone masonry wall strengthened by GFRP reinforced mortar coating on both sides of the wall.

The wall responded in shear and developed predominantly diagonal shear cracks (Fig. 53a). Eventually, the wythes separated and this caused degradation of resistance of the wall and its collapse. Each of the wythes remained only lightly damaged due to the strong coatings.

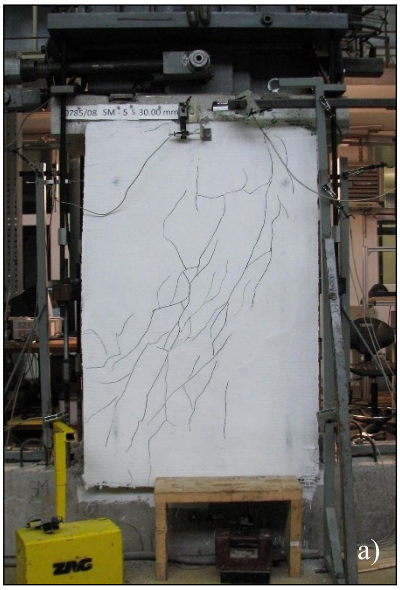


Fig. 53: Stone wall with coating on both sides during test. Shear damage on the coating (a), splitting of the wall due to lack of diatones (b).

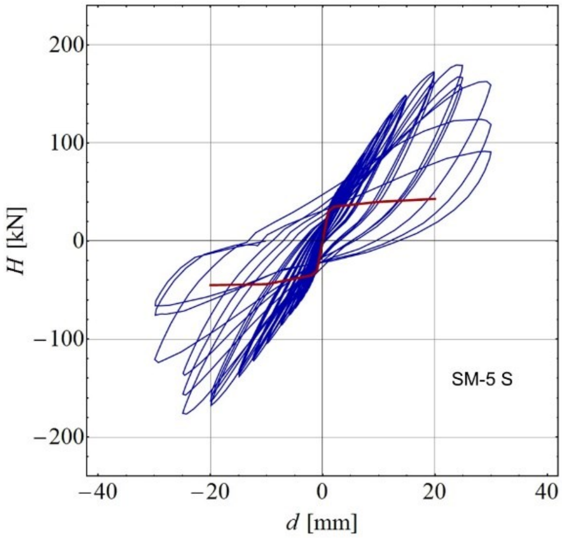


Fig. 54: Hysteretic response of stone masonry wall with GFRP reinforced mortar coating on both sides. Blue line shows the response of strengthened wall and red line indicates resistance envelope of the reference wall.

In this case, the resistance was quadrupled, and there was also an obvious increase in displacement capacity. The reference walls failed at about 20 mm lateral displacement whereas the strengthened walls failed at about 30 mm (a 50 % increase).

The tests on stone walls with coating on both sides show:

- Connection of wythes by diatones is crucial
- The coating to masonry bond in stone masonry is strong
- Strong mortar coating is very effective for stone masonry walls

- Two-sided coatings on stone masonry can quadruple shear resistance and increase displacement capacity by 50%.

6.1.7 Seismic behaviour of brick masonry strengthened by FRP reinforced coatings

In this section it is presented a summary of the test campaign by Gams et al. (2017), which deals with the strengthening of brick masonry with FRP reinforced coatings and uses a local brick masonry typical for the Program area. The topics addressed, like one or two-sided application are very relevant for the CONSTRAIN project and importantly influenced the strengthening solutions developed within it.

Within the test campaign, 28 brick masonry walls with dimensions 1575/1030/250 mm (height/length/thickness) were tested (Fig. 55, left) in a shear-compression test (Fig. 55, right), which simulates a masonry pier in a structure during an earthquake. The walls were constructed from commercially available bricks (compressive strength 29 MPa) and specially designed weak mortar (compressive strength 1.14 MPa). The measured compressive strength and elastic modulus of masonry were 4.1 MPa and 1.1 GPa, respectively.

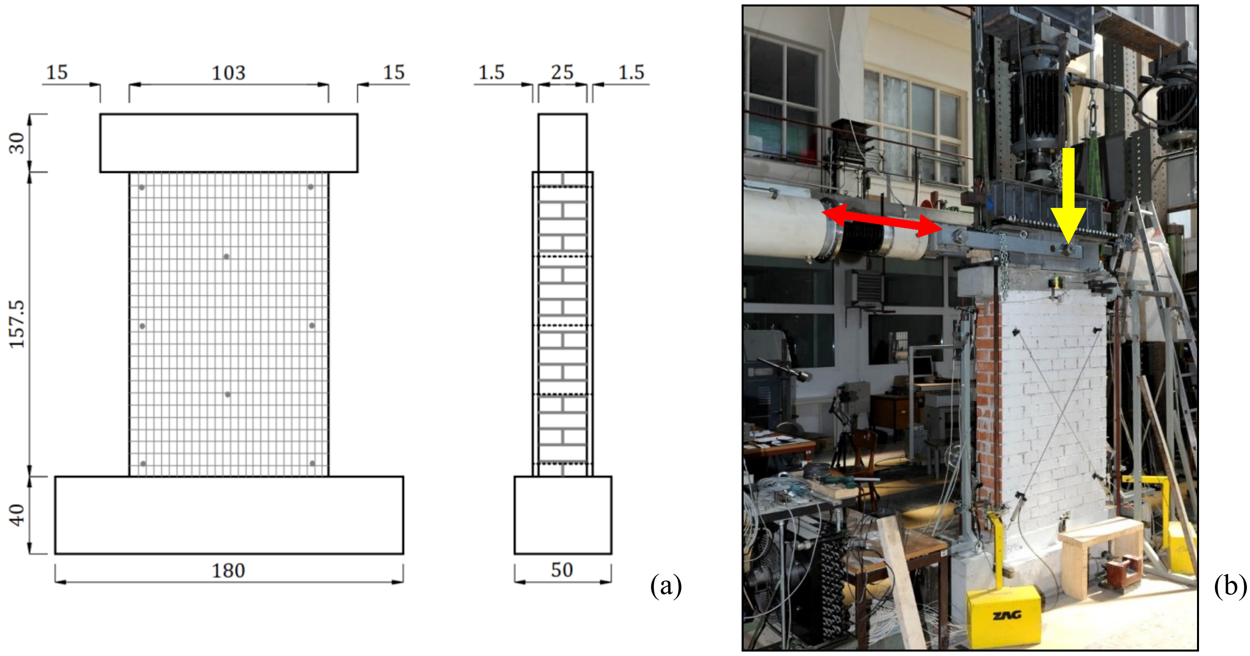


Fig. 55: Dimensions of the GFRP reinforced walls used in testing (a). Test setup for shear-compression test. Red arrow shows imposed horizontal displacements and yellow arrow shows compressive force (b).

In the test campaign, different materials (different FRPs and different matrices) and layouts were used. The anchors were of the carbon fibre type. The present synopsis is limited to walls with GFRP reinforced mortar coatings and focuses only on results related to the following topics:

- Effect of anchoring
- Effect of coating thickness

Effect of anchoring

Walls with four densities of anchors were used to analyse the effect of anchor density on seismic performance of brick masonry walls with GFRP reinforced mortar coating. The first wall had no anchors, the second 5 (3.3

anchors/m^2), the third 8 (5.3 anchors/m^2) and the fourth 13 (8.6 anchors/m^2). The coating was applied to both sides of the wall.

In all cases debonding occurred. In case there were no anchors, the entire coating separated from the wall (Fig. 56a). When there were many anchors, on the other hand, the bond was lost over a large area, but the coating was still attached to the wall and there was significant damage in the coating (Fig. 56b). Tests performed by Proença et al. (2012) show that anchorage spacing should be similar to the thickness of the wall to prevent onset of debonding failure before failure of the composite strengthened wall.

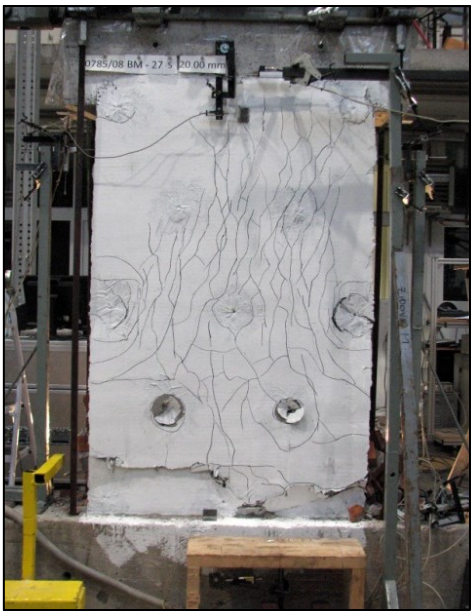


Fig. 56: Completely separated coating without anchors (a). Failure of bond and anchors in case of highest density of anchors (b)

The coating without anchors did not increase performance of the walls as the strengthened walls exhibited no increase in neither strength nor displacement capacity. On the other hand, the effect of the coating was the highest for the higher anchorage density. This effect is shown in the form of hysteretic relationship between lateral force and lateral displacement in Fig. 59Fig. . The coating increased shear resistance by 40% and displacement capacity by 25%.

Conclusions:

- Debonding of mortar coatings from brick masonry is a pressing problem
- Anchoring helps but very large densities of anchors are needed to alleviate the problem

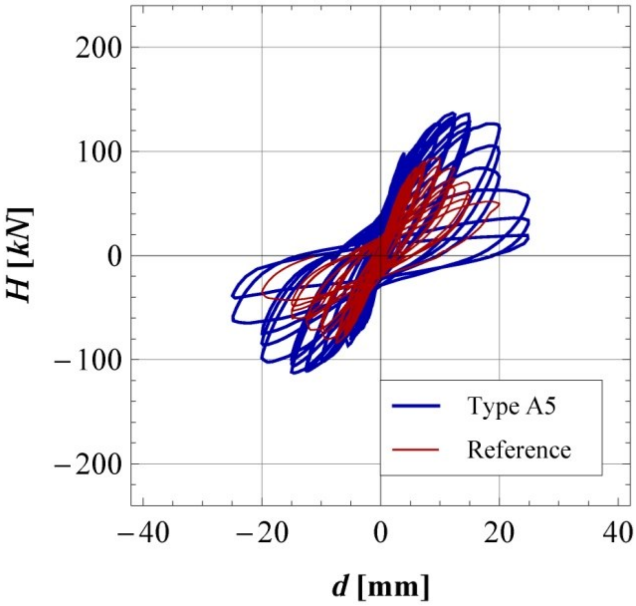


Fig. 58: Hysteretic response of brick masonry wall with GFRP reinforced mortar coating on both sides and 9 anchors/m^2. The blue line shows the response of the strengthened wall and the red line indicates the resistance of the reference wall.

Effect of coating thickness

To analyse the effect of the coating thickness, there were tested and compared three types of specimens. The first two are simply reinforced with a GFRP mesh oriented horizontally-vertically and have a coating thickness of 5 mm and 15 mm, respectively. The last is reinforced by a GFRP mesh placed in a more elaborate way (see Fig. 57, left). The first layer of the grid is placed diagonally over the entire surface and then there is another layer of reinforcement in the form of two 250 mm wide vertical strips at the sides of the wall. The thickness of the mortar is increased to 25 mm at the sides (from 15 mm in the center) due to the application of the second layer of mesh. The coating is anchored by 4 anchors at each corner.

The results show that there is a clear correlation between the strength increase of walls and the thickness of the coating. The thinnest coating (5 mm thickness) increased strength by 40%. Medium thickness (15 mm thickness) increased strength by 75 % and the highest thickness (25 mm) increased strength by 130 %. In the latter case, the displacement capacity increased by 50%. Furthermore, the wall with the strongest coating experienced a different failure mechanism from the rest. The coating cracked diagonally with a single large crack in which all the strands of the mesh fractured (Fig. 57, right).

The seismic response is improved not only in terms of strength and displacement capacity, but also in terms of dissipated energy. This can be seen from the area enveloped by the hysteretic loops shown in Fig. 58.

Conclusions:

- GFRP reinforced coatings should be at least 30 mm thick;
- Strong and well anchored GFRP reinforced coating can substantially increase strength and displacement capacity;
- The capacity to dissipate energy is greatly increased by a strong and effective GFRP reinforced mortar coating.

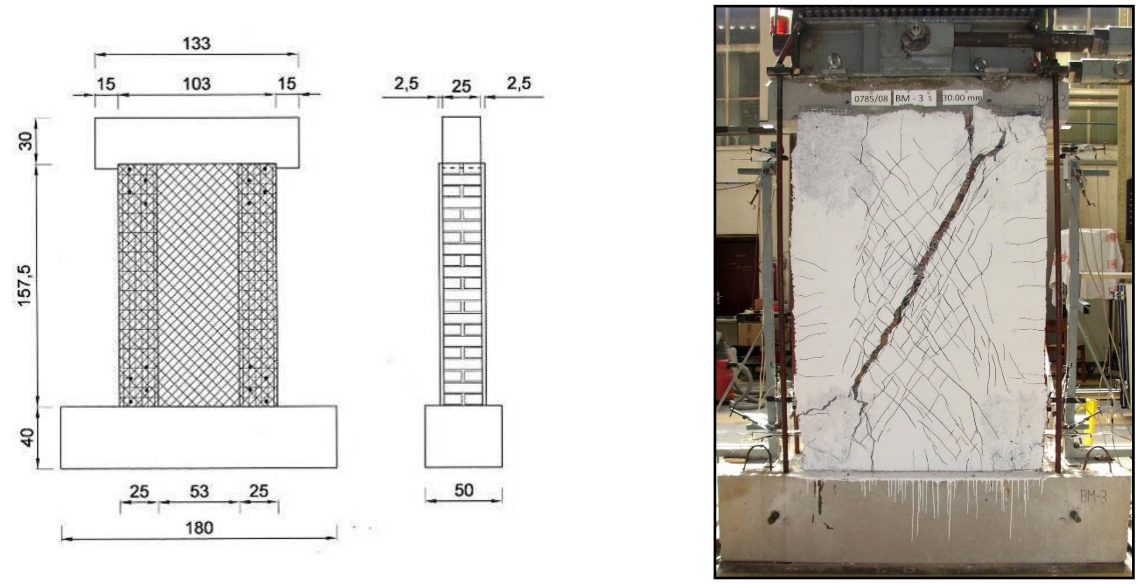


Fig. 57: GFRP layout for the wall with thickest coating, left. The failure of such wall, right.

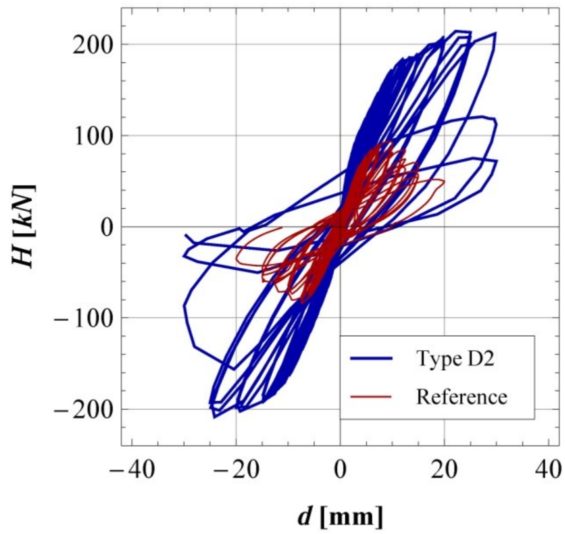


Fig. 58: Hysteretic response of brick masonry wall with 25 mm thick GFRP reinforced mortar coating on both sides and strong anchoring. Blue line shows the response of the strengthened wall and red line indicates the resistance envelope of the reference wall.

6.1.8 Seismic behaviour of hollow block masonry strengthened by wrapping with GFRP reinforced coating

The natural conclusion after the observed problems with the bond was to wrap the walls in the GFRP reinforced coating. The wrapping inherently alleviates problems with the bond and the coating retains part of effectiveness even if bond is lost.

This was thoroughly investigated by Triller et al. (2019) on hollow block masonry with weak cement-lime mortar, which was widely used in Slovenia in the post World War II reconstruction. Such masonry was used for construction of residential buildings up to 4-5 stories high without vertical confining elements (tie columns). These buildings require strengthening if they are to comply with the requirements of the current codes.

The masonry units used in the construction (shown in Fig. 59) had compressive strength of 15 MPa, and the strength of mortar was 2 MPa. A bi directional GFRP grid with strength 70 kN/m was used for the reinforcement. The anchors were made from glass fibres. The strength of masonry and elastic modulus were 3.8 MPa and 4.3 GPa, respectively.

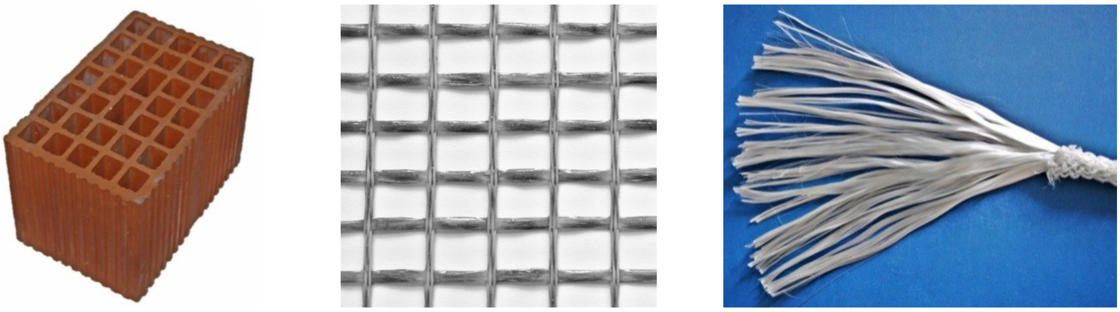


Fig. 59: Hollow clay block, middle. GFRP mesh, center. Glass fibres for anchoring, right.

Two reference and two strengthened walls were tested in shear-compression. The coating debonded and buckled (Fig. 60, left) but continued to support the wall because the GFRP was wrapped around the wall. Resistance of the wall increased by over 50 % due to strengthening. The displacement capacity was increased by a factor of 3.4 (Fig. 60, right).

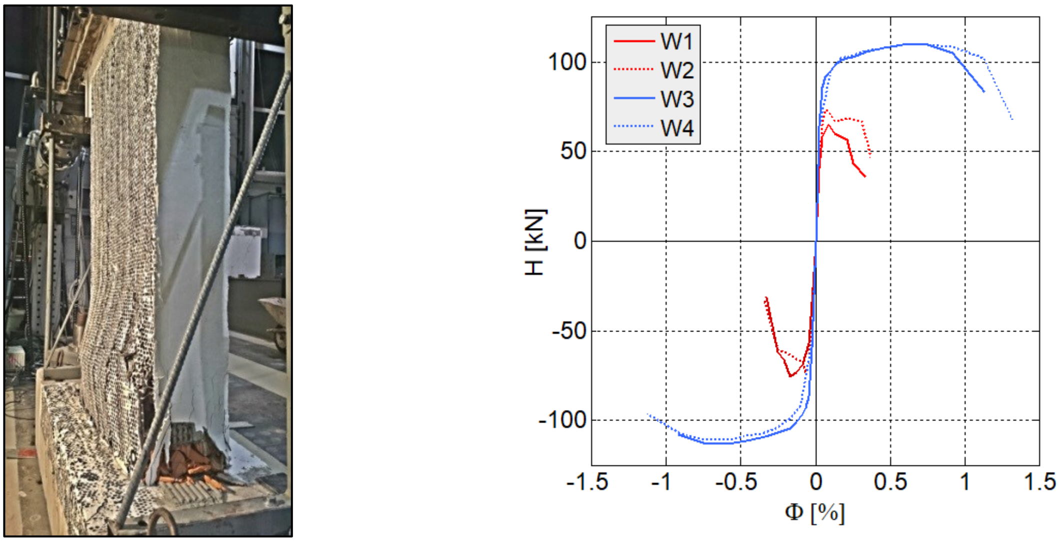


Fig. 60: Buckling of the coating, left. Envelopes of the hysteretic response of two reference walls (red) and two strengthened walls (blue), right.

The same method was used to strengthen a full-scale three-storey pilot building (Fig. 61). The effect on the pilot building was similar (45% increase in strength, large increase in ductility and displacement capacity), but it was quite difficult to achieve wrapping for all walls. Many anchors had to be used and the scope of the intervention was large. If this was used on a building which was in use, it would have to be almost completely emptied and even the windows removed. The method is thus effective, but cumbersome.

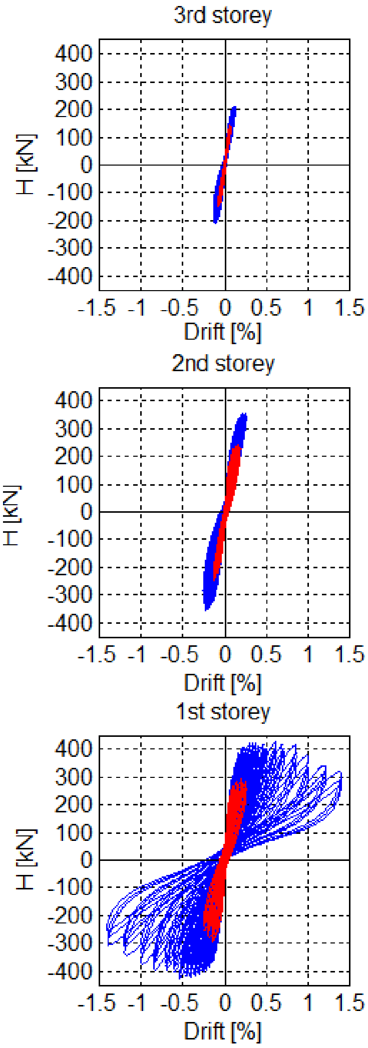


Fig. 61. Three storey pilot building before test, left. Hysteretic curves of unstrengthened (red) and strengthened (blue) structure, right

Conclusions:

- Wrapping is an effective way to strengthen masonry walls
- It is very invasive and difficult to do, especially for buildings in use

6.1.9 Structural repointing with steel strands (Reticolatus)

In this strengthening technique high strength stainless steel cords are inserted in the mortar joints of stone masonry walls to a depth of 30-40 mm. The nodes, generally one every two, are connected to the other face of the wall by means of transverse stainless-steel bars. The normal density of passing-through connectors is 5 – 6 per square meter. The cords are arranged in vertical and horizontal directions, forming approximately square meshes, the dimensions of which depend on the size of the stones in the masonry (Fig. 62). Normally the sides are 300-400 mm wide but should not be greater than the thickness of the wall.

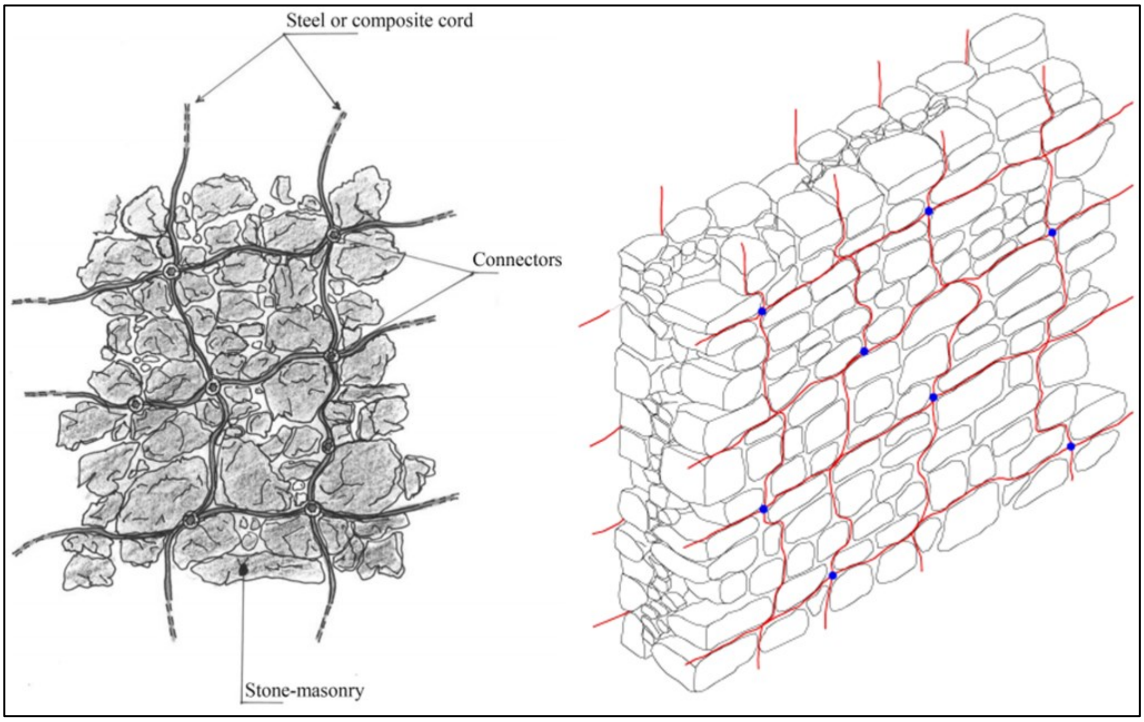


Fig. 62: Structural repointing with steel strands.

The cords forming the mesh are connected to the transverse bars by means of eyelets in which the cords can slide. After the installation is finished, moderate tension is applied to the cords, to make the mesh fully functional. A detail of the eyelet is shown in Fig. 63. In case the walls are too thick for the bars to pass through, the bar can be anchored into the wall through epoxy resin. Finally, the wires and nodes are covered by mortar to preserve the look of masonry and guarantee the durability of the intervention.

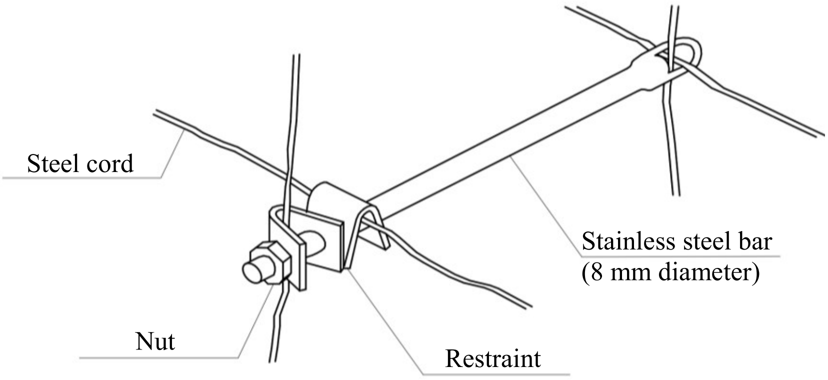


Fig. 63: Cord and eyelets disposition detail (passing through)

Advantages:

- Improved shear, bending and compressive strength;
- Minimally invasive and reversible.

Disadvantages:

- Cannot be used if joints are less than 8 mm thick

APPENIDX A

A1 Interventions to increase wooden floor stiffness and capacity

To increase the in-plane and out-of-plane stiffness of the existing wooden floors, without completely replacing them, there are various techniques available:

- Strengthening of wooden joists;
- Construction of a light reinforced concrete slab connected to the timber joists, by means of steel shear studs;
- Nailing an additional wooden plank on top of the existing one;
- Insertion of diagonal ties to increase the in-plane stiffness.

A1.1 Strengthening of bended wooden beams with carbon fibre pultruded sheets

Generally, the strengthening techniques for wooden beams are attained using FRP pultruded sheets or FRP strips on the lower surface of the beams, or steel plates to increase their tensile strength and reduce their deformation.

Before starting any intervention, the loads acting on the beams must be temporarily supported with floor props.

The intervention with carbon pultruded sheets, pre-impregnated with epoxy resin, is carried out by gluing them through a specific epoxy resin, with high and documented chemical-physical compatibility with the wood, on the lower surface of the beams, so to improve its flexural capacity and reduce its deformability. For the intervention to be effective, an adequate preparation of the wooden support is needed to ensure a good adhesion of the sheets to the existing timber joists. The preparation of the support is performed through the execution of the following operations:

- Cleaning of the wooden element by removing all inconsistent parts or those undergoing detachment, until obtaining a compact and mechanically resistant support that will not lead to the detachment of subsequent applications;
- Suction of the support to remove all dust;
- Near superficial cracks and/or deep fractures, block the detachment of the surfaces and restore the continuity of the element.

The operating procedure for the intervention with pultruded sheet positioned in a carved groove in the lower surface of the beam, is as follows:

1. Regularization of the lower surface of the beam, by planing and milling of the wooden element, to obtain a properly flat surface, suitable for gluing the pultruded sheet.
2. On the lower surface of the wooden beam, carve a groove for a depth of 8-10 mm, a width equal to the thickness of the lamina to be inserted increased by 10 mm, and a length equal to that of the sheet.
3. Prepare the wooden surface preferably within 24 hours prior to priming (see next point), to avoid superficial oxidation phenomena and contact with pollutants and dust. The elements before being treated with the primer must be left air conditioning in the intervention area, since it is essential that the humidity contained in the element to be repaired is ± 3% compared to that of the service conditions, to minimize dimensional variations and the consequent development of tensions between the parts to be bonded.
4. Priming with the use of a specific fluid epoxy product, in water-based dispersion, with high and documented chemical-physical compatibility with the wood, taking care that the impregnation is carried out until the product is no longer absorbed by the wood. The primer must be applied with successive treatments (Fig. 64a).

5. Cutting (with diamond blade) of the pultruded sheet as indicated in the project tables. Before positioning the sheet, remove (if present on the sheet) of the single or double protective film (recommended) in plastic material (peel-ply), that has the function to protect the sheet surfaces from dust and dirt during handling and cutting (Fig. 64b).
6. Applying of a specific epoxy adhesive with thixotropic consistency, with high e documented chemical-physical compatibility with the wood in the carved groove of the beam, covering the entire surface on which the sheet will be attached. The adhesive layer must be applied while the primer is still damp (Fig. 64a).
7. Positioning of the pultruded sheet in the carved groove of the beam and applying of a further layer of the specific epoxy adhesive over the sheet surface (Fig. 64c).
8. Applying of a thin layer of thixotropic epoxy adhesive over the exposed face of the sheet and spreading of dry quartz sand on the fresh resin to obtain an adequate surface for the adhesion of the paint, with a colour similar to that of the type of wood. Alternatively, instead of the sand and paint, a wooden strip obtained from the original wood can be laid over the "fresh" resin. In this case, the depth of the wooden strip must be counted in the total depth of the groove.

Fig. 64: Wooden beam strengthening with the use of an FRP pultruded sheet: applying of a special thixotropic epoxy resin in the beam groove (a); peeling of the dust protection ply from the FRP plate (b), positioning of the pultruded sheet (c)

While the operating procedure for the intervention with pultruded sheets positioned in carved grooves horizontally on the sides of the beam or vertically on the lower surface, is as follows:

1. On the lower surface of the wooden beam or on the sides, carve the notches by means of milling, for a depth equal to that of the sheet that will be inserted, increased by 5-10 mm, and a length equal to that of the pultruded sheet (Fig. 65a).

2. Prepare the wooden surface preferably within 24 hours prior to priming (see next point), to avoid superficial oxidation phenomena and contact with pollutants and dust. The elements before being treated with the primer must be left air conditioning in the intervention area, since it is essential that the moisture content in the element to be repaired has to be ± 3% of that of the service conditions, so to minimize the dimensional variations and the consequent development of tensions between the parts to be bonded.
3. Priming of the inner surfaces of the notches with the use of a specific fluid epoxy product, in a water-based dispersion, with high and documented chemical-physical compatibility with the wood, taking care that the impregnation is carried out until the product is no longer absorbed by the wood. The primer must be applied with successive treatments.
4. Cutting (with diamond blade) of the pultruded sheets as indicated in the project tables. Before positioning the sheets, remove (if present on the sheets) of the single or double protective film (recommended) in plastic material (peel-ply), that has the function to protect the sheets surfaces from dust and dirt during handling and cutting.
5. Applying of a specific epoxy adhesive with thixotropic consistency, with high e documented chemical-physical compatibility with the wood in the notches of the beam, to saturate the entire volume. The adhesive layer must be applied while the primer is still damp.
6. After applying of a further thin layer of the specific epoxy adhesive over the surfaces of the sheet, insert the pultruded sheets in the carved notches in the beam (Fig. 65b, c, d).
7. Manually remove the excess resin from the pocket with a spatula.
8. Applying of a thin layer of thixotropic epoxy adhesive over the exposed face of the sheet and spreading of dry quartz sand on the fresh resin to obtain an adequate surface for the adhesion of the paint, with a colour similar to that of the type of wood. Alternatively, instead of the sand and paint, a wooden strip obtained from the original wood can be laid over the “fresh” resin. In this case, the depth of the wooden strip must be counted in the total depth of the groove.

Fig. 65: Intervention through FRP sheets: carving the notches with a wood cutter (a), manual removal of the excess resin (b), positioning of the sheets (c and d)

During the various operations, take care to respect the following indications:

- Use cutting tools of appropriate shape and size, always kept well sharpened (absolutely do not use blades, bits or cutters for iron or concrete);
- Provide suitable supports so that the tools won't deviate when the blade meets wooden knots;
- Remove the chips often to prevent them from pressing on the surfaces causing friction and heating;
- Clean the surfaces from dust, shavings and splinters.

A1.2 Concrete slab

The system has been widely used for decades and extensively studied both from an analytical and experimental point of view. The composite section has a larger bending stiffness than the original floor and therefore, besides the bending capacity increase, a considerable reduction of the bending deformation is obtained. The new concrete slab stiffens the floor also in its plane (rigid diaphragm), when adequately connected to the load-bearing walls, allowing a correct transmission and distribution of seismic actions to the shear walls.

Before starting any intervention, the loads acting on the beams must be temporarily supported with floor props, so to avoid that the weight of the concrete slab before its hardening causes an increase of the existing flexural deformation of the floor.

The application procedure of the strengthening technique is very straightforward and concerns the following phases:

1. Demolishing of the existing flooring up to the planking;
2. Installation of a thin breathable and waterproof layer on the planking, turned up on the perimeter for at least the designed concrete slab thickness;
3. Installation of the timber-concrete connectors (nailed or injected) in line with the wooden beams at the designed distances;
4. Installation of the connectors of the new slab with the perimeter walls by drilling inclined holes in the masonry, inserting steel rebars (e.g. 1Ø16/m) and filling of the holes with a high resistance anti-shrinkage mortar or epoxy resin;
5. Positioning of the designed reinforcement steel bars and meshes;
6. Casting of the concrete slab.

It is also important to check that a good connection is guaranteed between the concrete slab and the wooden joists.

A1.3 <u>Interventions with tie rods</u>

In the case of multi-storey masonry buildings with several floors, the ties are placed at floor levels and positioned below them. As a basic criterion to be pursued whenever possible, and imperatively in the case of floors that do not guarantee an adequate contrast to the compression action (because of degradation, lack of size, etc.), the ties must be positioned adjacent to the transverse walls, both because they provide an effective contrast for the compression, and because this ensures an efficient connection between orthogonal walls. The most effective arrangement is a pair of twin ties (coupled ties) placed in parallel, on both sides of the same wall and connected to the timber element (Fig. 66).

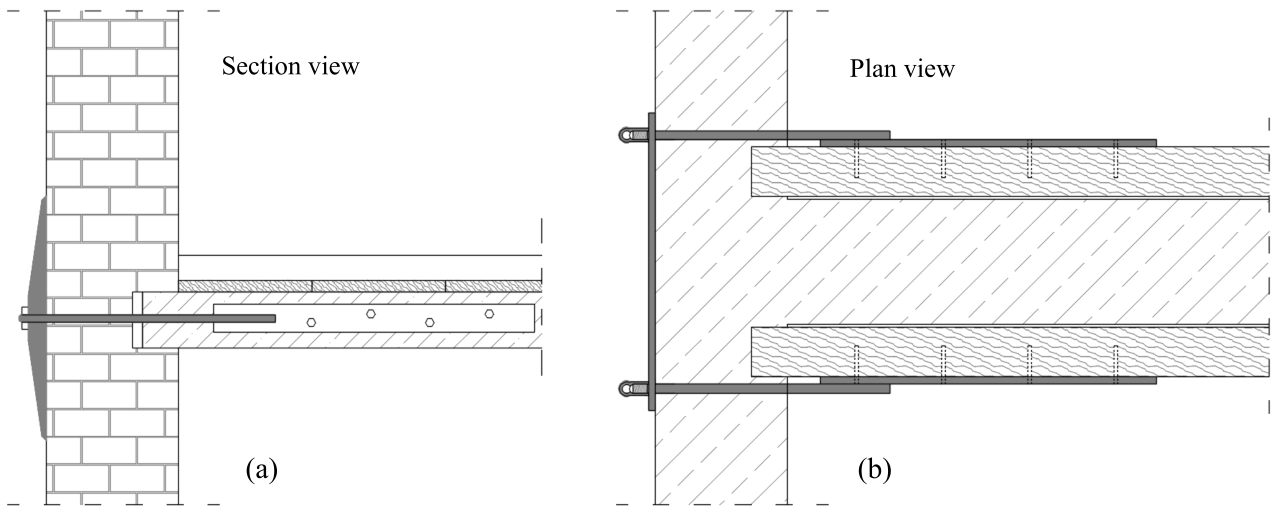


Fig. 66: Section (a) view of a simple tie rod adherent to the transverse wall at floor level and plan view (c) of coupled tie rods adherent to the transverse wall at floor level (ReLUIS 2011).

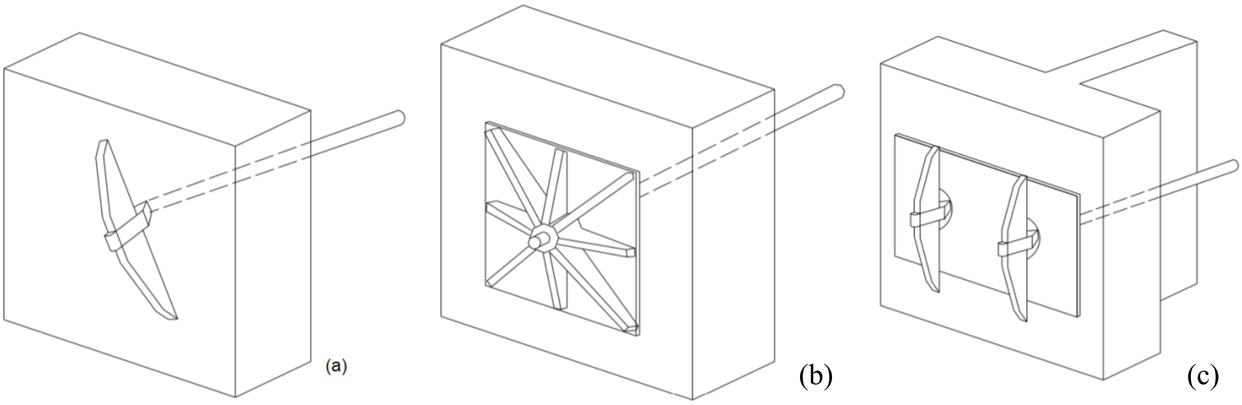
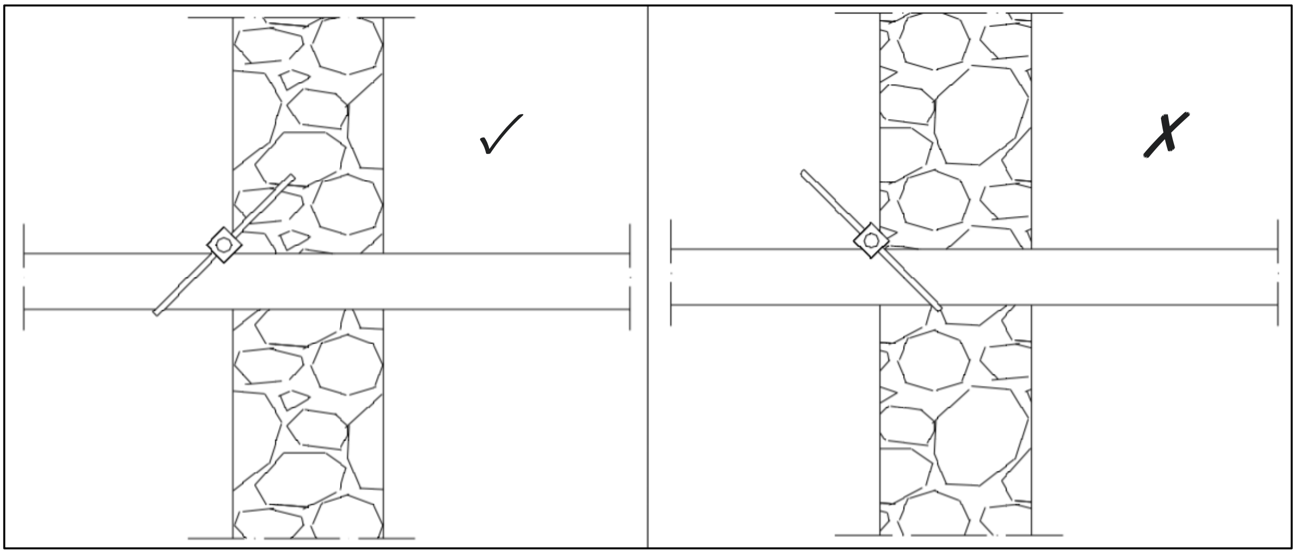


Fig. 67: Different types of anchor heads: stake type (a), ribbed plate (b), double stake and plate (c) (ReLUIS 2011)

In the case of a stake anchoring heads, the stake must not be positioned neither vertically, nor horizontally (Fig. 67a). The angle at which the stake should be positioned, must be chosen based on the placement of the local structures that can react to the anchor force. In Fig. 68 it is shown the correct position of the stake.



(a) *(b)*

Fig. 68: Correct placing of stake anchor heads (a) and incorrect one (b).

The pre-tension can be applied in two main ways:

1. By means of heating, according to the following execution phases:
    1. Tie rods and anchor heads disposition;
    2. Verification of straightness along the development of the tie;
    3. Slight pre-tension of the ties, by inserting the wedges in contrast in the anchor heads;
    4. Heating with suitable equipment of the central section of the tie rod, until loosening of the wedges and reaching the calculated elongation;
    5. Slight forcing of the contrasting wedges on the anchor heads;
    6. Cooling of tie rods.
2. By means of threaded ends (Fig. 69), the pre-tension is applied by tightening the nut at the threaded end, until the calculated elongation is reached. As an alternative to this method, the pre-tension can be applied using a double threaded intermediate tensioning sleeve with opposite threads left-right (Fig. 70). This type of pre-stressing of the ties allows for the following advantages:

- Possibility of restoring the right degree of tension over time of the chain (steel stress relaxation behaviour);
- A more reliable and controlled pre-stressing procedure;
- An easier installation process in the case of longer ties, since the tie is formed by two pieces of limited length.

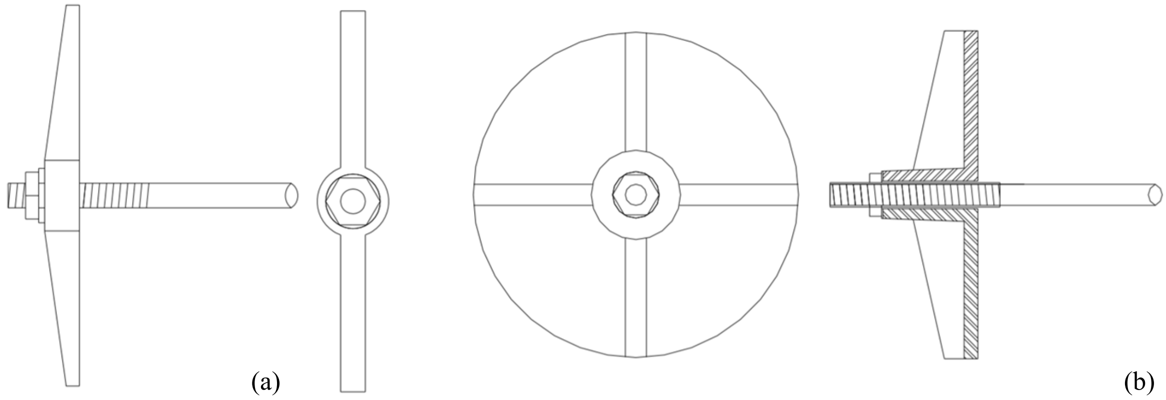


Fig. 69: Threaded ties: tie with end nut and holed anchor head (a); circular cast iron anchor (b)

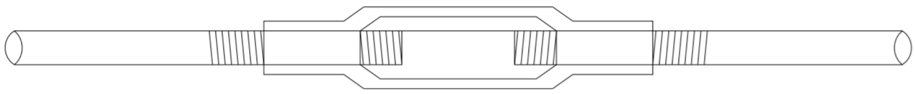


Fig. 70:Double threaded intermediate tensioning sleeve with opposite threads

The operating requirements for the installation of the tie rods are:

- The holes must be drilled with the use of a non-hammering drill, to avoid disconnections in the texture of the masonry walls;
- The support area of the plates must be carefully prepared with a regular and flat bed of cement mortar of appropriate mechanical performance;
- The tie rod will be pre-tensioned only after the mortar aging;
- The tie rods must be protected from weathering.

The bars or strands can be inserted into little grooves along the walls. In the corner of masonry, adequate distribution plates have to be used to protect the damage of the masonry (Fig. 71).

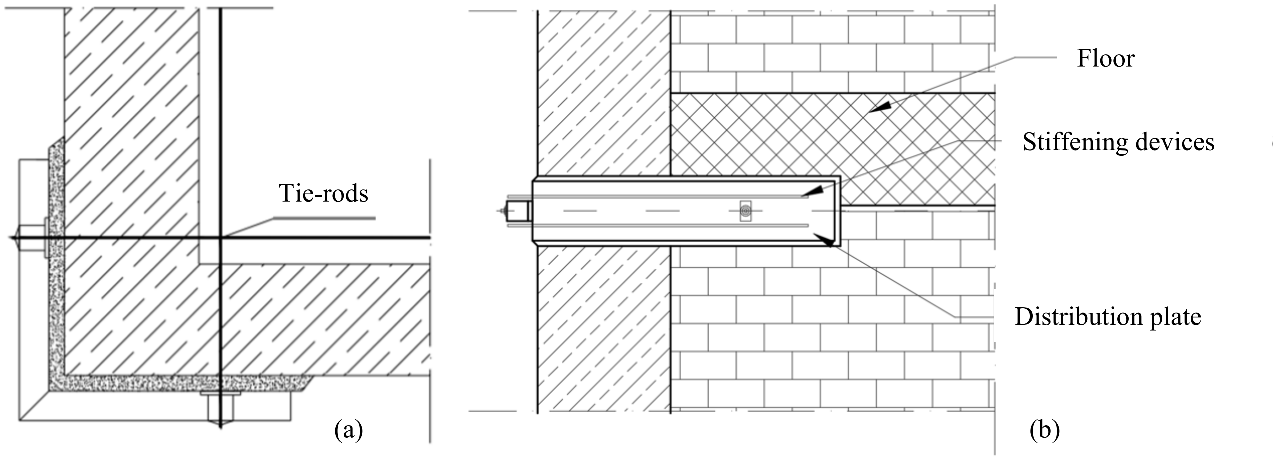


Fig. 71: Double angle tie rod: plan view (a) and perspective view (b)

A2 Interventions to increase capacity and ductility of masonry walls

As stated above, various strategies may be used to increase the shear resistance and the ductility of the masonry walls of existing constructions. In the following a description of the application phases is presented for the techniques:

- Grout injections;
- Reinforced cement mortar coating;
- Artificial diatons;
- FRP (Fiber Reinforced Polymer);
- CRM (Composite Reinforced Mortar);
- FRCM (Fiber Reinforced Cementitious Matrix).

A2.1 Grout injections

The operating procedure for grout injections is as follows:

1. Removal of the plaster and cleaning of the intervention wall surface;
2. Choice of injection points based on the type of wall structure and the crack pattern. Indicatively, the hole system will have a centre-to-centre distance between holes of 200-250 mm for solid brick masonry, up to a maximum of 400 mm for mixed masonry.
3. Drilling of the holes in the selected points with the use of a non-hammering drill, with an indicative diameter of Ø 16-20 mm. The depth of the perforations should be approximately 2/3 of the wall thickness. For thicknesses up to 60 cm it will be sufficient to work on one side of the wall only, for more consistent thicknesses it will be appropriate to work on both surfaces. The perforations must be conducted in the mortar joints.
4. Cleaning the holes with compressed air;
5. Sealing of the joints between bricks, stones, cracks and discontinuities with restoration mortar;
6. Positioning of the flexible plastic injection nozzles, indicatively with a diameter Ø 12-16 mm in correspondence with the holes to be injected, to a depth of at least 100-150 mm and sealing them with epoxy resin;
7. Saturation of the internal structure of the masonry with water, injecting it through the injection nozzles already prepared, to eliminate dust and saturate the original materials which would tend to dehydrate the injection mixture. In this way it is also possible to verify the existence of hidden injuries and/or fractures thanks to water leakage from the masonry. This operation must be performed at least 24 hours before carrying out the consolidation injections, to allow the elimination of stagnant water in the masonry;
8. Preparation of the injection binder mixture;
9. Proceeding from the bottom up and from the sides towards the center, the injection mixture is injected at low pressure (less than 0.2 MPa) to avoid the formation of over-pressure inside the wall mass. For very deteriorated masonry walls that do not withstand overpressures, it is possible to proceed with injections by gravity. The application of the product from the bottom upwards allows the air to come out, favouring a better filling of the gaps. The injection of the mixture must be carried out with manual or automatic grout pumps. Should the operation be performed manually, inject the product with needle syringes of adequate diameter and capacity. The pressure must be kept constant until the mixture escapes from the adjacent holes. The holes are then closed with wooden wedges and the consolidation continues respecting the foreseen work plan;
10. After the mixture has hardened, the nozzles are removed, and the seats are sealed with mortar.

The injection mixture will be made with a cement-free, pre-mixed hydraulic filler binder, based on eco-pozzolan and selected fine aggregates. The binder used for the injection mixture must be free from water-soluble salts (it must not negatively interact with any pre-existing sulphate salts in the structures to be consolidated, nor must it contain alkaline components like sodium and potassium, capable of triggering dangerous expansive phenomena with the stone elements alkali-reactive) and be able to achieve dimensional stability in a short time.

A2.2 Reinforced cement mortar coating

The operating procedure of the reinforced cement coating is as follows:

1. Removal of the plaster and cleaning of the intervention wall surface;
2. Removal of approximately 10÷15 mm of mortar from the joints on both sides;
3. Drilling of the holes with a rotating tool (core drill) for the insertion of the connection brackets;
4. Removal of debris and cleaning of the surfaces with water;
5. Insertion of the bars, approximately 6Ø(5÷6)/m^2 of wall and injection with un-shrinkable mortar;
6. Application of the first layer of cement mortar (e.g. grout) for ~15 mm;
7. Implementation of the welded steel mesh and it's connection with the brackets;
8. Application of the second layer of cement mortar (~25-35 mm).

A2.3 Artificial diatons

The procedure for installing artificial diatons is as follows:

1. Removal of the plaster and cleaning of the intervention wall surface;
2. Drilling of the hole with a rotating tool (core drill);
3. Insertion of the stainless-steel bar embedded in the mesh fabric sleeve;
4. Injection of the grout in the sleeve until complete filling of the hole.

A2.4 FRP (Fibre Reinforced Polymer)

When applying this strengthening technique two main approaches may be followed: Externally Bonded (EB) FRP and Near-Surface Mounted (NSM) FRP.

Externally Bonded (EB) FRP sheets or plates and, more recently, Near-Surface Mounted (NSM) FRP bars or strips, are the two application techniques that are commonly used.

When Externally Bonded (EB) FRP is employed, polymeric sheets or plates are applied to the surface of the masonry to be strengthened. In this case, the strengthening technique concerns the following steps:

1. Preparation of the wall to be strengthened via sandblasting and puttying;
2. Application of fiber sheets by manual lay-up to the surface of the wall to be strengthened;
3. Fibers are impregnated by an epoxy resin, which, after hardening, enables the newly formed laminate to become a part of the strengthened member.

When the NSM technique is employed, FRP composite rods are placed into groove cuts onto the surface of the element to be strengthened. In this case, the strengthening technique concerns the following steps:

1. Cutting of the grooves into the surface of the element to be strengthened;
2. The groove gets filled with an epoxy-based paste;
3. The rod is then placed into the groove and lightly pressed to force the paste to flow around the rod;
4. The groove is then completely filled with more paste and the surface is levelled.

The NSM technique provides several advantages over EB reinforcement, which include:

- Significantly higher debonding protection;
- Protection from the environment;

- Minimal impact upon the aesthetics of the structure;
- Reduced construction time, thus providing a minimally invasive option for seismically strengthening URM buildings and reduced cost.

A2.5 CRM (Composite Reinforced Mortar)

The application procedure of the strengthening technique concerns the following phases:

1. Removal of the existing plaster and the mortar from the joints between elements, 10-20 mm deep, on each wall face;
2. Application of a layer of cement scratch coat;
3. Drilling passing through holes, indicatively 25 mm in diameter, to allow for connectors insertion, indicatively 6 connectors per square meter;
4. Application of the FRP mesh on both faces;
5. Insertion of L-shaped connectors, usually made of FRP and injection of thixotropic epoxy resin inside the holes to fix the connectors to the masonry;
6. Application of the new lime mortar coating, around 30 mm thick.

A2.6 FRCM (Fibre Reinforced Cementitious Matrix)

FRCM strengthening systems, in the case of a single-ply fabric application, have a thickness ranging between 5 and 15 mm, excluding the levelling of the substrate.

The application procedure of the strengthening technique concerns the following phases (Fig. 72):

1. Preliminary preparation of the surface, which can be mechanically roughened to enhance adhesion;
2. Application of a first layer of mortar, followed by the positioning of the textile by means of a trowel;
3. Application of the final layer of mortar on top of the textile material.

Fig. 72: Strengthening technique: FRCM system

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