Stone masonry walls: Strengthening with TRM (I)

J. T. San-José, D. Garcia, R. San-Mateos & J. Díez
Labein – Tecnalia, Spain

ABSTRACT: The purpose of this paper is to present the state of an investigation aimed at strengthening decayed stone masonry walls with textile reinforced lime-cement mortars (TRM). The proposed solution could be applied by itself or jointly with other techniques of reinforcement, like sewing or injections, to guarantee the integrity of the wall. The validation of this strengthening system is carried out by a laboratory test campaign. The experimental study is based on the typology of the Spanish Romanesque walls, a plentiful constructive element in this country. The validation of the solution is being done by means of a characterization of the individual materials (stone, mortar, TRM), designing of the anchor system and construction, strengthening and testing of 1/3 scale stone walls. The wall specimens have been erected with the same configuration of the original ones. They are three-leaf masonry walls with an inner core made of low quality mortar and rough-cut sandstone pieces (remains from rough-shaping of the stones), poured between the two external layers, and they are deflected a common structural damage in these elements.

1 INTRODUCTION

The use of Fibre Reinforced Polymer (FRP) is becoming a common practice in the strengthening of masonry civil structures (ACI, 2002). Furthermore, these FRP systems seem to be a promising solution for cultural heritage, as in some occasions they could be reversible solutions, flexible to be applied in a wide range of structural elements and shapes, providing clean, safe and cost effective restoration techniques, requiring minimum intervention in the monument.

However, these systems that are currently designed and used for civil works (Bakis, 2002), required further development and research as per the following aspects have not been solved until now:

– Organic resins, used as matrix to encapsulate and bind the fibres and to bond the FRP laminates to ancient substrates, are incompatible with these existing heritage materials. They are also vulnerable to humidity and high temperatures.

– The fixing and anchorage systems are of a very limited efficacy, as they are designed basically for concrete substrates, thus compromising the reliability of these systems applied to decayed substrates of heritage structures (San José, 2006). The actual anchorage systems in civil works imply high visual impacts by using bolted metallic plates, steel profiles around the edges, high anchorage lengths affecting annexed elements, etc.

Consequently, new ideas have to be established for the heritage structures by combining advanced composites and light additional fixing systems to the substrates, such as simple bolting, FRP mats, inorganic mortars, etc (Casareto, 2002). One possible solution could be the substitution of the organic binder (polymer) by an inorganic mortar, lime or cement based, compatible with the specific materials used in each structure. Another issue is that with mortar as a matrix of the composite strengthening system, the fibres should be in a textile format instead of fabric.

The properties, the amount and the arrangement of the used fibre materials have a great influence to the characteristics of the composite. Requirements on the fibres are: high fibre tenacity, a modulus of elasticity much higher than that of the mortar matrix, small relaxation under permanent load, a good and constant adhesion between reinforcement and mortar, low cost and the possibility of processing them easily on textile machinery. Alkali-resistant man-made glass fibres (AR-glass), carbon and aramid essentially meet these requirements for the design and fabrication of textile reinforcements.
This new structural material, namely textile reinforced mortar (TRM), was developed as an evolution of short-fibres reinforced concrete, in order to obtain very thin-structured concrete elements with a high strength in compression as well as tension.

The results obtained from preliminary studies on the use of TRM as a strengthening solution of unreinforced masonry walls (Triantafillou, 2001) can be extended to heritage masonries where the use of epoxy resins is prohibited. For these masonry elements, a lower strength TRM system than for reinforced concrete structures will be suitable. Hence the use of lower properties fibres than carbon, for example AR-glass or basalt fibres can be adopted.

The need of a low cost TRM system is obvious, since there are many thousands of heritage buildings around the Mediterranean and many of them in countries where the cost is of major importance for the governments to fund a heritage monuments strengthening project. In a TRM system, mortar's cost is low compared to textile cost. Hence the cost of textile is predominant. For this reason the carbon and aramid high cost fibres are not suitable.

The expected results of this strengthening system are: an increase in ductility and tension/shear resistance, a decrease of cracks by located tensile loads and an improvement in the general behaviour, especially at the failure moment.

2 CONCEPT OF THE PROPOSED SOLUTION

Related to the TRM application as strengthening system on historical masonry structures, nowadays, there are in course multi-year development efforts regarding its ability to retrofit un-reinforced masonry walls (URM). The objective is to establish the adaptability of a full-compatible and highly durable structural strengthening system based in TRM, including:

- The strengthening core: a technical fibre textile, adaptable to strengthen different structural elements (vaults, aches, walls) and substrates (masonry, adobe bricks and timber).
- Fixing system: based on mortars or/and in anchorage devices, in case of need.
- Conditioning and finishing mortars: based on modified or lime-cement mortars, such as a compatible interface between the substrate and the TRM and improving its aesthetic integration. The effectiveness of any externally applied reinforcement is highly dependant on the bond between the composite and the substrate, therefore the interface behaviour is one of the key issues in the structural analysis.

The validation of the strengthening system is carried out by a lab test campaign, regarding characterization of the materials (stone, mortar, masonry and TRM), the design of suitable anchorage system and the construction, strengthening and testing (under static loads) of nine real stone walls made at 1/3 scale.

These structural tests were defined from the knowledge of this type of masonry (typology, materials, etc.) and the structural behaviour connected to the specific deficiency to eliminate. Therefore, a particular attention was taken in choosing the geometrical and the morphological characteristics and the constituent materials of the walls to test, to make them as much as possible representative of the Spanish Romanesque real typology, available in situ.

3 TEST CAMPAIGN

A set of nine walls was constructed with low strength lime-cement mortar and sandstone units, representing Spanish Romanesque walls and similar to walls often found in historical urban centres., with two external leaves and an internal core of rubble material. Both of them have the external leaf made of ashlar masonry and the internal leaf made of rough masonry. The walls are deflected, a common structural problem in these elements, having the following nominal dimensions: 2 m wide, 2 m high, 0,3 m thick and a 5 cm deflection, from the half height to the top.

3.1 Masonry

Two types of stone were used for the walls. For the ashlar masonry leaves, Sandstone1, a uniform fine grain sandstone rock, was used. It was received in
big blocks, and afterwards, it was cut in a cutting machine of samples with a diamond disc. For the rubble masonry leaves, Sandstone2, a darker rock, was used. It was received as irregular blocks and they were break manually by the bricklayers.

Cores of Ø30 mm were taken from these stones and tested, obtaining the following mechanical properties:

- Density (kg/m³) 2090 2066
- Compressive Strength (MPa) 36,20 64,60
- Flexural Strength (MPa) 6,28 5,14
- Elasticity Modulus E (MPa) 10.468 10.620
- Shear Modulus G (MPa) 4.046 4.635
- Poisson Ratio 0,3 0,15

In spite of the numerous attempts to obtain the compressive strength of the stone masonry from its typology, geometry and mechanical properties of units and mortar, up to now, prisms testing is an essential approach to know the behaviour of the entire walls under compression loads.

Additionally to the walls, prismatic specimens were casted with the same materials and configuration for each of the leaves. They were built over steel plates to facilitate the transport and assure the flatness on the universal test machine. Their dimensions are 50 cm wide, 40 cm high and 30 cm thick. The prims were stored inside, in an area free of drafts, monitoring the temperature and relative humidity of the curing environment (18–25°C and HR 60–85%).

Prisms were tested at the age of 150 days, with load velocity control under uniaxial compression load, in a universal compression test machine, recording the development of cracks and the values of stresses and displacements. In the table below, the ultimate compression stress ($f_M$) and the stress corresponding to the first crack is included ($f'_M$). A deformability modulus was also calculated considering the area of the initial cross section and the strain at ultimate stress.

The following conclusions were obtained:

- Dry ashlar masonry has the highest deformability modulus and more load capacity than the other combinations under compression load.
Ashlar masonry with bed mortar joints possesses the most uniform behaviour, with a slope of the strain-stress line practically constant.

### 3.2 Textile reinforced mortar

Textiles of TRM systems can be made of various types of fibres. However the basic architecture of a textile used in a TRM system is the same regardless the type of fibres used. A bidirectional textile at 0/90 degrees made of basalt fibres and with grid square openings of 25 mm has been adopted as preliminary design of the TRM system in this experimental research.

The basalt fibres have excellent alkali resistance, similar mechanical properties to glass, good fatigue resistance and much lower cost than carbon or aramid fibres. Basically, basalt is a natural material that is found in volcanic rocks with a melting point of about 1400°C, which can be found all over the world with differing chemical compositions. Basalt fibres show excellent natural adhesion to a broad range of binders, coating compounds and matrix materials in composite applications. This property can be further enhanced through optimized surface treatment.

The effectiveness of any externally applied reinforcement is highly dependant on the bond between the composite and the substrate. Therefore, the interface behaviour is one of the key issues in the structural response (CEB-FIP, 2001).

The characteristics of mortars that have to be taken into account are the workability, the rate of hardening and the shrinkage for the fresh mortar, and for the hardened mortar, the appearance, the moisture and air permeability, the compressive and tensile strength, the adhesion, the ability to tolerate movements and of course the wetness, frost and salt resistance.

In this context, the most important characteristics of the mortars are:

- Chemical and physical compatibility with the substrate. Mortar makes the environment in which stones must live. If stones and the walls made from them are to remain healthy, mortars and renders must be as compatible as possible with the stones they live with. In this context, cement based mortars are not recommended for this application.

- Resilience or flexibility to allow building deformation without causing substantial wall cracking. In this context, lime binders/mortars offer significant advantage over other types of binders, particularly the cement based ones, in that it remains slightly flexible, even when set and will allow the walls to move without developing large cracks. Another important characteristic of lime mortars, when compared to other types of mortars, is that it can self-repair/heal fine cracks. This occurs as a result of the rainwater slowly depositing fresh calcium carbonate taken into solution from the surrounding mortar.

- Water vapour permeability. It is very important that mortars are porous enough to allow moisture to pass through them and evaporate. This helps to keep houses dry and makes a healthy atmosphere inside. When the moisture level rises in the stone walls, lime plasters would allow the moisture to evaporate easily. Damp walls that have been rendered in waterproof cement will become wetter because moisture trapped behind the render will naturally rise to new and higher levels within the wall. This action can also damage and weaken walls as a result of salt, dissolved in rising moisture, crystallizing in the mortar behind the render and breaking it up.

A common mortar, used for rendering, plaster or as a finished coat, has been adopted. The dosage is 1-0,5-5 (white cement – lime – sand), with a maximum grain size of 2 mm. This mortar has been used for years to the inner leaf of Romanesque walls, demonstrating a good water vapour permeability and enough flexibility to allow deformations in the masonry building without cracking.

With this mortar and the selected technical textile of basalt fibres, previous tests were done in order to see the compatibility between resistant core and inorganic matrix. Flat specimens (fig. 6) were made for tensile test and textile reinforced mortar prisms (4 × 4 × 16 cm) for bending test.

Based on the test results the following comments can be done:

- The joint mortar-textile is highly dependent of the application procedure.

- Compared with glass-bitumen-coated textile, basalt fibres grid has less geometrical stability but a better adherence fibres-mortar because of a major wet effect of the yarns by the mortar.

- Ultimate failure under tension for basalt textile is less ductile than for glass-bitumen-coated textile but
in any case, TRM have a more ductile failure than FRP.
– The maximum load, both in tensile and flexural tests, is increased by the presence of the textile. Once the crack appears, the specimen is able to continue holding more load.

The knowledge of the cracking process is of crucial importance in calculating the load-bearing capacity, the deformation behaviour and the limiting values in designing the serviceability. The cracking distance and the crack width are determined by the reinforcement and bond characteristics. Cracking is determined not only by the stress but also by the bonding action between the textile reinforcement and the mortar matrix.

One of the main differences between short fibre reinforced concrete (FRC) and TRM is the design philosophy at ultimate load. FRC obtains its ductility from fibres to be pulled out of the matrix. For FRC the pull out load has to be always lower than fibre strength. TRM in contrast obtains its ductility from the fibre breaking strain.

### 3.3 Anchor devices

For the case that used mortars will not meet the required minimum properties, because of the low quantity of cement component, an anchoring technique of the TRM system on the substrate will be applied. The anchorage system has to be simple, easy to install and low cost. Fibre anchors have already been developed and have been used extensively in FRP systems (San José, 2007). Testing prove that similar fibre anchors can also be used with a TRM system.

At a first stage, these anchorage systems were tested jointly with the TRM for the evaluation of bond strength by two different experimental approaches: pull-off test and shear test, by using concrete cube specimens such as reference material.

Before the pull-off testing, the free external fibres were combined together in a yarn form, which was saturated with an epoxy resin to form a plate as illustrated in fig. 8, left. Whereas, for the shear test, the free ends of the textile were enfolded with a piece of rubber, and then enclosed into the grips of the testing machine, as shown in fig. 8, right.

Generally, all pull-out tested specimens failed by rupture of the fibre anchors, while the textile and the adhesive joints still intact with the concrete substrate. Concerning shear test, specimens failed by fracture of the adhesive joint at different load levels, or rupture of the basalt textiles. On the contrary, no failure was observed in any of the anchor devices employed. The following step will be the validation and adaptation of this proposed anchorage system with decayed substrates, usually low strength mortars.

### 3.4 Wall specimens construction and strengthening

Nine wall structures of $200 \times 200 \times 30$ cm were constructed by expert masons in Heritage interventions, with the same configuration of the historic original ones (Valluzzi, 2004). They are intentionally deflected, a common structural damage in these elements, and they have an inner core made of low quality mortar and rough-cut sandstone pieces (remains from rough-shaping of the stones), poured between the two external layers, like real three-leaf stone masonry walls.

Walls foundations were built on steel permanent moulds (length 2 m, wide 60 cm and high 30 cm). These metallic bases were filled in with bigger stones than the rest of the walls units and a more competitive mortar (1-0,5-5). The intention of it is to reproduce the natural foundations of the real walls, maintaining their boundary conditions.

855
Ashlar masonry leaf is made of perfect prismatic sandstone units (18 × 9 × 9 cm) bonded by bed joints of poor mortar. Rubble masonry leaf is made of irregular stones, with a maximum size of 35 cm, and bed and head mortar joints. The space between both leaves was filled up with mortar and irregular stone fragments.

The walls were built in three stages, halting their construction to three successive heights, because of the fall risk due to the low strength of the used mortar.

The shape of the cross section was obtained with auxiliary guides. This way, all the walls have similar external geometry. The first meter is perpendicular to the ground. From that point, the wall begins a curve, reaching a horizontal deflection of 5 cm at the top.

Connection between external leaves is obtained through the mortar internal core and some key stones. These are ashlar units placed tangentially to the plane of the wall, without appearing on the irregular masonry leaf (fig 9, left). The last 4 walls have a narrower layer of inner filling mortar and more stones keys than the other 5.

After five months of the building date, a finishing mortar layer, jointly with two different strengthening solutions, was applied to the walls:

- Transversal sewing with FRP bars. The main scope of this technique is the improvement of the connection between the leaves and the consequent reduction of the transversal deformations. Six low modulus CFRP (Ø7.5 mm) bars were used for each wall (around 1.5 bars per m²), inserted into holes (Ø12 mm) drilled approximately at 1/3 of the height from the bottom and the top, and at 1/4 of the width from the left and the right sides of the wall. The holes were executed through corresponding irregular masonry mortar joints, without crossing completely the ashlar masonry in order to not affect the external appearance.

- Surface treatment with TRM on one side. In some cases, the render mortar layer at the irregular masonry face has been reinforced in one or two layers with the technical basalt textile. Furthermore, the TRM is anchored to the wall by means of fibre anchor devices (around 10 per m²). The thickness of the strengthening layer is less than 2 cm. In case of application on an even surface, TRM thickness could be just a few millimetres.

A summary of the interventions is presented in the above table.

### 3.5 Test setup

The nine wall structures were tested under vertical compression load, by means of two hydraulic jacks and a metallic frame, under static conditions.

The frame is composed of two metallic groups of welded steel profiles, under and below the wall. The first group was positioned over the two jacks and it was rigidly connected, by means of four steel rods, to the second group at the foundation of the wall. There are additional steel profiles between the jacks and the top part of the wall. The load is transmitted through a 2 cm mortar layer to avoid stress concentrations.

The specimens were instrumented with 8 horizontal and 8 vertical inductive displacement transducers and
various strain gauges placed on the reinforced mortar and the visible face of some ashlar units. Two load cells measured the applied load. A data logger was used to register the data of the referred sensors and the time. In addition, the crack pattern was noted manually for each load level and a video camera registered the deformations in the cross section of the wall.

The compression was applied by successive load steps. The time between two steps was around 5 minutes. During this period, the deformations and cracks were examined and registered. In this way, the complete test took from 90 to 120 minutes.

Due to the size of the specimens, high load values and the brittleness of the masonry, careful safety measures were adopted. Therefore, the tests were performed by placing a scaffold box around the test frame.

3.6 Expected failure modes

The ultimate load is related with the failure mode. With this test configuration it is difficult to generate a local crushing zone because punctual loads were not applied. Exhaustion of the material is also improbable. The expected structural failures are the following:

- Swelling up of the outer leaves due to the poor connection and the low strength of the inner filling mortar.
- Buckling due to insufficient union of the leaves or eccentricities.
- Overturning of the head or the total the wall. These phenomena can appear by two causes, mainly: horizontal loads that generate a torque respect to the starting of the walls and problems of lying of foundations of the walls.
- Cracking by local tensile stress. In case of foundations in good conditions and leaves properly connected, the horizontal components of external loads can develop a stress state with tensile zones in the masonry. The low tensile strength of the structural element will be improved by the reinforced mortar, restricting the propagation of cracks at the same time.

3.7 Results

At the moment of writing this proceeding, the test campaign is in course. Four specimens have been tested, including the reference wall of each series. From the test results, the following comments can be done:

- Ultimate loads correspond quantitatively with the expected values. However, obtained loads are much higher than the compression strength provided by standards and traditional equations.
- Sewing with FRP rebar procedure has not been correctly executed. The failure mode in all the structures was originated from a disconnection of the ashlar masonry leaf from the rest of the wall. This indicates that the length anchorage in the ashlar units is not enough to generate a benefit. On the
other hand, there are a lot of cases where architectural requirements do not allow to cross or to even partially bore the stone units. In these situations a different approach must be carried on, placing the rods into the mortar joints and using anchor devices.

– Strain gauges on the face covered with mortar have revealed positive deformations in certain zones of the wall. The presence of tensile tensions is not easy to locate by conventional methods when the structure is damaged or there are structural deformations that affect geometry. These tensile loads can be partially assumed by the textile of the TRM.

– The combination of surface treatment with TRM and sewing with low modulus CFRP rebar has allowed to increase the ultimate load a 13% for a wall of the first typology (M5) respect the reference wall (M1).

Complete results and final conclusions of this experimental investigation are expected at the beginning of 2008. The analysis of the data will provide high value information.

– A better understanding of the behaviour of the masonry, specially the natural stone walls, and the capacities of the promising strengthening techniques previously described: surface treatment with TRM and sewing with rebar (increase of the bearing capacity, improvement of the failure mode, increase of the ductility, etc).

– A next generation FEM model will be calibrated. This model will consider the typology of the stone walls, the connection or adherence between leaves and the presence of reinforcements like the applied ones.

4 CONCLUSIONS

The effectiveness of TRM as a means of strengthening stone masonry walls is investigated in this study. The following conclusions are stated from the concluded works:

– The FRP, in its different formats (strips, rods, sheets or sheets), has probe to be a reasonable solution for the reinforcement of masonry structures. However, actual trends are focused in a more compatible technique (TRM).

– Materials cost of the intervention is significantly reduced. Lime-cement matrix is between 6 and 10 times cheaper than epoxy resins. Similar researches (Triantafillou & Papanicolaou 2005) on regular masonry have demonstrated a certain improvement of the mechanical properties, even with low cost fibre textiles.

– In order to design the anchorage solution, it is necessary to consider the substrate material nature, its conservation status, the load history, the aesthetic requirements and the reversibility.

– By the application of TRM solution, reinforced elements can be obtained without increasing significantly the original weight, and even without modifying their external appearance.

– The strengthening intervention could be done while the structure is in service.

ACKNOWLEDGEMENTS

This research is being financed by EU Commission through the OPERHA 517765 contract and the Basque Government through the SISMU contract.

REFERENCES


CEB-FIP. 2001. Externally Bonded FRP Reinforcement for
RC Structures.