Bending and fatigue behaviour of  reinforced concrete and masonry elements, strengthened with FRCM  materials

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# Milestone #1 - State of the Art

## FOREWORD - On the vulnerability of masonry structures

Masonry constructions and framed reinforced concrete structures represents the bigger part of the whole existing  built heritage. Both the construction typologies  are characterized by a wide use of structural and non-structural masonry elements: structural walls, infill walls, arches, vaults etc. Moreover, the masonry-based buildings family get bigger if we enclose in it the huge amount of civil-engineering constructions like ancient railway bridges, aqueducts, viaducts etc.

In the face of such a wide dissemination, these buildings are characterized by high vulnerability when subjected to earthquakes events, due to the fact that unreinforced masonry structures are designed just for vertical loads, therefore the strength of masonry under out of plane actions is demanded only to the bond between brick and mortar and on the mortar mechanical properties.

The use of fibre reinforced composite systems, in the last years has become a common practice in civil engineering application, in order to remedy this vulnerability problem: it represents a light-weight, easy, fast and non-invasive solution for strengthening and retrofitting existing masonry and reinforced concrete structures.

## Fibre reinforced composite materials for structural applications

Fibre reinforced composite materials are heterogeneous and isotropic materials widely used in civil engineering applications. They are constituted by a fabric textile, like glass, carbon, aramid and steel, and an organic or inorganic matrix.

Fibre-reinforced polymers (FRP) composites, characterized by thermoplastic or thermosetting organic polymers, like polypropylene, ABS , polyester and epoxy, are nowadays the most shared composite systems for strengthening and retrofitting both reinforced concrete and masonry elements. The new sensibility about seismic safety of structures, developed in Europe and Italy in the last decades, steers the engineer community toward new solution for seismic upgrading. In this direction, the use of FRP strips as seismic retrofitting or upgrading system, is proved to be a very effective and easy solution instead of conventional methods (Triantafillou 2011),(Angelillo et al. 2014). Despite their numerous advantages, such as light weight, excellent mechanical properties, resistance to corrosion, ease of installation and good performance at failure (Triantafillou 1998), (Triantafillou and Papanicolaou 2013), (Babaeidarabad et al. 2014), these typology of composites presents some drawbacks, strictly related to the organic matrix they are constituted: poor behaviour at temperatures above its glass-transition temperature, poor fire resistance, lack of vapour permeability, irreversibility to the application and incompatibility of resin and substrate materials(Papanicolaou et al. 2006), (Cardani et al. 2016). This last aspect is fundamental when approaching a strengthening application problem on masonry structure, since the polymer matrix penetrate the porous substrate and changes its chemical properties and so become not yet removable. Furthermore, the different permeability to vapour  of FRP and masonry causes the impossibility of water and salt to evaporate and come out from the support.

These are the main reasons that lead the scientific community to consider the application of fibre-reinforced organic polymers not suitable for masonry elements and ancient substrate, and thus, to start new investigation on inorganic binder composite materials which ensure an higher compatibility with masonry, vapour permeability, durability to external agents (Orlowsky and Raupach 2007), (Butler, Mechtcherine, and Hempel 2010) and reversibility of the application.

Fabric Reinforced Cementicious Matrix (FRCM) strengthening systems are between the most recent and innovative composite materials that represents a valid alternative to FRP composites, solving more of its highlighted drawbacks . It consist of two components:  an high strength fibre mesh and an inorganic cementicious or lime-based matrix. The first component is the proper structural reinforcement element, is made up of different types of woven dry fibres, like polyparaphenylene benzobisoxazole (PBO), glass, aramid, basalt, carbon, or even hybrid PBO-glass grids, where the warp and weft yarns are passing over and under each other and are connected by friction or bonded together  by mean of glue or melting  (Carozzi et al. 2017), (Carozzi, Milani, and Poggi 2014), (Carozzi and Poggi 2015). The fibre grid is embedded within an inorganic binder, that is typically a grout system based on cement and a low dosage of dry organic polymers that ensure proper workability, setting time and mechanical properties. The matrix is responsible for the stress-transfer between the fibres themselves and between fibres and support, therefore the compound has to be designed to allow the better chemical and mechanical compatibility with the textile and the substrate (Leone et al. 2017)(Gonzalez-Libreros, DAntino, and Pellegrino 2017)(Carloni et al. 2015). As mentioned above, the novelty of this inorganic matrix composed material is its suitability with ancient substrate and masonry, in reason of the vapour permeability compatibility between them, in addition to the high resistance to fire and UV radiation, the indifference to high temperature, unvarying workability time and ease of handling during application(DAntino et al. 2015).

The available scientific literature about FRCM composites proved that they are affective solutions for shear strengthening (Blanksvärd and Täljsten 2011)(Ombres 2015)(DAntino et al. 2017),  for confinement of reinforced concrete elements subjected to combined compressive and bending stress  (“Concrete Confinement with Textile-Reinforced Mortar Jackets” 2006)(Ombres 2014)(Peled 2007)(Bournas et al. 2009), and for flexural strengthening of masonry and RC elements. Few experimental and analytic papers are available in literature about the fatigue behaviour of FRCM composites.

In the next chapters will be presented the state of the art about FRCM reinforced concrete and masonry joints behaviour under bending and fatigue loading and post fatigue flexural strength to failure.

## Bending behaviour of reinforced concrete and masonry elements strengthened with FRCM - SoA

In the last thirty years several experimental campaigns has been performed in order to analyse the behaviour in bending of FRCM strengthened masonry and reinforced concrete elements (Papanicolaou and Papantoniou 2010), (Brückner, Ortlepp, and Curbach 2006), (Elsanadedy et al. 2013), (Triantafillou 2011), (Ombres 2011), (Elsanadedy et al. 2013).

The results shown that these materials can be an effectively alternative to FRP composites in flexural strengthening. Despite the two composite technologies provide similar strengthening improvements, in most cases, FRP composites appear to be more effective than FRCM, on equal fibre cross section applications, due to the better fibre impregnation by the epoxy resin, when compared to the cement-based binder, which induces a uniform tensile stress among the fibres of the bundle.

The effectiveness of FRCM composites for ﬂexural strengthening of RC beams is usually evaluated performing four points bending tests, it’s commonly acknowledged that the load versus displacement behaviour for FRCM reinforced RC beam subjected to flexure loading, is well approximated with a bi-linear curve: a first linear branch up to the first crack; at this point a load reduction occurs, with load decrements between 25% and 50% of the achieved load, depending on the amount or textile reinforcement in the TRC compound. A second linear branch with a lower slope, representative of the post first crack response of the beams, dependent on both the textile reinforcement ratio and the yarns-to mortar bond characteristics. In this phase the distributed cracks appeared and relative slippage developed at the interface between the mortar and the uncoated carbon filaments (Papanicolaou and Papantoniou 2010), (Hashemi and Al-Mahaidi 2012).

Experimental performed on RC elements shown that the majority of the FRCM strengthened beam specimens failed due to the loss of composite action related to the debonding of the strengthening material from the support. The debonding can occur in different way: (a) at the matrix-fibre interface with high matrix-fibre slip, in this case the total forces carried by fibres gradually decreases due to their gradual friction rupture. Sometimes, after the slippage, delamination with fraction surface within the matrix may occurs, essentially related to the matrix-fibre bond properties (Pellegrino and D’Antino 2013). (b) at the matrix-concrete interface, resulting in a very brittle failure mode, related to the poor bonding of the reinforcement to the substrate, due to a non-proper preparation of the surface before the application of the strengthening material. (c) debonding with fracture surface within the substrate, this failure mode is rarely observed for FRCM strengthening systems and is more likely to occurs for FRP reinforcement (D’Ambrisi and Focacci 2011), (Ombres 2009).

Although in the recent years numerous techniques has been analysed in order to increase the strength and ductility of unreinforced masonry walls under out of plane actions, just few works are available on the use of composite materials with inorganic matrix for this purpose. The experimental researches on this field highlighted that the failure observed in FRCM reinforcing systems are very different respect the ones experienced by FRP materials: the former materials allows a “pseudo-ductile” failure in reason of the friction and slippage phenomena  between textile and matrix during the crack propagation, whereas the latter are characterized by brittle debonding failures, within the composite or the substrate width.

The studies performed by (Papanicolaou, Triantafillou, and Lekka 2011) and (Valluzzi et al. 2014) shown that the failure in FRCM strengthened masonry structures may occurs according to the following modes: (a) cracking of the matrix and fibres slippage or tensile failure, (b) shear failure of the masonry panels at the supports with or without cracking of the matrix, (c) shear failure of the masonry panels at the supports with or without cracking of the matrix.

 (Colombi and anf Giulia Carozzi 2015) performed, at the laboratory of the Politecnico di Milano, a series of 16 three point bending tests on masonry elements composed of solid (695 l x 315 h x 100 t mm) and hollow  (740 l x 370 h x 80 t mm) clay bricks reinforced with PBO FRCM and PBO-glass hybrid FRCM composites, in order to simulate the behaviour of structural elements and infill walls subjected to an horizontal load perpendicular to the horizontal mortar joints of the wall. The specimens where subjected to monotonic out-of-plane load under displacement control at a rate of 0.2mm/min. The experimental tests performed on unreinforced control walls showed a brittle failure instead the reinforced ones behaves  according to the mentioned pseudo-ductile failure mode: the load-displacement behaviour is described by a sequence of 5 different phases: (1) a first elastic branch up to the peak load reaching, where no naked-eye visible cracks are present; (2) after the peak load reaching the curve shows a vertical drop, related to the cracking of the reinforcement matrix and the failure of the substrate; (3) the next phase is characteraized by a load increasing related to fibre friction phenomena within the bond length, the crack in the matrix increases and the load now is supported only by the fabric; (4) the tensile stress acting on the fabric is increasing due to the increment of vertical displacement, it results in a pull-out telescopic failure mode, with slippage phenomena between the internal filaments that are not completely impregnated and external filaments failure, that involves an abrupt loss of load; (5) the last branch is characterized by an almost horizontal branch at a low constant load up to the pull-out failure of the fabric. The results shown an evident increment of peak load between 138% and 166%, depending on the different kind of masonry and textile. The most significant increment is in terms of deformation work, with increments between 400% and 926% respect to the unreinforced walls. This parameter is fundamental in the case of seismic events since in many cases the damage to people are due to the collapse of structural and non-structural elements, this reinforcement technique could increase a lot the time before the collapse, and guarantee the people safety.

(D’Ambrisi, Focacci, and Caporale 2013) presented the design criteria adopted for the strengthening intervention of a railway bridge constituted by un-reinforced concrete vaults supported by masonry piers and masonry abutments. FRCM material reinforcement system was chosen because it was able to sufficiently increase the load carrying capacity of the structure and could be realized with the railway line in operating conditions. The analysis of the bridge structural behaviour and of the possible failure modes is reported in the paper, two possible collapse mechanisms were considered: four hinges collapse mechanism of a single vault with fixed abutments and the collapse with the rotation of a pier. The bridge was reinforced with two PBO-FRCM layers applied at the intrados of the vaults. The system was applied at the intrados due to the impossibility of applying it at the extrados with the railway line in operating conditions. In addition, a strengthening intervention with foundation piers has been realized to fix the rotation of the lower part of one of the piers.

## Fatigue behaviour of reinforced concrete and masonry elements reinforced with FRCM - SoA

An essential part of the worldwide existing transportation network is made of ancient highway and railroad bridges, they are continuously subjected to repeated and oscillatory loading during their service life history, due to vehicular traffic. When subjected to cyclic loadings, reinforced concrete and masonry structural elements experience stress concentrations flaws that, over the years, result in cracks formations that are steadily increasing and propagating due to the repeated loading.  As a consequence the structural integrity and, in general, the structure’s life expectancy significantly decrease. This concept is known as fatigue: the progressive failure of a material under repeated stresses (Colombi and Fava 2016), (Colombi and Fava 2015), (Casciati, Colombi, and Faravelli 1993), (Doliński and Colombi 1999), (McCall 1958).

The actual mechanism that causes fatigue failure in concrete is not well established, but it is commonly agreed that progressive micro and macro cracking result in increasing strains and deﬂections, eventually resulting in failure. Accordingly, the fatigue performance of RC is a function of both the concrete and steel properties and can be described in three distinct phases. The ﬁrst phase consists of an initial loss of stiffness due to the development of concrete cracks where local steel concrete debonding occurs at crack locations. This is followed by a second stage of steady crack propagation, crack widening, and further deterioration of the bond between steel and concrete, resulting in gradually increased strains and deﬂections. Within these two phases, a fatigue crack initiates in the reinforcing steel that steadily propagates within the cross section. After signiﬁcant reduction in steel area, the RC member approaches the third stage in which the rate of strength degradation drastically increases and is no longer steady. A brittle failure occurs in the steel reinforcement, and failure of the RC member is observed. The fatigue failure of RC is thus predominantly dependent on the steel reinforcement and rarely controlled by concrete (Schläfli and Brühwiler 1998), (Čavojcová et al. 2014). According to the American Concrete Institute (ACI), previous work determined a fatigue limit of 55% of the static strength, which corresponds to a fatigue life of 10 M cycles (ACI\_Committee\_215 1992).

Fibre reinforced composite materials has proven to be effective solutions for the increase of  the fatigue life of reinforced concrete elements, in reason of the re-distribution of the stresses, from the internal rebars to the composite itself, and the bridging effect that they provide when applied. Up to now many analytical and experimental papers are available in the scientific literature about the fatigue behaviour of reinforced concrete elements strengthened withe externally bonded FRP composites (Ekenel et al. 2006), (HUANG et al. 2011), (Ekenel and Myers 2009), (Gheorghiu, Labossière, and Proulx 2007), (Aidoo, Harries, and Petrou 2004), (Sena-Cruz et al. 2012). Studies show that FRP applied to RC increases member stiffness and capacity, delays crack initiation and propagation, reduces crack widths, increases fatigue life and residual strength compared to unstrengthened members. FRP strengthened RC members exhibit a similar damage progression to that of traditional RC in which signiﬁcant damage occurs in the early load cycles followed by gradually accumulated damage resulting in imminent failure. An primary mode of failure is caused by rupture of the steel reinforcement followed by FRP failure (typically FRP delamination). An enhanced fatigue performance occurs from the tendency of FRP to reduce the level of applied stress range in the steel reinforcement, which is a critical parameter in the fatigue performance of RC members strengthened with composite materials(Kim and Heffernan 2008).

To prevent fatigue failure, (ACI\_440.2R-08 2008) recommends limiting the stress level in the FRP to 0.20 *ffu*, 0.30 *ffu* and 0.55 *ffu* for glass, aramid, and carbon FRP, respectively, where *ffu* is the design monotonic failure stress. The Japan Society of Civil Engineers (JSCE 2001) recommends reducing the interface fracture energy by a factor of 0.7 in the case of fatigue loading, which results in a reduction of the design applied stress level by a factor of 0.84 with respect to the monotonic load-carrying capacity.

In reason of the limitations of the FRP technology, that have been widely discussed through the dissertation, in the last years, as described above, several investigations and experimentals has been performed on the FRCM composite systems under monotonic loading, but few studies on the fatigue performance of FRCM strengthened RC have been reported. In the coming rows the few available documents about RC elements reinforced with FRCM under cyclic loading are analysed.

(D’Antino et al. 2015) presented and discussed the behaviour of FRCM-concrete joints tested under fatigue and post-fatigue quasi-static monotonic loading, adopting the single-lap direct shear test setup. The aim of the experimental work was the investigation of the effects of different frequencies and load ranges on the following parameters: (a) the interfacial slip; (b) the dissipated energy during cycles; (c) the stiffness degradation of the interface; (d) the post-fatigue quasi-static monotonic behaviour. A fracture mechanics approach was proposed to describe the intermediate range of the fatigue crack growth for different frequencies. According to the results of precedent studies the experimental tests were conducted using three different frequencies, 1Hz, 3Hz and 5Hz, and under three different load ranges, 20-50%, 35-60% and 20-65%, with respect to the ultimate load obtained from quasi static tests conducted on specimens with the same geometry and materials and using the same test setup. Fifteen single-lap direct-shear tests were conducted on PBO FRCM-concrete joints under cyclic loading using the classical push–pull conﬁguration.

The results shown that the Fatigue failure of PBO FRCM-concrete joints is caused by rupture of the ﬁbres within the bonded area. This type of failure was different from the rupture of ﬁbres observed in a limited number of specimens previously tested under quasi-static monotonic loading by the authors. In fact, the former appears to be caused by the cyclic loading while sub-critical crack propagation occurs, whereas the latter is mainly caused by the non-uniform load distribution among the longitudinal bundles. In general, it was observed that the combination of high amplitude and high mean value of the load range implies greater damage measured in terms of global slip, energy dissipation, and interfacial stiffness degradation. The load frequency also appears to affect the fatigue response. In general, a decrease of the damage rate with increasing frequency measured in terms of dg/dN was observed. The use of a fracture mechanics approach that takes into account the inﬂuence of the frequency on the rate dg/dN allowed for describing the intermediate range of the fatigue crack growth in PBO FRCM-concrete joints. The results obtained conﬁrmed that the frequency affects the fatigue life as reported in the literature. The effect of cycles on the quasi-static post-fatigue behaviour of the PBO FRCM-concrete joints was investigated. The results suggest that an increase of the mean applied load value entails an increase of the interfacial damage. Further, the interface is rapidly damaged even for a relatively small number of cycles.

(Pino et al. 2017) investigated experimentally the parameters that most inﬂuence the ﬂexural fatigue performance of PBO FRCM-strengthened RC beams: amount of supplemental reinforcement, ultimate strength, applied stress range, fatigue life, failure modes, and residual strength.

In order to characterize the fatigue behaviour, the samples were tested under both monotonic and fatigue loading, at different stress ranges, finding for each range the corresponding fatigue life. The results has been used to determine the so called S-N curve, that relates stress range, Sr, that is the difference between the maximum and minimum applied stress, and fatigue life, N. Through this curve has been possible to evaluate the material’s endurance  limit, that is a property that express the greatest applied stress range that a material can sustain without failure occurring.

Fifteen 1829x305x155 mm RC beam specimens were prepared and tested with a standard three-point bending test setup (1,54 m span), five of them tested under monotonic loading up to failure and the remaining ten tested under cyclic load. All beams were containing stirrups reinforcements in order to avoid shear failure and  were strengthened with 1, 3 and 5 layers of PBO. The load procedure provided for a first phase where all cyclic loads were applied until 2 million of cycles. The specimens that reached a fatigue life of 2 M cycles moved to the second phase where they were tested statically to determine the post fatigue residual strength.

For all the strengthened beams was observed that the FRCM mitigated the crack opening on the flexural surface, which potentially slowed crack propagation better than in an unstrengthened RC beam. Has been denoted that FRCM improves the fatigue performance of RC structures, but the level of improvement is largely dependent on the amount of FRCM provided. For all the FRCM reinforced beams the fatigue failure occurs in reason of a brittle fracture of the steel rebars, followed by a sudden FRCM delamination. The specimens statically tested in the second phase showed a residual strength at least 95% of the non-conditioned static ultimate load.

(Aljazaeri and Myers 2017) performed a study on the fatigue performance of RC beams strengthened with FRCM composites under different exposures, evaluating the stiffness reduction of both reinforced and unreinforced beams. Eight 2133x305x203 mm RC beam specimens, with rebar shear and bending reinforcement, were strengthened with either one and four plies of PBO FRCM. Half of them were placed into environmental chamber and exposed to varying cycles of freezing and thawing, elevate temperatures and high relative humidity, based on Missouri state weather conditions. Some of these beams were subjected to self-weight loading conditions only, while the others were subjected to a sustain load up to 40% of their expected ultimate load capacities.

Beam specimens were subjected to a constant amplitude fatigue loading, up to 2 million cycles with a frequency of 5 Hz, using a four point bending setup over a span of 1888 mm. The applied fatigue load ranged between 35 and 65% of the expected ultimate load carrying capacity of the beam specimens, equivalent to the minimum and maximum expected loads that beam specimens can carry at a service stage in bridge engineering applications. All the specimens successfully completed the 2 million fatigue cycles and then were subjected to monotonic four point loading up to failure. The specimens strengthened with one ply failed by yielding of their longitudinal reinforcing bar followed by FRCM slippage, the ones reinforced with four plies of the FRCM composite system observed a different failure mode: an initial yielding of the longitudinal reinforcing bar followed by the FRCM system debonding at ultimate load.

A higher percentage of the stiffness degradation was observed during the first 250,000 fatigue cycles in all beam specimens with insignificant stiffness degradation observed at the end of 2 million cycles when the beam specimens stabilized under the constant fatigue loading. Exposing the beam specimens to high temperature and humidity inside the environmental chamber resulted in higher ultimate load capacities due to post-cure effects. In addition, the environmental exposure did not affect the beam specimens failure mode. The flexural capacity of the beam specimens was not affected by the long-term fatigue cyclic loading. Using four plies of the FRCM system greatly influenced both fatigue and flexure performance (ultimate load and displacement ductility).

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