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Advanced Composite Mortar System for Strengthening Historic Masonry

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ABSTRACT: Tyfo® Reinforced Mortar (TRM) System is a high performance composite material comprising layers of a fabric with parallel-aligned fibers and an inorganic matrix, which can be a cement-based or a non-cement-based (e.g. hydraulic lime) mortar. Tyfo® RM System is typically applied to the surfaces of existing masonry structures, with a view to provide strengthening or seismic retrofitting. The fabrics used for the Tyfo® RM System contain basalt or carbon fibers and they are known as Tyfo® EP-B Basalt Fabric or Tyfo® EP-C Carbon Fabric respectively. This study aims to investigate tensile testing of Tyfo® RM System involving the use of Tyfo® EP-B Basalt Fabric and Tyfo® EP-C Carbon Fabric, combined with cementitious mortars. The test method is described and the parameters under investigation are presented, namely the type of fibers, the type of mortar and the age at testing the specimens. Typical test results are further presented in terms of stress-strain plots as well as mean values and standard deviations for stresses, strains and elastic moduli. Finally, the paper discusses how the test results can be used for designing the Tyfo® RM System for a given demand.

1 GENERAL INSTRUCTIONS

The motivation for the development of Tyfo® Reinforced Mortar (TRM) System was a number of drawbacks associated with Fiber Reinforced Polymers (FRPs) used as a strengthening material on masonry structures. These drawbacks are associated to the use of organic resins as a bonding material. The most important issues are: (i) sensitivity to high temperatures, (ii) chemical incompatibility of epoxies with some substrate materials such as clay brick units, which is a conventional material for masonry structures, (iii) difficulty to application on wet surfaces, (iv) irreversibility of the technique. In order to overcome the aforementioned drawbacks, the use of cement-based or lime-based mortar as a bounding material was preferred instead of organic resins.

Other important compatibility issues, between existing and strengthening materials, are related to thermal expansion and strength. Thermal compatibility is an important characteristic of the proposed strengthening system. The thermal expansion coefficient of mortar is very similar to that of masonry. Moreover, basalt, which is the main strengthening fibers material, has thermal expansion coefficient equal to 70% of concrete and it is in the tolerable limits. The strength compatibility of the proposed method, on the other hand, is more pronounced since the fibers are open-weaved and thus exhibit much lower strength than that of the continuous FRP strips. Overall, the debonding strength is governed by the mortar material and the strength values are in the order of strength of masonry material. The composition of Tyfo® RM System, as well as the tensile properties and some basics of design are presented herein.

2 MATERIAL PROPERTIES

Tyfo® RM System comprises of open-weaved grid made of long woven or unwoven knitted fiber roves in at least two directions (vertical and horizontal) and an inorganic mortar matrix (cement-based or hydraulic lime mortars) as a bonding material (Papanicolaou et al, 2006; Triantafillou 2012a, b). The number of the roves in each direction can be altered if the mechanical properties of the composite material are aimed to be different in perpendicular directions (Triantafillou 2012b). The grid materials used in the TRM system are basalt or carbon fabrics. The grid of the TRM System provides tensile resistance to the strengthened elements and the matrix provides; 1) ductility on the contrary of the organic resins, which have a brittle behaviour, 2) protection of grid from the environmental conditions and 3) homogenous distribution of stresses among the fibres. For the calculation of the tensile strength of the TRM System, coupons consisted of 2 layers of the material were prepared. The configuration of those coupons is shown in Figure 1.

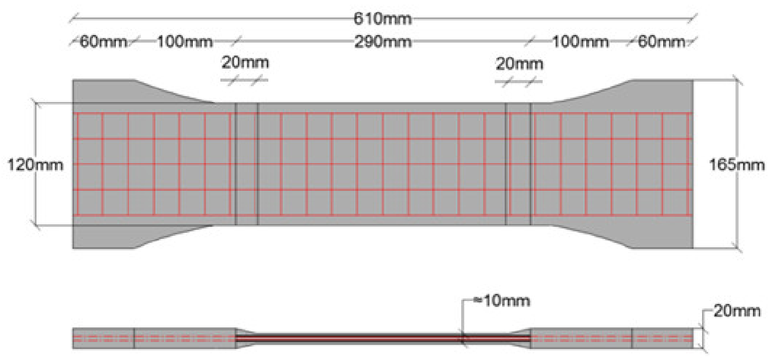

Figure 1. Configuration of coupons (Triantafillou 2012a).

The materials that were used for the construction of the aforementioned specimens, as well as, their properties are presented in the following Table 1 (Triantafillou 2012a).

Table 1. Properties of fabrics

Property	Tyfo EP-B Basalt	Tyfo EP-C Carbon
Bundles inside moulds	5	4
Spacing (mm)	25	30
Nominal weight per. sq. meter (gr/m^2)	170	220
Coated weight per. sq. meter (gr/m^2)	220	270
Density of fibres (kg/m^3)	2750	1800

The commercial names used for the two types of mortars are Tyfo® C-Matrix and Tyfo® C-Matrix Type F, for M1 and M2 respectively. The difference between the mortars is that the latter has greater resistance against fire.

The coupons were tested under uniaxial tension until the ultimate failure, which was due to tensile rupture of the fibres. The real stress – strain behaviour of 4 of the coupons, constructed with Tyfo® EP-B Basalt fabric and Tyfo® C-Matrix Type F mortar, is presented in Figure 2. For design purposes the stress – strain curve can be idealized in a tri-linear curve, which is shown in Figure 2. The quantities of practical interest on the simplified stress-strain curve are: the ultimate tensile strength f_u, the tensile stress at the transition area (second branch) σ_{tr}, the elastic tensile modulus (which practically is equal to the secant one) E and the ultimate strain ε_u.

Table 2. Properties of mortars

Mortar	Property	Age (days)	Value (MPa)
M1	Flexural strength	7	3.7
		28	7.7
	Compressive strength	7	22.8
		28	27.9
M2	Flexural strength	7	4.1
		28	6.6
	Compressive strength	7	28.9
		28	37.2

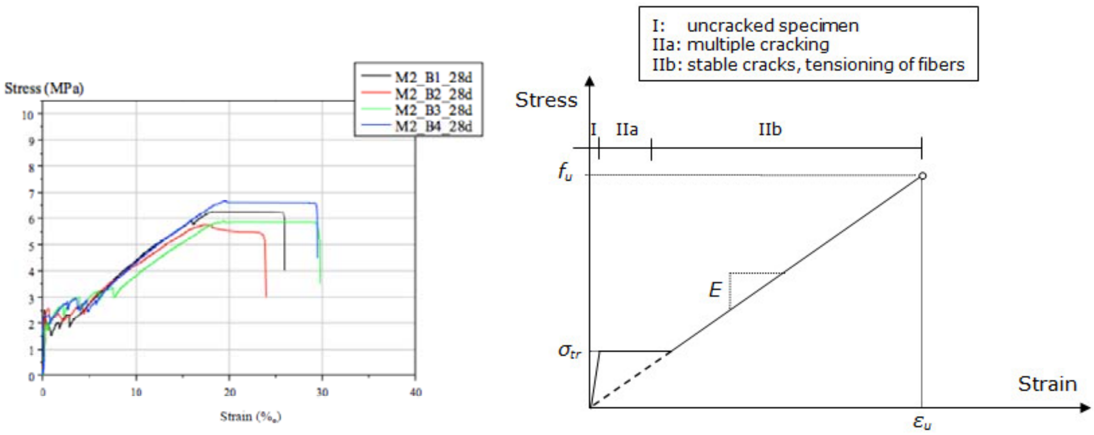

Figure 2. Left: Real stress-strain behaviour of the coupons constructed with Basalt fabric and C-Matrix Type F mortar, Right: Simplified stress - strain curve of TRM System (Triantafillou 2012a)

Comparing Figure 2, left and right, it is clear how the tri-linear behaviour was derived. The initial branch is the behaviour of the composite system before any crack appearance to the mortar matrix. In the second branch there are multiple cracks on the matrix, so the stiffness of the composite system is changed. In fact the actual behaviour of the second branch has a shape of a saw-blade, because of the initiation of cracks. The second branch can be idealized by a horizontal line, where the areas of the real curve are equal above and below of this line. This branch is extended until the stabilization of the cracks. Finally the third branch follows when all the cracks have been stabilized and the fibers bear the load until they fail (ultimate strength of the material).

The tensile properties of the TRM System were derived from the tests that were carried out on coupons. Tables with these properties, which are typical values, are presented in Table 3 and Table 4.

3 DESIGN ASPECTS

The TRM System can be used in several strengthening cases some of which are listed as (i) strengthening for the out-of-plane actions (against vertical & horizontal flexure or overturning), (ii) strengthening for the in-plane actions (against bending or shear actions), (iii) confinement of columns, (iv) strengthening of masonry arches, barrel vaults, domes and other curved masonry elements, (v) strengthening of lintels and ties areas, and (vi) strengthening of connections e.g. between floors and vertical walls.

Table 3. Typical & Design values for the TRM (EP-B w/ C-Matrix Type F) System (Triantafillou 2012a)

	EP-B w/ C-Matrix		EP-B with C-Matrix Type F	
Property[a,b]	Test Value	Design	Test Value	Design
Ultimate tensile strength, MPa	6.00	5.10	6.00	5.10
Elongation at ultimate	1.62%	1.62%	1.62%	1.62%
Tensile modulus, GPa	0.37	0.31	0.37	0.31
Tensile stress at transition, MPa	2.10	1.80	2.10	1.80
Layer thickness, mm	5	5	5	5

a) Coupons preparation and testing procedure based on Fyfe Company modified RILEM Committee's TC TDT draft recommendation "test method to determine the load bearing behaviour of tensile specimens made of textile reinforced concrete"
b) 28 days aged coupons

Table 4. Typical & Design values for the TRM (EP-C w/ C-Matrix) System (Triantafillou 2012a)

Property[a,b]	Typical Test Value	Design Value
Ultimate tensile strength, MPa	8.40	7.14
Elongation at ultimate	1.68%	1.68%
Tensile modulus, GPa	0.50	0.43
Tensile stress at transition, MPa	2.10	1.80
Layer thickness, mm	5	5

a) Coupons preparation and testing procedure based on Fyfe Company modified RILEM Committee's TC TDT draft recommendation "test method to determine the load bearing behaviour of tensile specimens made of textile reinforced concrete"
b) 28 days aged coupons

The applications of the TRM System are divided in two categories: in one category the critical state is correlated with the bond behaviour of the material (bond critical applications), therefore when a jacket is not properly anchored the material cannot take advantage of the higher tensile strength, because the failure comes by debonding at 0.3% design strain. Rupture of the material is a rare case, which has not been observed during the tests, but it might be the situation in contact-critical applications (i.e. full wrapping of a pier). In design cases instead of the ultimate strength of the TRM System, the stress at the debonding will be used for design purposes (usually the stress at the transition zone, σ_{tr}). On the other hand, there are cases where the proper anchorage of the TRM System can be ensured (e.g. confinement with full coverage of jackets and big enough overlap length). In those cases the design can be performed by considering a higher design strain. However, a further investigation is required to prove the argument.

For all cases the design values are derived from the characteristic values divided by the partial factor for the material. For the TRM System this factor is suggested as γ_t = 1.5 (Triantafillou 2012b).

3.1 Strengthening against out-of-plane vertical flexural failure

When a lateral out-of-plane action, caused by lateral loads such as wind or earthquake, strikes a wall made of masonry with restrains at top and bottom then a possible failure is a vertical crack approximately at the middle of the wall (Figure 3).

For the strengthened element (Figure 3b) there are two types of failure. The one is due to compression failure of the substrate (masonry) and the other due to failure of the TRM System by rupture or debonding. Both conditions should be examined in design and the governing condition should be taken into account.

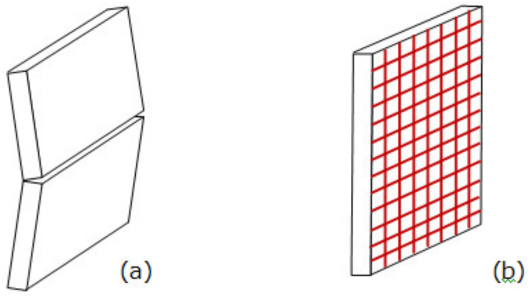

Figure 3. (a) Vertical flexural failure, (b) strengthening by TRM System (Triantafillou 2012b).

3.1.1 Compression Failure of Masonry

In this case it is assumed that the most compressed fibre of the cross section has reached the masonry ultimate strain ($\varepsilon_m = \varepsilon_{mu}$) and the strain at the very tensioned fibre is unknown ($\varepsilon_t \leq \varepsilon_{t,lim}$). According to the cross sectional analysis of the strengthened element, the design bending moment can be found by the following relation (Triantafillou 2012b):

$$M_{Rd,1} = lt^2 f_{md} \frac{1}{\gamma_{Rd}} \left[\frac{1}{2} \frac{\left(1-\frac{x_1}{t}\right)}{\frac{x_1}{t}} \omega_{t,1} + \frac{1}{2} k_1 \frac{x_1}{t} \left(1 - 2k_2 \frac{x_1}{t}\right) \right] \tag{3.1}$$

where, x_1 is the height of the compression zone, t is the thickness of the wall, l is the width of the wall, f_{md} is the design compressive strength of the wall, $\omega_{t,1}$ is the ratio of sectional properties of TRM System and URM, k_1 is equal to 0.8, γ_{Rd} is the flexure factor equal to 1.0, and k_2 is equal to 0.4.

3.1.2 Failure of TRM System by Rupture or Debonding

The assumption now is that the maximum strain of tension fibre is equal to the rupture or debonding stain of TRM System, whichever is smaller ($\varepsilon_t = \varepsilon_{t,lim} = \min[\varepsilon_{tb}, \varepsilon_u]$). From the cross sectional analysis, the design bending moment now is calculated by the following relation (Triantafillou 2012b):

$$M_{Rd,2} = lt^2 f_{md} \frac{1}{\gamma_{Rd}} \left[\frac{1}{2} \frac{\varepsilon_{t,lim}}{\varepsilon_{mu}} \omega_{t,2} + \frac{1}{2} k_1 \frac{x_2}{t} \left(1 - 2k_2 \frac{x_2}{t}\right) \right] \tag{3.2}$$

$$k_1 = \begin{cases} 1000\varepsilon_m \left(0.5 - \frac{1000}{12} \varepsilon_m\right) & if \ \ \varepsilon_m \leq 0.002 = \varepsilon_{m1} \\ 1 - \frac{2}{3000\varepsilon_m} & if \ \ 0.002 \leq \varepsilon_m \leq 0.0035 = \varepsilon_{mu} \end{cases} \tag{3.3}$$

$$k_2 = \begin{cases} \frac{8-1000\varepsilon_m}{4(6-1000\varepsilon_m)} & if \ \ \varepsilon_m \leq 0.002 \\ \frac{1000\varepsilon_m(3000\varepsilon_m-4)+2}{2000\varepsilon_m(3000\varepsilon_m-2)} & if \ \ 0.002 \leq \varepsilon_m \leq 0.0035 \end{cases} \quad (3.4)$$

Finally the design bending moment of the strengthened element is the smallest between the one from the Equation 3.1 and the one from the Equation 3.2.

3.2 Strengthening against out-of-plane horizontal flexural failure

The procedure of strengthening for the horizontal type of flexural failure is exactly the same as in the previous section. The equations are similar to the ones applied for the vertical flexural failure with the following adjustments. Firstly, the applied axial load should be equal to zero (N_{Ed} = 0). The crack direction is vertical and as a result the axial load does not provide a re-centering effect. Secondly the vertical compressive strength of masonry f_{md} has to be replaced by the horizontal compressive strength of masonry f_{mdh} . Note that the horizontal compressive strength is assumed to be around 50% of the vertical one (Triantafillou 2012b).

3.3 Strengthening against in-plane shear failure

Shear failure can occur when an element is subjected to in-plane lateral loads. Elements with high cross sectional aspect ratio (e.g. walls) are more susceptible to such a failure. In order to prevent that, the application of TRM System at both sides of an element (if possible) is recommended. The lateral load is parallel to the long sides of the wall in the case of shear loading, and the TRM System at the sides is activated. The shear resistance of the strengthened element is derived from the strength of masonry and the strength of TRM System (Triantafillou 2012a).

$$V_{Rd,st} = \frac{V_{Rd,m}+V_{Rd,TRM}}{\gamma_{Rd}} \quad (3.5)$$

$$V_{Rd,m} = f_{vd}tl^{\dagger} \quad (3.6)$$

$$V_{Rd,TRM} = 0.9l\left(nt_f\right)f_{td} \quad (3.7)$$

The value that derived from the Equation 3.5 should not be bigger than the compressive failure of the struts in a truss analogue ($V_{Rd,max}$) (CEN, 2005):

$$\frac{V_{Rd,max}}{tl} = \frac{1}{\gamma_{Rd}}2 \quad (3.8)$$

where γ_{Rd} is the shear factor equal to 1.2, t is the thickness of the wall, l is the length of wall, f_{vd} is the design shear strength of masonry, f_{td} is the design strength of TRM System and n is the number of sides strengthened with TRM System of thickness t_f each (e.g. n = 2 for 2-sided jacketing).

3.3.1 Shear Strengthening Example

An external axial load of 375 kN is applied at the wall presented in Figure 4. This wall is subjected to an earthquake with intensity of 0.4 g. The task is to examine if the wall can sustain that earthquake intensity and if not then propose a strengthening system by using TRM System. The properties of the wall and the properties of the strengthening material are presented in Table 5 and Table 6, respectively.

† If the shear strength of the unreinforced masonry is needed (i.e. the strength of the wall before strengthening) then according to EC6, the length of the wall *l* in the equation 3.6 has to be replaced by the length of the compressed part of the wall l_c.

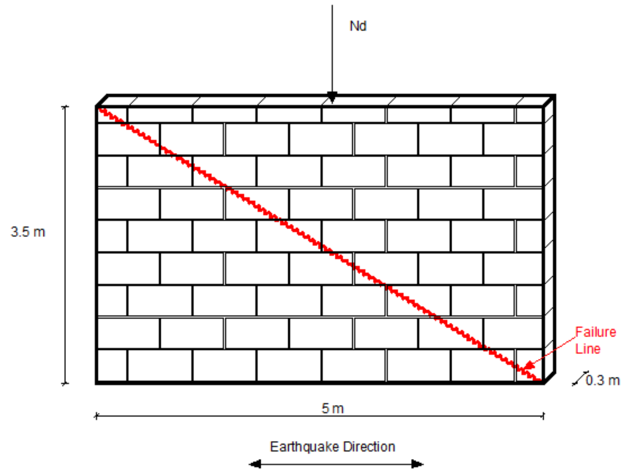

Figure 4. Wall subjected to in-plane load

Table 5. Example wall properties.

Property	Value
Length, m	5.0
Height, m	3.5
Thickness, m	0.3
Units	Clay bricks, Category II
Mortar	General Purpose
Compressive strength, MPa	2.0
Density (unit weight) of the wall, kN/m^3	18
Initial Shear Strength, MPa (CEN, 2005)	0.1
Partial factor for material (γ_M) (CEN, 2005)	2

Table 6. TRM System Properties used in the example (Triantafillou 2012a).

Property	Value
Grid Material	Tyfo EP-B Basalt Fabric
Mortar	Tyfo C-Matrix
Tensile ultimate strength, MPa	5.1
Elastic Tensile Modulus, GPa	0.31
Tensile stress at cracking, MPa	1.8
Ultimate Tensile Strain, %	1.62
Nominal Layer Thickness, mm	5
Number of layers that were used	2

Unreinforced masonry:

Shear Demand: $V_{Ed} = (W+N_{Ed})\cdot ag = (5\ (3.5)\ 0.3\ (18) + 375)\ 0.4 = 187.8\ kN$

Shear Capacity (Equation 3.6): $V_{Rd} = 168.9\ kN$

The wall cannot sustain the earthquake load: $V_{Ed} > V_{Rd}$, thus there is need for strengthening.

Strengthened masonry

(Contribution of Masonry) Shear Capacity (Eq. 3.6): $V_{Rd,m} = 168.9\ kN$

(Contribution of TRM) Shear Capacity (Eq. 4.12): $V_{Rd,TRM} = 0.9 \cdot 5 \cdot (2 \cdot 0.01) \cdot 1800/1.5 = 108\ kN$

Compression failure of the struts in a truss analogy

Shear Limitation (equation 4.13): $V_{Rd,max} = 2500\ kN$

Finally the shear resistance of the strengthening element is determined as:

$$V_{Rd,st} = (V_{Rd,m} + V_{Rd,l}) / \gamma_{Rd} = 230.75\ kN$$

The strengthened wall now can sustain the given earthquake. The resistance of the wall was enhanced by 36.6%.

3.4 *Strengthening against in-plane combined bending and axial load*

In-plane combined bending and axial load failure is a major risk for piers (parts of masonry structures between openings or tie areas). It is not common for elements with high cross sectional aspect ratio (thick masonry shear walls).

The scheme of strengthening is the same with the one of shear failure (Figure 5). The method is more or less the same with the "Out-of-Plane Vertical Flexure". The only difference is that here the stress and strain distribution, in the cross section analysis, are along the longitudinal direction of the wall l and not the transversal t. The types of failures are two as in the "Vertical Flexure" (compression failure of masonry and rupture or debonding of the TRM System, respectively), and the smallest of the below will be used as the design strength:

$$M_{Rd,1} = tl^2 f_{md} \frac{1}{\gamma_{Rd}} \left[\frac{1}{12} \frac{\left(1-\frac{x}{l}\right)^2 \left(1+2\frac{x}{l}\right)}{\frac{x}{l}} \omega_{t,1} + \frac{1}{2} k_1 \frac{x}{l} \left(1 - 2k_2 \frac{x}{l}\right) \right] \tag{3.9}$$

$$M_{Rd,2} = tl^2 f_{md} \frac{1}{\gamma_{Rd}} \left[\frac{1}{2} \frac{\varepsilon_{t,lim}}{\varepsilon_{mu}} \omega_{t,2} \frac{\left(1-\frac{x}{l}\right)\left(1+2\frac{x}{l}\right)}{6} + \frac{1}{2} k_1 \frac{x}{l} \left(1 - 2k_2 \frac{x}{l}\right) \right] \tag{3.10}$$

4 CONCLUSIONS

The application and usage of this new strengthening system are similar to the FRPs with epoxy resins. The bonding material that is being used for the TRM System is, however, a cement-based or a lime-based mortar. This has as a result the reduction of the effectiveness in terms of strength compared to FRPs. On the other hand, the TRM System is effective in terms of deformability (ductile behaviour), which is of crucial importance in seismic retrofitting (Papanicolaou et al., 2006). The ductile behaviour is a great advantage, because it ensures energy dissipation during an earthquake event and additionally keeps inertial forces to low levels. Another important advantage of the TRM System is the reversibility. It can be easily removed from a structural element, if this is needed (e.g. for a post-earthquake treatment of the damaged substrate). Additionally, the TRM System does not need any special treatment for reaction to fire. Finally, the TRM system is fully compatible to masonry in terms of thermal expansion and strength.

According to the example of the shear strengthening presented herein, it is observed that with few layers of the TRM System, the possible collapse of a typical wall subjected to a strong earthquake (0.4g of PGA), can be prevented. Moreover, it must be noted that the shear strength of the wall was enhanced by 36.6%. From a parametric study that was carried out, it has been concluded that the shear strength can be enhanced up to 70% for small intensity earthquakes (0.2 to 0.3g PGA) and up to 60% for stronger earthquakes (0.4g PGA).

As a final point, it is concluded that in many cases, the level of strengthening that is provided even by one layer of the TRM System (approximately 9 kN per 1m unit width) is adequate for enhancing the strength and ductility of masonry walls against several characteristic failures.

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