Composite Structures 107 (2014) 711–725

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Mechanical properties and numerical modeling of Fabric Reinforced Cementitious Matrix (FRCM) systems for strengthening of masonry structures

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ARTICLE INFO

Article history:
Available online 29 August 2013

Keywords:
Masonry
GF grid strengthening
Fabric Reinforced Cementitious Matrix FRCM
Non-linear behavior
Debonding

ABSTRACT

The behavior of single bricks and small masonry pillars strengthened by means of fabric reinforced cementitious matrix systems made with glass-fiber grids is discussed both from an experimental and numerical standpoint.

A standard Push–pull double lap test is performed on three different series of experimental set-ups for reinforced single bricks and on masonry pillars, evaluating the role played by the anchorage length on the overall behavior of the strengthened system.

Standard Italian bricks with very good mechanical properties are used, in order to evaluate the ultimate strength of the grid for delamination within the mortar. The masonry pillar is built with 3 bricks spaced out by two thick mortar joints. When dealing with the single bricks, three different anchorage lengths were tested, equal to 5, 10 and 15 cm, in order to evaluate the reduction of the ultimate strength induced by an insufficient anchorage.

To suitably interpret experimental results, both a newly developed analytical–numerical approach and a recently presented 3D FEM model were utilized to have an insight into experimental results.

In the analytical–numerical approach only the glass-fiber grid was considered and modeled by means of 1D Finite Elements interacting with the surrounding mortar by means of interfaces exhibiting a non-linear stress–slip behavior deduced from experimental data.

The 3D model uses 8-noded rigid elements interconnected by inelastic interfaces exhibiting softening. The incremental non-linear problem is solved by means of a robust Sequential Quadratic Programming routine already tested on medium and large scale examples with softening materials. The grid is modeled through non-linear truss elements, interacting with surrounding mortar by means of non-linear interfacial tangential stresses. Stress–slip behavior of the interface between the mortar and the textile is deduced through ad hoc experimentation conducted on a mortar specimen reinforced with a single yarn and subjected to a standard tensile test.

Good agreement was found between experimental evidences and numerical simulations, meaning that the combined approach proposed may be considered as reference for design considerations.

1. Introduction

Even the recent earthquake that occurred in Italy in May 2012 indicated that historical buildings, essentially constituted by masonry structures, are scarcely resistant to horizontal loads and therefore highly vulnerable to seismic actions. Such behavior is a common issue of masonry buildings in many countries worldwide and is essentially due to the low strength of the mortar joints when loaded out-of-plane.

Conventional retrofitting techniques, such as external reinforcement with steel plates, surface concrete coating and welded steel meshes, have proven to be complex, time expensive and add considerable mass to the structure which may increase the inertia forces induced by an earthquake.

Therefore, the use of FRP (Fiber-Reinforced Polymers) strips as reinforcements instead of conventional methods seems a suitable solution for the seismic upgrading, thanks to the limited invasiveness, speed of execution, and good performance at failure [1–7]. The FRP strengthening technique entails however several drawbacks, as for instance low vapor permeability, poor behavior at elevated temperatures, incompatibility of resins on different substrate materials, relative high cost of epoxy resins, no reversibility of the installation [8].

The use of inorganic matrices is a valid alternative to these problems [7]. It is well known, however, that cement based

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http://dx.doi.org/10.1016/j.compstruct.2013.08.026

Nomenclature

A_L	perimeter of the yarn
A_{FRP}	transversal area of a single yarn
c_I	peak strength of the interface between yarn and mortar
c_{II}	residual strength between yarn and mortar
δ	displacement
e	eccentricity of the load, 150 mm anchorage length
e_0	prescribed eccentricity in the numerical models (1D and 3D)
E_{FRP}	Young modulus of Glass Fiber grid
f	tangential unitary force between yarn and mortar (N/mm)
F	force
F_i	forces in the single yarns
F_u	ultimate strength
F_{u2}	residual strength of the overall system
$f_{u\text{-}FRP}$	ultimate value of stress in a yarn
L	distance between two contiguous yarns
L_b	length of the bonded region
L_u	length of the unbounded region
L_{2-3}	length of an interface finite element between nodes 2 and 3
n_{el}	number of elements
n_{in}	number of interfaces
n_y	number of yarns
k_n	axial elastic stiffness of the yarn
k_t	Tangential elastic stiffness of yarn–mortar interface
$\mathbf{K}_{el}$	assembled elastic stiffness matrix
$\mathbf{K}_{ep}$	interfaces hardening moduli matrix
K_T	stiffness of the mechanical system
u_i	displacement of the single yarn
u_x^E, u_y^E, u_z^E	kinematic variables: three centroid displacements
u_t^{Ei}	absolute displacement along **t** of element *Ei*
$\mathbf{t}$	direction versor
Δ_{b1}	yarn–mortar interface, slip value corresponding to the first strength drop
Δ_{b2}	yarn–mortar interface, slip value corresponding to the second strength drop
ΔL_u	overall displacement due to the unbounded part
ΔL_b	overall displacement of the bonded part
Δs^{P1}	tangential slip of point *P*1
Δs_e	displacement at the elastic limit
Δs_{u1}	displacement value reached when the tangential force shifts from peak to residual value
Δs_{u2}	displacement value reached in correspondence of a drop of tangential force from the residual value to zero
$\Delta\mathbf{F}$	vector of elements force and moment increments
$\Delta\mathbf{U}_{el}$	vector of elements displacement and rotation increments
$\Delta\lambda^+$ and $\Delta\lambda^-$	assembled plastic multiplier increment vectors
ε_u	ultimate axial strain of the GFRP yarn
ε_e	elastic axial strain of the GFRP yarn
ε_n	continuum strain
λ	parameter entering in the elastic equation of the yarn–mortar interface
ξ	geometric parameter entering in the elastic equation of the yarn–mortar interface
ϑ	rotation of the rigid device connecting perpendicularly the three yarns in correspondence of their extremes free to translate
σ	tensile stress
τ	tangential stress
Φ_x^E, Φ_y^E, Φ_z^E	kinematic variables: three rotations around the centroid

materials have low tensile strength and must be reinforced with tensile resistant components. Typically, steel bars are used in the conventional reinforced concrete (RC). In the last two decades innovative types of reinforcements have been introduced: short fibers (FRC, Fiber Reinforced Concrete [9]) and continuous fibers in a fabric form (TRC, Textile Reinforced Concrete). Typical applications are cladding panels, exterior sidings, shells, roofing or flooring tiles. Fabric Reinforced Cementitiuos Matrix (FRCM) composites represent a particular type of TRC [10] where a dry-fiber fabric is applied to a structure through a cementitious mortar enriched with short fibers. And they are specifically used for strengthening of structures. The mechanical properties of FRCMs depend on the bond between the fibers and the matrix and may vary if the yarns of the fabrics are pre impregnated with resin [11,12]. FRCM are often used to repair and strengthen existing structures as an alternative to FRP composites [13]. When compared with FRP composites, FRCM exhibits several advantages, as a greater resistance to high temperatures and ultraviolet radiations, as well as a better compatibility with the substrates [14].

On the other hand, FRCM composites have some drawbacks, as for instance the lower levels of adhesion between the yarns and the matrix and the fact that they must be made either with alkaline resistant glass fibers or the yarns must be protected with suitable coatings.

The typical failure mode of FRP is the debonding of the reinforcement from the substrate with a brittle behavior [8,15,16], while FRCM materials can present more complex failure modes. The typical stress–strain behavior of a FRCM is a tri-linear curve, with a first phase that increases linearly according to the Young's modulus of the mortar, a second phase where the cracks in the mortar start to grow, and a last phase in which the mortar is fully cracked and the curve assumes the same slope of the stiffness of the fabric [17].

Despite the great importance and the increasing diffusion of such innovative strengthening technique, at present no numerical models devoted to the prediction of the behavior or FRCM masonry reinforced specimens or structural elements are at disposal and limited experimental data are available. In this context, the present work studies in detail the strengthening of masonry structures with FRCM from both an experimental and numerical point of view. The experimental investigation, partially presented in [18], includes various activities, starting from the characterization of the Glass Fiber (GF) grid and two types of mortars (a cementitious and a lime based mortar). Similar series of tests were performed on FRP reinforced specimens by other authors to evaluate the capabilities of the strengthening system, including (1) push–pull tests on double lap reinforcements applied to a single brick [15,19], (2) a series of tensile tests on the reinforcement applied to a pillar [20] and (3) pull-out tests on single yarns immersed in a mortar block, performed to have an insight into the interface behavior. When dealing with the reinforced single brick, three anchorage lengths are analyzed, equal respectively to 50 mm, 100 mm and 150 mm.

The numerical investigation is aimed at simulating the experiments on the reinforced single brick and the masonry pillar. The final objective is to provide a validated tool for the design and the assessment of these reinforcement systems. Two complementary tools are proposed: a simplified analytical–numerical approach to model the specific interaction of the grids with the mortar by means of interfacial tangential stresses and a sophisticated fully