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E. Grande, E. Bertolesi, G. Milani, et al.

Curved Masonry Supports Strengthened with TRM Materials: Advanced FE Modelling

E. Grande[1,a)], E. Bertolesi[2,b)], G. Milani[3,c)], T. Rotunno[4,d)] and M. Fagone[5,e)]

[1]*Department of Sciences Engineering, University Guglielmo Marconi, Via Plinio 44, 00193 Rome (Italy)*
[2]*Department of Civil and Environmental Engineering, Brunel University London, UB8 3PH Uxbridge, UK*
[3]*Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy*
[4]*Dipartimento di Architettura (DiDA), Università degli Studi di Firenze, Piazza Brunelleschi 6, 50121 Florence, Italy*
[5]*Dipartimento di Ingegneria Civile e Ambientale (DICEA), Università degli Studi di Firenze, Piazza Brunelleschi 6, 50121 Florence, Italy*

[a)] *Corresponding Author: e.grande@unimarconi.it*
[b)] *elisa.bertolesi@brunel.ac.uk*
[c)] *gabriele.milani@polimi.it*
[d)] tommaso.rotunno@unifi.it
[e)] mario.fagone@unifi.it

Abstract. The article compares two numerical approaches with different levels of details used to simulate curved masonry supports subjected to single lap shear tests. The masonry pillars were strengthened on the extrados and on the intrados with TRM materials comprising a 100 mm wide PBO textile embedded into 10 mm thick mortar layer. The numerical analyses were carried out using two approaches: a heterogeneous micro modelling FE approach and a spring model approach. The first modelling strategy was developed using the commercial software Abaqus and it involved the separate modelling of the constituent materials (i.e., bricks and mortar joints) as well as the simulation of the PBO textile and mortar matrix. The second approach was specifically developed to analyze curved supports and it comprised the adoption of equivalent normal and shear springs used to model the components of specimens (support, matrix and reinforcement) and, moreover, the interface between reinforcement and matrix. It is worth mentioning that this numerical investigation is part of an ongoing experimental and numerical work focused on analyzing the effect of curved brittle supports on the adherence properties of innovative strengthening materials (i.e., FRPs) and herein extended to the adoption of TRM composites. In absence of a comprehensive experimental characterization of the TRM constituent materials, the mechanical properties of the textile and mortar matrix were deduced from available data provided by the manufacturer. The numerical results are herein presented and critically compared in terms of global force-displacement curves and damage maps obtained at the end of the simulations.

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INTRODUCTION

Textile Reinforced Mortar (TRM) materials represent a valid alternative to traditional strengthening composites (FRP) for the rehabilitation of ancient masonry/concrete structures [1-3]. They have been initially developed to overcome some disadvantages of FRPs applied on ancient brittle supports, namely: improve the breathability and compatibility and preserve the original substrate from the aggressiveness of more performant FRPs. Nevertheless, they demonstrated to possess some peculiar advantages, such as a good adhesion, coupled with equally peculiar disadvantages [1-5]. In details, they showed to experience mixed failure modes involving detachment phenomena, fiber slippage and inorganic matrix cracking, just to cite a few. Experimental investigations were then carried out at different scales to study their failure modes and their characteristics at the local level and to analyze their effectiveness on isolated structural elements [1-3]. Despite a great deal of effort by the research community in the first task, the gap between evaluating the effect that TRM reinforcing materials has on full-scale structures is still under study and the development of design formulas is at an embryonic stage. Indeed, few articles deal with this topic and if we focus our attention on those structures that most need rehabilitation, such as curved structures, the number of works drops further [2]. The reason for this is to be found in the heterogeneity of the materials that make up the TRMs, characterized by very different mechanical properties made to collaborate today in an increasingly efficient way. Therefore, the response of such materials is strongly influenced by the elastic and inelastic properties of the individual components and this complexity has to be considered when developing simplified analytical models. In the case of FRP composites, the main failure mode is represented by debonding and therefore the hypothesis of concurring all the nonlinearities in an interface between the fabric and the support, which remain substantially elastic, has a solid foundation supported by experimental evidence [4-10]. The same approach applied to TRM materials involves the introduction of important simplifications that can lead to non-negligible inaccuracies in the estimation of the collapse load. Thus, current available approaches for the simulation of TRM materials involve the adoption of advanced micro-modelling FE strategies assuming perfect adhesion between the components, inelastic interfaces or simplified FE strategies based on the reduction of the TRM strengthening to an homogeneous material with mechanical properties tuned on coupon tensile test results [8,10]. The present work is part of an extensive ongoing research collaboration between different national and international universities focused on the development of analytical/numerical approaches for the analyses of curved masonry supports strengthened with FRP and TRM materials. The present study is intended to discuss preliminary numerical results obtained by adopting two different computational strategies, namely: (a) a 3D heterogeneous micro-modelling FE model and (b) a spring-model approach. The numerical results in terms of global force-displacement curves and damage patterns are compared and critically discussed.

CASE STUDY

The case study at hand comprised the modelling of two masonry pillars strengthened with TRM materials comprising a 100 mm wide PBO textile embedded into approximately 10 mm thick mortar layer. The TRM strengthening was applied on the extrados (CBE) and intrados (CBI) of the pillars with internal radius equal to 3000 mm. Each specimen referred to a portion of double leaf masonry arch composed by five soft pressed fired bricks ($65 \times 120 \times 250$ mm) and four mortar joints having thickness ranging from 10 mm to 16 mm [4,5]. The computational study presented in this work is part of an ongoing experimental and numerical investigation developed by the authors on anchored and not anchored FRP strengthened masonries and further extended herein to TRM materials. The reader is referred to [5-7] for further details on the past investigations.

FINITE ELEMENT MODELLING

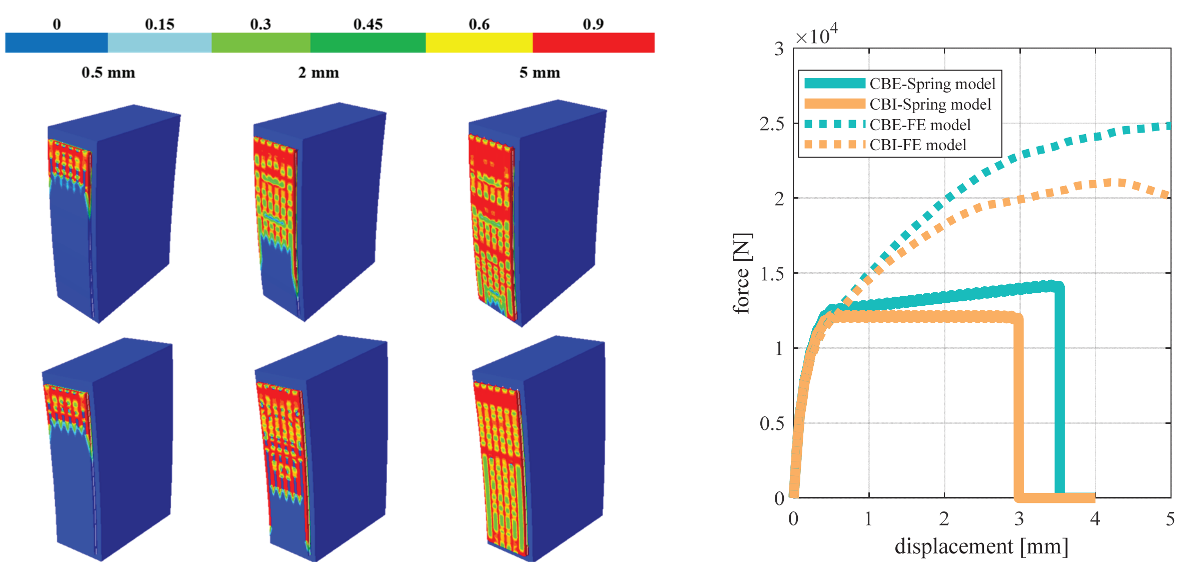
A 3D advanced micro modeling approach was adopted to simulate TRM strengthened masonry pillars subjected to single lap shear tests using the commercial FE software Abaqus. The FE strategy comprised the separate modelling of mortar joints, bricks, PBO textile and TRM matrix. The mechanical properties of the masonry support correspond to Set 3 in [6-7]. It is worth mentioning that in absence of results from lab investigations, which will be developed by the authors in the near future, the elastic and inelastic properties of the TRM strengthening were deduced according to the properties declared by the manufacturer (i.e., E_{PBO}=270GPa, E_{matrix}=7.5 GPa). The PBO textile, which comprised 7 bundles with resistant area equal to 0.758 mm^2, was supposed elastic during the simulations. The FE modelling strategy used a total of 47500 FEs comprising solid 4-noded FEs to simulate all the constituent materials and 2-noded truss FEs to model the PBO textile. The inelastic properties of the materials involved into the simulations were modeled by using the Damage Concrete Plasticity (CDP) model already available in Abaqus. The maximum tensile and compressive damage assumed for all the materials was 90%. Finally, a perfect bond between the PBO textile and TRM matrix and between the TRM strengthening and the masonry support was assumed in the simulations. Non-linear FE static analyses were carried out by applying a monotonically increasing vertical displacement to the PBO textile while keeping unchanged the BCs adopted in previous numerical studies developed by the authors [4-7]. The TRM strengthening effectiveness was evaluated starting from the global numerical curves obtained by monitoring the vertical displacements and reaction forces at the loaded end.

SPRING-MODEL APPROACH

Further numerical simulations were carried out by using the spring model approach recently proposed by the Authors in [8]. It consists of schematizing specimens strengthened by TRM systems by spring elements representing both the main components of the specimen (strengthening, matrix and support) and the reinforcement-matrix interface layers. Since the model was specifically developed for curves substrates, two types of springs at both lower and upper interface were provided: springs which only activates for tangential relative displacements between the strengthening and the matrix/support (denoted shear interface springs); springs which only activates for normal relative displacements between the reinforcement and the matrix/support (labelled normal interface springs). Moreover, a coupled behavior between tangential and normal springs was accounted for considering the influence of normal stresses on the bond behavior. The parameters characterizing the behavior of interface shear springs were deduced by using formulas available in literature together with the indications proposed by the Italian document CNR-DT200 [9], the latter opportunely arranged for the case of TRM strengthening systems. The obtained values are summarized in what follows: equivalent thickness of yarn tf =0.0455 mm, bond strength of lower and upper interface tbi=tbe=2.4749 MPa, slip at the end of ascending branch – lower and upper interface si0=se0=0.0365 mm, slip at the end of descending branch – lower and upper interface sif=sef=0.4833 mm and tensile strength of matrix ftm=1.75 MPa.

NUMERICAL SIMULATIONS

Numerical simulations using the spring-model and the micro-modelling approach were performed by considering the CBI and CBE specimens configurations, i.e., the case strengthened at the intrados and the one at the extrados, respectively. The obtained results in terms of tensile damage maps and force-displacement curves are reported in FIGURE 1-a and -b respectively. Both curves show an initial linear behavior followed by a nonlinear phase characterized by a stiffness degradation due to the attainment of the bond strength at the interface level.



-a -b

FIGURE 1. Numerical results obtained with: (-a) the FEM model and (-b) the spring model.

While in case of the specimen strengthened at the extrados (CBE) it is evident a ‘hardening’ effect due to the influence of normal stresses in compression, in case of the specimen strengthened at the intrados (CBI) the occurrence at the interface level of normal stresses in tension leads to a reduction of the bond strength and a post-peak behavior different from the specimen strengthened at the extrados. A similar response was obtained at the end of the 3D micro-modelling FE simulations. In details, it is possible to deduce that the two approaches showed a good agreement in terms of initial elastic phase and failure displacement while major discrepancies were obtained on the peak loads.

CONCLUSIONS

The paper discusses the numerical results obtained comparing two different computational strategies characterized by different levels of details: (a) a 3D micro-modelling FE model and (b) a spring model approach. Mechanical properties of the constituent materials involved during the simulations were tuned according to past investigation results, values recommended by the manufacturer and available recommendations from CNR-DT200. The numerical approaches were compared in terms of global force-displacement curves showing a good agreement in the initial elastic phase, influence of the TRM strengthening position and displacement at failure. Larger discrepancies were found on the peak loads. Globally three main conclusions can be drawn from the obtained results: (i) the first crack loads are almost independent on the position of the strengthening, (ii) the load bearing capacity of strengthening materials bonded at the extrados is higher than reinforcements applied at the intrados and (iii) the initial stiffness is almost independent on the position of the strengthening. Although information about the modelling approach better reproducing the experimental response will be available after the tests, the differences emerged in terms of peak load are mainly due to the modelling of the damage (at the reinforcement -matrix interface in case of the spring-model, and inside the 3D volume of matrix in case of the FE model). The comparison with the experimental tests will allow to capture the real mechanism and then, opportunely translate it into the two assumed approaches.

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