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Structural Integrity Procedia 00 (2022) 000–000

Structural Integrity Procedia

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II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

Refined modelling methods of structural reinforcements in the analysis of masonry bridges

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Abstract

Masonry arch bridges constitute a large part of today's Italian architectural heritage. Italy has the highest percentage in Europe of masonry railway bridges with respect to the total. Due to the processes of degradation and to the increased levels of the loads and of the safety requirements, rehabilitation and retrofitting of these bridges is required. Among the available reinforcement techniques, the use of reinforcements with mortar/cement matrix fiber nets has gained great popularity due to the advantages shown over traditional techniques in terms of strength and durability. The FRCM, acronym of "Fiber Reinforced Cementitious Matrix" is a valid reinforcement alternative to the use of polymeric matrix reinforcements, due to its greater compatibility with the masonry support. The Italian technical standards suggest a simplified method for the design of the reinforcement based on empirical coefficients that increase the mechanical properties of the masonry materials, disregarding the consideration of the complex crisis mechanisms occurring, especially in more complex systems like the multi-arch bridges.
The object of this work is the definition of a more refined and efficient method for the numerical modeling of FRCM reinforcement in the structural analysis of multi-span masonry arch bridge. Specifically, an equivalent reduced nets embedded in a mortar continuum determined with the area equivalence principle.
The model is calibrated based on experimental characterization tests carried out on PBO-Mesh, and on the constituents. A validation test of the model is performed with reference to arch models reinforced with PBO-Mesh experimentally tested.
The effectiveness of the proposed approaches is verified analyzing the seismic behavior of a masonry multi-span

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bridge, also considering the soil-structure interaction.

Keywords: masonry arch bridges; retrofitting of masonry bridges; fibre reinforcement; FRCM; PBO; numerical modeling of masonry bridges; reliability analysis.

1. Introduction

The assessment of seismic vulnerability of existing multi-arch masonry bridges is of fundamental importance, especially when they are located in earthquake-prone areas, such as Italy. The importance of these structures has driven the development of new reinforcement technologies. In the current scenario, the market offers a wide variety of reinforcement systems, the choice of which depends on the specific structure to be retrofitted. The paper aims to study new methods for modelling and verifying the seismic vulnerability of existing masonry multi-arch railway bridges reinforced with the so-called FRCM systems (Fibre Reinforced Cementitious Matrix), consisting of networks of inorganic material fibers embedded in a cement matrix. The study intends to define a numerical method to quantify their effectiveness and thus provide an accurate measure of the level of seismic retrofitting obtained, which is not currently available for this type of intervention in the regulations and guidelines in force today. It is also shown that accurate design of seismic retrofitting requires that the soil-structure interaction be incorporated into the numerical model.

2. FRCM reinforcement systems

Among the various reinforcement systems applicable to large masonry infrastructures, the attention was paid to FRCM (Fiber Reinforced Cementitious Matrix) systems present good resistance to high temperatures, chemical-physical compatibility with masonry and concrete substrates and vapor permeability. These composite systems are made up of a continuous phase (inorganic matrix) and a discrete phase (reinforcement mesh embedded in the matrix). Their use allows an improvement in the strength and ductility of the elements to which they are bonded and in the resistance to cyclic actions (e.g., actions arising from seismic phenomena)
The commercial FRCM system PBO Mesh 22/22 produced by Laterlite S.p.a. was used (*Fig.1* (a)). This system is composed of a bidirectional 22+22 g/m^2 PBO (polyparaphenylenebenzobisoxazole) mesh and a cementitious matrix MX-PBO. The mechanical characteristics of the reinforcing materials (PBO and matrix) were obtained from the technical data sheets provided by the manufacturer and from the results of previous experimental tests.

Fig.1 (a). PBO Mesh 22/22, (b). Embedded truss representation

The model of the FRCM system was implemented in the software MIDAS FEA NX. The mortar was modelled as a continuum damaging 3D solid, with mechanical properties derived from tests on the manufact, while the reinforcing network was modelled by means of Embedded Trusses. The Embedded Truss is a one-dimensional finite element representing a beam absorbed in a parent element (*Fig.1 (b)*) which acts as a multiplane constraint for the nodal displacements of the truss.

3. Equivalent mesh modeling

In order to reduce the computational burden of refined numerical models of multi-arch masonry bridges involving FRCM reinforcement, an equivalent modelling scheme of the real network (14 mm mesh) was evaluated. For this purpose, a finite element model of a masonry arch of 1.5m span and 1m depth in several configurations was created: unreinforced arch; reinforced arch with enhanced parameters (NTC Parameters), reinforced arch with 30-60-125-250-500 mm mesh. The equivalent network, assigned the mesh size, possess the same fiber section for unit of length as the real tissue. Regarding the mechanical characteristics of the materials, the arch masonry and the inorganic matrix are characterized by the Concrete Smeared Crack model, which considers the cracking behavior of both the materials, while an elastic linear behavior has been assigned to the reinforcing fibers of the FRCM system. (*Table 1*).

Table 1. Mechanical characteristics of materials

Material type	Young's modulus [N/mm²]	Poisson Ratio [/]	Unit weight [N/mm³]	Fracture energy of Tension Function [N/mm]
Arch masonry	$4{,}5 \cdot 10^{3}$	0,27	$2{,}0 \cdot 10^{-5}$	0,001
Matrix	$7{,}5 \cdot 10^{3}$	0,30	$2{,}0 \cdot 10^{-5}$	0,700
Embedded truss	$2{,}7 \cdot 10^{5}$	0,30	$2{,}0 \cdot 10^{-5}$	/

The model is composed by 67 mm sized 3D finite elements. Fixity is applied at the ends of the structure. The arch is loaded by a 0.5 mm vertical displacement (*Fig.2*).

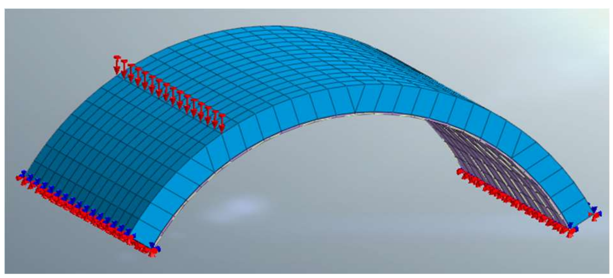

Fig.2. 3D Finite element model of the arch

With the aim of investigating the inelastic evolution of the system an incremental nonlinear analysis was carried out and the crack status at different loading steps was analyzed. The results confirmed, as expected, the formation of the first hinge near the loading zone. The Force-Displacement curves of all the investigated models, in terms of the total reaction in the loading area versus the imposed displacement, were finally compared (*Fig.3*).

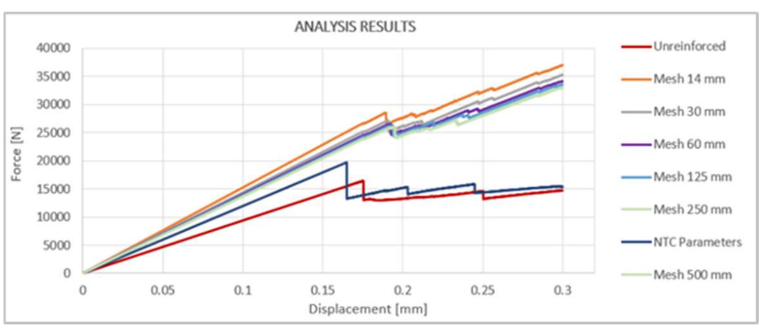

Fig.3. Analysis results

Fig.3 clearly shows that there is a remarkable difference between the response of the unreinforced arch and the FRCM straightened system. On the contrary, the response of all the reinforced systems is comparable. In addition, we note that the NTC parameters model deviates strongly from the behavior of cases with effective reinforcement modeling, leading to the error of 30,9% on the force value referred to the hinge opening.

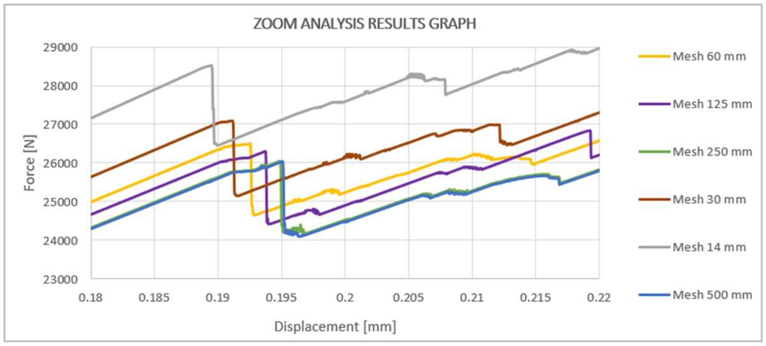

Fig.4. First hinge opening

Looking in detail at the hinge opening point (*Fig.4*), we can see that, as the fibre mesh size increases, the hinge opening displacement increases while the value of the force decreases. This behavior confirms that the equivalent mesh leads to a more ductile and less resistant system with respect to the model with a dense mesh.

It is evident from the results that the modeling of reinforcements is effective, and the use of the equivalent mesh involves tolerable approximations. In fact, by varying the mesh size from 14mm to 500mm, the maximum error on the force value corresponding to the opening of the first hinge is 8.7 %. Furthermore, an asymptotic behaviour of the curve is observed, with stabilisation of the error due to the use of an equivalent mesh network (*Fig.5*).

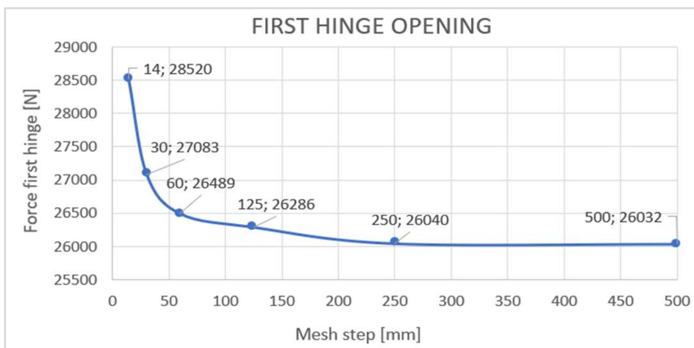

Fig.5. Error trend

4. Case study

4.1. Overview of the case study

The FRCM equivalent mesh modeling in section 3 was applied to the study of a multi-arch masonry bridge (*Fig.6*) with the aim of defining the seismic vulnerability of the structure and verifying the reliability of the modeling strategy. The structure is composed of five arches of variable spans (about 12 m) with a variable deck height from the ground level, with a maximum value of 20 m at the central piers; the arrangement of FRCM reinforcements at the intrados of the arches is planned with the aim of improving the seismic performance of the entire infrastructure.

Fig. 6. Geometrical representation of the bridge

4.2. Modeling procedure and numerical analysis

The finite elements model of the structure was developed using the Midas FEA NX software. Twelve different configurations were modeled, distinguishing fixed-base models and ground-based models (*Fig.7*) in which a mixed mesh composed by 8-node hexahedral and tetrahedral elements was used. The equivalent FRCM network with 500 mm fibre mesh size was used. It should be noted that, since the real type of soil P_S was particularly rigid, models were also developed with a second type of fictitious soil S_S, more deformable, for comparison. The models were labelled as follows. Fixed base models: unreinforced (F_B, F_B_1.5); reinforced (F_B+FRCM, F_B_1.5+FRCM); NTC parameters (NTC_par, NTC_par+FRCM). Soil-structure models: unreinforced (P_S, S_S); reinforced (P_S+FRCM, S_S+FRCM); (P_S_NTC_par, P_S_NTC_par+FRCM).
Models NTC_par include enhanced parameters of all the materials. Models NTC_par+FRCM include enhanced parameters of all the materials except FRCM which is equivalently modeled. Models _1.5 present fixity constraints at 1.5 m above the ground level. The latter is an assumption often made in professional practice.

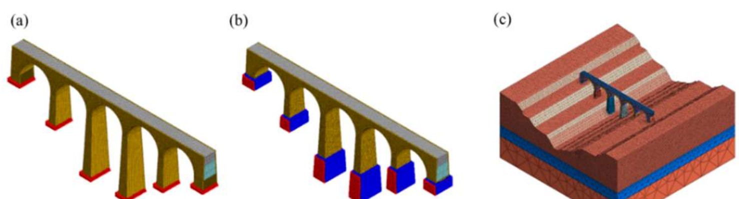

Fig. 7. (a) Fixed base model, (b) 1,5 m fixed base model, (c) Soil based model

As in section 3, the constitutive behaviour of the masonry of the load-bearing elements and of the FRCM matrix is ruled by the Concrete Smeared Crack model, while for the reinforcing fibers, the soil and the filling materials of the gable and piers the linear elastic behaviour was assumed (*Table 2*).

In cases where the FRCM system is present, the same procedure described in section 2 was followed. The medium FE mesh size was 0.40 m for masonry parts and matrix, 2 m for the first layer of soil, 5 m for the second layer and 20 m for the third one.
Firstly, modal analysis and response spectrum analysis have been performed. Then nonlinear static analyses (pushover) were carried out along the longitudinal and transverse direction of the bridge. Despite Italian technical regulations provide in vulnerability analysis for the calculation of the static load through the seismic combination formulation, considering the purposes of this study, the loads were exclusively applied in the two predominant directions, omitting their combinations. Specific control points were selected to follow the evolution of the state of the system, loaded in the two orthogonal directions. In addition, two collapse mechanisms have been identified.
For the longitudinal loading direction, the collapse mechanism involves four alternating intrados-extrados hinges in the first arch (*Fig.8 (a)*). In the transverse load direction, inelastic phenomena are concentrated in the bridge piers. Therefore, the collapse mechanism was identified in the bending failure of the latter (*Fig.8 (b)*).

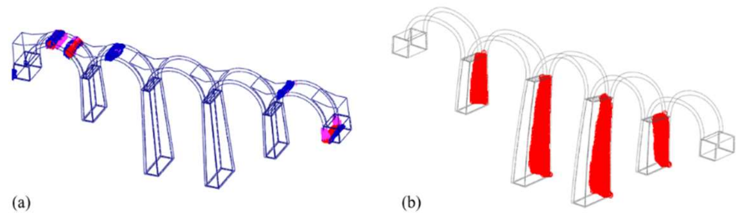

Fig. 8. Collapse mechanisms in the longitudinal and transverse direction.

Table 2. Material Characteristics

Material type	Young's modulus [N/mm^2]	Poisson Ratio [/]	Unit weight [N/mm^3]	Fracture energy of Tension Function [N/mm]
Masonry	$1{,}25 \cdot 10^{9}$	0,20	$1{,}80 \cdot 10^{4}$	20
Matrix	$7{,}50 \cdot 10^{9}$	0,30	$2{,}00 \cdot 10^{4}$	50
Embedded truss	$2{,}23 \cdot 10^{11}$	0,30	$2{,}00 \cdot 10^{4}$	/
Fill (tuff)	$9{,}00 \cdot 10^{8}$	0,20	$1{,}45 \cdot 10^{4}$	/
1st layer of PS soil	$8{,}84 \cdot 10^{8}$	0,35	$2{,}00 \cdot 10^{4}$	/
2nd layer of PS soil	$1{,}28 \cdot 10^{9}$	0,33	$2{,}09 \cdot 10^{4}$	/
3rd layer of PS soil	$2{,}13 \cdot 10^{9}$	0,35	$2{,}15 \cdot 10^{4}$	/

4.3. Analysis results

As an example, the results of the longitudinal pushover analysis are shown in Figure 10*,* in terms of displacement *(Fig.9 (a)),* compressive stresses *(Fig.9 (b)),* tensile stresses *(Fig.9 (c)),* plastic status *(Fig.9 (d))* and crack status *(Fig.9 (e))*.

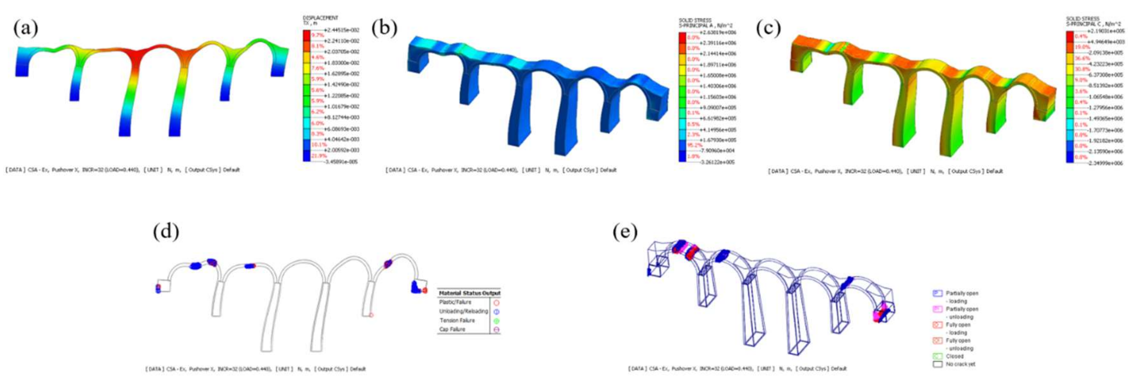

Fig.9. Example of output data for longitudinal pushover

Following the indications of the NTC regulation, as a result of the pushover analysis, the capacity curve (*Fig.10*) was determined for each of the investigated cases. The curve represents the trend of the resulting shear force at the base of the piers as a function of the displacement of the control point.

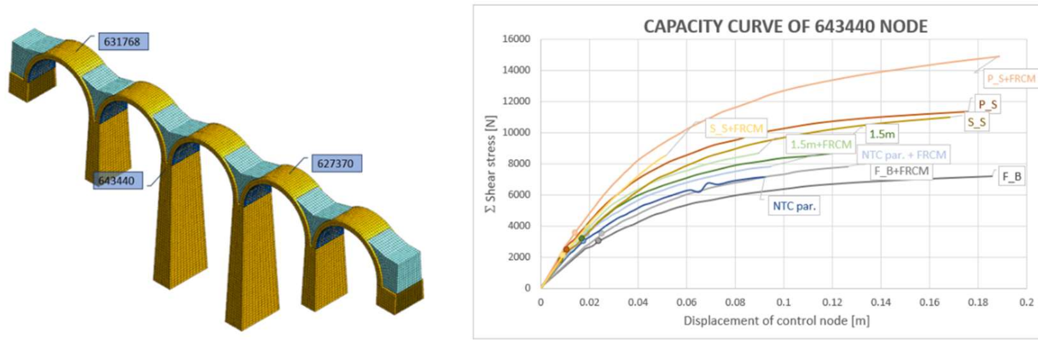

Fig. 2. (a) Control nodes for longitudinal pushover, (b) Capacity curves

The safety level of the structure was then evaluated through the calculation of the risk index (I_R), i.e., the ratio between the seismic capacity of the structure and the seismic demand, in term of Peak ground Acceleration:

$$I_R(PGA) = {}^{PGA_C}/_{PGA_D} \quad (1)$$

A value of I_R greater than unity ensures the seismic safety of the structure.

From *Table 3* fixed-base models with an FRCM reinforcement system with equivalent mesh have higher I_R values than in the case of an unreinforced bridge and higher than models with enhanced mechanical parameters. I_R values calculated in the models that include the soil are lower than the values for the fixed-base models. The fixed-base models therefore lead to an overestimation of I_R and thus to an underestimation of the interventions needed to implement the seismic retrofitting of the structure.

Table 3. Risk index value of 643440 node

Unreinforced Models	I_R	Reinforced Models	I_R
Fixed base	0,55	Fixed base + FRCM	0,61
1,5m Fixed base	0,48	1,5m Fixed base + FRCM	0,49
Fixed base NTC parameters	0,49	Fixed base NTC parameters + FRCM	0,57
PS Soil	0,36	PS Soil + FRCM	0,41
SS Soil	0,16	SS Soil + FRCM	0,19
PS Soil with NTC parameters	0,37	PS Soil with NTC parameters + FRCM	0,42

5. Conclusion

The aim of this paper was to focus on a wide range of large infrastructures (multi-arch masonry bridges) that are highly susceptible to seismic phenomena and in need of structural reinforcement interventions. In order to carry out a correct design and verification of seismic retrofitting works, it is necessary to accurately assess the residual vulnerability of the structures to be improved.

In this work, a numerical modelling strategy of a specific type of FRCM reinforcement has been proposed, which proves in vulnerability analysis to be more effective than a promptly assessment through the simple use of enhanced mechanical parameters of the materials, as suggested by the current Italian technical standards. The efficiency of the method has been shown for both fixed-base models and soil-structure models.
The following main conclusions can be drawn:

- The FRCM system modeling procedure, based on Embedded Truss elements and equivalent network mesh size is suitable for large structures such as multi-arched masonry bridges, as it does not significantly increase the computational load of the models and the calculation time of the analyses (651,9 s for the unreinforced structure vs. 817,9 s of the reinforced structure).
- The study of a prototype arch showed that the equivalent network methodology leads to a maximum error on the bearing capacity of the reinforced arch of 8.7%, when the actual FRCM net is modelled introducing an isoresistant fiber net of very large mesh size.
- The strategy is more reliable than other simplified methods, especially when in the structural analysis the effect of the foundation soil is included.
- In the case of a multi-arched masonry bridge, fixed-base models, even in the presence of not very deformable soils, lead to an overestimation of the Risk Index and thus to an underestimation of the seismic retrofitting interventions (*Fig.11*). For this reason, foundation soil modelling is strongly recommended, to properly design the necessary reinforcement interventions of the structure.

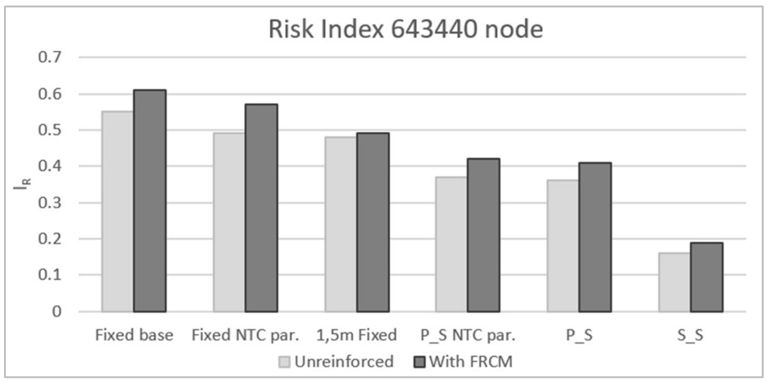

Fig. 11. Bridge Risk Index assessed with reference to the 12 numerical models investigated.

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Istruzioni per l'applicazione dell'«Aggiornamento delle "Norme tecniche per le costruzioni"», (Table C8.5.II).

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