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STRENGTHENING OF MASONRY ARCHES: THE "SANTA MARIA DELLE GRAZIE" CHURCH

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Abstract

The "Santa Maria delle Grazie" church is a monumental masonry complex on the isle of Ischia. The monument is on a mountaintop near the panoramic road leading from the city centre to the mouth of the Arso crater. The structural restoration, still ongoing, involves every part of the building to improve the seismic response. The main intervents concern the reinforcement of the walls, the reconstruction of the timber roof, the slabs and the collapsed portions and the strengthening of the intrados of the vaults and arches with the FRCM system. Two of the four facades, the South and the Est, are buttressed by a system of arches. The south arcades appear more vulnerable since they insist on a slope.

The arcades' reinforcement work involves applying a grid of PBO tapes in a cementitious matrix on the intrados. The purpose is to compensate for the lack of tensile strength of the masonry apparatus by counteracting the opening of plastic hinges. PBO (Polyparafenilenbenzobisoxazole) is a synthetic fibre used in structural reinforcement systems with a cementitious matrix. Compared to the most commonly used composite materials, it possesses remarkable mechanical characteristics and has high chemical compatibility with inorganic compounds. It is often used for reinforcing masonry buildings thanks to the high compatibility of the matrix with which it is applied to the masonry support.

The purpose of this research is to develop a simplified modelling strategy for FRCM-reinforced curved masonry structures able to use by technicians with a sufficiently accurate description of the mechanical behaviour of arches reinforced with FRCM composites.

Keywords: Masonry, Arches, FRCM reinforcement, PBO, numerical model, cultural heritage.

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1 INTRODUCTION

The European architectural, cultural heritage consists largely of masonry buildings which, by their nature and age can present significant structural problems especially and vulnerability with special regard to seismic actions. There are also numerous interventions in Italy to restore damaged or deteriorated structures, static consolidation, reinforcement of intact elements and structural improvement for buildings in seismic areas [1–6]. But while in the building sector the use of composite materials today boasts a rapid application development, thanks to the now reduced costs and the speed of execution of the interventions, the calculation methods are not yet completely refined.

The investigation of masonry curved structural elements is very difficult due to their complex behaviour. Determination of the input parameters for efficient numerical modelling is a great challenge also [7–9]. The laboratory analysis of the masonry arches helps to determine the effect of the necessary parameters, such as geometry, materials and strengthened methods on the behaviour of the structure [10–17]. Finally, the field tests with parallel numerical modelling provide valuable information on the real load-bearing capacity and behaviour of these structures.

One of the most effective materials for reinforcing masonry arches is FRP (Fibre Reinforcement Polymers) reinforcement or other composite materials [15, 18–21] using this system is quick and easy because it is placed on the outer surface of the structure. Composite materials such as FRP strips are capable of withstanding tensile forces, whereby the reinforced structure is able to resist both compression and tension. One of the most important benefits of the FRP technique is the possibility of maintaining the shape of the support being the strips thin and narrow. So it can also be a valid solution for historical structures from an aesthetic point of view [15]. However, the behaviour of the arch before and after the installation of the FRP strips is completely different [22].

Nowadays FRCMs (Fiber Reinforced Cementitious Matrix), consisting of inorganic matrices and various types of mesh/fabrics, are preferred due to their better compatibility with the masonry substrate. The combination of high tensile strength fabrics (or meshes) with cementitious matrices, having good thixotropic capabilities and vapour permeability, makes such composites suitable for reinforcing a large number of masonry structures, including the one belonging to the historical heritage. However, the mechanical interactions governing the response and the strength of FRCM-reinforced masonry structures are very complex, especially in the case of curved structures. Various types of fibres can be used in such composites, e.g. carbon, glass, basalt, aramid or polyparaphenylene benzobisoxazole (PBO).

The stress-strain response of FRCM composites under uniaxial tension is mainly trilinear, the first branch corresponding to the integrity behaviour, the second to the matrix cracking level and the third to the final damage situation of the fibre network [23–25], a, unlike the behaviour of FRP which is mostly linear up to failure. Another difference is the penetration of the inorganic matrix between the filaments of the tissue, which, due to the large size of the grains, could determine the so-called "telescopic yielding" of the composite under tension [26, 27]. Due to the above, the models developed for FRP composites cannot be used to correctly describe the mechanical behaviour of FRCM composites.

Several numerical procedures have been proposed in the literature to represent the mechanical behaviour of FRCMs, based either on macro [28, 29] or micro-modelling [30, 31] approaches. Modelling the FRCM-substrate interaction using nonlinear interface elements is a common feature of both approaches. A review of the modelling approaches for masonry strengthened with FRCMs and a brief discussion on the mechanical behaviour of masonry arches and barrel vaults reinforced with FRCM composites is contained in [32].

Many articles dedicated to bond-slip analysis refer to flat bonding surfaces [33–41], few instead to curved structural elements such as arches and vaults [42–49].

Failure modes associated with fabric creep are less frequent for reinforcements applied to the intrados. In such cases, failure is mainly associated with detachment of the reinforcement from the backing or of the fabric from the lower mortar matrix layer. These effects must also be properly considered in the definition of specific interface models.

The Italian CNR 215-2018 standard [50] presents a method to evaluate the local contribution of the FRCM as reinforcement when external loads induce tensile stresses unbearable for masonry arches. But in the case of global nonlinear analysis also assessing the contribution of reinforcement to the ductility of the structure, the matter gets complicated. The present paper proposes a simplified modelling approach for the numerical study of the arches reinforced with FRCM. The proposed strategy presents a quick solution for technicians to evaluate structural response in the presence of intrados FRCM reinforcement.

2 CASE STUDY: CHURCH OF *SANTA MARIA DELLE GRAZIE*

The Church of Santa Maria delle Grazie (Figure 1) and the annexed building is a masonry structure located in the municipality of Barano d'Ischia in the southeastern part of Ischia island.

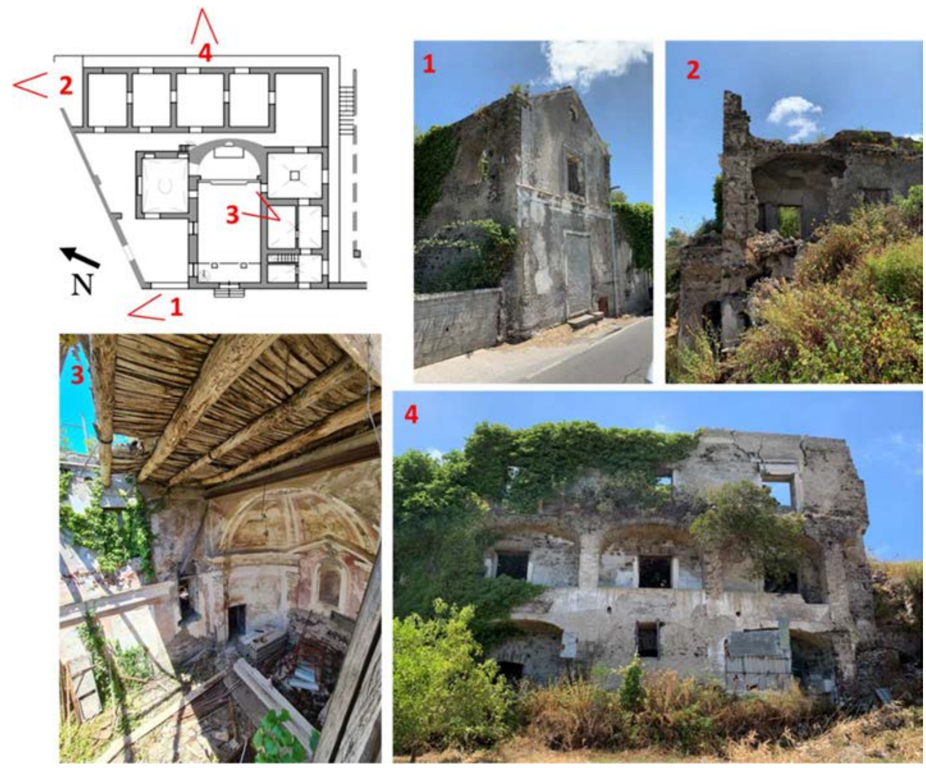

Figure 1 State of the structure before restoration

The complex of buildings is a construction whose original intended use was religious-built at the behest of the Baldino family in the late Baroque period, who lived in the annexe behind the church. In 1883 the Chapel, like the entire building of which it is part, was damaged by the disastrous earthquake that struck Casamicciola Terme. No restoration work is documented, at least until 1889. However, it is probable that a consolidation intervention, albeit minimal, was carried out in the following years, just as it is impossible to attribute to that seismic event the instability that still interests the artefact today. It was certainly open to worship until the first decades of the twentieth century. The closure of the church coincided with the death of R.do

Mattia Baldino, which took place in 1920. In the first decades of the last century, the transfer of family residence to another municipality on the island and the continuous hereditary disputes that developed within the family led to the progressive abandonment of the complex.

The lack of maintenance over several decades is undoubtedly the leading cause of the substantial deterioration. In 1992 the last heirs, Aniello and Raffaella Baldino sold the entire complex, including the Chapel, to the Municipality of Barano.

2.1 Structural retrofit intervention

The structure is made of Arso lava stone and lime mortar, with some parts arranged in regular blocks and others chaotically. The horizontals were made up of stone barrels, cross vaults, and wooden floors.

The state of the structure was very poor, and the whole complex was almost entirely obstructed by weeds, which had grown freely over the years of neglect (Figure 1). The deterioration has also been increased by the continuous exposure of the edifice to atmospheric agents due to its apical and isolated position. The masonry elements that are in an unfavourable place from the point of view of exposure to atmospheric agents, thermal variations, driving rain and winds are more susceptible to deterioration. These factors can, over time, indeed disfigure the material consistency of the masonry, affecting the internal states of cohesion. The structural elements, so disconnected, hit by the horizontal actions produced by the earthquake, can no longer find a binder capable of resisting [1].

The ground floor, occupied by the church with a rectangular apse, is entirely devoid of a roof affected by a generalised collapse or completed forcibly in the safety phase. The wall structures are intact and protected by a finishing layer fresco painted plaster and enriched with various mouldings. The church's facade is almost entirely devoid of the plaster finish layer, and the entrance door initially walled up was opened with the loss of the portal, already seriously damaged by time. Behind the church were residential areas of which today, almost exclusively, the perimeter walls remain, having collapsed or demolished for safety purposes. They are exposed to atmospheric agents and affected by widespread collapses and a deep and generalised crack pattern. The first basement floor is located about three meters below road level. The side bordering the road is blind, while the other three sides open freely onto the surrounding landscape. This floor mainly had service areas, such as rooms, vats for vinification, kitchens and washrooms.

The east and south sides were open onto panoramic balconies and loggias constituted by arcades (Figure 2), probably added after the first building. In some cases, arches were effectively disconnecting to perimeter masonries.

In general, the structural consolidation intervention was tackled to improve both the static and seismic capacity of the building. It is, therefore, possible to identify two levels of intervention, the first aimed at building on a global scale and the second at the mechanisms of local influence.

The first level involved widespread masonry consolidation in terms of increasing in-plane and out-of-plane strength by, at first, the reconstruction of mortar joints and then the plating with the FRCM technique performed with basalt meshes and inorganic matrix. The box-like behaviour has been improved by connecting masonry hammers and angles and inserting cross-link chains.

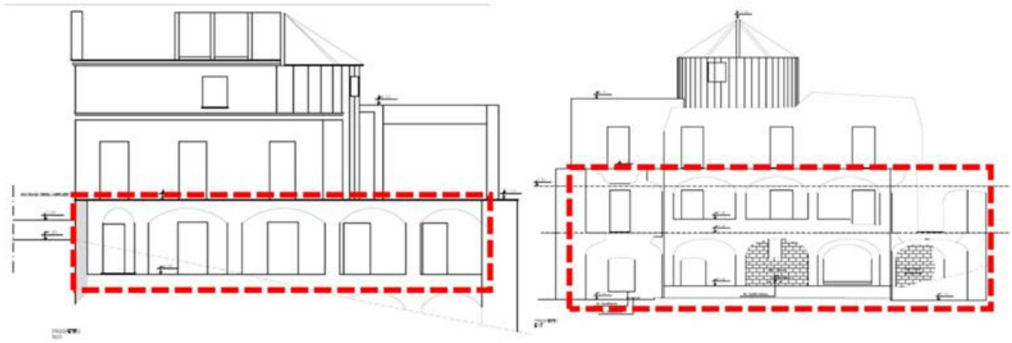

Figure 2 a) south façade; b) est façade

The second level synthetically involved the reconstruction of the timber roof, the application of stripes of PBO fibre in an inorganic matrix on the intrados of arches and vaults, including the south and est arcades, and the rebuilding of collapsed floors and flatbeds.

The loggias on the South and east facades consist of a succession of three-centred arches and variable spans. In particular, for the east arcade, the restoration project envisaged the entire reconstruction of the collapsed part of the east arcade and the application of unidirectional PBO tapes to the intrados for the arches of the south front. This type of passive intervention is used to compensate for the masonry's poor tensile strength, effectively counteracting the triggering of hinges.

The monumental complex hosts furthermore an experimental campaign focused on the structural health monitoring performed with NSHT [51, 52], a transducer whose sensing core is an optic fibre wire capable of providing axial strain with the Brillouin scattering technique.

2.2 The south arcade

The masonry arcade placed on the south front is made with a series of 5 arches, of which the first is a round arch, and the other four are three-centred. As shown in Figure 3, despite the round arch not being reinforced, the first two arches span 4.30 m, and the next two have spans of 3.55 and 3.25 m. The key height is 1.25 m for all arches. From the tests carried out by the restoration executing company, it emerged that there is no filling, and all the structure is made up of a single material.

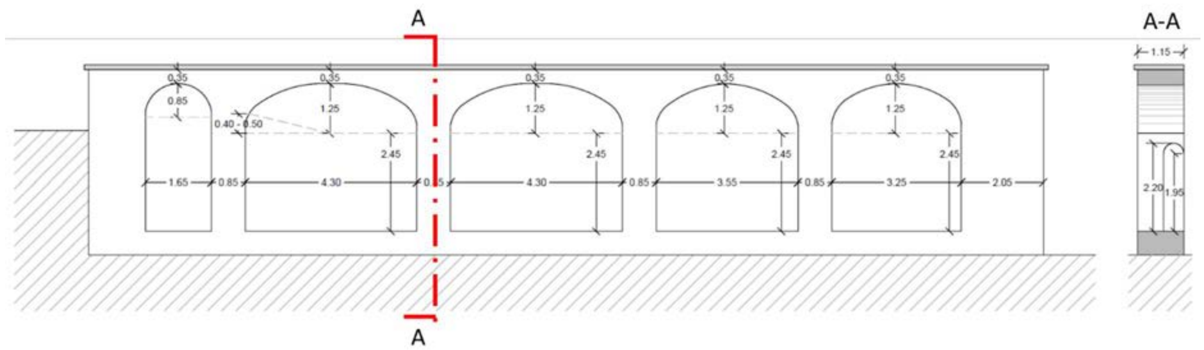

Figure 3 The south façade arches

As indicated, an FRCM-type intrados reinforcement was made on the arches with unidirectional PBO Mesh 44 fabric in an inorganic matrix. Three bands of 25 cm width were placed at the intrados, as shown with red lines in Figure 4. The intervention was completed with additional bands set orthogonally (Green lines in Figure 4), and Joint elements were posed at the intersection between longitudinal and transversal bands to prevent debonding from the support (Figure 4).

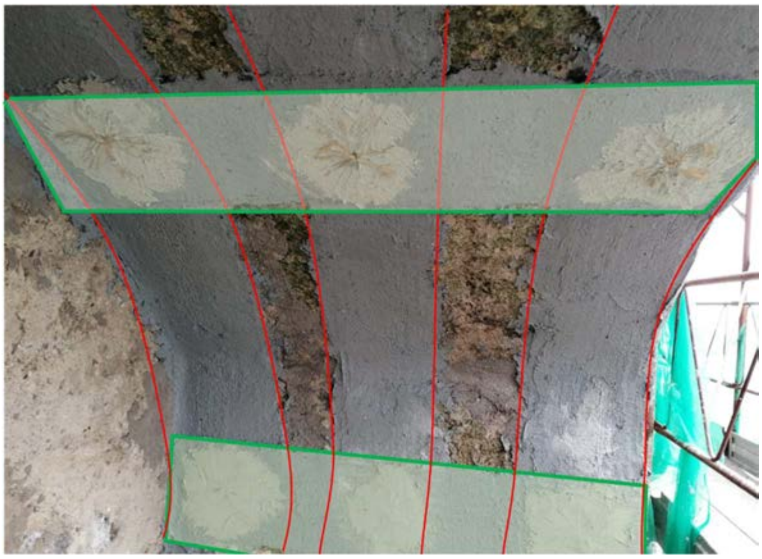

Figure 4 Intrados reinforcement. Red lines indicate longitudinal reinforcement bands, Green lines transversal ones. Joints element are at the intersection.

The original masonry is made of trachytic stone and mortar. The mechanical properties have been obtained based on semi-destructive tests on-site (double flat jacks). As regards the reinforcement intervention, the data relating to the mechanical properties of the materials were provided by the manufacturing company Ruregold Laterlite SpA.

3 NUMERICAL MODEL

The paper proposes a simplified model strategy to simulate the presence of FRCM reinforcement in the hypothesis of perfect adherence. The debonding problem at the composite-substrate interface faced in many studies and researchers [53, 54] is not taken into account pursuant to the presence of transversal layers and joints that should avoid detachment (Figure 4).

The arches were modelled using a 3D finite element model to compute the displacements and stress under different loading conditions with the software MidasGen® [55].

Several configurations were taken into account. The base FEM model is without FRCM reinforcement despite the others that simulate PBO composite presence in two different ways.

The first manner, more common in professional practice, provides a slightly more refined description, and reinforcement is modelled with plates having a thickness and mechanical properties as the FRCM composite material. This type of modelling is already a simplified way of representing the interaction between masonry and composite by not considering the debonding problem and not fully considering the issue of cracking the matrix. Just starting from the awareness that such simplifications lead to less accurate results considering, in any case, an additional modelling effort in implementing the plates elements, a challenge can be determining alternative simplified methods that could lead to the same results.

The paper presents a possible alternative developed as a second model of the reinforced structure in which the plate elements are missing. This simplification provides that the presence of FRCM was considered by giving the intrados solids row of the arch with improved mechanical properties.

The structure was modelled by 32728 solid elements at 8 and 6 nodes and 1152 plates (for the first reinforced model) for a total of 41128 nodes. It was constrained with interlocking at the base and in correspondence with the back buttress-arch to simulate the gearing of the stones with the backside masonry.

Figure 5 shows the base model and the reinforced ones.

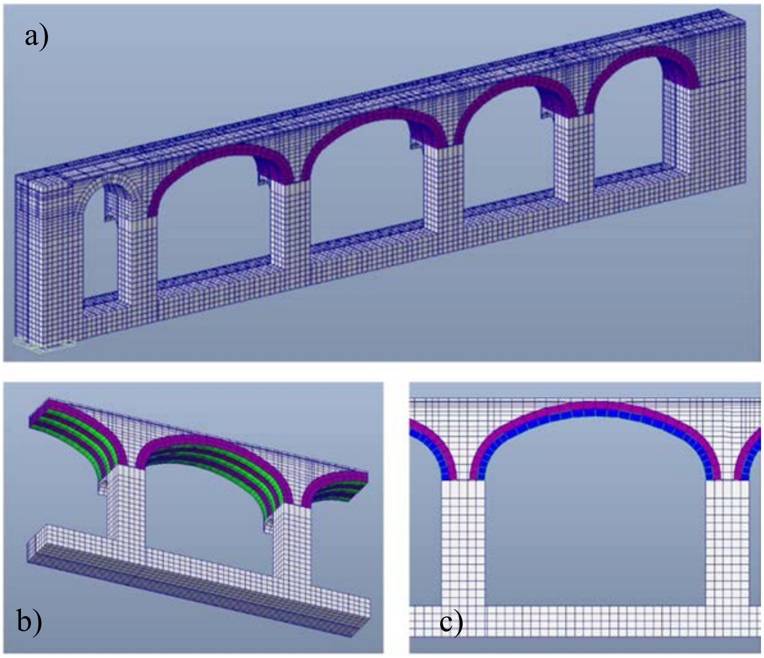

Figure 5 3D finite element model. a) Base model); b) Reinforced model with plates; c) Reinforced model with "boosted material"

A density of 14 kN/m³, modulus of elasticity equal to 900 N/mm² and Poisson's ratio equal to 0.15 were assumed for the masonry. For the FRCM composites, a density of 18 kN/m³, modulus of elasticity of 2750 N/mm² and Poisson's ratio of 0.1 were considered.

The model was calibrated, simulating a load test performed by the executing company on the second arch to verify the correct assumptions of mechanical parameters and constraints. The modulus of elasticity was adjusted iteratively since the displacement profile of the model matched the load test results.

Following Figure 6 represents the load test simulation.

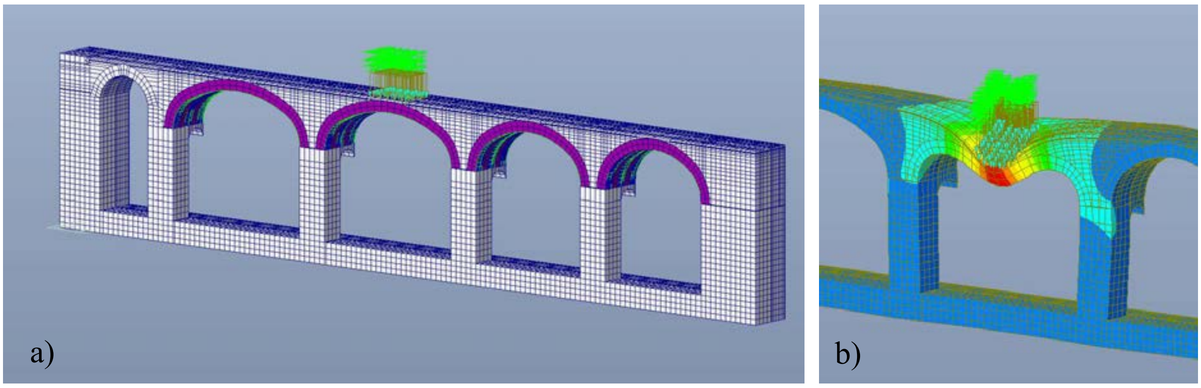

Figure 6 Simulation of Load test a) Load schematisation; b) Z-Displacement results

4 NONLINEAR ANALYSIS AND SIMPLIFICATION STRATEGY

Nonlinear analysis was performed. The "Strumas" failure criterion of MidasGen® [55] software was considered for masonry, and the Tresca one for FRCM composite modelled as plates.

Strumas is a model of equivalent homogeneous material defined as "micro-macro" [56] since, starting from the definition of a representative elementary volume and different constitutive links for the three constituents (blocks, horizontal and vertical mortar joints), through homogenisation, it reaches the bond of the masonry material to be used in the equivalent continuous analysis. The homogenisation technique is proposed by Pande [57] and is based on the equality of the deformation energy. The two primary hypotheses for constructing the equivalent material properties concern blocks and mortar joints considered in solidarity and vertical and horizontal mortar joints deemed continuous. In his work, Pande assumed that tensile cracking is the most critical non-linearity characterising masonry. The model predicts an indefinitely elastic behaviour in compression. At each increase in force, it returns from the values of the stresses and strains inside the elementary reference volume to those of the constituents. The procedure remains linear in each step, but if the principal tensile stress in a constituent exceeds the resistance, its contribution to the new stiffness matrix of the homogenized material is reduced or deleted. The reduction depends on a stiffness reduction parameter, which is reducible to values close to zero, corresponding to an almost elastic-plastic behaviour [58]. Therefore, the equivalent material's properties depend on the average size of blocks, vertical and horizontal joints, and related mechanical characteristics. The Strumas Model has the undoubted advantage of requiring easily available physical parameters, avoiding having to interpret the friction angle and allowing the anisotropic behaviour of the masonry to be described.

The proposed simplified model aims to simulate the presence of the reinforcements by a "super-layer" made of the intrados row of the arch solids element. The assumption on the basis of such equivalence is that the new strengthened material, which represents the reinforced masonry, works as masonry since its tensile strength limit is reached. This is because the FRCM composite does not actually contribute to the compressive strength of the masonry. So the proposed model considers that the "boosted masonry" failure criterion doesn't change despite the tensile strength.

At this point, the challenge is to find that tensile increase value such that the improved material makes the model equivalent to the plates-based one. In this paper, the answer to this challenge has been given by iteratively increasing this value until acceptable results are achieved. However, two load conditions were analysed to prevent the constraint conditions from too much influencing the results in terms of cracking pattern.

The first load case (eccentric load case) involves only the second three-centred arch (the same as the load test), for which a load of 15 kN/m^2 acting in the middle of the half span throughout the thickness of the arch has been modelled. In the second condition, a constant load is applied to the whole structure, increasing the weight of the arcade by four times. The structure reached a crisis in both cases, and yield points have been highlighted.

Different structural behaviours have been investigated by means of these two load conditions. In fact, while the structural response depends mainly on the arch itself in the eccentric load case condition, the structural response is widely different in the second case since the load is equally applied to the whole structure.

The "boosted" masonry's mechanical parameters were determined in the first load condition. By comparing iteratively displacements and stresses between the two reinforced models, an equivalent tensile strength value was reached. Definitively an amount of 10% of the tensile strength leads us to an acceptable result.

Following Figure 7 shows the comparison of displacement under the first load condition.

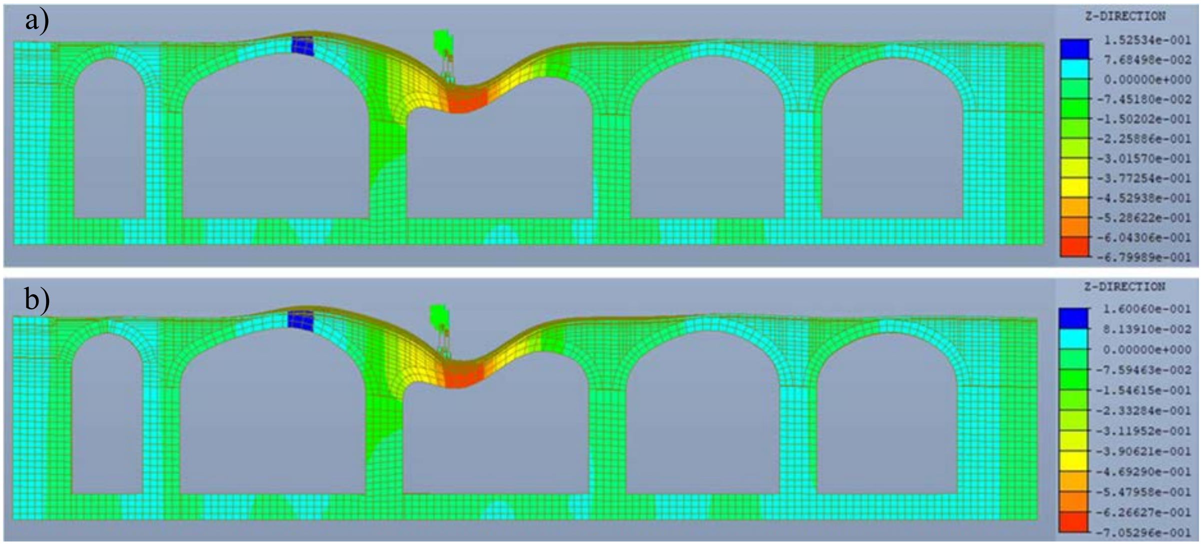

Figure 7 Z Direction Displacement Contouring for first load condition a) First reinforcement model (with plates); b) Second reinforcement model (with "boosted material")

Results show that the models have no substantial differences, and the entity of displacement differs by about 4% for maximum value.

Also stresses results were investigated with particular regard to the yield points.

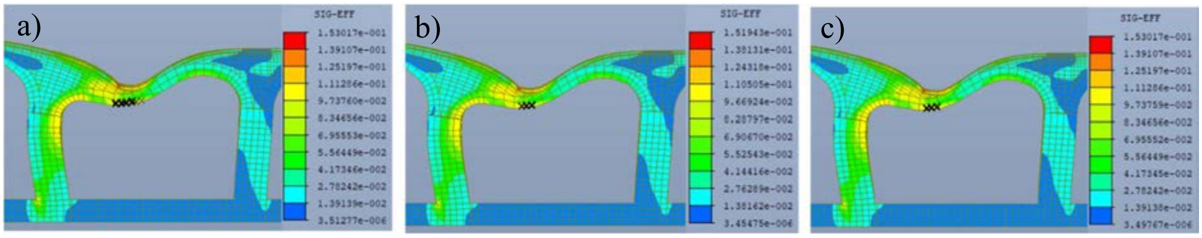

Figure 8 Solid effective stresses contouring for first load condition a) Base model); b) Reinforced model with plates; c) Reinforced model with "boosted material"

Figure 8 shows consistent stress values for the three models highlighting increased cracking in the most stressed sections of the unreinforced model. The two reinforced models show equivalent stress values and a reduced cracking trend.

In essence, it should be noted that it is possible to consider that the two simplified models provide the same result regarding displacements, stress values and cracking trends.

So the same mechanical parameters used in the first load case, were employed for the analysis of the second load case involving the whole structure. Following in displacements contouring are reported in the two reinforced models.

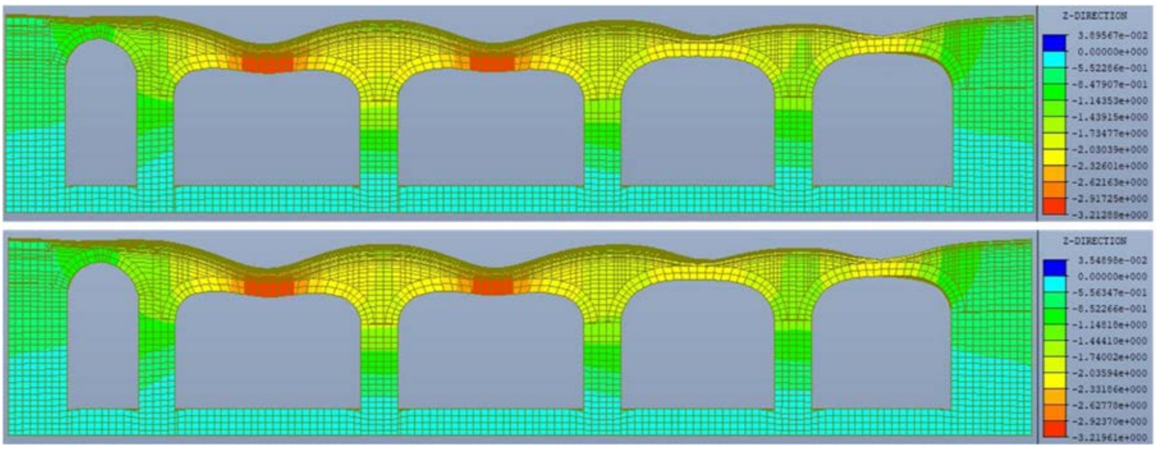

Figure 9 Z Direction Displacement Contouring for second load condition a) First reinforcement model (with plates); b) Second reinforcement model (with "boosted material")

Results show that the models have no substantial differences, and the entity of displacement differs by about 0.2% for maximum value.

Focusing on the stresses and cracking trend, following Figure 10 show result of second load case analyses.

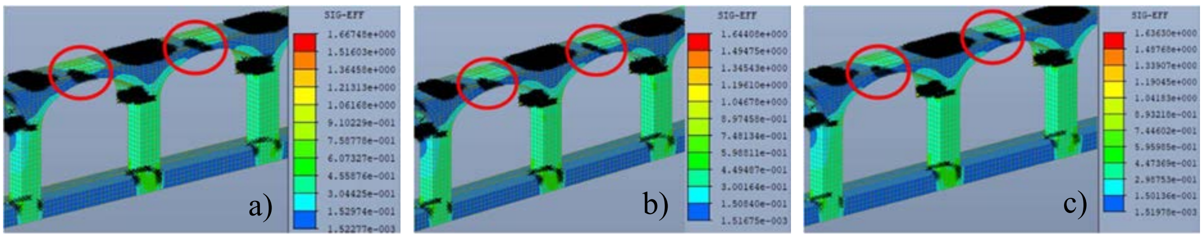

Figure 10 Solid effective stresses contouring of first two arches in second load condition a) Base model); b) Reinforced model with plates; c) Reinforced

As in the first load case, Figure 9 and Figure 10 highlight similar results for both reinforced model.

5 DISCUSSION AND CONCLUSION

This paper focuses on the simplified modelling of curved masonry structures reinforced at the intrados with FRCM.

The presented case study is the Santa Maria delle Grazie church sited in the municipality of Barano in Ischia Isle. The restoration of the monument is still ongoing and synthetically can be divided into global and local interventions. In particular, the structure presents two arcades in the South and East façades, probably with a buttress function for the building. The East façade arcade consists of a series of five arches, four of which, the three-centred ones, are reinforced on intrados with FRCM bands. Because of the presence of transversal bands and Joint elements, the reinforcement has been modelled with plates in perfect adherence with support, as is often the case in professional practice. Considering this model is very simplified, this paper investigates the possibility of equivalent simplified models. The proposed alternative aims to simulate the presence of the reinforcements by a "super-layer" made of the intrados row of the arch solids element. The assumption on the basis of such equivalence is that the new strengthened material, which represents the reinforced masonry, works as masonry since its tensile strength limit is reached. This is because the FRCM composite does not actually contribute to the compressive strength of the masonry. So in the proposed model the failure criterion (the Midas' Strumas one) despite the tensile strength, is considered both for masonry that for reinforced solid elements. Different structural behaviours have been investigated by means of two load conditions. In the first, the eccentric load case condition, the structural response depends mainly on the arch itself. The structural response is widely different in the second case since the load is equally applied to the whole structure. In both cases the two simplified models provide the same result regarding displacements, stress values and cracking trends.

Definitively this work analyses the possibility of performing a very simplified model to evaluate the contribution of FRCM reinforcement in global nonlinear analysis when it is possible to neglect debonding problems. This approach could be particularly useful in professional practice considering mechanical parameters and nonlinear relationships are often not available.

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