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Seismic Vulnerability Mitigation of a Masonry Church by means of CFRP Retrofitting

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Abstract

The paper presents some numerical results on a Romanesque masonry church located in Emilia-Romagna (Italy), a region recently stricken by a devastating seismic sequence on 20th - 29th May 2012. A full investigation of the damages and their comparison with advanced FE analyses, in both linear and nonlinear range are carried out. FE limit analyses are performed through non-commercial software proposed by one of the authors. A remarkable consistency is found among limit analysis results, real performance of the structure under seismic excitation and advanced nonlinear dynamic analyses. In particular, both damage patterns and active failure mechanisms found numerically are consistent with that observed on the church after the seismic event. The results put in evidence the insufficient strength of the apse for combined shear/bending actions, the columns of the central nave for bending, as well as the façade for overturning of the upper part. A seismic upgrading by means of CFRPs composite materials is proposed, designed and analysed quantitatively using FEs, finding an optimal fit between the required performance and the invasivity reduction. The interaction between CFRP strips and masonry substrate is accounted for assuming the behaviour of the reinforcement in agreement with Italian Guidelines for r.c./masonry strengthening with composite materials (CNR DT200). It is found that, with a targeted design, it is possible to prevent premature collapses of the macro-elements, strongly increasing the load carrying capacity of the structure.

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Keywords: Masonry Buildings; Strengthening Techniques; Composites; Seismic Vulnerability; CFRP Reinforcement

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1. Introduction

Masonry churches are traditionally quite vulnerable to seismic actions, exhibiting rather usually partial failure mechanisms active or prone to be active [1–14], even at very low levels of horizontal accelerations. This is a consequence of the much reduced interlocking between perpendicular walls, the almost absent box behavior and the inability of masonry to withstand tensile stresses.

Unfortunately, churches cannot be reduced to any standard static scheme [9, 15, 16]. Italian Guidelines for the Cultural Heritage [9] help practitioners in the safety assessment. To evaluate the acceleration at collapse, they suggest a quite rough and conventional approach based on pre-assigned partial failure mechanisms and the utilization of the kinematic theorem of limit analysis within the assumption of a no-tension material model for masonry. An abacus of twenty-eight possible collapse mechanisms, based on experience of failures observed during past earthquakes, is provided. On the other hand, a FE upper bound limit analysis procedure has been recently applied successfully by one of the authors of this paper on a variety of different examples, including many churches in seismic regions [17–22]. The material is modelled either homogeneous or heterogeneous, referring respectively the un-retrofitted and retrofitted masonry walls. In order to model the unreinforced masonry wall, a homogenization technique [19, 20], i.e. by replacing the heterogeneous assemblage of bricks and mortar with a continuous homogeneous material, is considered. For the retrofitted masonry walls a heterogeneous approach, non-homogenization between the masonry homogeneous material and the CFRP composite material is considered. Material properties are taken from Italian Code recommendations, presuming a limited knowledge (i.e. LC1 which recommends considering the median values for the elastic moduli and minimum ones for the strength).

One masonry Romanesque church located in the province of Ferrara is investigated. The case under study has been severely damaged by the recent earthquake occurred in 2012 in Emilia Romagna, Italy. A long seismic sequence occurred in the second half of May, with two peak events of *5.8* and *5.9* magnitude respectively on 20th and 29th May 2012. The seismic vulnerability is numerically assessed by mean of different analyses conducted on the church in the undamaged state. The analyses were able to mimic the damage patterns and active failure mechanisms observed after the seismic sequence. A strengthening intervention conducted by means of CFRP strips is numerically analyzed in detail, assuming the behavior of the strips –especially for what concerns delamination- in agreement with Italian Guidelines for r.c./masonry strengthening with composite materials (CNR DT200) [23]. Application of CFRP composites is analyzed in previous studies and it results an optimal technique for a consistent seismic upgrading [18, 24–27]. In order to have a better and more realistic insight into the behavior under horizontal loads of the church before and after strengthening, the commercial codes STRAUS7 and SAP2000 are utilized to perform both non-linear static and non-linear dynamic simulations. At this aim, respectively an elastic perfectly plastic approach obeying a Mohr-Coulomb failure criterion (STRAUS7) and an isotropic smeared crack “concrete” model are adopted to simulate masonry behavior under pushover and non-linear dynamic analyses. After proper scaling of the mechanical properties, indeed, it has been found that such approaches may fairly reproduce masonry behaviour in the inelastic range, even if orthotropy due to the texture is disregarded.

2. Brief description of the church

The church of Natività della Beata Maria Vergine, is located in Vigarano Mainarda, a small city near Ferrara, Italy. This church is a structure constituted by three naves, with approximate dimensions equal to 31 m × 20 m × 13 m (length × width × maximum height). The frontal view and the section along the aisle are shown in Figure 1. The façade results poorly interconnected with perpendicular walls, thus making the hypothesis usually done in global finite element analyses (perfect interconnection among transversal walls) rather questionable. The lateral walls of the central nave result highly perforated, both for the presence of large openings surmounted by arches interconnecting central and lateral naves and for the presence of relatively large windows in the upper part. The church is connected in the rear to a secondary sacristy on the left and to a large oratory on the right; only a part of this latter structure is considered in the FE model, since the focus remains the analysis of the church. Finally, it is worth emphasizing that a light wooden roof is present, which is in agreement with the building traditional technology of such typology of structures in the region considered. Its membrane stiffness is safely assumed negligible for horizontal loads, as well as the box behavior induced by its presence in the FE models. For this reason, only vertical loads transferred by the roof to the head of perimeter walls are introduced in the models.