Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 626-636

ECCOMAS Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

SEISMIC RETROFITTING TECHNIQUES FOR EXISTING MASONRY BUILDINGS

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Abstract. In many seismically active regions of the world there are large numbers of masonry buildings. Most of these buildings have not been designed for seismic loads. Recent earthquakes have shown that many of these buildings are seismically vulnerable and should be considered for retrofitting. Different conventional and unconventional retrofitting techniques are available to increase the strength and/or ductility of unreinforced masonry (URM) walls. This paper reviews and discusses seismic retrofitting of masonry walls with emphasis on the conventional techniques. Retrofitting procedures are discussed with regard to a case study: a stone masonry building in Irpinia region, damaged by the 1980 earthquake. The interventions are evaluated by means of finite elements with a macroelement obtained with an homogenization technique. Linear and nonlinear procedures are compared, and peculiarities of each procedure are shown.

Keywords: Masonry, homogenization, seismic behaviour, retrofitting techniques.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi:10.7712/120121.8514.19628

1 INTRODUCTION

Masonry structures are prone to extensive damage followed by failure and collapse when subjected to loads resulting from wind, earthquake and other natural or man-made events. Recent earthquakes and terrorist acts have clearly demonstrated that the development of effective and affordable strategies for the analysis and strengthening of masonry is urgently needed. Many older masonry structures currently in use were in fact designed and constructed with little or no consideration of these aggressive factors. In addition, recent changes in seismic requirements have left many URM buildings in need of strengthening. In many cases, these natural effects were not considered in ancient time [1]. Very few masonry buildings have been built in modern times, and knowledge of the related design methods is no longer part of a civil engineer's training [2]. Despite a growing need for rehabilitation and conservation of these structures, understanding of their behavior has been declining in the first decades of last century, and the available methods for assessing them are of questionable reliability. In recent times the strong need of rehabilitation, together with the development of numerical tools, has improved knowledge about assessment methods for masonry buildings [3]-[12]. As a response to the challenges offered by the assessment of URM, several intervention methods have been proposed [13]. Nevertheless the first step toward a complete assessment of an intervention method is the understanding of constitutive behaviour of both URM and reinforcement [15]-[26].

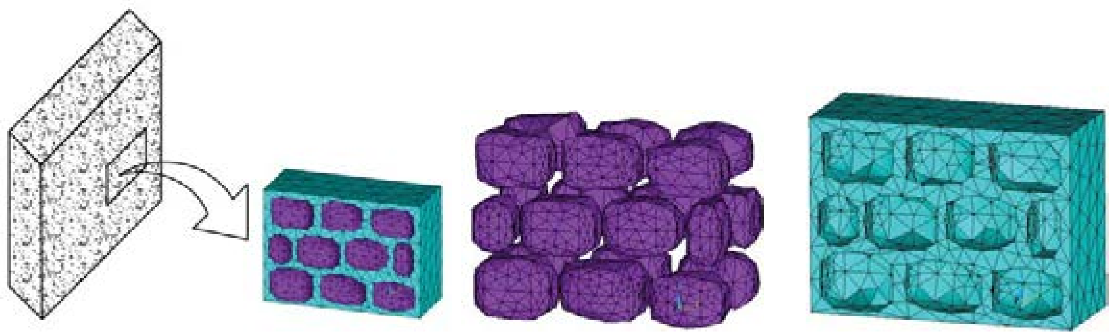
One of the reliable tools developed in the last years are the homogenization techniques. The development of these techniques in the field of composite materials has induced a similar approach in the field of masonry structures, in which the masonry material is the result of two different elements, spacely arranged in different geometries [27]. Since it is a key point in the bulk behaviour of masonry, careful attention must be posed on the behaviour of block-masonry interface [28, 29] and in the spatial arrangement of the blocks. Differently from fiber reinforced materials, in which a periodic structure can be often recognized, homogenization of non-periodic structures is a complex process [30]. Based on classical homogenization methods [31, 32], this paper presents an analysis of a stone masonry building performed before and after the reinforcement with grout injections. The basic cell of the omogenized medium is a non-standard one, with stone elements irregularly arranged in the representative Volume Element (RVE). Elementary load cases were developed in order to obtain the contitutive bulk parameters of the homogenized medium [33, 34]. According to the above considerations, the model has been developed by means of finite element analysis, since a closed form for the homogenization problem in this case is not available. A numerical finite element analysis was performed on this existing building taking into account the bulk parameters derived in the homogenization procedure. The case study is a stone masonry building with simple and irregular shape in Irpinia (a seismic region of Southern Italy), severely damaged by the 1980 earthquake.

2 THE STRUCTURAL MODEL

2.1 Homogenization

It is well known that the mechanical characteristics of masonry should be detected in order to define the constitutive laws of the material for the mathematical model assumptions. Nevertheless all the parameters defining these characteristics cannot be measured on site. The only parameters that can be measured at the moment on site are the modulus of elasticity, the Poisson ratio in the direction parallel to the bed joints, the value of the stress at onset of cracking on the external face of a wall. A masonry wall has in fact different properties along different axes according to the units texture and the directions and geometry of the mortar joints. To evaluate the different properties according the directions, an homogenization procedure has been performed to describe masonry as a composite medium in terms of macro or average properties so that it can be assumed to be an homogeneous material. The first problem to solve was the choice of RVE, i.e. the minimum material to evaluate the macro-parameters of masonry. In the case of periodic structure of masonry it is in general a simple problem to consider the basic cell as RVE. In Southern Italy irregular stone masonry is widely diffused, so that basic cells are not simple to recognize. In this paper an iterative method, based on test windows, was taken into account [35, 36] considering a linear elastic behaviour for both mortar and stone units. A 3D model was built for the RVE (Figure 1a), performig linear and non linear analyses and considering two different types of bonding between the mortar and the stone unit:

1. perfect bonding: in this case a bulk linear elastic behaviour for masonry was obtained as a result;
2. unperfect bonding: in this case an unilateral frictional contact with Mohr-Coulomb constitutive law for the interface mortar-stone unit was taken into account. A nonlinear elastic bulk behaviour was obtained for masonry.



(a) (b) (c)

Figure 1: Representative volume element (a), discretized stone units (b) and mortar matrix (c).

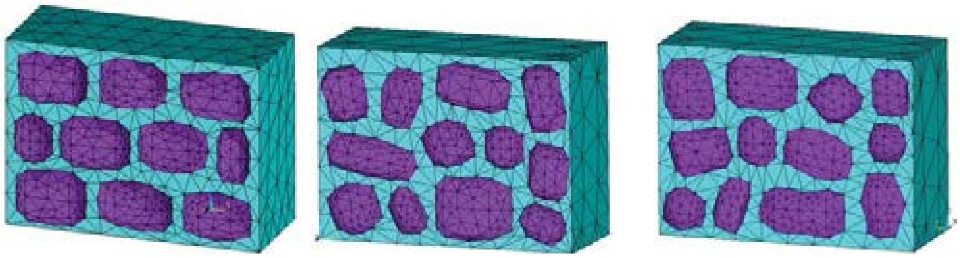
In Figures 1 the discretized model of the basic cell is shown: it is a 110×150×60 cm block in which 20 irregular stone units are embedded in a mortar matrix. The spatial distribution of the stones is irregular too. A finite element analysis was performed on the block, in order to evaluate the mechanical bulk properties to be employed in the numerical analysis of the entire building. Both the constituents were considered isotropic elastic [37]. Their mechanical properties are reported in Table 1.

A picture of the discretized basic cell is represented in Figure 2a. Numerical analyses have shown that negligible changes in the mechanical homogenized parameters were observed in masory panels with larger dimensions with respect to the chosen one, so that the above block can be considered as a representative volume element.

Several sensitive analyses were carried out on different, more chaotic spatial distributions of stones in a masonry panel having the same bulk dimensions, as that reported in

Material	Elasticity Modulus	Poisson coefficient	Friction coefficient
Stone	6000 MPa	0.23	0.60
Mortar	2500 MPa	0.20	

Table 1: Values of mechanical parameters.



(a) (b)

Figure 2: Discretized masonry block: basic cell (a) and tentative discretized cells (b).

Figure 2b. The analyses have shown that a transversal isotropic behaviour can be recognized in these last cases. The symmetry axis is that one orthogonal to the medium plane of the masonry panel. The anisotropic case has been chosen for the case study, both for the similarity of the stone arrangement with the real case and for the generality of the constitutive behaviour.

2.2 Numerical analysis

The results of the analysis performed by means of the ANSYS program [38] on the masonry block are shown in the following. Standard CONTA173 and TARGE170 were used to model the unperfect bonding, while elements SOLID45 were used to discretize both mortar and stone units.

Different load conditions were analyzed in order to obtain the compliance tensor for the homogenized medium. The stiffness tensor was obtained as the inverse matrix of the compliance one. As a syntesis of the results, the stiffness tensor for the homogenized medium is given in the two analyzed cases, with or without frictional contact. The stiffness tensor in the elastic case without frictional contact is reported in Tables 2a. As it can be seen, the stiffness matrix of the material modelled without frictional contact corresponds, as expected, to that of an orthotropic material, so that the symmetry of the matrix is preserved.

No interventions (MPa)					
10928	1826	1790	0	0	0
1826	6812	1321	0	0	0
1790	1321	5492	0	0	0
0	0	0	2045	0	0
0	0	0	0	1938	0
0	0	0	0	0	1488

(a)

Grout injections (MPa)					
18043	2256	2213	0	0	0
2256	10584	1514	0	0	0
2213	1514	8875	0	0	0
0	0	0	3802	0	0
0	0	0	0	2780	0
0	0	0	0	0	2570

(b)

Table 2: Stiffness elastic tensor (no frictional contact).

In this case, in fact, the existence of an elastic potential can be demonstrated. Table 2 refers to the constitutive model of the block without interventions, while Table 2b reports the same data in case of grout interventions.

The case in which frictional contact is taken into account is different: an unsymmetric constitutive matrix is the result of the dissipative behaviour due to the unilateral frictional contact. In this case, in fact, the dissipation cannot assure the existence of an elastic potential function for the material behaviour, which corresponds to a symmetric constitutive matrix.

The above symmetry cannot be observed in fact in the case of frictional contact, shown in Tables 3a. In this case too Table 3a refers to the constitutive model of the block without interventions, while Table 3b reports the same data in case of grout interventions.

As it can be seen, the homogenized material shows more deformability in the case of frictional contact with respect to the perfect bonding.

No interventions (MPa)					
7672	17146	9367	2525	8983	−4854
5878	5702	6188	2216	4771	−4891
2478	5783	3875	3464	3464	−181
−128	−208	−146	−1091	−1091	181
53	73	50	617	617	−53
−11	2	−12	58	58	711

(a)

Grout injections (MPa)					
14142	8850	8506	4406	1390	−9051
5787	8842	5505	2761	2247	−4273
4415	4274	6642	1632	1052	−4991
−109	−101	−207	566	−5	1806
35	52	37	21	653	−105
−4	10	−1	12	47	6908

(b)

Table 3: Stiffness elastic tensor (frictional contact).

This can be explained with the possibility of relative displacement between mortar and stones, due to chosen model of friction, which involves unilateral contact. To complete the set of data obtained by the homogenized procedure performed, the elastic bulk parameters in the two cases analyzed are reported in the following Tables 4a and 4b.

	No interventions	Grout injections
E_x [MPa]	10 928.07	18 043.00
E_y [MPa]	6812.06	10 584.03
E_z [MPa]	5492.05	8875.00
ν_{yx}	0.21	0.18
ν_{xy}	0.13	0.11
ν_{zx}	0.27	0.22
ν_{xz}	0.14	0.11
ν_{zy}	0.19	0.14
ν_{yz}	0.16	0.12
G_{xy} [MPa]	2045.57	3802.74
G_{yz} [MPa]	138.68	2782.28
G_{zx} [MPa]	1488.61	2574.19

(a) No frictional contact

	No interventions	Grout injections
E_x [MPa]	7453.99	14 067.99
E_y [MPa]	5091.56	8753.76
E_z [MPa]	3629.77	6695.40
ν_{yx}	0.41	0.39
ν_{xy}	0.47	0.43
ν_{zx}	0.41	0.39
ν_{xz}	0.46	0.43
ν_{zy}	0.42	0.38
ν_{yz}	0.44	0.40
G_{xy} [MPa]	800.19	1204.02
G_{yz} [MPa]	661.33	1277.46
G_{zx} [MPa]	697.49	1387.34

(b) Frictional contact

Table 4: Mechanical parameters.

In the two cases examined the elastic modulus increase is significant, while a less significant decrease can be observed in the Poisson coefficients. The expected overall increase of stiffness in the injected homogenized medium with respect to that without interventions is confirmed.

2.3 Structural analysis

A stone masonry building in Irpinia was chosen as a case study. It was built in 1930, with a planar *L* shape, and sort of regularity in the z-direction, being x and y the directions of the two external walls of the building (Figure 3a) and z the vertical one.

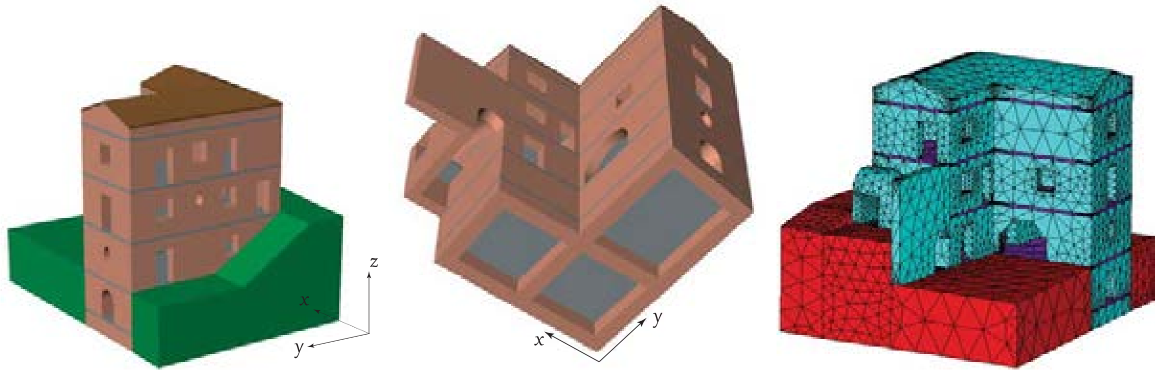


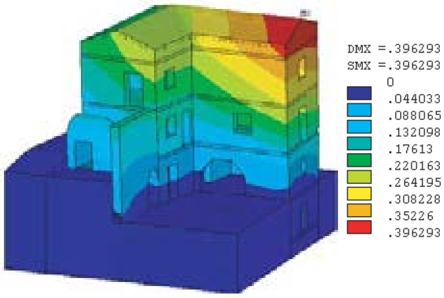
Figure 3: Pictures of the building with reference axes (a)-(b). Discretized model of the building (c).

The stiffness in the y-direction is higher to that in the x-direction as it can be seen in Figure 3b. The masonry walls were modelled with the bulk properties examined above, while floors and roofs were considered as plate elements with high in-plane stiffness (Figure 3c). The homogenized properties evaluated in the previous sections have been considered as the properties of the building masonry walls. The numerical analysis was performed by means of the numerical code ANSYS, with tethraedral four-node solid elements SOLID45.

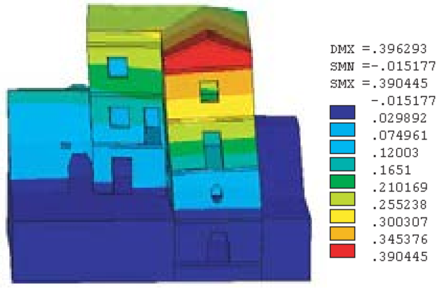
In the following a discussion about the displacements results is provided, in order to assess the reliability of the method proposed. Figure 4a presents the distribution of displacements for an earthquake loading along x-direction in the case of orthotropic behaviour. The constitutive model without frictional contact was taken into account. As it can be seen, the displacement evaluated at the top of the building is about 0.4 cm, better represented in Figure 4b. If the seismic loading is directed along the y-direction, the maximum displacement at the top of the building is about 0% of the previous, as expected according to the building geometry (Figure 4c).

The reduction of the displacement amount due to the contribute of grout injections in the case of orthotropic behaviour is represented in Figure 4d and 4e. As it can be seen, there is a similarity of overall behaviour of the structure, with increased stiffness due to the injections. The analysis performed and shown above involves orthotropic behaviour with a stiffness matrix in which the non-zero terms are derived from the stiffness matrix developed in the case of frictional contact. The isotropic model could not represent the behaviour of the real case study, as it can be seen in the following table, in which the results of a finite element analysis, involving both isotropic and orthotropic behaviour, has been reported.

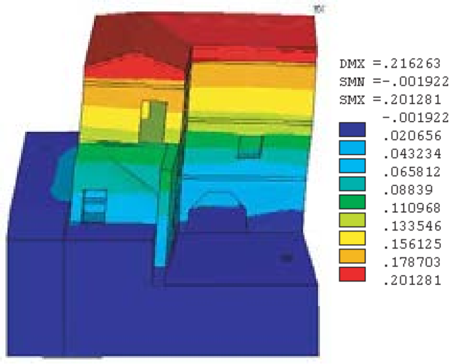
Tables 5 and 6 show that an elevate stiffness can be recognized in the isotropic case, so that the maximum displacements in the four load cases examined for the isotropic behaviour are about 15% of the displacements obtained in the corresponding orthotropic



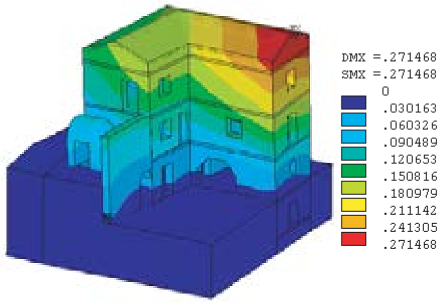
(a) Total displacements for earthquake x-loading (no interventions, orthotropic behaviour)



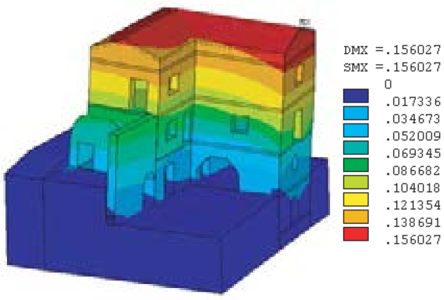
(b) Displacement x-direction for earthquake x-loading (no interventions, orthotropic behaviour)



(c) Displacement y-direction for earthquake y-loading (no interventions, orthotropic behaviour)



(d) Displacements x-direction for earthquake x-loading (with grout injections, orthotropic behaviour)



(e) Displacements y-direction for earthquake y-loading (with grout injections, orthotropic behaviour)

Figure 4: Results.

ones. Usually the isotropic models represent the different behaviour according the load directions only with reference to structural geometry, without considering the influence of the material geometry.

A similar finite element analysis has been performed and the displacements in the same four load cases for the orthotropic behaviour have been compared in three different cases: no interventions, grout injections and connections between the two wythes. This last case has been considered to evaluate the influence of transversal connections in masonry. In general, a good quality masonry presents different leaves with transversal connections, made in general by overlapped stones or long regular stones transversally placed. In the

	Isotropic case	Orthotropic case
x-direction-x-loading	0.057	0.390
y-direction-y-loading	0.035	0.201
Absolute x-loading	0.058	0.396
Absolute y-loading	0.037	0.216

Table 5: Maximum displacements in the elastic cases, no interventions (cm).

	No interventions	Grout injections	Steel connections
x-direction-x-loading	0.390	0.267	0.280
y-direction-y-loading	0.201	0.146	0.147
Absolute x-loading	0.396	0.271	0.284
Absolute y-loading	0.216	0.156	0.157

Table 6: Maximum displacements in the intervention cases, orthotropic behaviour (cm).

cases in which the leafs that constitute the wall are not connected, a retrofitting connection is needed. Traditional interventions involve the placement of transversal stones. Recently local interventions by means of steel bars have been considered. Due both to the cost and to the difficulties connected with the insertion of the bars, usually these last interventions are taken into account if the portion of the masonry wall requiring a retrofit intervention is limited. The analyses show that the performance of the building subjected to a retrofitting intervention made with grout injections is comparable with that of a good quality masonry building.

3 CONCLUSIONS

The geometric and physical-mechanical characterization of the masonry texture is a key point in the homogenization of historical buildings. The numerical homogenization analysis can be focused as a standard procedure to identify the fundamental parameter to correctly model a masonry structure. The outcomes of the proposed approach point out that the anisotropic analysis is accurately formulated and are strongly influenced by the modeling parameters. It has also been shown that isotropic analysis provides different results from the anisotropic one.

REFERENCES

[1] N. Domède, G. Pons, A. Sellier, Y. Fritih. Mechanical behaviour of ancient masonry. Materials and Structures, 42, 2008.

[2] D.C. Rai. A generalized method for seismic evaluation of existing buildings. Current Science, 94(3), 2008.

[3] D.E. Allen, J.H. Rainer. Guidelines for the seismic evaluation of existing buildings. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 33(2):91A-91-A(1), 1996.

[4] A. Iannuzzo, C. Olivieri, A. Fortunato. Displacement capacity of masonry structures under horizontal actions via prd method. Journal of Mechanics of Materials and Structures, 14(5), 703-718, 2019.

[5] C. Olivieri, M. Angelillo, A. Gesualdo, A. Iannuzzo, A. Fortunato. Parametric design of purely compressed shells. Mechanics of Materials, 155, 103782, 2020.

[6] M. Angelillo, C. Olivieri, M.J. DeJong. A new equilibrium solution for masonry spiral stairs. Engineering Structures, 238, 112176, 2021. DOI: 10.1016/j.engstruct.2021.112176

[7] D.B. Hom, J.H. Rainer. Seismic evaluation of existing buildings. ASCE,American Society of Civil Engineers, USA, 31(3), 2003.

[8] A. Gesualdo, M. Monaco. Seismic retrofitting techniques for existing masonry buildings. Journal of Civil Engineering and Architecture, 5(11), 1011–1018, 2011.

[9] M. Monaco, I. Bergamasco, M. Betti. A no-tension analysis for a brick masonry vault with lunette. Journal of Mechanics of Materials and Structures, 13(5), 703–714, 2018.

[10] A. Gesualdo, B. Calderoni, A. Sandoli, M. Monaco. Minimum energy approach for the in-plane shear resistance of masonry panels. Ingegneria Sismica, 36(1), 42–53, 2019.

[11] A. Gesualdo, B. Calderoni, A. Iannuzzo, A. Fortunato, M. Monaco. Minimum energy strategies for the in-plane behaviour of masonry. Frattura ed Integrità Strutturale, 14(51), 376–385, 2020.

[12] A. Iannuzzo, A. De Luca, A. Fortunato, A. Gesualdo, M. Angelillo. Fractures detection in masonry constructions under horizontal seismic forces. Ingegneria Sismica, 35(3), 87–103, 2018.

[13] A.S. Arya. Guidelines for repair, restoration, condition assessmentand seismic strengthening of masonry buildings. 13th International Brick and Block Masonry Conference, Amsterdam, 2006.

[14] M. Fraldi, A. Gesualdo, F. Guarracino. Influence of actual plastic hinge placement on the behavior of ductile frames. Journal of Zhejiang University-SCIENCE A, 15(7), 482–495, 2014.

[15] I. Mascolo, M. Fulgione, M. Pasquino. Lateral torsional buckling of compressed open thin walled beams: experimental confirmations. Int. J. Masonry Research and Innovation, 4(1/2), 150–158, 2019. DOI: 10.1504/IJMRI.2019.096829

[16] M. Monaco, M. Aurilio, A. Tafuro, M. Guadagnuolo. Sustainable Mortars for Application in the Cultural Heritage Field. Materials, 14(3), 598, 2021.

[17] M. Monaco, G. Faella, M. Guadagnuolo. Analysis of pozzolanic mortars for restoration. International Journal of Conservation Science, 12(1), 41–50, 2021.

[18] G. Buonocore, A. Gesualdo, M. Monaco, M.T. Savino. Improvement of Seismic Performance of Unreinforced Masonry Buildings using Steel Frames. in: Civil-Comp Proceedings: 106, B.H.V. Topping and P. Iványi eds., Civil Comp Press, Kippen, Stirlingshire, U.K., 2014. ISBN 978-1-905088-61-4

[19] A. Gesualdo, M. Monaco. Seismic vulnerability reduction of existing masonry buildings. Modelling of retrofitting techniques. Urban Habitat Construction Under Catastrophic Events. Vol. 1, 853–858, London, New York: CRC Press, Taylor & Francis Group, 2010. ISBN: 9780415606851

[20] A. Fortunato and A. Gesualdo and I. Mascolo and M. Monaco. P-Bézier energy optimization for elastic solutions of masonry-like panels. Int. J. of Masonry Research and Innovation, 2021. (In Press) DOI: 10.1504/IJMRI.2021.10037508

[21] M. Malena, M. Angelillo, A. Fortunato, G. de Felice, I. Mascolo. Arch bridges subject to pier settlements: continuous vs. piecewise rigid displacements methods Meccanica, 2021. (Under Review)

[22] I. Mascolo, A. Gesualdo, C. Olivieri, A. Fortunato. On rigid blocks detection in unilateral masonry-like structures. Int. J. of Masonry Research and Innovation, 2021. (In Print)

[23] M. ElGawady, P. Lestuzzi, M. Badoux. A review of conventional seismic retrofitting techniques for URM. Draft Second Revision of IS 13935, 2004.

[24] J. Macabuag. Dissemination of seismic retrofitting techniques to rural communities. EWB-UK National Research Conference 2010 'From Small Steps to Giant Leaps...putting research into practice' Royal Academy of Engineering, 19th February 2010, 2010.

[25] A. Smith, T. Redman. A Critical Review of Retrofitting Methods for Unreinforced Masonry Structures. EWB-UK Research Conference 2009 Hosted by The Royal Academy of Engineering, University of Bristol, 2009.

[26] M.R. Valluzzi, M. Munari, C. Modena, L. Binda, G. Cardani, A. Saisi. Multilevel approach to the vulnerability analysis of historic buildings in seismic areas, Part 2. Restoration of Buildings and Monuments, 13(6), 2009.

[27] A. Zucchini, P.B. Lourenco. MA micro-mechanical model for the homogenization of masonry. International Journal of Solids and Structures, 39, 2002.

[28] B. Luccioni, V.C. Rougier. Shear behaviour of brick–mortar interface in CFRP retrofitted or repaired masonry. International Journal of Mechanical Sciences, 52(4), 2010.

[29] P. Wriggers. Computational contact mechanics. Springer, Berlin, Heidelberg, New York., 2006.

[30] F. Cluni, V. Gusella. Homogenization of non-periodic masonry structures. International Journal of Solids and Structures, 41, 2004.

[31] S.G. Lekhnitskii. Theory of elasticity of an anisotropic elastic body, J.J. Brandstatter, San Francisco, 1963.

[32] S. Nemat-Nasser. Micromechanics: overall properties of heterogeneous materials, North-Holland, 1993.

[33] S. Pietruszczak, Z. Mroz. Formulation of anisotropic failure criteria incorporating a microstructure tensor. Computers & Geotechnics, 26, 2000.

[34] S. Pietruszczak, R. Ushaksaraei. Description of inelastic behaviour of structural masonry. International Journal of Solids and Structures, 40, 2003.

[35] A. Gesualdo, L. Nunziante. Omogeneizzazione di murature storiche (In Italian). Proceedings XVII National Congress AIMETA, Florence, ISBN: 88-8453-313-9, 2005.

[36] M. Modano, F. Fabbrocino, A. Gesualdo, G. Matrone, I. Farina, F. Fraternali. On the forced vibration test by vibrodyne. In: COMPDYN 2015, 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Crete Island, Greece, 25–27 May 2015 Crete Island, 209-2J, 2015.

[37] S.C. Cowin. The relationship between the elasticity tensor and the fabric tensor. Mechanics of Materials, 4, 1985.

[38] ANSYS. User's Manual, Version 8.0, Swanson Analysis Systems Inc. (SASI), Houston, PA, 2004.