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# MODELING AND SEISMIC ASSESSMENT OF MASONRY HISTORICAL STRUCTURES

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## ABSTRACT

Numerical modeling and analysis of masonry structures is one of the greatest challenges faced by structural engineers. This difficulty is attributed to the presence of joints as the major source of weakness, discontinuity and nonlinearity as well as the existence of uncertainties in the material and geometrical properties. In this paper, an anisotropic (orthotropic) finite element model is proposed for the macro-modeling of masonry structures. Based on this FE macro-model a computer code has been developed for the structural design and analysis of unreinforced masonry (URM) walls under plane stress. During the development procedure, special attention has been given at the graphic imaging of the analysis results. The program possesses the capability of automatic crack pattern generation and associated damage indices for a set of masonry failure criteria. These damage indices data have been proven to be an effective tool for the selection of the optimum repair scenario. The derived results in comparison with the available experimental findings demonstrate that the proposed procedure is effective and robust for the modelling and seismic assessment of masonry structures compared to available ones. Furthermore, the derived crack patterns seem to be a useful tool for the selection of the optimum scenario of the masonry structures.

***Keywords:*** damage index, failure criteria, historical mortars, masonry structures, material anisotropy, finite element modelling, seismic assessment.

## INTRODUCTION

Masonry structures are vulnerable to earthquakes, but their modeling and seismic assessment remains a challenge task both for scientists and practicing engineers. This mainly has to do with their complex, discontinue and multi face behavior as a material that exhibits distinct directional properties because the mortar joints act as planes of weakness. Furthermore, their brittle behavior and the considerable scatter of material mechanical properties make their structural modeling more complicated and difficult.

Utilizing numerical methods for the structural analysis of masonry structures contributes to a more thorough understanding of their structural behavior and to its more accurate protection and conservation. Among the plethora of computational methods and approaches, continuum mechanics finite element models, comprise one of the most widely used methodologies for the analysis of large masonry structures. Their extensive use is the outcome of a compromise between the accurate representation of the masonry's structural response and the computational cost incurred for analysing large structures. Nevertheless, despite such advantages, finite-element macro-models encounter two important challenges, namely, the

realistic representation of damage and a satisfactory independency of the solution to the structure of the used mesh discretization.

In this paper, an anisotropic (orthotropic) finite element model is proposed for the macro-modeling of masonry structures. Based on this FE macro-model, a computer code, in MATLAB environment, has been developed for the structural modeling and seismic vulnerability assessment of unreinforced masonry structures using a set of masonry failure criteria.

## FINITE ELEMENT MACRO-MODEL

The basic concepts of the finite element method are well documented and will not be repeated in this paper. Only the essential features will be presented. In this paper, an anisotropic (orthotropic) finite element model is proposed for the macro-modeling of masonry structures. Specifically, a four-node isoparametric rectangular finite element model with 8 degrees of freedom (DOF) has been used (Fig. 1).

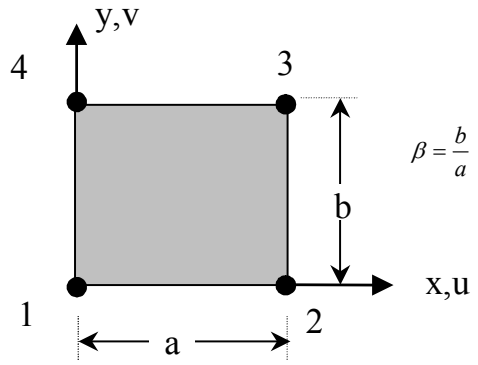



Fig. 1 - Finite element macro-model dimensions

The major assumption of modeling the masonry behavior under plane stress is that the material is homogeneous and anisotropic. Especially, the material shows a different modulus of elasticity $(E_x)$ in the x direction (direction parallel to the bed joints of brick masonry) and a different modulus of elasticity $(E_y)$ in the y direction (perpendicular to the bed joints). In the case of plane stress the elasticity matrix is defined by

$$E = \frac{E^2 G_{xy}}{1-\nu^2}\begin{bmatrix} \frac{1}{E_y G_{xy}} & \frac{\nu_{xy}}{E_y G_{xy}} & 0 \\ \frac{V_{xy}}{E_x G_{xy}} & \frac{1}{E_x G_{xy}} & 0 \\ 0 & 0 & \frac{1-\nu^2}{E^2} \end{bmatrix} \quad (1)$$

where $\nu_{xy}$ and $\nu_{yx}$ are the Poisson's ratios in the xy and yx plane respectively, and $G_{xy}$ is the shear modulus in the xy plane.

## FINITE ELEMENT CODE

Based on the above proposed FE macro-model, a computer code called MAFEA (MAsonry Finite Element Analysis), in MATLAB environment, has been developed for the structural design and analysis of unreinforced masonry (URM) walls. During the development procedure, special attention has been given to matrix processing techniques that economize storage and solution time by taking advantage of the special structure of the stiffness matrix. Especially, based on the symmetry, sparse, and band form to the principle diagonal of the stiffness matrix an iterative solution technique -such as the Gaussian elimination algorithm tailored to the specific case of banded matrix (half bandwidth)- is used for the solution of linear system equations of the structure.

During the development procedure, special attention has been given at the graphic imaging of the analysis results. The program possesses the capability of automatic crack pattern generation and associated damage indices for a set of masonry failure criteria. Specifically, anisotropic failure criteria such as the cubic tensor polynomial (Syrmakezis & Asteris 2001, Asteris 2010 & 2013) and isotropic failure criteria such as the ones proposed by Syrmakezis et al. 1995 and Kupfer et al. 1969 have been implemented in the program. For each criterion, a color image is generated depicting the failure areas of the masonry wall and highlighting in distinct ways the kind of stress underpinning the failure.

## DAMAGE INDEX

Damage control in a building is a complex task, especially under seismic action. There are several response parameters that can be instrumental in determining the level of damage that a particular structure suffers during a ground motion; the most important ones are: deformation, relative velocity, absolute acceleration, and plastic energy dissipation (viscous or hysteretic). Controlling the level of damage in a structure consists primarily in controlling its maximum response. Damage indices establish analytical relationships between the maximum and/or cumulative response of structural components and the level of damage they exhibit (Park et al. 1987). A performance-based numerical methodology is possible if, through the use of damage indices, limits can be established to the maximum and cumulative response of the structure, as a function of the desired performance of the building for the different levels of the design ground motion. Once the response limits have been established, it is then possible to estimate the mechanical characteristics that need to be supplied to the building so that its response is likely to remain within the limits.

For the case of masonry structures a new damage index is proposed by Asteris, which employs as response parameter the percentage of the damaged area of the structure relatively to the total area of the structure. The proposed damage index (DI), for a masonry structure can be estimated by

$$[DI] = \frac{A_{fail}}{A_{tot}} \times 100 \tag{2}$$

where $A_{fail}$ is the damaged surface area of the structure and $A_{tot}$ the total surface area of the structure.

## EXAMPLES

Two unreinforced masonry walls (Figure 2) under plane stress state were studied using the MAFEA program presented in the previous section, in order to quantify and to assess their seismic vulnerability. The mechanical characteristics of the masonry material are presented in Table 1. These cases have been selected as representative cases of flexural shear walls and of shear walls. It should be noted that the developed stress strongly depends on the type of the structural system. Especially, for flexural shear walls under seismic loading, most regions of the walls are under biaxial heterosemeous stress state.

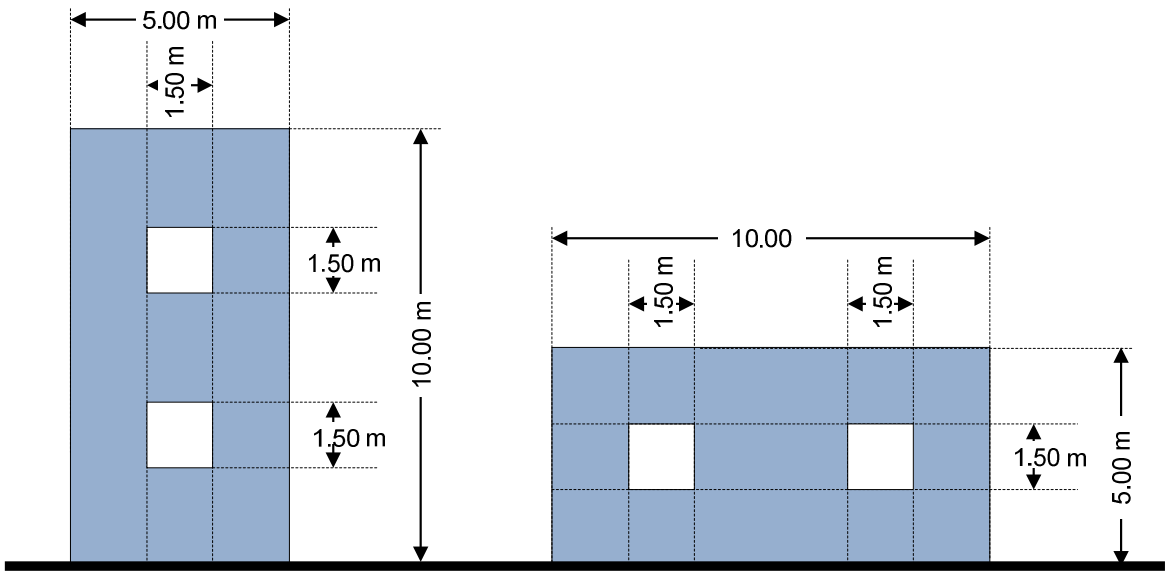



Fig. 2 - 2D anisotropic masonry walls with two openings

Both cases were studied for values of peak ground acceleration from 0.00 to 0.80 by step 0.08. Furthermore, for each one masonry wall the crack pattern have been derived (Figure 3) for two isotopic failure criteria. For each case, the failure areas were computed using the failure criterion proposed by Syrmakezis et al. 1995 as well as the failure criterion proposed by Kupfer et al. 1969. These two isotropic failure criteria have been adopted widely by many researchers for the failure estimation of masonry structures assuming masonry material as an isotropic material dispite its strongly anisotropic nature. Furthermore, a damage index for each criterion was computed. This kind of information is very useful for the cases necessitating the proposal of reinforcement measures for the constructions under study. This is due to the fact that different sets of reinforcement measures are needed for wall regions failing under biaxial tension, under biaxial compression, and under heterosemous stress state. The failure criteria are utilized to extract fragility curves regarding each failure criterion regarding the use of various restoration mortars toward the selection of the optimum repair scenario. Specifically, in this manner, the optimum restoration mortar in regards to the enhancement of the building's behavior under seismic action can be selected. Restoration mortars of compressive strength values 5, 10 and 15 MPa (Table 1) were evaluated, in order to cover the whole range of mechanical properties presented by restoration mortars, which

have been assessed to be compatible for use in monuments and historical buildings (Moropoulou et al. 2005).

The damage indices are presented in Figures 4 and 5 for the existing structure as well as for the three cases of repaired structures with the above mentioned three restoration mortars. These indices are very useful for the assessment of the seismic vulnerability of the existing masonry structures and for the quantitative estimation of the structures' vulnerability. In other words, these damage indices facilitate, in a significant manner, the determination (selection decision) of the optimum restoration scenario (among a plethora of restoration scenarios).

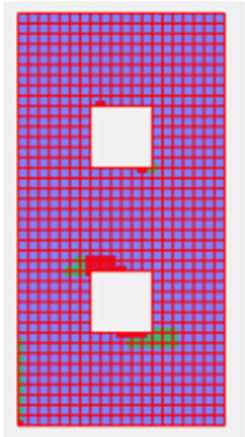
Table 1 - Materials Elastic Properties

| **Material** | **Moduli of elasticity [MPa]** | | **Compressive Strengths [MPa]** | | **Tensile Strengths [MPa]** | | **Poison's ratios** | |
|---|---|---|---|---|---|---|---|---|
| | $E_x$ | $E_y$ | $f_c^x$ | $f_c^y$ | $f_t^x$ | $f_t^y$ | $\nu_{xy}$ | $\nu_{yx}$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Masonry* | 4362.5 | 7555.0 | 4.3625 | 7.5550 | 0.40 | 0.10 | 0.20 | |
| Restoration Mortar A | 5000.00 | | 5.00 | | 5/8 | | 0.20 | |
| Restoration Mortar B | 10000.00 | | 10.00 | | 10/10 | | 0.20 | |
| Restoration Mortar C | 15000.00 | | 15.00 | | 15/12 | | 0.20 | |

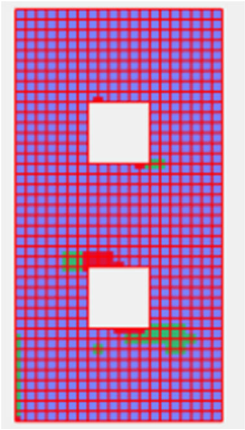
* The values of this masonry material have been estimated experimentally by Page (1981).

## CONCLUSIONS

The derived results in comparison with the available experimental findings- demonstrate that the proposed procedure is effective and robust for the modelling and seismic assessment of masonry structures compared to available ones. Furthermore, the derived crack patterns seem to be a reliable means for the selection of the most suitable and effective restoration scenario of the masonry structures. This is due to the fact that different sets of reinforcement measures are needed for wall regions failing under biaxial tension, under biaxial compression, and under heterosemous stress state.



PGA=0.24g-Syrmakezis et al. 1995



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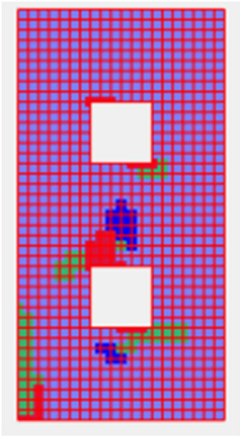
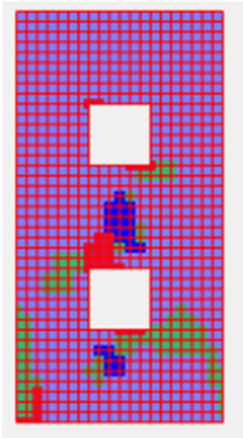


PGA=0.32g-Syrmakezis et al. 1995



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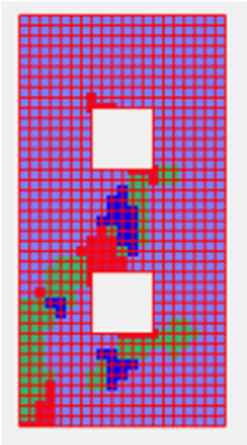

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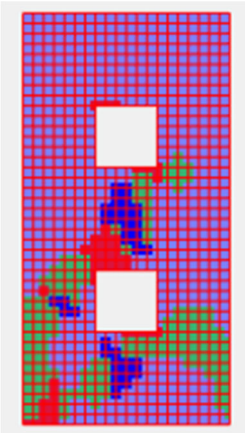

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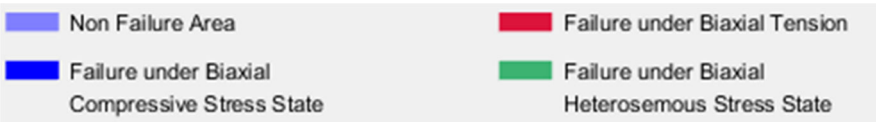
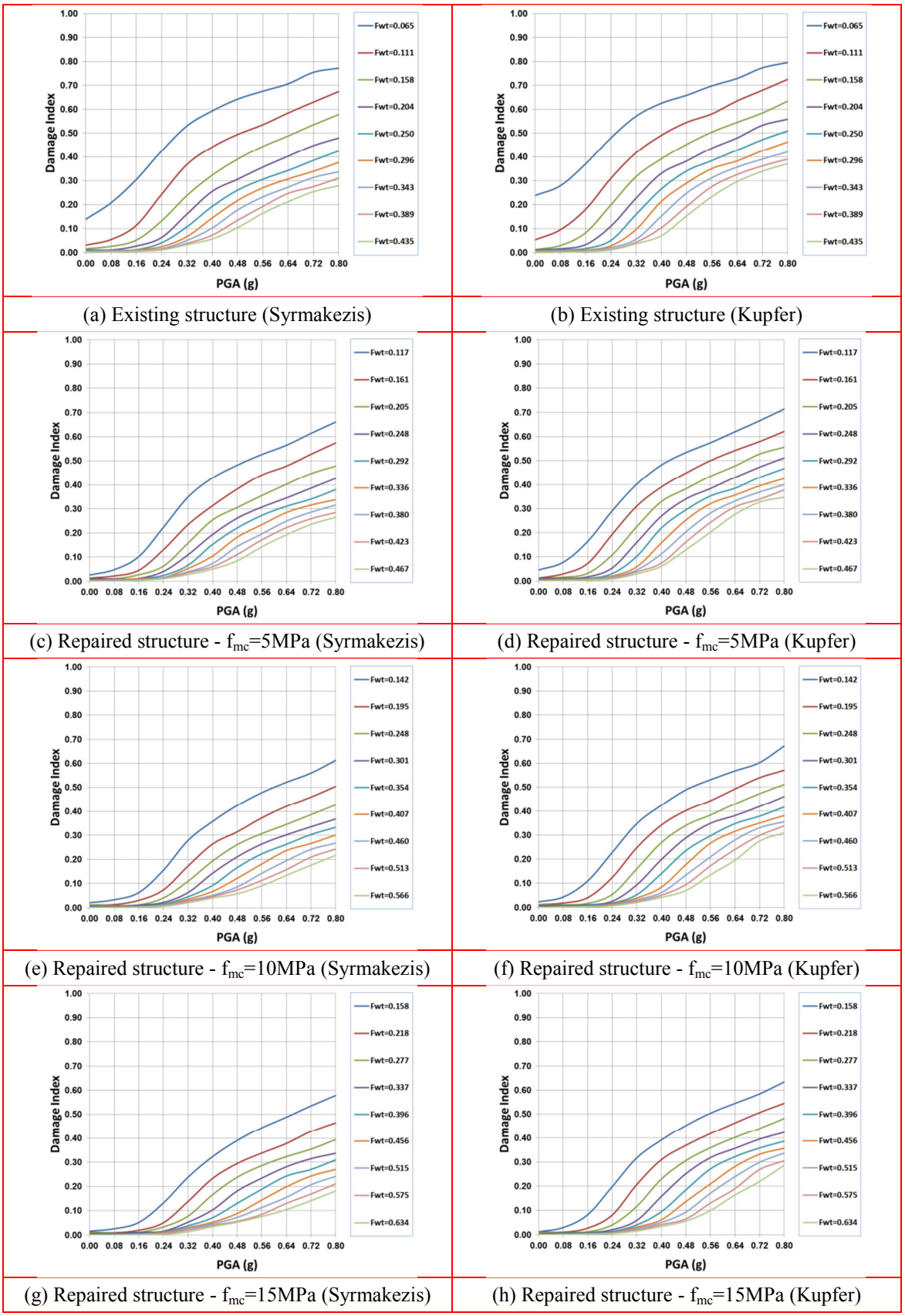



Fig. 3 - Mapping cracking pattern of masonry wall with two openings (Existing structure)




(a) Existing structure (Syrmakezis)

(b) Existing structure (Kupfer)

(c) Repaired structure - $f_{mc}$=5MPa (Syrmakezis)

(d) Repaired structure - $f_{mc}$=5MPa (Kupfer)

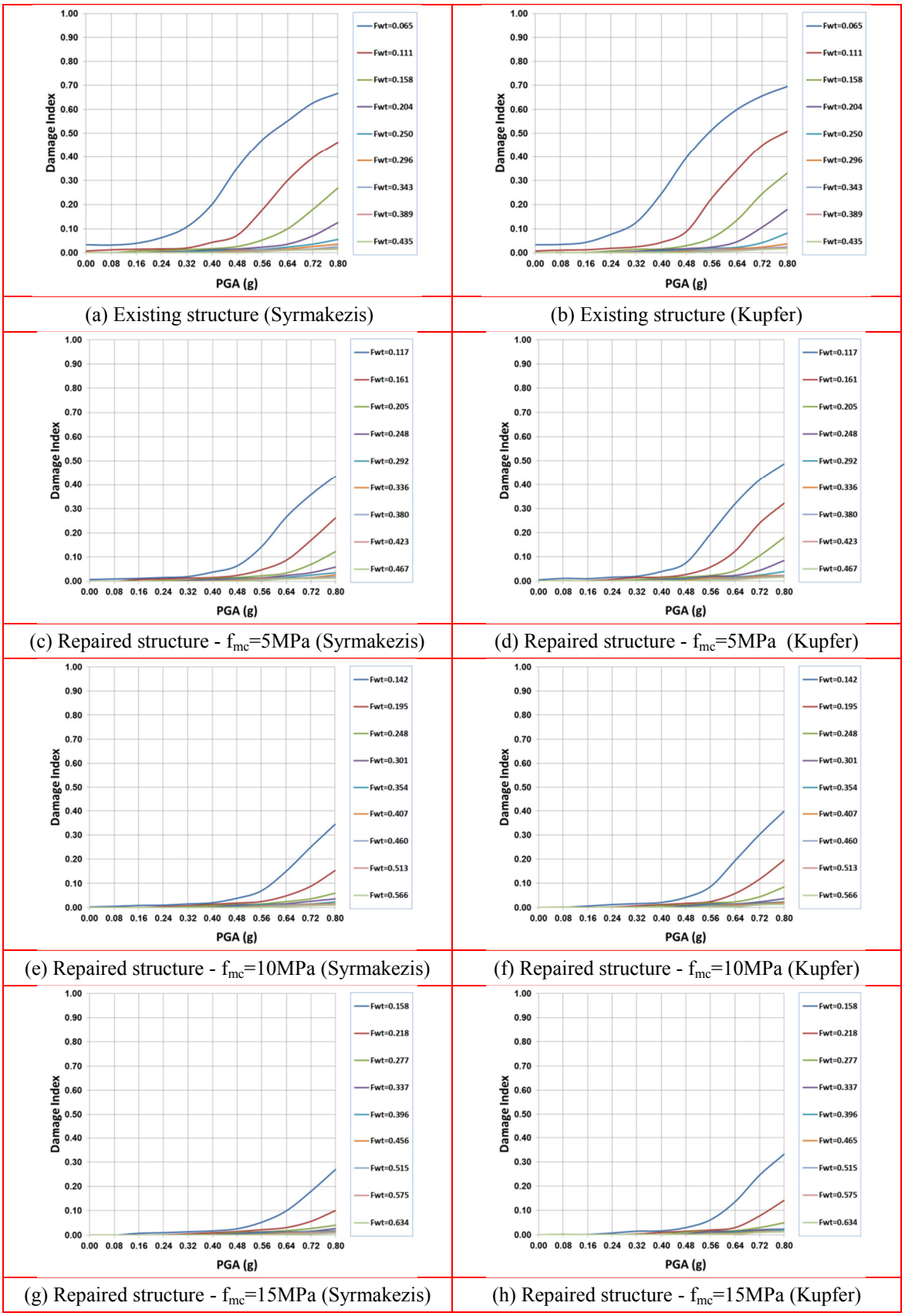
(e) Repaired structure - $f_{mc}$=10MPa (Syrmakezis)

(f) Repaired structure - $f_{mc}$=10MPa (Kupfer)

(g) Repaired structure - $f_{mc}$=15MPa (Syrmakezis)

(h) Repaired structure - $f_{mc}$=15MPa (Kupfer)

Fig. 4 - Damage indices for the existing flexural shear wall as well as for the three case of restoration scenarios with mortar compressive strength $f_{mc}$=5MPa, $f_{mc}$=10MPa and $f_{mc}$=15MPa using Kupfer and Syrmakezis failure criterion




(a) Existing structure (Syrmakezis) | (b) Existing structure (Kupfer)

(c) Repaired structure - $f_{mc}$=5MPa (Syrmakezis) | (d) Repaired structure - $f_{mc}$=5MPa (Kupfer)

(e) Repaired structure - $f_{mc}$=10MPa (Syrmakezis) | (f) Repaired structure - $f_{mc}$=10MPa (Kupfer)

(g) Repaired structure - $f_{mc}$=15MPa (Syrmakezis) | (h) Repaired structure - $f_{mc}$=15MPa (Kupfer)

Fig. 5 - Damage indices for the existing shear wall as well as for the three case of restoration scenarios with mortar compressive strength $f_{mc}$=5MPa, $f_{mc}$=10MPa and $f_{mc}$=15MPa, using Kupfer and Syrmakezis failure criterion

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## REFERENCES

[1]-Asteris P.G., Douvika M., Karakitsios P., Moundoulas P., Apostolopoulou M., Moropoulou A. A Stochastic Computational Framework for the Seismic Assessment of Monumental Masonry Structures. 5th International Conference on Integrity, Reliability and Failure, Faculty of Engineering, 2016, U. Porto.

[2]-Asteris P.G. Finite element micro-modeling of infilled frames. Electronic Journal of Structural Engineering, 2008, 8, p. 1-11.

[3]-Asteris P.G., Plevris V. Anisotropic Masonry Failure Criterion Using Artificial Neural Networks. Neural Computing and Applications (NCAA), 2016, DOI: 10.1007/s00521-016-2181-3.

[4]-Asteris P.G., Sarhosis V., Mohebkhah A., Plevris V., Papaloizou L., Komodromos P., Lemos, J.V. Numerical Modeling of Historic Masonry Structures. Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures, Edited by Panagiotis G. Asteris, Vagelis Plevris, 2015, chapter 7, p. 213-256; IGI Global.

[5]-Asteris P.G., Chronopoulos M.P., Chrysostomou C.Z., Varum H., Plevris V., Kyriakides N., Silva V. Seismic Vulnerability Assessment of Historical Masonry Structural Systems. Engineering Structures, 2014, 62-63, p. 118-134.

[6]-Asteris P.G. A simple heuristic algorithm to determine the set of closed surfaces of the cubic tensor polynomial. The Open Applied Mathematics Journal, 2010, 4, p.1-5.

[7]-Asteris P.G. Unified Yield Surface for the Nonlinear Analysis of Brittle Anisotropic Materials. Nonlinear Sci. Lett. A, 2013, 4(2), p. 46-56.

[8]-Kupfer H., Hilsdorf H.K., Rusch H. Behavior of concrete under biaxial stresses. Journal of the American Concrete Institute, 1969, 66(8).

[9]-Moropoulou A, Bakolas A, Anagnostopoulou S. Composite materials in ancient structures. Cement and Concrete Composites, 2005, 27(2), p. 295-300.

[10]-Moropoulou A., Bakolas A., Bisbikou K. Investigation of the technology of historic mortars. Journal of Cultural Heritage, 2000, 1(1), p. 45-58.

[11]-Moropoulou A., Bakolas A., Moundoulas P., Aggelakopoulou E., Anagnostopoulou S. Optimization of compatible restoration mortars for the earthquake protection of Hagia Sophia, Journal of Cultural Heritage, 2015, 14(3 SUPPL), p. e147-e152.

[12]-Moropoulou A., Apostolopoulou M., Moundoulas P., Aggelakopoulou E., Siouta L., Bakolas A., Douvika M., Karakitsios P., Asteris P.G. The role of restoration mortars in the earthquake protection of the kaisariani monastery. ECCOMAS Congress 2016 - Proceedings of the 7th European Congress on Computational Methods in Applied Sciences and Engineering, 2016, 3, p. 5340-5358, Crete; Greece.

[13]-Page A.W. The biaxial compressive strength of brick masonry. Proc. Instn. Civ. Engrs., 1981, 71(2), p. 893-906.

[14]-Park Y.J., Ang A.H.S., Wen Y.K. Damage-limiting a seismic design of buildings. Earthquake Spectra, 1987, 3(1), p. 1-26.

[15]-Syrmakezis C.A., Chronopoulos M.P., Sophocleous A.A., Asteris P.G. Structural analysis methodology for historical buildings. Architectural Studies, Materials and Analysis, 1995, 1, p. 373-382.

[16]-Syrmakezis C.A., Asteris P.G. Masonry failure criterion under biaxial stress state. Journal of Materials in Civil Engineering, 2001, 13(1), p. 58-64.

[17]-Tassios T.P., Chronopoulos M.P. A seismic dimensioning of interventions (repairs/ strengthening) on low-strength masonry building. Middle East and Mediterranean Regional Conference on Earthen and lowstrength masonry buildings in seismic areas, 1986, Ankara.

[18]-Zienkiewicz O.C., Valliapan S., King I.P. Elasto-plastic solutions of engineering problems, initial stress finite element approach. Int. J. Numer. Methods Engrg., 1969, 1, p. 75-100.