PROTECTION OF MEDITERANNEAN HISTORICAL STRUCTURES AGAINST EARTHQUAKES USING FRAGILITY CURVES

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ABSTRACT :
The post-earthquake rehabilitation and retrofitting of historical structures is an important issue in the entire Mediterranean basin, which is characterized by its richness in historical masonry structures as well as its high seismicity. The high importance of these structures, the need for evaluation of their present state and often the determination of the extent and the possible ways of reinforcement, impose the development of a methodology that could offer an estimation of their behaviour, taking into account the uncertainties that are introduced during the analysis. These uncertainties caused by the variety of structural materials used in the same monument, the difficulty of determining their mechanical properties and the random action of the earthquake phenomenon make essential the presentation of the vulnerability assessment presented in probabilistic terms. This is being accomplished by a methodology which leads to the construction of the fragility curves that can graphically represent the probability of certain damage ranks under the effect of various earthquakes intensities. Through this family of curves, it is possible to investigate the way that each factor affects the vulnerability of the structure, relatively to others. The application of the methodology proposed is illustrated through three typically buildings made of masonry, situated in Crete, Greece and constructed between the 18th and 19th century. Through these case studies the correlation of the earthquake intensity is being shown.

KEYWORDS:
fragility curves, historical structures, masonry structures, seismic vulnerability, probabilistic analysis

1. INTRODUCTION

One of the most important hazards threatening heritage structures is the seismic activity. In the Greek as well as in the entire Mediterranean area, the majority of cultural heritage buildings is made of masonry, which is highly vulnerable to earthquake actions due to low tensile strength, geometrical peculiarities, past earthquake damages and cracks, degradation, lack of proper conservation or even incompatible human interventions. In modern societies, historical structures' architectural and social value impose the need of their structural protection against earthquake ground motions combined with the application of special protection measures that permit reversibility, minimization of intervention and compatibility.
During the last years, considerable research has been carried out in order to investigate the causes of damage and to develop technologies suitable for seismic rehabilitation of existing masonry structures. For the analytical assessment of historical structures' seismic response, two sets of information should be taken into consideration. The first one involves structural properties (i.e. material strength, dynamic properties) and the later one concerns the parameters characterizing the seismic event (i.e. earthquake period, amplitude of vibration, direction). In both cases, many uncertainties are introduced during the structural and earthquake simulation.
In this paper, characteristic examples of historical masonry structures are presented and their seismic response is being investigated. These cases refer to existing outstanding historical buildings in Greece, which are:

- The Prefectorial edifice located in Rethymno, Crete
- The neoclassical residence of Prince George in Chania, Crete and

- A building made of masonry in Kazantzaki street in Sitia, Crete.

For these structures, finite element analysis is performed using proper finite element types for each case. Additionally, a qualitative and quantitative indication of structural failure is acquired, using a modified Von Mises failure criterion, adapted to masonry structures and the FAILURE software (Syrmakezis et al, 2005). For the estimation of seismic vulnerability, a developed methodology is applied, incorporating both the structural and seismic uncertainties. Using the results obtained, a classification of historical masonry structures is aimed, correlating their seismic response with their dynamic properties and applied earthquake parameters.
Section headings are to be in 11pt bold and full caps. Number headings consecutively. Leave two blank lines before Section Heading and one blank line between the heading and the first line of text. Between paragraphs of text leave one line gap. Paragraphs are not to have any indents. Text should be single spaced, left and right justified, providing 20mm left margin and 15mm right margin. Leave a 30mm margin at top and a 25mm margin at bottom.

2. DESCRIPTION OF THE STRUCTURES

2.1 The Prefectorial Edifice located in Rethymno

The Prefectorial edifice in Rethymno was constructed between 1844 and 1847 by the provincial governor of the city. In 1994 and until today, the building becomes headquarter of the prefectorial self-government in Rethymno. The building has three stories and its total length is 50.55 meters with a width that varies between 18 and 28 meters. The total area of the edifice is 3.175 m^2. The stories and the roof are wooden and its floor plan is organized through two perpendicular axis of symmetry.

Figure 1 Views of the Prefectorial edifice in Rethymno

*2.2 The Neoclassical Residence of Prince George in Chania_*

This residence was built in 1882 by the architect Nikola Magouzo to accommodate Prince George. When he resigned, it was used as military hospital, as a shelter and finally during 1968 and 1982 as offices of Crete's historical and archeological company. This building has a ground floor, a first floor and a basement. The total area of the edifice is 293.85 m^2 and its maximum height is 10.87 meters. Its roof and stories are wooden and also has some elements of reinforced concrete. Although the tractors placed at the four building's corners have been corroded, they still hold the masonry satisfyingly.

Figure 2 Views of the neoclassical residence of Prince George in Chania

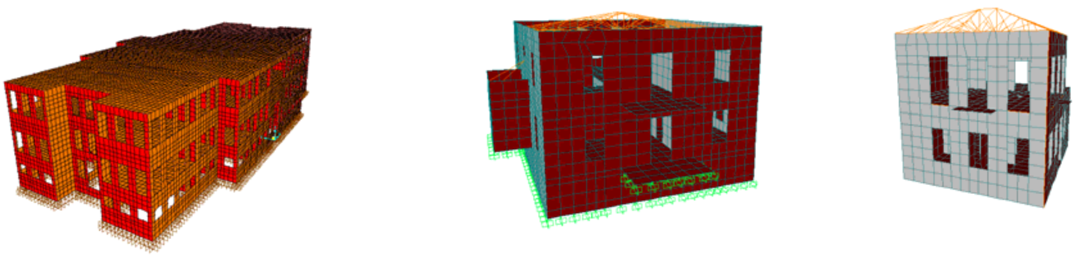
2.3 The two story Building in Kazantzaki Street in Sitia

This residence was built around 1900 and has two stories with a yard and an exterior staircase, which facilitates the access of the upper floor with the outdoors. The building's maximum height is 8.86 meters, the roof is wooden and the stories are made of reinforced concrete. Moreover, in the interior, the ground floor has symmetry through a main axis that divides the building.

Figure 3 Views of the two stories Building in Kazantzaki Street in Sitia

3. THE STRUCTURAL MODELS

For the analysis of these case studies, a finite element model was developed using the software SAP v.10.0.1 Nonlinear (Three Dimensional Static and Dynamic Analysis of Structures).
For the structural model of the Prefectorial edifice in Rethymno city 25.964 finite elements were used. The considered parameters are masonry with modulus of elasticity E=3,33GPa and wood with E=10GPa. The Neoclassical Residence of Prince George in Chania (3.692 finite elements) and the two story building in Kazantzaki road in Sitia (1.603 finite elements) are both modeled of stone masonry with modulus of elasticity E=1,80GPa, reinforced concrete with E=290GPa and wood with E=10GPa. Because of the strength tension's uncertainty, there were used 9 different values for the calculation of the compression's strength.
Actions applied on these models include dead and live loads, earthquake loads (PGA=0.16g, 0.24g, 0.32g, 0.40g) and vertical weight loading according to the buildings' materials.



Rethymno Chania Sitia

Figure 4 The finite element models of the structures

4. RESPONSE ANALYSIS

In order to evaluate the vulnerability of the structure when subjected to an earthquake event, it is necessary to determine the most vulnerable areas on the edifices. For this purpose the software "FAILURE", (Syrmakezis and Asteris, 2001) was used. This software provides an optical indication of failing areas on wall surfaces, when the structure is subjected to a single seismic event and it is based on the elaboration of finite element stresses

using a proper failure criterion. The criterion selected for these case studies is a modified Von Mises criterion, adapted especially for masonry structures.
The criterion is formulated by the interaction of four surfaces S1, S2, S3 and S4 as illustrated in Figure 5. Each surface represents a certain biaxial stress state: S1 represents a compression state in parallel to both principal axes, S2 describes a stress state of tension in parallel to one principal axis and a stress state of compression in parallel to the other, S4 exactly the reverse state and S3 is represents tension in parallel to both principal axes. An element is deemed to fail when direct and shear stresses applied specify a point on the circumference or outside the shaded area, projection of the solid.

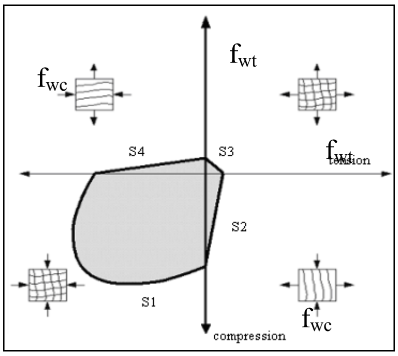


Figure 5 The modified Von Mises failure criterion

$$\text{S1:}\quad \sigma_{xx}^2+\sigma_{yy}^2-\sigma_{xx}\sigma_{yy}+3\,\tau^2-f_{wc}^2=0\ , \qquad \text{for}\ \ \sigma_{xx}\ \text{and}\ \sigma_{yy}\le 0 \tag{4.1}$$

$$\text{S2:}\ \sigma_{yy}+(1-\sigma_{xx}/a)\sqrt{f_{wc}^2-3\tau^2}=0\ , \qquad \text{for}\ \ \sigma_{xx}\ge 0\ \text{and}\ \sigma_{yy}\le 0 \tag{4.2}$$

$$\text{S3:}\quad \sigma_{xx}+\sigma_{yy}-a=0\ , \qquad \text{for}\ \ \sigma_{xx}\ \text{and}\ \sigma_{yy}\ge 0 \tag{4.3}$$

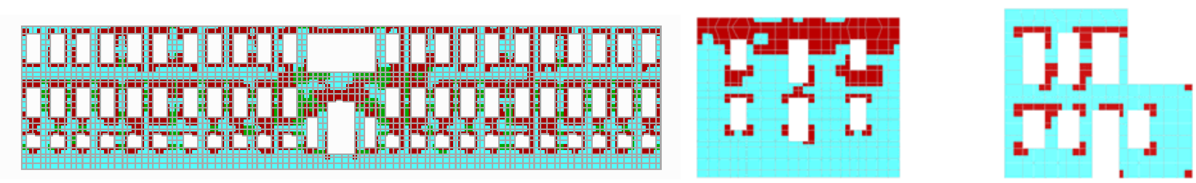
S4: symmetrical to S2 in respect to the bisectional level of the first quadrant

where:

$a=\left(f_{wt}/f_{wc}\right)\sqrt{f_{wc}^2-3\tau^2}$ and f_{wc} : compressive strength, f_{wt} : tensile strength

FAILURE's input data are quantified and graphical outputs of the failed areas are produced, for each plane. Besides the illustration of the failure location, a colour output distinguishes between the four different ways of failure, which are the biaxial failure in compression and in tension, the failure in compression in parallel to one principal axis and in tension to the other, and oppositely.

The obtained results are graphically provided, and are presented in Figure 6. The failure is shown on the external/internal face of the wall. Red areas represent failure under biaxial tension, while green areas represent failure under biaxial tension-compression. Blue areas have not failed.



Rethymno Chania Sitia

Figure 6 Failure results

5. FRAGILITY CURVES

For a given case study, it is possible to define the ground acceleration, which is expected to have a certain damage level on the structure considered. Additionally, materials' properties and the building's response, that influence its total capacity, demand the approach of some assumptions about the ground acceleration and the area's conditions. Usually, the values of those parameters aren't very accurate – they comprise instability and uncertainty due to the nature of these factors.

By processing the data that come from the FAILURE program, the fragility curves can easily be formed. After defining the areas that fail, the percentage of the total surface's damage is proposed to be calculated by the ratio A_{damage} / A_{total}l (where A is the surface), and after the elaboration of the statistical results comes out the probability-density function, which indicates the possibility of the quotient's certain value by the given PGA.

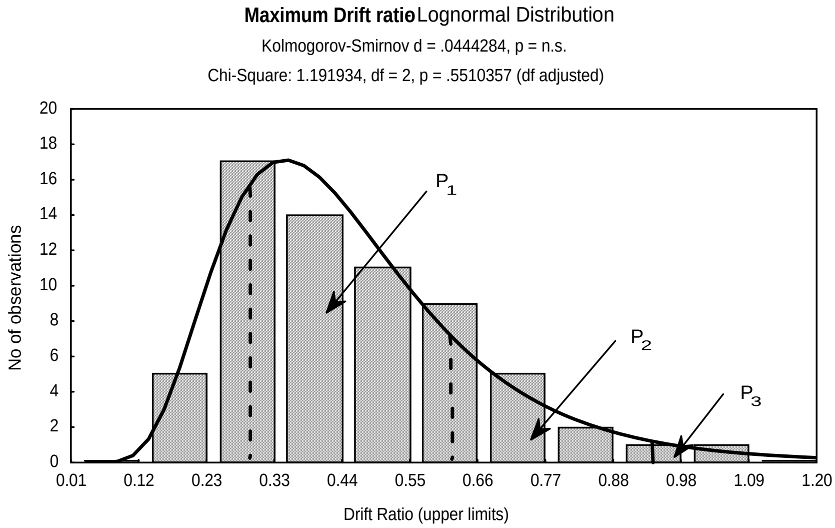


Figure 7 Diagram of density - Lognormal Distribution

The possibilities P_1, P_2 and P_3 are the areas between the failure limits that define the damage levels of the construction through the probability-density function: for random values the possibility that the building's response is between the values of the damage level's rate, is being expressed. Using fragility curves, one can distinguish the possibility of exceeding certain damage levels, as shown in table 1.

Table 5.1 Damage Levels

	No damage (%)	Small damage (%)	Medium damage (%)	Big damage (%)
Damage Level a	0-2.5	2.5-5	5-15	>15
Damage Level b	0-5	5-15	15-30	>30
Damage Level c	0-10	10-25	25-40	>40

Then, the case studies are being compared between them and the final assessment of the strength in tension can be analyzed, among with the buildings' seismic vulnerability.

In the following figures, the damage levels between the normal and the lognormal distributions for the three case studies in Chania, in Sitia and in Rethymno are depicted.

Damage level a

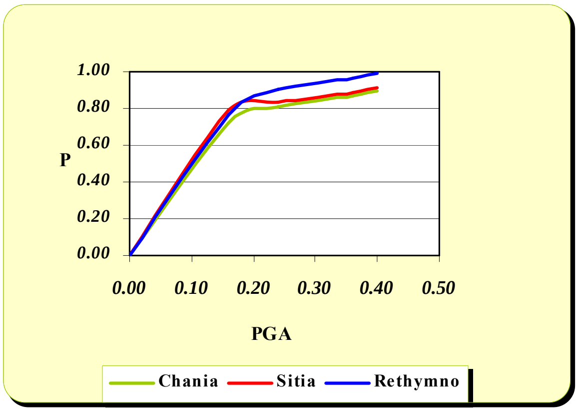
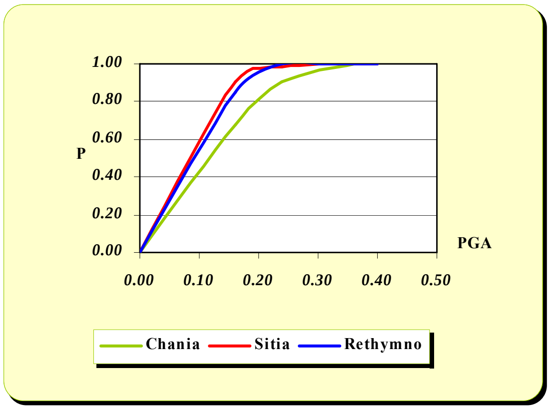
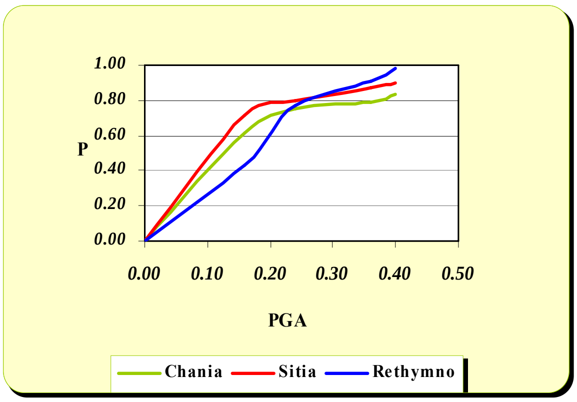
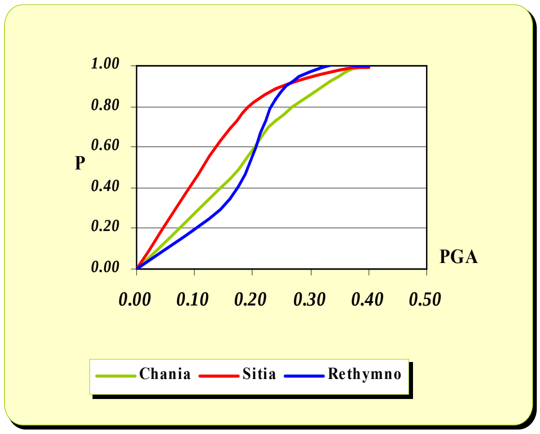
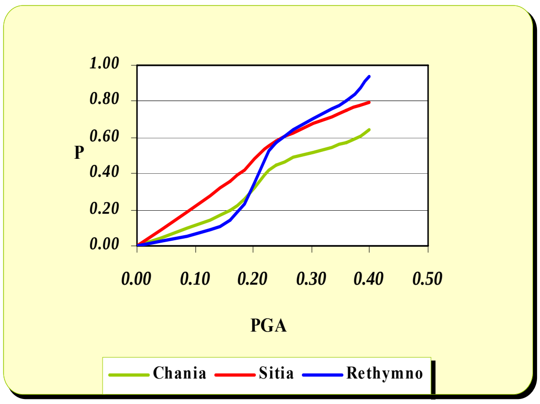
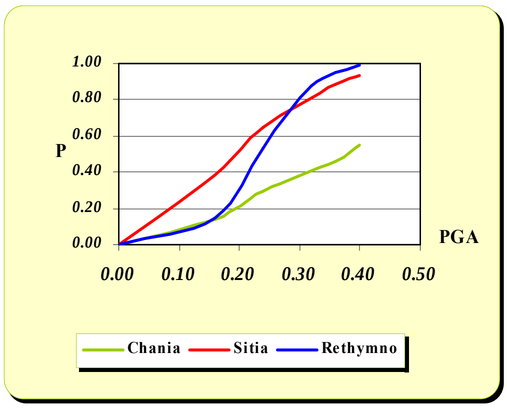
	Normal distribution	*Lognormal distribution*
Possibility of excess Small Damage		
Possibility of excess Medium Damage		
Possibility of excess Big Damage		

Figure 8 Damage Level a

Damage level b

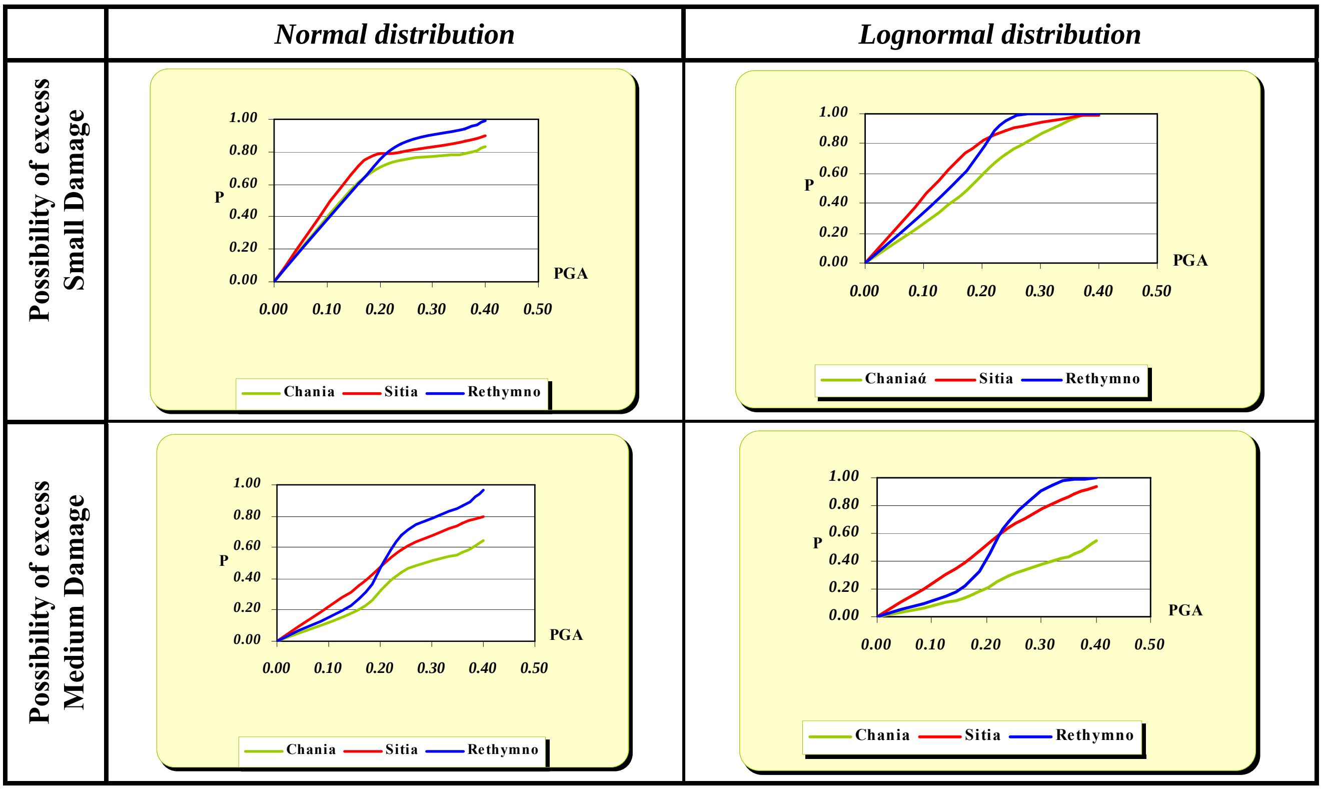


Figure 9 Damage Level b

Damage level c

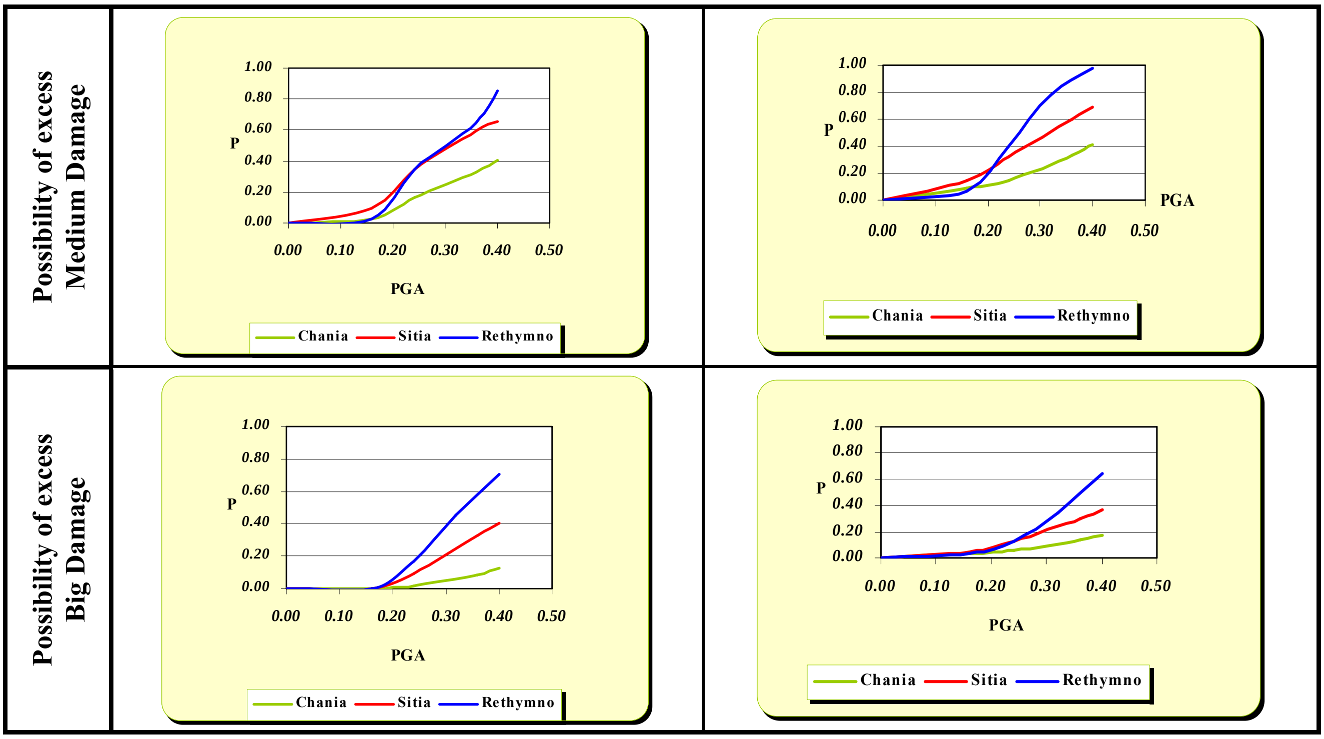


Figure 10 Damage Level c

From the above diagrams, it is being concerned that when the damage's possibility increases, the diagrams' deviation becomes larger. Moreover, for the same damage value, the possibility of excess becomes larger when the PGA increases.
Also, in all diagrams, the edifice in Rethymno has higher possibilities of excess for all damage levels. And the main conclusion is that the building considered has the highest vulnerability, during a possible seismic event, among the buildings considered.

6. CONCLUSIONS

The necessity of the use of three-dimensional finite elements in analyzing historical structures consisting of masonry systems has been investigated. A methodology for performing failure analysis has been proposed. The modified Von Mises failure criterion for biaxial stress state has been developed in order to adapt to masonry structures. Failure analysis has taken place implementing this criterion, for all three pairs of 3-D stresses. Graphical outputs have been obtained.

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