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SEISMIC ANALYSIS OF STONE MASONRY MONUMENTS USING CAD MODELS

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ABSTRACT

Object of the work presented herein, is the investigation of prospect for seismic analysis and evaluation of the geometric information that compose the structural body of a stone masonry monument using CAD models through a framework of research for its restoration. The use of CAD models involves the digital representation of a monument as well as the data manipulation for an adequate knowledge about its structural behaviour. The required target representing the deformed masonry in conjunction with F.E. analysis prescribes a modern confrontation of damaged monuments, as reported through pilot research projects.

KEYWORDS

CAD; masonry; stone; restoration; monument; modelling; seismic analysis; heritage.

INTRODUCTION

An historical structure called monument declares the demand of conservation in the future for the next generations and assigns an exceptional importance to any maintenance, conservation, revival and strengthening studies for the monument. The engineer should define the structural behaviour and condition of the monument and take precautions through future damages. The most important cause of severe damages - at least in Greece - is the earthquake.

Stone masonry monuments have complex structural behaviour which is difficult to be analysed because of the irregularity of the constructive materials as well as the construction techniques. These techniques differ from territory to territory and as the years go on new technologies arise and applied to the monuments. Chemical, physical and mechanical characteristics of the masonry structure can be observed only by in site experiments and laboratory tests. Monument's structural material are usually the stone, the wood and as connecting material the mortar. About the stone as constructive material, there is sufficient information concerning its structural behaviour, the latest decades by researchers worldwide. All these data come into the structural analysis with experimental considerations about the factors that chosen by the engineer and mainly affect the whole study (Benedetti D. *et al.*, 1980). Referring to the mortar, the connective material between the stones, the information is less in quantity.

This fact makes the difference between modern and historic buildings. Constructional materials (concrete, steel) of modern buildings are well known, referring to their structural behaviour. They are industrial materials that correspond to special rules - standards - established by each country or organisation. On the contrary, the quantity and quality of the materials in monuments, in conjunction with different constructive laws, makes necessary the individual analysis adopted to each one. It is obvious that there is not a unique solution of the analysis, because each scientist - engineer has different experiences and approaches the study assuming different values about factors concerning the structural condition of the monument. As a result we have multiple solutions for its support against future dynamic (seismic mainly) loads, but all these solutions must care and respect the monument.

All these studies are made with the use of computers and appropriate static/dynamic analysis programs. The analysis procedure includes the simulation (geometric, material properties, loading) of the monuments' structure, the solution phase, the evaluation of the results and finally, the restoration phase (Karantoni F. *et al.*, 1992).

This study involves the geometric modelling of the monument's load bearing structure using CAD models in order to represent with high accuracy the realistic structure. Pilot research studies that have been modelled with CAD systems, are presented in the next chapters and gave interesting results.

CAD MODELLING FOR STRUCTURAL EVALUATION

Computer Aided Design systems are usually practised mainly for drawing representation of a structure referring its morphological elements and secondary for structural analysis (Quintrand P., 1993). Modern structural analysis programs embed CAD modules, but with less capabilities than a stand alone CAD program offers. As a result the monument can't be represented sufficiently with high accuracy specially when it has complex morphology. It is almost a fact that the future engineering software will embed CAD and Finite Element Analysis with full capabilities through an environment that the user could easily exchange data between monument's model and structural simulation (Rojiani K. *et al.*, 1994). The use of CAD systems for model creation is described in the following headings through geometric description, data management and numerical modelling.

Geometric Description

The accurate geometric definition of partial structural elements of a monument, is a fundamental procedure for reliable monument's modelling (Verras D. *et al.*, 1993). This procedure known as survey becomes complicated when the morphology and the structure of a monument is not clearly noticeable. Two of the most common survey methods are the classic topographic method with geodetic field stations and the photogrametric analysis. Both methods have benefits and disadvantages and the final decision is made considering the methodology of the whole study. It is essential the two methods must combined and used together with an appropriate CAD system in order to achieve the desired modelling. This model should describe the geometry of the structure, the deformed masonry (including fractures, collapses, inclinations etc) and be flexible enough to exchange data between the structural and solid - geometric model (Verras D. *et al.*, 1994, Onate E. *et al.*, 1995).

In addition, separate partial interventions to the monument through its life must be clearly distinguished, aiming the adequate analysis of the structural behaviour of the constructive materials.

All these parameters must be taken under consideration in order to decide the best method for geometric survey of the monument. Through the pilot research studies that was analysed by the authors, the use of topographic survey with powerful field stations resulted obligatory for the surveying of the load bearing structure of the monument and its main morphological elements, combined with the use of photogrametric methods for surveying special morphological parts of the monument.

Data Management and Retrieval

As aforementioned, the information data involving a restoration project of a monument is huge enough, as a result of an interdisciplinary approach, parametric analysis and possible interventions through its life.

The development of a CAD data base using a digital monument model, is a modern confrontation in the data management procedure, as it was stated from the authors in the past (Verras D. *et al.*, 1993, 1994). Procedures like external referencing (*Xrefs*), entity blocking (*Blocks*), layer grouping (*Layers*), mesh generation etc., could be managed according the basic following administrative rules :

- Selective members output
- geometric coordinates file grouping
- relative information shorting

aiming always the right - orthologic - structure of the monuments' data base that must be developed (Verras D. *et al.*, 1995).

Subjects related to the development of an adequate knowledge about the structural behaviour of a stone masonry structure, are simulated in the work presenting herein, with the realistic rendering of the monuments' geometry for the calibration of the F.E. method in the analysis of the load bearing structure. It is adopted that the numerical modelling must be a main procedure of seismic analysis for the investigation of monuments' structural behaviour.

Numerical Modelling - Seismic Analysis

The development of a numerical model of a masonry monument should reflect the monuments' structural behaviour for a realistic simulation of the loading bearing structure.

Most of stone masonry structures have a pathology as a result of local collapses, compressive failures of the infill material and discontinuity etc., that may cause local instabilities before the overall collapse.

In those usually rigid structures like stone masonries, the equilibrium should subsumed by the compatibility of deformation, and the overall investigation results are depending on the constitutive laws of the materials.

The fact that there are more than one material in the structural body, makes the mathematic problem which is assumed to have an approximately solution with special arithmetic methods leading to the use of computer technology.

The linear analysis approach, parallel with the finite elements method, may produce at first phase, reasonable description of the procedure that is leading to rapture. The non-linear analysis is more complicated but it is more effective on the description of mortars' behaviour. In addition the results must checked with great care for the numerical instabilities that may appear when cracking intervenes (Macchi G., 1995). But in general, it should be stated that the non-linear approach is the road to further investigation.

The geometric irregularities contributes to the problem of the previous analysis, aiming the investigation concerning to realistic behaviour of the structure through better simulation.

PILOT CASE STUDIES

The aforementioned CAD models, were applied for seismic analysis of small scale stone masonry monuments, such as Palaeologinas' Mansion, - a historical building in the centre of Kalavrita in Greece, built in the 17th century and damaged by earthquakes and several interventions during the ages.

Also, two large scale stone masonry constructions, the "Chlemutsi" castle at Killini in Greece (fig.1) and the fortress of Patra (fig.2) have been modelled using CAD systems and at this time are in the final phase of investigation.

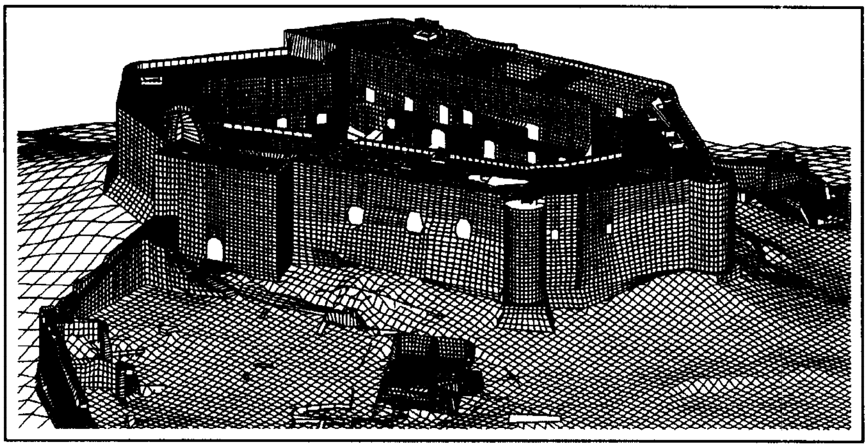

Fig. 1. Partial axonometric view of Castle Chlemutsi - Killini, Greece

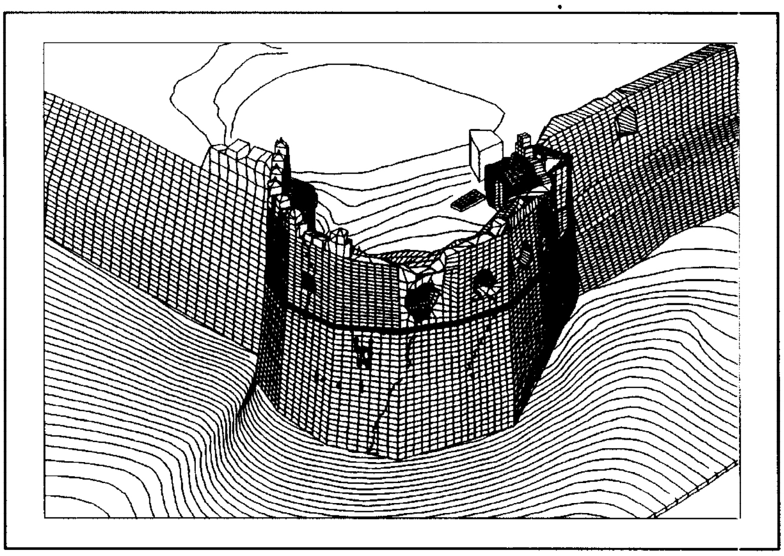

Fig. 2. Partial axonometric view of Patra's fortress, Greece

The two monuments are divided into several smaller parts, in order to decrease the huge size of the degrees of freedom in the structural analysis module. Therefore several partial CAD models created for this purpose.

In the following paragraphs is presented the linear analysis approach with finite element method that was applied for the Palaeologinas' Mansion. The building outlined with a lot of damages and interventions in the most of its parts, which have influenced the loading bearing structure of the monument.

The three dimensional representation of the monuments' solid model (fig.3), is rendered by structural and morphological elements that are described by three dimensional coordinates of surveyed points and construct them, in space with non-plane surfaces (*meshes*) that build their geometry. All weak components, deformations, vertical inclinations, cracks etc., are stated through the CAD model and contribute to further analysis of the loading bearing structure.

Three dimensional coordinates of mesh members are extracted as numerical declarations of distortions and applied in the finite element method linear analysis of the whole monument.

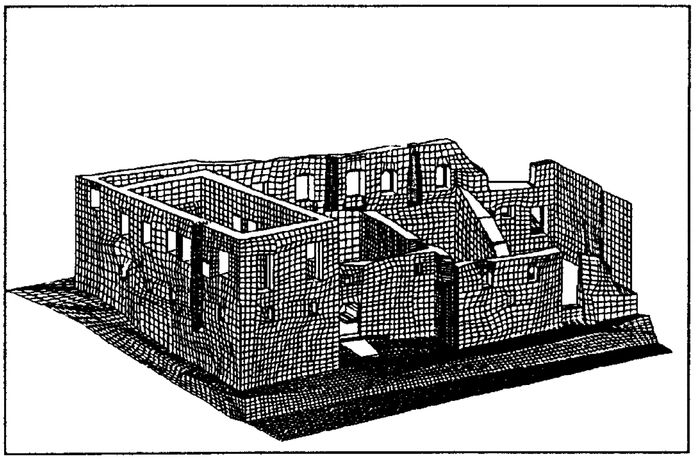

Fig. 3. 3d-model of Palaeologina's mansion

The monuments' stone masonry main body structure, was analysed under seismic loads acting in two directions X and Y, parallel and normal to the wall surface, according to the recorded acceleration response spectrum of 16th October 1988 at Killini in Greece (fig.4).

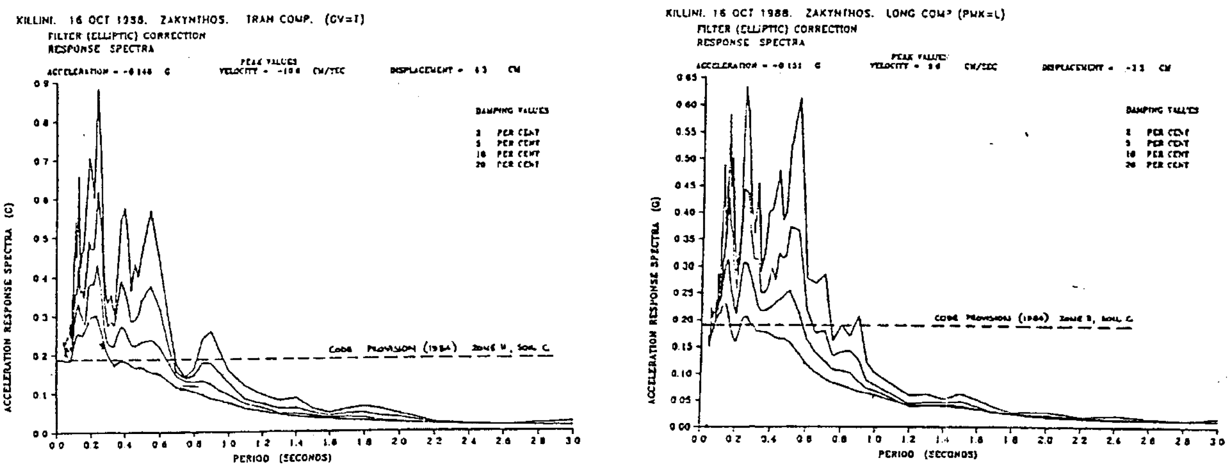

Fig. 4. Acceleration response spectrum - Transverse (left) and Longitudinal (right) components

The ground acceleration is input as a digitised response - spectrum acceleration versus time period. The ground excitation occur simultaneously in two perpendicular directions in the x-y plane. The modal responses associated with a particular direction of excitation are first calculated and then combined using the complete quadratic combination technique. The total response is then calculated by summing the responses from the two directions by square root of the sum of the squares method.

The full structure simulated in a first phase for non-deformed geometry and in another phase, for the full application of survey process, as a result of the realistic deformed condition of structural members with a CAD model. It was adopted the same material properties, the external loading (steady and recycled) and approximately the number of joints. In addition was used the same finite elements type.

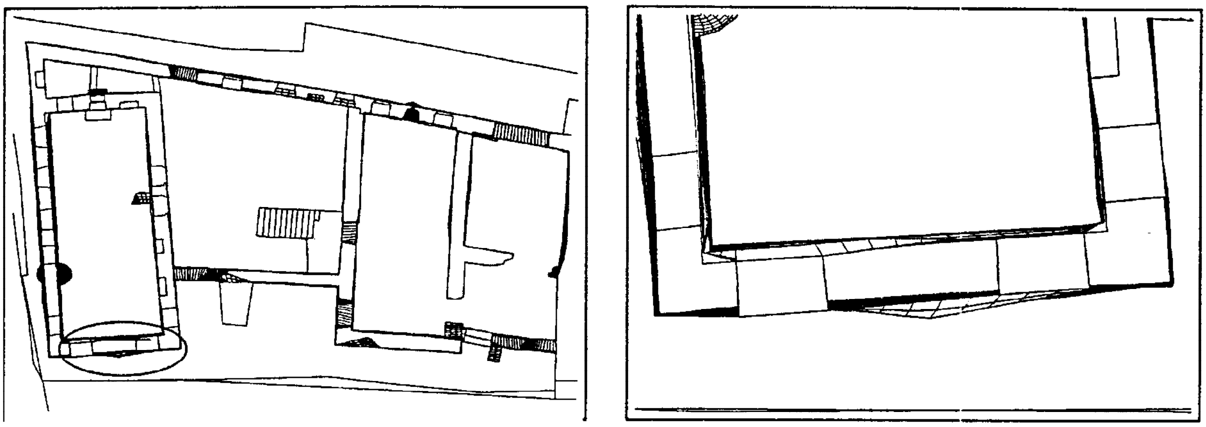

Fig. 5. Plan view of Palaeologina's mansion (left) and detail of the monument (right)

Figure 5 presents the plan view of Palaeologina's mansion witch has serious damages and remarkable deformations and one characteristic detail of a wall masonry. The results of the two analyses are presented in the following figures for this particular wall.

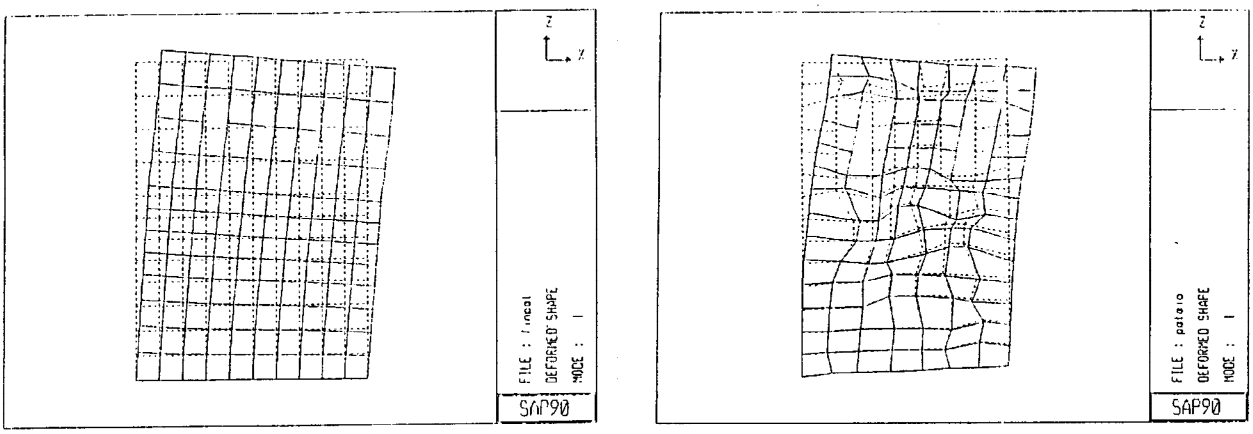

Fig. 6. Deformed shapes of undeformed (left) and deformed (right) geometry.

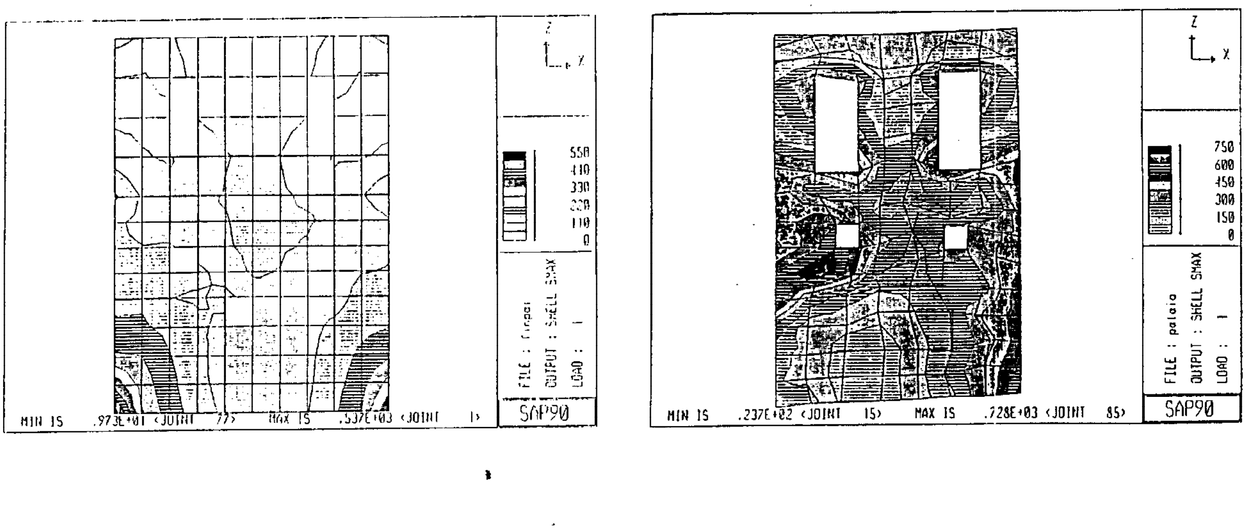

Fig. 7. Smax of undeformed (left) and deformed (right) geometry

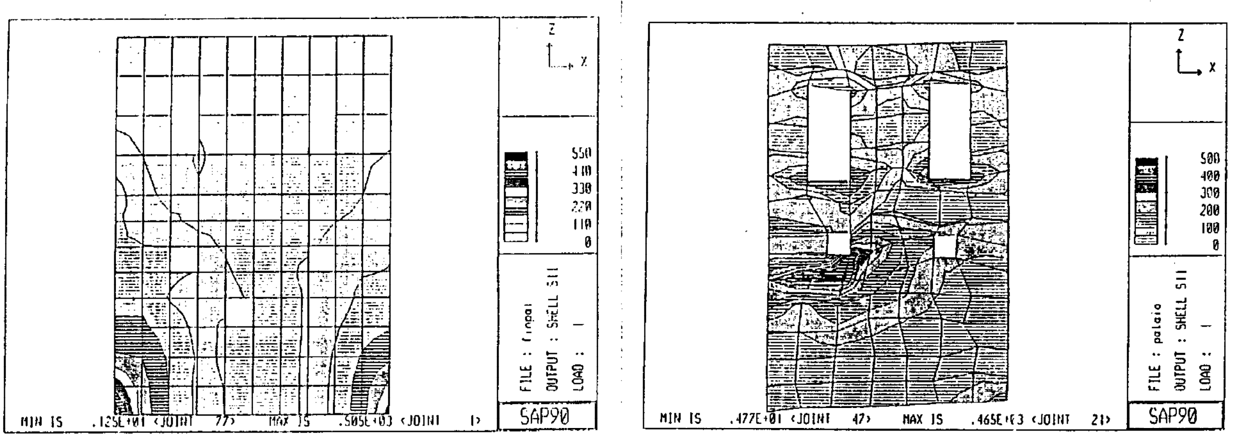

Fig. 8. S11 of undeformed (left) and deformed (right) geometry

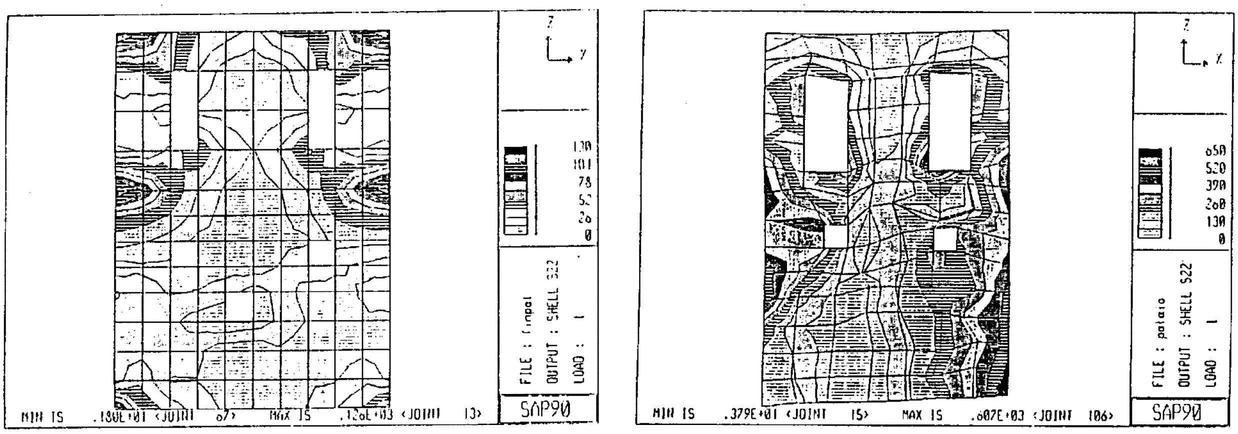

Fig. 9. S22 of undeformed (left) and deformed (right) geometry

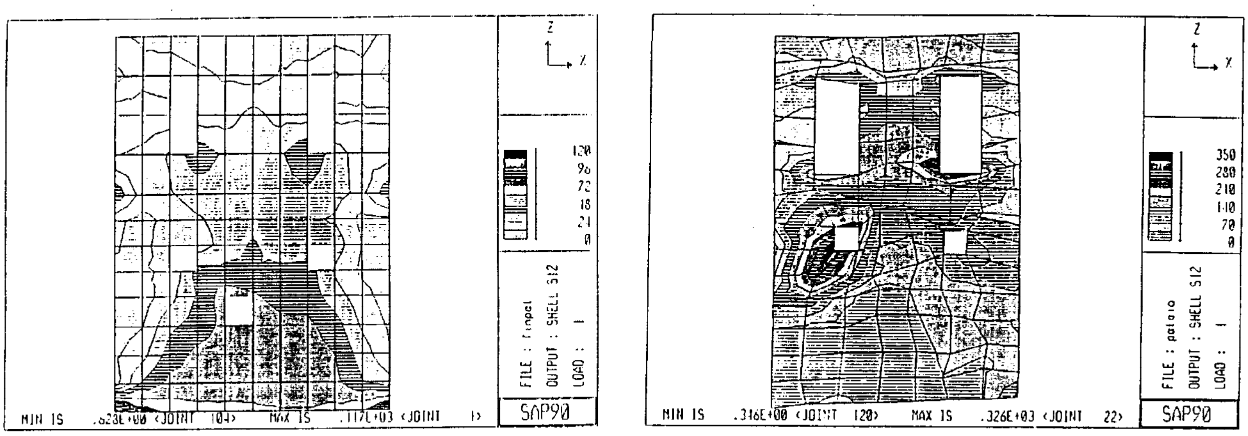

Fig. 10. S12 of undeformed (left) and deformed (right) geometry

CONCLUSIONS

The development of analytic - realistic Computer Aided Design Models, for the seismic analysis of stone masonry monuments, gave interesting results. Full defined the geometric monuments' shape, in area scale factor independently (large scale monuments such as a castle and other smaller like traditional buildings), giving the possibility of a more accurate structural analysis and investigation of its loading bearing behaviour simulation. It is encouraging that there will be continuous future approaching to seismic analyses parallel to computer growing technology.

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