# REUSE OF STONE MASONRY BUILDINGS AND THE SEISMIC BEHAVIOR OF THE COMPOSITE STRUCTURES

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**Keywords:** Masonry buildings, Dynamic analysis, Finite element, Building pounding, Contact body

**Abstract.** A parametric investigation about the seismic behavior of an existing unreinforced masonry building and its behavior after the reuse is presented in this article. Unreinforced masonry buildings very often, are rehabilitated with new added structural elements. In some cases where only the perimeter walls from the old building are kept, another structural system is placed inside and outside the initial structure and proper connections are done at special places in order to have cooperation between these two different structural systems which are from different material, like reinforced concrete or steel and have different stiffness. When this connection is rigid, one composite structure with different dynamic characteristic must be analyzed in order to calculate the seismic resistance of the final building. If looseness of this connection is happened, perhaps under a strong earthquake, pounding phenomenon is developed. The pounding phenomenon of adjacent buildings during earthquakes has been receiving considerable attention in recent years. This is due to the fact that many incidents of seismic pounding have been recorded in many parts of the world. As a case study, finite element method was used for static and dynamic analysis of a masonry traditional structure in Crete at present state and the new state according the architectural design for reuse. Experimental methods in situ and software tools in order to determine the stiffness of the structure and how it is affected after the proposal of the reuse when the static core is altered were used. A full 3D detailed model of the building under static and dynamic loading scenarios, assuming different hypothesis for the interconnection between the two existing structures (masonry and reinforced concrete one) and between the core and the external walls on the architectural proposal of reuse, were analyzed. For modeling and analysis, the SAP and MARC finite element software, were used. With SAP this interconnection was simulated using total nodes' compound and links as well, in order to find the most realistic modeling of the behavior of the interaction of the two different structural systems, at the points of contact. With Marc the method of contact bodies was chosen, in order to assume that in both cases, the whole structure would respond as one, and cooperate smoothly during the seismic assessment, or the different structural systems would separate and would develop relative movements. The comparison between present state and new state of the structure with advanced computational methods were useful. The numerical analysis has given a valuable picture of possible damage mechanisms providing useful hints for the introduction of further optimization of the architectural design and the practical application.

## 1 INTRODUCTION

Many countries, especially in southern Europe, are greatly exposed to seismic hazard, which causes valuable building heritage to be high at risk of severe damage or even destruction when exposed to strong earthquake ground motions. This problem mostly stands for traditional, historical and monumental constructions, due to the fact that most of them frequently lack basic seismic features. Typical problems of masonry structures concern aspects like inherent structural lacks, material degradation, geotechnical problems, buckling behavior of slender elements and dynamic loading vulnerability as presented and fully described in Karantoni's book for masonry structures where masonry's seismic behavior is also analyzed [1].

The definition of reliable models and methods for seismic risk assessment of vulnerable constructions is thus very interesting topic. A great number of studies in the literature are dedicated to destructive and non-destructive static and dynamic tests on masonry structures, to procedures for the identification of mechanical parameters as well as to calibration of the reliable structural models.

The main goal is a wide knowledge of the structure to avoid inadequate, unsuitable or dangerous rehabilitation operations, and to select non-invasive and reversible techniques for the best exploitation of material and technology features. On the other hand, modelling the mechanical behaviour of masonry may play an important role, due to both inherent material complexity and great scatter in mechanical properties. The random character of masonry mechanical features, in fact, makes the prediction of structural risk quite critical. Effective procedures for the identification of the structural parameters from static and dynamic testing are thus required. In particular, dynamic measurements may be very useful for the identification of mechanical properties and soil restraints and, consequently, for the calibration of advanced numerical finite element models.

The current paper is dedicated to the modelling of a building dating back to 1900 DC in Crete and its proposal of reuse. In particular, the methodology defined to reach the goals consisted of: 1) defining a FEM of the existing building using two individual softwares (Sap2000, Marc Mentat), 2) identifying mode shapes and frequencies, 3) defining the most appropriate way to model the connection between two different structural systems, 4) defining the finite element model of the solution of reuse and 5) identifying the mode shapes, frequencies and seismic behavior of the proposed, extended building.

## 2 POUNDING PHENOMENON

Interactions between insufficiently separated structures, or their parts, due to the out-of-phase vibrations have been repeatedly observed during major earthquakes. This phenomenon, often referred as the earthquake-induced structural pounding, may lead to considerable damage or can be even the reason of the structure's total collapse. Several numerical models have been adopted to simulate pounding force during impact and research has been done to investigate the accuracy of the impact force models mentioned based on the results of a shaking table experimental study [2]. The dynamic characteristics of adjacent buildings may differ significantly due to the structural systems and material selected. Out-of-phase vibrations may also be induced if adjacent buildings are subjected to earthquake loading and collision or pounding may occur if the separation distance is inadequate. Pounding of adjacent buildings may cause serious structural damage and sometimes the collapse of buildings. As the periods of adjacent buildings are equal or very close to each other, the required separation distances are very small. However, as the periods of adjacent buildings vary, the required separation distances start to increase due to out-of-phase vibrations. A larger separation distance is required for both adjacent buildings having a longer fundamental period [3]. Also from research, the conclusion that structures with different period developed different damages under the same earthquake was extracted [4].

From experimental and theoretical simulations of seismic poundings between adjacent towers, under sinusoidal excitations, the maximum relative impact velocity always develops at an excitation frequency between the natural frequencies of the two towers. The standard distance attains a maximum when the excitation frequency is close to that of the more flexible tower. Pounding appears to amplify the response of the stiffer structure but suppress that of the more flexible structure; and this agrees qualitatively with previous shaking table tests and theoretical studies [5].

It is important, the phenomenon of friction which is developed between the adjacent structures, under a dynamic excitation to be included in the analysis since it influence the dynamic response of the structures. A special case of restoration, where only the perimeter walls from an old two-story masonry building are kept and another structural system from reinforced concrete frame with horizontal reinforced concrete slabs is placed inside the initial structure, was studied in [6]. These two different structural systems from different materials and having different stiffness are connected at special places in order to have cooperation. When this connection is rigid, a composite structure with different dynamic characteristics is analyzed in order to calculate the seismic resistance of the final building. If looseness of this connection is happened, perhaps under a strong earthquake, pounding phenomena are developed partial to some walls or the whole structure. A unilateral frictional contact model was used to the all the inside areas of the masonry walls, in order to model this phenomenon. From the results, it was shown that the energy dissipation mechanism which work in the case of small displacements would leads to negative results when the sliding movements between concrete frame and the masonry goes beyond some limits [6].

## 3 UNILATERAL CONTACT ANALYSIS

The possibility that some separation appears between two parts of a structure coming into contact is known as a unilateral contact phenomenon. This is a typical variable-structure nonlinearity, which involves either-or decisions in the mechanical model. The frictional stick-slip nonlinearity is an analogous phenomenon. Both problems belong to the area known as nonsmooth mechanics [7], [8]. The reason is that the arising models (functions) are nondifferentiable in the classical sense. The knowledge of basic theory, one can use effectively currently available general purpose finite element software for the static and dynamic analysis of stone structure with unilateral frictional joints (interfaces).

Unilateral contact along interfaces is a suitable model for nonlinear analysis of masonry structures [9, 10]. A number of potential interfaces are defined and along these interface separation and frictional effects are considered. The actual state at each point of the interface will be found after the solution of the problem. In case of unilateral contact and friction, several empirical or semi-empirical algorithms have been proposed and modern general-purpose finite element software (like MARC [11] which is used for this study) can be used for the solution of several real-life problems. Effective use of the available models and the limits of their applicability require the use of some theoretical knowledge. In this case, a mixture of augmented Lagrangian type procedures, for the treatment of the unilateral contact mechanism, and of smoothing techniques, for the frictional part, is used.

The analysis of contact behavior is complex because of the requirement to accurately track the motion of multiple geometric bodies, and the motion due to the interaction of these bodies after contact occurs, including the representation of the friction between surfaces. The numerical objective is to detect the motion of the bodies, apply a constraint to avoid penetration and apply appropriate boundary conditions to simulate the friction behavior. Therefore a constraint minimization problem has to be solved where the constraint is the ‘no penetration’ constraint.

For the solution of the contact problem the direct constraint method is used in the following application. In this procedure, the motion of the bodies is tracked and when contact occurs, direct constraints are placed on the motion using boundary conditions, both kinematic constraints on transformed degrees of freedom and nodal forces. The constraint imposed ensures that penetration does not occur. In our model these constraints are modeled by the definition of tying relations for displacement components of the contacting nodes. Specific the following must be defined: the contact bodies which describe the boundaries of interfaces, the contact tolerance in order to have realistic results, the area in which the contact possible occur which is used in case where we know from the beginning where contact will be and in order to reduce the computation time, the contact procedure, the separation procedure defining the separation criterion which can be based on normal stress or normal force and the friction model.

Figure 1: The building being studied.

## 4 NON LINEAR FINITE ELEMENT ANALYSIS OF EXISTING BUILDING

The structure being studied is located at Vamos Village of Chania in Crete (Fig.1). It is consisted by two sub-buildings; the earlier building of masonry that was previously constructed in 1922 and the subsequent addition of ricks built in 1985. The masonry part has a rectangular cross-section in plan with 10 x 7m long sides. Its height is 7.15m (east-west side) and 4.90m (north-south side). The wooden roof is gabled with cover made of tiles while along the long sides there are reinforced concrete tie-beams. Wooden loft covers the half area of the plan at a height of 3.15 from the ground. The dimensions of the addition brick part are 5x6 m, its height is 3m and is covered with a concrete slab.

In order to define the mechanical properties of the building materials a number of semi-destructive and non-destructive tests was held which included site inspections, tests using Schmidt Hammer, coring and compressive tests on the core samples and ultrasound tests. Spanos, Spathakis et Trezos describe in detail these test techniques in TEE's manual, as well as they were used in structure in Tsinaraki's and Relias's master thesis [12] [13] [14]. Thus, the elastic modulus was found to be about 1.543 GPa given Poisson ratio equal to 0.15 [15] and the masonry's specific weight was calculated about 19.02 KN/m2.

### 4.1 Modeling and analysis with software SAP

A 3D geometrical model of the whole structure was developed in Sap2000. In order to properly assess the structural interaction among the different consisted parts of the structure, this model accurately reproduces all its components including openings and recesses, all except the loft's wooden overlay. Considering the fact that it is not based directly on the stone masonry thus it doesn't affect the main building, this was replaced by its loads which were applied directly to the roof beams.

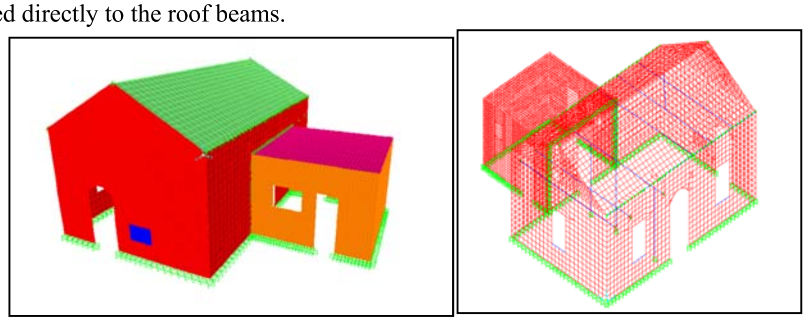

Figure 2: a) Finite elements used (different materials), b) Discretization of structure.

A densely finite element mesh is used to the model. The whole masonry structure, including the brick masonry, fixed at its base and 4-node shell-thick elements with 6 degrees of freedom has been used for discretization (Figure 2a-b). These elements combine plate and shell functions supporting forces and moments of inertia in all dimensions. The concrete plate was modeled by the same way. The wooden linear elements (beams and columns) and the reinforced concrete tie-beams were simulated by frame elements while the roof was modeled using shell-thin elements due to its overlay extreme thinness. The compounds of beams with columns were considered fixed while at the contact points of the beams with stone masonry and reinforced concrete tie-beams, links were assumed. The elastic material properties of used materials (except the stone masonry) were found in literature [1] [16], as given in the Table 1:

| | E (GPa) | v | ρ ($KN/m^2$) |
|---|---|---|---|
| WOOD | 1.0 | 0.20 | 8 |
| BRICK | 1.5 | 0.15 | 20 |
| CONCRETE | 20.0 | 0.20 | 20 |

Table 1: Material properties.

In order to study the connection of the two different structural systems (stone-brick), two models were developed; the first model, SAP_I considers that the contact points has fixed conditions anchors that are obtained by joining the nodes together so that they are in absolute contact preventing motion in all 3 dimensions. In the second model, SAP_II, soft non-linear springs (with 6 degrees of freedom) are considered at these points in both directions X and Y, following the law of local bond-local sliding. The springs have short length, equal to 2cm, in relation to the building in order not to affect the general geometry of the structure body. In this case, the coefficient $K=F_{bond}/s$ of rigidity was calculated equal to 42680 KN/m.

Both models were tested in modal analysis and low frequencies were calculated since the structure has increased stiffness. The deformations from modal analysis correspond qualitatively with those observed in the visual inspection. The most stressed sides are the smaller ones (south-north) and especially the areas above the openings, fact that is demonstrated by the cracks that exist above them. The southern and northern stone wall is strained mainly by out of plane bending and, in some modes, occurs small scale shear failure. Also, the most critical points of the masonry are, as expected in all constructions of this kind, the angles of the ground plan where are in strained either compressive or tensile almost every Eigenmode. Finally, plan rotation is observed in SAP_I model that is not proved by the cracks recorded in field inspections (fig. 3). SAP_II model seems to me more realistic compared to the actual condition of the structure (fig. 4).

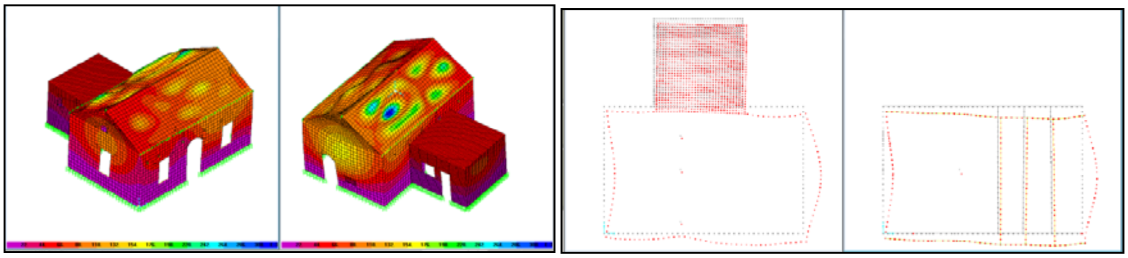

Figure 3: Deformed structure in SAP_I model for modal f=15.7 Hz.

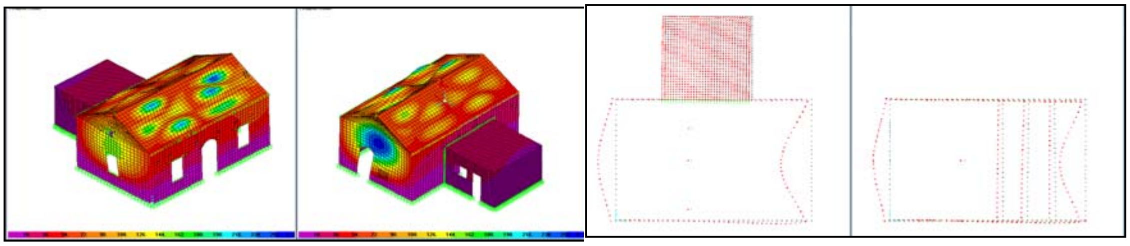

Figure 4: Deformed structure in SAP_II model for modal f=15.53 Hz.

### 4.2 Calibration & verification of the models using ambient vibration tests/

At the same time, in situ ambient vibration experiments were performed using accelerometers. With this method, accelerations in the time domain are recorded through which the corresponding natural frequencies are extracted. Subsequently, the displacements of the structure corresponding to these frequencies were exported after elaborating the recorded accelerations using the appropriate software (ARTeMIS EXTRACTOR) [17][18]. These frequencies match almost perfect with the Eigen frequencies that were calculated from modal analysis with SAP something that verifies the accuracy of the simulation. Branco et Guerreiro use the same technique, validating the accuracy of the simulation by comparing the modal frequencies measured in situ with these which came out the numerical analysis [19]. Also, Ramos, Marques, Lourenco, De Roeck, Campos-Costa et Roque study two historical buildings which were, firstly, strengthened and they were numerically and experimentally tested, after, to verify the strengthening's reliability as well as Formisano, Florio et Landolfo follow the same methodology at Sindone Palace in order to prove the validity of the numerical model and the measurements [20][21].

In addition to this, the resulting Eigenmodes from the vibration tests to a greater percentage compare with that obtained by the model SAP_II (fig. 5). This leads to the conclusion that the enclosing links at the contact points of two different structural systems achieve better simulation of the real situation of the construction.

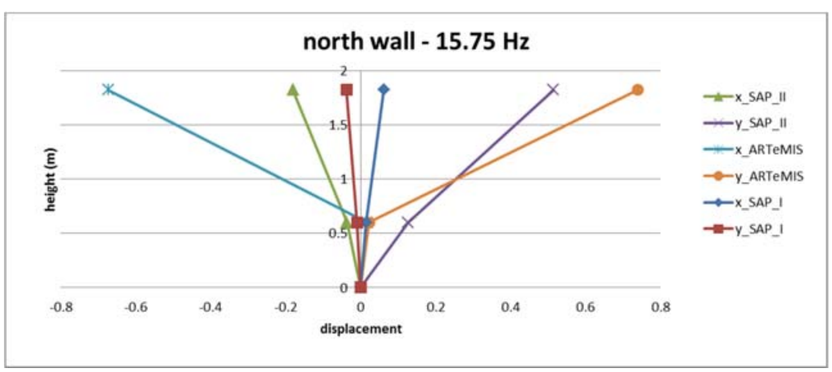


Figure 5: Eigenmode from different occasions of modal analysis.

### 4.3 Modeling and analysis with software Marc Mentat

A full 3D detailed model of the masonry building was developed in Marc Mentat. For the discretization of the structure 9556, 8-node solid elements were used with 3 degrees of freedom (fig. 6a). Three finite elements were assumed in the thickness direction of the wall. Starting from a coarse finite element mesh, a dense mesh was final selected, which give convergence of the results independent of the finite element mesh.

As far as the following boundary conditions were considered: 1)gravity load, 2) fixed displacement at the base, 3) face load of the roof, 4) face load of the concrete structure, 5) face load of the floor on the first floor and

6) point load on the stairs, as shown in figure 6b. In order to properly assess the structural interaction among the different consisted parts of the structure, this model accurately reproduces all its components including openings and recesses, all except the loft's wooden overlay. The same material properties as to models in SAP were used. Considering the fact that it is not based directly on the stone masonry thus it doesn't effects on the main building, this was replaced by its loads which are applied directly to the corresponding beams.

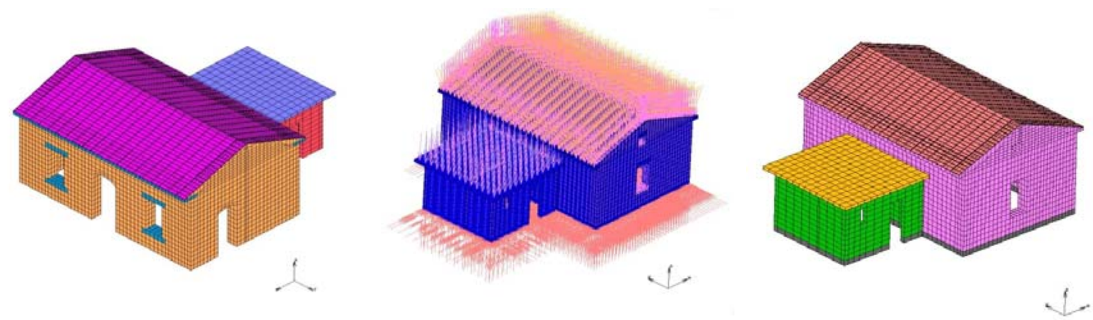

Figure 6: a) Finite elements used in Marc, b) Boundary conditions and c) Contact bodies

In order to consider the unilateral contact effects in our analysis, the various parts of the structure were separated and were connected with unilateral frictional interfaces (fig. 6c). First the assumption that the whole structure would respond as one and cooperate smoothly during the seismic assessment was done (model MARC_I). Second the assumption that the different structural systems would separate and would develop relative movements was considered in order to study the interconnection between the masonry and the concrete structure next to it (model MARC_II).

The criterion about separation is based on the normal stresses which are developed at the outer nodes of the contact bodies. The yield limit was considered equal to 0.1MPa. In various researches the friction coefficient between masonry and concrete has been evaluated with experimental measurements. The values are mainly ranging between 0.5 and 0.9, although in some cases the value of 0.3 is presented [22, 23]. In our applications the friction coefficient was considered equal to 0.7. More research on the perceived values is needed to be done in the future since these are influenced by the way of masonry construction, the materials and the method of reinforced concrete beam construction.

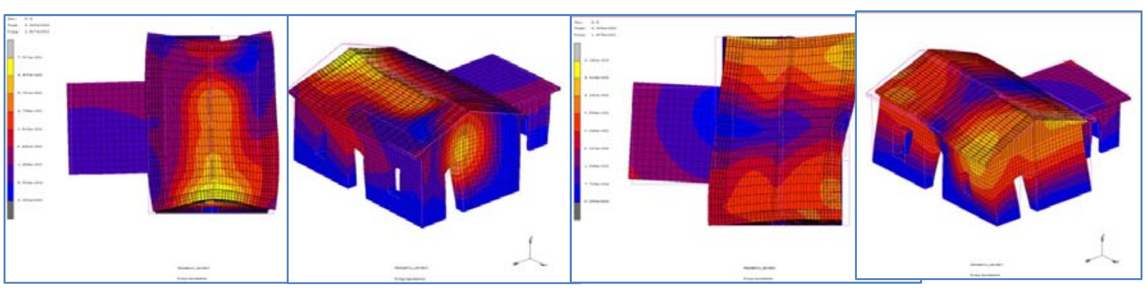

Figure 7: Deformed structure in MARC_I model for modal f4=18.37 Hz and f5=18.75 Hz.

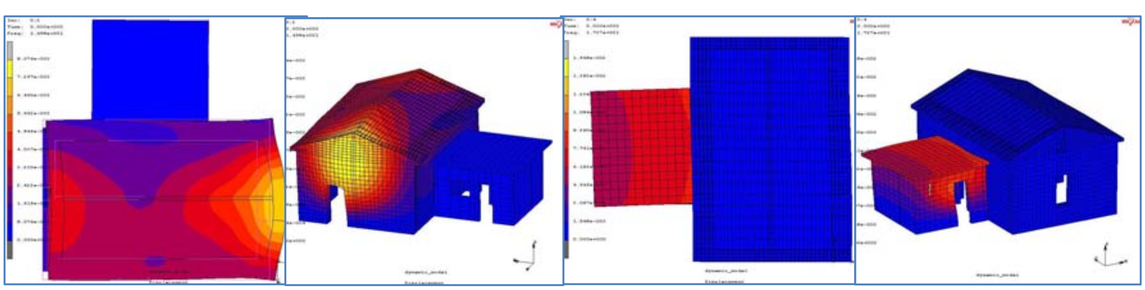

Figure 8: Deformed structure in MARC_II model for modal f2=14.58 Hz, and f4=17.37 Hz.

Both models were tested in modal analysis. The deformations from modal analysis (fig. 7) correspond qualitatively with those observed in the visual inspection and compare well with those extracted from SAP models even though there are differences to the frequencies (fig. 7). So it is important to verify the models with experimental results since the way of simulation, the discretization and the type of finite elements used, the numerical results are affected. Also the consideration that separation and sliding phenomenon can be developed lead to estimation of frequency in which mainly the concrete-brick building vibrates (fig. 8).

## 5 NON LINEAR FINITE ELEMENT METHOD OF THE ARCHITECTURAL PROPOSAL OF REUSE

In the following, the architectural proposal of reuse was studied and simulated which includes the creation of a local culture center. The basic idea of the new design is the link and smooth transition from the old to the new: the new structure is coming out of the old masonry as a natural evolution (fig. 9). The stone masonry part is maintained and reused as folk art museum. The building is extended to the ground floor and a new floor is developed with metal frame which is intended to be a multi-purpose hall.

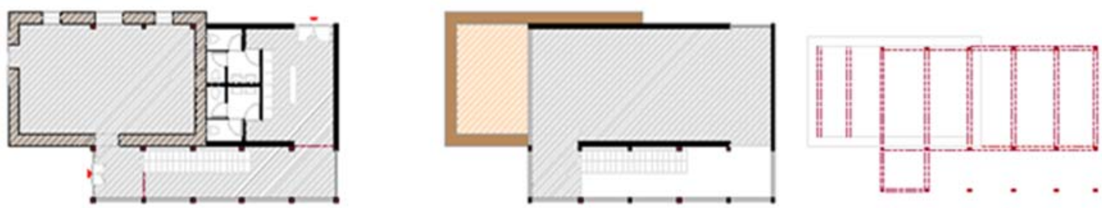

Figure 9: a) Ground floor b) First floor, c) Structural system.

### 5.1 Modeling and analysis with software SAP

Redesign and simulation process of the new building is a continuation of the existing model which has already presented previously. The steps followed are the same as those of the simulation process of the existing building. The new elements added is the metal frame of the new building, the concrete slabs of the roof and the top of stairs, cement walls, glass panels and cables in the floor ceiling (fig. 10). The cement walls did not modeled but calculated as loads on the metal frame as neither the glass elements of the facade after considered negligible weight to the metal frame. Furthermore objective of this thesis is the general assessment of the proposal and not the very constructive study.

Mechanical properties were taken from literature and the finite elements used are similar with the initial model. Stone masonry and concrete slabs were discretized with shell-elements and the metal frame (metal beams and columns) were simulated using frame elements.

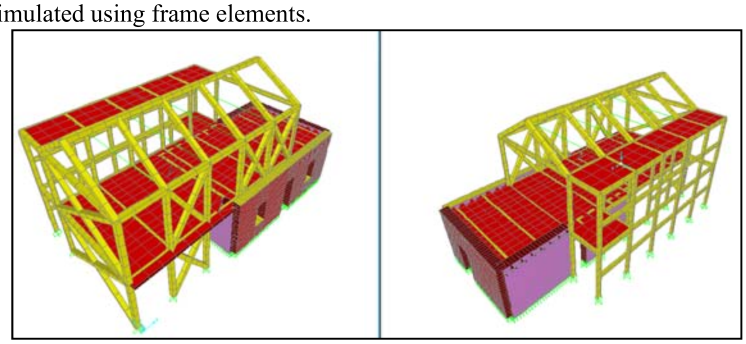

Figure 10: Model of the proposed & redesigned building.

The whole structure is fixed at his base, the compounds of beams with columns were considered to be fixed preventing motion in all dimensions while the contact points of the concrete slabs with the stone masonry and the metal frame were replaced with joints considering that these different materials can collaborate. At this point, it should be mentioned that a gap between the metal columns of the ground floor and the stone masonry was considered, equal to 0.055m, to insure avoidance of conflict between the two elements.

After being tested in modal analysis, the new building appears lower frequencies (table 2) which indicate greater flexibility of the structure due to metal parts that transfer almost all the superstructure loads directly to the ground, relieving the already "tired" stone-shell. The deformations observed in these modes are small and transport. The cross beams, provided for the east side of the metal frame, are preventing the increased stress concentration thereby preventing bending and buckling of steel columns.

Imposing seismic loadings through the spectrum proposed by the National Codes or through recorded seismic sequences, of earthquake in Chania (1988, 1994) and Heraklion (1983), it is concluded that the gap which was provided between the metal columns and masonry, equal to 0.055 m, is sufficient that these two parts of the structure will not collide [24].

| | SAP_II_modal (Hz) | Proposal of reuse_modal (Hz) |
|---|---|---|
| $f_x$ | 15.53 | 13.855 |
| $f_y$ | 16.82 | 11.774 |
| $f_z$ | 40.44 | 30.637 |

Table 2: Modal frequencies of the models: SAP_II & Model of reuse.

### 5.2 Modeling and analysis with software Marc Mentat

Based on the architectural idea, only the masonry walls without the concrete structure and the structural core were modeled and analyzed in order to be compared later with the architectural proposal (MARC_III).

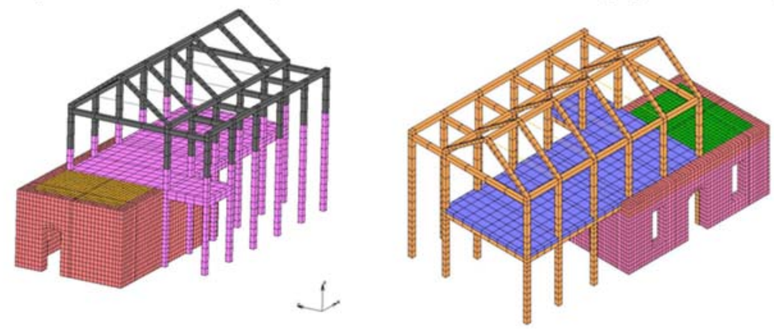

Figure 11: a) 3-D model_finite element in Marc, b) Contact bodies.

The same process which was described above was followed to model of the proposed, redesign building (MARC_IV), fig. 11a. Also the consideration that separation and sliding phenomenon can be developed between old masonry walls and the new structure were studied (model MARC_V), fig.11b.

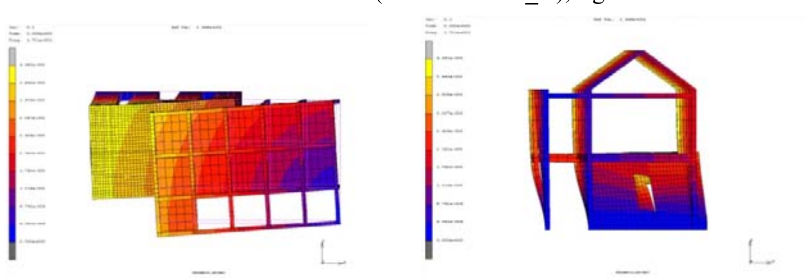

Figure 12: Deformed structure in MARC_IV model for modal f1=17.31 Hz.

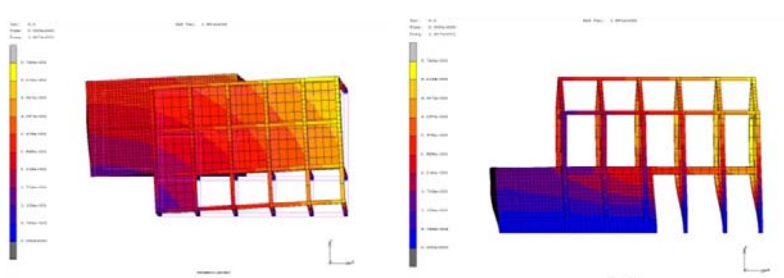

Figure 13: Deformed structure in MARC_IV model for modal f2=19.37 Hz.

All models were tested in modal analysis and indicative results are shown in figures 14-16. The consideration that separation and sliding phenomenon can be developed lead to estimation of lower frequencies (table 3) and lower deformations to masonry structure (fig. 16).

| | MARC_III_modal (Hz) | MARC_IV_modal (Hz) | MARC_V_modal (Hz) |
|---|---|---|---|
| $f_1$ | 6.90 | 17.31 | 16.26 |
| $f_2$ | 8.50 | 19.37 | 17.85 |
| $f_3$ | 10.50 | 22.84 | 21.78 |

Table 3: Modal frequencies of the models: MARC_III, MARC_IV & MARC_V.

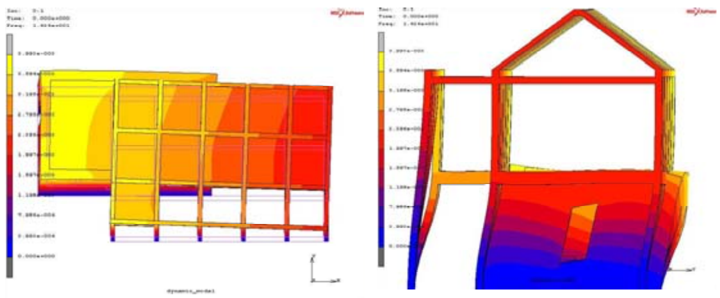

Figure 14: Deformed structure in MARC_V model for modal f1=16.26 Hz.

## 6. CONCLUSION

The study of existing structures requires an integrated approach consisting of FEM analysis but also experimental investigations. As was evident from the results, the use of different software and different types of finite element led to different, in terms of scale, results. Using shell elements instead (Sap) of solid ones (Marc), the structure seems to have greater flexibility. In addition to this, Marc software exported higher eigen-frequencies from Sap2000 both in the model of the existing building and the model of reuse although both programs came to similar eigenmodes as shown in the diagrams, fig. 15, below:

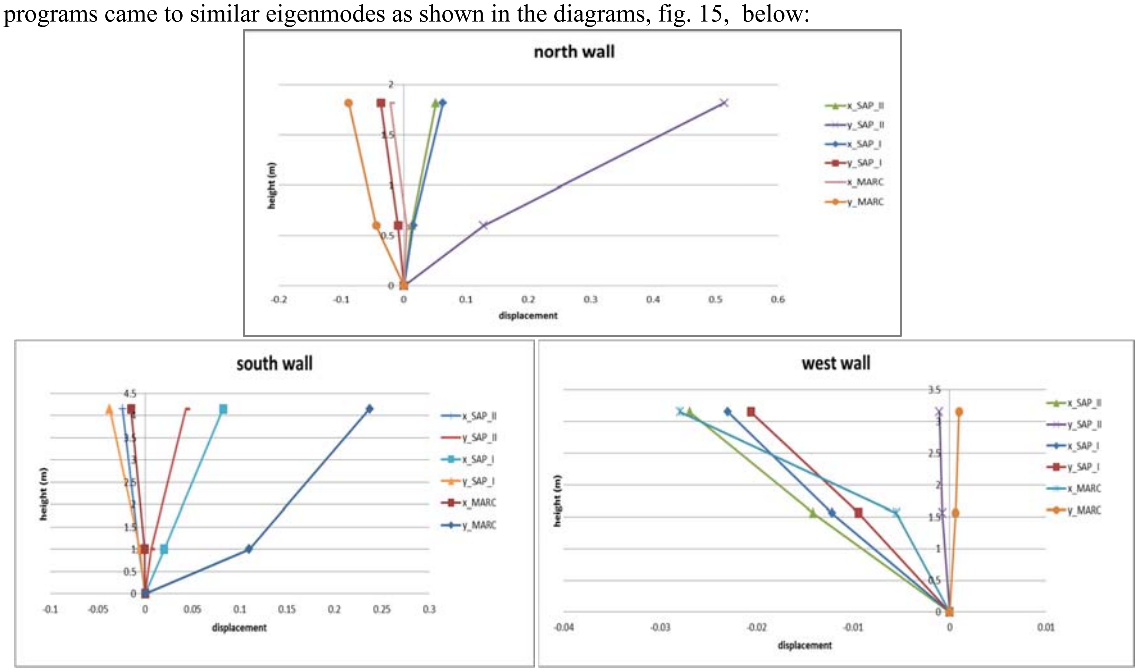


Figure 15: Eigen modes of S-N-W wall of the existing structure for a frequency of 16 Hz, approximately.

From the diagrams above, it is obvious that Marc models with glue conditons between contact bodies and Sap model without the assumption of springs at the points of contact of the two different structural systems gives relative results. The plan rotation and the displacement modes that these two models are displaying do not justify the real condition of the building and the cracks that exist.

This leads to the fact that using soft springs or assuming contact conditions with friction and separation for building modeling, becomes more accurate and reflects the actual state of it.

From the analysis it was concluded that critical areas relates with the bending of the small sides of the masonry as well as the increased stress concentration at the lintel of the openings. More research is needed for the contact parameters estimation, and the dynamic response of the composite structure which is proposed.

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