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STRUCTURAL ANALYSIS AND DIAGNOSIS OF MASONRY TOWERS

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Abstract. *The Mediterranean basin is characterized by medium up-to high level of seismic hazard but historical masonry structures, as well as a large number of old, still existing buildings, have been designed only for vertical loads; they were erected according to well established rules of common practice. In countries around the Mediterranean basin the main reason for structural failure is the combination of vertical and seismic actions. Strong earthquakes caused damages or collapse of bell towers in Greece. The few survived till today masonry "slender" campaniles are of considerable age (over one hundred years) and many of them are masterpieces of architecture in the past centuries The aim of this paper is to perform an analysis of this kind of structures. The finite element program SAP 2000 has been used for the study of the dynamic response of bell towers.*

1 INTRODUCTION

Masonry bell-towers are scattered over Greece with various densities and features from North to South. Although characterized by different stylistic decorations, age of construction and original function, their comparable geometric and structural ratios yield to the definition of an autonomous structural type. In a very concise definition, they can be described as monuments in which the total height is the prevalent dimension. Consequently, these monuments are featured by notable slenderness and this also represents one of the main differences from other historic monuments (churches, palaces, etc) or even ordinary buildings.

In Corfu, an island in north-western Greece, there exist many impressive high bell towers, which are a very important part of its main town's history, Figure 1. Bell towers are some of the only tall structures in the town, which allowed them to be invaluable surveying posts during times of war. In the past, these towers have been built as a symbol of strength, ability, and faithfulness to God (in accordance with Venice structural tradition) [1]. Their purpose lay in pointing to heaven and looking forth to survey. In times of peace, the towers were rung for celebration and mourning, to mark the hours, and in correlation with the Christian Orthodox festivals. In the past, bells were rung frequently, to call people to mass, celebrate Christian events and holidays, even just to keep time. There was at least one bell-tower in every neighborhood and typically, the inhabitants look upon their local bell tower with great pride.

Figure 1: The bell tower of St. Spyridon in the town of Corfu and the bell tower St. Mathias in the village of St. Mathias in Corfu.

Nowadays, it has become common that the bells are played automatically, and there is no reason for a bell ringer to inspect them. Since there is no bell ringer visiting the tower daily, there is no one there to observe the towers' condition and the bell-towers can easily fall into a state of disrepair. Also Corfu bell-towers were erected in areas of relatively high seismic activity. So, in addition to that, it has become evident that the bell-towers have suffered from damages and cracking caused by earthquakes and lack of repair, Figure 2. It is obvious that a seismic strengthening is essential for them, in order to avoid a total collapse and help them to survive.

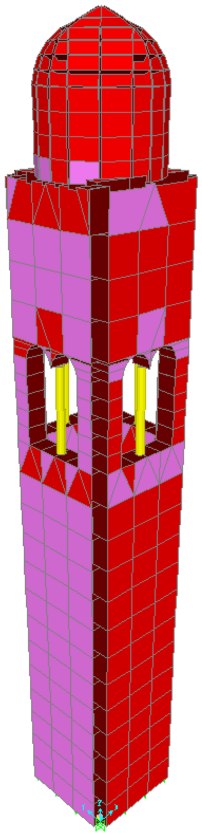
Figure 2: Corfu bell-towers have suffered from damages and cracking from earthquakes.

2 DYNAMIC ANALYSIS OF A CORFU BELL-TOWER

For the investigation of a bell-tower's dynamic behavior, it is important to have a clear understanding of its structural parts. A bell tower usually consists of a strong base and a high body with the belfry. The foundation and the ground floor of the tower are constructed with heavier and thicker walls than its top parts near the belfry. Thus the most important parts of a bell tower are the base, the shaft, and the belfry. The base is usually the heaviest part and it is constructed with a non-porous stone material which should be strong enough to bear the structural pressure of the tower.

The shaft of a bell tower is by far the largest physical component of the tower. There are staircases and/or ramps that traverse the shaft, often with several landings on the way up. The shaft is usually made of bricks joined by mortar. The form and the strength of the bricks that were used varied according to the year the tower was erected, as brick manufactures improved the quality of their products over the time in order to reach a better brick resistance to higher pressures. On each of the belfry sides there was a double arch supported by a pier on either side and by a stone column in the center of the double arch. Above the belfry was the bell tower roof, a curved dome of bright red color, based on a cubic drum. The belfry is usually constructed using bricks and in many cases elaborated decorations of stone or clay are added. Generally, inside the belfry bells are supported by wooden beams.

To evaluate the dynamic behavior of a typical Corfu bell-tower, an analytical model with 3D shell and frame elements (Finite Element Method) was developed [2], Figure 3. The tower, built in 18th century, was constructed by solid bricks and lime mortar and its height is 30m approximately. The mass of masonry structure is distributed throughout the wall. So, masonry structures should be analyzed by F.E.M. with shell or solid elements.



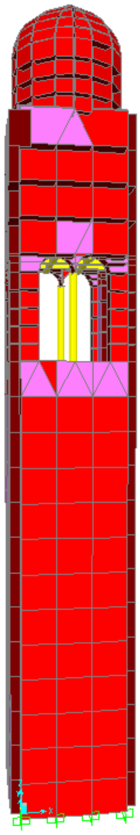


Figure 3: The analytical model with 3D shell and frame elements (F. E. M.) of the brick masonry bell tower of St. Spyridon church.

Eurocode-6 has been chosen to define the mechanical properties of masonry [3]. So, the characteristic compressive is given by relation: $f_{wc} = k \cdot f_b^{0.65} \cdot f_m^{0.25}$
where k is constant concerned with the characteristic compressive strength of masonry, f_b is the normalized compressive strength of a masonry unit and f_m is the compressive strength of

mortar. The design compressive strength is given by: $f_d=f_k/\gamma_M$ where the γ_M factor for masonry depends on the category of construction control (A↔ high, C ↔low), and the category of manufacturing control of masonry units (I↔ high quality control, II↔ normal quality control). So it was belonged in C- II category (γ_M=3.0) and group 3 (k=0.40). The modulus of Elasticity is given by: $E_{wo}=1000\ f_{wc}$ (EC-6, part 6-1, 3.8.2), but the existing pattern of cracking in vertical masonry reduces the initial module of Elasticity. We assume that the relationship between module of Elasticity of masonry with cracking and the initial could be: $E_{wcr}=2/3E_{w0}$ [2]. So, according to EC-6 [3], are computed:

- $f_{wc} = k \cdot f_b^{0.65} \cdot f_m^{0.25}$=1.977MPa, f_b=10 MPa , f_m=1.5 MPa
- γ_M=3.0, f_{wd}=1.977/3.0=0.659 MPa =0.66 MPa
- γ_s=18 KN/m^3, m_s=1.83 t/m^3, v_s=0.15
- $E_{w0} = 1000 \cdot f_{wc} \approx 1000 \cdot 1.977\text{MPa} = 1977\text{MPa}$,

Take into account the cracking on the masonry walls of the bell-tower, the modulus of Elasticity [2] was considered: $E_{wcr} = \frac{2}{3} \cdot E_{w0} = 1318\text{MPa}$

As mentioned above, linear elastic analysis was carried out using SAP 2000 software [4], for bell-tower. The direction of ground acceleration corresponded to the X,Y,Z directions within SAP 2000. The elastic spectrum from Eurocode-8 [5] was used anchored to a basic ground acceleration of 0.24g in agreement with the Greek Code which defines that Corfu belongs to seismic zone II, [6]. The seismic effects were then computed according to the current Greek Code, which is in agreement with international recommendations in the field. For the modal-superposition analysis of the campanile subjected to dynamic loads, the Ritz-vector analysis was carried out, Table 1. The reason that Ritz-vectors yield such excellent results is that they take into account the spatial distribution of dynamic loading, whereas the direct use of the natural mode shapes neglects to consider this important piece of information [7]. From the results of analysis it was observed that the maximum tensile stress in the bell-tower wall occurs in and beneath the arched areas of the structure, Figures 3, 4.

TABLE: Modal Participating Mass Ratios						
OutputCase	StepType	StepNum	Period	Sum X	Sum Y	Sum Z
Text	Text	Unitless	Sec	Unitless	Unitless	Unitless
MODAL	Mode	1	0,804665075757687	0,668088266720404	0,269050824814542	0,326614495946
MODAL	Mode	2	0,804455755016951	0,937222642478108	0,937294521854523	0,342717051450069
MODAL	Mode	3	0,212709743387249	0,93722805917312	0,937295851377053	0,577575609146506
MODAL	Mode	4	0,180149087725579	0,962382698363414	0,952399660717094	0,725058159804196
MODAL	Mode	5	0,179919323666419	0,977499812580864	0,977372937779653	0,727327438238441
MODAL	Mode	6	0,097052126918034	0,988780467356508	0,988793766898423	0,727327970356743
MODAL	Mode	7	0,089594901548331	0,988782474356307	0,988795870222625	0,868269794564422
MODAL	Mode	8	0,072873496569045	0,988986719108734	0,989172571874361	0,868297509032224
MODAL	Mode	9	0,072591757981155	0,989372927218454	0,989401032238826	0,868549652096247
MODAL	Mode	10	0,062773389254450	0,989807455836377	0,990183935978465	0,931823929789266
MODAL	Mode	11	0,062659722221446	0,990625535821399	0,990581489970038	0,933742377853662
MODAL	Mode	12	0,036460877453832	0,992706971961866	0,992745097568064	0,933746669803796

Table 1: Results of dynamic analysis. Periods and Modal Participating Mass Ratios for the first 12 modes.

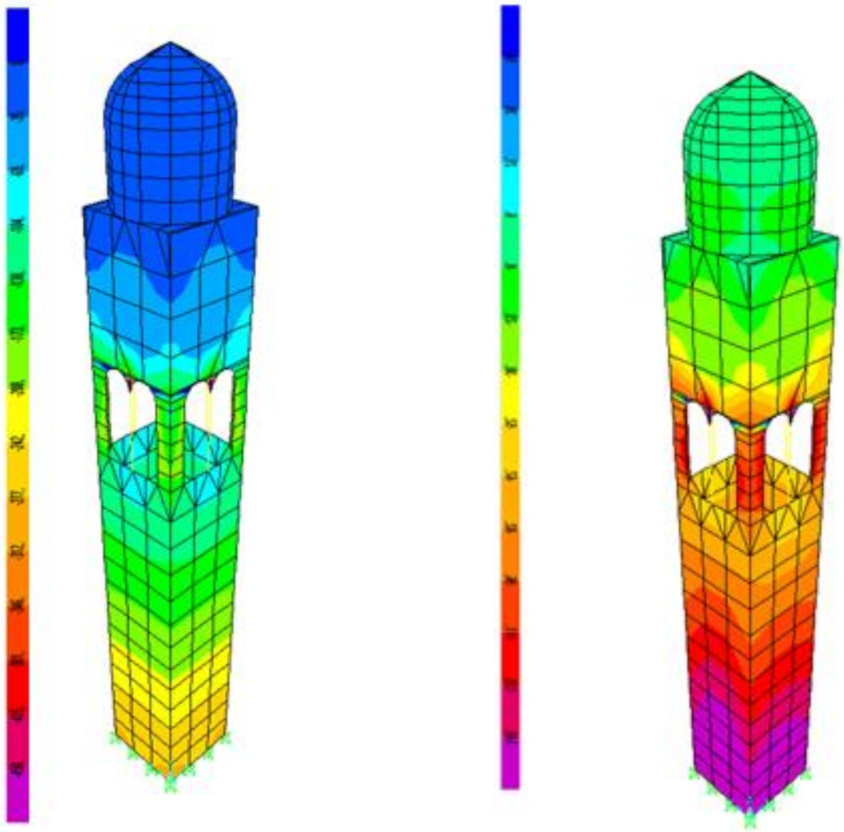


Figure 3: Stress patterns of the model under vertical loading and seismic loading correspondingly.

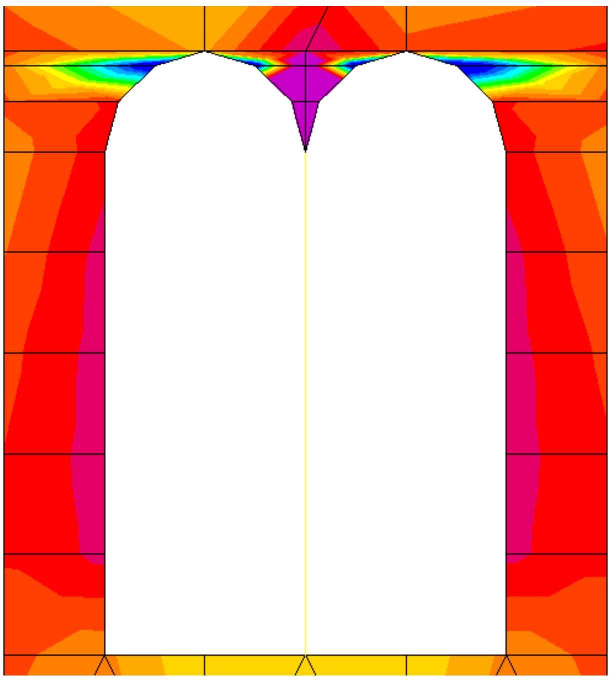


Figure 4: The maximum tensile stress in the bell-tower wall occurs in the arched areas of the structure.

3 DESIGN OF THE STRENGTHENING SCHEME

The analysis and design of strengthening scheme is a real challenge. A higher degree of damage in a historical masonry building is expected during an earthquake if the seismic resistance of the building is inadequate. The decision to strengthen it before an earthquake occurs depends on the building's seismic resistance. The structural system of deficient bell tower should be adequately strengthened in order to attain the desired level of seismic resistance. *A "Monument Safety" level corresponds to a situation in which the maximum probable earthquake (during an assigned time of reference, considerably longer than for ordinary buildings) is expected to produce repairable damages only (EC-8, Part 1-4, Annex F, F 4.4)*, [5].

The term strengthening comprises technical interventions in the structural system of a building that improves its seismic resistance by increasing the strength, stiffness and/or ductility. New codes and guidelines are founded on the concept of a structural system being designed or rehabilitated to achieve a particular level performance during an anticipated earthquake. These documents on the strengthening of existing masonry buildings, to increase its seismic resistance are:

- FEMA 273: *Guidelines for the Seismic Rehabilitation of Buildings.*
- New Zealand Draft Code [NZDC]: *The Assessment and Improvement of the Structural Performance of Earthquake Risk Buildings.*
- SERC Report: *Formulation of Guidelines for Assessment of Strength and Performance of Existing Buildings and Recommendations on Retrofitting Schemes to Ensure Resistance to Earthquake.*
- UNIDO Vol. 4: *Post-Earthquake Damage Evaluation and Strength Assessment of Buildings under Seismic Conditions.*
- EUROCODE 8: *Design Provisions for Earthquake Resistance of Structures – Part 1-4 General Rules for Strengthening and Repair of Buildings.*

The strengthening scheme of FEMA 273 [8] and EUROCODE-8 [5] consist many strengthening techniques to remedy structural deficiency, as shown in the Table 2. For monumental buildings emphasis is given to strength material type and the adequate technique to success that is the application of a strengthening mortar on the walls of the inside facade.

The simulation method for the strengthen mortar (concrete) that was proposed is based on the principals of Eurocode-6 [3] and Eurocode-2 [9]. The stress-strain diagram for the design masonry [3], Figure 5, is the same as that for the design concrete [9], Figure 6, parabolic up to 0.2%, rectangular up to 0.35%.

So a wall of masonry could be simulated as a wall of a concrete with mechanical properties of masonry, Figure 7. As a consequence of this strengthening scheme, the overall ductility of the structural system was improved. From the results of frequencies, it was observed that reinforced jacket improves the behavior of the bell-tower, Figure 8.

No	FEMA 273	EUROCODE-8
1	Infilled Openings	Reduction of the mass , particularlt at high levels, e.g., by remival of heavy rooof covering, etc.
2	Enlarged Openings	Reduction of the eccentricity between the mass and the stiffness centers, to avoid large torsional effcts, especially in buildings with strong diapfragmatic action on the floor
3	Shotcrete	Strengthening of walls by means of reinforced concrete "jackets" or steel profiles
4	Coatings for (URM) walls	Improvements of the quality of the masonry (e.g. by grouting). Due consideration should be given to the subsequent increase of stiffness and decrease of damping
5	Reinforced Cores for (URM) walls	improvements of the connections between the resisting elements (e.g. anchorage of the horizontal diaphragms in the vertical bearing elements, etc.
6	Prestressed Cores for (URM) walls	Application of vertical and horizontal confining elements to the walls
7	Braced Masonry walls	Addition of new bracing walls
8	Stiffening Elements	Improvement of the diaphragmatic action of the floors by increasing their in-plane shear stiffness and resistance
9	Enlargment of footings by placement of reinforced shotcrete or with additional reinforced concrete section	Repair or strengthening of foundation

Table 2: Strengthening techniques in accordance with FEMA 273 and EUROCODE-8

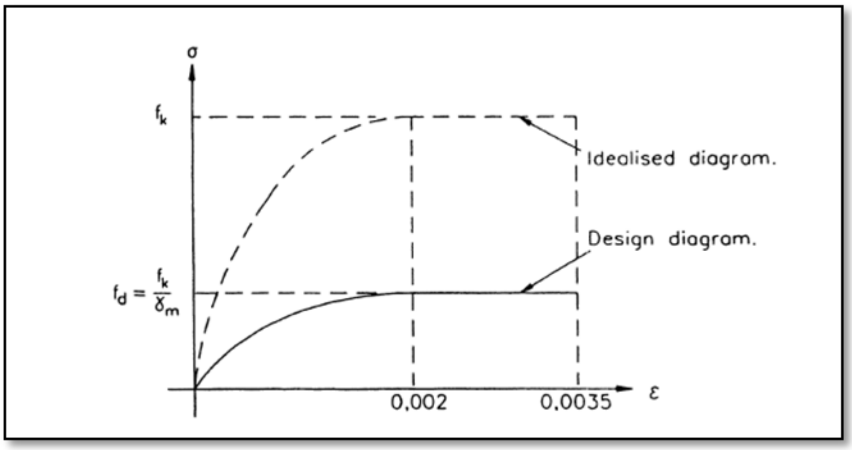


Figure 5: Stress-strain relationship for the design of masonry in bending and compression (EC-6, Part 6-1-1, section 3.8.1, fig. 3.3).

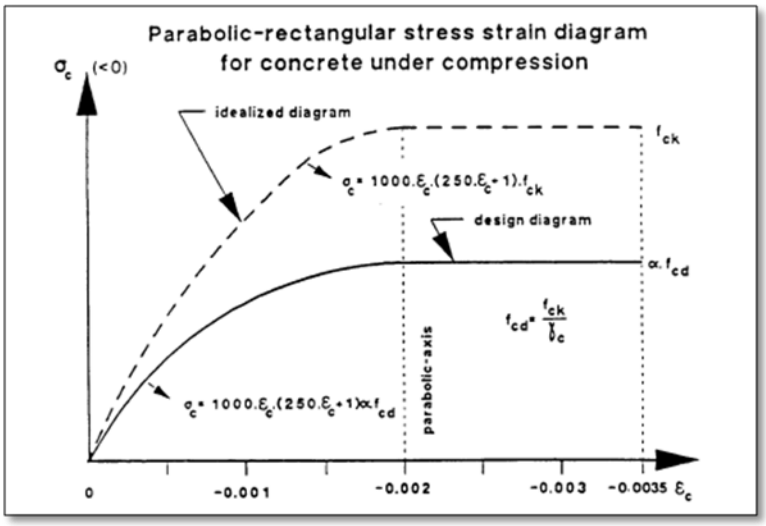


Figure 6: Stress-strain relationship for the design concrete in compression
(EC-2, Part 2-1-1, section 4.2.1.3.3, fig. 4.2).

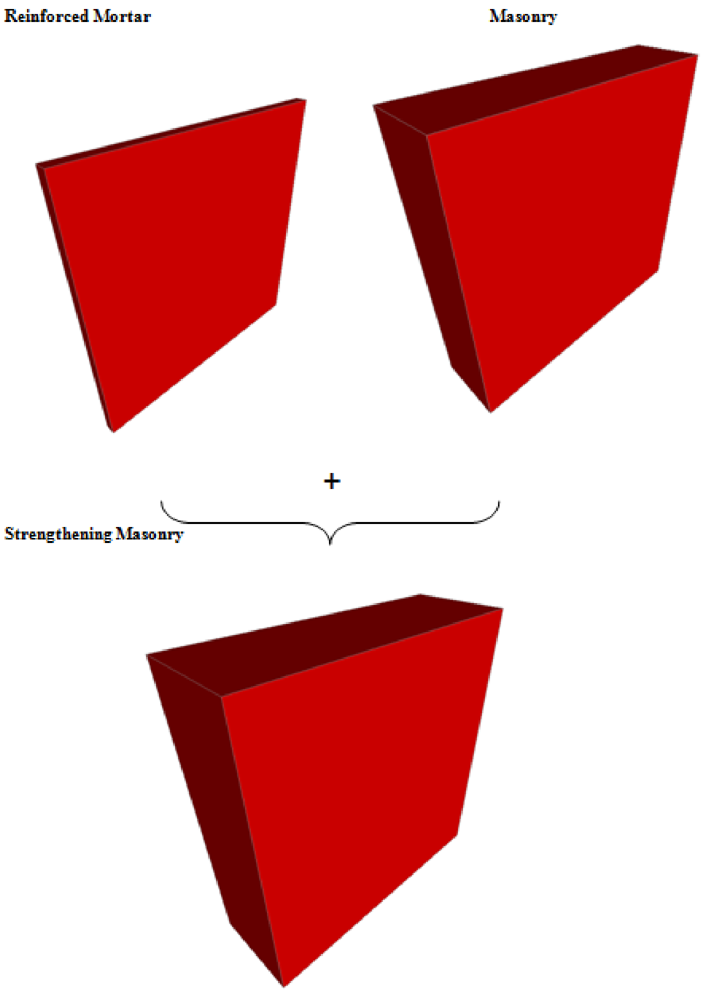


Figure 7: A simplified scheme of strengthening masonry with reinforced mortar (gunite) applying on to interior wall.

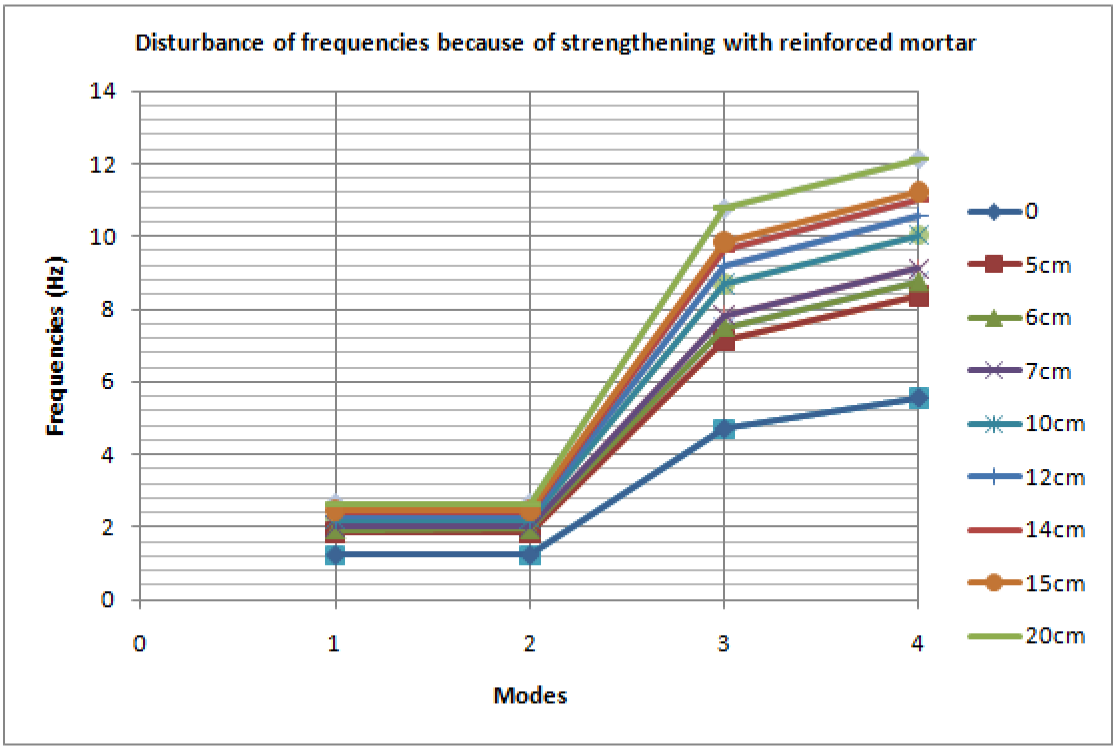


Figure 8: Results of frequencies because of strengthening scheme with different thickness of reinforced jacket.

4 CONCLUSION

In this paper it has researched the benefits of reinforced concrete strengthening of historical masonry bell towers. This method is proposed as strengthening method from FEMA 273 [8] and EUROCODE-8 [5]. The simulation method for reinforced concrete (gunite) strengthening that it proposed is based on the principals of Eurocode-6 [3] and Eurocode-2 [9]. From the results of frequencies, it was observed an increasing of the total stiffness of a bell tower and generally an improvement of the overall ductility its structural system.

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