Seismic strengthening of old masonry building using steel ties system –case study

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RÉSUMÉ. *Les techniques de renforcement des constructions en maçonnerie utilisant des tirants en acier sous forme de corsetage sont largement employées dans le confortement des structures. L'efficacité du procédé a été prouvée à travers le retour d'expérience de plusieurs cas d'ouvrages renforcés ayant montré des performances acceptables lors de séismes relativement sévères. Cet article présente ainsi un cas de renforcement d'édifice de type mauresque de valeur historique par un système de corsetage composé de contours fermés conçus pour pouvoir absorber les tractions naissantes lors d'un mouvement sismique. Une description de l'expertise de la structure est d'abord présentée avec les résultats d'essais de vibrations ambiantes. L'accent est mis sur l'étude dynamique de la structure avant et après renforcement. La performance globale de cette technique de renforcement est évaluée en termes de réponses structurales montrant l'efficience de la structure renforcée. En parallèle, l'interaction entre le système de corsetage et les murs de maçonnerie est examinée à travers la distribution des efforts dans les tirants d'acier et les murs de maçonnerie.*

ABSTRACT. *Strengthening techniques of unreinforced masonry buildings based on iron ties can be considered as one of the oldest and most common system of active consolidation, whose effectiveness is worldwide recognised by numerous cases of acceptable performances of many retrofitted buildings under recent severe earthquakes. In the present particular case, the strengthening concerns an ancient building which represents a valuable heritage of a typical Moresque style of a residence palace. For this purpose a steel tie system is designed to link together the walls of the building in order to enhance its box-like behaviour and absorb tensions that may be created in the masonry walls when subjected to earthquake ground motion. A brief description of the structural assessment of the buildings is first given together with the results of the ambient vibration testing. A particular emphasis is put on the dynamic analyses of the structure before and after retrofitting. The overall performance of the strengthened structure is evaluated through the force and displacement distributions which show the superior performance of the retrofitted structure. In parallel the interaction between the steel ties system and the masonry walls was examined in terms of the load distribution in the steel ties and the stress concentration in the masonry walls.*

MOTS-CLÉS : *Technique de renforcement, maçonnerie, corsetage, vibrations ambiantes, analyse dynamique.*

KEYWORDS: *Retrofit technique, masonry wall, steel ties system, ambient vibrations, dynamic analysis.*

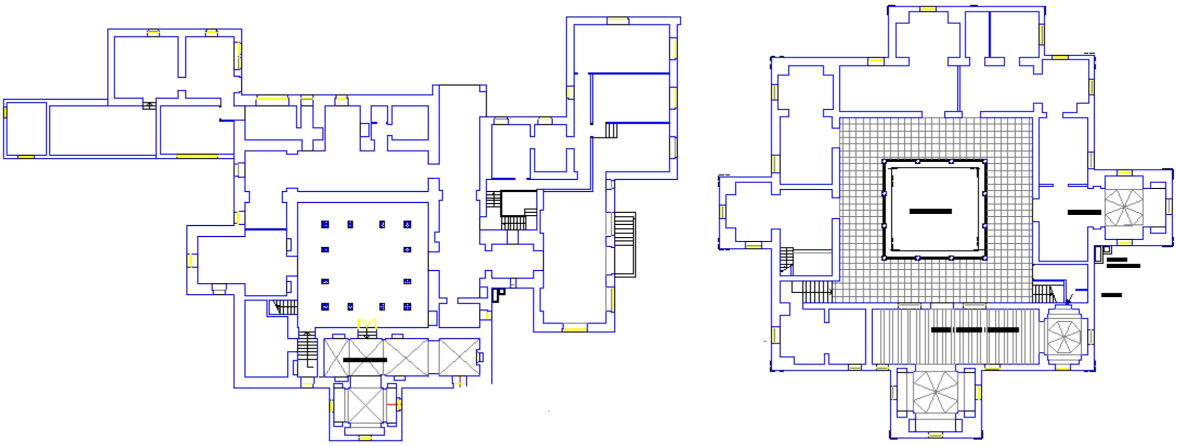
1. Introduction

Severe damage are still being surveyed in stone masonry buildings during recent earthquakes, which confirms the need for improving the knowledge of the seismic response of such type of constructions and the reliability of retrofitting techniques (Haplan and al. 2010 and Magines G. 2007). Most of the damage is due to structural failure such as extensive cracking or partial collapse of walls, damage of masonry crossing and corners and disconnection of walls. The common causes of these failures are attributed to the weak tensile strength of the masonry. Hence, the use of steel ties to link together the walls of the building in order to enhance its box-like behavior and absorb the tensile forces which is created in different parts of the walls is one of the most efficient strengthening techniques. The design and analysis of steel ties system is a challenging task for the practitioner engineer because of the complex behavior of the masonry (Kotorman and al. 1998) as well as the interaction with the steel elements. This paper focuses on the structural diagnostic of an ancient masonry building to identify the structural degradations and assess the overall dynamic and damping characteristics using ambient vibration testing. On the basis of the dynamic analysis, critical zones were identified and a strengthening technique based on steel ties system was adopted. The performance of the retrofitted structures is assessed through the response of the structure to ground motion acceleration.

2. Description of the structure

The edifice is an ancient masonry building with a partial basement, a ground level and a first floor constructed in 1895 in Algiers. It comprises a central patio covered by a roof made of wooden frame with glass infill, typical of Moresque architecture at that time (Figure 1). The shape of the building is irregular in plan and elevation (Figure 2, 3). The main lateral load-resisting system consists of load bearing walls made of stone rubble masonry with a mortar of mud and clay stabilized by gypsum. The floor and roof are made of vaulted masonry and wood structure. The thickness of the walls varies between 40.0 cm and 50.0 cm and is perforated by numerous window and door openings. The in plan dimensions of the building is about 26.0 m in both direction and the height reaches 11.0 m.

Figure 3. *Exterior and interior views of the building*



a- Ground floor layout *b- First floor layout.*

Figure 2. *Plan view of the building*

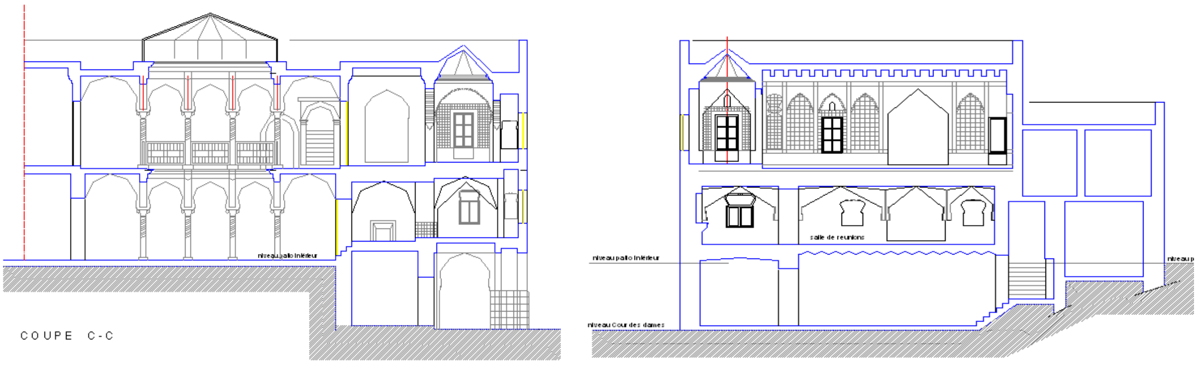


Figure 3. *Elevation view of the building*

The building survived several moderate earthquakes that occurred in the vicinity of Algiers and a major one that happened about 40km away in May 2003. An investigation was carried out in search of imprints the earthquakes have left. The damage inflicted by the last earthquake is significant and consists of many cracks initiated at the corners of the building, around the openings and across the vaults of the floor (Figure 4). Therefore a special strengthening technique is needed for this edifice to prevent further damage and to enhance its resistance and ductility capacity.

Figure 4. *Initiated cracks at the corner of the building and the openings*

3. Ambient vibration testing

An efficient seismic strengthening can only be achieved when the elastic, mass and damping characteristics of the structure are assessed to a sufficient degree of accuracy in order to evaluate the actual structural capacity of the construction. The elastic dynamic properties, particularly the natural frequencies and the corresponding mode shapes are a combined measure of the structural characteristics of the construction. These model characteristics can be successfully estimated, especially in elastic range, using the well known ambient vibration testing (Aras and al. 2011). Today, ambient vibration testing has become widespread as a fast and economical means of finding the modes of vibration of structures. It has reached the stage of being fully computer-based, which has made its application very efficient (Bourahla and al. 2008). In this paper we present briefly the main issues pertaining to this particular modal testing; FRF measurement techniques, testing procedure, and modal parameter estimation method. For this particular case where the plan configuration of the building is relatively simple, the optimum sensor locations were chosen by inspection. Two measurement points by floor, one at the centre and another at the edge were used to detect lateral and torsional mode shapes. The tests were performed using three degrees of freedom seismometer type Lennartz electronic (Le3Dlite) and a data acquisition system type City Shark II. The gain was set to 1024 to obtain a good signal resolution without any saturation and the rate was set to 100 Hz. The measured signals were processed using the GEOPSY program [Wathelet 2005] capable to perform most of the signal processing operations for the analysis of ambient vibration data. The recording time for each sequence was set to 5 mn and found to be largely sufficient to obtain smooth transfer function curves. In total 4 measurement points were performed. Figure 5 shows the locations and the orientations of the sensors on the top floor.

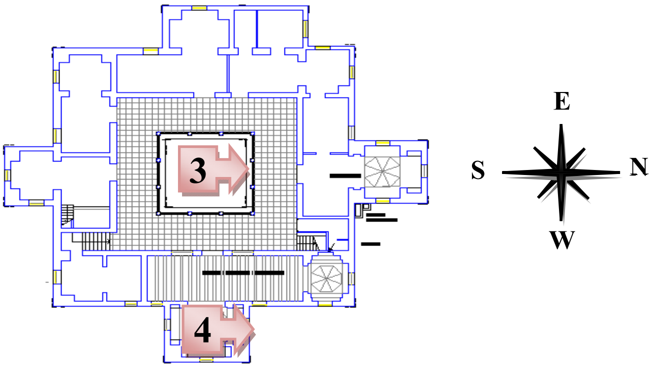


Figure 5. *Sensor locations on the top floor*

4. Natural frequency identification

The natural frequencies of the structure were simply identified using a "peak cursor" on the Frequency Response Functions (FRF). As mentioned before the shape of the structure is relatively simple with distinct translational and torsional modes. Each curve of the Frequency Response Functions (FRF) has separate peaks corresponding to different modes. The peaks on the different curves are used to cross-check the measured frequencies and compared to those of the analytical model. The first few lower frequencies were identified (Table 1) and representative FRF curves are shown in Figures 6, 7 and 8. The continuous lines represent the average curves and the dashed lines are the limits of standard deviations. The measured fundamental mode in the E-W direction lays in the interval 4.05 Hz - 4.15 Hz which corresponds to the Y-axis analytical mode with a frequency of 3.84 Hz. In the S-N direction, the measured frequency is in the interval 4.25 Hz – 4.30 Hz corresponding to the analytical frequency of 3.94 Hz along the X-axis. The torsional mode was identified from the FRF curves recorded at the edge of the floors and varies from 4.75 Hz to 5.89 Hz. The corresponding analytical frequency is 4.47 Hz.

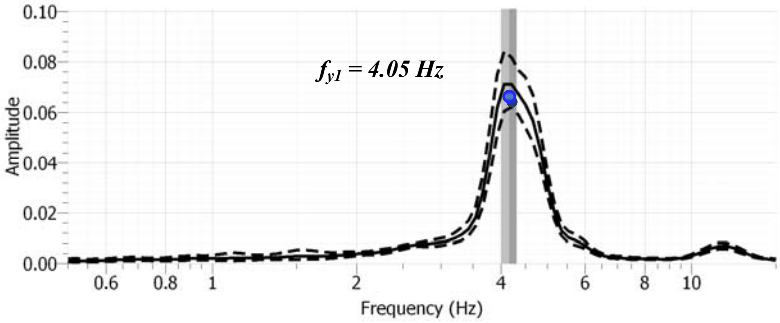


Figure 6. *E-W component of the FRF curve recorded on point location 4*

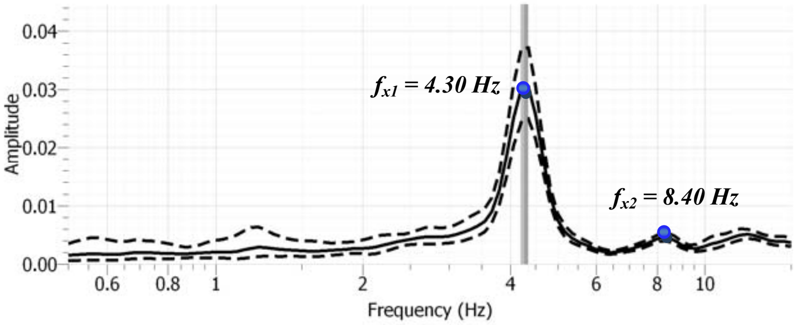


Figure 7. *N-S component of the FRF curve recorded on point location 3*

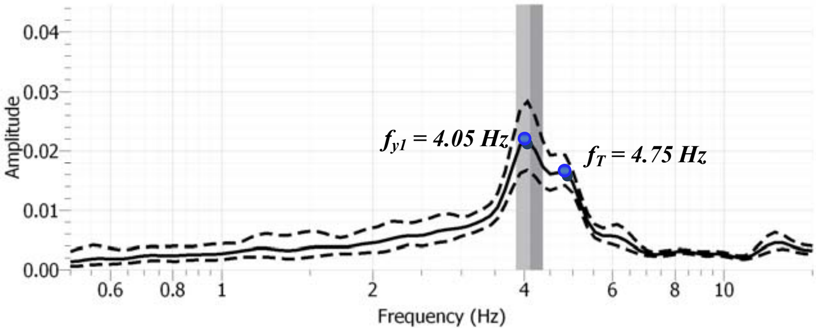


Figure 8. *E-W component of the FRF curve recorded on point location 2*

The damping coefficients for the different frequencies were determined using the time domain interpolation. Considering the low level excitations, the damping ratios are relatively low for this type of constructions. In general, the measured frequencies and those obtained from the analytical model described below are in good agreement as shown on Table1.

Table 1 *Measured and computed frequencies of the building.*

Mode	**Computed**				**Measured**	
Direction	**Frequency**	**Mass participation ratio**			**Frequency**	**Damping**
	Hz	X	Y	Z	Hz	%
E-W	3.84	0.03%	**71.0%**	0.00%	4.05	1.25
N-S	3.94	**72.0%**	0.01%	0.00%	4.30	1.92
Torsion	4.47	1.00%	1.20%	0.00%	4.75	2.65
N-S	8.57	0.17%	**11.0%**	0.00%	8.40	2.93

5. Analysis of the existing building

In order to perform an elastic seismic analysis of the initial existing building, a three-dimensional analytical model was elaborated using the finite element program SAP2000 (CSI 2004). The model included the entire masonry walls, the floor and roof diaphragms. A modal analysis was first carried out to validate the model. The physical and mechanical properties of masonry material assumed in this analysis were based on the available test data found in the literature. The material is supposed to be isotropic and homogeneous with an elastic modulus E = 800 N/mm^2, a Poisson coefficient ν=0.15 and a specific weight γ = 18 kN/m^3. These values yielded natural frequencies close (less than 10%) to those measured using the ambient vibration method.

The seismic analysis was performed according to the Algerian seismic code RPA99v2003(CGS 2003). The design spectra was derived for an S2 soil category (compact soil), acceleration factor for zone III and a reduction factor R = 2.5 (masonry building). The spectrum response analysis was carried out to determine the storey drifts and the highly stressed zones in the walls. The lateral deformations were far below the allowable storey-drift which confirms a common feature of this type of construction with several interior and exterior rigid lateral load bearing walls. The shear capacity of the walls is satisfactory. The stress distribution in the walls (Figure 9), however, shows that the masonry around openings is subjected to substantially greater tensile stress demand.

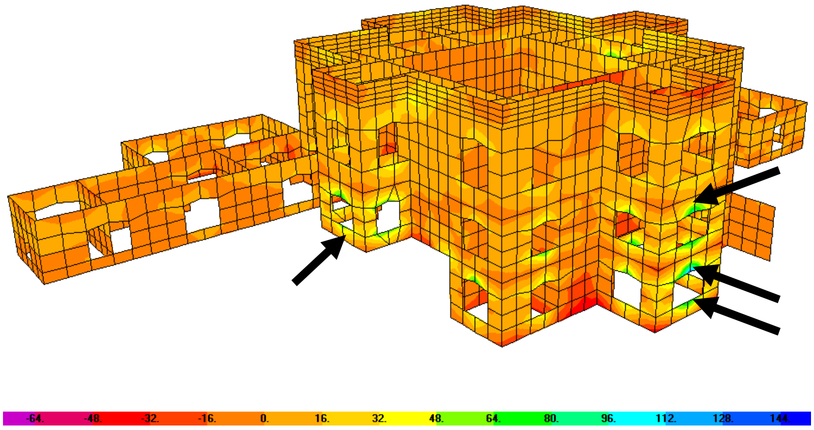


Figure 9. *Stress distribution in the masonry walls*

6. Strengthening of the structure

As mentioned earlier, the rigidity of the building is acceptable and the shear capacity of the walls is also sufficient to resist the seismic forces. The critical regions are located in the vicinity of the lower openings with fairly high tensile stresses. Therefore the strengthening is mainly intended to relief the local stress concentration around the openings and to prevent walls dislocation at the corners. For the first purpose, reinforced concrete frames are set in the large openings of the lower storeys. For the second one, a steel tie system is designed to link together the walls of the building in order to enhance its box-like behaviour and consequently reduce the risk of wall-floor and wall-wall dislocation. The strengthening scheme includes also repairing all the cracked masonry walls and the floors. This paper focused on the structural strengthening using the steel ties. This technique is used to attach individual or a group of walls by means of post-tensioned steel ties to absorb the tension stress in the masonry walls induced by an earthquake ground motion. The method used for this particular case is based on subdividing the in plan configuration of the building into simple rectangular contours which allow to bind exterior walls with the floor and create a kind of belts around each contour (Figure 10).

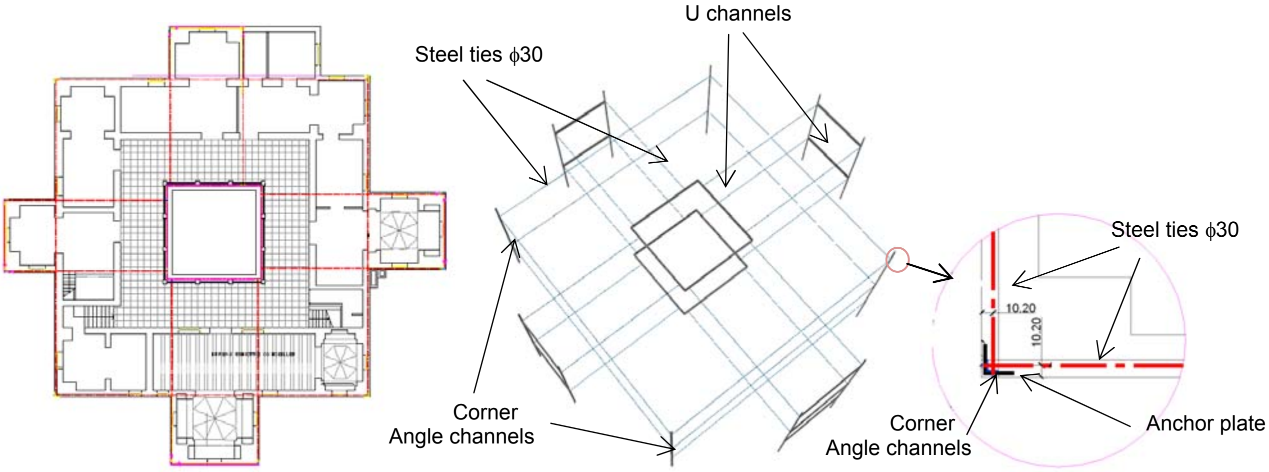


Figure 10. *The steel ties system*

7. Performance of the strengthened building

The performance of the existing structure and the strength enhancement provided by the steel tie system is predicted by numerical simulation using the FE method. The accurate representation of masonry walls and the strengthening system for structural analysis is a complex problem. For the purpose of this study, a simple model based on a pre-defined failure mechanism has been adopted. The basic concept is that the connections between the exterior walls are assured by the steel ties. The separate parts are modeled, possibly connected at boundaries, with zero gap elements. In the present analysis the model was subjected to a ground acceleration recorded at a station located in Dar-El-Beida during the Boumerdes earthquake 2003 (Algeria). The E-W component with a peak acceleration of 0.52g and a duration of 27 seconds is used to carry out the nonlinear modal analysis at constant time interval 0.005 seconds. Internal viscous damping (Rayleigh damping) equal to 7 % is assumed. The initial model without steel ties is first considered. The global response measured in terms of the lateral displacements and the link axial forces indicate that the exterior walls will undergo severe lateral displacements leading to a disconnection at the corner as shown on Figure 11. The displacement time histories at the top floor corner are plotted on Figure 12. A larger response of the exterior wall can be noticed during the strongest part of the ground motion. The axial force of the link element at the same location shows the tension free response.

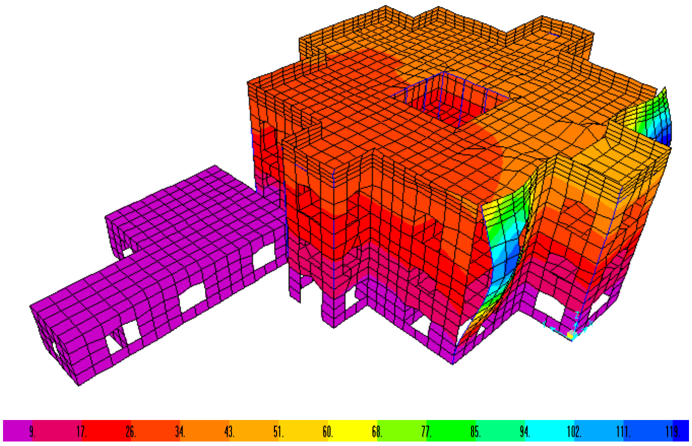


Figure 11. Maximum displacement distribution before strengthening

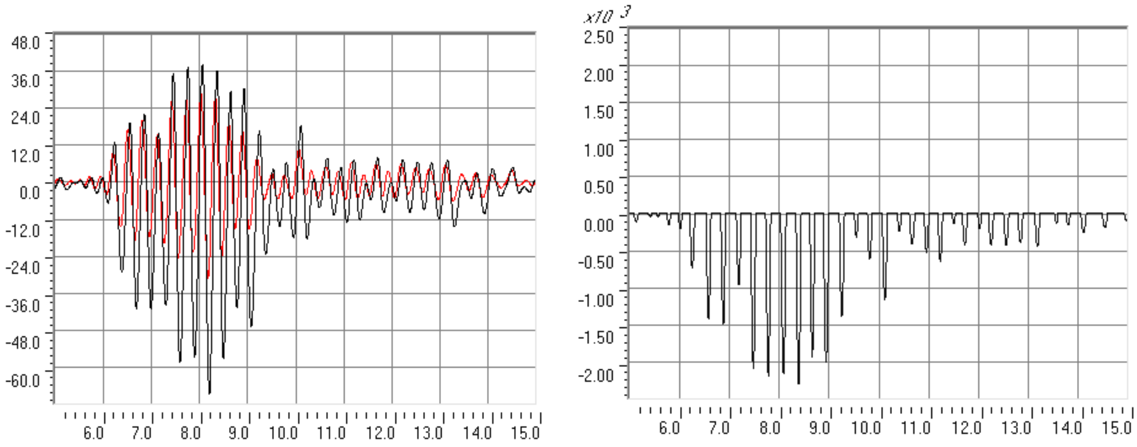


Figure 12. Top floor and exterior wall displacement time histories and link element axial force

A second model is considered in which a frame elements are incorporated to simulate the steel ties system. Under the same earthquake ground motion conditions to which the initial model has been subjected, the building with the strengthening system exhibit different behaviour. The exterior walls remained connected at the corners (Figure 13) where the tensions were completely absorbed by the steel ties. The axial force time histories of the link element and the steel rod show that the forces developed at the connecting point is alternating between the link element in compression and the steel tie in tension (Figure 14). It should be noted that the compression in the steel ties may be completely removed by an additional post tensioning.

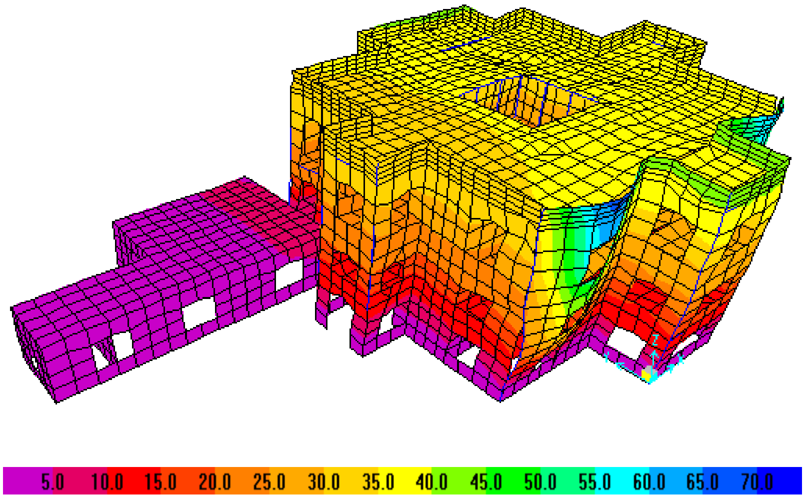


Figure 13. Maximum displacement distribution after strengthening

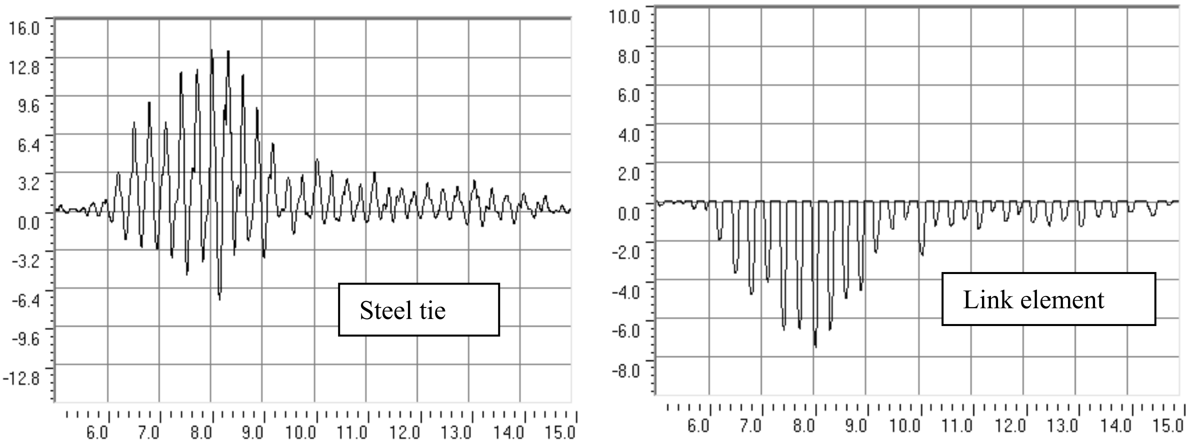


Figure 14. Axial force response time histories of the link element and the steel tie

8. Conclusion

Severe damages to stone masonry bearing walls are still being reported by post-earthquake investigations of recent events. The structural failures are commonly attributed to the weak tensile strength capacity of this type of structures. The use of steel ties systems as a closed simple square or rectangular contours has been recognized to be efficient in linking together the walls and enhancing the box-like behaviour of the structure to absorb the tensile forces that may appear during an earthquake excitation. An illustrative case study of a rehabilitation of an ancient masonry edifice is carried out. Series of ambient vibration testing were first used to determine the frequency and damping characteristics of the structure. The structural deficiency is confirmed by an analysis of the existing structure where a strengthening scheme based on steel ties system is adopted. To evaluate the performance of the retrofitted structure an analytical model using finite element method is elaborated where the wall to wall connections are modeled by gap elements. The response of the structure to a ground acceleration time history showed the superior performance of the system.

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