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Dynamic analysis of a historical monument: retrofit using shape memory alloy wires

Karim Hamdaoui* and Zahira Benadla[a]

Department of Civil Engineering, Faculty of Technology, University of Tlemcen, B.P. 230, 13000, Tlemcen, Algeria

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Abstract. The effectiveness of using the advanced seismic protection technology based on shape memory alloy (SMA) dampers to preserve a historical minaret is investigated. The proposed studied case, the minaret of Mansourah, is a seven century old minaret located in Tlemcen, Algeria. Its original height was of 47m, while nowadays, the monument is half destructed and its current height reaches the 40m. The proposed seismic retrofit is based on the technique that utilizes SMA wires as dampers for the upper flexible part of the minaret. The effectiveness of the proposed technique is numerically evaluated via non-linear finite element analysis using the structural software ANSYS. The effectiveness of the proposed device in mitigating the seismic hazard is demonstrated by the effective reduction in its dynamic response.

Keywords: minarets; historical monument; shape memory alloys; dynamic analysis

1. Introduction

Minarets, as an important element of mosques in the Islamic architecture, date back to the Umayyad period (661-750). Their first apparition was in Basra (Iraq), when its governor, Ziyad Ibn Ubayh, reconstructed the mosque of the city and added a stone minaret (in 665) in a way to be in harmony with the urban evolution and the population excess (Mo'nis 1981). Their significance is principally due to their function in the "Athan" (the call to pray), when the "Moathin" (the person calling to pray) go up to the top of the minaret recalling people for the pray time. They may present several architectural forms depending on the period and the site of the construction.

From the structural point of view, old minarets are considered as a vertical cantilever built with techniques based on experience, using traditional natural materials found in the area of their location and without any special design. These structures are generally complex and are constructed with materials that have nonlinear behavior under heavy load. In addition, their structural behavior is considerably conditioned by a long history of damages.

When dealing with the retrofitting of historical monuments, not invasive solutions need to be performed since the standard methods often do not give structures sufficient resistance against expected dynamic actions. Innovative techniques based on the use of SMA devices (Casciati *et al.*

*Corresponding author, Ph.D., E-mail: karim@unipv.it
[a] Ph.D., E-mail: z_benadla@mail.univ-tlemcen.dz

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2009, Ozbulut *et al.* 2011) have been studied and experimentally tested to protect historical monuments against seismic hazard, guarantee the structural stability and, at the same time, respect as much as possible their integrity (Wind-Chime 2007, Casciati and Al-Saleh 2010, Casciati and Faravelli 2010).

Commercial products of the Nickel/Titanium (Ni-Ti) alloys were already adopted in the seismic retrofitting of historical monuments (Auricchio *et al.* 2001, Saadat *et al.* 2002). Furthermore, a numerical simulations when implementing the constitutive law of a Ni-Ti alloy as a subroutine in the retrofitting of a large Egyptian monolithic statue, was shown in (Casciati and Osman 2005). The mechanical characteristics of the Ni-Ti alloys have been investigated in Casciati (2003) and Torra *et al.* (2013).

Technically speaking, the application of the Ni-Ti alloys might not be the best candidate for the seismic retrofit of cultural heritage structures. The main reasons are their expensive cost and limited range of potential transformation temperatures. Therefore Casciati and Faravelli (2004) checked the availability of the Cu-based alloy for the monumental retrofitting application. Several mechanical and fatigue tests were performed on this kind of alloys (Casciati *et al.* 2007, Casciati and van der Eijk 2008, Casciati and Marzi 2010, Casciati and Marzi 2011, Carreras *et al.* 2011, Casciati *et al.* 2011). In the experimental work by Casciati and Hamdaoui (2008), pre-tensioned Cu-based SMA wires were, first, anchored on a scaled masonry wall model built by superposed bricks to reproduce the properties of a monumental structure. Following the conclusions from this laboratory test, Chrysostomou *et al.* (2008) inserted the same type of SMA ties on a real monumental structure; the aqueduct of Larnaca in Cyprus. From the gathered results, the insertion of SMA wires showed a significant effect on the dynamic characteristics of the monument. Recently, the reduced-scale tests realized by AlSaleh *et al.* (2011) on a 1/16th minaret model to see the effect of Cu-based SMA wires on the structure’s behavior gave evidence that proposed process works correctly on tall systems.

In this study, the behavior of a historical minaret is numerically investigated, before and after being retrofitted using SMA dampers. The effectiveness of such technique is assessed based on the action of two recent Algerian earthquakes: (i) the May 21, 2003 Boumerdes earthquake of intensity X and magnitude 6.8 that provoked 2278 casualties, 11450 injured and 182000 inhabitants that lost their house, and, (ii) the December 22, 1999 Ain-Temouchent earthquake, of magnitude 5.7, that killed at least 28 people and made thousands of families homeless.

2. The studied case

2.1 The site of Mansourah

The historic site of Mansourah, classified as national patrimonial cultural heritage, is one of the most remarkable monuments in Algeria. The city of Mansourah (Fig. 1(a)) was founded by the Merinid Sultan, King Abu Yacoub, in 1299 to compete the commercial pole of Tlemcen (now, some 4 km away) (Marçais 1950). Renowned for its sumptuous palaces, shops, baths, beautiful gardens and its famous great mosque, Mansourah covered an area of 101 hectares. The city was completely surrounded by ramparts, where less than the half are still visible today.

The mosque of Mansourah (Fig. 1(b)) (Marcais 1903) has an empty rectangle shape, where the 60m width and 85 m length enclosure is occupied by a central court. All what remain now are the walls around it with the leftovers 12 gates, as well as the front half of its minaret. The main door of the mosque was pierced in the minaret (Fig. 2(a)), giving a peculiarity not found in any other mosque of Tlemcen. Through that beautifully decorated gate, one entered by following a 10 m length archway passage in a gallery overlooking the mosque's court. The door comes in a semicircular arch form with 2.50 m span, wrapped in two lobed arches. It should be noted that the life of the city of Mansourah was extremely brief and, presently, the only remains is the minaret with its framing in ruins (Fig. 2(b)). It is worth mentioning that the vestiges of this historic site carried out some restoration work during and after the French colonial period.

2.2 The minaret of Mansourah

The minaret is seen as the land mark of the city of Tlemcen. Their principal figures are:

- 40m height (47m before its half collapse) with a base of 10x10 m^2 (Fig. 3);
- Construction material is cut stone;
- A vaulted main entrance piercing the middle of the minaret;
- An empty core housing six levels;
- An access ramp.

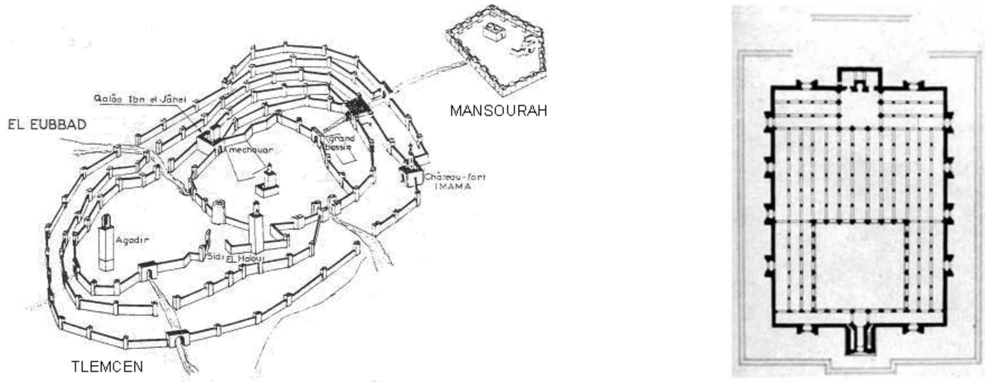
In 2001, a virtual restoration of the half destructed minaret to its original state was performed in the University of Tlemcen, Algeria (Kada 2001). Adopting this original configuration, the distinct element method, suitable for load-bearing masonry buildings, was used to model the ruin of the studied structure (Kara Slimane 2005). This analysis leaded to the conclusions that the ruin of the minaret was the consequence of removing the keystone of the gallery forming the entrance of the mosque (Ghomari 2010) (Fig. 4).

3. Original finite element model

3-D finite element models of the studied minaret are built within the ANSYS 11.0 structural software (ANSYS 2003). Solid elements are used to model the structure and its element by assuming the minaret's material behavior as linear elastic, homogeneous and isotropic. The architectural details, doors and windows are taken into account in the created model. However, the walls that are in contact with the minaret and the soil-structure interaction effects are excluded in the developed numerical models.

In the aim to be as close as possible to a realistic model, an equivalent modulus of elasticity for the whole structure was taking into account. This E_{eq} was calculated based on the cut stone mechanical characteristics and those of the mortar between the stone layers. Due to its monument status, no specimen can be extracted and, therefore the mechanical stone's properties that we adopted (reported in Table 1) were based on the literature survey and existing reports (Harbit 2005) (Kara Slimane 2005).

It is important to note that the best way to create a realistic finite element model of the studied structure would be by mean of ambient vibration tests on the selected minaret (Wenzel and Pichler 2005, Hamdaoui 2006, Bani-Hani *et al.* 2008, Chrysostomou *et al.* 2008). The obtained finite element model is shown in Fig. 5: the mesh consists on a total of 3044 solid elements and 1037 nodes.



(a) (b)

Fig. 1 (a) Location of Mansourah in the 14th century, (b) A plan view of its great mosque (Ghomari 2010)

(a) (b)

Fig. 2 Ruins of Mansourah's mosque: (a) General view on minaret, (b) Back view and traces of ramparts

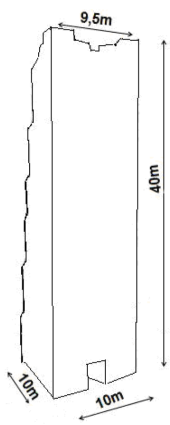


Fig. 3 Geometric characteristics of the minaret of Mansourah

Table 1 Mechanical characteristics of the construction materials

	Cut stone	Mortar
Elastic modulus (MPa)	20833	4003
Unit weight (KN/m^3)	25	15.4
Poison ratio	0.2	0.2
Compressive strength (MPa)	14.69	6.7

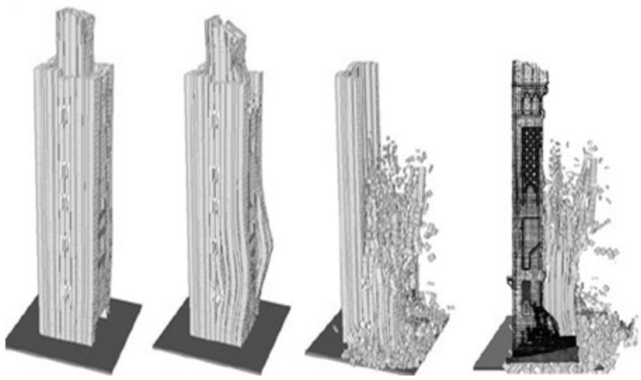
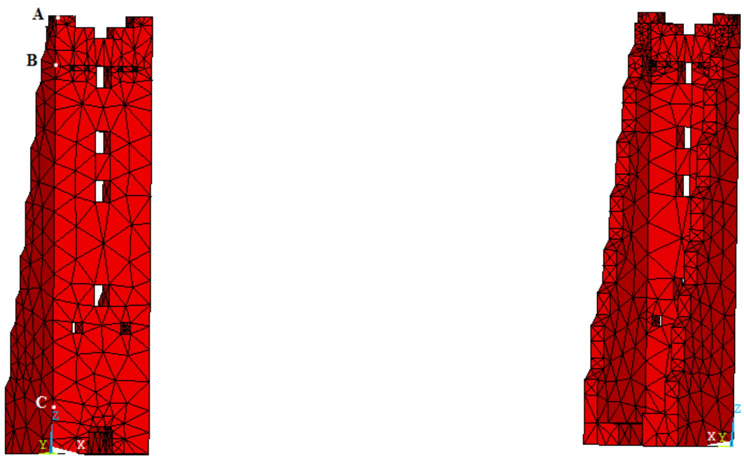


Fig. 4 Model of the minaret's collapse (Ghomari 2010)



(a) (b)

Fig. 5 Details of the 3D finite element model: (a) In front view and (b) Back view

4. Dynamic analyses of the minaret

The minaret models are analyzed based on the accelerograms records of two destructive Algerian earthquakes:

1. The May 21, 2003 Boumerdes earthquake (PGA=0.34 g) (Bendimerad 2004): by applying a 33% fraction action of its accelerogram (Fig. 6(a)), recorded at Kaddara station at an epicentral distance of 20 km. The idea behind the choice of the 33% fraction is based on the classification of the seismic zones in the Algerian para-seismic regulations “RPA 99 V.2003” (RPA99 2003). It is noted in that official technical document that the PGA of Tlemcen region, classified as seismic zone 1 (zone of low seismicity), is almost the third (1/3) of the PGA of Boumerdes region that is classified in the seismic zone 3 (zone of high seismic activity);
2. The December 22, 1999 Ain-Temouchent earthquake (PGA=0.059 g): since the main shock of this earthquake was not registered, the aftershock on January 27, 2000, recorded at Ain-Tolba station, was considered in this study. Here, the model was excited by a synthetically generated accelerogram (Faravelli 1988, Boumechra *et al.* 2010) consistent with this aftershock (Fig. 6(b)). The selected generation process is the Sabetta and Pugliese method (Sabetta and Pugliese 1996), defined on the basis of three parameters:
   - Magnitude: MS = 5.7 (Ain-Temouchent earthquake);
   - Epicenter distance: 85km, Distance between the causative fault of the Ain-Temouchent earthquake’s and the site of the studied minaret;
   - The soil is supposed to be stiff (according to the geological study of the site).

Two sets of analyses are performed; the first is to analyze the minaret at its actual state, without any retrofitting. In the second, the model is analyzed again when the SMA wire dampers are inserted. Note that the two actions were applied along the y-direction.

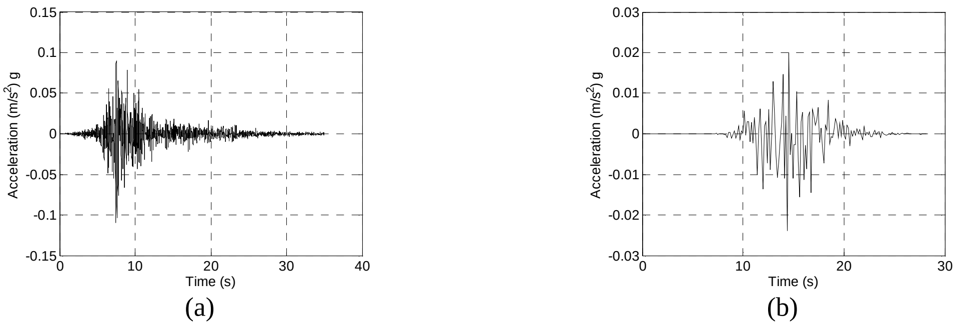


Fig. 6 (a) Accelerogram record of the 33% fraction of Boumerdes earthquake (PGA=0.11 g), (b) Simulated signal from an aftershock of Ain-Temouchent earthquake (PGA=0.024 g)

Table 2 Peak displacement and acceleration values for the specific nodes before retrofitting

Label	Displacement (mm)	Acceleration (m/s²)	Label	Displacement (mm)	Acceleration (m/s²)
ABC	4.1070	1.7489	ATC	1.3099	0.1818
BBC	3.2960	1.4272	BTC	1.0728	0.1495
CBC	0.0349	0.0270	CTC	0.0093	0.0016

4.1 The Minaret before being retrofitted

In the following section, the results when analyzing the minaret in its virgin state are reported. The displacements and accelerations computed in y-direction at the three selected nodes: *A* (situated at 40 m height), *B* (situated at 35.6 m height) and *C* (situated at 3.5 m height) (Fig. 5(a)) under the two dynamic actions (the 33% fraction of Boumerdes seismic event and the simulated signal based on Ain-Temouchent earthquake) before using SMA wires are shown in Table 2.

It is seen that the maximums (either for displacement or acceleration) are reached at note *A*. The registered maximum displacement is around 4.1 mm under the 33% fraction of Boumerdes action, where it reaches only 1.3 mm when the analysis is drawn based on Ain-Temouchent action. For the maximum acceleration, it is 1.75 m/s^2 under the first dynamic action and 0.18 m/s^2 under the second one.

Note that displacements and accelerations labels mean respectively: the selected node (*A*, *B* or *C*), the applied dynamic action (*B* means Boumerdes and *T* for Ain-Temouchent) where, the last character distinguishes between the cases without SMA wires (as *C*) and the case when the structure is equipped with the SMA wires (as *S*).

4.2 The Minaret after being retrofitted

The proposed seismic retrofit is based on the use of SMA wires as dampers for the upper flexible part of the minaret. For this purpose, the original finite element model is modified by inserting five equidistant SMA wires of 3.5 mm diameter and 1 m length. These ties are assembled with the minaret's stone using L shape steel angles.

SMAs, with their shape memory effect (remembering their original shape), super-elasticity property (recovering large deformations) and self healing ability (moving back to their initial configuration) (Faravelli and Marzi 2010), behave in a hysteretic way without permanent strain (Auricchio *et al.* 1997).

The basic idea under the proposed technique is to connect part of the minaret elements by SMA wires that should behave as follow (Auricchio *et al.* 2001):

- Under service loads; the device does not apply any static force to the structural elements that connects (and consequently it is called "self-balanced");
- Under low intensity dynamic horizontal actions (wind, small intensity earthquakes) the device remains stiff, as traditional steel ties do, not allowing significant displacements;
- Under higher intensity dynamic horizontal actions (i.e., design earthquakes) the stiffness of the device significantly decreases, allowing the minaret "controlled displacements", while the force remains almost constant. This behavior should reduce the amplification of accelerations (as compared to stiff connections). The structure should be able to sustain a high intensity earthquake without collapse, though undergoing some minor damage;

Table 3 Peak displacement and acceleration values for the specific nodes after retrofitting

Label	Displacement (mm)	Acceleration (m/s^2)	Label	Displacement (mm)	Acceleration (m/s^2)
ABS	3.0682	0.4749	ATS	1.3009	0.1722
BBS	2.5130	0.3875	BTS	1.0684	0.1393
CBS	0.0345	0.0117	CTS	0.0089	0.0015

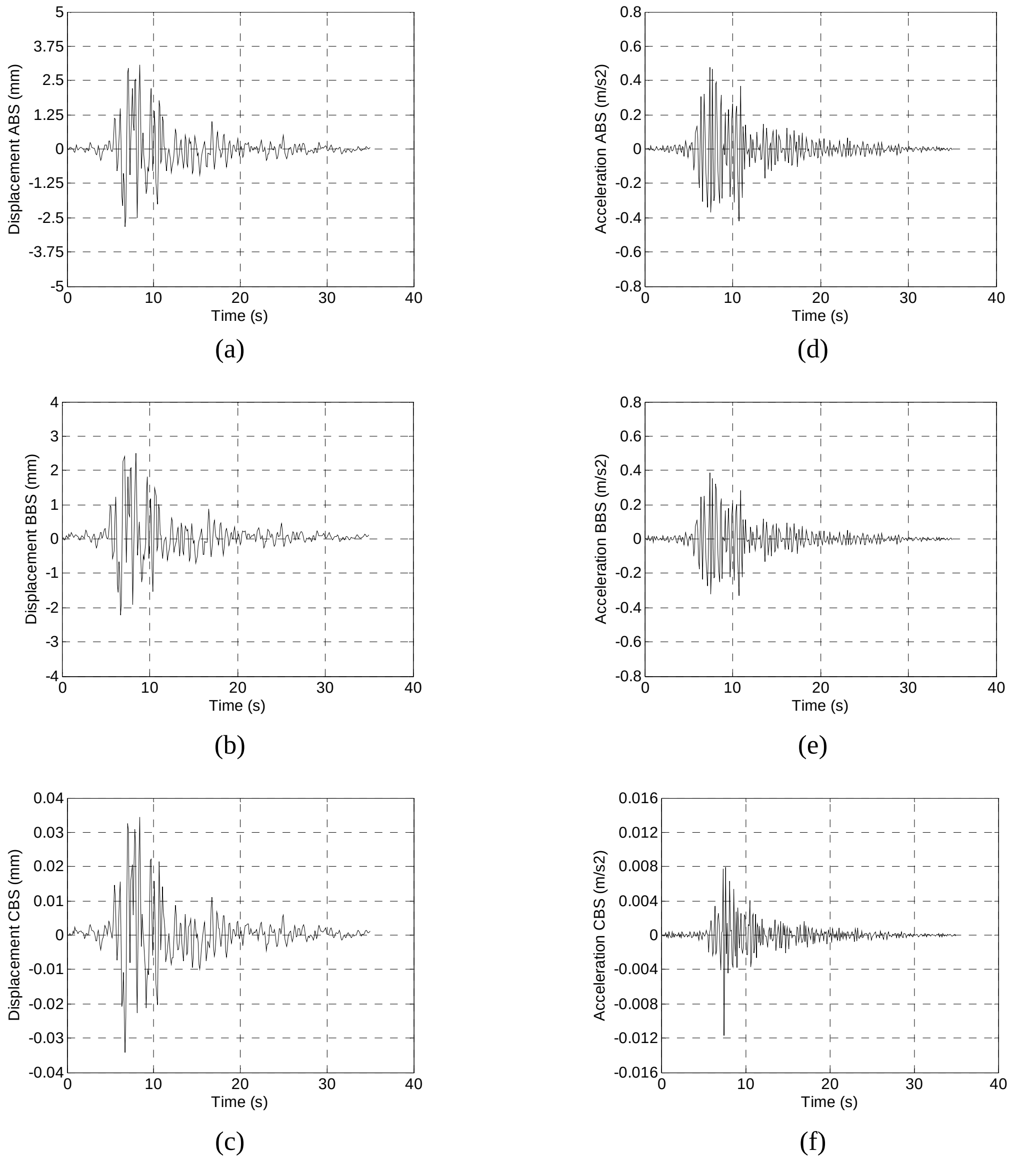


Fig. 7 (a), (b), (c) Lateral displacements and (d), (e), (f) Accelerations at the three selected nodes under the 33% fraction of Boumerdes action (with SMA wires)

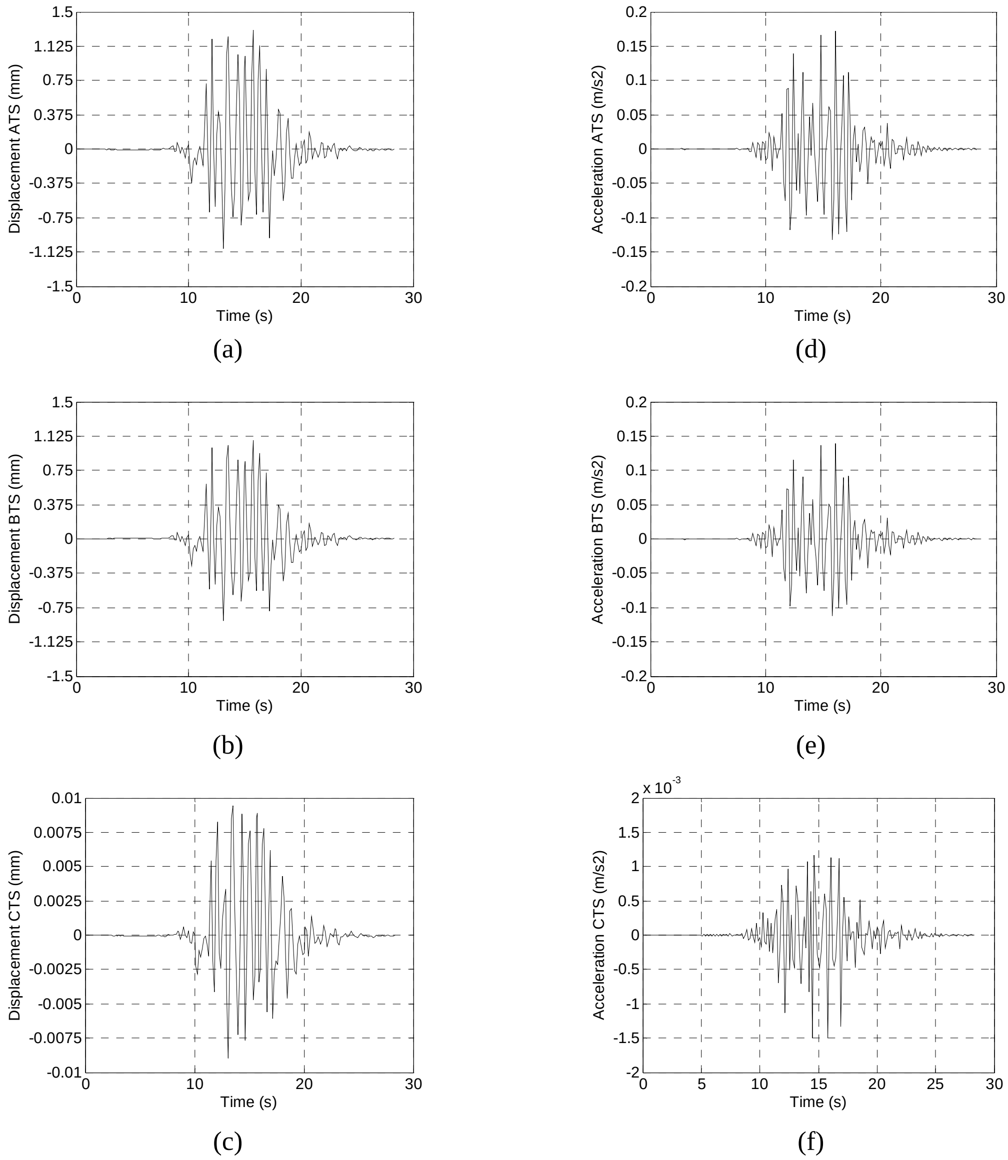


Fig. 8 (a), (b), (c) Lateral displacements and (d), (e), (f) Accelerations at the three selected nodes under the simulated signal based on Ain-Temouchent (with SMA wires)

- Under extraordinary dynamic horizontal actions (i.e., earthquakes stronger than the design earthquake), the stiffness of the device increases and thus prevents instability.

Note that the characteristics of the proposed (Cu-Al-Be) SMA wires are the same as the previously used in the laboratory tests by Casciati and Hamdaoui (2008) and Hamdaoui (2009).

Now, the gathered results, in term of maximum displacements and accelerations at the same selected nodes when using SMA dampers are presented in Table 3. The registered maximum displacement under the reduced Boumerdes action is around 3.1 mm (0.47 as acceleration max). It is still around 1.3 mm under the simulated Ain-Temouchent action (0.17 for the acceleration max).

Figs. 7 and 8 show lateral displacements and accelerations at the same nodes (*A*, *B* and *C*), respectively, under the 33% fraction of Boumerdes action and the simulated Ain-Temouchent signal when SMA ties are used as dampers.

4.3 Discussion of results

In term of maximum displacement, a reduction of 16.63% is seen under the 33% fraction action of Boumerdes earthquake (considered as a moderate intensity action), where it is almost 0.17% under the simulated signal from the aftershock of Ain-Temouchent seismic event (regarded as a low intensity action). As it is seen, the displacement's reduction is small in the first simulation and is neglected for the second one. To explain this result, it is important to recall that the "displacement reduction" is not the major criterion to see the effectiveness of the proposed device as for steel ties. The SMA wires, by their super-elastic ability allow this kind of displacements to permit the energy dissipation (Casciati and Faravelli 2008).

In term of maximum acceleration, an important reduction of 67.43% is registered under the Boumerdes fraction action, where it is only of 7.54% under the low action based on Ain-Temouchent earthquake. This result is justified by the basic behavior of SMA devices that, as mentioned in the sub-section 4.2, remain stiff as traditional steel ties do, not allowing significant displacements, under low intensity dynamic horizontal actions (as the simulated signal based on Ain-Temouchent action earthquake- PGA=0.024 g). But under higher intensity dynamic horizontal actions (as the moderate one of Boumerdes- PGA=0.11g) the stiffness of the device significantly decreases, allowing the minaret "controlled displacements", while the force remains in the plateau (almost constant). The reduction of 67.43% confirm that the behavior reduce the amplification of accelerations.

In the Fig. 9, a comparison between maximum displacements and accelerations at the node *A* under the 33% fraction of Boumerdes action is drawn for the two cases: before and after implementing SMA wires.

Additionally, a comparison based on the frequency contents (drawn via Matlab (2004)) for the two discussed situation (without, then with SMAs) could be represented in this sub-section.

Fig. 10(a) shows the detected frequencies as peaks in the case of Boumerdes dynamic action. The first, the fundamental frequency, (1.93 Hz) is a horizontal translational mode along y-axis, the second one (2.92 Hz) is also a horizontal translational mode but along x-axis, where the third one is a torsional mode with a frequency of 4.15 Hz. In Fig. 10(b), Ain-Temouchent action was so weak that the frequencies were not clearly detected. Recall that the engendered displacement from this dynamic action was only 1.3 mm. The peak in this graph (2.56 Hz) is only a medium between the first and second detected frequencies from Boumerdes action.

Now, and via the graphs in Figs. 11 and 12, a comparison between the periodograms drawn for the output signals from Boumerdes and Ain-Temouchent dynamic actions is presented. A different behavior of the minaret with SMA wires could be clearly observed.

Fig. 11 shows that the peaks representing the detected frequencies move to the right position confirming that the further added force from the SMA device increase the minaret's stiffness. The fundamental frequency shifts from 1.93 Hz to 2.29 Hz, where the second and the third move respectively from 2.92 Hz and 4.15 Hz to 3.49 Hz and 4.76 Hz. Additionally, the reduction, although small, of the peak ordinates seen when the SMA are mounted validates the minarets' retrofit process proposed by AlSaleh *et al.* (2011). In Fig. 12, the SMA effect is not considerably sensed because of the weakness of the applied dynamic action (Ain-Temouchent). Here, it is important to note that the proposed retrofit does not affect the response under events commonly occurring in the area, but provides the required protection under likely extreme shocks.

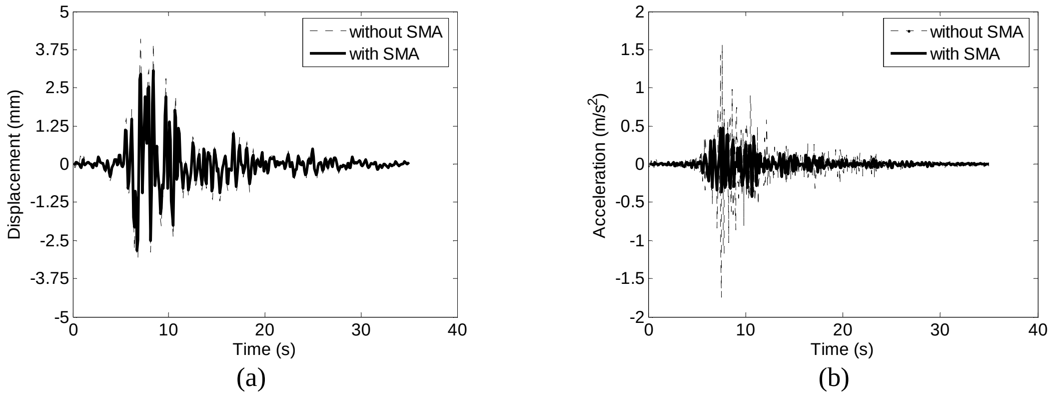


Fig. 9 Comparison between maximum (a) displacements and (b) accelerations at node A under the 33% fraction of Boumerdes action for the two cases

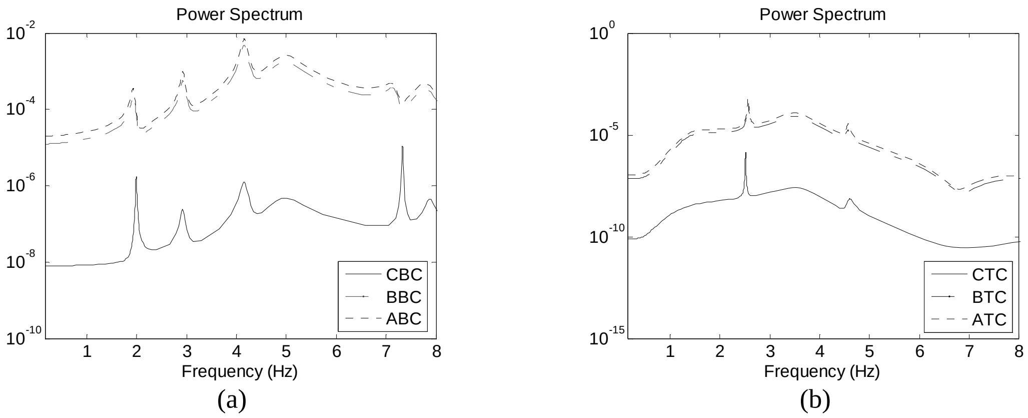


Fig. 10 Frequency contents for (a) Boumerdes action and (b) Ain-Temouchent simulated signal

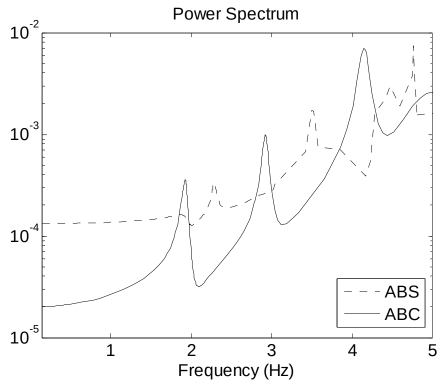


Fig. 11 Comparison between periodograms from Boumerdes action before and after adding SMA wires

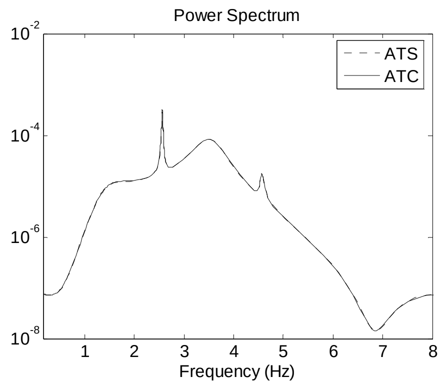


Fig. 12 Comparison between periodograms from Ain-Temouchent action before and after adding SMA wires

5. Conclusions

Numerical study on the dynamic behavior of a 13th century historical minaret before and after structural rehabilitation was investigated in this study. The proposed retrofitting technique is based on the use of Cu-Al-Be shape memory alloy wires as dampers for the seismic protection of the proposed model. The minaret was analyzed by applying, in the y-direction, the accelerograms records of two recent Algerian earthquakes; the action of the M=6.8 May 21, 2003 Boumerdes earthquake, then the synthetic accelerogram obtained using the Sabetta and Pugliese method by considering as source an aftershock of the M=5.7 December 22, 1999 Ain-Temouchent earthquake. Displacements and accelerations were computed and processed to extract the first three frequencies of the studied monument before and after mounting SMA ties. The results confirm the efficiency of the proposed device in mitigating likely extreme shocks by showing a reduction of accelerations, displacements and frequencies under the two dynamic records.

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