The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Diagnostics and Seismic Protection of a Historical Minaret using SMA Devices

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ABSTRACT

In the present paper, the results on the effectiveness of using an advanced seismic protection technology to preserve a historical minaret are investigated. The selected studied case, namely "the minaret of Mansourah", seen as the land mark of the city of Tlemcen (Algeria), is described via a geometric and material analyses. Moreover, an explanation of the rupture phenomenon that causes its half destruction is reviewed. Nowadays, the minaret's height reaches the 40m, while its original height was of 47m. A seismic retrofit technique of the selected structure is proposed based on the technique that utilizes the shape memory alloy (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 minaret model is analyzed by applying a fraction action of the M=6.8 May 21, 2003 Boumerdes earthquake, then the full action of the synthetic accelerogram obtained using the Sabetta and Pugliese method considering as source an aftershock of the M=5.7 December 22, 1999 Ain-Temouchent earthquake. The effectiveness of the proposed device in mitigation the seismic hazard is demonstrated by the effective reduction in its dynamic response.

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1. INTRODUCTION

The first minarets date back to the Umayyad period, around 45 years after the construction of the first mosque in the year 622. Since then, they became an important element of mosques in the Islamic architecture, because of 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 that is the pray time, five times a day.

Minarets may present several architectural forms depending on the period and the site of the construction. Old ones, as monumental structures, are usually built using traditional natural materials found in the area of their location. From the structural point of view, they are considered as thin and tall engineering structures built with techniques based on experience, without any special design. These structures are generally complex and are constructed with materials that have nonlinear behavior under heavy load (Wenzel 1999). In addition their structural behavior is considerably conditioned by a long history of damages.

Previous works by the first author constituted the experimental and numerical applications on Cu-based SMA for the retrofitting of historical monuments and as base isolation systems. Pre-tensioned SMA wires were, first, anchored on a scaled masonry wall model built by superposed bricks to reproduce the properties of a monumental structure (Casciati S and Hamdaoui 2008). Following the conclusions from this laboratory test, SMA ties were then inserted on a real monumental structure, the aqueduct of Larnaca in Cyprus (Chrysostomou et al. 2008). In an other application, Cu-based SMA bars were assembled in a suitable geometry creating an innovative base isolation system (Casciati et al. 2007) (Casciati F and Hamdaoui 2008). A prototype of the device was also built and experimentally tested on the shaking table.

In this study, the behavior of an old minaret is investigated, before and after being retrofitted using SMA dampers, via numerical analyses. The effectiveness of such retrofitting technique is assessed based on the load of two recent Algerian destructive earthquakes: (i) the May 21, 2003 Boumerdes earthquake (Bendimerad 2004) 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 STUDIED CASE

2.1 The site of Mansourah

The historic site of “Mansourah” (means “the victorious”), is one of the most remarkable monuments in the Algerian west. Founded by the Sultan Abu Yacoub in 1299, the city of Mansourah (Fig. 1) was constructed to compete the commercial pole of Tlemcen (Marçais 1950), that is around 4km away. Renowned for sumptuous palaces, shops, baths, beautiful gardens and its famous great mosque, it covered an area of 101 hectares and was completely surrounded by walls, where there are still a few remnants today.

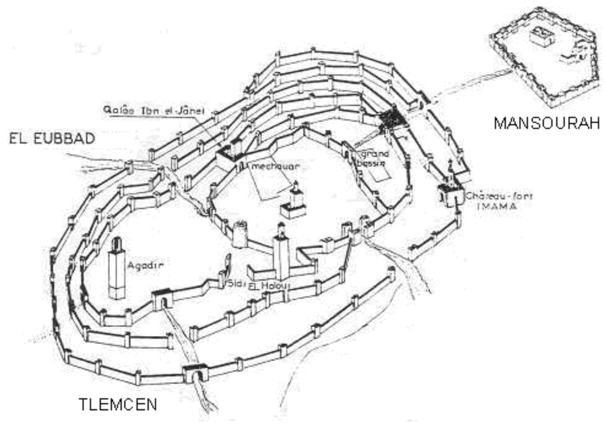


Fig. 1 The location of the city of Mansourah with the pole of Tlemcen (14th century)

The mosque of Mansourah (Marcais 1903) has an empty rectangle shape, where the enclosure, of 60m width and 85m length, is occupied by a central court. All what remain now are the walls around it with the leftovers twelve gates that pierced its enclosure, as well as the front half of its minaret. The main door of the mosque was pierced in the minaret (Fig. 2a), giving a peculiarity, not found in any other mosque of Tlemcen. 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. 2b).

(a) (b)

Fig. 2 Ruins of the mosque of Mansourah: (a) The minaret; (b) Traces of ramparts

2.2 The minaret of Mansourah

The principal figures of the minaret are:

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

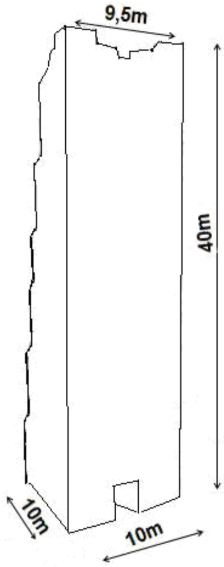


Fig. 3 Geometric characteristics of the minaret of Mansourah

Numerical modeling is nowadays considered indispensable to understand and simulate the mechanical structural behavior. In 2001, a virtual restoration of the studied minaret to its original state was performed in the University of Tlemcen (Kada 2001). Adopting this original configuration, the distinct element method, suitable for load-bearing masonry buildings, was used to model the ruin of the minaret (Kara Slimane 2005). This analysis leads 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).

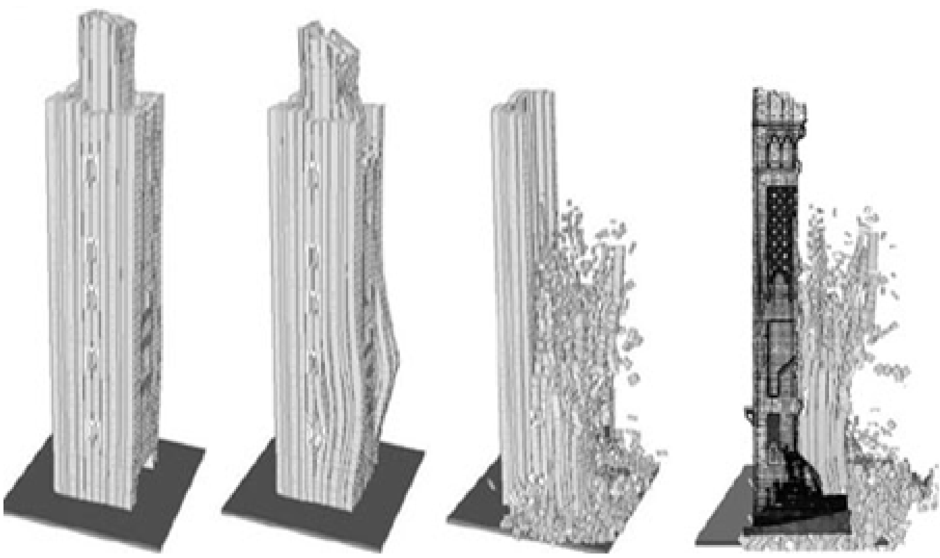


Fig. 4 Model of the minaret’s collapse (Kara Slimane 2005)

3. ORIGINAL FINITE ELEMENT MODEL

Three-dimensional 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 model.

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. The adopted mechanical stone and mortar properties are based on the literature survey and existing reports as shown in table 1 (Harbit 2005) (Kara Slimane 2005).

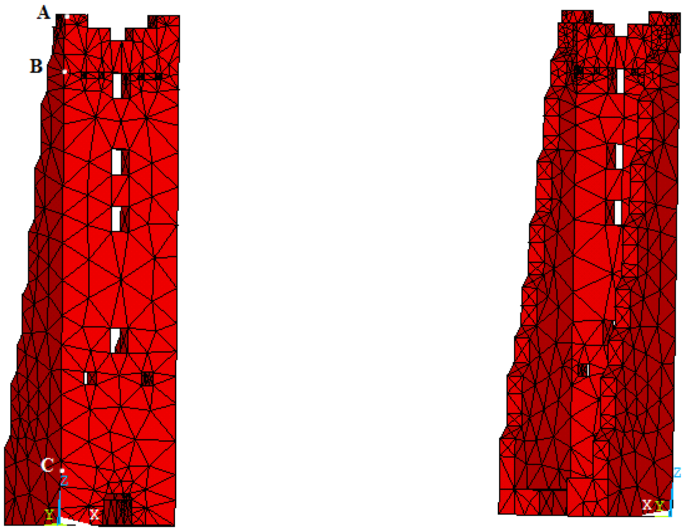
It is important to note that the best way to create a realistic finite element model of the studied structure is by conducting ambient vibration tests on the selected minaret (Wenzel and Pichler 2005; El-Attar et al. 2006; Hamdaoui 2006; Bani-Hani et al. 2008; Chrysostomou et al. 2008). The structural modal characteristics (mode shapes, natural frequencies) could be easily determined by Fourier analysis of ambient noise recorded by accelerometers installed at strategic locations (Dusi et al. 2007) with the relevant advantage to obtain information about the structure's state of damage without destructive experiments (that by-the-way are not allowed on historical monuments).

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. 5 shows the obtained finite element model: the mesh consists on a total of 3044 solid elements and 1037 nodes.

Following the modal dynamic analysis, the natural frequencies and periods of the main modes of vibration are determined. The first one, 0.493s of period, is a horizontal translational mode along y-axis, the second mode, period of 0.447s, is also a horizontal translational mode but along x-axis, where the third one is a torsional mode with a period of 0.083s.



(a) (b)

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

4. DYNAMIC ANALYSES OF THE MINARET

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

1. The May 21, 2003 Boumerdes earthquake (PGA=0.34g): by applying a 33% fraction action of its accelerogram (Fig. 6), recorded at Kaddara station at an epicentral distance of 20km. 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=0.059g): 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) consistent with this aftershock (Fig. 7). 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.

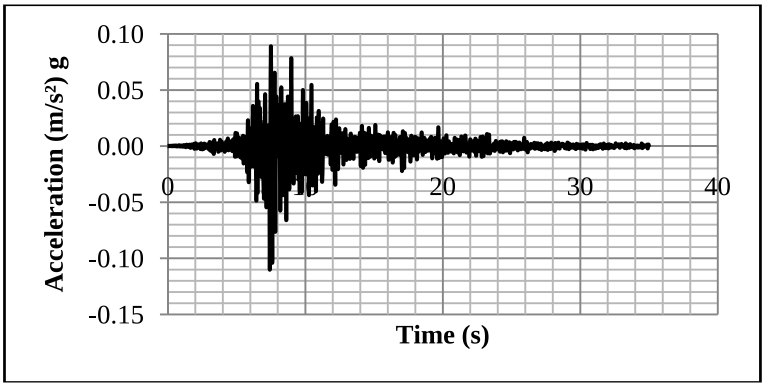


Fig. 6 Accelerogram record of the 33% fraction of Boumerdes earthquake (PGA=0.11g)

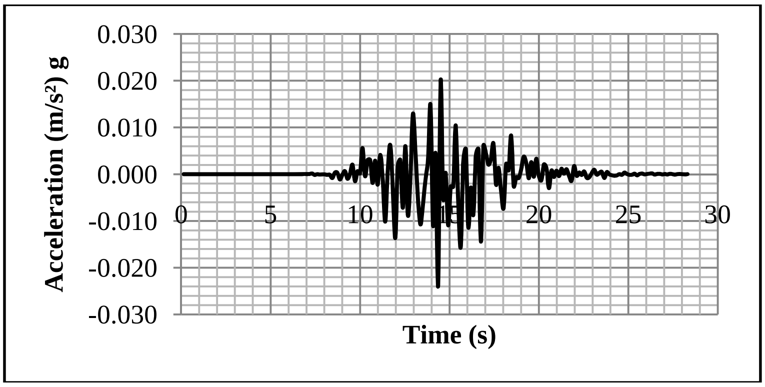


Fig. 7 Simulated signal from an aftershock of Ain-Temouchen earthquake (PGA=0.024g)

4. 1 The Minaret Before Retrofitting

In the following section, the results when analyzing the minaret in its current virgin state are reported. The maximum displacements and accelerations of three selected nodes *A*, *B* and *C* (Fig. 5a) are shown in table 2, for the two selected dynamic action. It is seen that the maximums (either for displacement or acceleration) are reached at note *A*, situated at 40m of height. The registered maximum displacement is around 4.1mm under the 33% fraction of Boumerdes action, where it reaches only 1.3mm when the analysis is drawn based on Ain-Temouchent action. For the maximum acceleration, it is 1.75m/s^2 under the first dynamic action and only 0.18m/s^2 under the second one.

Figs. 8 to 11 show the lateral displacement and acceleration at the node *A*, under the 33% fraction of Boumerdes action and the simulated signal based on Ain-Temouchent action, without using SMA wires.

Table 2 Maximum displacements and accelerations for specific nodes before retrofitting

Nodes	*Boumerdes*		*Ain-Temouchent*	
	Max Disp (mm)	*Max Acc (m/s²)*	*Max Disp (mm)*	*Max Acc (m/s²)*
A	4.1070	1.7489	1.3099	0.1818
B	3.2960	1.4272	1.0728	0.1495
C	0.0349	0.0270	0.0093	0.0016

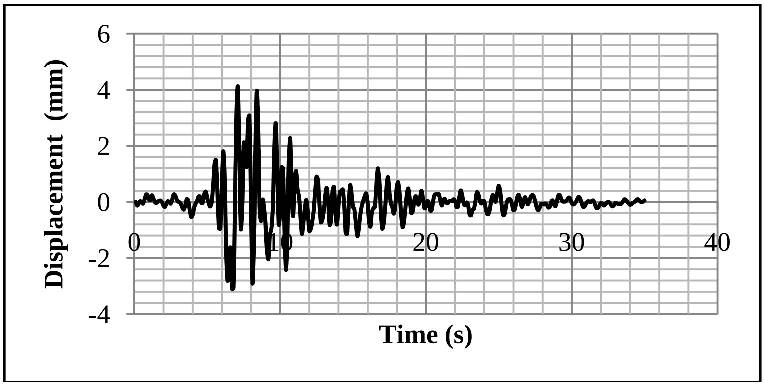


Fig. 8 Lateral displacement at node *A* situated at *40m* under the 33% fraction of Boumerdes action (without SMA wires)

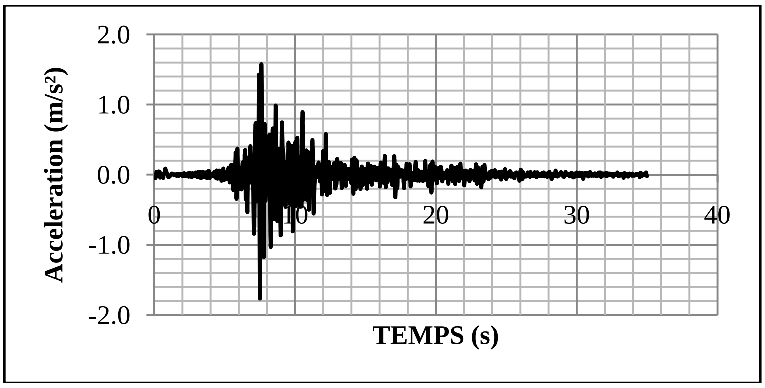


Fig. 9 Acceleration at node *A* situated at *40m* under the 33% fraction of Boumerdes action (without SMA wires)

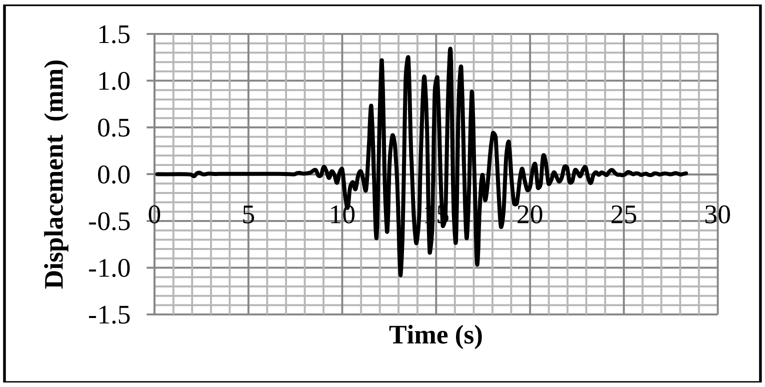


Fig. 10 Lateral displacement at node *A* situated at *40m* under the simulated signal based on Ain-Temouchent action (without SMA wires)

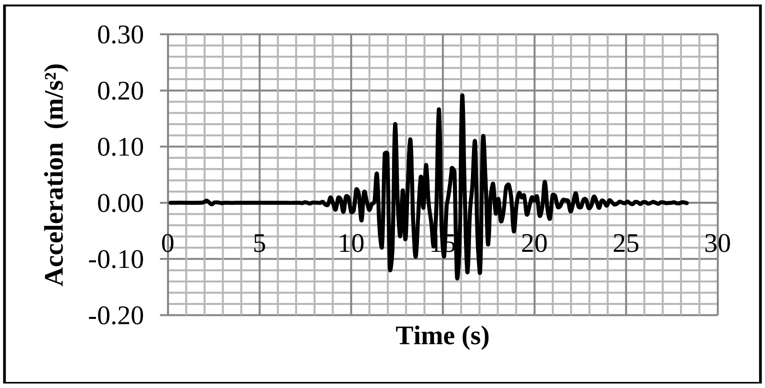


Fig. 11 Acceleration at node *A* situated at *40m* under the simulated signal based on Ain Temouchent action (without SMA wires)

4. 2 The Minaret after being Retrofitted

The proposed seismic retrofit technique of the selected structure 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, previously detailed in section 3, is modified by inserting five SMA wires of 3.5mm diameter and 1m length. These ties are assembled with the minaret's stone using *L* shape steel angles.

In its loading-unloading stress-strain curve (Fig. 12a), the SMA material is first loaded (*ABC*), showing a nonlinear behavior. Then, when unloaded (*CDA*), the reverse transformation occurs. This behavior is hysteretic with no permanent strain (Auricchio et al. 1997). The basic idea under the proposed technique is to connect part of the minaret elements by SMA devices 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;
- Under extraordinary dynamic horizontal actions (i.e. earthquakes stronger than the design earthquake), the stiffness of the device increases and thus prevents instability.

The characteristics of the proposed (Cu-Al-Be) SMA wires, to be used in the material ANSYS model, are the same as the previously used in the laboratory tests in (Casciati F and Hamdaoui 2008, Hamdaoui 2009). They are (Fig. 12b):

- E = 60 000 MPa (linear elastic modulus of elasticity of the SMA in the austenite phase);
- υ = 0.3 (Poisson’s ratio);
- C_1 = 140 MPa (starting stress value for the forward phase transformation);
- C_2 = 270 MPa (final stress value for the forward phase transformation);
- C_3 = 200 MPa (starting stress value for the reverse phase transformation);
- C_4 = 70 MPa (final stress value for the reverse phase transformation);
- C_5 = 0.03 (maximum residual strain);
- C_6 = 0.27 (parameter accounting the different responses in tension / compression);
- C_7 = 20 000 MPa (modulus of elasticity of the SMA in the martensite phase).

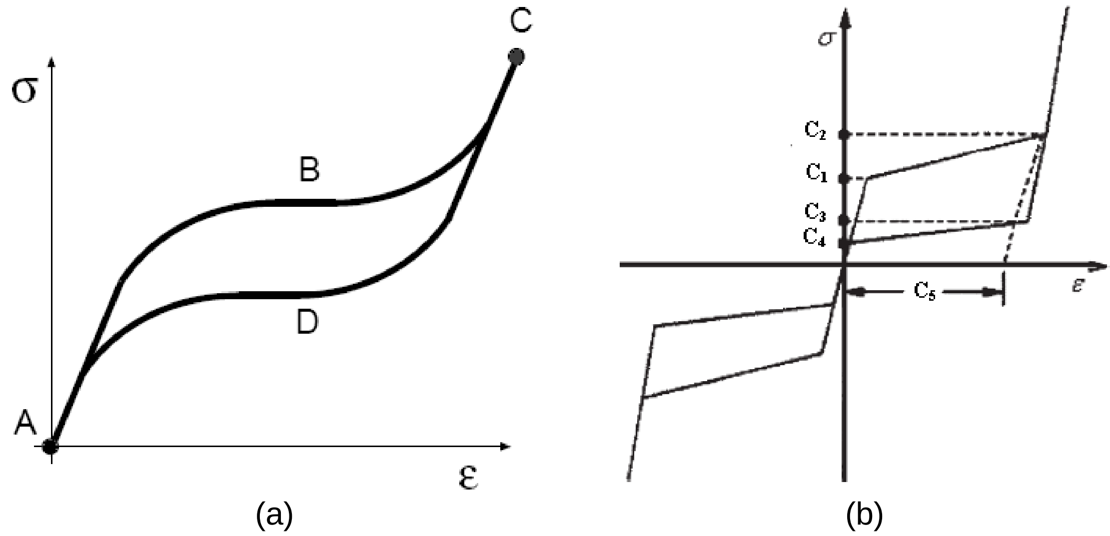


Fig. 12 (a) Typical and (b) idealization of the super-elasticity behavior of SMA

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

Figs. 13 to 16 show the lateral displacement and acceleration at the node *A*, under the 33% fraction of Boumerdes action and the simulated signal based on Ain-Temouchent action, when using the SMA ties as dampers.

Table 3 Maximum displacements and accelerations for specific nodes after retrofitting

Nodes	*Boumerdes*		*Ain-Temouchent*	
	Max Disp (mm)	*Max Acc (m/s²)*	*Max Disp (mm)*	*Max Acc (m/s²)*
A	3.0682	0.4749	1.3009	0.1722
B	2.5130	0.3875	1.0684	0.1393
C	0.0345	0.0117	0.0089	0.0015

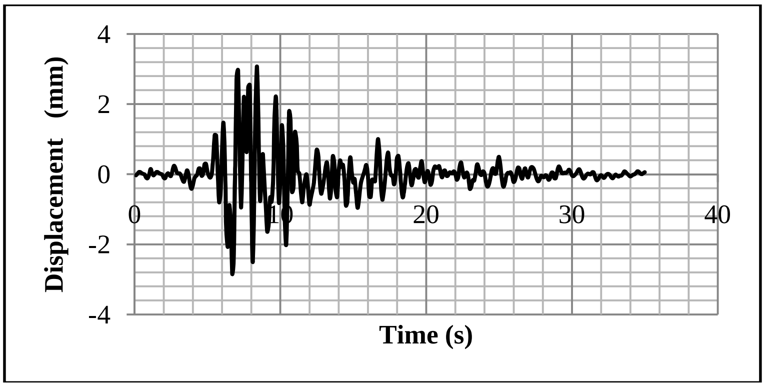


Fig. 13 Lateral displacement at node *A* situated at *40m* under the 33% fraction of Boumerdes action (with SMA wires)

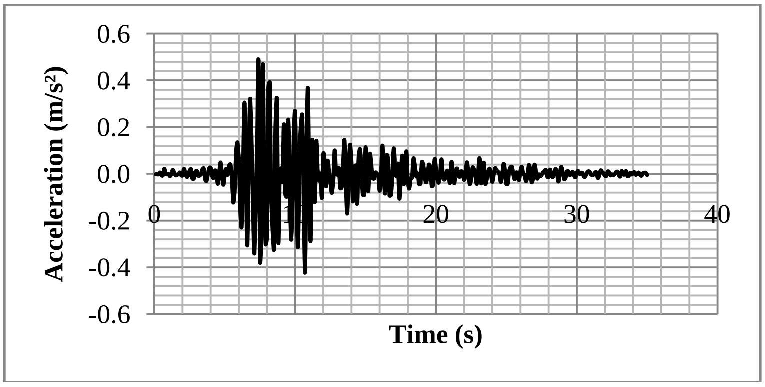


Fig. 14 Acceleration at node *A* situated at *40m* under the 33% fraction of Boumerdes action (with SMA wires)

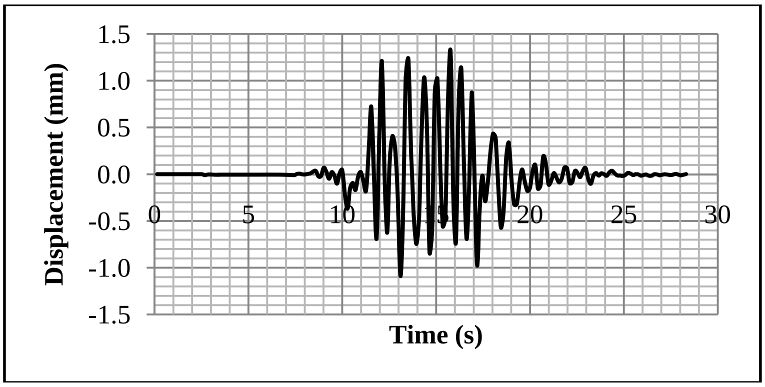


Fig. 15 Lateral displacement at node *A* situated at *40m* under the simulated signal based on Ain-Temouchent action (with SMA wires)

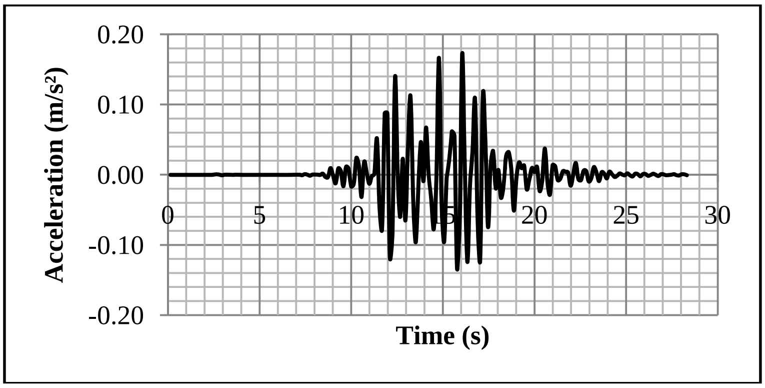


Fig. 16 Acceleration at node *A* situated at *40m* under the simulated signal based on Ain-Temouchent (with SMA wires)

4. 3 Discussion of the 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.

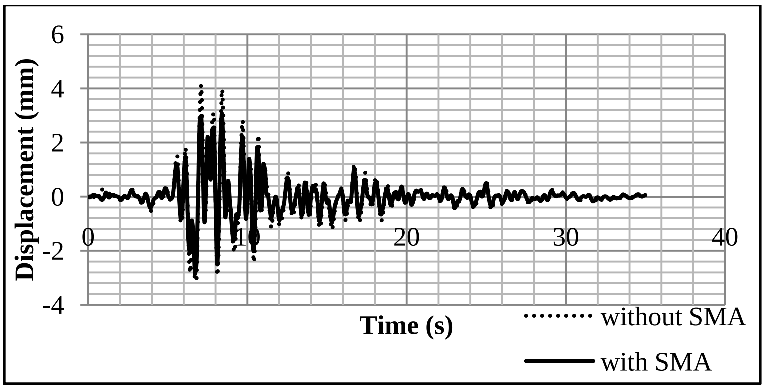


Fig. 17 Comparison of maximum displacement at node *A* under the 33% fraction of Boumerdes action with, and without the SMA wires

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 Fig 12a, 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=0.024g). 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, as mentioned in the sub-section 4.2, the behavior reduce the amplification of accelerations.

It would be appreciated to confirm this result by seeing the structural behavior of the minaret when the SMA wires are replaced by steel ties, either for displacements of acceleration, as done in the thesis by Hamdaoui (2009).

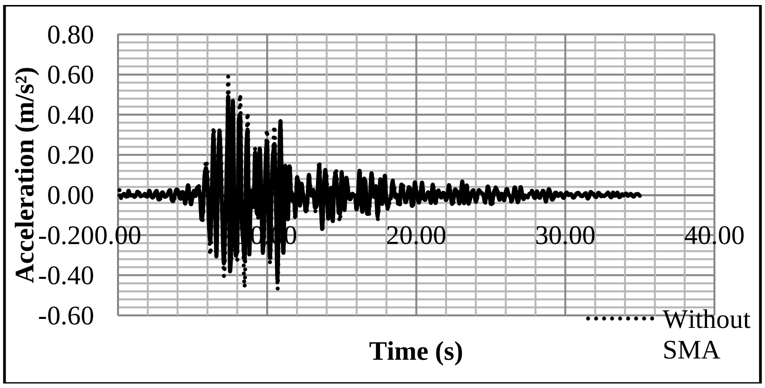


Fig. 18 Comparison of maximum acceleration at node *A* under the 33% fraction of Boumerdes action with, and without the SMA wires

5. CONCLUSION

The retrofitting technique, based on the use of Cu-Al-be shape memory alloy wires as dampers, is presented for the seismic protection of a 13^{th} century historical minaret in Tlemcen, Algeria. The results confirm the efficiency of the proposed device when being evaluated under the fraction action of Boumerdes earthquake, and the full action of the synthetic accelerogram obtained using the Sabetta and Pugliese method considering as source an aftershock of Ain-Temouchent earthquake. It is shown that the applied SMA device behaves correctly as its constitutive low and reduces significantly the dynamic response of the studied structure.

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