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Comparative Study of Seismic Analysis for Reinforced Concrete Frame Infilled with Masonry and Shape Memory Alloy Wire

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ABSTRACT
Finite Element Method (FEM) analysis was implemented to investigate and compare the performance of a reinforced concrete bare frame, infilled with and without straw bale wall and Shape Memory Alloy (SMA) diagonal wires, subjected to seismic loads and earthquake ground excitations. Equivalent lateral force (static), response spectrum and time history method of seismic analysis were embarked upon to determine the frame capacities, investigate their failure mechanisms and compare their residual and inter storey drift with one another. Also their respective maximum storey displacements have been graphically presented alongside with moments and shear forces. It has been observed from this analysis that under the lateral force, bare frame and straw bale wall infill experienced Maximum Top Storey Displacements (MTSD) of 55.63 and 55.61 mm, respectively. The maximum storey displacement was reduced to 11.19 mm with the application SMA as a concentrically brace members which give 79.8% reduction in the maximum storey displacement. Under UBC97 spectrum, the maximum top storey displacement reduced by 47.3, 52.4 and 73.5% for straw bale wall, SMA brace frame and SMA-straw bale frames respectively. Under Elcentro earthquake ground excitation, the maximum top storey displacement reduced by 0.02, 7.5 and 78.9% for straw bale wall, SMA brace frame and SMA-straw bale frames, respectively. From the results of the analysis, the displacement of the frame is drastically reduced by a concentric application of SMA wires in the frame. The computed force-deformation response used to assess the overall structural damage and its distribution was found to have a sufficient degree of accuracy.

Key words: Shape memory alloy, reinforced concrete frame, seismic analysis, displacement, straw bale

INTRODUCTION
The application of modern control techniques to diminish the effects of seismic loads on building structures offers an appealing alternative to traditional earthquake resistant design approaches. Over the past decade there has been significant research conducted on the use of damper devices for dissipating seismic energy. Recently many investigations have been conducted to evaluate and analyze the seismic response of structures equipped different types of damper. Viscous dampers and other active control measures (Adedeji, 2006b) are known as effective energy dissipation devices improving structural response to earthquakes. The damping force developed by the viscous damper depends on the physical properties of the fluid used in the device (Semih and Ahmet, 1992).

In the other hands, the role of viscous damping in preventing buildings from collapse during intense earthquake ground motion was extensively investigated by using numerical modeling (Adedeji, 2006a, 2008; Jinkoo and Sunghyuk, 2002). Also some numerical studies were performed to evaluation influence of structural passive supplemental damping systems on structural and nonstructural seismic fragilities of buildings. Comparison of the fragility on building with and without passive control systems indicated that the viscous dampers are very effective in attenuating seismic structural response (Providakis, 2008). Due to the widespread technique for computer simulation and analyzing of structures with supplemental dampers subjected to steady-state excitation is direct integration technique which is generally implemented in finite element method (Diclelia and Mehta, 2007).

The aim of this project therefore was to investigate the application of shape memory alloy wire in seismic control of a framed building as a concentric brace element in a reinforced concrete frame building to reduce the maximum storey displacements. A nonlinear Finite Element Method (FEM) analysis were implemented to investigate and compare the performance of a reinforced concrete bare frame infilled with and without straw bale wall and combination of SMA and straw bale wall under seismic loads and earthquake ground excitations.

Equivalent lateral force (static), response spectrum and time history method of seismic analysis were embarked upon to determine the frame capacities, investigate their failure mechanisms and compare their residual and inter storey drift with one another. Also their respective maximum storey displacements have been graphically presented alongside with moments and shear forces.

Some recent devastation effects and mode of failures of earthquake on buildings are shown in Fig. 1 and 2.

Fig. 1: Collapsed buildings after a magnitude 6.9 earthquake, in Yushu County, April 14, 2010. Source: REUTERS/CCTV

Fig. 2: A destroyed building after an earthquake at Jiegu Town, of Yushu Source (AP Photo/Xinhua, Wu Hong)

SHAPE MEMORY ALLOY (SMA)

Shape Memory Alloys (SMAs) are unique materials that have the ability to undergo large deformation and return to a predetermined shape upon unloading (Dolce *et al*., 2004). The distinct and unique properties of SMAs have been used in a wide variety of applications in different fields and industries such as aviation, medical equipment and implants (Dolce *et al*., 2004). SMAs are gradually gaining recognition and finding new applications in various engineering fields. Recent experimental and numerical investigations have also demonstrated numerous possibilities of utilizing SMAs in civil engineering structures to protect buildings and bridges against earthquakes (Dolce *et al*., 2004; Salichs, 1996).

Seismic analysis methods: Linear elastic analysis of building structures can be performed by using static or dynamic approaches. Briefly, static analysis is performed by considering the building structure as stationary and the loads acting on the structure as constant and not time dependent. The equivalent lateral force method, which is recommended by most of the earthquake codes (UBC, 1997), is a static method widely used in the elastic analysis of multi-storey structures subjected to earthquake loads. In contrast to static analysis, dynamic analysis is based on the behavior of the structural system in a time domain. The modal superposition method and the time history method are the dynamic analysis methods most commonly suggested by earthquake codes.

These three methods (the equivalent lateral force method, the modal superposition method and the time history method) are summarized in the following sections.

Equivalent lateral force analysis method: This method is used to determine the first natural vibration period; the total equivalent seismic load; design seismic loads acting at storey levels; points of application of design seismic loads and analysis of the structural system.

Modal superposition analysis method: This method involves selection of design spectrum; determination of mode shapes and periods of vibration; determination of the level of response from the design spectrum for the period of each of the modes considered; calculation of the participation of each mode corresponding to the single degree of freedom response read from the curve; addition of the effects of modes to obtain combined maximum response; conversion of combined maximum response into shears and moments and analysis of the building for resulting moments and shears in the same manner as in static loads.

Time history analysis method: This is by selecting the earthquake record, digitizing the record as a series of small time intervals; setting up of the mathematical model of the structure; the application of the digitized record to the model and determination of the maximum member stresses by using the output records.

Equivalent lateral force analysis method procedure: This method is used to determine the first natural vibration period; the total equivalent seismic load; Design seismic loads acting at storey levels; points of application of design seismic loads and Analysis of the structural system.This method is based on the characteristic properties of the earthquake as represented by the acceleration spectra determined (Adedeji, 2010; Lap-Loi *et al*., 2009; Adedeji, 2006c) based on past earthquake for undamped one-mass systems with varying fundamental periods T. The procedure of lateral force calculation is outlined as follows;

Total lateral force: Every building shall be constructed to withstand minimum total lateral forces, determine independently in the direction of the principal axis of the building as given by the formula:

$$V = C\,W \tag{1}$$

Where:
V = Total lateral force or shear at the base
W = Total weight of the building above the base, including dead load and live load
C = Numerical coefficient which is defined empirically as:

$$C = \frac{0.015}{T} \tag{2}$$

where, Period T is the fundamental period of vibration of the building in seconds in the direction considered and is,

$$T = \frac{0.05H}{\sqrt{b}} \tag{3}$$

where, H is the total height of the building and b is the width of the building along the considering directions. The weight W of the building includes all the dead load plus Live load for the floors and no Live load for the roof.

Applied lateral forces: The total lateral force V is distributed over the height of the building in accordance with the following formula:

$$F = Vw\frac{h}{\Sigma(wh)} \tag{4}$$

Where:
F = Lateral force applied at any level x
w = Weight at level x
h = Height of level x above the base, wh is the summation of the products wh for the structure under consideration

METHODOLOGY

The Reinforced Concrete (RC) frame and its modelling: A three-storey RC moment resisting frame has been selected in this study since it has been observed that medium rise RC buildings are particularly susceptible to damage during earthquakes (Bariola, 1992). The building has been designed accordance with Uniform Building Code (UBC, 1997) assuming that it is located in the seismic western part of Canada on firm ground with un-drained shear strength of more than 100 kPa. The elevation and plan of the building are shown in Fig. 3 and its material properties

Table 1: Material properties used in the finite element program

Material	Property	Value
Concrete	Compressive strength	30 N mm^{-2}
	Density	24 kN m^{-3}
	Modulus of elasticity	210×10^{6} kN m^{-2}
	Poisson's ratio	0.2
	Tensile strength	3 N mm^{-2}
Shape Memory Alloy (SMA)	Density	64.5 kN m^{-3}
	Modulus of elasticity	75×10^{6} kN m^{-2}
	Poisson's ratio	0.3
	Damping capacity	0.05 (5%)
	Diameter (used)	50 mm
Straw Bale Wall	Density	1.3 kN m^{-3}
	Modulus of elasticity	13.333 kN m^{-2}
	Poisson's ratio	0.12
	Thickness (used)	250 mm

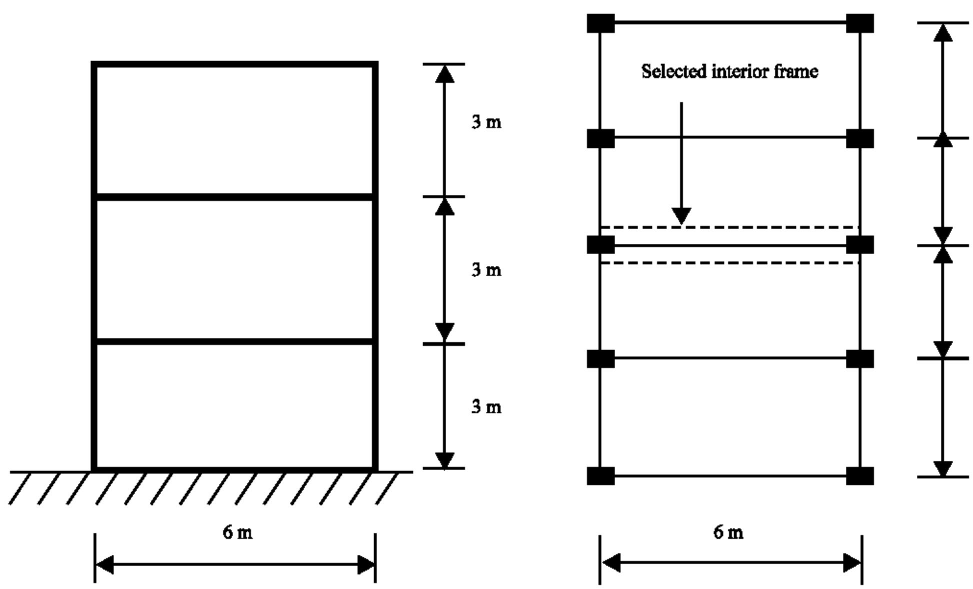

Fig. 3: The RC framed structure, (a) elevation and (b) plan

used in the finite element program are shown in Table 1. The design PGA is 0.1 g (UBC,1997) and the moment frames are designed assuming a moderate level of ductility.

Different frame modelled arrangements: Figure 4 shows the various RC frame model configurations used in the analysis. Frame 1 contains bare frame (without an infill element) as shown in Fig. 4a. In Frame 2 the frame is attached with diagonal (Adedeji and Ige, 2003; Adedeji, 2003) wires of Shape Memory Alloy (SMA) as shown in Fig. 4b. Frame 3 contains a straw bale infill frame as shown in Fig. 4c while Frame 4 shown in Fig. 4d is composed of straw bale and SMA.

Analysis simulation using SAP 2000: SAP2000 software had been found worthy and better in term of dynamic and static analysis of structures based on the following points:

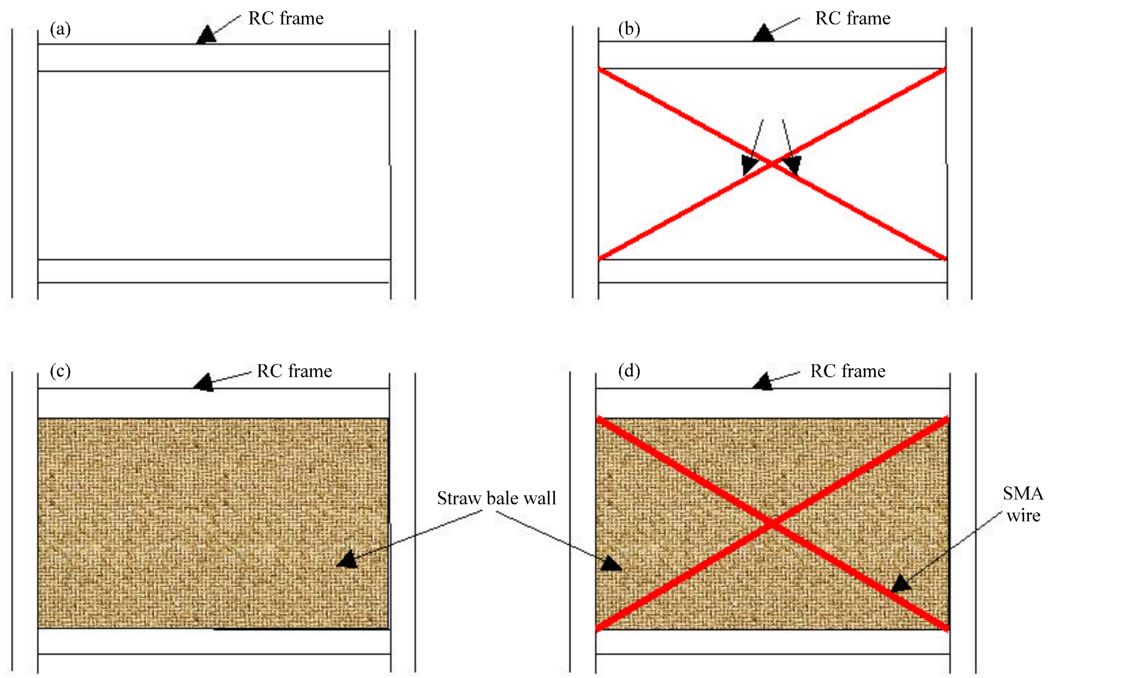

Fig. 4: Arrangement of the frames used in analyses, (a) Bare frame (frame 1), (b) frame with SMA wire brace (frame 2), (c) Straw bale infill frame (Frame 3) and (d) SMA with straw bale infill frame (frame 4)

- It has in-built ground motion records which other software do not possessed
- It is versatile in handling various types of analysis either linear or non linear
- It is one of the software that has the best user friendly graphical interface
- It possessed numerous code of practice (standards) used through out the world such codes include; British codes, Universal Building Code, Canadian Code and American Building Codes
- It had been certified by several professionals through-out the world to be one of the best dynamic analysis packages, if only the steps involved are properly followed
- The analysis procedure can be divided into three folds: Preprocessing-Solving-Post processing

Analytical model for the ground motion records: There are many earthquake records, but in this project the Elecentro earthquake record of 1946 was employed because it was the one of the highest magnitude that has ever been recorded with a magnitude 9.2. In lieu of this, the record was employed to know the worst conditions of failures that may be experienced on the building and also to know the efficiency of the various frame arrangements in Fig. 4. In Fig. 5 however, the input data relating to the time against ground acceleration of Elcentro earthquake of 1946 was plotted.

RESULTS OF THE ANALYSIS

In Fig. 6 the loading arrangement of the building is shown. The uniformly distributed load on the beams were derived based on the dead and live loads of the building using ultimate limit analysis design and the lateral forces are derived from equivalent lateral earthquake force

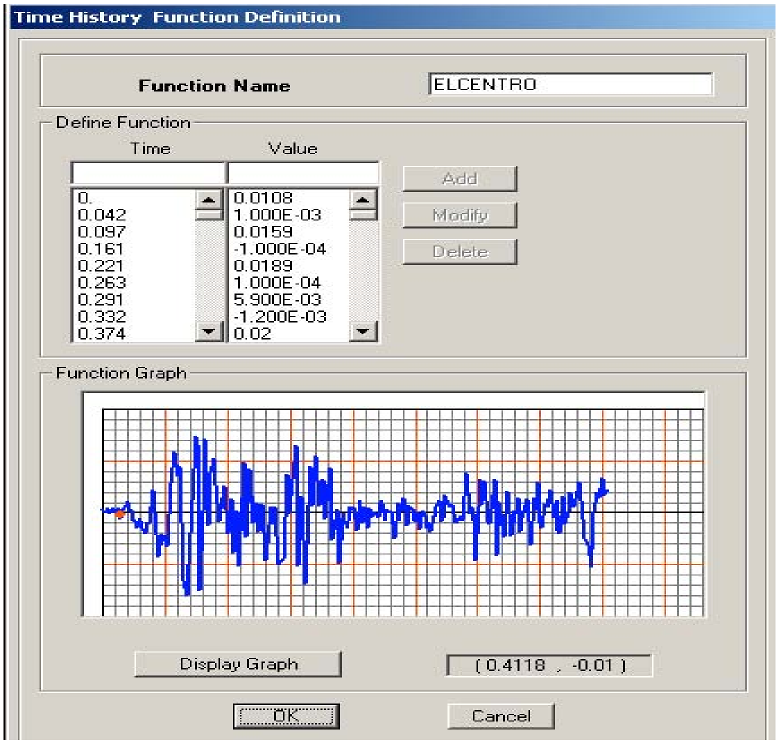

Fig. 5: Ground acceleration time history of elcentro scaled to 0.1 g

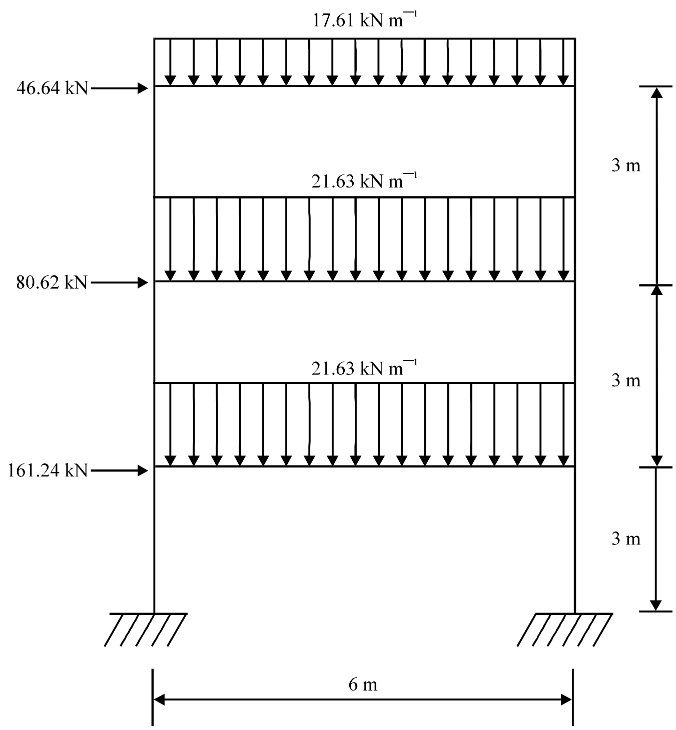

Fig. 6: Loading arrangement of the model

procedure stated in section two of this abstract. The lateral force at each floor is equivalent to the shear force at each floor.

DEFORMATION OF THE FRAME

In Fig. 7 and various modes of failure experienced on the building due to the ground excitation are shown.

Figure 8-10 show the summary of inter storey displacements under static analysis, response spectrum analysis and time history analysis respectively.

DISCUSSION OF RESULTS

The results of static, response spectrum and time history analyses of a frame structure under different configuration are discussed here. A case study on the static and dynamic analyses of four frames under Elcentro earthquake ground motion were presented and critically analysed to determine the performance of individual frame members In terms of maximum floor displacements. The assessment of effectiveness of SMA wire as a concentrically brace element in a frame was particularly investigated.

Case study 1: Static analyses of the frames: This section presents the results of the static analyses of Frames 1 to 3. It can be observed that under the lateral force, Frame 1 (bare frame) and

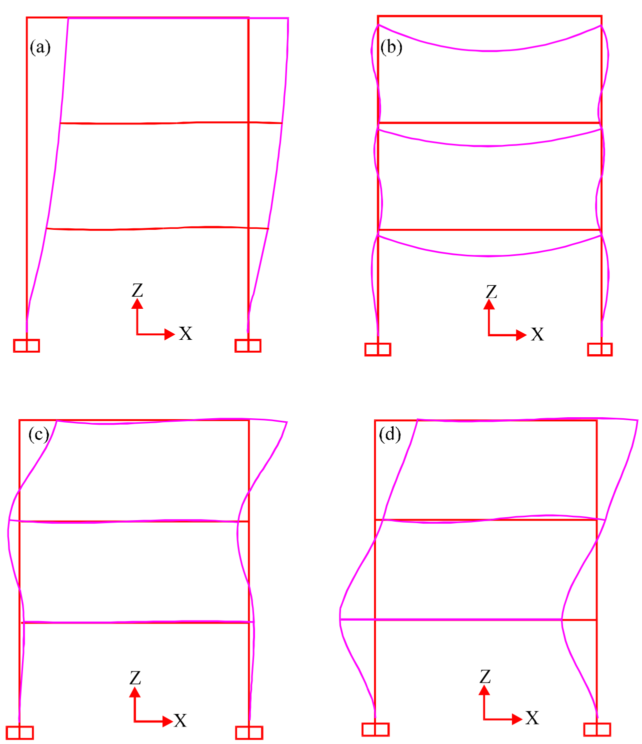

Fig. 7: Modes of deformations of the frame under the ground excitation, (a) Sway deformation due to lateral forces, (b) bending deformation due to vertical load, (c) Sway/vertical deformation at upper floor and (d) Sway/vertical deformation all floors

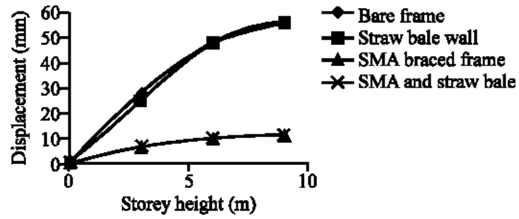

Fig. 8: Comparison of all frames under static analysis

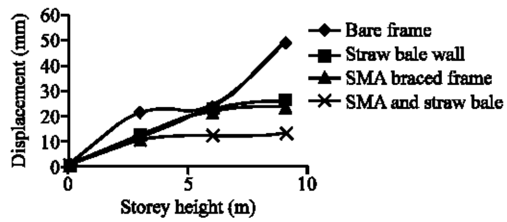

Fig. 9: Comparison of all frames under response spectrum analysis

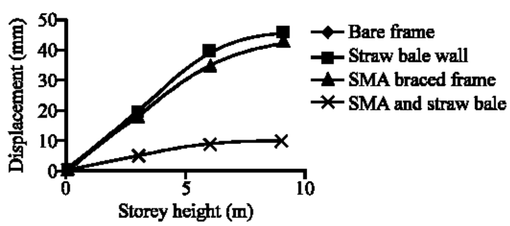

Fig. 10: Comparison of all frames under time history analysis

Frame 2 (straw bale wall infill) experienced Maximum Top Storey Displacement (MTSD) of 55.63 and 55.61 mm, respectively. The maximum storey displacement reduced to 11.19 mm with the application SMA as a concentrically brace members which give 79.8% reduction in the maximum storey displacement.

Case study 2: Response spectrum analyses of the frames: Presented here are the results of response spectrum analyses of the frame under considerations. At the top storey, the maximum displacements exhibited by the frame under different frame configurations have been observed that under UBC97 spectrum, the maximum top storey displacement reduced by 47.3, 52.4 and 73.5% for straw bale wall, SMA brace frame and SMA-straw bale frames respectively.

Case study 3: Time history analyses of the frame: The results of the frame under time history analyses method show that the maximum top storey displacements exhibited by the frame under different frame configurations, under Elcentro earthquake ground excitation, was reduced by 0.02, 7.5 and 78.9% for straw bale wall, SMA brace frame and SMA-straw bale frames, respectively. Figure 11-13 show the displacements at each floor against time under time history analysis of Elcentro ground excitation.

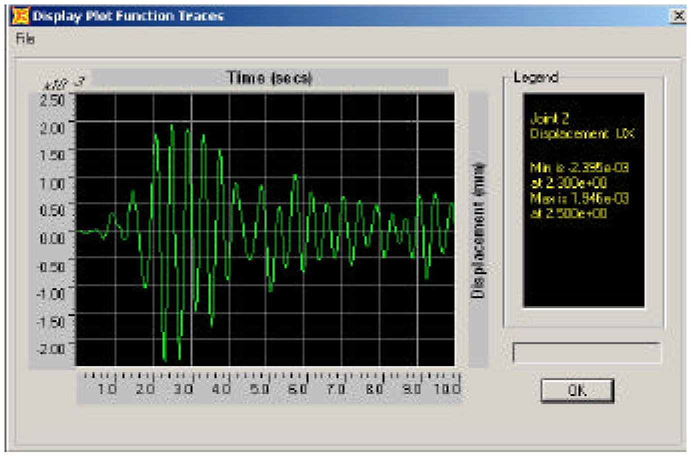

Fig. 11: Displacement-time graph at first floor

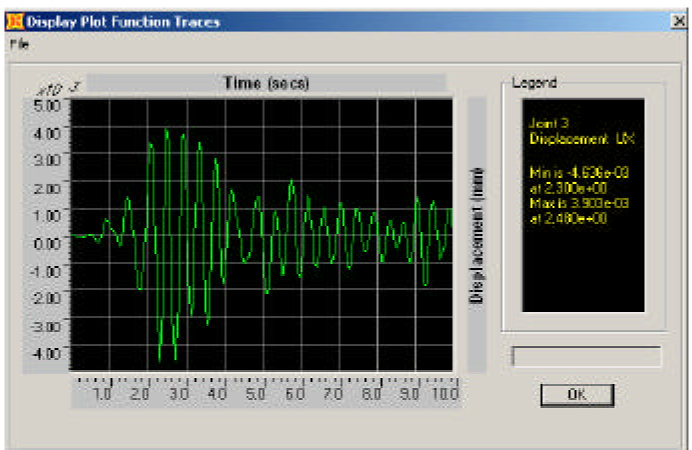

Fig. 12: Displacement-time graph at second floor

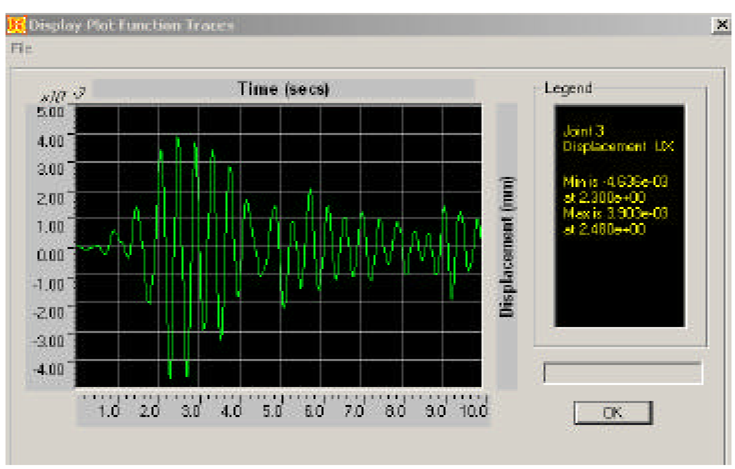

Fig. 13: Displacement-time graph at the roof level

CONCLUSIONS

From the results of the analysis, the following conclusions are drawn:

- The displacement of the frame has been drastically reduced by a concentric application of shape memory alloy wire in a reinforced concrete frame in a seismic prone area
- Though, under time history analyses method, the maximum top storey displacements exhibited by the reinforced concrete frame with the straw bale infill has insignificant effect, the use of Shape Memory Alloy wires in conjunction with straw bale wall is effective
- The computed force-deformation response can be used to assess the overall structural damage of a structure with the composition of the SMA and its distribution to a sufficient degree of accuracy

RECOMMENDATION

Further work is to be carried out with the use of small-scale shake table test to present a proof of the concept of this study on a seismic performance of a SMA cross-bracing system in a frame building with the straw bale and other sustainable masonry infill materials. Also other form of SMA arrangement should be examined to check their efficiency with the cross-bracing system used in this analysis for other frame materials (wood, plastic etc.).

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