PARAMETRIC STUDY ON THE NONLINEAR DYNAMIC BEHAVIOR OF BASE ISOLATED REINFORCED CONCRETE PLANE FRAME

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ABSTRACT:

This paper present a theoretical study of base isolation effects on the dynamic response of reinforced concrete plane frames with infilled panels which were considered as plane concrete shear walls under the effect of two different earthquakes motions. Three reinforced concrete plane frames where considered in this study with different aspect ratios (height of the building to its width), the first frame consist of a two span and two story building (Aspect ratio =1.0), the second frame consist of a two span and three story building (Aspect ratio =1.5), and the third frame consist of a two span and four story building (Aspect ratio =2.0), the span and height of the story is equal to (4.0m). The analysis where carried out by finite element method using a developed FORTRAN 77 program. The nonlinear behavior of the frame elements; beam column elements, are considered in terms of the yield function defined by the member capacity under the effects of bending-axial loading condition considering the shear failure as a separate failure criteria. The infilled panel was modeled by plane stress four nodes elements and nonlinear behavior of these infilled panel was included by considering cracking and failure under biaxial state of stresses. It was concluded that using base isolation instead of fixed foundations led to a relatively better response of the frame in terms of lateral drift and residual displacements, and that using the infilled panel caused a significant reduction in the lateral drift of the frames having different height to width ratio.

KEYWORDS: Base isolation, dynamic, frame, infill, non-linear.

1. INTRODUCTION

Base isolation is an effective strategy to protect structural and non-structural elements from the effect of seismic loads, by controlling the displacements and accelerations in the structure. This is achieved by reducing the forces in the structural elements and maintaining them in the elastic state and minimizing the damage in non-structural elements. Base isolation is a technique in which the base isolators are installed in the foundation of structure to reduce the damage due to motion that earthquakes may cause. An isolation system consist of thin sheets of rubber bonded to steel plates, therefore it provides suitable vertical rigidity to carry up the vertical and gravitational loads from the structure and gives horizontal flexibility that allows the structure to shift the fundamental frequency of the isolated structure away from the dominant frequency range of most earthquakes, as well as energy dissipation due to relatively high hysteresis damping. The present work add the effect of non-linear behavior of both reinforced concrete frame members and infilled panels on the earthquake response of base isolated reinforced concrete plane frames having different height to width ratios.
However, most studies carried out by structural engineers have focused on the performance of base isolated structures. (Shatawi et .al 2008) studied the effect of base isolation on the response of four steel frames, using rubber bearing with new constitutive relations of rubber, the study proved the activity of rubber bearings in reducing accelerations in stories. (Ounis et .al) studied the effect of damping on base isolated structures, by taking a wide range of damping ratios, the study showed that by increasing the damping ratio lateral displacements are reduced and also the forces transmitted from the ground are reduced by increasing the

damping ratio. (Komur et .al 2011) made a comparative study between fix base and base isolated structures using lead rubber bearings, the study showed the effect of base isolators on the base shear values and story acceleration. (Islam et .al 2011) studied the effect of seismic loads on the response of four reinforced concrete frames, using lead rubber bearings and high damping rubber bearings, the results showed that high damping rubber bearings gave better results in reducing base shear while lead rubber bearings gave better results in reducing story accelerations.

2. AIM OF STUDY

The main aim of the present study is to predict the behavior of plane reinforced concrete frames with base isolators and plane concrete walls used as infill panels under the effect of earthquake motions, the main parameters to be investigated are :

a. Displacement with time for all frames under the effect of earthquake motion at a particular point.
b. Predicting the shear cracks at beam-column joints during the earthquake motion.
c. Predicting the formation of plastic hinges at members end.
d. Infill panel condition due to earthquake motion.

3. STRUCTURAL ELEMENTS SIMULATION

3.1. Frame Element

The analytical model used in this study to simulate the plane frame is the two node beam-column element consist of lumped plasticity model (Mario 1987), (Tseng and Penzein 1975) shown in Fig.1, which consist of three zones:

a. Rigid block zone which is located at both ends of the element, where it's length is proportionate with the amount of interaction between the beam and column.
b. Plastic hinge zone at both ends of the element with zero length, which represents the non-linear (Plastic) behavior of the element.
c. The third zone which represents the remaining distance between the plastic hinges, with length assumed equal to the length of element and having linear (Elastic) behavior.

The present study is based on the following assumptions:

a. Specifying the Force-Deformation relation which is derived from the Elastic-Plastic model, where every frame element has a yield strength that represents threshold between the elastic and plastic behavior.
b. Specifying the ultimate shear capacity of each element section to specify the shear failure.
c. Specifying the interaction diagram between the axial forces and bending moments which is considered as the failure surface.

The linear behavior of the element remains between both ends of the element, where the non-linear behavior is assumed to be lumped at the end nodes and in case of any non-linear behavior, a suitable reduction is made to Elastic stiffness matrix of frame element.

3.2. Infill Panel Element

In the present study, a four node isoperimetric plane stress element was used to simulate the infill panel, (Chandrupatla 2000) where the infilled panel can be assumed as one element or can be divided into several elements. Usually four node plane stress element has two components only, in the present study a third component has been added (Rotational degree) to achieve compatibility with the frame element, so the infill panel element has three components of displacement (u_i, v_i, θ_z) and three components of forces (P_{xi}, P_{yi}, M_{zi}) as in Fig.2.

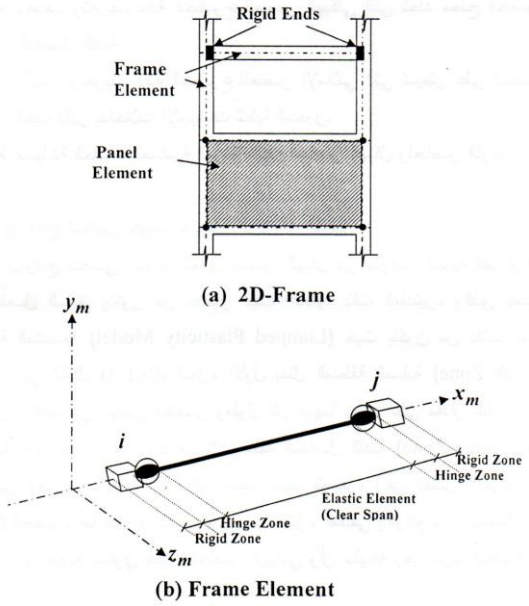


Figure 1. Beam-Column element

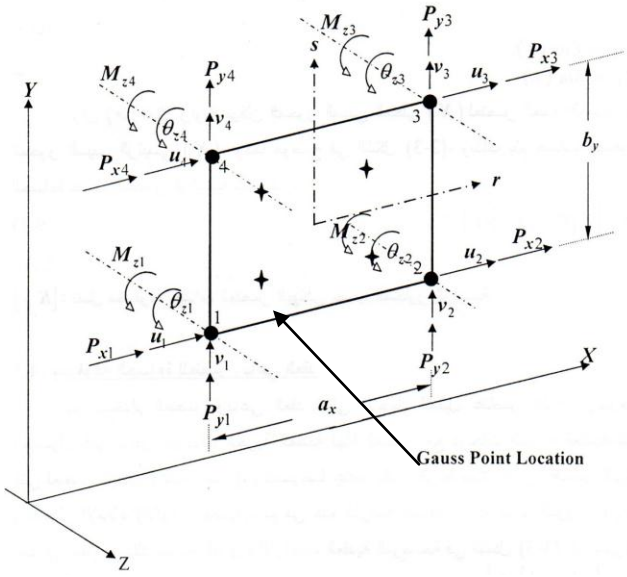


Figure 2. Isoperimetric four node element

To specify the non-linear behavior of infilled panel, three cases have been considered:
a. Yield Condition.
b. Cracking Condition, in one or two orthogonal direction (Mehrabi and Shing 1997).
In the present study it was assumed that the infill panel remains elastic under the effect of a tensile stress until that stress reaches the tensile strength of the infill material (f_t'), which can be calculated from the following equation:

$$f_t' = f_r = 0.62(f_c')^{0.5} \quad (1)$$

Where:

f_c': Compressive strength of infill material (MPa)

And in this case cracking is assumed to occur at plane normal to the principal stress direction.

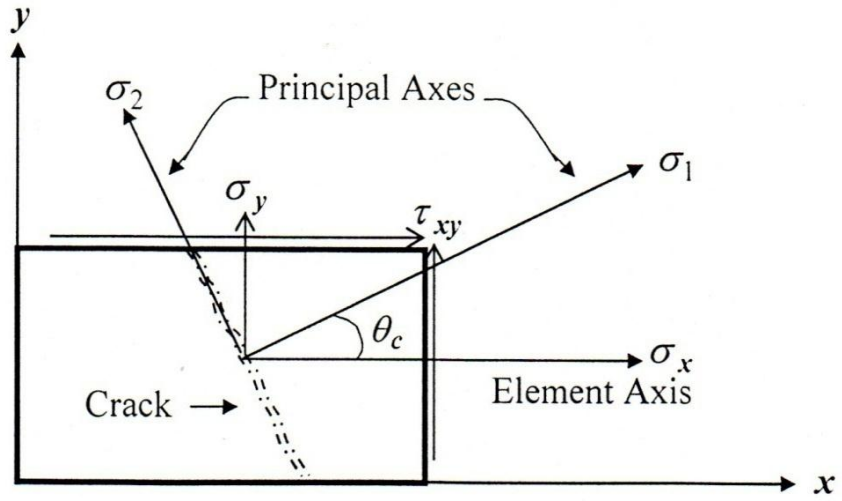


Figure 3. Cracking in the principle axes of infill panel

c. Crushing Condition.

When the infill panel is in the yield condition it is assumed that its behavior is perfectly plastic till it reaches the crushing condition, then it losses all its properties (strength and stiffness), this condition is achieved when the equivalent compression strain ($\boldsymbol{\varepsilon_0}$) becomes larger than the crushing strain of the infill material

And in any the above cases the elastic stiffness matrix of infill panel is modified according to the case.

3.3. Base Isolator simulation

Every base isolator has been simulated by three springs, horizontal ,vertical and (torsional) bending in z-direction to achieve compatibility with the frame element degrees of freedom, every stiffness is calculated according to the shape, dimension, number of rubber and steel layers and shear modulus of rubber. The stiffness of base isolator is calculated as mentioned above, (Naeim and Kelly) and (Kelly and Konstantinidis), in the present study circular high damping rubber bearings were used, so the following equations are use:

$$K_h = \frac{G_r A_b}{t_r} \tag{2}$$

$$K_v = \frac{E_{cb} A_b}{t_r} \tag{3}$$

$$EI = 2G_r I_b S^2 \tag{4}$$

$$S = \frac{r}{2\, t_{rs}} \tag{5}$$

Where:

K_h : Horizontal stiffness of base isolator.

K_v : Vertical stiffness if base isolator.

EI :Bending stiffness of base isolator.

G_r :Shear modulus of rubber.

A_b :Area of steel shims.

t_r :Total thickness of rubber layers.

t_{rs} :Thickness of single rubber layer.

E_{cb} :Instantaneous modulus of elasticity.

S :shape factor.

I_b :Moment of inertia.

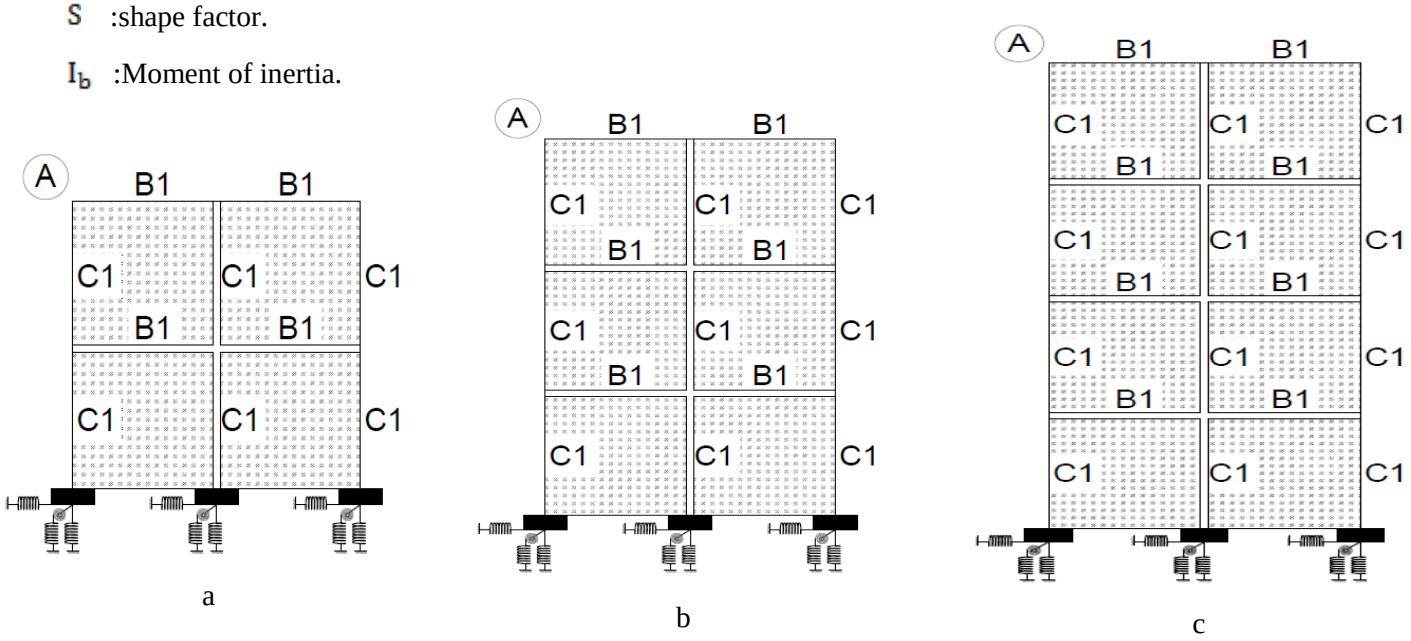


Figure 4. Base isolated reinforced concrete frames with infilled panels
(a) Aspect ratio=1 (b) aspect ratio=1.5 (c) aspect ratio=2

Physical Properties of analyzed R/C Frames
$f_c' = 25$ MPa
$f_y = 400$MPa

$E_c = 20{,}000$MPa
$E_s = 200{,}000$MPa
$\varepsilon_u = 0.0038$

$\rho_{r.c} = 0.24 \times 10^{-8}$N.s^2/mm^2

Physical Properties of Infill Panel
Thinckness = 60mm
$f_c' = 25$ MPa
$E_c = 30000$MPa
$\varepsilon_u = 0.0038$
$f_t = 3.0$MPa

Physical Properties of High Damping Rubber Bearings
Rubber Shear Modulus Gr = 0.624 N/mm^2
Diameter of Isolator = 600mm
Thickness of one Rubber layer = 4.0mm
Number of Rubber Layers = 50.0
Damping ratio = 5%
Column dimension (C_1) = 300x300mm
Beam dimension (B_1) = 300x400mm

4. EARTHQUAKE INPUT

Two earthquake records were taken into account in the present study, El-Centro 1940, shown in Fig.6 , and NewHall in Santa Clarita Valley ,Fig.7. Acceleration versus time where entered in the program algorithm, with (10 secs) duration and time step of (0.002 secs). Newmarks prediction corrected method is adopted to solve the equations of motion.

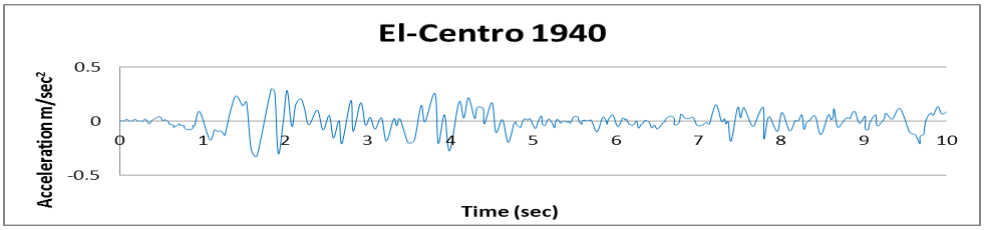


Figure 5. El-Centro earthquake

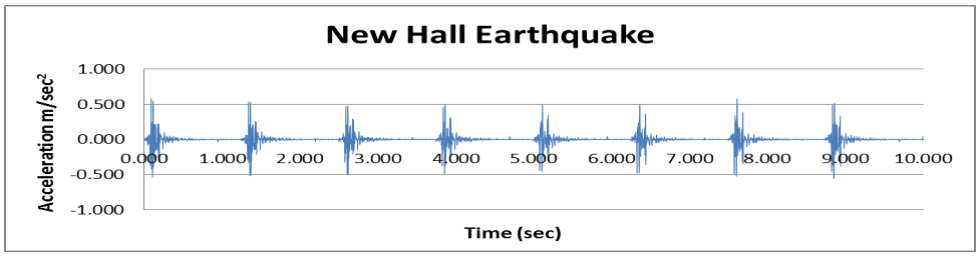


Figure 6. New Hall earthquake

5. RESULTS AND GRAPHS

5.1. Displacements

The predicted results in terms of displacement at point (A) for the three structures are shown in Figures (7-9). For both earthquake motions, the largest displacement was predicted in the frames with aspect ratio=2.0, while the smallest displacement was predicted in the frames with aspect ratio=1.0. Residual displacements were acceptable for all frames at both earthquake motions, which indicates the ability of base isolator to limit the plastic deformation of the concrete structures also the effective rule the damping of base isolator plays in reducing residual displacements. The figures show that the residual displacements at the end of earthquake duration is only margined in case of El-Centro earthquake, while the response due to the New Hall is quite different from that of El-Centro. Table (1) shows the maximum displacement and time of their occurrence for the three structures.

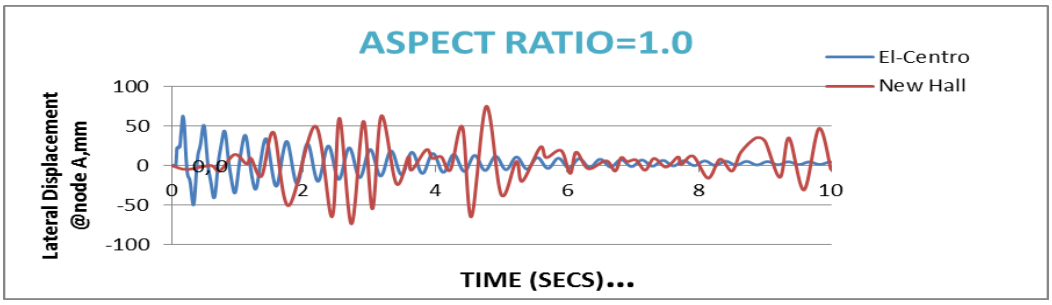


Figure 7. Lateral displacement versus time for base isolated frame with aspect ratio =1.0

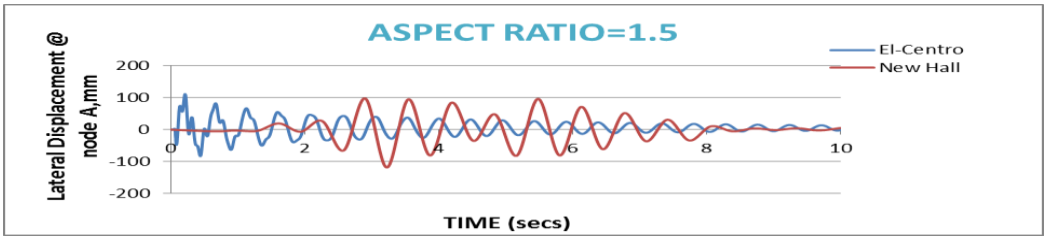


Figure 8. Lateral displacement versus time for base isolated frame with aspect ratio =1.5

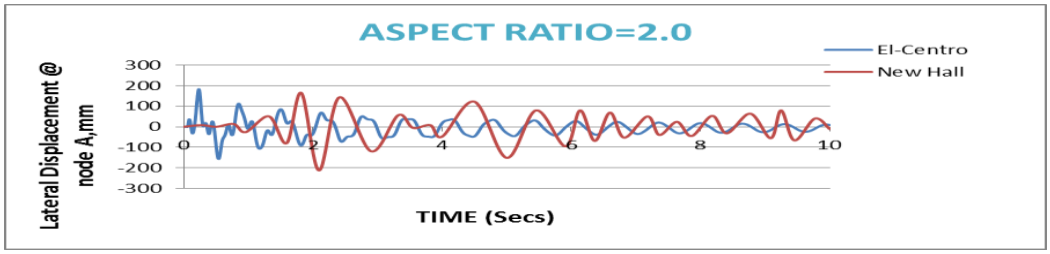


Figure 9. Lateral displacement versus time for base isolated frame with aspect ratio =2.0

Table 1. Maximum displacements during El-Centro earthquake

Aspect ratio	Maximum disp.(mm)		Time (sec)	
	El-Centro	NewHall	El-Centro	NewHall
1.0	62.8	75	0.17	4.7
1.5	111	97.5	0.21	2.9
2.0	173	-212.8	0.22	2.09

A special case was taken to compare between the response of base isolated and fixed frame subjected to El-Centro earthquake for structure with aspect ratio=1.5 and the predicted results are shown in Fig. 10. The difference was obvious in terms of displacements.

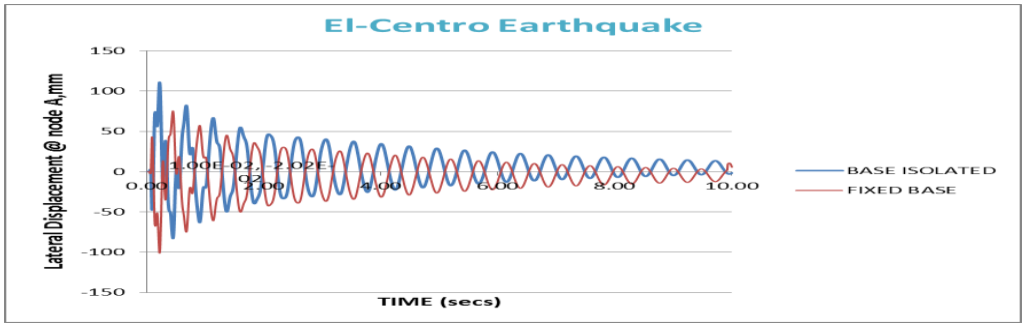


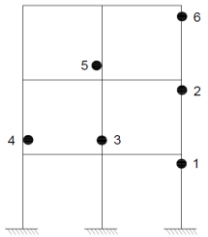
Figure 10. Lateral displacement versus time for base isolated and fixed base frame with aspect ratio =1.5

5.2. Plastic Hinges & Shear Cracks

Plastic hinges, shear cracks and infill conditions at the end of the earthquake are presented in Table (2). No plastic hinges or shear cracks were predicted during and at the end of both earthquakes for all frames with base isolators, this is an indication that all the frame elements remained in the elastic condition. On the other hand, plastic hinges and shear cracks were predicted in the fixed frame with aspect ratio=1.5 under the effect of El-Centro earthquake, the sequence of time of different defects formation are presented in Table (2).

Table 2. Sequential formation of plastic hinges and shear cracks.

Hinge	Time(sec)	Type
1	1.2	Shear crack
2	1.7	Plastic hinge
3	5.4	Plastic hinge
4	6.1	Plastic hinge
5	7.8	Plastic hinge
6	8.9	Plastic hinge



6. CONCLUSIONS

Non-linear analysis were performed on base isolated reinforced concrete plane frames with infill panels using Newmark adjusted step by step method. Three frames with different aspect ratios were taken (aspect ratio=1.0,1.5 and 2.0), two earthquake motions were simulated (El-Centro & New Hall) with a duration of 10 seconds with 0.002 sec time step to solve the equations of motion. The following conclusions were gained:

a. Base isolation has been proved to be a sufficient device to protect structures from the harm that earthquake can cause and all members of the frames remained in elastic conditions.

b. High relative displacements were found after analysis. But the relative displacements between stories were minimized which means a reduction in strains and stresses in the structure.

c. Infill panels increases the lateral stiffness of the whole structure, and is an effective device to protect structures from ground motions.

d. No plastic hinges or shear cracks were noticed during both earthquake motions for base isolated structures, which indicates the ability of base isolators to efficiently dissipate energy. While; plastic hinges and shear crack were developed in the fixed frame.

REFERENCES

Ounis, H.M., Ounis, A. and Kaab, M.Z. (2011).Effects of The Damping on The Seismic Response of a Base Isolated Building.World J Young Researchers, 1(2):20.

Chandrupatla, T.R. and Belegundu, A.D. (2000). Finite Elements in Engineering, Prentice-Hall of India, New Delhi.

Islam, A.B.M., Jameel, M. and Jummat, M.Z. (2011).Study on Optimal Isolation System and Dynamic Structural Responses in Multi-Story Buildings. International Journal of the Physical Sciences, Vol.6(9), pp. 2219-2228.

Kelly, J.M. and Konstantinidis, D.A. (2011). Mechanics of Rubber Bearings for Seismic and Vibration Isolation. A John Wiley & Sons, Ltd., Publication .

Komur, M., Karabork, T. and Deneme, I. (2011). Nonlinear Dynamic Analysis of Isolated and Fixed-Base Reinforced Concrete Structures. Gazi University Journal of Science, 24(3), pp. 463-475.

Mario Paz. (1987). Structural Dynamics Theory and Computation. CBS Publishers and Distributors in Arrangement with Van Nostrand Reinhold Company Inc., New Delhi.

Mehrabi, A.B., and Shing, P.B. (1997). Finite Element Modeling of Masonry Infilled R/C Frames. J. of Struct. Engg. Div., ASCE, Vol.123, No.5, pp.604-613.

Naeim, F. and Kelly, J.M. (1999). Design of Seismic Isolated Structures: From Theory to Practice. A John Wiley & Sons, Ltd., Publication.

Ounis, H.M., Ounis, A. and Kaab, M.Z. (2011).Effects of The Damping on The Seismic Response of a Base Isolated Building.World J Young Researchers, 1(2):20.

Shatnawi, A.S., Najmi, A.S., Abdel-jaber, M.S and Amareen, I.M. (2008). Non-Linear Seismic Response of Base-Isolated Frames Structures Using Rubber Bearings. Jordan Journal of civil Engineering, Vol.2, No.2.

Tseng, W.S., Penzein, J. (1975). Seismic Analysis of Long Multiple Span Highway Bridges. Earthquake Engg. And Struct. Dyn.Vol.4, pp.3-24.