



ISSN: 1813-162X (Print) ; 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: <http://www.tj-es.com>
TJES
 Tikrit Journal of
 Engineering Sciences

Haider S. Al-Jubair *

Fareed H. Majeed

 Civil Engineering Department
 Basrah University
 Basrah
 Iraq

Analyses of the Base Isolated Buildings; Nonlinear Model Time History Versus Codes' Methods

ABSTRACT

Multi-story hypothetical reinforced concrete buildings of variable geometric configurations (symmetrical, vertically irregular, horizontally irregular, with and without shear walls); with the isolated bases via high damping rubber bearing and friction pendulum systems, are analyzed using finite element method under seismic load function (North-South component of the ground motion that recorded at a site in El Centro, California in 1940) via SAP2000-V16 software. Four methods of analysis are adopted. The accuracy of the nonlinear model time history is compared with that recommended by the international codes, namely; nonlinear direct integration, equivalent lateral force, and response spectrum methods. The bilinear hysteretic model of base isolation system and the Rayleigh damping framework for superstructure are adopted. The results support the powerful nonlinear model time history analysis, due to the negligible deviations from those predicted by the robust nonlinear direct integration method. The response spectrum method is proved to be more reliable than the equivalent lateral force method which over predicts the displacement and rotation profiles for the isolated buildings.

Keywords:

Seismic load
 nonlinear modal time history
 isolated buildings
 shear walls
 irregularity of buildings

ARTICLE INFO

Article history:

Received 24 January 2017
 Accepted 01 June 2017
 Available online 30 September 2017

© 2017 TJES, College of Engineering, Tikrit University

DOI: <http://dx.doi.org/10.25130/tjes.24.3.08>

تحليل أبنية معزولة زلزالياً: تأريخ زمني مشروط لا خطي ضد طرق المدونات

الخلاصة

تم تحليل أبنية افتراضية متعددة الطوابق من الخرسانة المسلحة ذات خصائص هندسية متغيرة (متناظرة، غير منتظمة عمودياً، غير منتظمة أفقياً، بوجود وعدم وجود جدران قص) معزولة زلزالياً عند القاعدة بواسطة منظومات مرتكزات مطاطية عالية الإخماد أو بندول الاحتكاك، باستخدام طريقة العناصر المحددة تحت دالة حمل زلزالي (المركية الشمالية-الجنوبية لهزة مسجلة عند موقع في ال سينترو – كاليفورنيا عام 1940م) بواسطة برنامج SAP2000 V16. تم تبني أربع طرق تحليل. قورنت دقة طريقة التأريخ الزمني المشروط اللاخطي مع نظيراتها التي توصي بها المدونات العالمية، وهي طرق: التكامل اللاخطي المباشر، الحمل الجانبي المكافي، والاستجابة الطيفية. مثلت منظومة عزل القاعدة بدورة هسترة خطية ثنائية ومثل إخماد المنشأ العلوي ببنية Rayleigh. أسندت النتائج اقتدار تحليل التأريخ الزمني المشروط اللاخطي، تبعاً للانحرافات المهمة عن نتائج طريقة التكامل اللاخطي المباشر، ذات الدقة العالية. برهنت طريقة الاستجابة الطيفية أنها أكثر موثوقية من طريقة القوة الجانبية المكافئة والتي أعطت قيم مبالغ بها لقطاعي الازاحة والدوران للأبنية المعزولة.

1. INTRODUCTION

The concept of passive base isolation has two basic types of isolation systems. These two basic types are

- 1- The system that uses an elastomeric bearing. In this approach, the building is decoupled from the horizontal components of the earthquake ground motion by

interposing a layer with low horizontal stiffness between the structure and the foundation.

- 2- The system that uses sliding. In this approach, the system is limiting the transfer of shear across the isolation interface by using sliders or rollers between the structure and the foundation

This paper investigates the accuracy of the nonlinear model and provides time history analysis for the isolated buildings compared with the code methods. The two

* Corresponding author: E-mail : hayderaljubair@yahoo.com

isolator types are representative of the sliding and elastomeric systems which are represented by the Friction Pendulum System (FPS) and the High Damping Rubber Bearings (HDRB), respectively. The skeleton of the studied cases is illustrated in Table 1.

Table 1

Skeleton of the studied cases.

Case study No.	Type of base	Type of reinforced concrete superstructure	Method of analysis
1	High damping rubber bearing	Symmetrical building	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history
2	High damping rubber bearing	Symmetrical building with shear walls	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history
3	High damping rubber bearing	Vertically irregular building	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history
4	High damping rubber bearing	Vertically irregular building with shear walls	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history
5	High damping rubber bearing	Horizontally irregular building	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history
6	High damping rubber bearing	Horizontally irregular building with shear walls	Direct integration
			Equivalent lateral force
	Friction pendulum		Response spectrum
			Modal time history

2. MODELING THE ISOLATED BUILDINGS

The buildings are modeled using the finite element method and using SAP2000 program software. A directional material model is used for superstructure of the building, in which uncoupled stress-strain behavior is modeled for one or more stress-strain components. When the state of stress or strain reaches a critical value, the concrete can start failing by fracturing. The fracture of

concrete can occur in two different forms. One is by cracking, under tensile type of stress states, and the other by crushing under compressive type of stress states.

The force-deformation behavior of the two systems of the isolators is modeled as non-linear hysteretic represented by the bi-linear model as shown in Fig. 1. The isolator is modeled using six springs. The springs for the three deformations: axial, shear in the x-z plane, and pure bending in the x-z plane as shown in Fig. 2. The hysteretic models for bearings is used to account for all the energy dissipation and the viscous damping using the Rayleigh damping framework is used for the superstructure.

The geometric configurations of the superstructures are shown in Figs. 3 and 5. A 150mm thick slab and 150 mm thick shear wall are considered with (400 mm × 600 mm) beam of typical sections and column size of (600 mm × 600 mm).

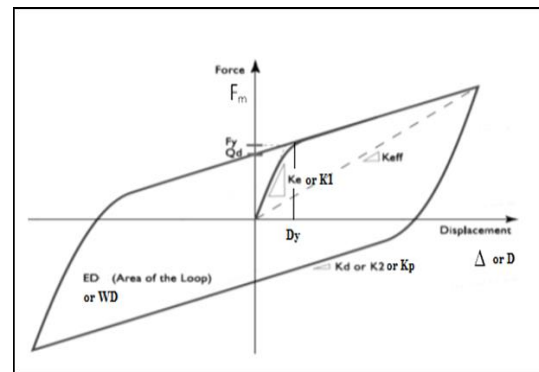


Fig. 1. Parameters of basic hysteresis loop of an isolator for bilinear modeling [1].

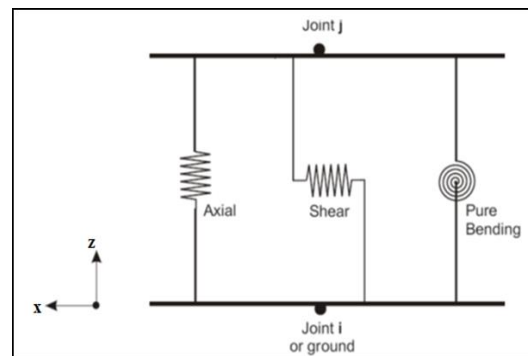


Fig. 2. Three of the six independent springs in a Link/Support element [2].

3. APPLIED LOADS

The reinforced concrete buildings are analyzed for dead, live, and earthquake functional loads. The minimum design dead load on each floor consists of loads due to floor slab, beams, columns and portion walls. The floor live load is taken as 3kN/m² and the roof live load is taken as 1.5 kN/m². The North-South component of the ground motion recorded at a site in El Centro, California in 1940, shown in Fig. 6, is applied to the building. All of the dead load and only 25% of the live load is considered in the seismic analysis [3].

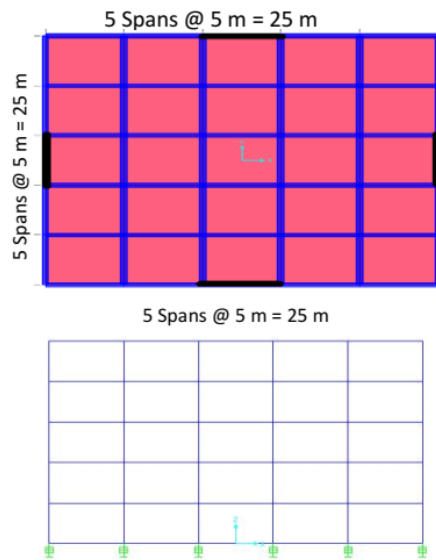
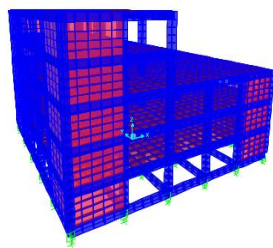
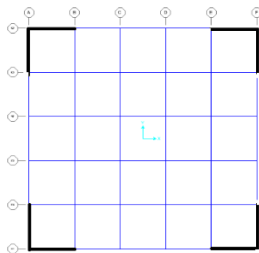


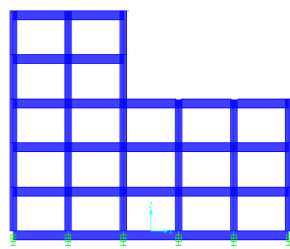
Fig. 3. Symmetrical building.



a. 3D view

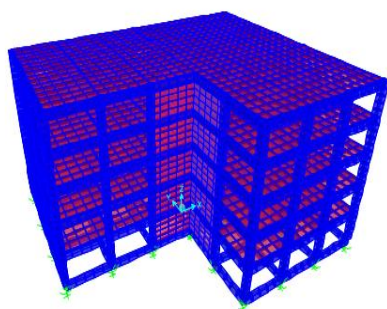


b. Plan

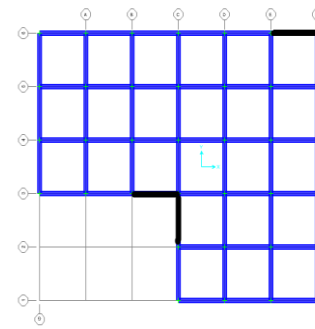


c. Section

Fig. 4. Vertically irregular building.



a. 3D view



b. Plan

Fig. 5. Horizontally irregular building.

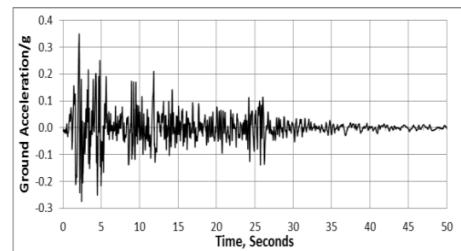
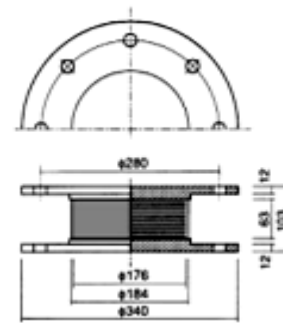
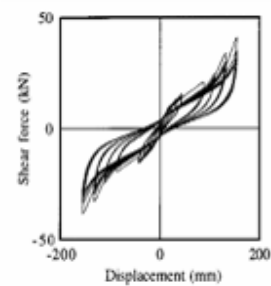


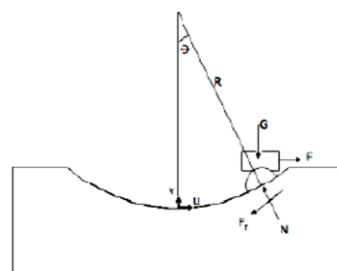
Fig. 6. El Centro, California in 1940 earthquake [4].



a. High damping rubber bearing used in the earthquake simulator tests with dimensions in mm [6].



b. Corresponding force-deformation hysteresis for HDRB [6].



c. Mechanism of the friction pendulum system [7].

Fig. 7. The characteristics of isolation systems.

4. DESIGN OF BASE ISOLATORS

The isolators are designed according to the procedures that described in the UBC-97 [5]. The characteristics of the high damping rubber bearing system are illustrated in Fig. 7(a) and (b) whereas, the mechanism of friction pendulum system is shown in Fig. 7(c).

The characteristics of the superstructure materials and the design parameters of the isolation systems are summarized in Tables 2 and 3, respectively.

Table 2

The superstructure material properties

Symbol	description	unit	Value
f'_c	The cylinder ultimate compression strength of concrete	N/m ²	25
f_y	The yield stress of steel reinforcement	N/m ²	410
E_c	The modulus of elasticity of concrete	N/m ²	23000
ρ_c	The concrete density	kg/m ³	2400
ν_c	Poisson's ratio of concrete	---	0.15

Table 3

Design parameters of the isolators.

Data	Parameter and unit	Value for HDRB	Value for FPS	Nomenclature
Input	T (sec)	2.5	2.5	Design period
	β (%)	20	20	Effective damping
	D (mm)	200	200	Design displacement
				maximum vertical load in service condition including seismic action
	W (kN)	2000	2000	
				friction coefficient
	μ	-	0.02	
	K_{eff} (kN/m)	1500	1370	Effective stiffness
	Q (kN)	88	40	Short term yield force
	K_2 (kN/m)	1200	1150	Inelastic stiffness
Output	K_1 (kN/m)	12000	115000	Elastic stiffness
	D_y (mm)	8.1	0.4	Yield displacement
	R (mm)	-	1700	radius of curvature

4.1. Codes' Analyses Methods

The codes (IBC2012 [3], UBC97 [7] and FEMA 273 [8]) provide three methods to analyze base isolated buildings, as mentioned below:

- 1- Equivalent lateral force method.
- 2- Response spectrum analysis.
- 3- Nonlinear direct integration method.

Since the nonlinear direct integration method can be used for all isolation systems regardless of height, size, geometry, location, and nonlinearity and gives an accurate solution to the dynamic response isolated base buildings, it will be considered as a reference for the comparison.

4.2. Equivalent lateral force method

The following steps summarize this analysis procedure:

- 1- The components and elements above the isolation system should be designed and constructed to resist a minimum lateral seismic force (V_s).

$$V_s = \frac{K_{Dmax} D}{R_1} \quad (1)$$

where:

K_{Dmax} : isolator stiffness.

D : design displacement of the isolator.

R_1 : seismic load reduction factor for isolated building.

- While FEMA 273 and IBC2000 define the reduction factor (R_1), as three-eighths of the (R), factor for the seismic force-resisting system, the UBC97 give (R_1) directly based on the type of the lateral force resisting system that used in the building above the isolation system.
- 2- The total force should be distributed over the height of the building above the isolation interface as follows:

$$F_x = \frac{V_s W_x h_x}{\sum_{i=1}^n W_i h_i} \quad (2)$$

where:

F_x : shear force at level x .

h_i : height above the base to level i .

h_x : height above the base to level x .

W_x : portion of total load that is located at or assigned to level x .

W_i : portion of total load that is located at or assigned to level i .

4.3. Response Spectrum Analysis

The response spectrum technique is really a simplified special case of modal analysis. The modes of vibration are determined in period and shape using usual way. The maximum response magnitudes corresponding to each mode are found by reference to a response spectrum. The design earthquake spectrum should be used to calculate the total design displacement of the isolation system and the lateral forces and displacements of the isolated building. For comparison purposes, the El Centro earthquake response spectrum is shown in Fig. 8.

4.4. Nonlinear Modal Time History Analysis

For the isolated building, the superstructure behaves (nearly) as a rigid body and the main effect of nonlinearity

belongs to the isolator devices of buildings. Therefore, the nonlinearity of the isolators has very important effect on the behavior of the buildings.

In this paper, the dynamic analysis of the buildings with nonlinear isolators and linear superstructure is considered and the results are compared with their corresponding values the obtained from the nonlinear direct integration method.

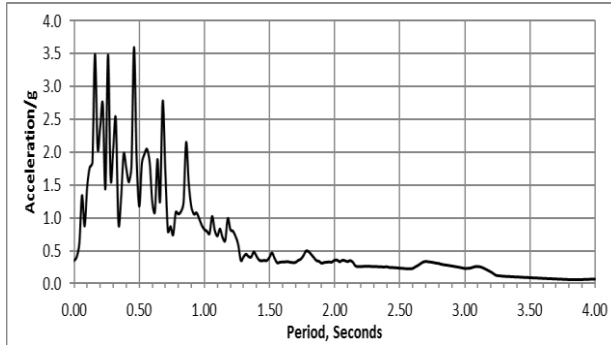


Fig. 8. The El Centro earthquake response spectrum.

5. RESULTS

Fig. 9 shows the displacement at center of mass in each story of the isolated buildings, as determined by the equivalent lateral force method (EQ), response spectrum analysis (RS), and nonlinear direct integration method (DI). Fig. 10 shows the rotation at center of mass in each story for irregular isolated buildings. For the six case studies, the response spectrum method is proved to be more reliable than the equivalent lateral force method which over predicts the displacement and rotation profiles for the isolated buildings.

For the first case study, Fig. 11, a shows comparison between nonlinear modal time history (NMTH) and nonlinear direct integration (DI) methods of friction pendulum base of isolated building in terms of total base shear, maximum displacement and maximum acceleration. The differences in results are negligible and the nonlinear modal time history analysis is proved to be the most accurate among the methods provided by the codes.

Table 4

Percentage increase in total base shear of building analyses by NMTH from DI

Case Study No.	Isolation Type	Increase (+)%
1	FPS	+ 1.2
	HDRB	+ 1.3
2	FPS	+0.9
	HDRB	+1.2
3	FPS	+1.1
	HDRB	+1.4
4	FPS	+0.9
	HDRB	+1.1
5	FPS	+0.7
	HDRB	+0.9
6	FPS	+0.8
	HDRB	+0.9

displacement that corresponding to the nonlinear modal time history analysis compared with the nonlinear direct integration method, for the six case studies.

The results support the powerful nonlinear modal time history analysis, due to a negligible deviation from those predicted by the robust nonlinear direct integration method.

Table 5

Percentage increase in maximum displacement of building analyses by NMTH from DI.

Case study No.	Isolation Type	Increase (+)%
1	FPS	+ 0.5
	HDRB	+ 0.2
2	FPS	+0.4
	HDRB	+0.3
3	FPS	+0.7
	HDRB	+0.3
4	FPS	+0.5
	HDRB	+0.4
5	FPS	+0.6
	HDRB	+0.3
6	FPS	+0.6
	HDRB	+0.2

Table 6

Percentage decrease in response of maximum acceleration of building analyses by NMTH from DI.

Case study No.	Isolation Type	Decrease (-) %
1	FPS	- 1.3
	HDRB	- 1.1
2	FPS	-0.8
	HDRB	-0.7
3	FPS	-1.2
	HDRB	-1.4
4	FPS	-1.3
	HDRB	-1.3
5	FPS	-1.2
	HDRB	-0.9
6	FPS	-0.8
	HDRB	-1.1

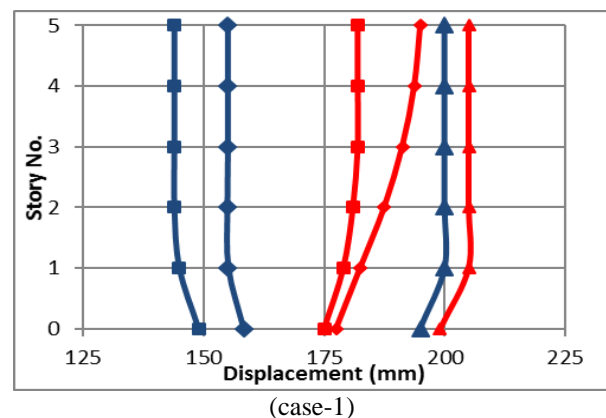
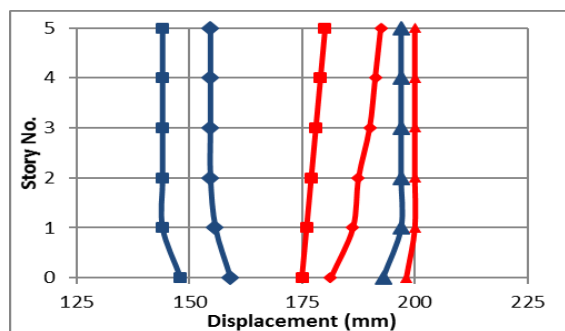
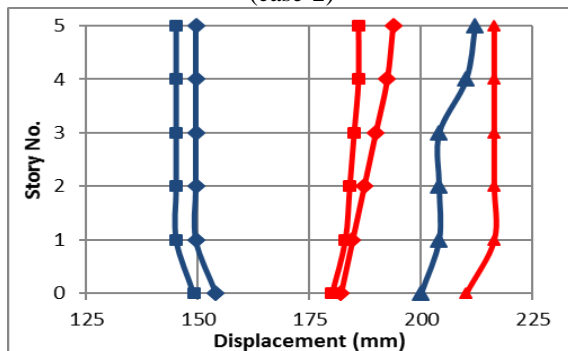


Fig. 9. Continues

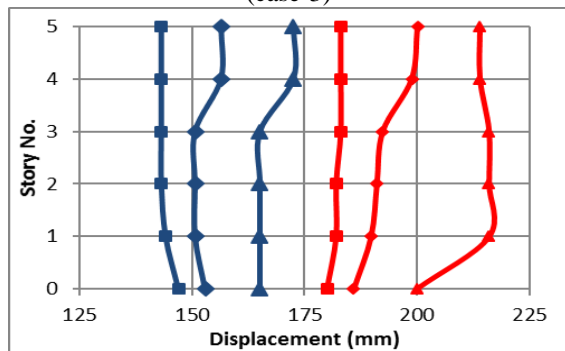
Tables 4 - 6, show the differences percentage in total base shear, maximum acceleration and maximum



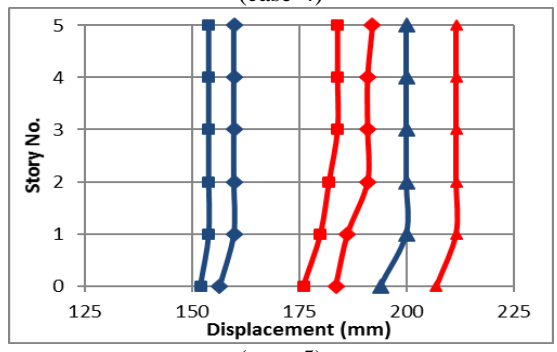
(case-2)



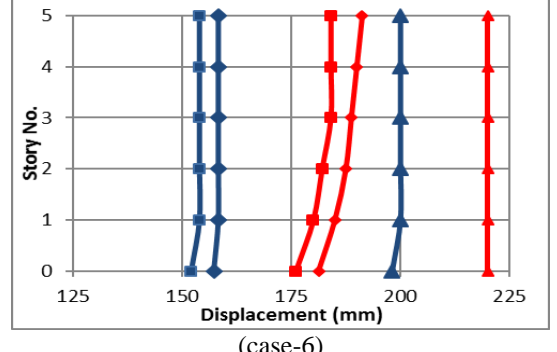
(case-3)



(case-4)



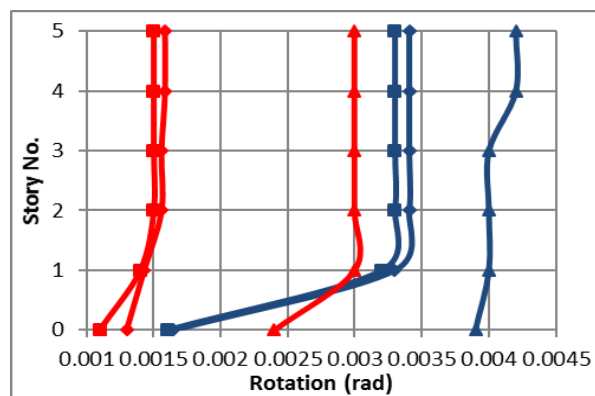
(case-5)



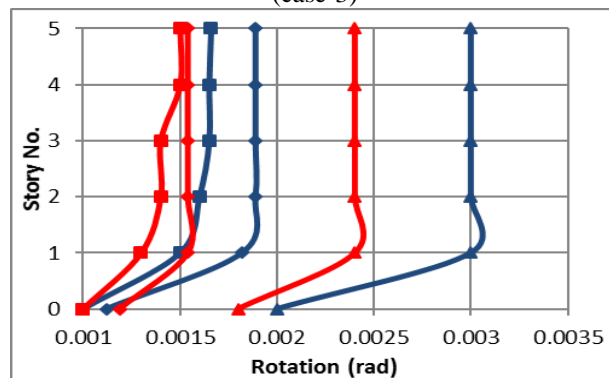
(case-6)

■ FP-DI ■ FP-EQ ■ FP-RS
 ■ RB-DI ■ RB-EQ ■ RB-RS

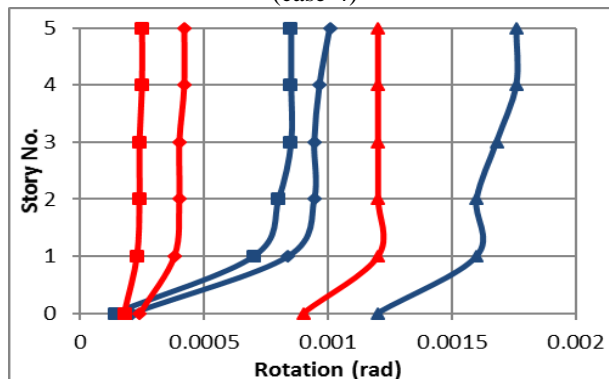
Fig. 9. The displacement at center of mass.



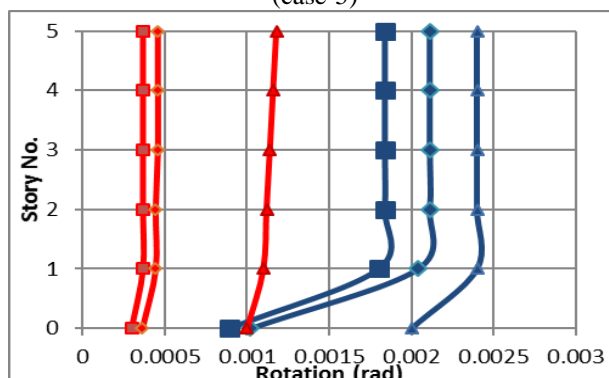
(case-3)



(case-4)



(case-5)



(case-6)

■ FP-DI ■ FP-EQ ■ FP-RS
 ■ RB-DI ■ RB-EQ ■ RB-RS

Fig. 10. The rotation at center of mass.

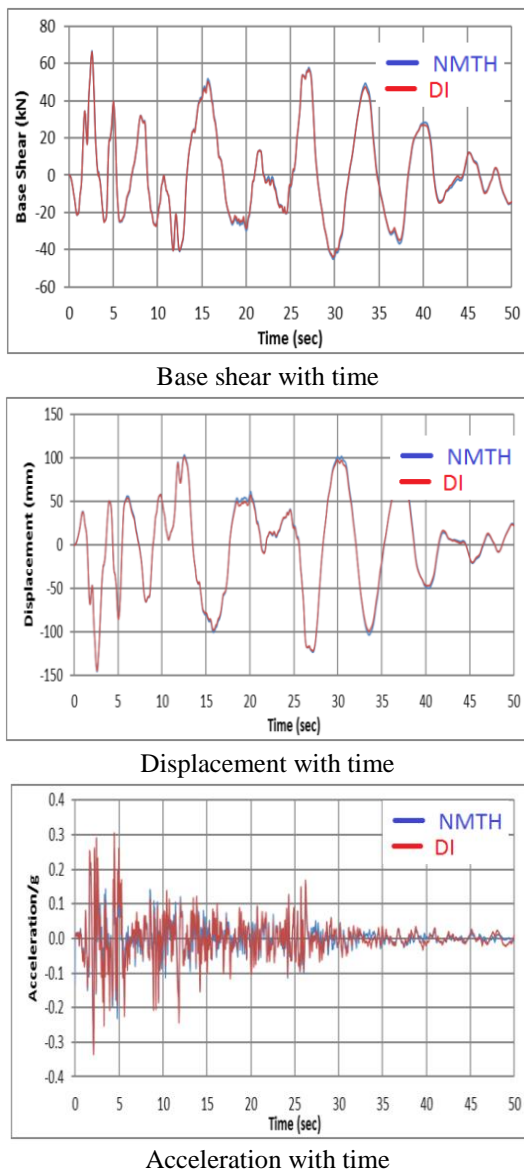


Fig. 11. Comparison between NMTH and DI for FP (case-1).

6. CONCLUSIONS

1. The nonlinear modal time history gives an identical result to the robust nonlinear direct integration method, in a record run time for all cases, the max deviation is 1.4% which is negligible.
2. The response spectrum analysis proved to be more reliable than the equivalent lateral force method which is over predicts the displacement and rotation profiles for the isolated buildings and overestimates the response compared with nonlinear direct integration method. The max deviation for RS method is 30% whereas it is 170% for EQ method.
3. The irregularity of the building (vertically and horizontally) that affected the accuracy of the response spectrum analysis and equivalent lateral force method compared with the direct integration method. For RS method, the max. deviation without irregularity is 15% and with irregularity is 30% and for EQ method, the max deviation without irregularity is 45% and with irregularity is 170%.

4. The inclusion of shear walls has variable effect on the accuracy of the response spectrum analysis and equivalent lateral force method. For RS method, the max deviation without irregularity is 10% and with irregularity is 30% and for EQ method, the max deviation without irregularity is 30% and with irregularity is 170%.
5. The building irregularity and inclusion of shear walls have a negligible effect on the accuracy of the nonlinear modal time history analysis.

REFERENCES

- [1] Jena K. Passive vibration control of framed structures by base isolation method using lead rubber bearing. Master of Technology in Structural Engineering, Thesis. National Institute of Technology. Rourkela; 2006.
- [2] CSI Analysis Reference Manual for SAP2000, ETABS, SAFE and CSI Bridge; 2011.
- [3] International Building Code 2012. International code council. INC. USA; 2011.
- [4] Chopra A. Dynamics of structures, theory and applications to earthquake engineering. 3rd edition, Upper Saddle River: New Jersey; 2007.
- [5] Naeim F and Kelly J. Design of seismic isolated structures: from theory to practice. John Wiley & Sons, Inc; 1999.
- [6] Higashino M and Okamoto S. Response control and seismic isolation of buildings. Taylor and Francis: USA; 2006.
- [7] Uniform Building Code. Structural engineering design provisions, USA; 1997.
- [8] Federal Emergency Management Agency (FEMA 273). Building Seismic Safety Council, Washington, D.C; 1997
- frequency magnetic fields. *Mutat Research* 1998; **410** (2): 167-183.
- [5] Ahlbom A, Cardis E, Green A, Linet M, Savitz D, Swerdlow A. (ICINRP) ICIRP International commission on non-ionizing radiation protection standing committee on epidemiology: Review of the epidemiology literature on EMF and health. *Environmental Health Perspectives* 2001; **109** (6): 911-933.
- [6] Delaplace LR, Reilly JP. Electric and magnetic field coupling from high voltage AC power transmission lines-classification of short-term effects on people. *IEEE Transactions on Power Apparatus and Systems* 1978; PAS-97: 2243-2252.
- [7] Baris D, Armstrong BG, Deadman J, Thériault G. A mortality study of elec. utility workers. *Occupational and Environmental Medicine* 1996; **53**: 25-31.
- [8] Davanipour Z, Sobel E, Bowman JD, Qian Z, Will AD. Amyotrophic lateral sclerosis and occupational exposure to electromagnetic fields. *Bioelectromagnetics* 1997; **18**: 28-35.
- [9] Matthew NO. Elements of Electromagnetic: Sadiku; 2005.