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

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Abstract

Multi-story hypothetical reinforced concrete buildings of variable geometric configurations (symmetrical, vertically irregular, horizontally irregular, with and without shear walls); with isolated bases via high damping rubber bearing and friction pendulum systems, are analyzed by using finite element method under seismic load function (North-South component of the ground motion recorded at a site in El Centro, California in 1940) via SAP2000-V16 software. Four methods of analysis are adopted. The accuracy of nonlinear modal time history is compared to that of methods recommended by 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 powerfulness of the nonlinear modal time history analysis, due to the negligible deviations from those predicted by the robust nonlinear direct integration method. The response spectrum method 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.

تحليل أبنية معزولة زلزالياً : تأريخ زمني مشروط لاخطي 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 عالي الإخماد أو بندول الاحتكاك، باستخدام طريقة العناصر المحددة تحت دالة حمل زلزالي (المركبة 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 المهملة عن نتائج طريقة التكامل اللاخطي المباشر، ذات الدقة العالية. برهنت طريقة الاستجابة الطيفية أنها أكثر موثوقيةً من طريقة القوة الجانبية المكافئة والتي أعطت قيم مبالغ بها لقطاعي الازاحة و الدوران للأبنية المعزولة.

الكلمات الدالة : الحمل الزلزالي، التأريخ الزمني المشروط اللاخطي، الأبنية المعزولة زلزاليا، جدران القص، اللاإنتظام في الأبنية.

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Introduction

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

1-The system that uses elastomeric bearings. 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 has been done to investigate the accuracy of the nonlinear modal time history analysis for the isolated buildings compared with code methods. The two isolator types are representative of sliding and elastomeric systems will have 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).

Modeling the Isolated Buildings

The buildings are modeled using the finite element method by using SAP2000 program software. A directional material model is used for superstructure of building, in which uncoupled stress-strain behavior is modeled for one or more stress-strain components. When the state of stress or strain reaches 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 types of stress states.

The force-deformation behavior of the two systems of 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 three of the deformations: axial, shear in the x-z plane, and pure bending in the x-z plane are 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)-(5). A 150mm thick slab and 150mm thick shear wall are considered with (400x600mm) beam typical sections and column size of (600x 600 mm).

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

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 3 kN/m^2 and the roof live load is taken as 1.5 kN/m^2. 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].

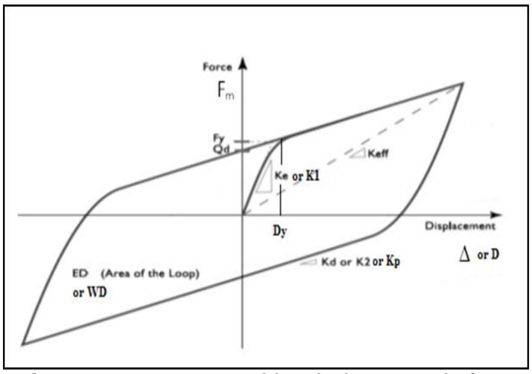


Fig. 1. Parameters of basic hysteresis loop of an isolator for bilinear modeling [1].

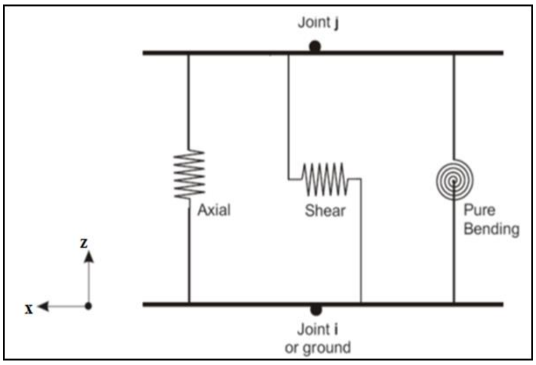


Fig. 2. Three of the six independent springs in a Link/Support element [2].

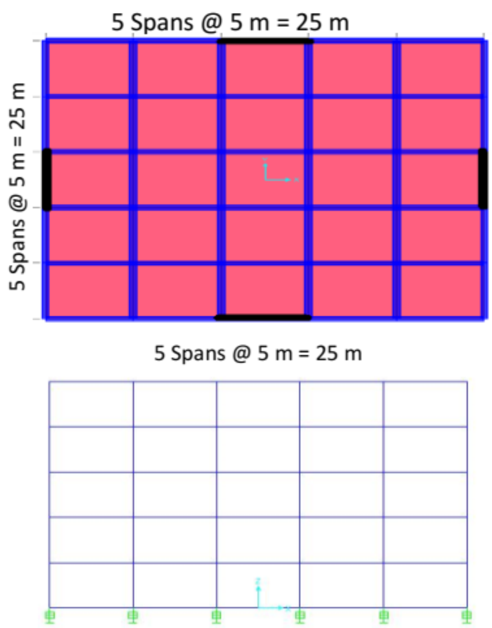
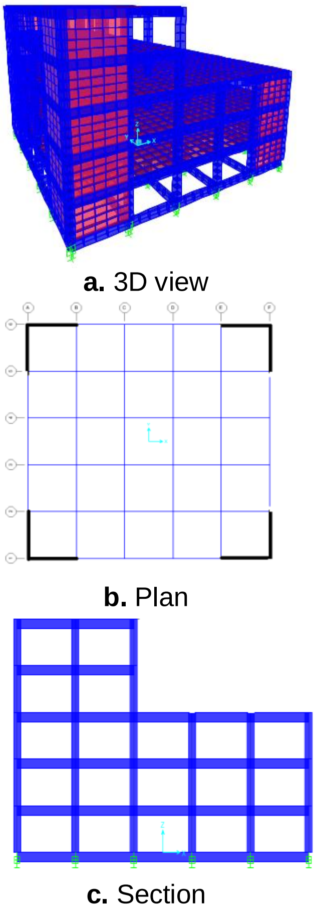


Fig. 3. Symmetrical building.

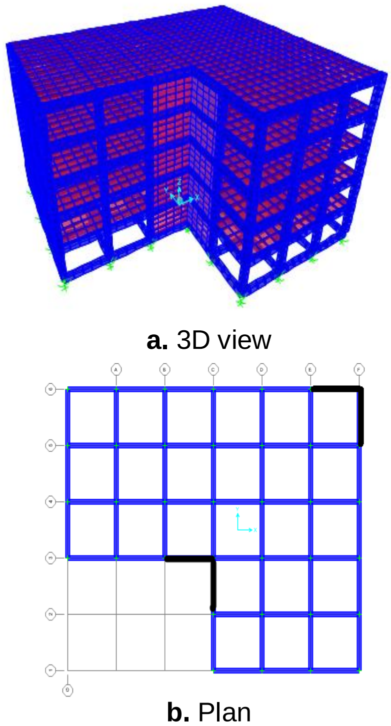


a. 3D view

b. Plan

c. Section

Fig. 4. Vertically irregular building.



a. 3D view

b. Plan

Fig. 5. Horizontally irregular building.

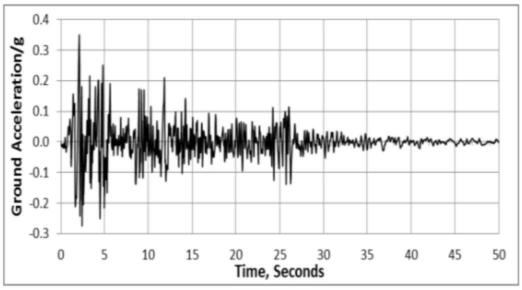
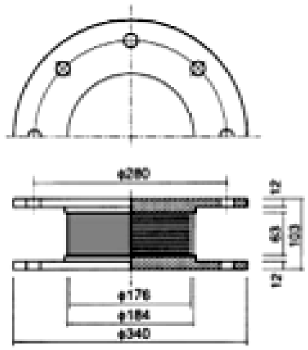
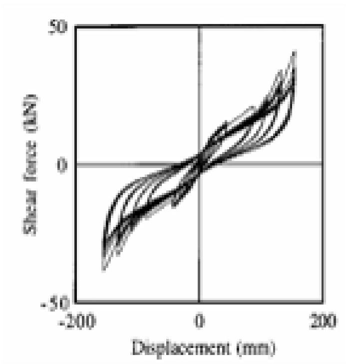


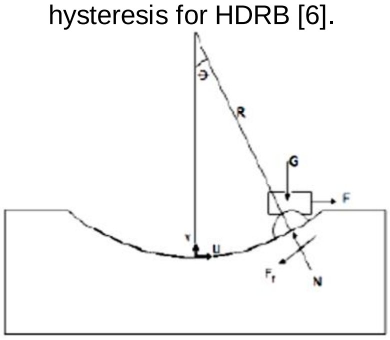
Fig. 6. El Centro, California in 1940 earthquake [4].



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.

Design of Base Isolators

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

The characteristics of 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/mm^2	25
f_y	The yield stress of steel reinforcement	N/mm^2	410
E_c	The modulus of elasticity of concrete	N/mm^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 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
	W (kN)	2000	2000	maximum vertical load in service condition including seismic action
	μ	----	0.02	friction coefficient
Output	K_{eff} (kN/m)	1500	1370	Effective stiffness
	Q (kN)	88	40	Short term yield force
	K_2 (kN/m)	1200	1150	Inelastic stiffness
	K_1 (kN/m)	12000	115000	Elastic stiffness
	D_y (mm)	8.1	0.4	Yield displacement
	R (mm)	----	1700	radius of curvature

Codes' Methods of Analyses

The codes (IBC2012[3], UBC97 [7] and FEMA 273 [8]) provide three methods to analyze base isolated buildings, as mention 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 of base isolated buildings, it will be considered as a reference for the comparison.

Equivalent lateral force method

The following steps can have summarized for 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).

$$V_S = \frac{K_{D\max} D}{R_1} \tag{1}$$

where:
K_{Dmax} : stiffness of isolator.
D : design displacement of isolator.
R_1 : seismic load reduction factor for isolated building.

While FEMA 273 and IBC2000 defined the reduction factor (R_1), as three-eighths of the (R), factor for the seismic force-resisting system, the UBC97 give the (R_1) directly based on the type of lateral force resisting system used for 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:

$$F_x = \frac{V_S W_x h_x}{\sum_{i=1}^{n} W_i h_i} \tag{2}$$

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.

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 in the usual way and 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 shown in Fig. (8) is used.

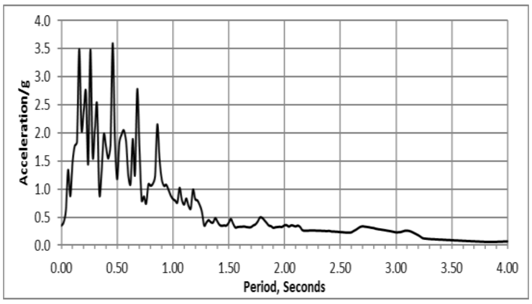


Fig. 8. The El Centro earthquake response spectrum.

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 isolators has very important effect on the behavior of buildings.

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

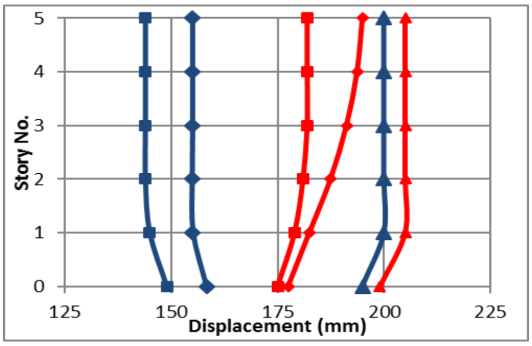
Results

Figure (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).

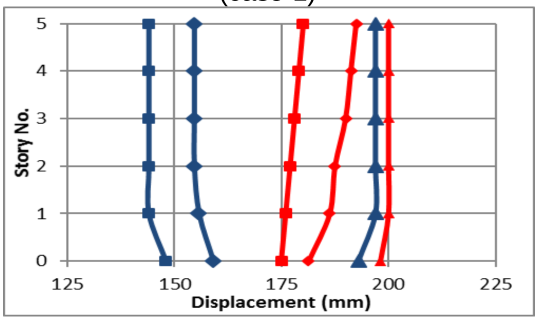
Figure (10) shows the rotation at center of mass in each story for irregular isolated buildings.

For the six case studies, the response spectrum method proved to be more reliable than the equivalent lateral force method which over predict the displacement and rotation profiles for the isolated buildings.

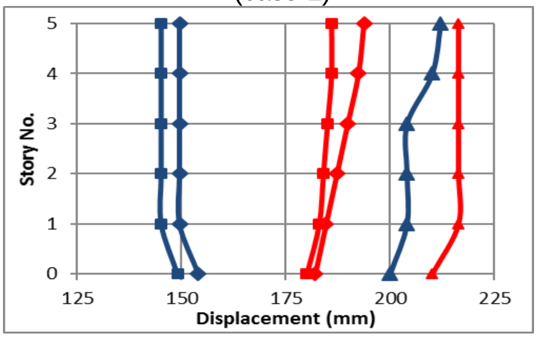
For the first case study, Fig. (11), shows comparisons between nonlinear modal time history (NMTH) and nonlinear direct integration (DI) methods of friction pendulum base isolated building in terms of total base



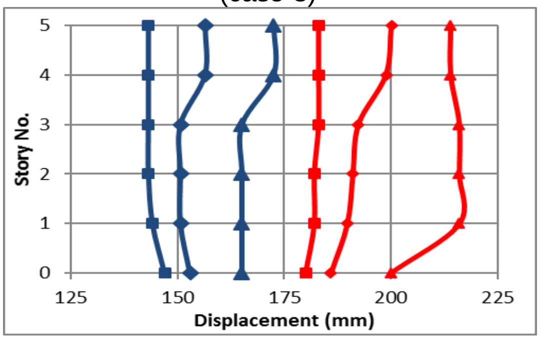
(case-1)



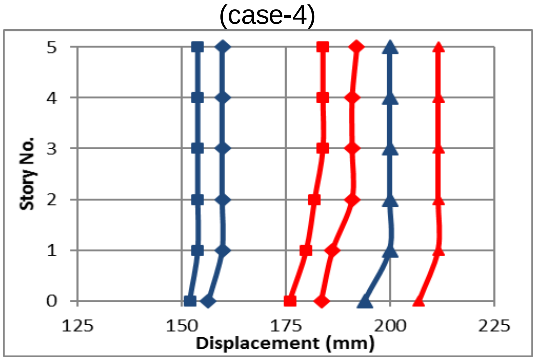
(case-2)



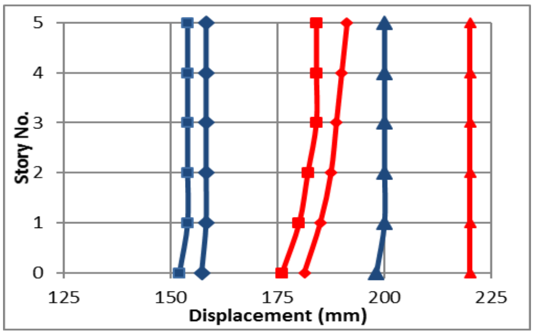
(case-3)



(case-4)

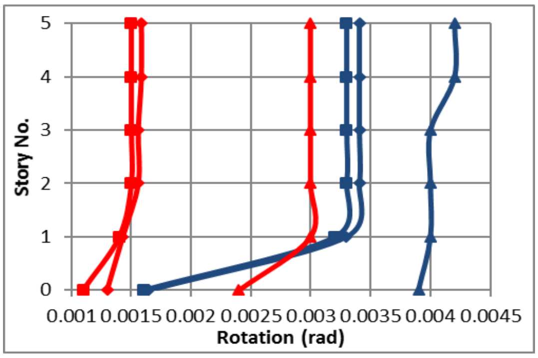


(case-5)

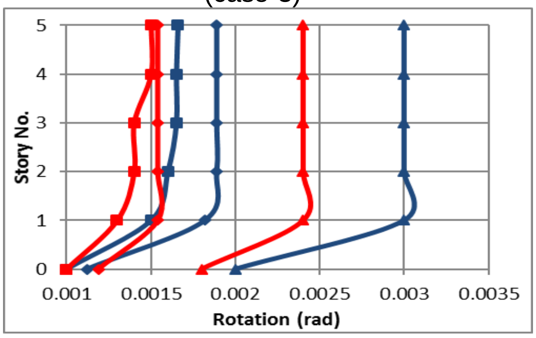


(case-6)

Fig. 9. The displacement at center of mass

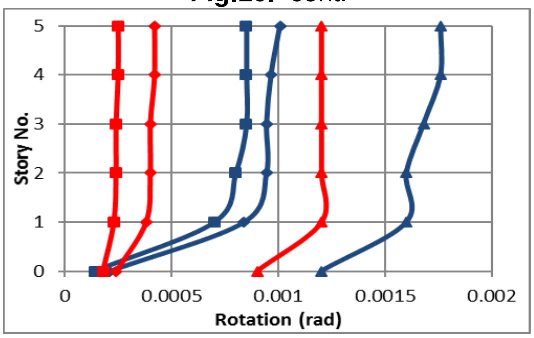


(case-3)



(case-4)

Fig.10. cont.



(case-5)

Fig. 10. Continuous ..

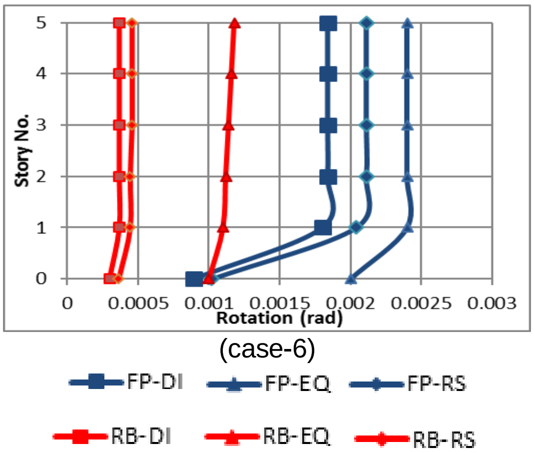
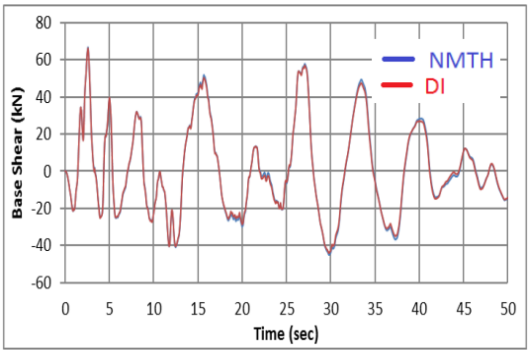
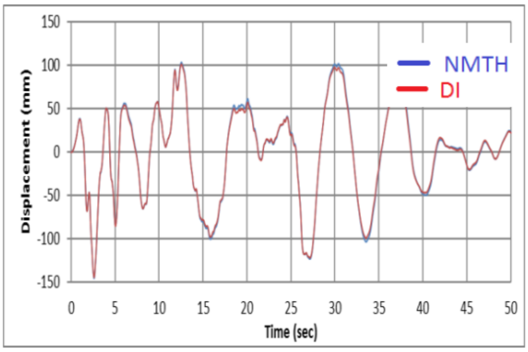


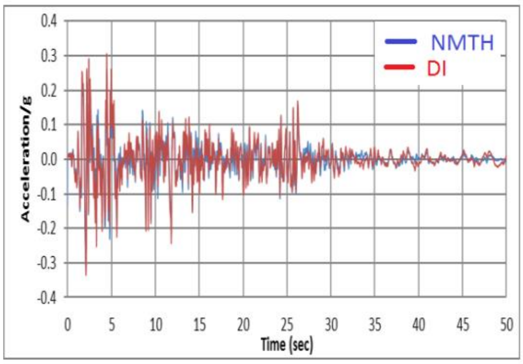
Fig. 10. The rotation at center of mass



Base shear with time



Displacement with time



Acceleration with time

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

shear, maximum displacement and maximum acceleration.

The differences in results are negligible and the nonlinear modal time history analysis proved to be the most accurate among the methods provided by the codes.

Tables (4)-(6), show the percentage differences in total base shear, maximum acceleration and maximum displacement corresponding to the nonlinear modal time history analysis compared to the nonlinear direct integration method, for the six case studies.

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

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

The results support the powerfulness of the nonlinear modal time history analysis, due to the negligible deviations from those predicted by the robust nonlinear direct integration method.

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

Conclusions

1. The nonlinear modal time history gives identical results 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 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 building (vertically and horizontally) 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 negligible effects on the accuracy of the nonlinear modal time history analysis.

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