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RESPONSE OF TWO-STOREY RC FRAME WITH SPECIAL BASE-ISOLATION USING RUAUMOKO 2D PROGRAM

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The control of structural vibrations due to ground motion can be done by the installation of a passive, active, and hybrid base isolation system. The primary function of the base isolator is to support the superstructure and provide huge horizontal flexibility and a long period of vibration. In this paper, a special HRDB base isolator is made from natural rubber with special elastic property and hardness. This base isolator is designed to support gravity loads of two-story RC building. The experimental hysteresis loop of this isolator is validated with analytical modeling hysteresis loop using Hysteresis program. The Bouc hysteresis rule was chosen as a model the hysteresis loop, and it is similar to experimental hysteresis loops. Later, a single bay two-story RC frame with a base isolation system was modeled using Ruaumoko 2D program subjected to three levels of earthquake excitations. After analyzing this frame under the 1994 Pacoima Dam Earthquake, the 1995 Kobe Earthquake and the 1940 El-Centro 1940 Earthquake. The numerical results show that this isolator is quite efficient in reducing the damage of structural and non-structural elements of the structure through minimizing inter-story drift, lateral displacement, and story acceleration. Therefore, this special HRDB based isolator is recommended to be used for low rise and medium-rise building in seismic regions.

Keywords: Special Base Isolator, Hysteresis Loop, Inter-story drift, lateral displacement, long period of vibration.

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1. INTRODUCTION

Most of the reinforced concrete buildings in Malaysia were designed and constructed using a non-seismic code of design such as BS8110. This non-seismic code doesn't not have any provision for earthquake loading and these buildings are vulnerable to damage and collapse due to moderate and severe earthquake ground motion, respectively. When an earthquake happens, the horizontal movement of the ground exerts the dynamic load to the structure that causes damage to the buildings and infrastructures. The severity damage of RC buildings depends on the magnitude of the earthquake and the ductility of the structure. The National Earthquake Information Centre (NEIC) had recorded an average of 50 earthquakes per day and the cost of damages due to these earthquakes were over 2.9 trillion US dollars from 1990 to 2012 [1]. Peninsular Malaysia can be affected by a long-distant earthquake from Sumatra or Mentawai segment which located between Sunda Subduction zone and Sumatera fault line [2]. Whereas in East Malaysia, there are at least two active fault zones between Ranau and Mount Kinbalu which are Mensaban Fault and Lobou-Lobou fault [3]. Traditionally, many RC buildings in Malaysia were designed and constructed without considering seismic load. Therefore, many research and strategies have been developed and proposed to protect the RC structures during earthquake excitation. Some of the strategies which can be considered during the design stage are to use Eurocode 8 (seismic code practice) by including seismic loads, retrofitting and strengthening damaged structures, and provide a special base isolation system at bottom of the column for low-rise and medium-rise buildings. One of the most efficient ways of controlling the structure behavior during an earthquake is base isolating of structure [4]. Base isolation is made of the combination of natural rubber, steel plates, lead core, and Smart Material Alloy (SMA) [5]. It is installed between the substructure and superstructure to decouple them and weakening the tie between them. When the earthquake waves hit fixed-base structures, they sway in a similar direction of earthquake wave and the inter-story drift is bigger than the allowance drift as permitted in the seismic design code of practice. Contradictory, if the base-isolated structure is hit by an earthquake then the base isolation device moves in the opposite direction of the earthquake and reduces the inter-story drift to keep the structure safe. Base isolation must support the superstructure, provide a high degree of horizontal flexibility, increases the natural fundamental period of the structure, and reduces inter-story drifts so that the damage of the structures can be reduced significantly [6,7,8]. There are three base isolation systems such as passive, active, and hybrid base isolation systems. The three types of isolators are Elastomeric Rubber Bearings, Sliding Bearings, and Friction Pendulum Bearings [9]. The main focus of this study is to use a special base isolator made from HDRB which is a type of

Elastomeric Rubber Bearings due to its excellent performance for low-rise and medium-rise RC buildings, and this base is locally available because of a high level of rubber production in Malaysia. Recently, many experiments have been conducted to determine the seismic performance of several types of base isolators under compression test, single direction, and bi-directional test using strong floor and shaking table [4, 10, 11, 12, 13]. Moreover, modeling and simulating the behavior of base isolation using dynamic software programming is faster and cheaper when compared with conducting experimental work. The seismic behavior of a base isolator is determined by plotting hysteresis loop (load versus displacement) where the area of the hysteresis loop shows the amount of energy dissipated during testing. It is important to model and simulate the exact behavior of base isolation using the developed equations or computer software. By modeling base isolator in ABAQUS as a hyper-viscoelastic material model (UMAT) and considering the non-linearity characteristics of base isolation shows the effectiveness of this technology for earthquake resistant structures [14]. Thus, the aim of this paper is to model the hysteresis loop of special base isolation using Hysteresis program and to model a two-story RC frame designed using BS8110 with special base isolation using RUAUMOKO 2D program. The model of the two-story RC frame which represents a common residential building in Malaysia is evaluated its seismic performance by running this model under three levels of earthquake excitations.

2. METHODOLOGY

Fig. 1 depicts the dimensions of a single bay half-scale two-story (reducing in the scale of the frame is due to limitation of laboratory's space as experimental research on the model will be conducted) RC frame with a brick wall at the second floor and a mass concrete block at the top. The two-story RC building was designed using the non-seismic code of design namely BS8110 specifically to cater to a low-rise structure. The overall height of the RC frame is 3700mm, length of 3800mm, and width of 1800mm seated on the strong floor. A total number of four special base isolation units are positioned between the foundation beam and the strong floor for a later experiment but for 2D numerical analysis, only one frame is considered. The detail dimensions of beams, columns, slabs, and foundations beam together with properties of construction materials used are tabulated in Table 1. The target compressive strength of concrete is 30 MPa and characteristic high yield strength of the reinforcement bar is 450 MPa. Fig. 2 shows the cross-section and side elevation of the special base isolation system which made from HDRB [16]. It is consisting of alternative layers between natural rubbers and steel shims where the rubber layers are reinforced with steel shims. The reinforcing steel shims constrain the rubber layers from lateral expansion and provide high vertical stiffness, but have no effect on the shear stiffness [17, 18, 19, 20, 21]. The overall dimension of a square HRDB based isolation unit is 250mm x250mm with a thickness of 85.5 mm. Table 2 shows the specific dimension and mechanical properties of the HRDB base isolation. The nominal shear modulus of HRDB base isolation system is 2.3 MPa. The mechanical properties of HRDB such as shear modulus are very important where they control the horizontal flexibility displacement and the long natural fundamental period of the structures under earthquake excitation.

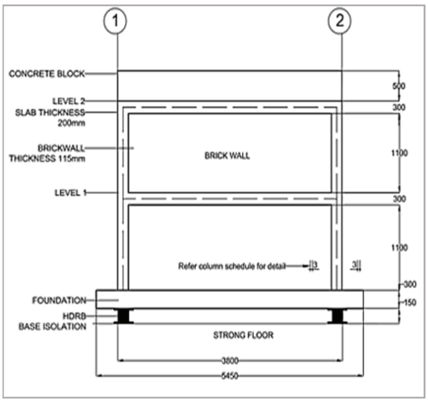


Fig. 1. Front view with dimensions of half-scale two-story RC frame with brick wall

Table 1. Specific dimensions and properties of two-story RC frame

Specification	Values
Number of Stories	2
Height of each story (mm)	1100
Thickness of foundation (mm)	300
Thickness of slab (mm)	200
Cross section of beams (mm^2)	200 x 300
Cross section of columns	200 x 200
Steel grade (MPa)	450
Concrete Grade (MPa)	30
Cement Type	OPC
Concrete Density (kN/m^3)	24
Single Brick Dimension (mm^3)	228x114x76
Density of Brick (kN/m^3)	22

The shear strain of HRDB base isolator is 175% with a strain rate of 5.5/s and the maximum shear stress under shear test is 2.4 MPa [16]. During ground motion, the base isolation system should behave in the linear behavior so that the structure does not experience the residual displacement after the cataclysm of an earthquake. Thus, another significant mechanical property of the HRDB base isolation system is shear elastic stiffness where the value of this parameter is 1888 kN/m. The Rauamoko 2D and 3D software is a coding program developed by Dr. Athol J. Carr using Fortran Computer Language from the University of Canterbury, Christchurch, New Zealand [15]. This program is designed to carry out the analysis of structures particularly buildings and bridges subjected to earthquakes and other dynamic excitation. It is also used for earthquake excitation studies including modeling of base-isolation systems and for studies on earthquake excited pounding between buildings. Likewise, this program is capable to cover a wide range of material behavior from linear to non-linear and from elastic to inelastic analysis. All the structural components of the buildings such as slabs, beams, columns, base isolators, foundations, and non-structural members are entered into the program in coding and numbering form. The two-story RC frame which designed according to BS8110 where there is no provision for seismic load but includes the wind load. In the Ruaumoko 2D program, the input data file including all properties of the analysis is written in a Notepad file with an extension of DAT. The type of analysis selected is dynamic time-history using Newmark constant average acceleration. The beams and columns properties are based on the design data and the base isolator is assumed to be a transverse spring element.

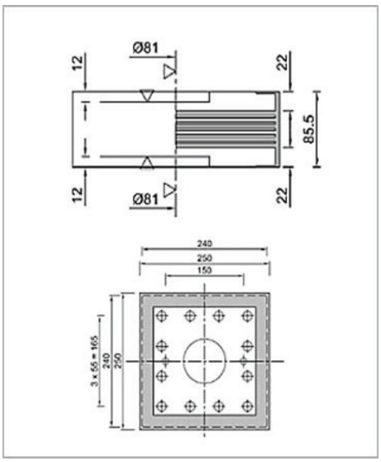


Fig. 2. Cross-section and side elevation of special base isolation unit [16]

Table 2. Specific dimensions and properties of HRDB base isolation system [16]

Particulars	Specifications
Cross-section (mm^2)	240 x 240
Number of rubber layers	6
Thickness of one rubber layer (mm)	5
Thickness of one steel layer (mm)	2.3
Nominal shear modulus (MPa)	1.2

Fig. 3 shows the diagram of the two-story RC frame after running Ruaumoko 2D program. There are 10 numbers of nodes and 9 numbers of elements where nodes 1, 2, 3, 4, 9, 10, and element 1, 4 were representing the base isolators in two dimensions. For dynamic time history analysis for this study, three past earthquake records were selected from the Quake Folder in Ruaumoko 2D program. Table 3 displays these three earthquake records based on their Peak Ground Acceleration (PGA) which representing three levels of earthquake excitations ranging low, medium, and high. The seismic performance of RC frame will be based on these three selected earthquakes. Table 4 presents the 1994 Pacoima Dam Earthquake excitation with PGA of 1.28g, the 1995 Kobe Earthquake with PGA of 0.83g, and the 1940 El-Centro Earthquake record with the lowest PGA of 0.214g. All the earthquake excitations record the time for 20 seconds.

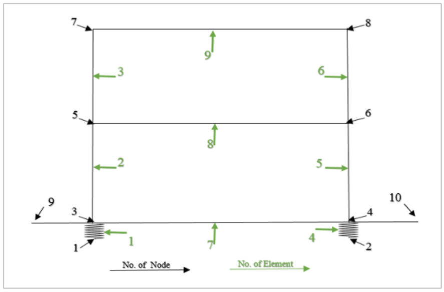
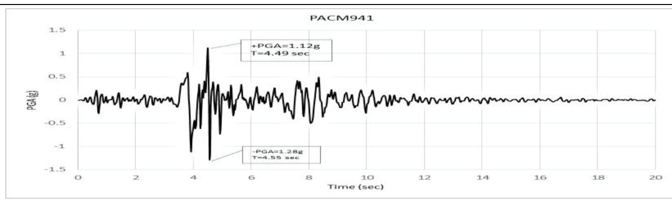
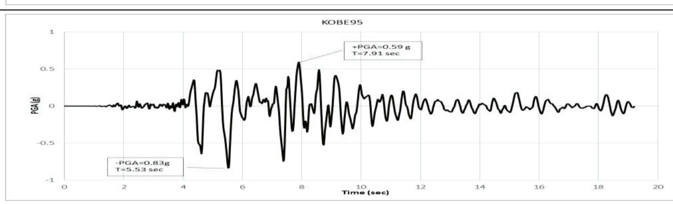
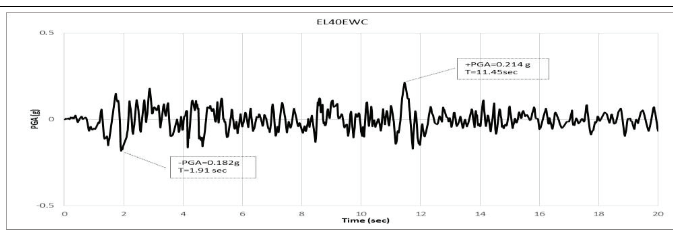


Table 3. Past earthquake records used in the time history analysis

Fig. 3. Mapping nodes and elements for RC frame based on input data file

Earthquake Record	Magnitude	Scale	PGA (g)	Location	Duration (sec)	Year
PACM941.EQS	6.7	Great	1.280	USA	59.98	1994
KOBE95NS.EQN	6.9	Strong	0.830	Japan	19.20	1995
EL40EWC.EQB	5.5	Moderate	0.214	USA	20.00	1940

Table 4. Accelerograms of three past earthquakes for the first 20 seconds

Earthquakes	Earthquake Accelerograms
PACM941	
KOBE95	
EL40EWC	

3. RESULTS AND DISCUSSIONS

It is essential to compare and validate the experimental hysteresis loop and modeling hysteresis loop of base isolator using Hysteres program. The important parameters that need to determine from the hysteresis loop are lateral strength capacity, elastic stiffness, ductility, and equivalent viscous damping. Next, these parameters are used to model the seismic behavior of a two-story RC frame under three different levels of earthquake excitations. The analysis of spectral acceleration, spectral displacement, maximum displacement, and maximum load will be discussed in the following sub-section in this paper.

3.1 COMPARISON OF HYSTERESIS LOOP USING HYSTERES PROGRAM

Fig. 4 portrays the comparison between the experimental conducted by a previous researcher [16] and modeling hysteresis loop where there is good agreement between them. The maximum lateral strength capacity of the special base isolator is 150kN and maximum lateral displacement is 0.055m. In addition, Table 5 tabulates the comparison of parameters in terms of percentage between experimental and modeling of hysteresis loop for the base isolator. The percentage difference for maximum lateral strength capacity between experimental and modeling for HRDB base isolator is 2.79%. Whereas, the percentage difference for elastic stiffness and equivalent viscous damping is 9.7% and 5.45%, respectively.

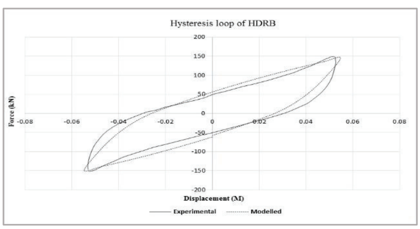


Fig. 4. Comparison between experimental [16] and modeling of hysteresis loop HRDB

Due to the elastic behavior of the special based isolator, the ductility for experiment and modeling hysteresis loop is 1 because both of them are behaving under the elastic limit which means that the structure will go back to its original position after the earthquake without any residual displacement on the two-story RC frame.

Table 5. Parameters comparison between experimental and modeling hysteresis loops

Parameters	Experimental	Modeling	% Difference
Maximum Lateral Strength Capacity	149.38 kN	145.20 kN	2.79
Elastic Stiffness	1888.42 kN/m	1703.8 kN/m	9.7
Ductility	1	1	0
Equivalent Viscous Damping	0.2000	0.1891	5.45

There are 58 numbers of hysteresis rules available in the Ruaumoko 2D Appendices Manual [15]. Among these hysteresis rules, the BOUC Hysteresis rule (IHYST=23) was chosen because this hysteresis loop has a similar hysteresis loop with the experimental result. In modeling the HDRB base isolator conducted by Bhuiyan [16], the experiment hysteresis loop was verified with modeling hysteresis loop. In order to model the hysteresis loop of a base isolator, the parameters for Bouc hysteresis rule are shown in Table 6 are being used. These parameters of the hysteresis loop are used as data input to model the seismic behavior of special base isolator which denotes Element 1 and Element 4 of the two-story RC frame as shown in Fig. 3. The following sub-section will discuss maximum acceleration and displacement of the RC frame under three past earthquakes accelerogram records.

Table 6. Parameters of hysteresis loop using Bouc hysteresis rule (IHYST=23)

Parameters	Range	HDRB
A1 (Loop Fatness)	(0.1 to 0.9)	0.8
A2 (Loop Pinching)	(-0.9 to o.9)	-0.55
A3 (Stiffness)	Usually 1.0	0.56
A4 (Degradation)	Usually 1.0	1
A5 (Strength)	Usually 1.0	1
N (Power Factor, Controls Abruptness)	(1 to 3) Usually 1	1
D3 (Strength Degradation)	(0.0 to 0.1) (0.0 no degradation)	0
D4 (Loop Size Degradation)	(0.0 to 0.2) (0.0 no degradation)	0
D5 (Stiffness Degration)	(0.1 to 0.9)	0
Mode (=0 Constintino Version =1 Baber and Wen Version)		0
Init (=0 Normal =1 Bi-linear until first unloading after yielding)		0

3.2 MAXIMUM ACCELERATION AND DISPLACEMENT OF RC FRAME

Fig. 5 shows the spectral displacement versus undamped natural period for three selected earthquake excitations which were plotted using Dynaplot program (part of Ruaumoko 2D).

These spectral displacements were recorded at Node 7 which located at the roof level of the two-story RC frame. Fig. 6 illustrates the pseudo-spectral acceleration versus undamped natural period for three earthquake Accelerograms for damping ratios of 0%, 2%, 5%, 10%, and 20% at Node 7. It is observed that when the percentage damping ratio increases, spectral displacement and spectral acceleration are decreasing with respect to a similar time. The percentage damping ratio for the two-story frame with a special base isolator is modeled for 20% of the damping, but the normal damping RC frame without base isolator is 5%. The next result will discuss on the disparities between 5% and 20% of damping ratio of the two-story RC frame for maximum displacement at the roof, first, and the ground floor under three past earthquake records.

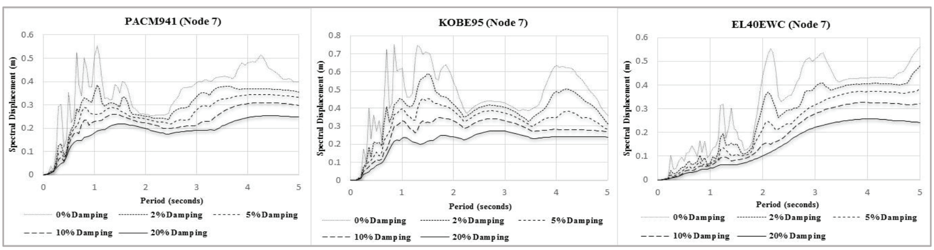


Fig. 5. Graph of spectral displacement versus time for three past earthquake records

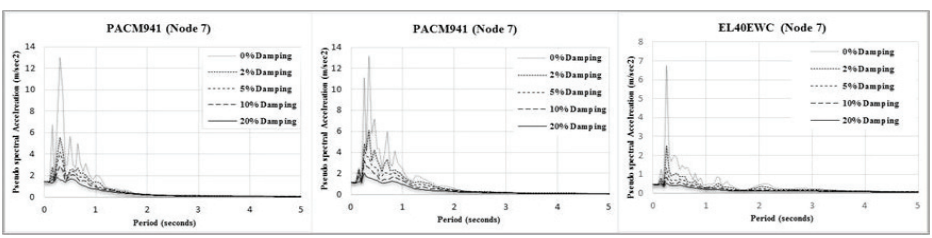


Fig. 6. Pseudo spectral acceleration for three selected past earthquake excitations

Table 7 illustrates the percentage difference between the maximum displacement between 5% damping and 20% damping. Hypothetically, 5% damping represents the behavior of the RC frame without base isolator and 20% represents RC frame with HRDB base isolator. The lateral displacement and times data are obtained based on Fig. 5 on the ground floor (Node 3), first floor (Node 5), and roof level (Node 7). The maximum lateral displacement recorded at the roof floor under the 1995 Kobe Earthquake is 454.9 mm at a time of 1.50 seconds at 5% damping. Conversely, the two-story RC frame with base isolator and 20% damping can reduce the maximum lateral displacement to 274.5 mm and increasing the fundamental natural period to 2.85 seconds. Normally, the base isolator can reduce the lateral displacement between 24.57% and 39.65% while increasing the fundamental natural period between 2% and 45.61%.

Table 7. Percentage different of maximum displacement between 5% damping and 20% damping

Three Past Earthquake Records	Floor	5% Damping		20% Damping		% Difference Displacement for 5% and 20% damping
		Lateral Displacement (mm)	Time (sec)	Lateral Displacement (mm)	Time (sec)	
PACM941.EQS	Ground	315.8	4.51	238.2	4.60	24.57%
	First	328.1	4.10	244.4	4.50	25.50%
	Roof	344.1	4.35	253.7	4.45	26.27%
KOBE95NS.EQN	Ground	452.9	1.40	240.6	4.25	55.68%
	First	453.9	1.50	274.3	2.85	39.56%
	Roof	454.9	1.50	274.5	2.85	39.65%
EL40EWC.EQB	Ground	399.4	5.00	257.7	4.05	35.47%
	First	393.6	5.00	249.8	4.65	36.53%
	Roof	387.8	5.00	257.9	4.05	33.49%

Table 8 tabulates percentage differences of maximum acceleration recorded at ground floor labeled as Node 3, first floor labeled as Node 5, and roof level labeled as Node 7 between 5% damping and 20% damping. All the values obtained in this table are referred to in Fig. 6. The maximum acceleration was recorded at the roof level of the RC frame under the 1995 Kobe Earthquake at time 0.250 second. However, the biggest percentage difference in maximum acceleration between 5% damping and 20% damping is 62.04% occurs at a time of 0.250 seconds. By putting the base isolation system at a two-story RC frame, the acceleration of the structures can be reduced more than half as recorded by the 1940 El Centro Earthquake from 0.139 m/s^2 to 0.052 m/s^2. Thus, it can be concluded that by equipped two-story RC frame could reduce the acceleration and the same time can reduce the structural damage drastically.

Table 8. Percentage difference of maximum acceleration between 5% and 20% damping

Three Past Earthquake Records	Floor	5% Damping Ratio		20% Damping Ratio		% Different Acceleration 5% and 20% Damping
		Maximum Acceleration (m/s^2)	Time (sec)	Maximum Acceleration (m/s^2)	Time (sec)	
PACM941.EQS	Ground	0.397	0.300	0.184	0.250	53.65%
	First	0.413	0.300	0.186	0.250	54.81%
	Roof	0.426	0.300	0.188	0.250	55.86%
KOBE95NS.EQN	Ground	0.414	0.250	0.196	0.250	52.65%
	First	0.428	0.250	0.201	0.250	53.03%
	Roof	0.439	0.250	0.206	0.250	53.07%
EL40EWC.EQB	Ground	0.127	0.250	0.049	0.250	61.40%
	First	0.132	0.250	0.051	0.250	61.36%
	Roof	0.137	0.250	0.052	0.250	62.04%

3.2. MAXIMUM LATERAL LOAD AND DISPLACEMENT OF RC FRAME

The maximum lateral load and displacement in pushing and pulling direction of the RC frame are obtained using Dynaplot program from the Ruaumoko 2D software. Table 9 tabulates the lateral load and lateral displacement under three past earthquake records. It can be observed that the maximum lateral load and displacement occurred at the roof level because a concrete block was placed at top of the frame. The lateral load in pushing and pulling directions are similar for all the three of earthquakes because they carry the same load. However, the maximum displacement is recorded under the 1994 Pacoima Dam Earthquake at 24.36mm in pushing direction at roof level and the lowest lateral displacement is -5.621mm in pulling direction under the 1940 El-Centro Earthquake. By converting the maximum lateral displacement to drift, the maximum drift recorded by the 1994 Pacoima Dam Earthquake is 0.92% drift. Therefore, it can be concluded that the two-story RC frame with the HRDB base isolation system is safe under this earthquake and there is no structural damage.

Table 9. Lateral load and lateral displacement in pushing and pulling directions

Past Earthquake Records	Floor level	Pushing Direction		Pulling Direction	
		Load (kN)	Displacement (mm)	Load (kN)	Displacement (mm)
PACM941.EQS	First floor	34.56	23.60	-34.56	-19.86
	Roof	46.40	24.36	-46.40	-20.54
KOBE95NS.EQN	First floor	34.56	16.97	-34.56	-16.09
	Roof	46.40	17.51	-46.40	-16.65
EL40EWC.EQB	First floor	34.56	6.837	-34.56	-5.621
	Roof	46.40	7.043	-46.40	-5.831

3.3. TIME HISTORY ANALYSIS

One of the most accurate ways to evaluate the dynamic response of the structure under an earthquake excitation is time history analysis in which the structure is subjected to past or artificial earthquake accelerograms. In the Ruaumoko program, different earthquake recodes exist and can be added in the input data. The natural period of the base-isolated RC frame has elongated to 0.248 seconds compare to its fixed-base version which is 0.073seconds, so the elongation in natural period it thee building protect the structure from earthquake's damage. By decreasing the building lateral displacement, drift, and accelerations in the seismic design stage, it can increase the occupant safety under moderate and severe earthquake excitations. The limitation of drift and displacement in the building can avoid the non-structural elements' damage such as cladding, partitions, and pipework with an acceptable deformation and deflection range. In this study, the moment-resisting frame which designed based on BS8110 where there is no seismic consideration can survive under earthquake excitation by installing a special base isolation system. The HDRB base isolator shows a promising story displacement within limit even though its ductility increases the story displacement [11] where most of the lateral displacement is taken by the base isolation system. However, some of the other design codes provide story drift limitations for fixed-base and base-isolated structures. According to IBC code, the maximum drift for a normal building is 0.7% to 2.5% of the effective height that falls between 21.2mm and 75.87mm. In Eurocode 8, the drift limitation is 1% to 1.5% for base-isolated structures, the maximum drift of the frame still within limit. Fig. 7 shows the maximum inter-story drift of the two-story RC frame with the base isolation system under three past earthquake records. The highest inter-story drift was recorded under the 1994 Pacoima Dam Earthquake because it has the highest Peak Ground Acceleration (PGA = 1.28g).

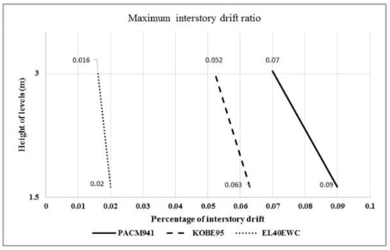


Fig. 7. Maximum interstory drift of the frame under three earthquake accelerograms

4. CONCLUSIONS

The conclusions and recommendations based on the comparison of hysteresis loop and modeling of two-story RC frame can be drawn as follows:

- Bouc hysteresis rule (IHYST=23) which is rule number 23 was chosen from the Ruaumoko 2D Manual to be the best fit with the experimental hysteresis loop for hysteretic behavior of the HDRB base isolation system.
- The HDRB base isolation system has about 19% of equivalent viscous damping that significantly dissipates the seismic wave energy through its mechanical behaviour and it elongated the natural period of the structure significantly.
- The maximum story displacement is 33.67mm for the roof under the highest PGA (Pacoima Dam earthquake records) that is equal to a 1.1% drift. Even though, this maximum percentage of drift is within limit compared to EC8, IBC, FEMA, and ASCE, still it is high for the double story RC frame.
- The high story displacement and low inter-story drift pinpoints that most of the displacement is taken by the base-isolator and HDRBs have been efficient in taking the drift of the structure.
- The maximum floor acceleration is significantly low on each floor as the highest acceleration is 0.0018g in the roof from the Pacoima Dam earthquake record. The low acceleration avoids the non-structural element and structural elements damage due to earthquakes.
- The lateral load and displacement of the structure due to earthquake increase in direct relation with the increase of story weight and height. The maximum load is 34.56 KN and 46.40 KN for

first and roof respectively, and the displacement increases as the PGA of the earthquake record increases from 24.36mm to 7.04mm due to Pacoima Dam and El-Centro earthquake records respectively.

- By the increase of the Damping the spectral acceleration and spectral displacement decrease hugely. This decrease is more than 50% for spectral acceleration and less than 50% for spectral displacement between 5% damping and 20% damping. There are 55.86% and 26.27% reduction due to the highest PGA record in spectral acceleration and displacement respectively for the roof floor. Also, 62.04% and 33.49% reduction due to PGA record in spectral acceleration and displacement respectively for the roof floor.
- As the PGA increases, deference in spectral acceleration and spectral displacement decreases slightly between 5% and 20% damping ratios. So, the efficiency of damping slightly reduces for earthquakes having high PGA. Additionally, a higher damping ratio is slightly more beneficial for a higher level of the structure.

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LIST OF FIGURES AND TABLES:

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