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Demand response modification factor for the investigation of inelastic response of base isolated structures

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Abstract. In this study, the effect of flexibility of superstructures and nonlinear characteristics of LRB (Lead Rubber Bearing) isolator on inelastic response of base isolated structures is investigated. To demonstrate the intensity of damage in superstructures, demand response modification factor without the consideration of damping reduction factor, demand RI, is used and the N2 method is applied to compute this factor. To evaluate the influence of superstructure flexibility on inelastic response of base isolated structures, different steel intermediate moment resisting frames with different heights have been investigated. In lead rubber bearing, the rubber provides flexibility and the lead is the source of damping; variations of aforementioned characteristics are also investigated on inelastic response of superstructures. It is observed that an increase in height of superstructure leads to higher value of demand RI till 4-story frame but afterward this factor remains constant; in other words, an increase in height until 4-story frame causes more damage in the superstructure but after that superstructure's damage is equal to the 4-story frame's. The results demonstrate that the low value of second stiffness (rubber stiffness in LRBs) tends to show a significant decrease in demand RI. Increase in value of characteristic strength (yield strength of the lead in LRBs) leads to decrease in the demand RI.

Keywords: superstructure flexibility; LRB isolator characteristics; inelastic response of base isolated structures; demand RI, N2 method

1. Introduction

The seismically isolated structure is a high performance structure and because of that, codes obligate a restricted response modification factor without the consideration of damping reduction factor, R_I, for this structure to limit ductility demand (FEMA-450 2003, ASCE/SEI Standard 7-05 2005). Therefore, ductile materials and ductile structural lateral resisting systems may not be a good choice to use in the superstructure of seismically base isolated structures. Up on the aforementioned, the use of seismic isolation is limited to just very important structures; Structures that because of their importance, having an elastic superstructure is pertinent for them, like a nuclear power plant. Investigation of nonlinear behavior of base isolated structures is a necessity to find out the hidden inelastic capacity of base isolated structure to help for more optimized design of superstructure by proposing higher value of R_I in parallel with losing the least performance. For this purpose, demand

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response modification factor without the consideration of damping reduction factor, demand R_I, is used as a means of judging inelastic response of base isolated structures.

The main goal of this study is to investigate the effect of superstructure flexibility and characteristics of LRB isolator on the inelastic response of superstructure by means of evaluation of demand R_I. Therefore, first of all, a methodology is proposed to evaluate the demand R_I for seismically isolated structures.

To evaluate the influence of superstructure flexibility, 2-story, 4-story and 6-story steel IMRFs (Intermediate Moment Resisting Frame) were investigated. To evaluate the effect of LRB isolator's characteristics on inelastic response of base isolated structures, variations of post-yield stiffness (source of flexibility at isolation level) and variations of characteristic strength (source of damping at isolation level) were investigated.

In several researches, Jangid and *et al.* evaluated the effect of isolators' characteristics and superstructure flexibility on elastic response of superstructures (Kulkarni and Jangid 2002, Matasagar and Jangid 2004, Sharma and Jangid 2009).

In Ordonez *et al.* (2003), the behavior of base isolated buildings which unwillingly respond in the inelastic range was investigated.

In further studies, expanded for base-isolated steel structures, designed according to the U.S provision, Ryan and et al assessed the nonlinear response of designed isolated structures under different levels of severity of ground motion to evaluate the performance of base isolated structures (Sayani *et al.* 2010, Erduran *et al.* 2010).

In Palazzo and Petti (1996), a methodology for calculation of demand response modification factor for base isolated structures was investigated. In this parametric research, the influence of characteristics of isolator and superstructure on demand ductility reduction factor was investigated.

In the present study the nonlinear static analysis, N2 method, is used to evaluate nonlinear response of base-isolated structures. The use of nonlinear static analysis via N2 method was first introduced by Fajfar (1999, 2000). Later this method was expanded for seismically base-isolated structures (Kilar and Koren 2008, 2010). In Kilar and Koren (2010), a limited test parametric study of idealized SDOF systems has been performed in order to determine whether or not the same 'equal displacement rule' and the same equations as in the original N2 method could be used to calculate the inelastic spectra for base-isolated structures. Therefore, Extensive nonlinear dynamic analyses on a series of idealized SDOF systems with different non-zero post-yield stiffnesses ($\alpha \geq 0$) and different initial stiffnesses/periods for systems in the long-period range (T>Tc) were conducted by Kilar and Koren to illustrate that the single mode pushover analysis procedure of N2 is applicable for base isolated structures with elastomeric bearings in a specific range of damping. However, there are several restrictions on N2 method for base isolated structures. One important limitation of the N2 method is the assumption of a time independent displacement shape for the pushover analysis, which can be inaccurate for structures where higher mode effects are significant. In here-in study, a displacement shape corresponding to provisional distribution of design base shear in height of the building is assumed in which imposes more damage to the superstructure in comparison to time history loading (Kilar and Koren 2010). Limitations on damping of isolation system and superstructure flexibility which alter the real response of superstructure were under attention (Kilar and Koren 2008, 2010). Therefore, for case studies in this study, damping ratio at isolation level is limited to 30% and the height of superstructure is limited to 6 stories. In aforementioned ranges, N2 method can be used to evaluate inelastic response of superstructure reliably.

Practical use of pushover analysis on base-isolated structures was also conducted to demonstrate yielding of the superstructure under severe near-field earthquakes (Providakis 2008).

Here-in, the objectives of this study are: (i) Investigation on the influence of superstructure flexibility and nonlinear characteristics of LRB isolator on inelastic behavior of superstructures. (ii) To propose a methodology to calculate demand R_I (iii) and to compare the demand R_I with its provisional counterpart.

2. Demand R_I

2.1 Code review

There are two kinds of response modification factor. One is supply response modification factor or abbreviated, response modification factor, R, and the other is demand response modification factor, Demand R. response modification factor (or behavior factor (EC8 2004) is one that seismic design codes (UBC 1997, FEMA-273 1997) introduced to designers to use in their design in order to take into account the available inelastic capacities of structures, but demand response modification factor is one computed under a specific type of earthquake or a group of earthquakes and demonstrates the value of entering the structure to nonlinear range.

Today, seismic design codes give constant values of response modification factor, R, for various types of seismic force-resisting systems for fixed base structures with the aim of restricting inelastic deformation at a level adequate for the protection of human life (Life Safety) in case of a major seismic event. To calculate R factor for base isolated structures in ASCE7-05, performance objective is immediate occupancy at major earthquakes (FEMA-450 2003.

In forced-based seismic design procedures, response modification factor in seismic codes consists of ductility reduction factor and the so-called over-strength factor. For seismically isolated structures, there is another extra factor, damping reduction factor. So, response modification factor for base isolated structures can be expressed as

$$R = R_{\xi}.R_{\mu}.R_s \tag{1}$$

In ASCE7-05, base shear for design of superstructures, can be calculated via

$$V_{ss} = \frac{K_{Dmax}.D_D}{R_I} \tag{2}$$

After simplifying the above equation

$$V_{ss} = \frac{\alpha.{S_{D1}}/{T_D}}{B_D.R_I} W \tag{3}$$

α is a safety factor which amplifies the design base shear via 30% amplification of minimum design stiffness (FEMA-451 2006), then: $\alpha = 1.3$.

In ASCE7-05, damping reduction factor, R_{ξ}, is defined as damping coefficient at design earthquake (DE), B_D. Response modification factor without the consideration of damping reduction factor, R_I, Numerical coefficient related to the type of seismic force-resisting system above the isolation system in which accommodated nonlinear capacity of superstructure consists of ductility reduction factor and over-strength factor. W is the effective seismic weight of the structure above the isolation interface.

Then

$$B_D = R_\xi \tag{4}$$

$$R_I = R_\mu . R_s \tag{5}$$

$$V_s = \alpha . \frac{S_{a,5\%}}{R_\xi . R_\mu . R_s} W \tag{6}$$

$$R = R_I . R_\xi \tag{7}$$

In the aforementioned paragraphs, the components of R factor as illustrated in seismic design code were discussed, but as our target in this study is the computation of demand R_I, in following paragraph, the methodology which is used for calculation of demand R_I is discussed. To estimate this factor, maximum considerable earthquake (MCE) is selected as the seismic load.

2.2 Scientific background

In an equivalent SDOF (Single Degree Of Freedom) system as the representative of a base isolated structure, demand ductility reduction factor is defined as (Fajfar 1999, 2000, Kilar and Koren 2008, 2010)

$$R_\mu = \frac{S_{ae,Damped}(T)}{S_{ay,Damped}(T)} = \frac{S_{ae,\xi}}{S_{ay,\xi}} \tag{8}$$

R_μ: demand ductility reduction factor due to the nonlinear behavior and damping of the superstructure

T: The elastic period of equivalent SDOF system

$S_{ae,Damped}(T)$: Damped acceleration required for elastic behavior corresponding to T

$S_{ay,Damped}(T)$: Demand Acceleration required for inelastic behavior corresponding to T

In a MDOF (Multi Degree Of Freedom) base isolated structure by assuming the base fixed, the demand over-strength factor is defined as (Uang 1991, Mwafy and Elanshai 2001, Maheri and Akbari 2003, Karavasilis *et al*. 2007)

$$R_s = \frac{V_y}{V_d} \tag{9}$$

R_s: demand over strength factor

V_y : yield (actual) strength at performance point under maximum considerable earthquake (MCE)

V_d : design strength (superstructure's design base shear, V_{ss})

In the following, the correction factor, η, has been introduced to get an approximate estimate of high damping elastic response spectra from their 5% counterpart, using the Eq. (10) and Eq. (11) (Cardone *et al*. 2009)

$$\mathrm{S}_{\mathrm{de},\xi} = \eta . \mathrm{S}_{\mathrm{de},5\%} \tag{10}$$

$$S_{ae,\xi} = \eta . S_{ae,5\%} \tag{11}$$

$S_{de,\xi}$: damped spectral elastic displacement
η: Correction factor that takes into account the damping effects

The relationship between damping reduction factor, R_ξ and correction factor can be expressed as EC8 (2004) Eq. (3.6)

$$R_\xi = \frac{1}{\eta^2} \tag{12}$$

After the damping ratio, ξ, is determined, the damping reduction factor can be computed from Eq. (13) with limitation to 50% of critical damping (Ramirez *et al*. 2002, Cheng *et al*. 2008)

$$R_\xi = \frac{2.31 - 0.41\ln(5\%)}{2.31 - 0.41\ln(\xi)} \tag{13}$$

R_ξ: Damping reduction factor due to the higher damping of the isolators

3. Modeling and assumptions

To demonstrate the configuration of frames and loading, a 2-story building steel structure is selected and is illustrated in Fig. 1. The total number of bays is 3 and the width of the bays is 6 m each. The height of ground floor on isolation system is 0.5 m. The height of each floor is 3.6m. The dead load is DL=6 KN/m^2 for all floors, and live load is LL=2 KN/m^2 for all floors except for ground floor in which it is 5 KN/m^2. Therefore, the total effective seismic weight for each floor, W, is considered as 100%DL+25%LL. The frames are regular. All beam-column joints are assumed fully rigid. The diaphragms are considered rigid, too. The lateral resisting system for the superstructure is intermediate moment resisting frame for all case studies. The columns are made of box-type steel sections and beams are made of IPE steel profiles. Other geometrical specifications are illustrated in Fig. 1. The mechanical properties of steel used in superstructures are demonstrated in Table 1.

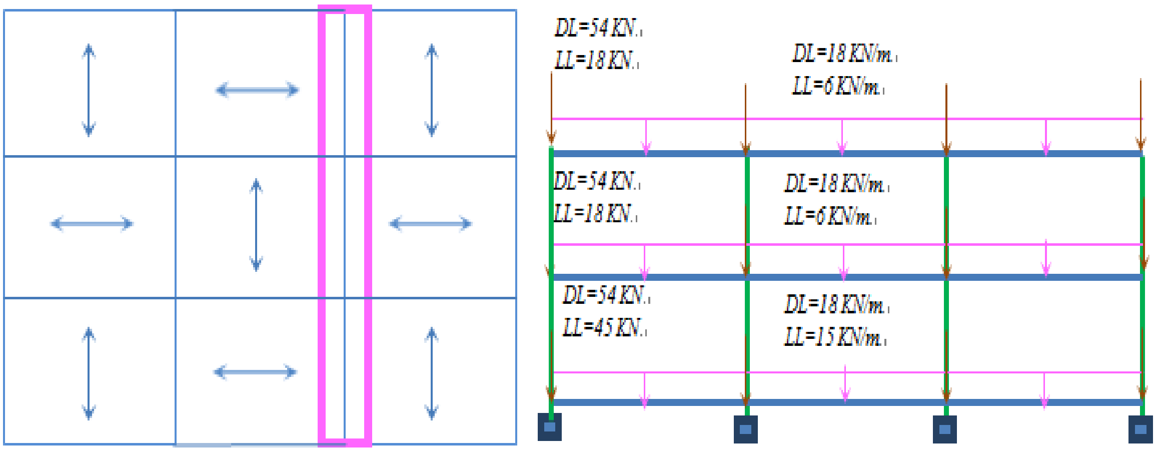
The type of isolator units in this study is lead rubber bearing (LRB isolator). The LRB isolator unit's characteristics are illustrated in Table 2. The initial stiffness k_e is defined as the ratio of the yield strength to the yield displacement as expressed in the equation $k_e = F_y/D_y$, while the post-yield stiffness k_p is given by the formula

$$k_p = \frac{G * A_r}{t_r} . f_L \tag{14}$$

Where G is the shear modulus of the rubber, A_r is the cross sectional area of the rubber layers, t_r is the total thickness of rubber consisting of n layers and the factor f_L is equal to 1.5 (FEMA-273 1997). The characteristic strength Q (at zero displacement) is given by this equation

$$Q = A_{pb} . \sigma_{ypb} \tag{15}$$

Where A_{pb} is the area of lead core and σ_{ypb} is the yield strength of lead core. Nonlinear parameters of a LRB isolator are illustrated in Fig. 2.



(a) (b)

Fig. 1 Selected 2-story isolated steel IMRF: (a) The plan and selected frame and (b) gravitational loading

In the design of LRB isolator, the initial stiffness is assumed post yield stiffness multiplied by 10 and yield strength of lead core is assumed 8 Mpa. The isolation systems and superstructures are designed according to current U.S provisions (ASCE/SEI Standard 7-05 2005, AISC Standard 341-05 2005).

The frames are assumed to be located in California coasts with mapped parameters as below

$$S_S = 150\%g$$
$$S_1 = 60\%g$$

Then, the DE and MCE spectra can be constructed as depicted in Fig. 3.

Table 1 Mechanical properties of steel material

Mechanical properties of steel material	
Modulus of elasticity	$2.01*10^8$ KN/m^2
Poisson ratio	0.3
Yield tensile strength	240000 KN/m^2
Ultimate tensile strength	370000 KN/m^2

Table 2 Mechanical Properties of LRB isolator material

Mechanical properties of LRB isolator material	
Allowable compressive strength	$7.84*10^3$ KN/m^2
Ultimate shear strain	200%
Allowable shear strain	100%
Initial stiffness/post yield stiffness	6.5-10
Yield strength of lead core	8-10 Mpa

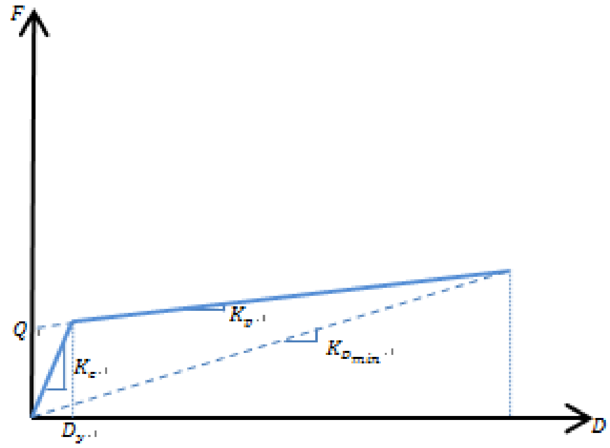


Fig. 2 Force-displacement diagram for a nonlinear LRB isolator

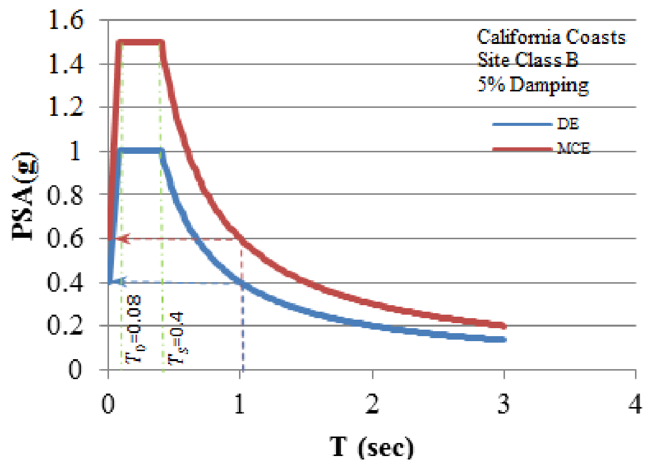


Fig. 3 The DE and MCE spectra corresponding to the site of construction

In Fig. 2:
Q: Characteristic strength Q (at zero displacement)
k_e: Initial stiffness
k_p: Post-yield stiffness
$K_{D_{min}}$: Minimum effective stiffness at design earthquake
D_y: Yield displacement

In Fig. 3:
PSA: Pseudo Spectral Acceleration
T_0: $0.2S_{D1}/S_{DS}$
T_s: S_{D1}/S_{DS}
S_{D1}: Design, 5 percent damped, spectral response acceleration parameter at a period of 1 s
S_{DS}: Design, 5 percent damped, spectral response acceleration parameter at short periods

3.1 Superstructure design

By acquiring the requirements (ASCE/SEI Standard 7-05 2005), the analysis method is equivalent static analysis

$$V_S = \frac{K_{D_{max}} . D_D}{R_I} \tag{16}$$

In ASCE 7-05, for steel IMRF R_I is

$$1 \le R_I = \frac{3}{8} R = \frac{3}{8} * 4.5 = 1.7 \le 2 \tag{17}$$

When static analysis method is used, drift ratio should not exceed $0.015 h_s$ under Design Earthquake.

$$Drift\ Ratio = \frac{\delta_{el,V_s}}{h_s} \le \frac{0.015}{\boldsymbol{R_I}} \tag{18}$$

$$Drift\ Ratio \le 0.88\% \tag{19}$$

It should be mentioned that the change in nonlinear characteristics of isolation system will change the effective parameters and then will influence the superstructure design force. Therefore, with changing the isolation nonlinear characteristics, the design base shear will change. This is a very important point which is included in the design of superstructures.

For design and nonlinear static analysis, the finite element program ETABS2000 (ETABS 2000, 2009) which accomplishes the pushover analysis procedure in a piece-wise linear fashion was used to investigate the inelastic response of the superstructure.

3.2 LRB isolator design

After designing the superstructure and gaining the final mass, the nonlinear characteristics of isolators are computed with regard to the effective values which were used in superstructure's design and with regard to an assumed value for one of nonlinear characteristics such as D_y. Eq. (20), Eq. (21) and Eq. (22) are used for this purpose. Finally, the iterative procedure to acquire the exact nonlinear characteristics has been done.

$$\xi_{eff} = \frac{4Q(D_D - D_y)}{2\pi K_{eff} {D_D}^2} \tag{20}$$

$$K_{eff} = K_p + \frac{Q}{D_D} \tag{21}$$

$$D_y = \frac{Q}{K_e - K_p} \tag{22}$$

K_{eff}: effective stiffness
ξ_{eff}: effective damping
D_D: design displacement
$K_{D_{min}}$: minimum effective stiffness at design earthquake

K_e: elastic stiffness
K_p: post-yield stiffness
F_y: yield strength
D_y: yield displacement
Q: characteristic strength
K_e: elastic stiffness
K_p: post-yield stiffness
F_y: yield strength
D_y: yield displacement
Q: characteristic strength

It is worthwhile to mention that in order to design the elements of LRB isolators, practical limitations in flexural and shear deformation, vertical compression and tension and buckling in large displacement as proposed in the James Kelly's researches, were implemented (Kelly 1997, Naeim and Kelly 1999). The aforementioned limitations are related to stability of isolation systems that are checked at MCE as the code, ASCE/SEI Standard 7-05 2005, urges.

4. Nonlinear static analysis

4.1 Nonlinear modeling of superstructure and isolation system

The plastic hinges are assigned to the superstructure according to FEMA 356 (2000). The plastic hinges are assigned at the end of beams and columns. For beam elements, plastic hinges are caused by uniaxial bending moments; and for column elements, plastic hinges are caused by axial loads and uniaxial bending moments.

Considering both the limitations on web and flange slenderness (in beams and columns) and maximum axial force to capacity axial force ratio, the nonlinear characteristics of superstructures' elements are defined in Table 3 and illustrated in Fig. 4. 5% strain hardening is assumed for steel material of superstructures.

In Table 3 and Fig. 4:
b_f: Flange width of the beam
t_f: Flange thickness of the beam
h: Column depth
t_w: Web thickness of the column
F_{ye}: Expected yield strength of the material
θ_y: Yield rotation
M_y: Yield moment

4.2 N2 method

The base isolated structures have been pushed with an inverted triangular lateral load distribution. However, there are more real lateral load distributions (Kilar and Koren 2010) for

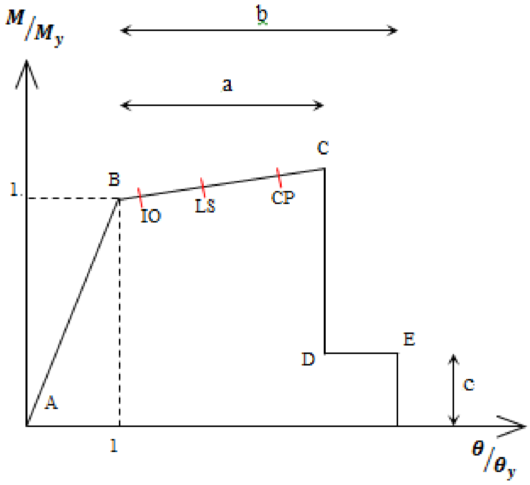


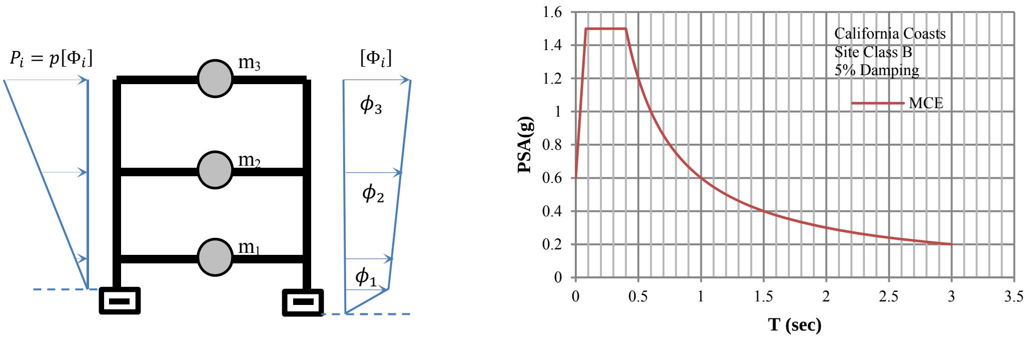
Fig. 4 Typical moment-rotation curve in pushover analysis

Table 3 Modeling parameters and acceptance criteria for nonlinear procedures as used in present study

Component/Action	Modeling parameters			Acceptance criteria				
	Plastic rotation angle, radians		Residual strength ratio	Plastic rotation angle, radians				
				IO	Primary		Secondary	
	a	b	c		LS	CP	LS	CP
Beams								
$\frac{b_f}{2t_f} \geq \frac{65}{\sqrt{F_{ye}}}$ Or $\frac{h}{t_w} \geq \frac{640}{\sqrt{F_{ye}}}$	$4\theta_y$	$6\theta_y$	0.2	$0.25\theta_y$	$2\theta_y$	$3\theta_y$	$3\theta_y$	$4\theta_y$
Columns								
$\frac{b_f}{2t_f} \geq \frac{65}{\sqrt{F_{ye}}}$ Or $\frac{h}{t_w} \geq \frac{460}{\sqrt{F_{ye}}}$	$4\theta_y$	$6\theta_y$	0.2	$0.25\theta_y$	$2\theta_y$	$3\theta_y$	$3\theta_y$	$4\theta_y$

pushing base isolated structures, the inverted triangular lateral load is used in order to avoid underestimation of the inelastic response of base isolated structures. To assemble the lateral load distribution, a displacement shape corresponding to provisional distribution of design base shear in height of the building is assumed. The minimum effective stiffness at MCE, $K_{M_{min}}$, is used to gain a desired displacement demand in the elastic modal analysis.

For seismic loading, the MCE spectrum which is the representative of assumed seismic hazard of the region is used. In Fig .5, a simplified model for nonlinear analyses, selected lateral load distribution and the seismic load are illustrated.



(a) (b)

Fig. 5 (a) Simplified model for nonlinear analyses and selected lateral load distribution and (b) seleceted MCE spectrum for nonlinear static procedure

In Fig. 5(a):
$[\Phi_i]$: assumed displacement shape in height
m_i: Mass of floor in story i
P_i: Vector of lateral load in story i
p: Controller of the magnitude of the lateral load

In Fig. 6, a rational methodology to compute demand R_I by means of N2 method is presented and the procedure for the calculation of this factor is described as below.

Step 1: After the pushover curve for the base isolated structure is gained, this curve with a transformation factor, Γ, will move to the SDOF coordinate system. "Equal displacement rule", which is proven for base isolated structures on elastomeric bearings (Kilar and Koren 2010) has been applied to gain the target displacement point of the superstructure at MCE.

$$\Gamma = \frac{\sum m_i \Phi_i}{\sum m_i {\Phi_i}^2} = \frac{m^*}{\sum m_i {\Phi_i}^2} \tag{23}$$

Γ: Transformation factor between MDOF and SDOF system
m_i: Mass of floor in story i
Φ_i: Normalized displacement in story i
m^*: Mass of the equivalent SDOF system
T^*: Period of the equivalent SDOF system
For a damped elastic SDOF system, the following relation applies

$$S_{de,\xi} = \frac{T^2}{4\pi^2} . S_{ae,\xi} \tag{24}$$

For a damped inelastic SDOF system with a bilinear force-deformation relationship, the acceleration spectrum and the displacement spectrum can be determined as Vidic *et al.* 1994

$$S_{d,\xi} = \frac{\mu}{R_\mu} S_{de,\xi} \xrightarrow{T \geq T_c \text{ then: } R_\mu = \mu} S_{d,\xi} = S_{de,\xi} \tag{25}$$

Step 2: Subsequently, as it is illustrated in Fig. 6a, by the use of the displacement performance point in SDOF coordinate system, demand ductility reduction factor and demand damping reduction factor can be calculated from Eq. (8) and Eq. (13).

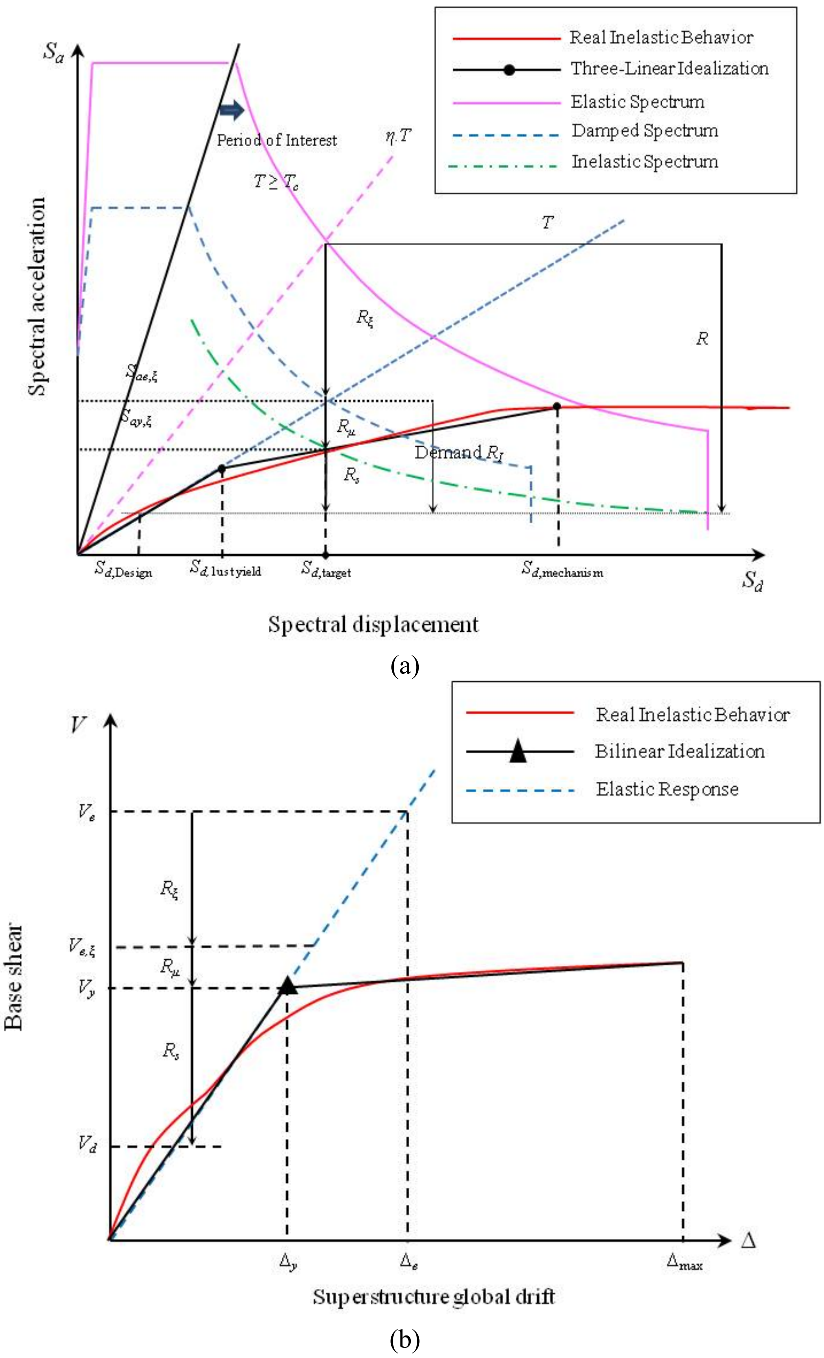


Fig. 6 The methodology used to evaluate demand R_I

Step 3: In the following, the superstructure in MDOF coordinate system is considered fixed without isolator and is pushed till the displacement performance point at MCE. The capacity curve for base isolated structures without isolators is illustrated in Fig. 6(b). Therefore, demand over-strength factor can be computed from Eq. (9). Then, by means of demand ductility reduction factor and demand over-strength factor, demand R_I can be computed.

Whenever the value of demand R_I factor increases, the inelastic response of base isolated structure is more severe. It is necessary to remind that we do not define a damage limit state to calculate the supply R_I. Instead, the inelastic response of superstructure under a specific earthquake, Maximum Considerable Earthquake (MCE) in a high seismic hazard region, is investigated. Therefore, the here-in calculated R_I is demand R_I.

If

$$R_{I_{Demand}} \geq R_{I_{Supply}} (= R_{I_{Code}}) \tag{26}$$

The inelastic response of superstructure will exceed its provisional allowable limit.

In Fig. 6(a):

R: Demand response modification factor
Demand R_I: Demand response modification factor without the consideration of damping reduction factor
R_{μ}: Demand ductility reduction factor
R_s: Demand over-strength factor
R_{ξ}: Demand damping reduction factor
$S_{ae}(T)$: Acceleration demand required for elastic behavior corresponding to T
$S_{ae,\xi}(T)$: Damped acceleration demand required for elastic behavior
$S_{ay,\xi}(T)$: Damped yield acceleration demand
$S_{d,Design}(T)$: Displacement demand equivalent to superstructure's design base shear level
$S_{d,1st\ yield}(T)$: Displacement demand at first yield in superstructure
$S_{d,target}(T)$: Displacement demand at performance point at MCE
$S_{d,Mechanism}(T)$: Displacement demand at collapse point of superstructure
η: Correction factor that takes into account the damping effects
T: Period of idealized base isolated structure as SDOF system
T_c: Corner period between the constant acceleration and the constant velocity range

In Fig. 6(b):

V_e: Elastic strength
$V_{e,\xi}$: Damped elastic strength
V_y: Yield strength
V_d: Design strength
Δ_e: Elastic global drift of superstructure
Δ_y: Yield global drift of superstructure
Δ_{max}: Collapse global drift of superstructure

5. Case studies

To evaluate the influence of superstructure flexibility on inelastic behavior of base isolated structures, the 2-story, 4- story and 6-story steel IMRFs have been investigated in this study. This is the first group of our case studies and we name it group A. The configuration of these frames is illustrated in Fig. 7. The LRB isolator unit's nonlinear characteristics are identical for all these frames and are selected in a way that isolation occurs even in the most flexible superstructure (6-story frame). The nonlinear characteristics and equivalent linear characteristics for the isolator unit of this group are shown in Table 4 and Fig. 8. The frames' sections for this group are demonstrated in Table 5-7.

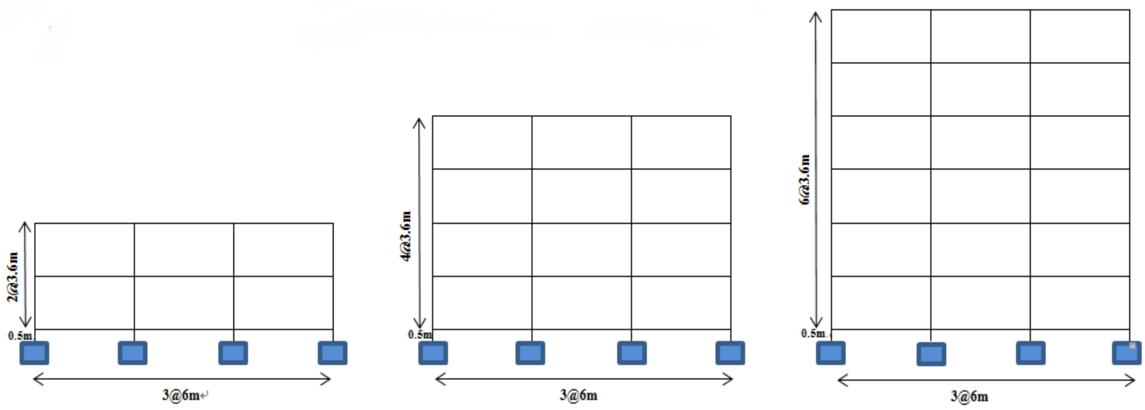


Fig. 7 Geometry of the intermediate moment resisting frames under investigation (Group A)

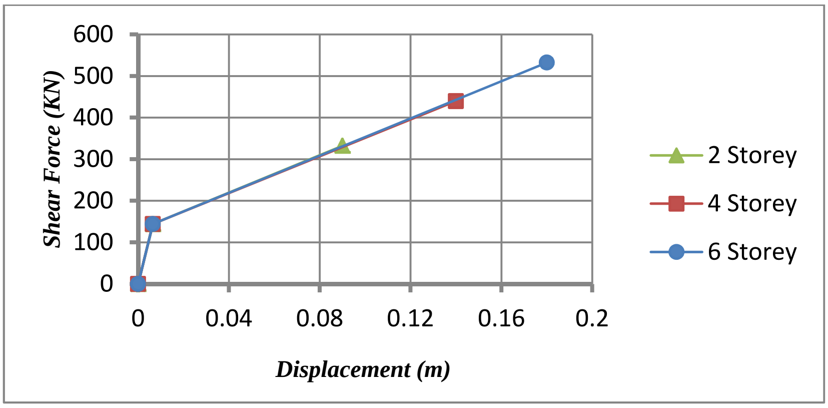


Fig. 8 Designed LRB isolator units' force-displacement diagram (Group A)

Table 4(a) Nonlinear characteristics of designed LRB isolator units

For isolator unit (KN, m, sec)				
Q	K_p	D_y	$\alpha=K_{pl}/K_{el}$	F_y
32.43	557.02	0.0065	0.10	36.03

Table 4(b) amplitude-dependant characteristics of LRB isolator units at DE

Number of Storys	$W_{Designed}$	S_{D1} =0.4 g					$K_{D\ min}$ For Isolator Unit
	100%DL+25%LL	$T_{eff\text{-}D}$	$\xi_{eff\text{-}D}$ (%)	B_D	D_D	$\frac{V_{ss}}{W}$	
2-story	1935.0	1.47	15	1.38	0.091	0.130	904.2
4-story	3236.8	2.04	17.62	1.46	0.139	0.103	784.4
6-story	4579.8	2.50	22.75	1.60	0.180	0.089	737.2

Table 4(c) amplitude-dependant characteristics of LRB isolator units at MCE (Group A)

S_{M1} =0.6 g					
Number of Storys	$T_{eff\text{-}M}$	$\xi_{eff\text{-}M}$(%)	B_M	D_M	$K_{M\ min}$
2-story	1.64	10.76	1.24	0.198	720.7
4-story	2.21	7.99	1.13	0.291	668.6
6-story	2.68	6.50	1.07	0.373	644.1

Table 5 Designed Sections of 2-Story building frame (Group A)

2-Story		
Story Level	Columns	Beams
Ground	Box220x20	IPE400
1st Story	Box220x20	IPE360
2nd Story	Box180x16	IPE330

Table 6 Designed Sections of 4-Story building frame (Group A)

4-Story		
Story Level	Columns	Beams
Ground	Box260x20	IPE450
1st Story	Box260x20	IPE400
2nd Story	Box240x20	IPE400
3rd Story	Box220x20	IPE360
4th Story	Box180x16	IPE330

Table 7 Designed Sections of 6-Story building frame (Group A)

6-Story		
Story Level	Columns	Beams
Ground	Box300x20	IPE500
1st Story	Box300x20	IPE450
2nd Story	Box280x20	IPE450
3rd Story	Box260x20	IPE450
4th Story	Box240x20	IPE400
5th Story	Box220x20	IPE360
6th Story	Box180x16	IPE330

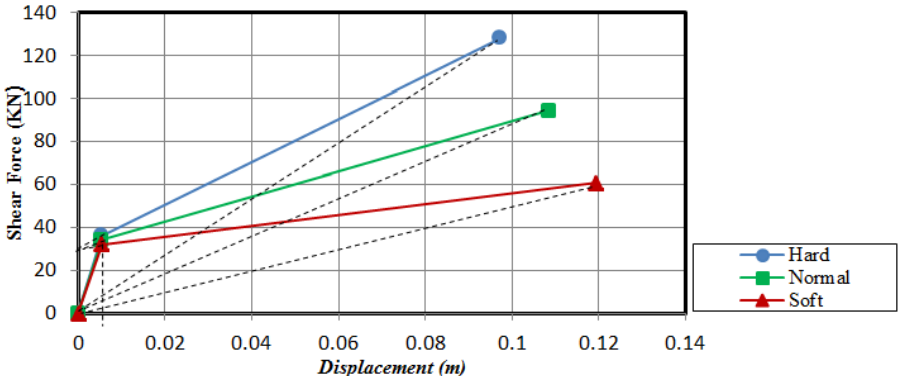


Fig. 9 Designed LRB isolator units' force-displacement diagram (Group B)

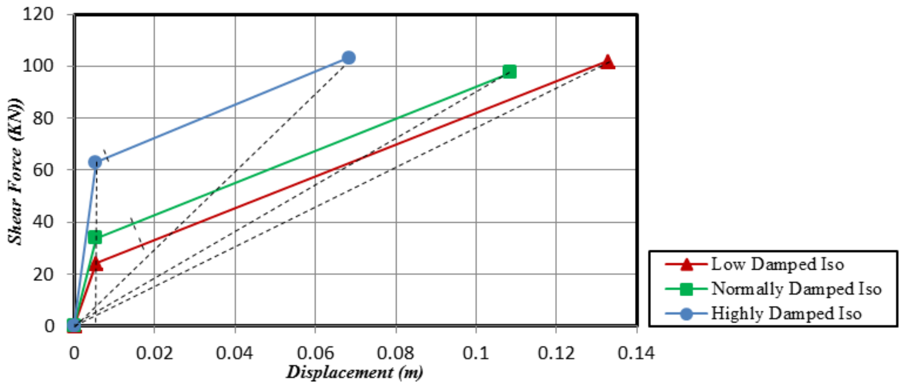


Fig. 10 Designed LRB isolator units' force-displacement diagram (Group C)

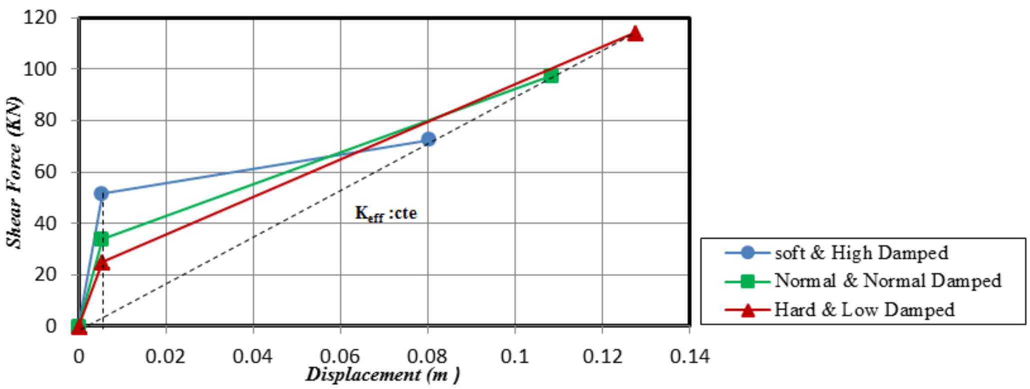


Fig. 11 Designed LRB isolator units' force-displacement diagram (Group D)

In group B, yield displacement and characteristic strength are assumed constant and the effect of post-yield stiffness is investigated on inelastic response of the superstructure. However, it is noticeable that changes in post-yield stiffness have significant influence on effective period and consequently on seismic design force, V_{ss}.

In group C, yield displacement and post-yield stiffness are assumed constant and the effect of characteristic strength is investigated on nonlinear response of the superstructure. The seismic design force, V_{SS}, is almost identical for all frames of this group.

In group D, yield displacement and effective stiffness at design earthquake are assumed constant and an effort has been made to find out the best nonlinear curve for the isolation system in such way that the least yielding occurs in the superstructure.

For group B, C and D the force-displacement relation, nonlinear characteristics and equivalent linear characteristics for LRB isolator unit at DE and MCE, and their equivalent superstructure frame sections are illustrated in Tables 8-10 and Fig. 9-11. The effective parameters of the isolator unit which are used in Tables 8- 10 are described as:

$T_{eff\text{-}D}$ and $T_{eff\text{-}M}$: Effective period of base isolated building respectively at DE and MCE
$\xi_{eff\text{-}D}$ and $\xi_{eff\text{-}M}$: Effective damping ratio of isolation system respectively at DE and MCE
B_D and B_M: Damping coefficient of isolation system respectively at DE and MCE
D_D and D_M: Displacement of isolator unit respectively at DE and MCE
V_{ss} : Design base shear used for design of superstructure($= V_d$)
$K_{D\,min}$ and $K_{M\,min}$: Minimum effective stiffness of base isolated building respectively at DE and MCE
$K_{D\,max}$ and $K_{M\,max}$: Maximum Effective stiffness of base isolated building respectively at DE and MCE (these effective stiffness are just used to amplify the design force shear for design and stability control of base isolated structures)

Table 8(a) Nonlinear characteristics of designed LRB isolator units

For Isolator Unit (KN, m, sec)							
Isolator Type	Q/W	Q	K_p	D_y	$\alpha=K_{pl}/K_{el}$	K_e	F_y
Hard	0.0633	30.80	1000	0.0054	0.15	6703.45	36.20
Normal	0.0633	30.80	586	0.0054	0.09	6289.45	33.96
Soft	0.0633	30.80	250	0.0054	0.04	5953.45	32.15

Table 8(b) Amplitude-dependant characteristics of LRB isolator units at DE

S_{D1} =0.4 g					W	$K_{D\,min}$
$T_{eff\text{-}D}$	$\xi_{eff\text{-}D}$	B_D	D_D	$\frac{V_{ss}}{W}$	100%DL+25%LL	For Isolator Unit
1.22	11.11	1.25	0.097	0.201	1956.72	1323.08
1.50	15.06	1.38	0.109	0.148	1935.40	861.18
1.96	23.80	1.63	0.119	0.096	1922.74	503.09

Table 8(c) Amplitude-dependant characteristics of LRB isolator units at MCE

S_{M1} =0.6 g				
$T_{eff\text{-}M}$	$\xi_{eff\text{-}M}$	B_M	D_M	$K_{M\,min}$
1.29	7.08	1.09	0.176	1175.37
1.62	9.90	1.20	0.201	739.60
2.26	16.38	1.42	0.237	380.06

Table 8(d) Designed Sections of 2-Story building frame (Group B)

2-Story						
Story	Soft Isolator		Normal Isolator		Hard Isolator	
Level	Columns	Beams	Columns	Beams	Columns	Beams
Ground	Box200x14	IPE400	Box240x14	IPE450	Box260x16	IPE500
1st Story	Box200x14	IPE330	Box240x14	IPE360	Box260x16	IPE400
2nd Story	Box180x14	IPE300	Box220x12	IPE330	Box240x16	IPE330

Table 9(a) Nonlinear characteristics of designed LRB isolator units

For Isolator Unit (KN, m, sec)							
Isolator Type	Q/W	Q	K_p	D_y	$\alpha=K_{pl}/K_{el}$	K_e	F_y
Low Damped	0.0433	21.07	586	0.0054	0.13	4487.41	24.23
Normal Damped	0.0633	30.80	586	0.0054	0.09	6289.45	33.96
High Damped	0.1233	59.99	586	0.0054	0.05	11695.56	63.16

Table 9(b) amplitude-dependant characteristics of LRB isolator units at DE

S_{D1} =0.4 g					$W_{Designed}$	$K_{D\ min}$
$T_{eff\text{-}D}$	$\xi_{eff\text{-}D}$	B_D	D_D	$\frac{V_{ss}}{W}$	100%DL+25%LL	For Isolator Unit
1.62	10.13	1.21	0.133	0.156	1935.40	743.17
1.50	15.06	1.38	0.109	0.148	1935.40	861.18
1.17	26.59	1.71	0.068	0.152	1935.40	1410.82

Table 9(c) amplitude-dependant characteristics of LRB isolator units at MCE

S_{M1} =0.6 g				
$T_{eff\text{-}M}$	$\xi_{eff\text{-}M}$	B_M	D_M	$K_{M\ min}$
1.70	6.26	1.06	0.239	674.13
1.62	9.90	1.20	0.201	739.60
1.37	20.54	1.54	0.132	1041.67

Table 9(d) Designed Sections of 2-Story building frame (Group C)

2-Story For Low, Normal & High Damped Isolator		
Story Level	Columns	Beams
Ground	Box240x14	IPE450
1st Story	Box240x14	IPE360
2nd Story	Box220x12	IPE330

Table 10(a)Nonlinear characteristics of designed LRB isolator units

For Isolator Unit (KN, m, sec)							
Isolator Type	Q/W	Q	K_p	D_y	$\alpha=K_{pl}/K_{el}$	K_e	F_y
Hard & Low Damped	0.0433	21.07	700.1	0.0054	0.15	4601.54	24.85
Normal & Normal Damped	0.0633	30.8	585.9	0.0054	0.09	6289.36	33.96
Soft & High Damped	0.1033	50.26	259.9	0.0054	0.03	9567.42	51.66

Table 10(b) amplitude-dependant characteristics of LRB isolator units at DE

S_{D1} =0.4 g					$W_{Designed}$	$K_{D\ min}$
$T_{eff\text{-}D}$	$\xi_{eff\text{-}D}$	B_D	D_D	$\frac{V_{ss}}{W}$	100%DL+25%LL	For Isolator Unit
1.50	8.98	1.17	0.127	0.174	1949.20	871.52
1.50	15.06	1.38	0.108	0.148	1935.40	865.35
1.50	32.04	1.86	0.080	0.110	1931.60	863.65

Table 10(c) amplitude-dependant characteristics of LRB isolator units at MCE

S_{M1} =0.6 g				
$T_{eff\text{-}M}$	$\xi_{eff\text{-}M}$	B_M	D_M	$K_{M\ min}$
1.57	5.58	1.03	0.228	792.40
1.62	9.90	1.20	0.201	739.60
1.85	25.65	1.68	0.164	567.11

Table 10(d) Designed Sections of 2-Story building frame (Group D)

2-Story						
Story Level	Soft & High Damped		Normal & Normal Damped		Hard & Low Damped	
	Columns	Beams	Columns	Beams	Columns	Beams
Ground	Box200x16	IPE400	Box240x14	IPE450	Box240x16	IPE450
1st Story	Box200x16	IPE360	Box240x14	IPE360	Box240x16	IPE400
2nd Story	Box180x16	IPE330	Box220x12	IPE330	Box220x16	IPE330

6. Results

In this section, the results of nonlinear static analyses are presented. The obtained pushover curves for base isolated structures from ETABS2000 program were transferred to SDOF

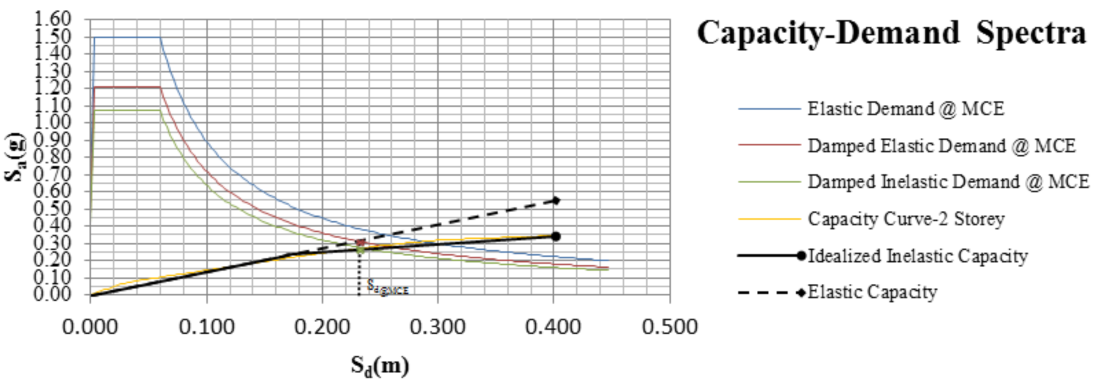


Fig. 12 Selected capacity curve of base isolated structure at SDOF coordinate system for estimation of demand ductility reduction factor (Group A, 2-Story Frame)

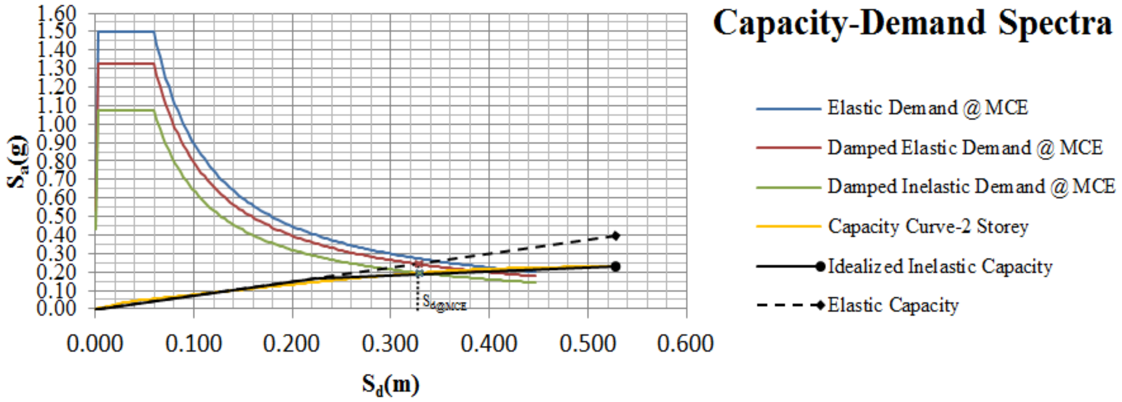


Fig. 13 Selected capacity curve of base isolated structure at SDOF coordinate system for estimation of Demand Ductility Reduction Factor (Group A, 4-Story Frame)

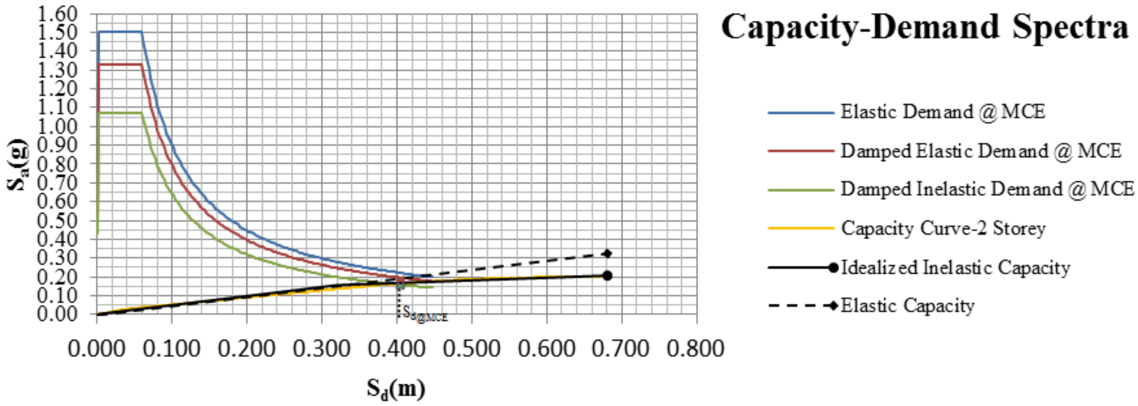


Fig. 14 Selected capacity curve of base isolated structure at SDOF coordinate system for estimation of demand ductility reduction factor (Group A, 6-Story Frame)

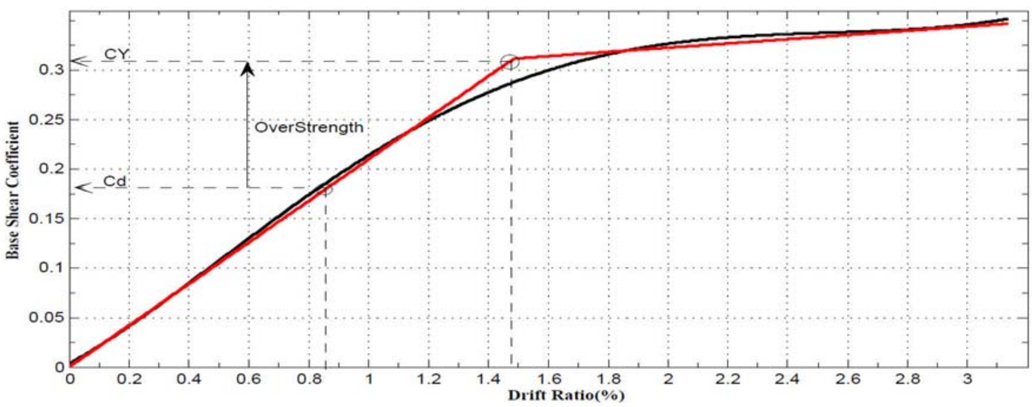


Fig. 15 Selected capacity curve of base isolated structure without isolator units at MDOF coordinate system for estimation of Demand Over-Strength Factor (Group A, 2-Story Frame)

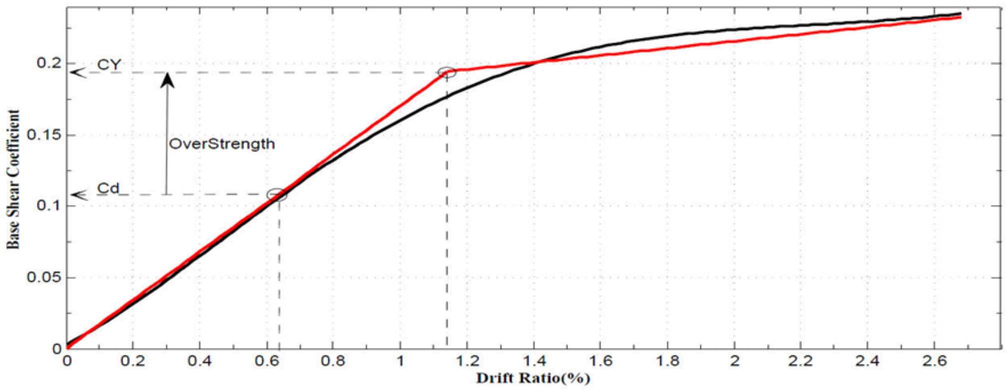


Fig. 16 Selected capacity curve of base isolated structure without isolator units at MDOF coordinate system for estimation of Demand Over-Strength Factor (Group A, 4-Story Frame)

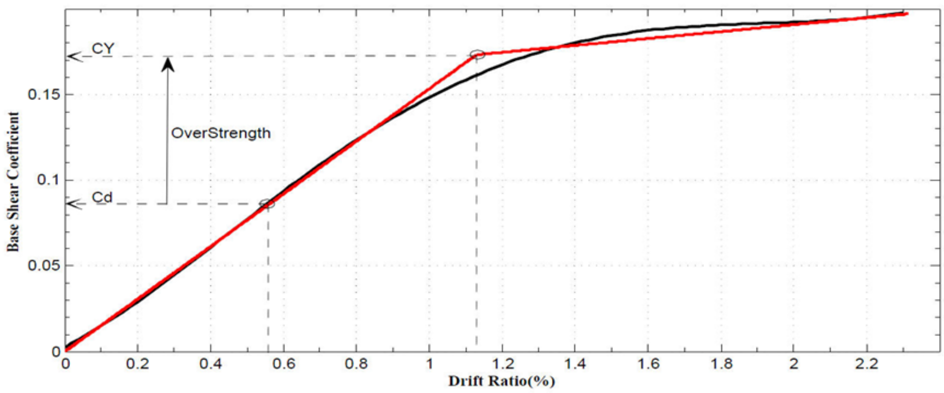


Fig. 17 Selected capacity curve of base isolated structure without isolator units at MDOF coordinate system for estimation of Demand Over-Strength Factor (Group A, 6-Story Frame)

coordinate system via a written code in MATLAB software (MATLAB 2009a 2009) in order to calculate the demand ductility reduction factor. Later on, the superstructure became fixed without isolator units and the superstructure was pushed till performance drift point which was estimated in the previous step. Thenceforth the demand over-strength factor could be calculated. Finally, the demand R_I can be computed. The aforementioned procedure is done for each group of case studies. For instance, the results of these pushover curves are illustrated comprehensively for group A in Fig. 12-17. In the aforementioned figures, the idealized inelastic capacity curves were determined based on the equal displacement principle.

6.1 Ductility reduction factor and over- strength factor (Demand)

The results of computation of components of demand R_I of group A through group D are demonstrated in Tables 11- 14. In these tables, for each group, the period of equivalent SDOF system, T^*, demand damping coefficient at MCE, B_M, demand ductility coefficient ,μ, demand ductility reduction factor, R_μ , demand over-strength factor, R_s and consequently demand R_I, are presented.

Table 11 The effect of superstructure flexibility on demand RI parameters of the frames- Height of superstructure: var. (Group A)

Num of Storys	Lateral Resisting System	T*(s)	B_M	μ	R_μ	R_s	R_I
2-Story	IMRF	1.64	1.24	1.13	1.13	1.68	1.90
4-Story	IMRF	2.31	1.13	1.24	1.24	1.89	2.34
6-Story	IMRF	2.89	1.07	1.19	1.19	1.95	2.31

Table 12 The effect of post-yield stiffness of LRB isolator unit on demand RI parameters of the frames - K_p: var. (Group B)

2-Story							
K_p - (KN/m)	Lateral Resisting System	T*(s)	B_M	μ	R_μ	R_s	R_I
1000	IMRF	1.38	1.17	1.33	1.33	1.46	1.94
586	IMRF	1.64	1.28	1.15	1.15	1.57	1.81
250	IMRF	2.23	1.42	1.07	1.07	1.55	1.66

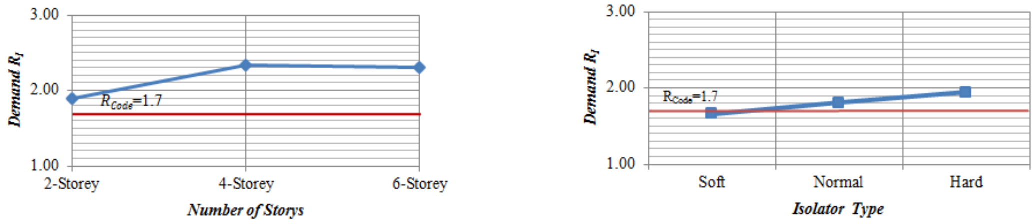
Table 13 The effect of post-yield stiffness of LRB isolator unit on demand RI parameters of the frames- $\frac{Q}{W}$: var. (Group C)

2-Story							
Q/W	Lateral Resisting System	T*(s)	B_M	μ	R_μ	R_s	R_I
4.33%	IMRF	1.76	1.13	1.20	1.20	1.69	2.03
6.33%	IMRF	1.64	1.28	1.15	1.15	1.57	1.81
12.33%	IMRF	1.38	1.57	1.10	1.10	1.38	1.52

Table 14 The effect of post-yield stiffness of LRB isolator unit on demand RI parameters of the frames-K_p&$\frac{Q}{W}$: var. (Group D)

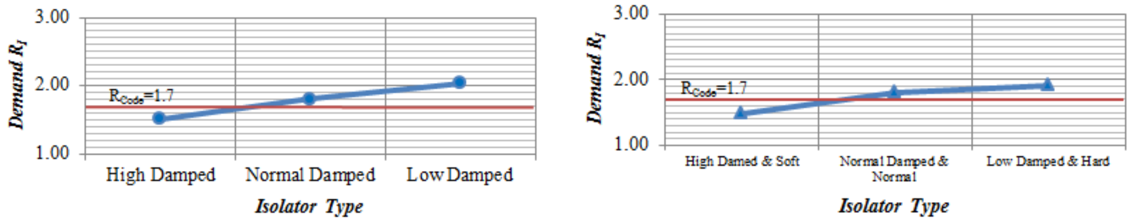
2-Story								
$K_{eff} = cte$		Lateral Resisting System	T*(s)	B_M	μ	R_μ	R_s	R_I
K_p - (KN/m)	Q/W							
700	4.33%	IMRF	1.52	1.16	1.21	1.21	1.70	2.06
586	6.33%	IMRF	1.64	1.28	1.15	1.15	1.57	1.81
260	10.33%	IMRF	2.89	1.74	1.00	1.00	1.48	1.48

In group A, increase in superstructure flexibility through an increase in height of frames, results in a significant increase in demand ductility reduction factor from 2-story to 4-story, but from 4-story frame to 6-story frame, there is a little drop in demand ductility reduction factor. This is due to little difference between elastic and inelastic capacity for the taller frames at major earthquakes. A continuing increase in demand over-strength factor whenever the height of the frames increases is observed. The final result of increase in height of superstructures results in an increase in demand R_I till 4-story frame and afterward no change is observed in this factor by



(a) (b)

Fig. 18 The effect of number of story and post-yield stiffness of LRB isolator unit on R_I Factor



(a) (b)

Fig. 19 The effect of damping of LRB isolator unit and both post-yield stiffness and damping of LRB isolator unit on R Factor

increase in height from 4-story to 6-story.

In group B, decrease in post-yield stiffness results in decrease in the demand ductility reduction factor but not significant change in the demand over-strength factor. The final result of decrease in post-yield stiffness culminates in decrease in demand R_I. Therefore more flexibility at isolation level, leads to smaller damage at the superstructure.

In group C, an increase in characteristic strength results in decrease in both demand ductility reduction factor and demand over-strength factor. As a result, a decrease in demand R_I is observed.

In group D, the effective stiffness at design earthquake is assumed constant. The main variable parameters are post-yield stiffness and characteristic strength. The results for this group demonstrate that isolation system with the least value of post-yield stiffness and the highest allowable value of characteristic strength, will result in minimum value of demand R_I factor and so the least value in the inelastic behavior.

6.2 Demand R_I in comparison to its provisional counterpart

In Figs. 18-19, the values of demand R_I based on superstructure and isolator unit's characteristics under a specific lateral load distribution are presented and compared with the fixed value of provisional R_I (ASCE/SEI Standard 7-05 2005). In Fig. 18(a), the demand R_I in all cases was exceeded the R_{Code} and the maximum value of R_I in group A is denoted to 4- and 6- story frame with values of 2.3. In Fig. 18(b), The R_I factor oscillates between the R_{Code}. The hardest isolator has the highest value of R_I factor. In Fig. 19(a), The R_I alters around the provisional R_I, too. Lower characteristic strength at isolation level, has higher value of R_I. In Fig. 19(b), considering the results of Figs. 18(b) and 19(a), the best isolator unit is the one that has the softest rubber and has the highest characteristic strength. Therefore, the superstructure will suffer the least damage. The oscillation of estimated demand R_I around the provisional R_I demonstrates the exactness of the proposed method for calculating the demand R_I.

7. Conclusions

In the present study, the effect of superstructure flexibility and nonlinear characteristics of LRB isolator on inelastic response of superstructure has been investigated via evaluation of demand R_I. Some of the major conclusions are as follows:

1- A rationale methodology is proposed to evaluate the demand R_I for base isolated structures in order to investigate inelastic response of base isolated structures.

2- An increase in superstructure flexibility by means of a rise in height of the superstructure results in an increase in the demand R_I and so more severe damage in the superstructure but from 4-story frame to 6-story frame, the value of the demand R_I remains constant and so no more severe damage is observed.

3- An increase in flexibility at isolation level via the decrease in post-yield stiffness culminates in lower demand R_I.

4- An increase in damping ratio at isolation level via the increase in characteristic strength results in lower demand R_I and lighter damage at the superstructure.

5- The most optimized LRB isolator is one that has the least value of post yield stiffness and the higher value of the characteristic strength in which makes the superstructure to sustain the least damage.

6- The oscillation of estimated R_I factor around its provisional counterpart verifies the accuracy of the proposed methodology.

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