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Retrofitting of vulnerable RC structures by base isolation technique

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Abstract. The scale and nature of the recent earthquakes in the world and the related earthquake disaster index coerce the concerned community to become anxious about it. Therefore, it is crucial that seismic lateral load effect will be appropriately considered in structural design. Application of seismic isolation system stands as a consistent alternative against this hazard. The objective of the study is to evaluate the structural and economic feasibility of reinforced concrete (RC) buildings with base isolation located in medium risk seismic region. Linear and nonlinear dynamic analyses as well as linear static analysis under site-specific bi-directional seismic excitation have been carried out for both fixed based (FB) and base isolated (BI) buildings in the present study. The superstructure and base of buildings are modeled in a 3D finite element model by consistent mass approach having six degrees of freedom at each node. The floor slabs are simulated as rigid diaphragms. Lead rubber bearing (LRB) and High damping rubber bearing (HDRB) are used as isolation device. Change of structural behaviors and savings in construction costing are evaluated. The study shows that for low to medium rise buildings, isolators can reduce muscular amount of base shears, base moments and floor accelerations for building at soft to medium stiff soil. Allowable higher horizontal displacement induces structural flexibility. Though incorporating isolator increases the outlay, overall structural cost may be reduced. The application of base isolation system confirms a potential to be used as a viable solution in economic building design.

Keywords: aseismic building; base isolation; nonlinear dynamics; linear dynamic analysis; seismic excitation; structural insinuation; economic insinuation

1. Introduction

Raising possibility of earthquake occurrence all over the world attracts attention for safe building design under seismic loading. The risk is significantly higher for fixed based (FB) building as the stochastic responses become vulnerable due to higher stiffness of superstructure. Hence, seismic research is being resorted to new technology for mitigation of seismic hazard on structure (Borzi *et al*. 2013, Ozmen *et al*. 2013). Isolating the superstructure from substructure is an innovative alternative which is being practiced at recent decades. Seismic isolation separates

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the building structure from damaging earthquake by providing flexibility and energy dissipation capability through incorporation of isolation device between the foundation and superstructure (Ismail *et al*. 2010). The approach can cope with simple structural design to mitigate or reduce potential seismic damage. Base-isolation is an attractive retrofitting strategy as well to improve the seismic performance of existing bridges and monumental historic buildings (Islam *et al*. 2012b, Kampas and Makris 2012, Naeim and Kelly 1999, Tornello and Sarrazin 2012). Existing literature says the vulnerability of seismic excitation (Eleftheriadou and Karabinis 2012, Yön *et al*. 2013) and its essential treatment by innovative strategy. Since the 1995 Hyogoken-nanbu earthquake, construction of seismic base isolated (BI) buildings have been seen to increase rapidly including residential buildings, nuclear power plants, office buildings, hospitals and schools.

It is believed that isolation technology is very effective in improving the seismic performance of low- and medium-rise buildings, but not to be advised for high-rise buildings. A substantial amount of work has been done on base-isolated buildings. Ariga *et al*. (2006) investigated the resonant behavior of base-isolated high-rise buildings under long-period ground motion; Takewaki (2008) investigated the robustness of base-isolated high-rise buildings under code-specified ground motion, and concluded that base-isolated high-rise buildings have lower robustness than base-isolated low-rise buildings; Takewaki and Fujita (2009) studied the earthquake input energy to base-isolated high-rise buildings by both time-domain and frequency-domain methods; Pourzeynali and Zarif (2008) optimized the parameters of the base isolation system, using genetic algorithms, to simultaneously minimize the displacement of the top story and that of the base isolation system.

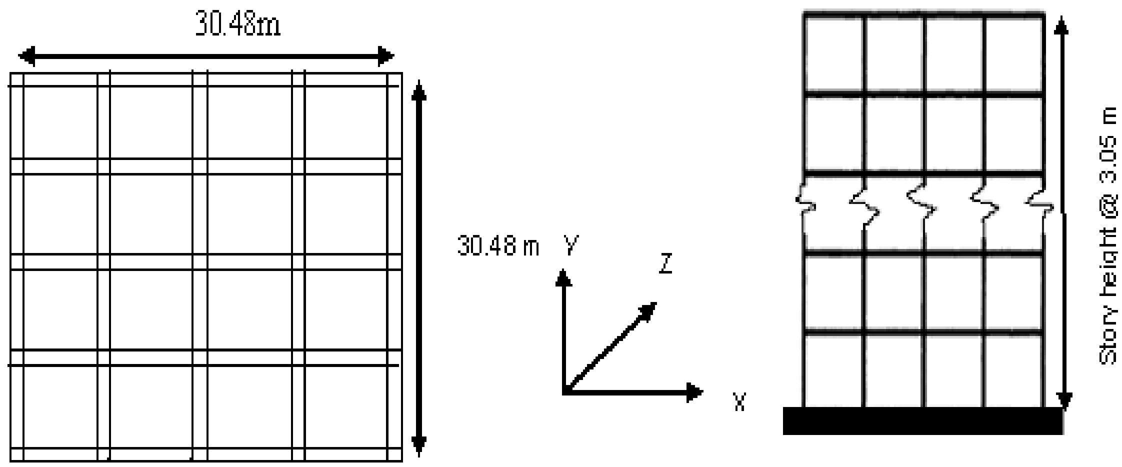
Since isolators are easily damaged by uplift when taller buildings are subjected to major earthquakes some new devices to avoid damages by uplift of the isolators have been invented (Roussis and Constantinou 2006) .Several past and recent researches in the area of base isolation have focused on the use of elastomeric bearings, such as HDRB (Bhuiyan *et al*. 2009) and LRB (Providakis 2008). Jangid (2007), Providakis (2008) investigated seismic responses of multi- story buildings for near fault motion isolated by LRB. Dall'Asta and Ragni (Dall'Asta and Ragni 2006, Dall'Asta and Ragni 2008) have conducted experimental tests, analytical model and nonlinear dynamic analysis of HDRB. Base isolator with hardening behavior under increasing loading has been developed for medium-rise buildings (up to four stories) and sites with moderate earthquake risk (Pocanschi and Phocas 2007). Long period building responses were evaluated by Olsen *et al*. (2008). The seismic isolation approach for multi-story buildings have been evaluated and reviewed in few more studies (Casciati and Hamdaoui 2008, Dicleli and Buddaram 2007, Lu and Lin 2008, Polycarpou and Komodromos 2010, Spyrakos *et al*. 2009).

However, in spite of growing familiarity of the isolation approach worldwide, incorporating the device practically for local buildings in Dhaka, Bangladesh area is still an issue to fit with the native requirements. Therefore feasibility study for rubber bearing in building base in terms of structural as well as economical concern is of burning importance. Bi-directional seismic loading of the in-situ environment is an additional issue as well. Furthermore, time history and response spectrum techniques need to be performed concurrently for buildings to check precise isolated behaviors. In this study, suppression of the dynamic response of building structures supported on elastomeric bearings has been studied by equivalent static, linear and nonlinear dynamic analyses with advanced finite element program (Islam *et al*. 2014a). The time domain method considers nonlinearities present in the structural system. In addition, the combined models of HDRB and LRB in structural base are incorporated to evaluate the economic feasibility. The analysis and design of isolators for a sample 8-story residential building in Dhaka using SAP 2000 (CSI 2004, Habibullah 2005) have been performed first. The displacement behaviors, base shear and base moments for fixed and isolated buildings have been investigated. Design parameters of isolator for numerous buildings of 4 to 10-stories have been evaluated. Lastly, net cost savings for using isolator in buildings of varying elevation have been evaluated.

2. Mathematical modeling

The plan area and the story-wise elevation considered for 10 to 4 story in this study have been shown in Fig. 1. The superstructure is modeled as a linear elastic system. Moment resisting concrete frame has been considered. The base isolators are fixed to the foundation at the bottom and to the base mass at the top. The subsequent simplified assumptions are made for the analyses.

- The superstructure and base is modeled by consistent mass approach having six degrees of freedom at each node.
- The isolator placed between base and floor is assumed to be infinitely rigid.
- The main building is expected to remain within the elastic limit during seismic excitation. Since the base isolation system lessens the structural responses to relatively low values, this assumption is reasonable.
- The floor slabs are simulated as rigid diaphragms (lumped mass and rigid floor assumption).
- The columns providing the lateral stiffness are inextensible.
- The nonlinearities arising due to large deformation, base isolator bearings and seismic forces are duly considered.
- The base isolator carries the vertical load without undergoing vertical deformation.
- LRB and HDRB are used as isolation device.
- The structural system is subjected to double directional horizontal component of the earthquake ground motion (bi-directional support excitation assumption)
- No soil-structure interaction is considered in the analyses.



(a) (b)

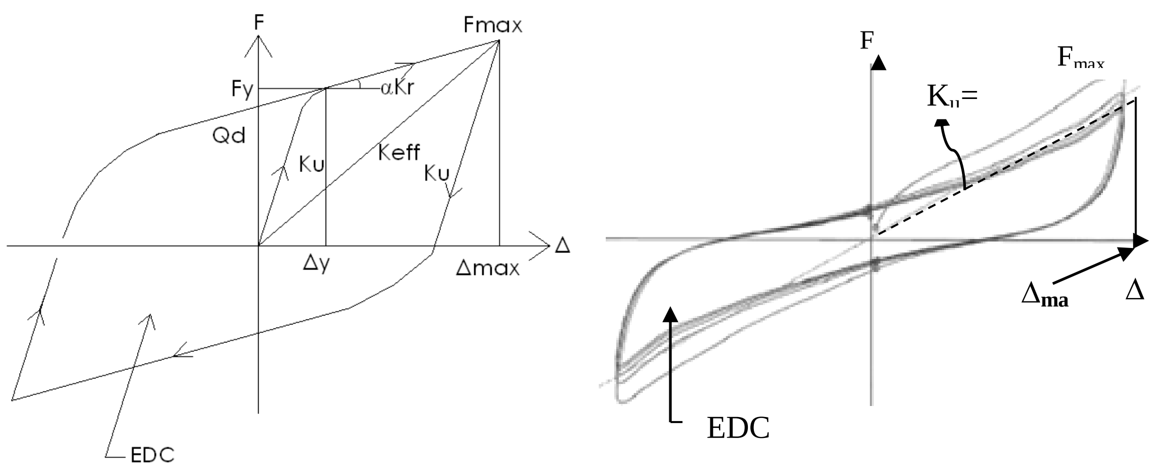
Fig. 1 Model of multi-storied buildings (FB or BI): (a) Plan View, (b) Elevation

2.1 Isolators design

The HDRB and LRB isolators are designed as per the procedure mentioned by Kelly *et al.* (Kelly *et al*. 2006). A computer code ISODES (Islam *et al*. 2013a), has been developed to iteratively design both the isolators. The total seismic weight, dimensions, layer thickness and number of bearing layers are considered as initial input. The isolator parameters such as post elastic stiffness, high initial stiffness, yield strength, post yield stiffness ratio and effective damping are computed using above code. These parameters are then defined in SAP 2000 (CSI 2004). The bearings are linked at the bottom of each column. The detail sequential procedure for design of both isolators follows the flow chart shown by Islam *et al*. (Islam *et al*. 2012b). The higher shear strain limit for HDRB results in smaller plan size compared to LRB (Kelly 2001). Due to large vertical stiffness of HDRB, it can carry heavy loads from the structure (Islam *et al*. 2011). So for the present study, interior columns are isolated using HDRB and the exterior columns are supported by LRB. Dynamic analysis of three dimensional building has been carried out considering the associated nonlinearities.

2.2 LRB and HDRB linking

LRB is formed of a lead plug force-fitted into a preformed hole in a low damping elastomeric bearing. The steel plates in the bearing force the lead plug to deform in shear. The non-linear force deformation behavior of the isolation system is modeled through the hysteresis loop characterized by three parameters namely: (i) Characteristic strength, Q_d, ii) Post-elastic stiffness, K_r, iii) Yield displacement, Δ_y (Matsagar and Jangid 2004). An idealized hysteresis for bearing is as shown in Fig. 2(a). The relation between force intercept at zero displacement and yield strength of isolator is given by Eq. (1).



(a)LRB (b)HDRB

F_{max}=Maximum force, Kr=Post-elastic Stiffness, K_u=Elastic (or unloading) stiffness, Qd=Characteristic strength, F_y=Yield Force, K_{eff}=Effective stiffness, Δ_{max}=Maximum bearing Displacement, Δ_y=Yield Displacement, EDC=Energy dissipated per cycle=Area of hysteresis loop

Fig. 2 Idealized non-linear force-displacement curve of bearing

$$Q_d = \sigma_y A_{pl} \tag{1}$$

Where, σ_y is depending on the vertical load and lead core confinement.

The post-elastic stiffness

$$K_r = \frac{G_\gamma A_r}{T_r} \tag{2}$$

The elastic (or unloading) stiffness (Kilar and Koren 2009) is defined as

$$K_u = 6.5K_r(1+\frac{12A_{pl}}{A_r}) \tag{3}$$

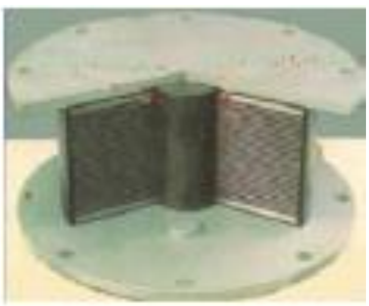
Hysteresis loop area

$$A_h = 4Q_d\ (\Delta_m - \Delta_y) \tag{4}$$

HDRB consists of thin layers of high damping rubber and steel plates built in alternate layers. Horizontal stiffness of the bearing is controlled by the low shear modulus of elastomer while steel plates provides high vertical stiffness as well as prevent bulging of rubber. HDRB executes lower horizontal stiffness to get higher natural period. The stiffness and energy dissipation characteristics for HDRB are highly nonlinear and dependent on shear stain. Force-deformation behavior of the isolator is also considered for modeling HDRB as nonlinear (Fig. 2b) force displacement hysteresis. The post elastic stiffness for this modeling follows Eq. (2). But here the hysteresis loop area is obtained from the shear strain corresponding to shear modulus and damping. The elastic (or unloading) stiffness is defined as

$$K_u = K_r \tag{5}$$

The deformation behavior of LRB and HDRB under loading is shown in Fig. 3 and Fig. 4 respectively.



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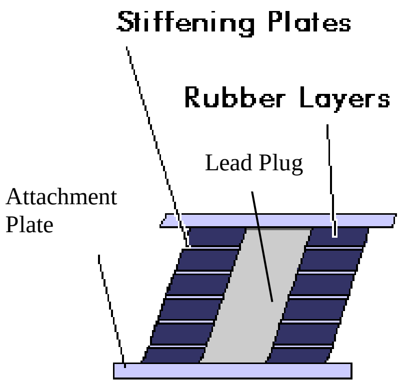
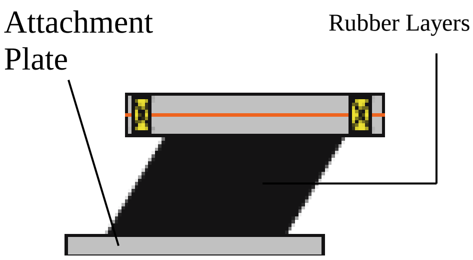


(b)

Fig. 3 Lead rubber bearing (a) Geometry and (b) Deformation due to loading

(a)



(b)

Fig. 4 High damping rubber bearing: (a) Geometry and (b) Deformation due to loading

2.3 Structural analyses

Three analysis techniques considering sequential order of complexities have been chosen for the structural analysis. Linear static analysis, linear dynamic (response spectrum) analysis and nonlinear dynamic (time history) analysis are carried out all the both FB and BI structures using the finite element method (FEM) software SAP 2000 (CSI 2004). The buildings were considered to be located on soft to medium stiff soil. The time history method is relatively more time consuming, lengthy and costly. The response spectrum analysis, on the other hand, is relatively more rapid, concise, and economical. Yet both of these dynamic approaches are adopted to investigate the real structural response variations.

2.3.1 Static analysis

Linear static analysis, the simplest of all is done as a minimum level of complexity. Seismic lateral load was determined choosing the factors: Z, R, Soil Profile, etc. along with lateral load for wind from the related coefficients. Formula for earthquake and wind analysis has been taken from Bangladesh National Building Code, BNBC (BNBC 1993) as follows.

Earthquake Load

$$\text{Base Shear} = \frac{ZIC}{R} \tag{6}$$

Where, Z=Seismic zone factor, I=Importance factor=f(Occupancy), R=Response modification factor=f(structural system), $C = \frac{1.25S}{T^{2/3}}$ Soil structure interaction, S=f(soil profile), T=time period=f(structural system), W=effective weight of structure=total dead load+specified portion of other loads

Wind Load:

Sustained wind pressure

$$q_z = C_c C_I C_Z V_b^{\,2} \tag{7}$$

Where, q_z=sustained wind pressure at height z, KN/m^2, C_c=velocity to pressure conversion=47.2×10^{-6}, C_I=Structure importance coefficient, C_Z=Combined height and exposure coefficient, V_b=Basic wind speed at km/h, p_z=$C_G C_p q_Z$, p_z=Design wind pressure at height z, KN/m^2, C_G=Gust coefficient, C_p=Pressure coefficient.

2.3.2 Equation of motion

The equations of motion of the super structure remain the same for all base isolation systems. The equations are written as follows

$$[M]\{\dot{y}+\ddot{y}_b\}+[C]\{\dot{y}\}+[K]\{y\}=-[M][T_g]\{\ddot{y}_g\} \tag{8}$$

Where, [M], [K] and [C] are the mass, damping and stiffness matrices of the superstructure respectively (Hong and Kim 2004) corresponding to the degrees of freedom (DOF) at the slabs; $\{y\}=[y_x, y_y, y_z]^T$, the vector of displacements at the slab related to the base mass; $\{y_b\}=[y_{bx}, y_{by}, y_{bz}]^T$ is the vector of the base displacements relative to the ground; $\{\ddot{y}_g\}$ is the ground acceleration vector and [T_g] is the earthquake influence coefficient matrix.

2.3.3 Linear response spectrum analysis

There are computational advantages in using the method for prediction of displacements, velocity and acceleration of ground subjected to structural systems (Wilson 2002). Equations of motion for linear analysis are transformed into normal coordinate system. Response-spectrum analysis has been performed using mode superposition. These modal values were combined following complete quadratic combination (CQC) technique. The directional combination was done by SRSS method.

The approach offers computational pluses in prediction of displacements, velocity and acceleration of ground subjected to structural systems. Equations of motion for linear analysis are transformed into normal coordinate system. Applying the normal coordinate transformation the decoupled equation of motion for individual modes leads to

$$[M_n]\{\dot{y}(t)_n+\ddot{y}_b(t)_n\}+[C_n]\{\dot{y}(t)_n\}+[K_n]\{y(t)_n\}=-[M][T_g]\{\ddot{u}(t)_g\} \tag{9}$$

The solution can be carried out individually for each decoupled modal equation as the succeeding Eq. (10). ζ is modal damping ratio and ω_n is un-damped natural frequency

$$\ddot{y}(t)_n+2\zeta\omega_n\dot{y}(t)_n+\omega_n{}^2 y(t)_n=-\ddot{u}(t)_g \tag{10}$$

Total acceleration of the unit mass in single degree-of-freedom system, governed by Eq. (10), is given by

$$\ddot{u}(t)_T=\ddot{y}(t)+\ddot{u}(t)_g \tag{11}$$

Eq. (10) can be solved for $y(t)$ and substituting the term into Eq. (11) yields

$$\ddot{u}(t)_T=-2\zeta\omega\ \dot{y}(t)-\omega^2 y(t) \tag{12}$$

Maximum modal displacement can be obtained for a typical mode n with period T_n and corresponding spectrum response value $S(\omega_n)$. The maximum modal response associated with period T_n is calculated by Eq. (13) and maximum modal displacement response by Eq. (14).

$$y(T_n)_{MAX}=S(\omega_n)/\omega^2 \tag{13}$$

$$u_n = y(T_n)_{MAX}\, \Phi_n \tag{14}$$

Modal superposition technique in Response Spectrum method is only applicable to linear analysis and so the method of using building response factors is not strictly correct (Wilkinson and Hiley, 2006). So to consider nonlinearities, time domain analysis is of utmost importance.

2.3.4 Nonlinear time history analysis

The method of non-linear time history analysis used in SAP 2000 (CSI 2004) is performed. P-delta effect has been considered here for geometric nonlinearity. Boundary nonlinearity in the system has also been included. Direction integration was done by Hilber-Hughes-Taylor Alpha method.

The governing equations of motion are obtained considering equilibrium of all forces at each degree of freedom. The equation of motion for super structure and isolated base is shown in Eq. (15)

$$[M]\{\dot{y}+\ddot{y}_b\}+[C]\{\dot{y}\}+[K]\{y\}=-[M][T_g]\{\ddot{y}_g\} \tag{15}$$

where, [M], [K] and [C] are the mass, damping and stiffness matrices of the superstructure respectively; {y} is displacement of super structure; {y_b} and {$\ddot{y}_g$} are base displacement and acceleration relative to the ground; [T_g] is the earthquake influence coefficient matrix.

All nonlinearities are restricted to the base isolator elements only. The above dynamic equilibrium equations considering the super structure as elastic and base isolator as nonlinear can be written as

$$M\ddot{y}(t)+C\dot{y}(t)+K_L y(t)+r_N(t)=r(t) \tag{16}$$

Where K_L is the stiffness matrix for the linear elastic super structure; C is the proportional damping matrix; M is the diagonal mass matrix; r_N is the vector of forces from nonlinear degrees of freedom in the isolator elements; y, $\dot{y}$, and $\ddot{y}$ are the relative displacement, velocity and acceleration with respect to ground; r is the vector of applied loads.

The effective stiffness at nonlinear degrees of freedom is arbitrary, but varies between zero and the maximum stiffness of that degree of freedom. The equilibrium equation can be rewritten as

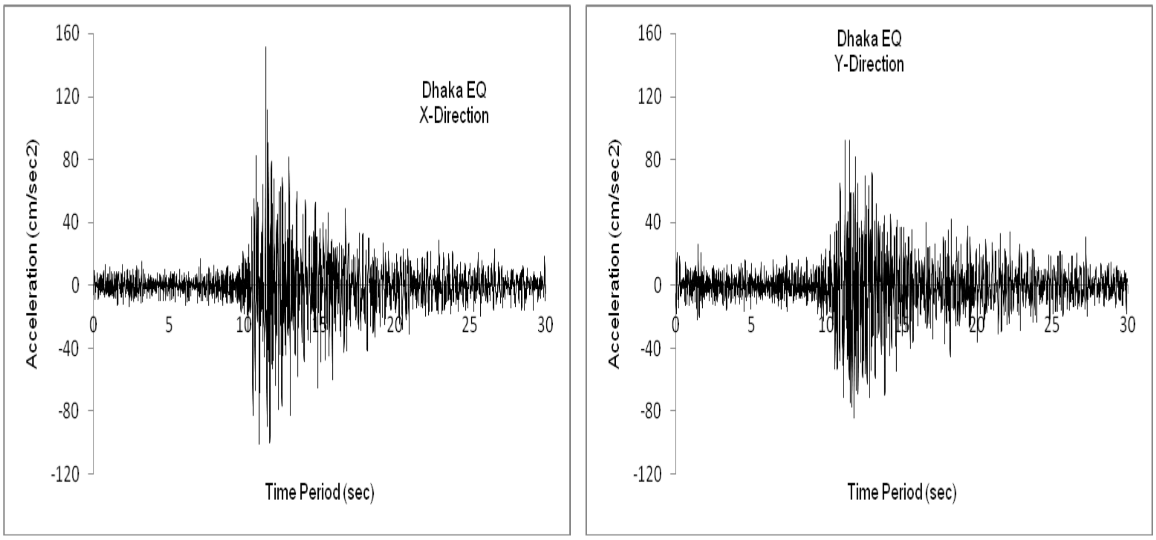
$$M\ddot{y}(t)+C\dot{y}(t)+K_L y(t)+r_N(t)=r(t)-[r_N(t)-K_N y(t)] \tag{17}$$

where

$$K=K_L+K_N \tag{18}$$

K_L=stiffness matrix of all linear elements, K_N=stiffness matrix for all of the nonlinear degrees of freedom

The site specific time history load is applied quasi-statically with high damping. The nonlinear analysis considers a ramp type of time history function which increases linearly from zero to one over a length of time. The nonlinear modal equations are solved iteratively in each time step. The program contemplates that the analysis results vary during a time step. The iterations are carried out until the solution converges. If convergence cannot be achieved, the program divides the time step into smaller sub steps and tries again.



(a) (b)

Fig. 5 Time History for Dhaka EQ (a) *X*-direction and (b) *Y*-direction (Islam *et al*. 2014b)

3. Numerical Study

3.1 Building of study for base isolation

The building of study is taken as multistoried residential building located in Dhaka of 4 spacing @ 7.62m c/c in both direction is chosen. Here, $f'c$=28 MPa, fy=414 MPa, dead load (excluding self-weight)=4.8 KPa, live load=2.4 KPa, slab thickness=150 mm, exterior corner columns are all 750×750 mm, exterior middle columns are all 950×950 mm, interior columns are all 1000×1000 mm, grade beams are 300×375 mm each, exterior beams are 525×825 mm each and interior beams are 600×900 mm each in sizes. At the outset, 8-story residential building has been analyzed and all the structural and economical insinuations are investigated. Then taking the same plan and dimension (Fig. 1), the building has been analyzed for 08 to 04 story. Base isolators are designed and structural changes as well as cost savings have been evaluated for all the studied buildings.

3.2 Consideration for linear static analysis

A model of the previously shown building was prepared and it was loaded as described in the problem. For equivalent static analysis of the conventional fixed based building, procedures described at BNBC (BNBC 1993) are adopted. Apart from this, for isolated building response, modification factor has been taken as RI=2.0 and importance coefficient has also been chosen as 1.0 as per occupancy category (UBC 1997).

3.3 Consideration for isolation design

Rubber Isolators have been designed here considering vertical load, isolator types and different properties using excel spreadsheet tool ISODES formulated by the equations and conditions. For sequential design of isolator are given for both HDRB and LRB, the considerations have been mentioned in the subsequent section with proper evidences. The range of properties for rubber is restricted and some properties are related to others, such as, the ultimate elongation, material constant and elastic modulus having all functions of shear modulus. The common rubber properties chosen for the isolators are shear modulus: 400 KPa, ultimate elongation: 650%, material constant k: 0.87, elastic modulus: 1350 KPa. This is basic information used for the design process. Damping is varying for the isolators. HDRB and LRB have been assigned at interior and exterior columns. Type of isolators and loads acting on the column base subjected to the bearings and the load data's required for ISODES are characterized as shown in Table 2.

4. Dynamic analysis

Assigning the properties to the isolators, the bearings are linked at the bottom of the respective columns, that is, in base level to ensure all the properties in the spring. The structure with isolators is then analyzed by SAP 2000 (CSI 2004).

Table 2 Types and number of isolator with imposed load (8-story BI building)

Bearing Types and Load Data	LRB	HDRB	Total
Type	Isolator1	Isolator2	
No. of Bearings	16	9	25
Average DL+SLL (KN)	3811	6635	
Maximum DL+LL (KN)	4293	6816	
Maximum DL+SLL+EQ (KN)	4345	6820	
Seismic Weight (KN)			118883
Total Wind Load (KN)			2505

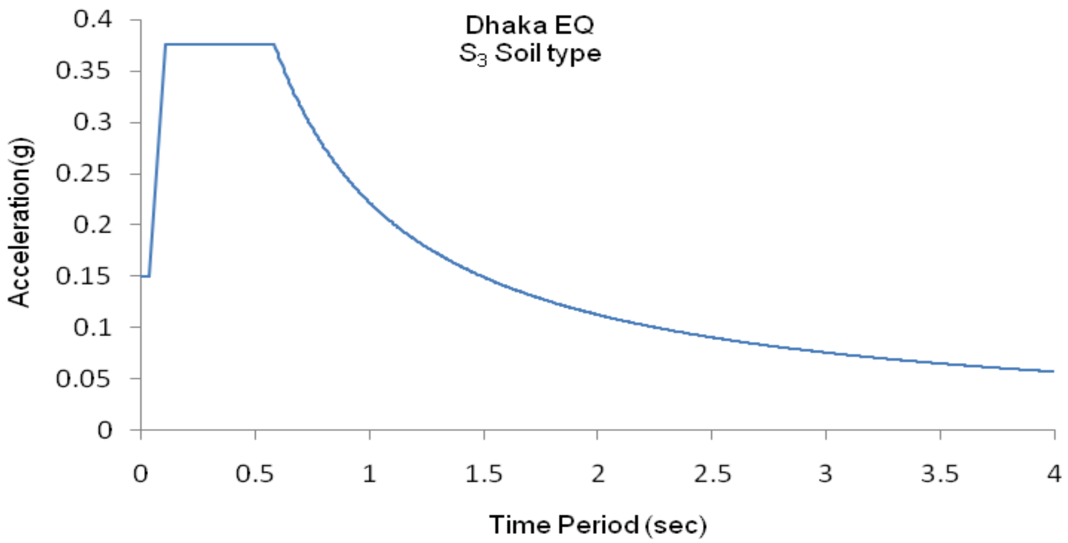


Fig. 6 Response spectrum for Dhaka EQ (Islam *et al*. 2014b)

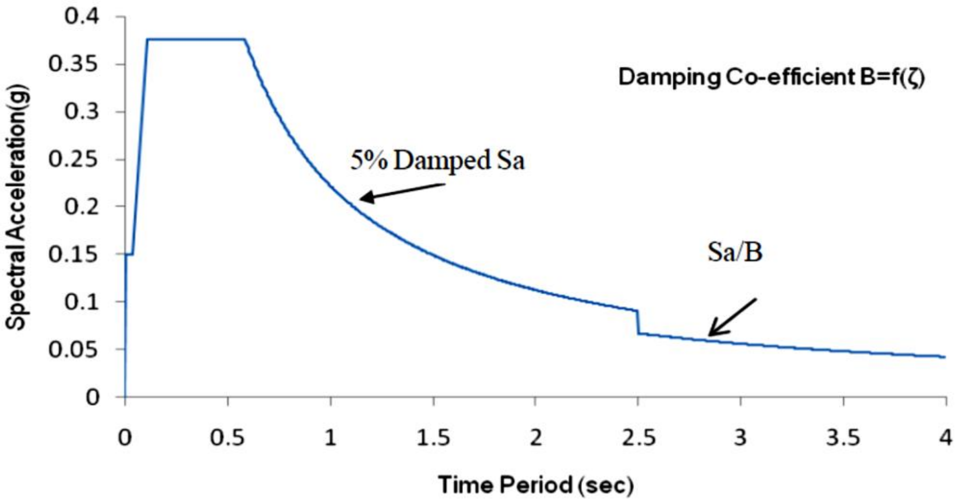


Fig. 7 Composite response spectrum of Dhaka EQ for BI building (Islam *et al*. 2013a)

4.1 Design earthquake for analysis

Dhaka earthquake time history data (Islam *et al*. 2013b) that was properly modified from the recently occurred Natore earthquake record has been considered here for the analysis. Natore represents the closest point from Dhaka where any sort of ground shaking has ever been recorded (Islam *et al*. 2012a). The time history for Dhaka earthquake and design smooth response spectrum for Dhaka earthquake (Islam *et al*. 2014b) have been shown in Figs. 6 and 7 respectively. The two components of earthquake ground motions are designated as x (EW direction) and y (NS direction). The seismic responses follow the parameters soil characteristics, site location, seismic coefficients as per BNBC (BNBC 1993) and UBC (UBC 1997). Dynamic analysis for response spectrum and time history has been performed for FB structure to see the governing type of analysis. Then after linking them with the properties of isolators from isolation system design procedure and at the respective column base, dynamic analysis is again performed.

4.2 Consideration for response spectrum analysis

The response spectrum analysis follows the usual procedure for this method of analysis. Here the response spectrum is modified to account for the damping provided in the isolated modes to use a composite spectrum. The 5% damped spectrum has been reduced by the B factor in the isolated modes (Fig. 7). This is the smooth response spectrum smoothen from the real response spectrum to use in the linear dynamic analysis.

4.3 Consideration for time history analysis

A non-linear time History analysis was also performed by choosing the selected time history, that is, ground motion that resembles the site condition of Dhaka (Figure 5). Each building model and damping system configuration was analyzed for the 30 second duration of each record at a time step of 0.005 seconds.

5. Results and discussion

5.1 Viability for incorporating isolator

The structural time period is considered within the reasonable value, that is, ≤1.0 second (Kelly 2001, Kelly *et al*. 2006, Naeim and Kelly 1999) for isolating. The site permits horizontal displacements at the base of the order of 200 mm or more and lateral load (Base Shear) due to wind is lesser than 10% of the weight of the building (Deb 2004) as requirement (Table 1). Therefore, isolator can be incorporated at the base of the structure as an alternative to conventional FB design.

5.2 Validation of Isolator performance

The designed isolator parameters are shown in Table 3 and Fig. 8. Two things need to be considered, 1) the status of the isolation bearings to safely support the loads and 2) the performance of the isolation system. The isolation bearing status is checked by the factors of safety with satisfactory performance. The performance of the isolated structure has been evaluated for the design basis earthquake (DBE) and maximum credible earthquake (MCE). The seismic coefficient C_A =0.22 and C_V=0.32 relates to DBE in current studies. To check the performance against MCE, these coefficients C_{AM} and C_{VM} for Z=0.15 and soil profile S3 are 0.35 and 0.55,

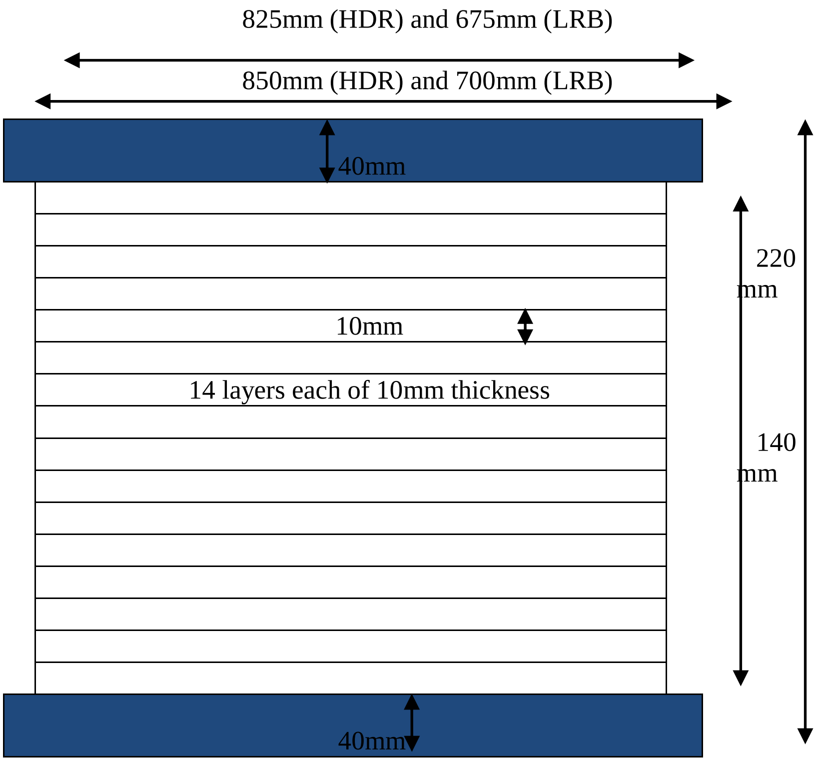


Fig. 8 Dimensions of designed HDRB and LRB for 8-storied building

Table 1 Static analysis results (8-story FB building)

Parameter	Rating
Total weight of Building	118883 KN
Governing Axial load on Interior Column	6816 KN
Governing Axial load on Exterior Column	4293 KN
Base Shear (EQ load)	4528 KN
Base Shear (Wind load)	2692 KN
Maximum Top story Displacement (EQ load)	12.33 mm
Maximum Top story Displacement (Wind load)	6.10 mm
Base Displacement (EQ and Wind load)	0
Base Moment (EQ load)	84589 KN-m
Base Moment (Wind load)	46420 KN-m

Table 3 Designed result of Isolator Dimensions (8-story BI building)

Bearing Dimensions	LRB	HDR
Plan Dimension (mm)	700	850
Layer Thickness (mm)	10	10
No. of Layers	14	14
Lead Core Size (mm)	125	--
Shape (S= Square, C=Circular)	C	C
Total Height (mm)	220	220

respectively. Both assessments for earthquake levels are satisfactory. Again, all the values of maximum (top) displacements (Tables 1 and 5) lie below the static isolator allowable design displacement 237.53 mm for MCE level of earthquake. Hence, the isolator properties are satisfactory.

5.3 Structural insinuation

Linear static as well as linear and nonlinear dynamic analyses of the building structures for non-isolated and isolated cases have been performed. Thorough study finds out the structural response variation of 8-story prototype building with and without elastomeric bearings. Henceforward, the requirements for isolation system have been assessed for 4 to 7 story building structures.

5.3.1 Shift of Time period

The time period for the BI building is shifted to 3.31 sec having frequency=0.31 Hz, which is significantly higher compared to the time period of FB building (0.72 sec) having frequency=1.39 Hz. This indicates the flexibility of the BI structure. Again, the BI building frequency is in between the usual range of frequency in case of isolated structure 0.3-0.5 Hz (Islam *et al*. 2013a).

5.3.2 Top displacement and drift

The results of structural investigation obtained from the equivalent static analysis are shown in Table 1. In case of the fixity, displacement at base is considered as zero. The maximum displacement at top of the structure is occurred for seismic load and it values to 12.33 mm. Dynamic analysis for response spectrum and time history has also been performed for FB structure is shown in Table 4 and compared with static load case. Between the two methods, linear response spectrum analysis and nonlinear time history analysis, the former shows the greater result which is, however, still lower than the static case. The results for the static load case are higher because they follow some empirical formula which are more conservative compared to the real values of result for the safety of structure.

Linear static as well as linear and nonlinear dynamic analysis of the building structure with isolator shows the subsequent results of the mentioned structural parameters (Tables 5 and 6). Tables 1 and 5 show that, the displacement for BI building increases in a reasonable amount than the displacements of FB case. However, it is interesting that total frame is shifted for the case as the isolator is moved up to 265.49 mm. This movement of isolator decreases the total structure drift.

Therefore, it is observed that due to incorporation of isolation system, the displacement of both the superstructure and isolator increases as the superstructure becomes more flexible. This trend is true for static, response spectrum and time history analysis. However, the structural elements of multi-storied building experiences lower structural drift for dynamic analysis.

5.3.3 Shear and moment

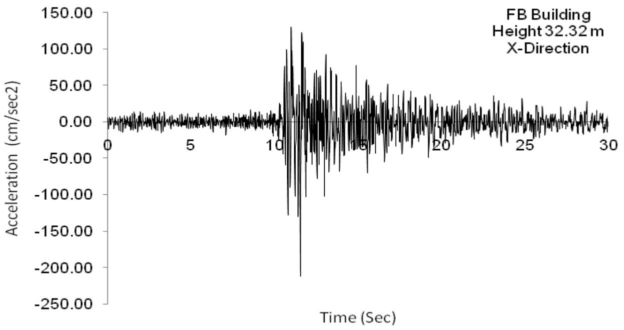
Maximum values of shears and moments at the base are illustrated in Table 6. As the isolator makes the structure flexible, base shear and base moment reduce in a large amount due to isolator insertion. The maximum base shear for BI building reduces up to 30~40% compared to the FB building. Furthermore, the base moment is also reduced similarly up to 25~35%.

5.3.4 Floor acceleration

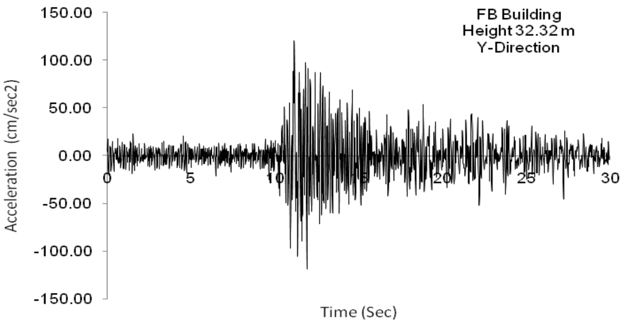
Acceleration time histories for the seismically isolated building are given in Figs. 9-10 for top floor of the structure. Here, the floor acceleration retorts at the top floor and base of the building in the considered cases (non-isolated or isolated foundations) for seismic horizontal excitations. In the case of building on seismic isolators, the spectral horizontal accelerations reasonably reduces with respect to corresponding accelerations evaluated in the case of non-isolated building. It is expected due the low frequencies observed for main building modes. The peak floor accelerations in this case at top is 0.209 g in *x*-direction which is about 29.81% greater and 0.128 g in *y*-

Table 4 Dynamic analysis results of 8-story FB building

Parameter	**Static analysis**	**Response Spectrum analysis**	**Time History analysis**	
Base Shear (KN) in *X* direction	4528	4274	2876	
Base Shear (KN) in *Y* direction	4528	2882	2041	
Base Moment (KN-m) in *X* direction	84589	58280	40735	
Base Moment (KN-m) in *Y* direction	84589	79631	39923	
Top story Displacement in *X* Direction (mm)	12.33	9.48	4.88	Drift (mm)
Top story Displacement in *Y* Direction (mm)	12.33	4.34	5.50	

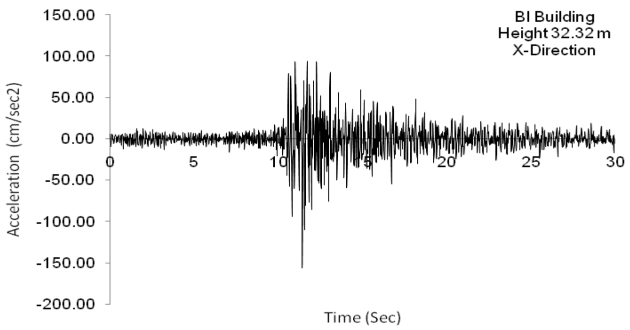


(a)

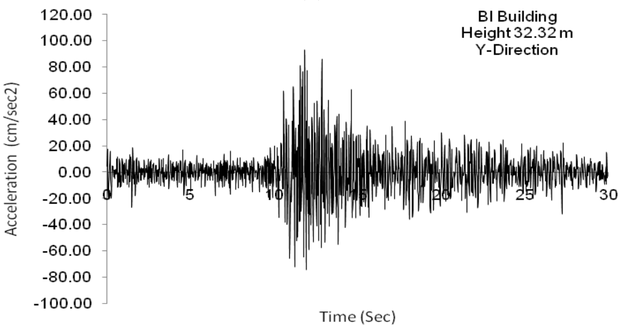


(b)

Fig. 9 Top floor acceleration time history (Fixed Based case) in (a) *X* direction, (b) *Y* direction



(a)



(b)

Fig. 10 Top floor acceleration history (Isolated Based case) in (a) *X* direction, (b) *Y* direction

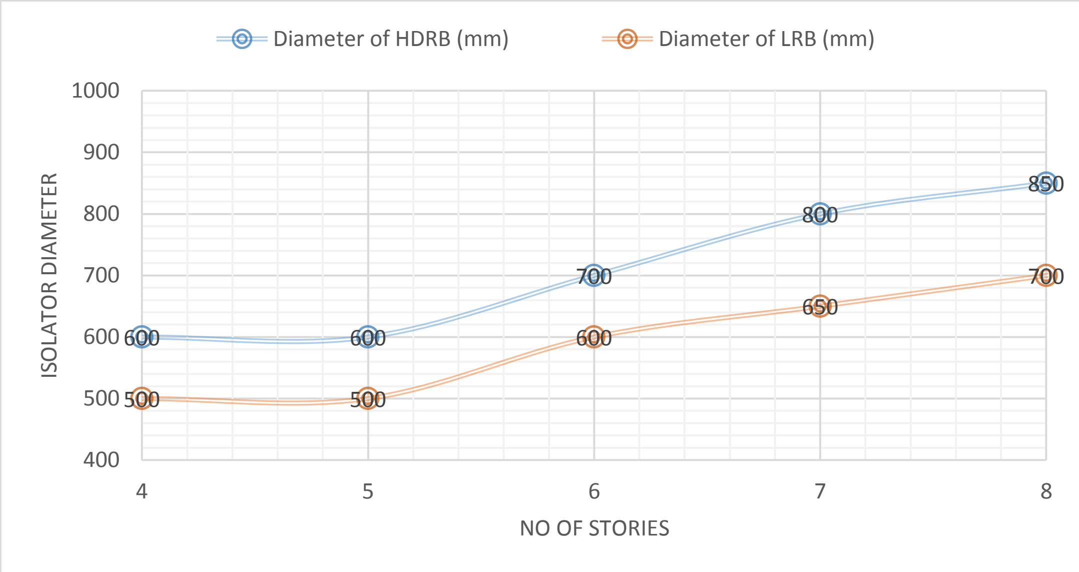


Fig. 11 Isolator size for BI buildings for varying elevation

Table 5 Roof displacement at static and dynamic analysis of 8-story BI building

Parameter	Isolator Displacement (mm)	Top story displacement (mm)	Drift (mm)
X- Direction (Static Analysis)	265.49	303.44	37.95
Y- Direction (Static Analysis)	265.49	303.44	37.95
X- Direction (Response Spectrum Analysis)	154.2	172.20	18.0
Y- Direction (Response Spectrum Analysis)	46.26	51.66	5.4
X- Direction (Time Domain Analysis)	14.56	23.04	8.48
Y- Direction (Time Domain Analysis)	28.14	42.55	14.41

Table 6 Base Shear and Base Moment at dynamic analysis of 8-story BI building

Parameter	Response Spectrum analysis	Time History analysis
Base Shear (KN) in X direction	1838.33	237.71
Base Shear (KN) in Y direction	551.67	454.87
Base Moment (KN-m) in X direction	8105.33	7745.74
Base Moment (KN-m) in Y direction	27017.39	5918.57

direction which is about 39.13% lower than the input ground excitation. For the isolation flexibility, the structure experiences a mentionable amount of acceleration at base which is valued at 0.163 g in *x*-direction and 0.097 g in *y*-direction. For isolated building, peak acceleration at top floor reduces by 13~15% of the corresponding top point acceleration of the fixed one. Isolated building exerts well amount of acceleration at base. But for the fixed one, at base, there is a null acceleration excitation and displacement.

5.3.5 Bearing properties for varying elevation

For the same plan area, the building has been analyzed for 4, 5, 6, 7 and 8 story to predict the bearing requirements. For every building, properties of HDRB and LRB are designed separately and the structures were analyzed also after linking the bearings properly for satisfactory member configuration. With the increase in number of stories, the diameter of isolator and number of layers requirement increases in case of BI buildings while fixing the layer thickness 10 mm. The same size of isolation is needed up to 5 story building, while the diameter increases assigning same number of layers in case of building up to 7 story building as shown in Fig. 11. For 8 story structure, diameter also increases along with number of layers requirement of 14 layers; but fixing layer thickness same as 10 mm demands allowable displacement to be larger. Again, the structural parameters for the 4, 5, 6, 7 and 8 storied buildings are checked. Rigorous analysis predicts about reasonable amount of savings in reinforcement and cost as well with the value for fixed based building.

For all the isolated structures, the displacement of both the superstructure and isolator increases as superstructure becomes more flexible. This trend is true for static, response spectrum and time history analysis.

5.4 Economic insinuation

There are both direct and indirect costs and cost savings related with the system. Though the installation of the isolation system adds to first cost than a non-isolated system, the use of isolators reduces the reinforcement requirement of a building and ultimately reduces the total cost. So the cost for isolators and the cost of changes to the structural configuration is potentially the largest component of the first cost and is a function of the building layout.

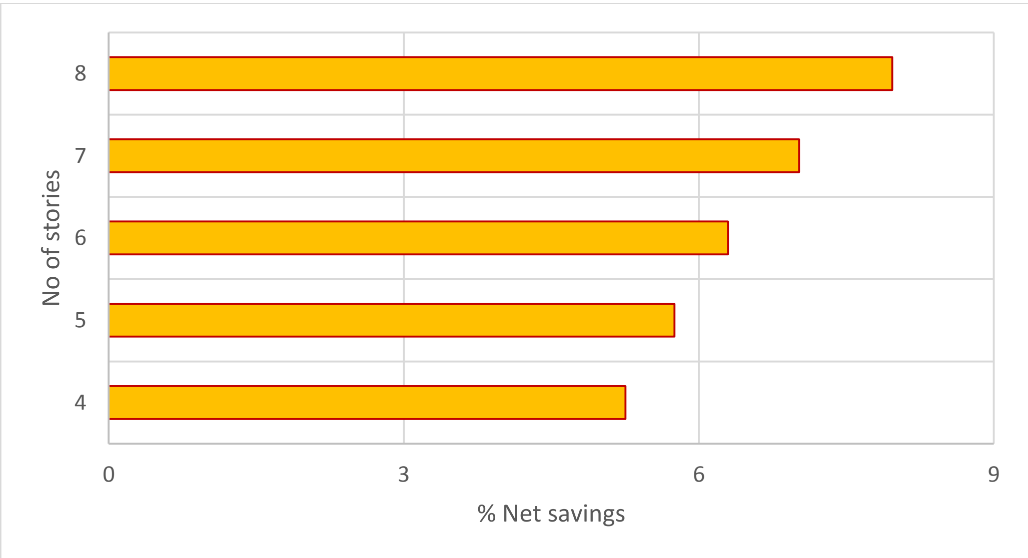


Fig. 12 Net cost savings in base isolated building with No. of Story

5.4.1 Cost analysis of FB and BI buildings

For the 8-story modeled building, savings from the reinforcement requirement along with cost are determined. Considering similar sections of horizontal and vertical members, savings come up to 24.39% from the reinforcement reduction. The reinforcement savings of column and beam for the 8-story building are seen as significant. MS steel price has been taken as 0.65 $ per kg. It is to mention that, for the case of detailing, about 3% cost is to be added with the required amount for fixed base structure. On the other hand, isolation devices adjoin a huge initial cost for the building. Isolator cost depends on the layer thickness, number of layers, diameter of isolator etc. Cost per isolator depending on the sectional properties has been collected from Holmes Consulting Group Ltd. (HCG 2009). Along with the price, 3% installation cost has been added at around. It is shown that, though isolators add a countable amount of cost at the construction of structure, reinforcement savings of beams and columns compensates that cost. Even there is a drastic reduction (Fig. 12) of the net cost of the 8 storied building through the flexibility offered by the seismic base isolation devices.

Reinforcement required for grade beams increases slightly (6%-10%) for insertion of isolators. However, reduction of cost for reinforcement in upper floors for horizontal and vertical members (that is, beams and columns) compensates that cost. Thus a saving of cost through reinforcement is achieved. A net saving of cost considering isolator and reinforcement stands at a reasonable amount of around 8%. After a certain structural elevation, the rate of cost savings reduces with increasing number of story.

5.4.2 Synopsis of net savings with building elevation

All the building from 4 to 8 stories was also designed to get the reinforcement needed for both FB and BI case. Savings of reinforcement thorough columns and beams like as 8 storied building are compared in respect of the FB case designed reinforcement. Reinforcement savings are then evaluated in percentage of individual FB case for 4 to 8 story buildings. It is seen that there is a drastic reduction of reinforcement up to 20~25% in the case of incorporating base isolation in low to medium rise buildings. Apart from this, the percentage of net cost savings for BI buildings (considering isolation cost) against non-isolated buildings with different number of story of building is as shown in Fig. 12. It is clear that reduction of the structural responses results in diminution in cost up to about one twelfth of total expenses while the superstructure of multi-storied building is separated through insertion of base isolators.

5.5 Eco-friendly insinuation

While using isolator, member section can be reduced if the reinforcement lessening is not the foremost concern. Thus, the size of structural member or the steel reinforcement could be reduced to save cost, while satisfying the safety and serviceability requirement/provisions from the local design codes. This, in turn, reduces the negative impact on environment while extracting these natural resources such as rock blasting and iron ore mining. An added benefit of using reduced structural member size in multistoried building construction might be aesthetically pleasing from architectural point of view. This enhances the usable clear space within the multi-story building.

The essence of base isolation is not only saving on building design costs, reducing the elemental dimensions but rather reduction of deaths, downtime and repair costs after eventual hazard.

6. Conclusions

Following conclusions have been drawn from the present study:

• Due to incorporation of isolation system, the displacement of both the superstructure and isolator increases as the superstructure becomes more flexible. This trend is true for static, response spectrum and time history analyses. However, the structural elements of multi-storied building experiences lower structural drift for dynamic analysis.

• Drastic reduction in maximum isolated base shear and base moment is observed for base isolated case compared to the fixed base shear leading to safe structural design.

• For BI building, the spectral horizontal accelerations significantly reduce due to the low frequencies of main building modes compared to non-isolated building. Moreover, the reduction of responses peak accelerations at the support level is about ten times for isolators with respect to the case without base isolation.

• The size of structural member or the steel reinforcement could be reduced to save cost, while satisfying the safety and serviceability requirement/provisions from the local design codes. Thus, the negative impact on environment for extracting these natural resources like, rock blasting and iron ore mining is reduced.

• Isolation system can reduce the member section of the structural element where member dimension is vital than reinforcement. An added benefit of using reduced structural member size in multistoried building construction might be aesthetically pleasing from architectural point of view. This also enhances the usable clear space in the building.

• The spirit of base isolation is not only saving on building design costs, reducing the elemental dimensions but rather reduction of deaths, downtime and repair costs after eventual hazard. For medium to low rise building structures, where the foremost apprehension is the restriction of the seismic excitation at the supports of critical components, base isolation approach is an efficient alternative.

• In this study, the most effective choice is considered of HDRB and LRB bearings, as resulting in a lower isolation frequency and then in lower peak structural parameters. Other isolation systems can also be incorporated to justify the optimization.

Acknowledgments

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References

Ariga, T., Kanno, Y. and Takewaki, I. (2006), “Resonant behaviour of base-isolated high-rise buildings under long-period ground motions”, *Struct. Des. Tall Spec. Build.*, **15**(3), 325-338.

Bhuiyan, A.R., Okui, Y., Mitamura, H. and Imai, T. (2009), “A rheology model of high damping rubber bearings for seismic analysis: Identification of nonlinear viscosity”, *Int. J. Solid. Struct.*, **46**(7-8), 1778-1792.

BNBC. (1993), *Bangladesh National Building Code*, Bangladesh: Housing and Building Research

Institute, Bangladesh Standard and Testing Institute.

Borzi, B., Vona, M., Masi, A., Pinho, R. and Pola, D. (2013), "Seismic demand estimation of RC frame buildings based on simplified and nonlinear dynamic analyses", *Earthq. Struct.*, **4**(2), 157-179.

Casciati, F. and Hamdaoui, K. (2008), "Modelling the uncertainty in the response of a base isolator", *Prob. Eng. Mech.*, **23**(4), 427-437.

CSI. (2004), *Linear and nonlinear static and dynamic analysis of three-dimensional structures*, In Computer & Structures Inc. SAP 2000 (Ed.), Berkeley, CA.

Dall'Asta, A. and Ragni, L. (2006), "Experimental tests and analytical model of high damping rubber dissipating devices", *Eng. Struct.*, **28**(13), 1874-1884.

Dall'Asta, A. and Ragni, L. (2008), "Nonlinear behavior of dynamic systems with high damping rubber devices", *Eng. Struct.*, **30**(12), 3610-3618.

Deb, S. (2004), "Seismic base isolation-an overview", *Curr. Sci.*, **87**(10), 1426-1430.

Dicleli, M. and Buddaram, S. (2007), "Comprehensive evaluation of equivalent linear analysis method for seismic-isolated structures represented by sdof systems", *Eng. Struct.*, **29**(8), 1653-1663.

Eleftheriadou, A.K. and Karabinis, A.I. (2012), "Seismic vulnerability assessment of buildings based on damage data after a near field earthquake (7 September 1999 Athens - Greece)", *Earthq. Struct*., **3**(2), 117-140.

Habibullah, A. (2005), *Static and Dynamic Finite Element Analysis of Structures*, SAP 2000, Computers and Structures Inc. Berkeley, California.

HCG. (2009), *Structural and Civil Engineers*, Holmes Consulting Group Ltd., Auckland, Newzealand.

Hong, W. and Kim, H. (2004), "Performance of a multi-story structure with a resilient-friction base isolation system", *Comput. Struct*., **82**(27), 2271-2283.

Islam, A.B.M.S., Ahmad, S.I., Jameel, M. and Zamin, M.J. (2012a), "Seismic base isolation for buildings in regions of low to moderate seismicity: Practical alternative design", *Practice Period. Struct. Des. Constr*., **17**(1), 13-20.

Islam, A.B.M.S., Ahmad, S.I., Jumaat, M.Z., Hussain, R.R., Rahman, M.A. and Darain, K.M. (2014a), "Efficient design in building construction with rubber bearing in medium risk seismicity: case study and assessment", *J. Civ. Eng. Management*, **20**(5), 621-631.

Islam, A.B.M.S., Hussain, R.R., Jameel, M. and Jumaat, M.Z. (2012b), "Non-linear time domain analysis of base isolated multi-storey building under site specific bi-directional seismic loading", *Auto. Constr*., **22**, 554-566.

Islam, A.B.M.S., Hussain, R.R., Jumaat, M.Z. and Darain, K.M. (2014b), "Implication of rubber-steel bearing nonlinear models on soft storey structures", *Comput. Concrete*, **13**(5), 603-619.

Islam, A.B.M.S., Hussain, R.R., Jumaat, M.Z. and Rahman, M.A. (2013a), "Nonlinear dynamically automated excursions for rubber-steel bearing isolation in multi-storey construction", *Auto. Constr.*, **30**, 265-275.

Islam, A.B.M.S., Jameel, M., Uddin, M.A. and Ahmad, S.I. (2011), "Simplified design guidelines for seismic base isolation in multi-storey buildings for Bangladesh National Building Code (BNBC)", *Int. J. Phys. Sci.*, **6**(23), 5467-5486.

Islam, A.B.M.S., Jumaat, M.Z., Hussain, R. and Alam, M.A. (2013b), "Incorporation of rubber-steel bearing isolation in multi-storey building", *J. Civ. Eng. Management*, **19**(sup1), S33-S49.

Ismail, M., Rodellar, J. and Ikhouane, F. (2010), "An innovative isolation device for aseismic design", *Eng. Struct*., **32**(4), 1168-1183.

Jangid, R.S. (2007), "Optimum lead-rubber isolation bearings for near-fault motions", *Eng. Struct.*, **29**(10), 2503-2513.
Kampas, G. and Makris, N. (2012), "Time and frequency domain identification of seismically isolated structures: advantages and limitations", *Earthq. Struct*., **3**(3-4), 249-270.
Kelly, T.E. (2001), *Base isolation of structures: design guidelines*, Holmes Consulting Group Ltd.
Kelly, T.E., Robinson, W.H. and Skinner, R.I. (2006), *Seismic Isolation for Designers and Structural Engineers*, Robinson seismic Ltd.
Lu, L.Y. and Lin, G.L. (2008), "Predictive control of smart isolation system for precision equipment subjected to near-fault earthquakes", *Eng. Struct.*, **30**(11), 3045-3064.
Matsagar, V.A. and Jangid, R.S. (2004), "Influence of isolator characteristics on the response of base-isolated structures", *Eng. Struct.*, **26**(12), 1735-1749.
Naeim, F. and Kelly, J. (1999), *Design of seismic isolated structures: from theory to practice*, Wiley.
Olsen, A., Aagaard, B. and Heaton, T. (2008), "Long-period building response to earthquakes in the San Francisco Bay Area", *Bull. Seismol. Soc. Am*., **98**(2), 1047.
Ozmen, H.B., Inel, M. and Cayci, B.T. (2013), "Engineering implications of the RC building damages after 2011 Van Earthquakes", *Earthq. Struct*., **5**(3), 297-319.
Pocanschi, A. and Phocas, M.C. (2007), "Earthquake isolator with progressive nonlinear deformability", *Eng. Struct*., **29**(10), 2586-2592.
Polycarpou, P.C. and Komodromos, P. (2010), "Earthquake-induced poundings of a seismically isolated building with adjacent structures", *Eng. Struct*., **32**(7), 1937-1951.
Pourzeynali, S. and Zarif, M. (2008), "Multi-objective optimization of seismically isolated high-rise building structures using genetic algorithms", *J. Sound Vib*., **311**(3-5), 1141-1160.
Providakis, C.P. (2008), "Effect of LRB isolators and supplemental viscous dampers on seismic isolated buildings under near-fault excitations", *Eng. Struct*., **30**(5), 1187-1198.
Roussis, P.C. and Constantinou, M.C. (2006), "Uplift-restraining Friction Pendulum seismic isolation system", *Earthq. Eng. Struct. Dyn*., **35**(5), 577-593.
Spyrakos, C.C., Koutromanos, I.A. and Maniatakis, C.A. (2009), "Seismic response of base-isolated buildings including soil-structure interaction", *Soil Dyn. Earthq. Eng*., **29**(4), 658-668.
Takewaki, I. (2008), "Robustness of base-isolated high-rise buildings under code-specified ground motions", *Struct. Des. Tall Spec. Build*., **17**(2), 257-271.
Takewaki, I. and Fujita, K. (2009), "Earthquake input energy to tall and base-isolated buildings in time and frequency dual domains", *Struct. Des. Tall Spec. Build*., **18**(6), 589-606.
Tornello, M.E. and Sarrazin, M. (2012), "Base-isolated building with high-damping spring system subjected to near fault earthquakes", *Earthq. Struct*., **3**(3-4), 315-340.
UBC. (1997), *Uniform Building Code, Earthquake regulations for seismic isolated structures*, Paper presented at the International conference of building officials, Whitter, CA, USA.
Wilkinson, S. and Hiley, R. (2006), "A non-linear response history model for the seismic analysis of high-rise framed buildings", *Comput. Struct*., **84**(5-6), 318-329.
Wilson, E. (2002), *Three-dimensional static and dynamic analysis of structures (3rd ed.)*, Computers and Structures Inc. Berkeley, California.
Yön, B., Sayln, E. and S.Koksal, T. (2013), "Seismic response of buildings during the May 19, 2011 Simav, Turkey earthquake", *Earthq. Struct*., **5**(3), 343-357.

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