

Full Length Research Paper

Simplified design guidelines for seismic base isolation in multi-storey buildings for Bangladesh National Building Code (BNBC)

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Seismic base isolation is now a days moving towards a very efficient tool in seismic design of structure. Increasing flexibility of structure is well achieved by the insertion of these additional elements between upper structure and foundation as they absorb larger part of seismic energy. However in Bangladesh, this research is still young for building structures. Therefore, this is a burning question to design isolation device in context of Bangladesh. Effort has been made in this study to establish an innovative simplified design procedure for isolators incorporated in multi-storey building structures. Isolation systems namely lead rubber bearing (LRB) and high damping rubber bearing (HDRB) have been selected for the present schoolwork. Numerical formulation and limiting criteria for design of each element have been engendered. The suitability to incorporate isolation device for seismic control has been sight seen in details. The study reveals simplified design procedures for LRB and HDRB for multi-storey buildings in Bangladesh. The detail design progression has been proposed to be included in Bangladesh National Building Code (BNBC).

Key words: Seismic base isolation, simplified design, building structures, rubber bearing, response modification, base shear, yield force, shear modulus, damping.

INTRODUCTION

It may come as a surprise that the rubber foundation elements can actually help to minimize earthquake damage to buildings, considering the tremendous forces endured even in a major quake. The separation of the structure from the harmful motions of the ground occurs by providing flexibility and energy dissipation capability through the insertion of the isolators between the foundation and the building structure (Ismail et al., 2010a). Unlike the conventional design approach, which is based upon an increased resistance (strengthening) of the structures, the seismic isolation concept is aimed at a

significant reduction of dynamic loads induced by the earthquake at the base of the structures themselves (Micheli et al., 2004). Invention of lead rubber bearing (LRB, 1970's) and high damping rubber (HDR, early 1980's) gives a new dimension to the design of base isolated structure (Hussain et al., 2010).

The use of elastomeric bearings such as HDRB and LRB has been moved to popular phenomena in recent days. Jangid (2007) and Providakis (2008) investigated seismic responses of multi-storey buildings for near fault motion isolated by LRB. Islam et al. (2010b) has studied isolation system at low to medium risk seismicity. Dall'Asta and Ragni (2006, 2008) have covered experimental tests, analytical model and nonlinear dynamic behavior of HDRB. Bhuyan et al. (2006) has developed a rheology model for high damping rubber bearing for

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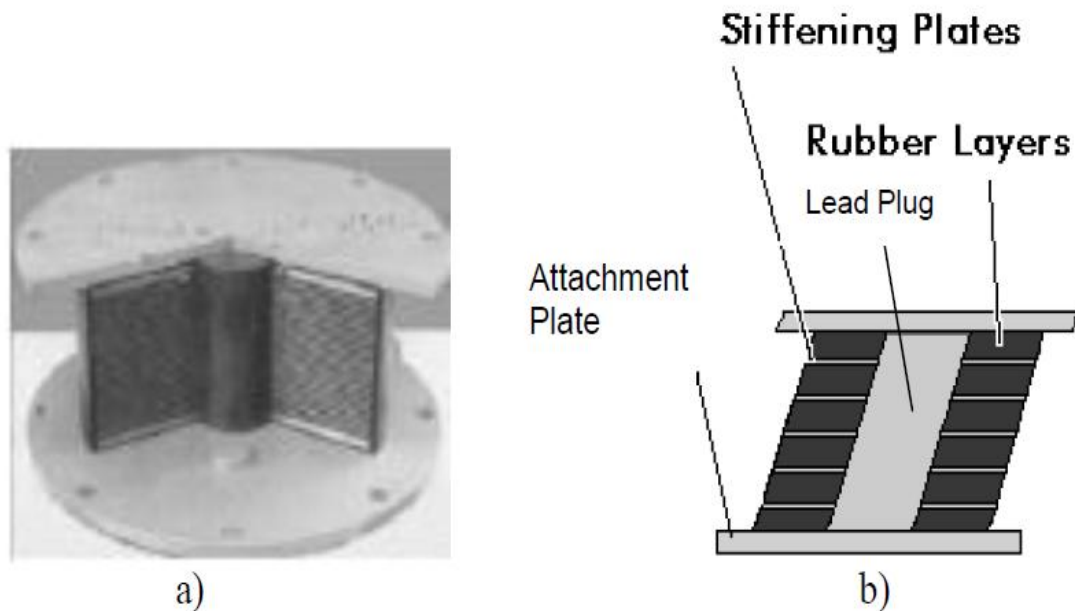


Figure 1. Lead rubber bearing (a) geometry and (b) deformation due to loading.

seismic analysis identifying nonlinear viscosity. Although it is a relatively recent technology, earthquake induced responses and seismic isolation for multi-storey buildings has been well evaluated and reviewed (Hong and Kim, 2004; Barata and Corbi, 2004; Lu and Lin, 2008; Spyarakos, 2009; Shahri et al., 2010; Islam et al., 2011a). Base isolator with hardening behavior under increasing loading has been developed for medium-rise buildings (up to four story) and sites with moderate earthquake risk (Pocanschi and Phocas, 2007). Resonant behavior of base-isolated high-rise buildings under long-period ground motions was dealt by Ariga et al. (2006) and long period building responses by Olsen et al. (2008). Wilkinson and Hiley (2006) presented a non-linear response history model for the seismic analysis of high-rise framed buildings. Dicleli and Buddaram (2007) and Casciati and Hamdaoui (2008) have also given effort in progresses of isolated system.

Islam et al. (2011b) have studied regarding optimal isolation systems and the dynamic characteristics of structural responses in multi-storey buildings. The vicinity Dhaka, Bangladesh has been considered in this work for case study. Islam et al. (2011c) added the soft-story consideration for multi-storey buildings in the similar region to evaluate the structural behavior. A number of isolators varying the characteristics of LRB and HDRB have been incorporated in between the superstructure and substructure with evaluations in detail. Yeh (2011) dealt with the adaptive fuzzy control for earthquake-excited buildings with lead rubber bearing isolation. However, this isolation technique has not yet been considered for practical implementation for multi-storey buildings in

Bangladesh region. So through study in this concern is very burning issue. In addition, there is a lacking of proper research on how to implement the device in Bangladesh vicinity at a practical consistent manner. So the objective of this paper is to describe a comprehensive study to introduce a simplified design procedure so that the design and incorporation of isolator becomes environment friendly in every region of Bangladesh and building constructors as well. Many types of isolation system have been developed elsewhere in the world to provide flexibility and damping to a structure in the event of seismic attack. Among the categories, lead rubber bearing (Figure 1) and high damping rubber bearing (Figure 2) are the most commonly used isolator nowadays. So the detail procedure is suggested for design LRB and HDRB as seismic isolation device.

ASSESSMENT TO IMPLEMENT ISOLATOR

The major steps that should be followed to assess a structure whether it is suitable for isolation or not, are listed subsequently. One can easily take a better decision whether to go for isolation or not, by simply following the given discussion.

The weight of structure

Practically used most of the isolation systems work best with heavy masses. To obtain an effective isolation a long period of response is needed. The period is proportional

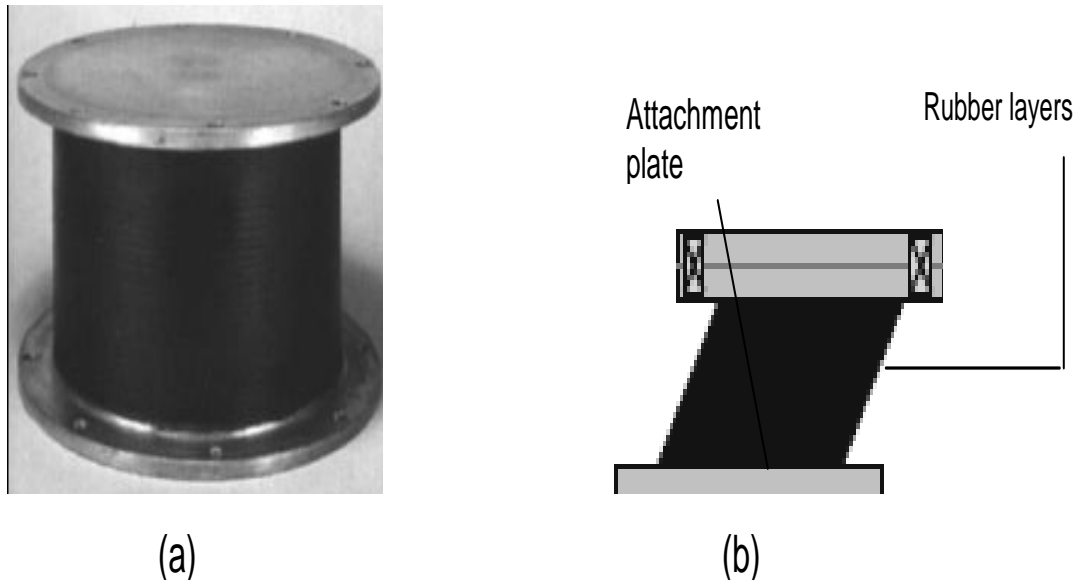


Figure 2. High damping rubber bearing: (a) Geometry and (b) Deformation due to loading.

to the square root of the mass M and inversely proportional to the square root of the stiffness K .

$$T = 2\pi \sqrt{M/K} \quad (1)$$

To achieve a given isolated period, a low mass must be associated with a low stiffness. Isolators do not have an infinite range of stiffness. Lightweight buildings may be able to be isolated with sliding systems. However, even these will not to be cost effective for light buildings for different reasons. In real terms, this usually makes the isolators more expensive as a proportion of first cost for light buildings.

The time period of structure

The most suitable structures for base isolation are those with a short natural period, especially less than about 1.0 s (Naiem, 1999). In general, the time period of the non-isolated structure supposed to be isolated should be less than 2.0 s, although there are exceptions (Kelly, 2001); for buildings, that is usually less than 10 stories and for flexible types of structures. Practical isolation systems do not provide an infinite period, rather they shift the period to the 1.5 to 3.5 s range. If the structure in question is already in this period range, then provision of base isolation would not give much benefit, although in some cases energy dissipation at the base may help.

Subsoil conditions

Isolation works best on rock and stiff soil sites. Soft soil

has a similar effect to the basin type conditions. It will modify the earthquake waves so that there is an increase in long period motion compared to stiff sites. Soft soil does not rule out isolation in itself but the efficiency and effectiveness will be reduced.

Near fault effect

One of the most controversial aspects of base isolation is that system will operate if the earthquake occurs close to the structure (within about 5 km). Close to the fault, a long period, high velocity pulse in the ground acceleration record can occur which is called "fling". Isolation is being used in near fault locations, but the cost is usually higher and the evaluation is more complex. In reality, any structure near to a fault should be evaluated for the "fling" effect.

Configuration of the structure

If the dynamic characteristics and site conditions are suitable for isolation, the most important item to consider is the configuration of the structure. Base isolation requires a plane of separation. Large horizontal offsets will occur across this plane during an earthquake. The space (often termed the "rattle" space) needed to allow for these displacements may range from less than 100 mm in low and moderate seismic zones up to 1 m or more in high seismic zones close to a fault. If there is an obstruction within this distance, then isolation will not work. For new buildings, this is not usually a problem although the maximum clearance available may impose a

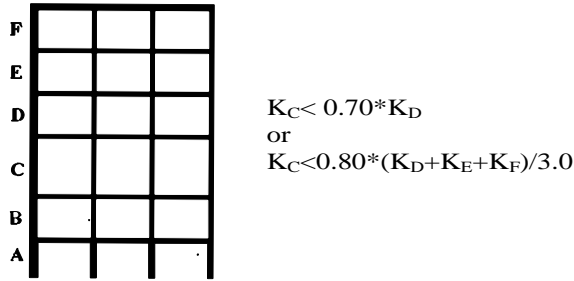


Figure 3. Vertical irregularity due to soft story.

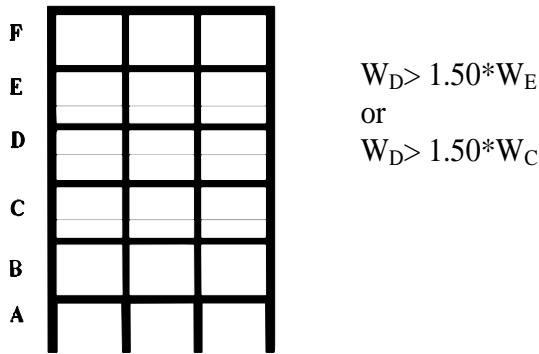


Figure 4. Vertical irregularity due to mass distribution.

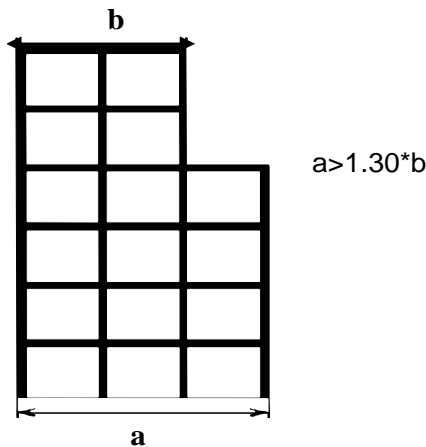


Figure 5. Geometric irregularity.

restraint on the design of the isolation system. It will rule out the retrofit of buildings that closely about other buildings. Configuration of a structure means either 'regular' or 'irregular' structure. The vertical and geometric irregularities are of basically 5 types. They are shown in Figures 3 to 7.

Detailing of the isolation system is simplest if the plane of isolation is horizontal, so sloping sites may cause

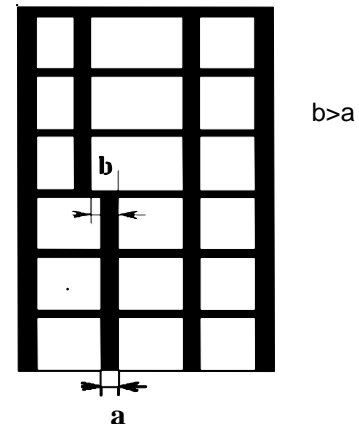


Figure 6. In-plane displacement.

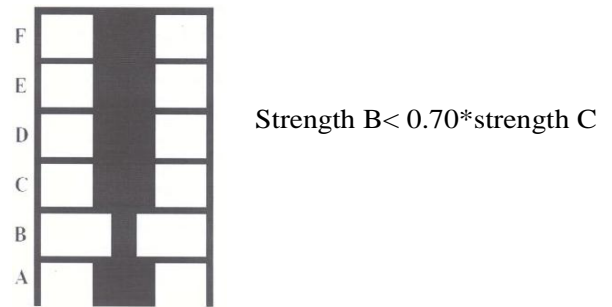


Figure 7. Weak story.

problems. In theory, there is no need to step the isolation plane, in that a vertical separation plane as well as horizontal separation plane will be required. For buildings, the most efficient building configuration to isolate is one that requires a crawl space or basement anyway. The isolation system requires a diaphragm immediately above to distribute loads and this means the ground floor must be a suspended floor. If the ground floor would otherwise be a slab on grade then isolation will add a significant first cost. This cost penalty is accentuated if there are only a few floors in the building. For example, adding an extra suspended floor to a two story building will add a high percentage cost. For retrofit of structures, cost effectiveness is usually determined by how difficult it is to separate the structure and support it while the isolators are installed. Providing the separation space is often more difficult for existing structures than for new ones.

Aspect ratio of structural system

Most practical isolation devices have been developed to operate under compression loads. Sliding systems will separate if vertical loads are tensile. Elastomeric based

Table 1. Suitability check list for isolation requirement.

Item	Check
Seismic status	
Level of earthquake risk	Is earthquake design required? Seismic isolation is best suited for moderate and high seismic areas
Seismic design requirements	If seismic design adds to costs significantly then isolation is likely to be more effective
Site suitability	
Geologic conditions	Potential for resonance effects may rule out isolation (e.g. Mexico City)
Site sub soil conditions	Stiff soil is best for isolation. As site condition becomes softer, isolation becomes less effective and more expensive
Distance to fault	Near fault motions may add to the response at the isolated periods. If the distance to the nearest active fault is small isolation displacements may be excessive
Structural suitability	
Weight of the structure	Heavy structures tend to be the most cost effective to isolate.
Period of the structure	Generally, the period of the non-isolated structure should be less than 2 seconds, although there are exceptions.
Structural configuration	Isolators are usually placed in a crawl space or basement. If a slag-on-grade is planned, these will be replaced with a suspended floor; Large aspect ratio of the structural system (height to width ratios) may cause overturning problem; For retrofit, assess how difficult to separate the structure from the ground

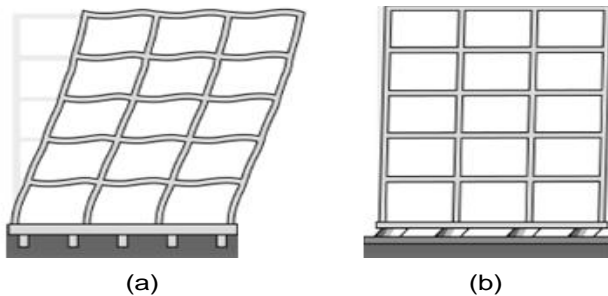


Figure 8. Change of deflection pattern while using isolator; (a) conventional structure, and (b) base -isolated structure.

systems must resist tension loads by tension in the elastomer. In tension, cavitation occurs at relatively low stresses (compared to allowable compressive stresses) which reduces the stiffness of the isolator. For these reasons, isolation systems are generally not practical for structural systems that rely on tension elements to resist lateral loads, for example, tall cantilever shear walls or narrow braced or moment frames.

A general rule of thumb is that the system should be suitable for isolation provided significant tension does not occur at any isolator location for the design level earthquake. Tension is accepted for the maximum considered earthquake but may complicate the analysis. If tensile stresses in elastomeric bearings exceed the

cavitation limit then the effect of the reduced axial stiffness may need to be assessed; for sliding systems, uplift will occur at these locations and again, the effect of this may need to be assessed. Checklist for the aptness of choosing isolation (Kelly et al., 2006) has been summarized as shown in Table 1.

STRUCTURAL PARAMETERS FOR ISOLATION SYSTEM

Base isolated system is now playing an important role in structural engineering and its implementation is abruptly increasing. The deflection patterns of conventional fixed based and isolated based building structure (Figure 8) clearly identify its advantages. The benefits will arise from the reduction in the base shear coefficient and the floor accelerations as they affect structural and non-structural fixings.

There may be direct, first cost savings associated with these. More likely, there will be indirect savings from increased seismic safety and reduced earthquake damage. Whether these can be included into the accounting depends very much on the building cost. But Bangladesh National Building Code has no guideline for incorporating base Isolator as well as its design consideration, procedure and specification. In this lesson, a procedure in light of UBC (1997) guideline has been proposed that may be included in BNBC as standard for

Table 2. Response modification coefficients for structural systems above isolation interface.

Structural system	Lateral force resisting system	Fixed base R	Isolated base R_I
Bearing wall system	Concrete shear Walls	6	2.0
	Masonry shear Walls	6	2.0
Building frame system	Steel eccentrically braced frame (EBF)	10	2.0
	Concrete shear walls	8	2.0
	Masonry shear walls	8	2.0
	Special steel concentric braced frame	8	2.0
Moment resisting frame	Special moment resisting frame (SMRF)		
	Steel	12	2.0
	Concrete	12	2.0
	Intermediate moment resisting frame (IMRF)		
	Concrete	8	2.0
	Ordinary moment resisting frame (OMRF)		
	Steel	6	2.0
	Shear walls		
Concrete with SMRF	12	2.0	
Concrete with steel OMRF	6	2.0	
Masonry with SMRF	8	2.0	
Masonry with steel OMRF	6	2.0	
Dual system	Steel EBF		
	With steel SMRF	12	2.0
	With steel OMRF	6	2.0
	Concentric braced frame		
	Steel with Steel SMRF	10	2.0
	Steel with Steel OMRF	6	2.0

designing isolator for buildings in Dhaka. Two types of isolator namely HDRB and LRB have been considered in this study. Design procedure of the type of isolator is presented here.

Response modification coefficient

Response modification factor is very vital for isolated structures as it holds a smaller value for the same structural system (Kelly et al., 2001). Table 2 shows the values of R and R_I .

Element force below the isolation system

The foundation and all structural elements below the isolation system are to be designed for a force equal to the effective horizontal stiffness multiplied by

displacement as in Equation (2).

$$F_B = K_{Dmax} D_D \quad (2)$$

Element force above the isolation system

The structure above the isolators is to be designed for the least shear force F_S , providing all the provisions for non-isolated structures denoted in Equation (3).

$$F_S = \frac{K_{Dmax} D_D}{R_I} \quad (3)$$

This elastic force in the isolation system accounts for ductility in the structure. Always R_I will be less than R that is to be maintained for avoiding high ductility in the structure above the isolation system. The value of F_S calculated as above is not to be taken as lower than any

Table 3. Structural importance coefficient.

Occupancy category	Occupancy or function of the structure	I
Essential facilities	Needed after the emergency (Hospitals, fire and police stations, emergency vehicle garages. aviation control towers, communication centers, fire suppressing equipment. etc.)	1.25
Hazardous facilities	Housing toxic or explosive substances	1.25
Special occupancy	Schools > 300 students. Universities > 500 students, any buildings > 5.000 occupants. occupants restricted > 50	1.0
Standard occupancy	Occupancies not listed in 1 to 3 and towers belongings to utilities	1.0
Low risk structures	Utilities except towers	1.0

of:

1. The lateral seismic force for the building in case at same weight W and a period equal to the isolated period T_D .
2. The base shear force corresponding to the design wind load, F_w .
3. $1.5 * F_y$

The base shear coefficient for a fixed base structure is calculated from Equation (4) and for isolated structure by Equation (5) as well.

$$C = \frac{C_v I}{RT} \quad (4)$$

$$C_I = \frac{C_v I}{R_I B_D T} \quad (5)$$

Taking $C_{VD} = C_V$ and so to meet the requirements of criteria above, $C_I \geq C$, the two equations can be combined to provide B_D as the following relation

$$B_D \leq \frac{R}{R_I I} \quad (6)$$

Therefore B_D limits according to Figure A1 (Skinner et al., 1993). Table 3 essentially illustrates the values of structural importance coefficients (I) as per occupancy categories.

Drift limitation

The drift limitations for isolated structures may also limit the design of the structural system. The allowable drift is different for dynamic response spectrum and time history analysis cases.

$\delta \leq 0.015 / R_I$ for Response spectrum analysis

$\delta \leq 0.020 / R_I$ for Time history analysis

DEVICE MODELING

The form of this function for a particular element depends on the device modeled which follows the succeeding criteria.

1. HDR bearings are modeled as either a linear elastic model with viscous damping included or with the hysteretic loop directly specified.
2. LRBs are modeled as either two separate components or as a single bi-linear element.

The modeling must be such that damping is not included twice, as viscous and hysteretic. Element damping is applied to the rubber component, which has some associated viscous damping, but not to the lead component.

STRUCTURAL ANALYSES WITH ISOLATORS

The model can be analyzed using a number of procedures with increasing the order of complexity as (1) static analysis and (2) dynamic analysis.

Static analysis

Linear static analysis is the simplest of all and is limited to small, regular buildings and would almost never be sufficient. It is necessary to calculate the following factors: N_a and N_v , MM , $Z * N_v$, C_{AD} , C_{VD} , C_{AM} and C_{VM} to perform a linear static analysis. Seismic coefficients are intended to define the minimum spectral ordinates to be used in design. The terms C_A and C_V correspond to constant- acceleration and constant-velocity regions of the response spectrum respectively. The values of C_A and C_V have been shown in modified form following seismic coefficients charts adopted in UBC (1997) as per soil profile of Bangladesh. Tables 4 and 5 present the seismic coefficients C_A and C_V in tabular form respectively.

Table 4. Seismic coefficient C_A .

Soil profile type	Seismic zone coefficient, Z				
	Z=0.075	Z=0.15	Z=0.2	Z=0.3	Z=0.4
S _{1a}	0.06	0.12	0.16	0.24	0.32 Na
S _{1b}	0.08	0.15	0.20	0.30	0.40 Na
S ₂	0.09	0.18	0.24	0.33	0.40 Na
S ₃	0.12	0.22	0.28	0.36	0.44 Na
S ₄	0.19	0.30	0.32	0.36	0.36 Na
Other	Site specific geotechnical investigation and dynamic site response are to be performed to determine seismic coefficients.				

Table 5. Seismic coefficient C_v .

Soil profile type	Seismic zone coefficient, Z				
	Z=0.075	Z=0.15	Z=0.2	Z=0.3	Z=0.4
S _{1a}	0.06	0.12	0.16	0.24	0.32 Nv
S _{1b}	0.08	0.15	0.20	0.30	0.40 Nv
S ₂	0.13	0.25	0.32	0.45	0.56 Nv
S ₃	0.18	0.32	0.40	0.54	0.64 Nv
S ₄	0.26	0.50	0.62	0.84	0.96 Nv
Other	Site specific geotechnical investigation and dynamic site response are to be performed to determine seismic coefficients				

Dynamic analysis

Dynamic analysis procedures shall be based on an appropriate ground motion representation and shall be performed using acknowledged principles of dynamics. Dynamic analysis can be done by frequency domain using seismic response spectra and time domain utilizing earthquake time history.

Response spectrum analysis

A linear response spectrum analysis is the most common type of analysis used. This is sufficient for almost all isolation systems based on LRB and/or HDR bearings. This analysis will be done by the response spectrum curve for specific soil condition of target location for a damping ratio of 0.05. The response spectra can be chosen as given in BNBC (1993) or the developed response spectra in Islam et al. (2011e).

Time history analysis

Linear time history analysis provides little more information than the response spectrum analysis for a much greater degree of effort and so is rarely used. Site specific time history of earthquake is needed to be

generated or properly scaled consistent with maximum ground acceleration of the vicinity. The time history developed at Islam et al. (2011d) for Dhaka earthquake can be used after proper scaling of the respective site condition.

Nonlinear time history analysis is required for (1) systems on very soft soil, (2) systems without a restoring force, (3) velocity dependent systems and (4) systems with limited displacement capability.

DESIGN OF ISOLATION SYSTEM

Design iteration

Because of this displacement dependence, the design process is iterative, as shown in forms of flow chart in Figure 9 for elastomeric bearing isolation systems (lead rubber and high damping rubber). A further complication arises for these types of bearing in that, as well as period and damping, the minimum plan size of the bearing is also a function of displacement.

The iterative process involves:

1. At each isolator locations, select a bearing plan size based on vertical load and assumes a displacement at the target period and damping.
2. Calculate the effective stiffness, period and equivalent

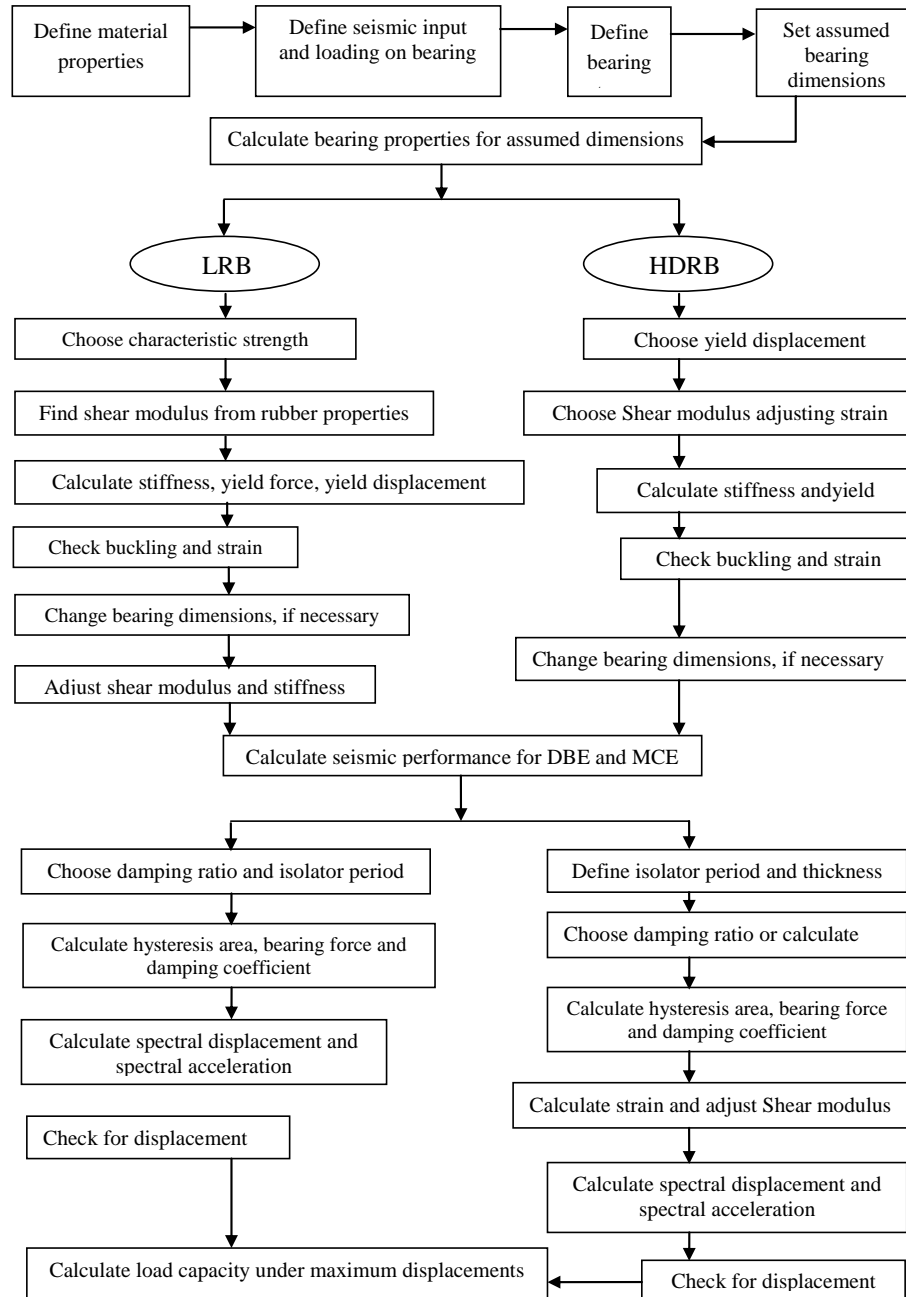


Figure 9. Design flow chart of isolator properties.

viscous damping at the assumed displacement.

3. From the seismic load parameters, calculate the actual displacement for this stiffness and damping.

4. Calculate revised damping for this displacement. Repeat step 3 if necessary.

5. Check and adjust the minimum plan size required to support vertical loads at this displacement if necessary.

These steps are repeated until convergence is attained. Generally, the higher the vertical load on an elastomeric

bearing the easier it will be to achieve long effective periods.

Considerations for rubber characteristics

The procedures are based on some empirical data of damping coefficient, shear modulus, shear strain, yield stress, post-yielded stiffness etc. whereas different values are taken from different tables and figures.

Table 6. Damping coefficient.

Effective damping (percentage of critical) ^{a,b}	Damping coefficient B_D or B_M
2	0.8
5	1.0
10	1.2
20	1.5
30	1.7
40	1.9
50	2.0

^a:The damping coefficient based on the effective damping of the isolation system determined in accordance with the requirements; ^b:The damping coefficient based on linear interpolation for effective damping values other than those given.

Selection damping coefficients (B_D and B_M)

For the effective damping in the system at the design basis earthquake (DBE) and maximum capable earthquake (MCE) response levels, Table 6 gives a relationship to find out the damping coefficient B_D for isolator for critical damping ratio. Alternatively a very close approximation to the table values is given by Equation (7). β is damping ratio which is to be chosen and adjusted with iterative computation.

$$\frac{1}{B_D} = 0.25(1 - \ln\beta) \quad (7)$$

Range of rubber compounds

Properties of rubber compounds used for isolation generally ranges as in Table A1. There is uncertainty about the appropriate value to use for the bulk modulus, E_∞ , with quoted values ranging from 1000 to 2000 MPa. A value of 1500 MPa is recommended for design. For a relatively low damping rubber formulation, the properties vary as in Table A2. Again there are a large number of high damping formulations available and each manufacturer typically provides a range of elastomers with varying hardness and damping values. The properties are a function of the applied shear strain. The properties used for this design were as plotted in Figure A2.

Allowable displacement

Isolator displacements may be typically of at least 300 mm and in some cases twice that much, 600 mm. The larger displacements require bearings with larger plan sizes and this in turns leads to the higher bearing to retain the flexibility.

Shape factor

The shape factor of an internal layer, S_i , is demarcated as the loaded surface area divided by the total free to bulge area. Equation (8) shows the relation of this shape factor for circular and square HDR bearings.

$$S_i = \frac{B}{4t_i} \quad (8)$$

However lead rubber bearings having a hole for the lead core leads the shape factor relation as in Equation (9).

$$S_i = \frac{A_b - A_{pl}}{\pi B_b t_i} \quad (9)$$

Vertical stiffness

The vertical stiffness of an internal layer of bearing isolator is calculated from the following Equation (10).

$$K_{vi} = \frac{E_c A_r}{t_i} \quad (10)$$

where, the compressive modulus, E_c , is a function of the shape factor and material constant as mentioned in Equation (11).

$$E_c = E[1 + 2kS_i^2] \quad (11)$$

In the equation for vertical stiffness, a reduced area of rubber, A_r , is calculated based on the overlapping areas between the top and bottom of the bearing at a displacement, Δ .

$$A_r = A_b \left(1 - \frac{\Delta}{B_b}\right) \quad \text{for square bearing} \quad (12)$$

$$A_r = 0.5 \left\{ B^2 \sin^{-1} \left(\frac{\Sigma}{B_b} \right) - \Delta \Sigma \right\} \quad \text{for circular bearing} \quad (13)$$

where

$$\Sigma = \sqrt{(B_b^2 - \Delta^2)} \quad (14)$$

When the effective compressive modulus, E_c , is large compared to the bulk modulus E_∞ , then the vertical deformation due to the bulk modulus is included by dividing E_c by $(1 + E_c / E_\infty)$ to calculate the vertical stiffness. Bulk modulus effects are used to when the vertical stiffness is used to calculate vertical deformations in the bearing but not the shear strains due to vertical load.

Compressive rated load capacity

The vertical load capacity is calculated by summing the total shear strain in the elastomer from all sources. The total strain is then limited to the ultimate elongation at break of the elastomer divided by the factor of safety appropriate to the load condition. The shear strain from vertical loads, ϵ_{sc} , is calculated as

$$\epsilon_{sc} = 6S_i \epsilon_c \quad (15)$$

where

$$\epsilon_c = \frac{P}{K_{vi} t_i} \quad (16)$$

If the bearing is subjected to applied rotations the shear strain leads to

$$\epsilon_{sr} = \frac{B_b^2 \theta}{2t_i T_r} \quad (17)$$

The shear strain due to lateral loads is

$$\epsilon_{sh} = \frac{\Delta}{T_r} \quad (18)$$

For service loads such as dead and live load the limiting strain criteria are

$$f\epsilon_u \geq \epsilon_{sc} \quad (19)$$

Factor of safety in Equation (19) is to be maintained as 3 ($f = 1/3$). And for ultimate loads which include earthquake displacements, the formulation is modified as Equation (20) maintain constraint for factor of safety 1.33 ($f = 0.75$).

$$f\epsilon_u \geq \epsilon_{sc} + \epsilon_{sh} \quad (20)$$

Combining these equations, the maximum vertical load, P_V , at displacement Δ can be calculated from following equation.

$$P_V = \frac{K_{vi} t_i (f\epsilon_u - \epsilon_{sh})}{6S_i} \quad (21)$$

Strain limitation

The total strain formulation is used with the exception that the MCE displacement is designed using $f = 1.0$.

1. The total strain is a constant value for each load combination, rather than a function of ultimate elongation. Strain due to non-seismic deformations, $\epsilon_{s,s}$ and a strain due to seismic displacements, $\epsilon_{s,eq}$. The limits are then:

$$\epsilon_{sc} \leq 2.5 \quad (22a)$$

$$\epsilon_{sc} + \epsilon_{s,s} + \epsilon_{sr} \leq 5.0 \quad (22b)$$

$$\epsilon_{sc} + \epsilon_{s,eq} + 0.5\epsilon_{sr} \leq 5.5 \quad (22c)$$

2. The shear strain due to compression, ϵ_{sc} , is a function of the maximum shape factor:

$$\epsilon_{sc} = \frac{3SP}{2A_r G(1+2kS^2)} \quad (23)$$

For $S \leq 15$, or

$$\epsilon_{sc} = \frac{3P(1 + \frac{gGkS^2}{E_{\infty}})}{4GkSA_r} \quad S > 15 \quad (24)$$

The equation for $S \leq 15$ is a re-arranged form of the equations above with the approximation that $E = 4G$. The formula for $S > 15$ has approximated $(1+2kS^2) \approx 2kS^2$ and adjusted the vertical stiffness for the bulk modulus effects.

Allowable vertical load

The allowable vertical load on the bearing will be obviously the smaller value of the rated load P_V or the buckling load P_{cr} .

Tensile rated load capacity

Equation for P_V is same as compressive rated load capacity with the exception of the matter that the strains are the sum of the absolute values.

Buckling load capacity

Buckling load capacity from which the buckling load at zero displacement is:

$$P_{cr}^0 = \frac{R}{2} \left[\sqrt{1 + \frac{4TQ^2}{R}} - 1 \right] \quad (25)$$

The constants T , R and Q of Equation (25) are calculated as:

$$T = E_b \frac{H_r}{T_r} \quad (26)$$

$$R = K_r H_r \quad (27)$$

$$Q = \frac{\pi}{H_r} \quad (28)$$

$I_m = B_b^4/12$ for square bearings, $I_m = \pi B_b^4/64$ for circular bearings

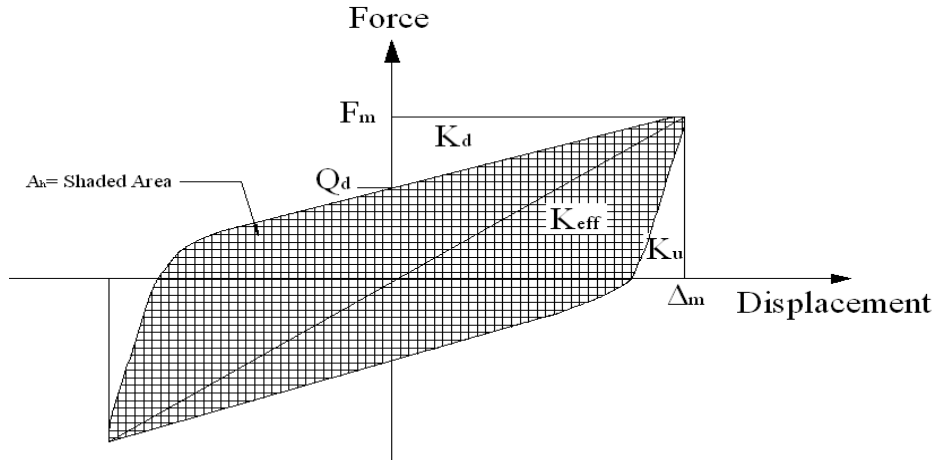


Figure 10. Typical rubber bearing hysteresis.

$$H_r = (nt_i) + (n-1)t_{sh} \quad (29)$$

$$E_b = E(1+0.742S_i^2) \quad (30)$$

For an applied shear displacement, the critical buckling load at zero displacement is reduced consistent with the effective "footprint" of the bearing in a similar fashion to the strain limited load as presented in Equation (31).

$$P_{cr}^y = P_{cr}^0 \frac{A_r}{A_g} \quad (31)$$

Lateral stiffness and hysteresis parameters for bearing

A typical hysteresis for a lead-rubber bearing is as shown in Figure 10. The force intercept at zero displacement is termed Qd, the characteristic strength (Equation (32)).

$$Q_d = \sigma_y A_{pl} \quad (32)$$

$\sigma_y = 7$ to 8.5 MPa depending on the vertical load and lead core confinement.

The post-elastic stiffness:

$$K_r = \frac{G_r A_r}{T_r} \quad (33)$$

The elastic (or unloading) stiffness for HDRB is assumed as in Equation (34a) and this value K_u for LRB comes through the Equation (34b).

$$K_u = K_r \quad (34a)$$

$$K_u = 6.5K_r \left(1 + \frac{12A_{pl}}{A_r}\right) \quad (34b)$$

Effective stiffness:

$$K_{eff} = F_m / \Delta, \quad (35)$$

where

$$F_m = Q_d + K_r \Delta \quad (36)$$

Effective period:

$$T_e = 2\pi \sqrt{\frac{W}{g \Sigma K_{eff}}} \quad (37)$$

Hysteresis area for LRB follows Equation (38) whereas in case of HDRB, the area of hysteresis loop leads to the counter calculation of subsequent Equation (39).

$$A_h = 4Q_d(\Delta_m - \Delta_y) \text{ for LRB,} \quad (38)$$

Equivalent viscous damping

$$\beta = \frac{1}{2\pi} \left(\frac{A_h}{K_{eff} \Delta^2} \right) \quad (39)$$

The maximum isolator displacement is then derives as in Equation (40).

$$\Delta_m = \frac{S_a T_e^2}{4\pi^2 B} \quad (40)$$

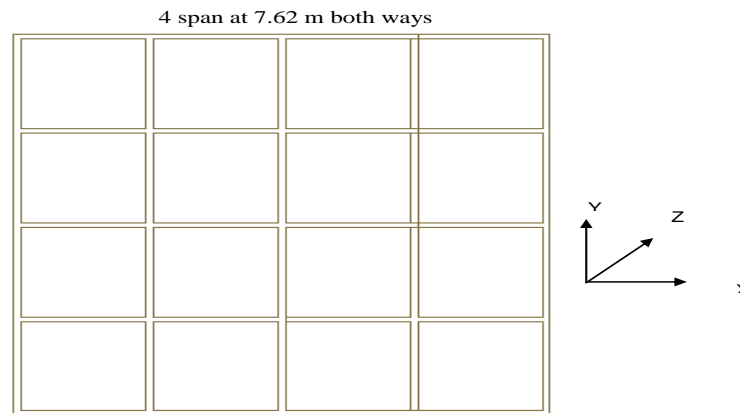
where S_a = the spectral acceleration at T_e .

Lead core confinement

The lead core used in LRB will have an apparent yield level which is a function of the theoretical yield level of lead, 10.5 MPa and the degree of confinement of the lead. Figure A3 shows the effect of lead core on

Table 7. Factor of safety for strain and buckling.

	Factor of safety	Remark
Gravity	>3.0 for both strain and buckling	>6.0 for high seismic zone
DBE	>1.5 for both strain and buckling	2.0 preferable
MCE	>1.25 for both strain and buckling	1.5 preferable

**Figure 11.** Plan view of the multi storied building.

displacement. The maximum lead core force is assumed to be 25% of characteristics strength, Q_d .

Isolator dimensions

The dimension (B) of bearing isolator is very vital for incorporation after design and there are some constraints from which the optimum size of bearing will be selected. The cases for evaluation the optimum dimensions are as follows.

1. B is to be ensured as required for the maximum gravity loads.
2. The increment of B for iterative design based on a F.S. of 3 in the design progresses equals 50 mm
3. t_i = generally 10 mm, may be reduced to 8 mm or even 6 mm if vertical loads are critical. t_i should not exceed 10 mm for LRBs but thicker layers may be used for elastomeric or HDR bearings.
4. The number of layers defines the flexibility of the system which to be set so that the isolated period is in the range required and so that the maximum shear strain is not excessive.
5. The ratio of $Q_D/W = 3$ to 10%

Factors of safety

For ensuring the structural protection, it is urged for calculation of the strain and buckling force that the

suggested factor of safety is strictly maintained. The constraints for preferable factor of safety for gravity, DBE and MCE loading have been set out in Table 7.

Supplementary bearing constraints

1. The ratio of reduced area to gross area > 25% and preferably > 30%.
2. The maximum shear strain < 250% and preferably < 200%.

CASE STUDY

Building configuration

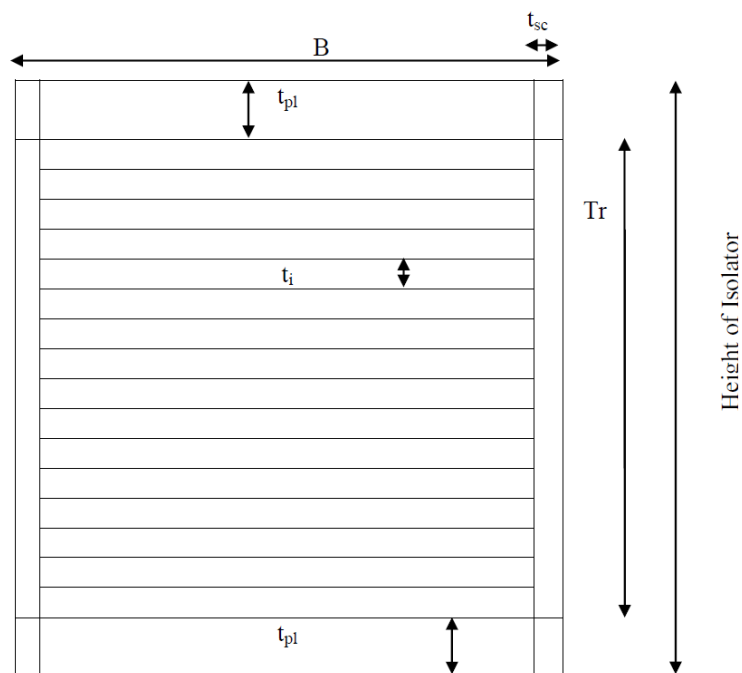
Four moment resisting frame buildings located at Dhaka, Bangladesh of squared plan size at 4span at 7.62 m at both directions having 4, 6, 7, 8, 9 and 10 story shown in Figure 11 were used in the analytical study. For each building, total seismic weight were assumed to be distributed equally over all floors including the base floor as well as equally over all columns. This assumption allowed the same isolation systems to be used for all columns in a building.

Design of isolator

Lead rubber bearing (LRB) and high damping rubber

Table 8. Isolator components requirement for different stories.

No. of story	Diameter of isolator, B (mm) (HDRB and LRB)	Layer thickness, t_i (mm)	Thickness of mountain plates, t_{pl}	Thickness of shim plate, t_{sc}	No. of layer
4	600 and 500	10	40	12.5	12
5	600 and 500	10	40	12.5	12
6	700 and 600	10	40	12.5	12
7	800 and 650	10	40	12.5	12
8	850 and 700	10	40	12.5	14
9	900 and 750	10	40	12.5	15
10	950 and 800	10	40	12.5	16

**Figure 12.** Typical element dimensions of bearing.

bearing (HDRB) were incorporated on the buildings. The designs were completed using the developed spreadsheet ISODES which implements the design procedures as described previously. Internal 9 columns are separated by HDRB and the external 16 columns by LRB as well. LRB is formed from a lead plug force-fitted into a preformed hole in a low damping elastomeric bearing as shown in Figure 1. Whereas, HDRB consists of thin layers of high damping rubber and steel plates built in alternate layers as shown in Figure 2. The design basis includes S_3 type soil profile for Dhaka, Bangladesh having seismic zone coefficient, $Z = 0.15$ and beyond 15 km of a Type A fault. The vertical loads have been obtained from the analyses of structures using sophisticated finite element program SAP 2000 (2005). The results in Table 8 have been drawn through the

developed design program. The segments of typical isolator are given in Figure 12.

Evaluation of designed isolators

The diameter of Isolator and number of layers requirement increases with the increase in number of stories in both isolated building while fixing the layer thickness, 10 mm. But the most important question is how this increasingly occurs. Table 8 shows that up to 5 stories isolation requires the same ingredients and then diameter requirement increases up to 7 stories assigning same no. of layers. From 8 to 10 story buildings bearing diameter also increases along with numbers of layers requirement but fixing layer thickness same as 10 mm demands

allowable displacement to be larger. It is worth mentioning that for all the model, the structural time period is below the unit value, Seismic base shear is lesser than the wind induced shear and wind induced shear is less than ten percent of total seismic weight. Consequently, the isolated multi-storey building models in this study suited the viability criteria of incorporating isolation device between foundation and superstructure as well.

Conclusion

Although the seismic base isolation is going to be popular all over the world, in the vicinity of Bangladesh, its implementation for building structures is still young. A detail research has been carried out in this work to establish a new criteria basis design procedure for isolators incorporated in building structures. Isolation systems namely lead rubber bearing (LRB) and high damping rubber bearing (HDRB) have been selected for the present research. Mathematical formulation and limiting criteria for design of every individual part have been stimulated. The suitability to incorporate isolators for seismic control has been explored in details. The study divulges simplified design procedures for LRB and HDRB for buildings in Bangladesh. The detail design progression has been proposed to be included in Bangladesh National Building Code (BNBC).

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APPENDIX

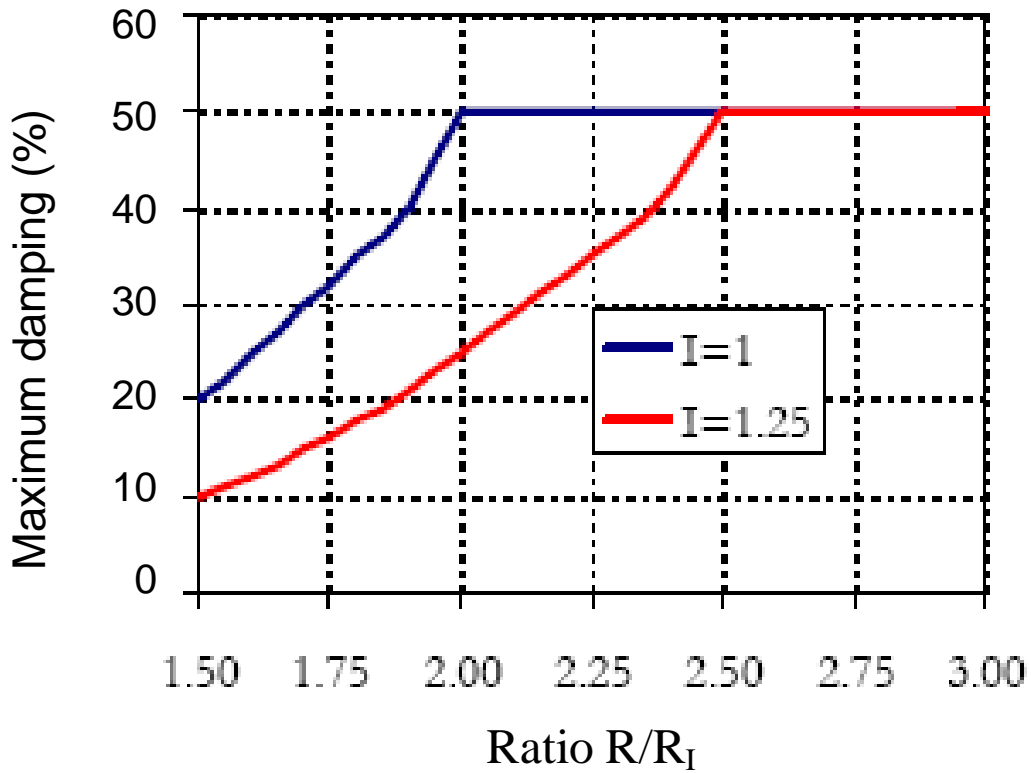


Figure A1. Allowable damping for structural response modification and importance factor.

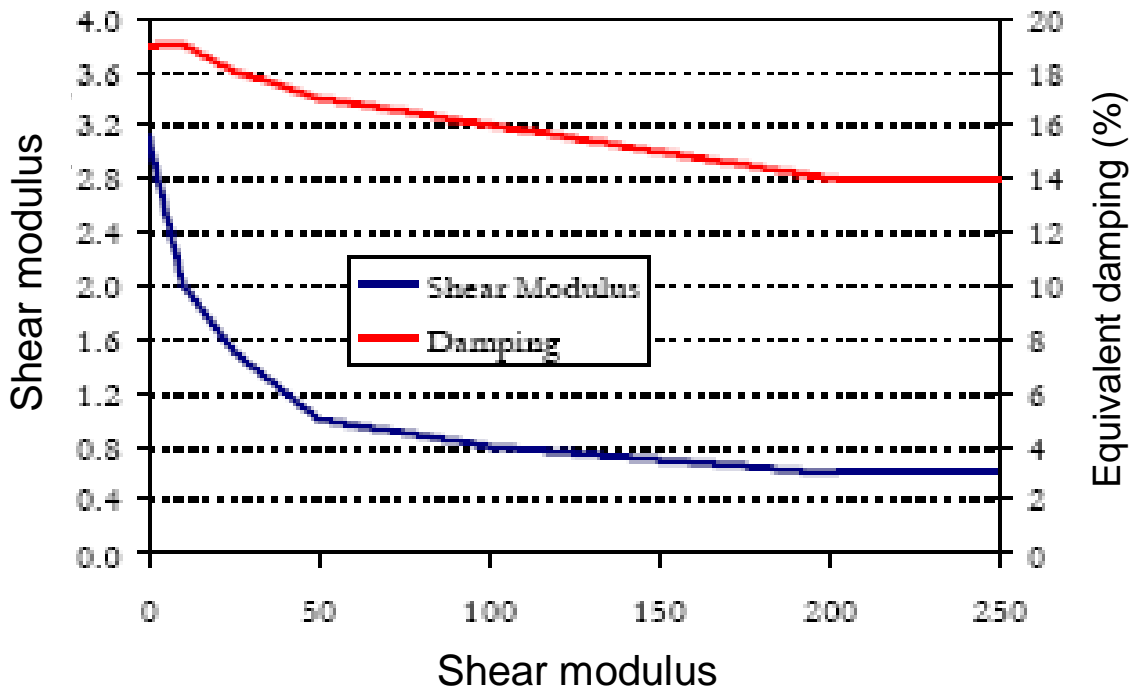


Figure A2. High damping rubber properties.

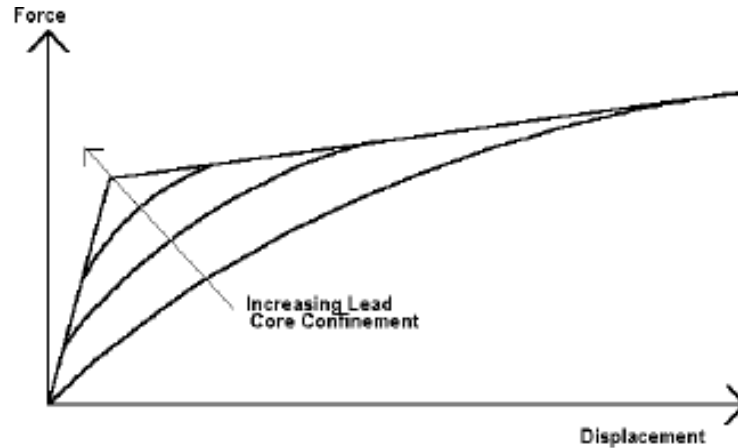


Figure A3. Effect of lead core confinement.

Table A1. Natural rubber properties.

Hardness IRHD \pm 2	Young's modulus E (MPa)	Shear Modulus G (MPa)	Material constant, k	Elongation at break Min. (%)
37	1.35	0.40	0.87	650
40	1.50	0.45	0.85	600
45	1.80	0.54	0.80	600
50	2.20	0.64	0.73	500
55	3.25	0.81	0.64	500
60	4.45	1.06	0.57	400

Table A2. Shear- damping relation for relatively low damping rubber.

Shear strain (%)	Shear modulus (MPa)	Equivalent damping (%)
10	1.21	12.72
25	0.79	11.28
50	0.57	10.00
75	0.48	8.96
100	0.43	8.48
125	0.40	8.56
150	0.38	8.88
175	0.37	9.36
200	0.35	9.36

Symbols and notations

A_b	Bonded area of rubber
A_g	Gross area of bearing, including side cover
A_h	Area of hysteresis loop (or EDC = energy dissipated per cycle)
A_{pl}	Area of lead core
A_r	Reduced rubber area
B	Overall plan dimension of bearing
B_b	Bonded plan dimension of bearing
B_D	Damping coefficient at DBE

B_M	Damping coefficient at MCE
C	Base shear coefficient for fixed based building
C_i	Base shear coefficient for isolated based building
C_A	Seismic coefficient correspond to the constant-acceleration region
C_V	Seismic coefficient correspond to the constant-velocity region
C_{AD}	Seismic coefficient correspond to the constant-acceleration region of the DBE Response Spectrum
C_{VD}	Seismic coefficient correspond to the constant-velocity region of the DBE Response Spectrum
C_{AM}	Seismic coefficient correspond to the constant-acceleration region of the MCE Response Spectrum
C_{VM}	Seismic coefficient correspond to the constant-velocity region of the MCE Response Spectrum
DBE	Design Basis Earthquake
D_D	Displacement at design basis earthquake
E	Elastic modulus of rubber
E_b	Buckling modulus
E_c	Effective compressive modulus
E_∞	Bulk modulus
f	Factor applied to elongation for load capacity = $1 / (\text{Factor of Safety})$
F_B	Maximum base shear force transmitted through the isolation system to the structure above. This is the base shear for elastic performance.
F_s	Elastic base shear reduced by the isolated response modification factor
F_m	Force in bearing at specified displacement
F_w	Base shear corresponding to wind load
F_y	Yield force
g	Acceleration due to gravity
G	Shear modulus of rubber
G_γ	Shear modulus of rubber (at shear strain γ)
H	Height of the building
H_c	Height of inertia load
H_r	Height free to buckle
I	Structural importance factor
I_m	Moment of inertia
k	Material constant
K	Stiffness
K_{Dmax}	Maximum effective horizontal stiffness at design displacement (DBE)
K_d	Yielded stiffness of lead rubber bearing = K_r
K_{eff}	Effective stiffness
K_r	Lateral stiffness after yield
K_u	Elastic lateral stiffness = Initial stiffness
K_v	Vertical stiffness of bearing
K_{vi}	Vertical stiffness of layer i
M	Mass
MCE	Maximum Capable Earthquake (Maximum Credible Earthquake)
M_M	MCE response coefficient,
N_a	Near source factor at constant acceleration
N_V	Near source factor at constant velocity
n	Number of rubber layers

P	Applied vertical load
P_{cr}	Buckling load
P_Y	Maximum rated vertical load
Q_d	Characteristic strength (Force intercept at zero displacement)
R	Fixed base response modification coefficient
R_I	Isolated base response modification coefficient
S	Dimensionless site coefficient for the soil profile characteristics
S_a	Spectral acceleration
S_i	Shape factor for layer i
T	Time period
T_e	Effective time period
T_D	Isolated period at DBE
t_i	Rubber layer thickness
t_{sc}	Thickness of side cover
t_{sh}	Thickness of internal shims
t_{pl}	Thickness of mounting plates
T_r	Total rubber thickness
W	Total seismic weight
Z	Seismic zone factor
Δ	Applied lateral displacement
Δ_m	Maximum applied displacement
Δ_y	Yield displacement
β	Damping ratio = ξ
β_{eff}	Effective damping
$\bar{\delta}$	Drift
ϵ_u	Minimum elongation at break of rubber
ϵ_c	Compressive strain
ϵ_{sc}	Shear strain from applied vertical loads
ϵ_{sh}	Shear strain from applied lateral displacement
ϵ_{sr}	Shear strain from applied rotation
$\epsilon_{s,s}$	Strain due to non-seismic deformations
$\epsilon_{s,eq}$	Strain due to seismic displacements
θ	Applied rotation
σ_y	Lead yield stress