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Design approach of high damping rubber bearing for seismic isolation

Patrick L.Y. Tiong[*1], James M. Kelly[2a] and Tan T. Or[3b]

[1]*Research and Development Division, Base Isolation Technology (Asia) Sdn Bhd, Lot PT 34252, Jalan Sekolah, Rantau Panjang, 42100 Klang, Selangor Darul Ehsan, Malaysia*
[2]*Department of Civil and Environmental Engineering, 782 Davis Hall, University of California, 94720-1710 Berkeley, United States of America*
[3]*Doshin Rubber Products (M) Sdn Bhd, Lot PT 34252, Jalan Sekolah, Rantau Panjang, 42100 Klang, Selangor Darul Ehsan, Malaysia*

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Abstract. Structural control through seismic isolation using elastomeric rubber bearing, which is also known as High Damping Rubber Bearing (HDRB), has seen an increase in use to provide protective from earthquake, especially for new buildings in earthquake zones. Besides, HDRB has also been used in structural rehabilitation of older yet significant buildings, such as museums and palaces. However, the present design approach applied in normal practice has often resulted in dissimilar HDRB dimension requirement between structural designers and bearing manufacturers mainly due to ineffective communication. Therefore, in order to ease the design process, most HDRB manufacturers have come up with catalogs that list all necessary and relevant product lines specifically for structural engineers to choose from. In fact, these catalogs contain physical dimension, compression property, shear characteristic, and most importantly, the total rubber thickness. Nonetheless, other complicated issues, such as the relationship between target isolation period and displacement demand (which determines the total rubber thickness), are omitted due to cul-de-sac fixing of these values in the catalogs. As such, this paper presents a formula, which is derived and extended from the present design approach, in order to offer a simple guideline for engineers to estimate the required HDRB size. This improved design formula successfully minimizes the discrepancies stumbled upon among structural designers, builders, and rubber bearing manufacturers in terms of variation order issue at the designing stage because manufacturer of isolator is always the last to be appointed in most projects.

Keywords: structural control; seismic mitigation; base isolation; seismic bearing; bearing design

1. Introduction

Seismic (or base) isolation with High Damping Rubber Bearing (HDRB) is possibly one of the best passive mitigation approaches to minimize the effects of earthquake on structures (Tiong *et al*. 2014). The base isolation decouples the superstructure from ground motion by exerting relatively lower lateral stiffness and thus, the base shear demand is greatly decreased. This is especially achieved by elongating the period of the base-isolated structure, which takes it out of the peak spectral demand, as illustrated in Fig. 1 (Kelly and Konstantinidis 2011). In addition to the period of elongation, the base isolation also increases the critical damping ratio of the structure that generates a reduction in the spectral demand at an optimum damping value. In fact, due to its significant implication, many researchers worldwide have looked into the effectiveness of HDRB, for instance, Kikuchi and Aiken (1997), Chung *et al.* (1999), Chaudhary *et al.* (2001),Wu and Samali (2002), Moroni *et al*. (2004), Braga and Laterza (2004), Narasimhan *et al.* (2009), Falborski and Jankowski (2012), Malek *et al*. (2012), Fan *et al*. (2015) and Chen *et al.* (2016). Nonetheless, to the authors' best knowledge, the present design approach of HDRB that has been widely adopted was recommended by Naeim and Kelly (1999), which was later translated into other design codes (CEN 2005, 2007). In addition, several other publications of the design guidelines include the Manual for Menshin design of highway bridges (Kawashima 1992) and the AASTHO codes (Anderson *et al.* 2000, AASTHO 2010). Hence, the objective of this paper is to improve the present iterative design procedure, in which multiple constraints have to be satisfied and more than a single-step procedure is required to attain an optimum design. Although the iterative steps can be programmed for easier calculation in spreadsheet (Chauhan and Shah 2013); in practice, most structural engineers do not deal with the design of rubber bearing and the rubber manufacturers are not involved in the structural design stage. Hence, the key question that arises is: 'Who is responsible for the final design of HDRB?' Moreover, structural engineers do not go through the iterative processes to arrive at the optimum dimension of the required HDRB. As such, the communication process between the manufacturer and the structural engineer can be enhanced if consent is given to structural engineers to estimate the suitable size for each HDRB using a simple formula.

∗Corresponding author, Ph.D.
E-mail: patrick@baseisolation.com
[a]Professor
[b]Professor

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Furthermore, as mentioned previously, the conventional design process (or design flow) of an HDRB base-isolated system requires iterative processes between the estimation of bearing parameters (such as the size or dimension of the HDRB) and its detailing (number of steel plates), which in return, determines the overall height of the HDRB. The design flow begins with the assumption of target period TD of the isolated structure, which is normally found in the range of 2.0 to 3.0 s (Naeim and Kelly 1999). After that, the next step is the determination of effective bearing lateral stiffness (KH) by calculating Eq. (1).

$$K_H = M \times \left(\frac{2\pi}{T_D}\right)^2 \tag{1}$$

Where M is the mass (or vertical loading) supported by the rubber bearing.

Then, the design displacement D_D can be obtained by adhering to several codes procedure, such as EC8 and ASCE 7-10 (2010), or even from the displacement design spectra for the specific site. The rubber thickness (t_r) is determined based on the design displacement, adhering to allowable design shear strain limits (CEN 2005, 2007). By obtaining the total rubber thickness (t_r); shear modulus (G), effective shear stiffness (K_H), and the required cross-sectional area (A) of the rubber bearing can be determined from the relationship portrayed in Eq. (2).

$$K_H = \frac{G_{1.5} \times A}{t_r} \tag{2}$$

After obtaining the dimension of bearing at this stage, the design is preceded with detailing and buckling load check. In this phase of design, trial-and-error process cannot be avoided because the designers only have retrieved the bearing diameter ϕ and the total rubber thickness t_r. Nevertheless, these two bearing parameters are sufficient for the designers to initially estimate (or guess) the shape factor S.

However, one should note that since the shape factor S and the frequencies (both horizontal and vertical) of the rubber bearing are inter-related to each other, any amendment to these parameters at this stage of design (should the bearing fails to fulfill buckling load checking) can lead to alteration to the whole parameter of the rubber bearing. In a normal state, the buckling capacity (P_{crit}) of the bearing can be augmented either by increasing the bearing diameter ($\emptyset$), or by increasing the number rubber layers (n). Nonetheless, the design process has to be restarted from the beginning if these approaches are employed as the total rubber thickness (t_r) and the choice of shear modulus (G) are influenced by the increasing diameter. Eventually, this calls for the trial-and-error process, in which the design flow reflects a loop of repetition (or iteration) until the final bearing dimension and the detailing successfully fulfill the criteria outlined for the inspection. Although design spreadsheet has been found to ease the iterative design process for HDRB bearing, this paper proposes a single equation specially for structural engineers to estimate the approximate diameter of the HDRB easily so as to determine the size of pedestal and foundation support without the need to wait for the final design from the manufacturer.

2. Improved HDRB design

The present design of HDRB procedures involves a trial-and-error looping process, in which the design starts from shear stiffness requirement and then determined for compressive load effect on horizontal stiffness, buckling, roll-out, and most importantly, vertical strain limit. Meanwhile, the aspects of roll-out and vertical strain limit are excluded from this paper since the proposed formula does not cater to those in the present development stage (please refer to Naeim and Kelly (1999) for further details).

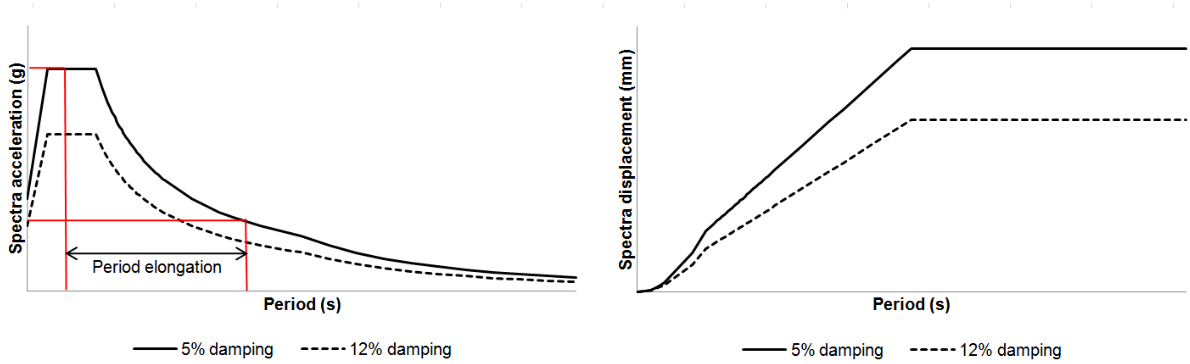
The balance in each of the design check often results in designers with the necessity to re-sketch the design from scratch until convergence is met, as illustrated in Fig. 2. Moreover, all iterations are required to be carried out until all parameters are satisfied and convergence is attained.

In addition, many HDRB manufacturers display the tendency to produce their own standardized size of bearings, depending on the vertical load. Unfortunately, instead of performing iterative design process of HDRB, structural engineers are only required to choose from the product catalogs of the required size based on the displacement demand and vertical loading capacity. Furthermore, the performance of HDRB does not depend solely on the total vertical load because the design displacement depends on different spectral demands, in which standardization becomes impossible, and therefore, should not be represented by pre-determined value for engineers to choose from. As a result, no relevant rationale exists behind the standardization of rubber bearing products that are solely based on vertical loading and some values of random displacement demand.

Other than that, the main problem faced in the conventional rubber bearing design is the lack of boundary limit for engineers and designers to initiate the design process even though provided with the well-known equation that starts the flow with estimation of the shear modulus $G_{1.5}$ at a higher strain (typically 150%) and the cross-sectional area of the rubber bearing A, as shown in Eq. (3).

$$t_r = \frac{G_{1.5} \times A}{K_H} \tag{3}$$

In addition, there is an extremely limited boundary condition at this very initial step of the design flow for engineers to refer in order to determine the values of shear modulus and the size of bearing to be applied (Islam *et al*. 2011). On top of that, a majority of manufacturers tend to categorize shear modulus into soft (ranges from 0.4 to 0.7 MPa), nominal (0.8 to 1.1 MPa), and hard compounds (1.2 to 1.4 MPa). Therefore, unless an identical past project is available for reference, the normal practice is to randomly guess any comfortable $G_{1.5}$ value (ranges from 0.4 to 1.4 MPa) and then, section area A can be determined. However, bearing designers usually employ a varied range of shear modulus values to achieve a similar isolator dimension to avoid using extra mould that incurs added cost.



(a) (b)

Fig. 1 Period Elongation of Base-Isolated Structure in (a) Acceleration and (b) Displacement Spectra

Besides, rubber with higher shear modulus has higher hardness level, and therefore, possesses higher penetration resistance.

Nevertheless, some of the main drawbacks identified in this conventional practice that disrupt the smooth flow of the design process are listed in the following:

(a) The rubber bearing section requires larger shape factor S at the end of the design process to compensate for buckling load due to the inadequate bearing dimension chosen, which may result in taller bearing that is subjected to lower rollout capacity;

(b) The bearing is overdesigned and thus, results in heavier bearing (material wastage);

(c) The bearing results in massive vertical deformation under compression due to inadequate vertical stiffness;

(d) The conditions of unsuitable bearings detailed from points (a) to (c) are only determined by engineers at the very end of the design process, which would require a restart of the design from the beginning, especially if changes or amendments are made to the involved input parameters.

Therefore, in order to overcome the limitation detected in the design of elastomeric rubber bearing section, this study recommends two limiting boundary conditions to be applied by fellow engineers as guidelines in preliminary selection of the bearing parameters in order to initiate the design process, aimed at eliminating the need to perform multiple iteration of the design flow due to the conventional trial-and-error method. The first boundary condition uses vertical deformation Δ_V; while safety factor against buckling load SF is the second boundary condition, which are discussed in detail in this paper. Besides, it is worth to mention that the proposed design equation offers the principal design quantities of the isolator obtained directly without iteration, whereas the secondary design quantities, such as buckling load roll-out and other interactions, can be easily solved when the main isolator dimensions are identified.

The well-known structural dynamic relationship between the angular frequency (ω), the stiffness (k), and the mass (m) of a lumped mass vibrating system is best described in Eq. (4).

$$\omega = \sqrt{\frac{k}{m}} \tag{4}$$

Therefore, the vertical angular frequency (ω_V) of the rubber bearing can be defined

$$\omega_V = \sqrt{\frac{K_V}{W/g}} \tag{5}$$

Where W is the lumped mass acting on the rubber bearing and K_V is the stiffness of the rubber bearing

Besides, Eq. (5) can be further expanded, by acknowledging that the vertical stiffness K_V is in the function of instantaneous compression modulus of the rubber-steel composite E_c, cross-sectional area of the HDRB A, and the total rubber thickness t_r, as shown in Eq. (6).

$$K_V = \frac{E_c \times A}{t_r} \tag{6}$$

Therefore, Eq. (5) becomes

$$\begin{aligned}\omega_V^2 = \frac{\frac{E_c \times A}{t_r}}{P} = \frac{E_c \times A}{P \times t_r} &= \frac{\left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2 + K}\right) \times A}{P \times t_r} \\ &= \left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2 + K}\right) \times \left(\frac{A}{P \times t_r}\right)\end{aligned} \tag{7}$$

The cross-sectional area of the rubber bearing section, A, is determined earlier through the deformability required by the rubber bearing to provide the most effective target isolation period, T_D, through Eq. (8)

$$A = \frac{K_H \times t_r}{G_{1.5}} \tag{8}$$

And

$$K_H = \frac{4\pi^2 P}{T_D^2} \tag{9}$$

Substituting Eqs. (8) and (9) into Eq. (7), the square of vertical angular frequency of the rubber bearing becomes

$$\omega_V^2 = \left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2+K}\right)\times\left(\frac{\frac{K_H t_r}{G_{1.5}}}{P\times t_r}\right) = \left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2+K}\right)\times\left(\frac{\frac{4\pi^2 P\times t_r}{G_{1.5}T_D^2}}{P\times t_r}\right) = \left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2+K}\right)\times\left(\frac{4\pi^2}{G_{1.5}T_D^2}\right)$$

Interestingly, the inverse of the square of bearing angular frequency (ω_V^2) in Eq. (4), multiplied with gravity force g, gives the estimated vertical deflection of the rubber bearing (Δ_V).

$$\Delta_V = \frac{1}{\omega_V^2}\times g = \frac{9.81}{\left(\frac{6G_{0.2}S^2K}{6G_{0.2}S^2+K}\right)\left(\frac{4\pi^2}{G_{1.5}T_D^2}\right)} \tag{10}$$

However, when the buckling load is insignificant to the HDRB design (i.e., for base isolation of very lightweight structure), Eq. (10) can be reduced to Eq. (11) for engineers to estimate the required bearing parameters by limiting the targeted total vertical deflection. Besides, one should note that the above developed equation is only recommended for determining shape factor S that does not exceed 10 so that the equation achieves at least 10% accuracy. Meanwhile, for bearing with extremely large shape factor, the compressibility of the bearing may be significant and hence, must be taken into consideration.

$$\Delta_V = \frac{9.81}{(6G_{0.2}S^2)\left(\frac{4\pi^2}{G_{1.5}T_D^2}\right)} = \frac{0.409G_{1.5}T_D^2}{\pi^2 G_{0.2}S^2} \tag{11}$$

Nevertheless, time elastomeric rubber bearings are mostly used to support relatively heavier structure, whereby the vertical load carried by the rubber bearing should be looked into to avoid buckling mechanism. In addition to buckling, the amount of vertical loading will, beyond certain limit, affect the effective shear stiffness of the isolation system.

Hence, in order to include the buckling limit into the proposed boundary condition, the relationship between buckling load (P_{crit}) and compression modulus of rubber (E_c) is first established from Eq. (12) (Naeim and Kelly 1999).

$$P_{crit} = \frac{\pi}{t_r}\sqrt{\left(E_c\frac{I}{3}\right)G_{0.2}A_s} \tag{12}$$

Therefore

$$E_c = \frac{6G_{0.2}S^2K}{6G_{0.2}S^2+K} = \frac{3P_{crit}^2 t_r^2}{I\pi^2 G_{0.2}A_s} \tag{13}$$

By substituting Eq. (13) into Eq. (11), the equation becomes

$$\Delta_V = \frac{1}{\omega_V^2} = \frac{g}{\left(\frac{3P_{crit}^2 t_r^2}{I\pi^2 G_{0.2}A_s}\right)\left(\frac{4\pi^2}{G_{1.5}T_D^2}\right)} = \frac{G_{0.2}G_{1.5}IA_sT_D^2 g}{12P_{crit}^2 t_r^2}$$

Therefore

$$P_{crit}^2 = \frac{G_{0.2}G_{1.5}IA_sT_D^2 g}{12\Delta_V t_r^2} \tag{14}$$

Moreover, one interesting fact is that the horizontal stiffness (K_H) of the rubber bearing decreases with the increase in applied vertical loading, as carried by the bearing. This reduced horizontal stiffness (K_H), in comparison to the initial target design lateral stiffness (K_H^0), is given by Naeim and Kelly (1999):

$$K_H = K_H^0\left[1-\left(\frac{P}{P_{crit}}\right)^2\right] \tag{15}$$

Furthermore, the design process exerts a limiting boundary condition of allowing accuracy at a minimum level for the usual formula used in obtaining K_H within the range of 10% (which is acceptable in practice). Thus, the multiplication factor becomes

$$\left[1-\left(\frac{P}{P_{crit}}\right)^2\right] \geq 0.9 \tag{16}$$

Therefore

$$0 < \left(\frac{P}{P_{crit}}\right)^2 \leq 0.1 \tag{17}$$

And

$$P_{crit}^2 \geq \frac{P^2}{0.1} \tag{18}$$

In addition to having a minimal effect on the horizontal stiffness, Eq. (18) also guarantees that the safety factor against buckling is 3.2.

With such, Eq. (14) becomes

$$\frac{G_{0.2}G_{1.5}IA_sT_D^2 g}{12\Delta_V t_r^2} \geq \frac{P^2}{0.1} \tag{19}$$

The expanded Eq. (19) becomes

$$\frac{\pi^2}{480\Delta_V t_r^2}\left(\frac{\emptyset_S}{2}\right)^6 G_{0.2}G_{1.5}T_D^2 \approx \frac{P^2}{g} \tag{20}$$

Where $\emptyset_S$ is the diameter of steel shim = $\emptyset - (2\times \text{cover})$

Although the proposed single Eq. (20) involves a total of seven parameters, all these parameters are not new and each of them actually appears in the conventional procedures, as demonstrated in the example calculation that follows. It appears that the proposed equation depends heavily on the vertical deflection Δ_V that is often omitted by structural engineers.

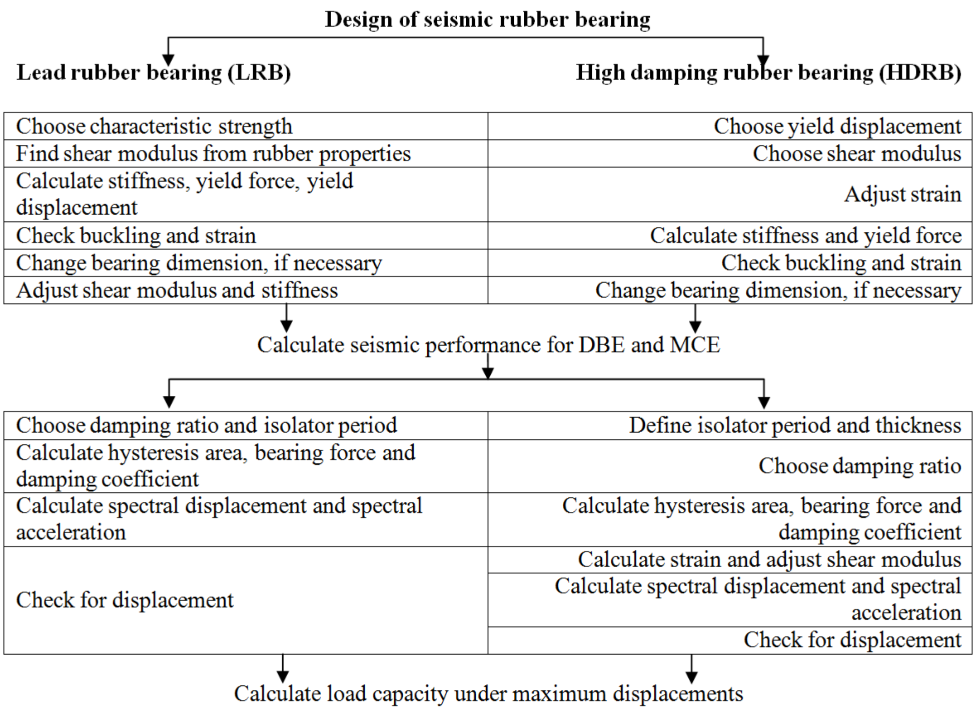


Fig. 2 General design steps of HDRB (modified from Islam *et al.* 2011)

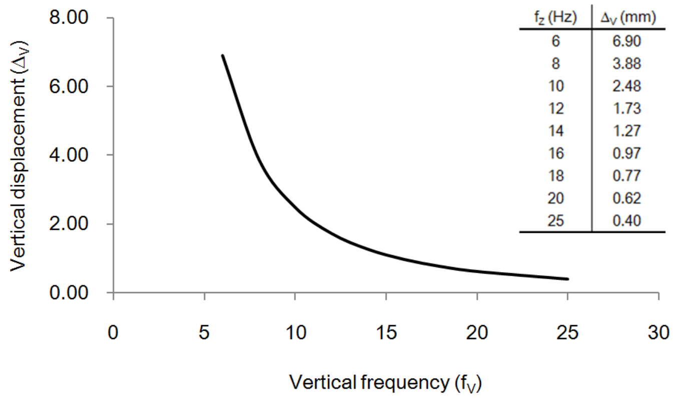


Fig. 3 Plot of vertical frequency as a function of vertical displacement

Moreover, Fig. 3 portrays the vertical deflection as a function of vertical frequency f_V for the convenience of structural engineers.

Furthermore, it is highly important to note that the proposed equation excludes the bearing roll-out capacity. In fact, the maximum allowable roll-out displacement δ_{max} can be calculated by using the conventional formula

$$\delta_{max} = \frac{\emptyset}{1 + \left(\frac{GA}{P}\right)\left(\frac{h}{t_r}\right)} \qquad (21)$$

In which h is the total height of HDRB.

3. Example calculations

Consider a column with total axial load of 100 ton (approximately 981kN), subjected to seismic loading that imposes maximum displacement requirement of 200 mm. The target design period T_D is 2.5 s.

Please refer to Table 1.

4. Conclusions

This paper proposes an improvement to the present HDRB design through an equation that clearly exemplifies the fact that the diameter (or size) of a particular HDRB depends on the vertical loading, the shear modulus, the target period, the vertical deflection, and the total rubber thickness.

Table 1 Example of calculations between the conventional design approach and the proposed single equation

Step	Conventional method	Proposed equation
1	$K_H = M \times \left(\frac{2\pi}{T_D}\right)^2 = 0.632 kN/mm$	$\frac{\pi^2}{480\Delta_V t_r^2}\left(\frac{\emptyset_S}{2}\right)^6 G_{0.2}G_{1.5}T_D^2 \approx \frac{P^2}{g}$
2	At design shear strain γ = 1.0, $t_r = D_D$ = 200 mm Assuming $G_{1.5}$ is 0.4 MPa and $G_{0.2}$ is 0.7 MPa	By assuming vertical deflection Δ_V of 1mm
3	$K_H = \frac{G_{1.5} \times A}{t_r}; \phi = 650$ mm $S \approx \frac{f_V}{f_H\sqrt{6}} = \frac{10(\text{assumed})}{\frac{\sqrt{6}}{T_D}} \approx 10$	$\frac{\pi^2}{480(0.2^2)}\left(\frac{\emptyset_S}{2}\right)^6 (0.7 \times 10^6)(0.4 \times 10^6)(2.5^2) \approx \frac{100000}{9.81}$ $\emptyset_S \approx 645$ mm
4	$E_c = \frac{6G_{0.2}S^2K}{6G_{0.2}S^2 + K} = 347 \times 10^6 N/m^2$ $K_V = 548 \times 10^6 N/m$ $f_V = 11.8$ Hz Therefore, the assumed S of 10 is adequate	
5	$S = \frac{\emptyset}{4t}, t = 16.25$ mm $nt = t_r, n = 13$ layers	
6	$P_{crit} = \frac{\pi}{t_r}\sqrt{\left(E_c\frac{I}{3}\right)G_{0.2}A_s} = 6610$ kN	
7	$K_H = K_H^0\left[1 - \left(\frac{P}{P_{crit}}\right)^2\right] \approx 0.96K_H^0$	
	Therefore, the diameter of 650 mm is deemed suitable to provide the adequate lateral stiffness.	The minimum diameter of steel plates is 645 mm to provide minimum safety factor against buckling of 3.2 and thus, the lateral stiffness at 200 mm displacement is within a margin of ± 10% of designed stiffness.

Moreover, the comparison made between the conventional iteration process and the proposed single equation revealed almost identical diameter of HDRB. Since all these parameters are well-addressed by engineers at the beginning of the design stage, the required size of HDRB can be estimated easily by employing a single equation, instead of carrying out the iteration process. This, eventually, can help structural designers to easily estimate the size of HDBR without the need of waiting for confirmation from the manufacturer design team. Thus, the need to redesign the HDRB or worse, improper sizing of pedestal or stump beneath and above the base isolator; can be avoided all together. However, it is worth to mention that the conventional iterative procedures are still required when it comes to the final design. It is not the objective of this paper to eliminate the conventional design approach but rather, this simplified design formula serves as a guideline for less experienced structural engineers to begin with an appropriate bearing size.

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