

# Seismic Base Isolation of Steel Frame Structure by Hollow Rubber Bearings

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## ABSTRACT

Effectiveness of rubber bearing in providing seismic base isolation depends very much on the lateral stiffness of these rubber bearing. The competency is increased by lowering the bearing's horizontal stiffness. This can be easily achieved by either reducing its diameter or increasing its height without compromising the rollout and buckling stability of the rubber bearing. This paper presents shake table testing of fixed base steel frame structure (FBS) in comparison to two identical base-isolated models with solid rubber bearings (BISRB) and hollow rubber bearings (BIHRB), respectively. It is noted the optimum diameter reduction recommended will be 40%. Generally, the seismic performance of BIHRB is superior to both FBS and BISRB, by producing lower floor accelerations and inter-story drifts.

**Key Words:** *seismic, base isolation, rubber bearing, steel frame.*

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**1. INTRODUCTION**

The basic concept of seismic base isolation is rather simple; that is to decouple the superstructure from the horizontal movement component of the ground motion. This is achieved by introducing an isolation interface between the foundation and ground floor of

superstructure as illustrated in Figure 1. Theoretically, the base isolation increases fundamental period of the superstructure. Development of elastomeric rubber bearing base isolator in recent decades had contributed much to the concept of base isolation [1].

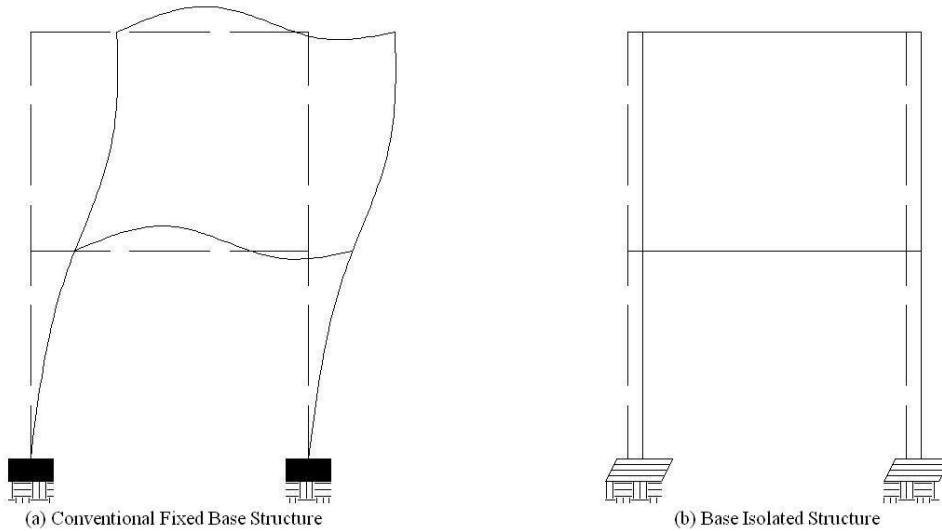


Figure 1. Structural Response of Fixed Base (a) and Base Isolated (b) Structure.

The conventional seismic resistant design of building requires the constructed structure to be strong, ductile and most importantly attached firmly to the ground. Among these codes are the popular International Building Code (IBC) [2], European Code 8 (EC8) and American Standard (ASCE 7-05) [3]. The main drawback faced in this fixed-base design is that it is often difficult to minimize both the inter-story drift and floor response acceleration at the same time [4]. Inter-story drift can be minimized through construction of a horizontally stiffer building. However, a stiffer building leads to higher floor acceleration response. Therefore, seismic base isolation offers as a better alternative with the fact that both inter-story drift and floor acceleration are able to be minimized simultaneously.

Effective base isolation depends mostly on its low horizontal stiffness,  $K_H$ . Due to limitations imposed by mechanical characteristics of the elastomeric rubber bearing component, the lower bound of total rubber height ( $t_r$ ) is limited by the height of the base isolator. Equation 1 denotes formula for determining preliminary area ( $A$ ) in corresponding to  $K_H$ , shear modulus  $G$ , and  $t_r$  [5]. The lower the value of  $K_H$  produces a more flexible rubber bearing in the horizontal direction, which is deemed as more effective base isolator. From the equation, it is clear that the  $K_H$  is reduce able by either increasing the total rubber thickness  $t_r$  or decreasing the cross sectional area  $A$  of the rubber bearing.

$$K_H = \frac{G \times A}{t_r}$$

However, both actions of reducing cross sectional area  $A$  and increasing total rubber thickness  $t_r$  tends to contribute to a taller yet thinner rubber bearing, which may cause

rollout instability. This instability is caused by the characteristics of the rubber bearing which cannot uphold any tensile stress. The bearing is deemed unstable should the movement (rollout displacement) between top and bottom rubber exceeds 88% of its least plan dimension,  $b$  (Figure 2). The rollout displacement  $\delta$  can be estimated as shown in Equation 2. It is noted that the rollout displacement will be increased should either  $t_r$  or  $A$  decreased.

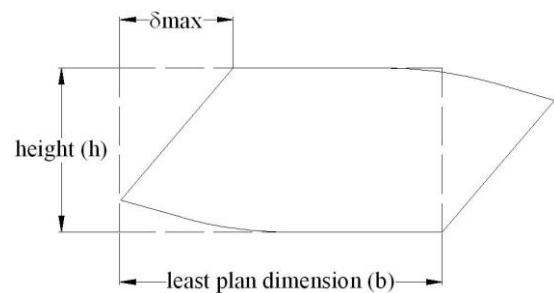


Figure 2. Rollout Mechanism of Rubber Bearing.

$$\delta = \frac{b}{1 + (G/p)(h/t_r)}$$

Where  $p$  = stress due to vertical load;  $G$  = shear modulus; and  $t_r$  = total rubber thickness

Studying Equation 1 and Equation 2, it is obvious that the governing parameters which determine the elasticity of the rubber bearing also influenced its safety level. Their relationship is interrelated. Therefore, the main obj (1) of this study is to obtain the optimum values of these governing parameters to produce a rubber bearing with

more effective horizontal stiffness with efficient safety factor. This is achieved through reduction of cross sectional area  $A$  of the rubber bearing by introducing a hollow section within the conventional solid rubber bearing. The mechanical behavior and overall structure isolation capability by the rubber bearings are studied experimentally. The research information will then be used to propose an alternative rubber bearing base isolator with different geometry than the conventional kind.

The concept of base isolation was only being put to engineering practice in early 70s' despite its founding in 1909. Although researches regarding base isolators have been intense throughout these years, most of the studies were concentrating on developing high-end isolation system [1, 6], while some were focusing on development of theoretical analysis of base isolator itself [7-12]. Derham et al [13], Abe et al [14], Burtscher et al [15, 16], Pu et al [17], Eibl et al [18], and Taranath [19] investigated the behavior of multilayered laminated rubber bearings with and without supplementary damping elements. These isolators are called high damping rubber bearings (HDRB).

The stability of elastomeric rubber bearings were studied intensively by Buckle et al [20], Furata et al [21], Nagarajaiah and Buckle [22], Tsai and Kelly [23], Kelly [24], Kato et al [25], Takhiroov and Kelly [26] and Warn et al [27]. These studies however, were focusing more onto developing better understanding in terms of buckling behavior or vertical stiffness of typical rubber bearings without holes. Iiba et al [28] studied the effects of 3 directional earthquake loadings on base isolated houses. One of the base isolation system used was rubber bearings with hole in the center. However, the study did not conclude any research information regarding the effect of having such holes. In another different study by Kang et al [29], the authors investigated performance of elastomeric isolator having hole and lead plug. Instead of using steel shims, fiber reinforcements were used as reinforcing plates between rubber layers. The holes were said to be insignificant to influence effective stiffness and damping of the isolators. One main reason could be that size of hole is relatively too small to be effective (less than 2% of cross-sectional area of the rubber bearing).

The main challenge faced in implementation of base isolation system especially in developing countries is the cost issue. Besides practicality and effectiveness, cost plays a very important role for any seismic design guideline to be well-accepted by builders, as mentioned in Author et al [30]. Despite demonstrating good energy dissipation in terms of seismic threats [31-36] most base isolation applications are meant for large, expensive structures which contain sensitive equipments. Targeting this need to minimize the production cost of rubber bearings and also the gap of knowledge as far as to the authors' consent, the performance of base isolation system using hollow rubber bearings has not been explored. Hence, the objective of the study is to investigate the optimum diameter reduction in producing a hollow rubber bearing to replace the existing solid one. Besides the stability and behavior of the hollow rubber bearing itself, the performance of its base isolation capability in providing seismic isolation for typical steel

frame structure will be evaluated.

**2. METHODOLOGY**

The research methodology adopted in this study comprises two main laboratory phases. They are (1) design and testing of elastomeric rubber bearing base isolator, and (2) shake table testing of base-isolated steel frame structure, which will be presented detail below.

**2.1. Design of Rubber Bearing**

In order to compare the effectiveness of conventional solid rubber bearing (SRB) with the interested hollow rubber bearing (HRB), the geometry properties of both rubber bearings have been kept as identical as possible. Detailed mechanical design procedure for the similar rubber bearings can be found in [5, 37]. The governing parameters used preliminary in determining the geometrical property (height and diameter) of the rubber bearing are targeted shear strain ( $\gamma$ ), design displacement ( $D_D$ ), outer diameter ( $\phi_{out}$ ), inner diameter ( $\phi_{in}$ ), and rollout displacement ( $\delta$ ). The design parameters are as listed in Table 1 while  $\phi_{out}$  and  $\phi_{in}$  are illustrated in Figure 3.

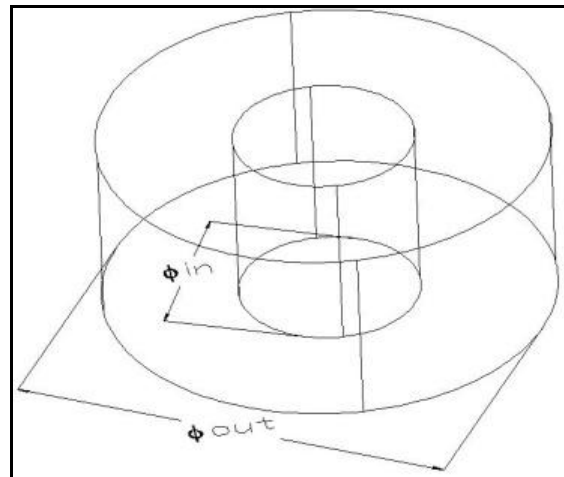


Figure 3. Outer and Inner Diameter of Rubber Bearing ( $\phi_{out}$  and  $\phi_{in}$ ).

The dimension of inner diameter for HRB,  $\phi_{in}$  has been determined from optimum value which satisfies both  $\delta$  and safety factor (SF) boundary limits. In general, SF indicates ratio of critical load ( $P_{crit}$ ) to bearing load ( $W$ ).  $P_{crit}$  signifies the maximum load capacity of the rubber bearing to avoid localized buckling of the composite steel-rubber component. Analytical formulas for SF and  $P_{crit}$  are shown in Equation 3 and Equation 4, respectively.

$$SF = \frac{P_{crit}}{W}$$

$$P_{crit} = \frac{\pi}{t} \sqrt{\frac{E_s \times I \times G \times A}{3}}$$

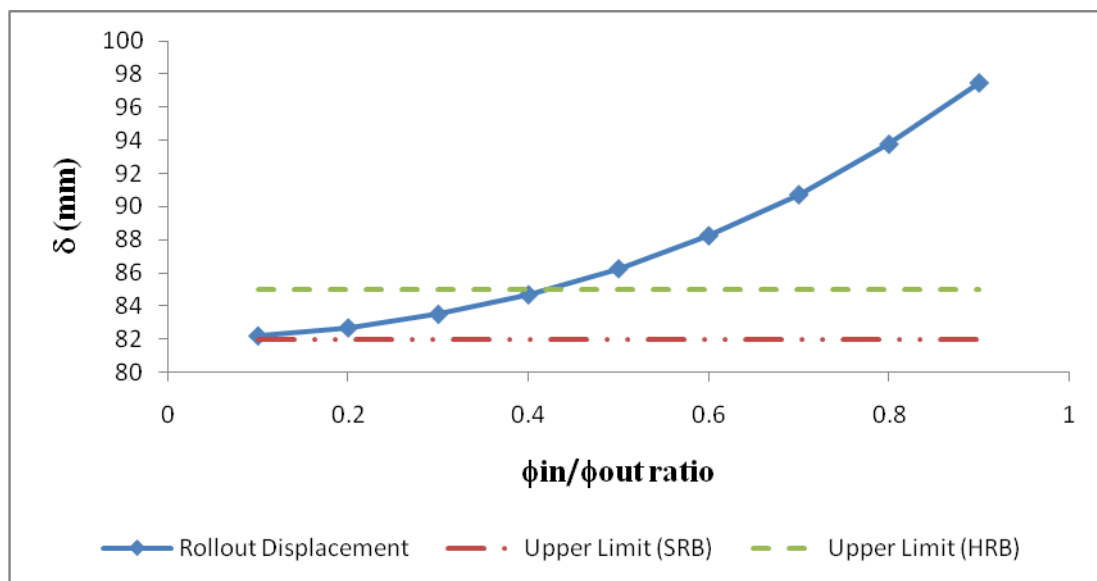
where  $I = \frac{\pi}{4} \left( \frac{\phi_{out}}{2} \right)^4$ , As is the cross sectional area of steel shims and  $G$  represents the shear modulus of rubber component

Table 1. Design parameters for SRB and HRB.

	Unit	SRB	HRB
$\gamma$	-	1.5	1.5
$D_D$	Mm	50	50
$t_r = \frac{D_D}{\gamma}$	Mm	35	35
$\delta_{\max} = D_D$	Mm	50	50
$\phi_{\text{out}} \geq \frac{\delta_{\max}}{0.88}$	Mm	102	102
$\phi_{\text{in}}$	Mm	0	40.8
Quantity of Rubber Layer	Nos.	12	12
Thickness of 1 Rubber Layer	Mm	2.8	2.8
Quantity of Steel Shim	Nos.	11	11
Thickness of 1 Steel Shim	Mm	2	2
$\delta$	Mm	82	85
SF	-	5.9	2.7

Figure 4 and 5 show graph plots of  $\delta$  and SF (in vertical axis) versus ratio of  $\phi_{\text{in}}/\phi_{\text{out}}$ . The optimum value for  $\phi_{\text{in}}/\phi_{\text{out}}$  is determined from the graph which satisfied both condition of (1) maximum rollout displacement  $\delta_{\max} \leq$

$0.88\phi_{\text{out}}$  and (2) minimum  $SF \geq 2$ . To ease manufacturing process and enhance standardization, the selected parameters for both SRB and HRB are as listed in Table 1.

Figure 4. Rollout Displacement  $\delta$  versus ratio of diameter reduction  $\phi_{\text{in}}/\phi_{\text{out}}$ .

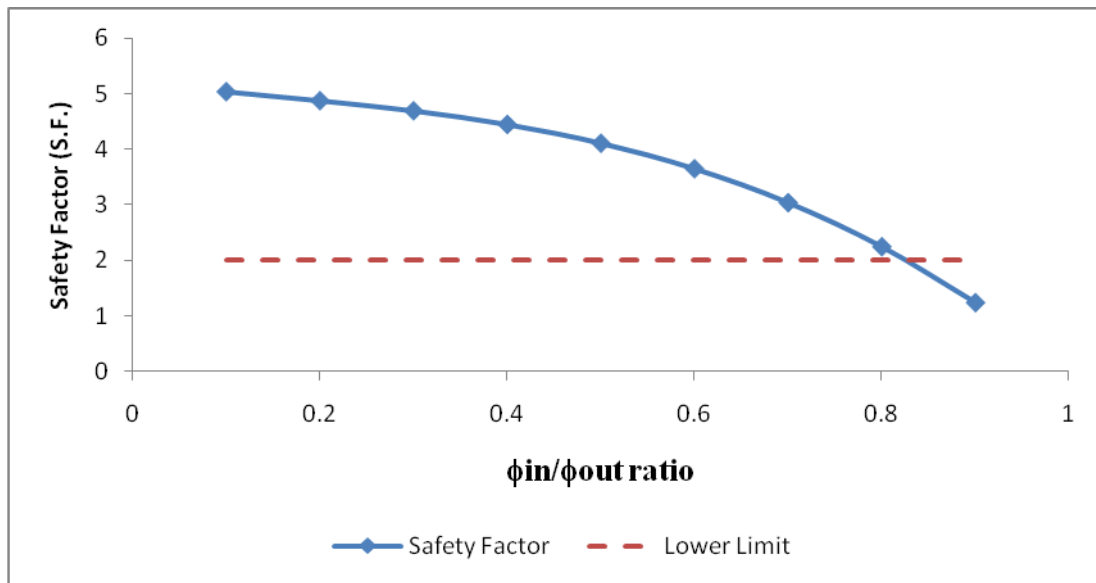


Figure 5. Safety Factor (S.F.) versus ratio of diameter reduction  $\phi_{in}/\phi_{out}$ .

### 2.2. Dynamic Testing of Rubber Bearing

The dynamic mechanical performance ( $K_H$  and equivalent damping ratio,  $\zeta$ ) of both SRB and HRB have been evaluated by conducting series of laterally applied quasi-static cyclic loading using typical Elastomeric Testing Machine, ETM. Due to the configuration of the testing machine, two rubber bearings are tested together simultaneously (also known as the double shear testing arrangement as shown in Figure 6). Vertical compression

load of 25kN and displacement controlled lateral loading of 150% shear strain are applied to the rubber bearings concurrently. By estimating total vertical dead load of the superstructure to be approximating 10 tons which would be carried by 4 nos. of rubber bearings at base layer, the loading distributed to each isolator would be 2.5 tons ( $\approx 25kN$ ). The vertical load is kept constant throughout the test while the rate of laterally cyclic loading is maintained at 0.50Hz for five sinusoidal cycles per test.



Figure 6. Double Shear Testing Setup of Rubber Bearing by ETM.

### 2.3. Design of Steel Frame Superstructure

Three identical single bay superstructures to be tested have been designed in accordance to BS5950-1:2000 [38]. The 2-storey special moment resistant frames are designed under 8 tons of maximum gravity load

excluding its self-weight. It has been estimated that the total dead load per structure would be approximately 10 tons, which is well below the shake table capacity of 12 tons. These Uniform Rectangular Section (URS) steel frames are not designed for any lateral force resistance. The storey-to-storey height is 1.0m while both length and

width of the frame is 2.0m. Detail plan of the structure is shown in Figure 7 while Table 2 lists down the designed section properties of its structural element.

#### 2.4. Shake Table Testing of Superstructure

Laboratory shake table test has been carried out on the three identical steel frame structures with each frame having different base support condition. One of the frames emulates conventional fixed-base structure (FBS) while the two remaining frames consist of base isolated

structure with solid rubber bearing (BISRB) and hollow rubber bearing (BIHRB) respectively. The structures are subjected to base excitation from the 1940 El-Centro (North-South component) response history in one direction only, with peak ground acceleration (PGA) of 0.313g (Figure 8). Time domain of the response history is scaled to half of the original records to fulfill dynamic similitude requirements. This enhances the predominant period of the ground motion to be consistent with the first mode frequency of the structure.

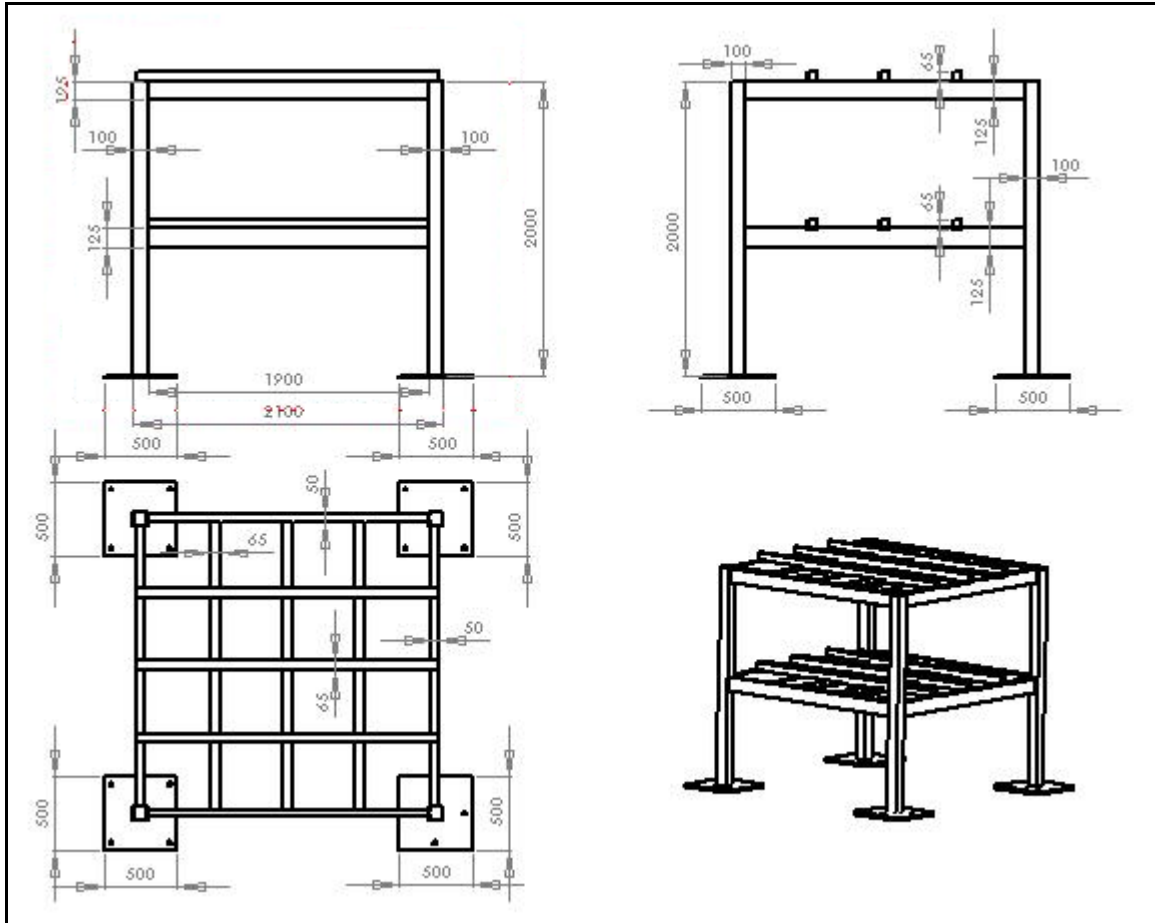


Figure 7. Sketching and Dimension of Steel Frame Superstructure.

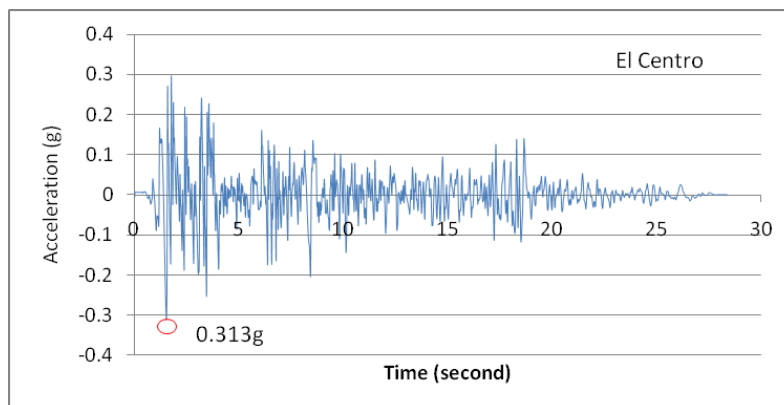


Figure 8. Time History Loading from 1940 El-Centro (North-South Component).

Table 2. Steel Frame Element Sizes.

Primary Beam	Secondary Beam	Column
URS 125 x 50 x 45	URS 65 x 65 x 4	URS 100 x 100 x 5
Note: URS = Uniform Rectangular Section		

Interested measurements from the shake table test would be absolute floor accelerations at each storey level of the structure. Instrumentation for FBS includes mounting of 2 accelerometers at the center of column each floor, contributing to a total of 6 accelerometers plus an additional one to be installed onto the shake table itself. The configuration of sensors for BISRB and BIHRB has been similar to the FBS. The only difference is that

additional 2 accelerometers are mounted at the top plate above the rubber bearings to capture the difference in acceleration between bottom base and base level above isolation interface. Illustration of the monitoring instrumentation is presented in Figure 9. Supplementary information of instrumentation system is listed in Table 3.

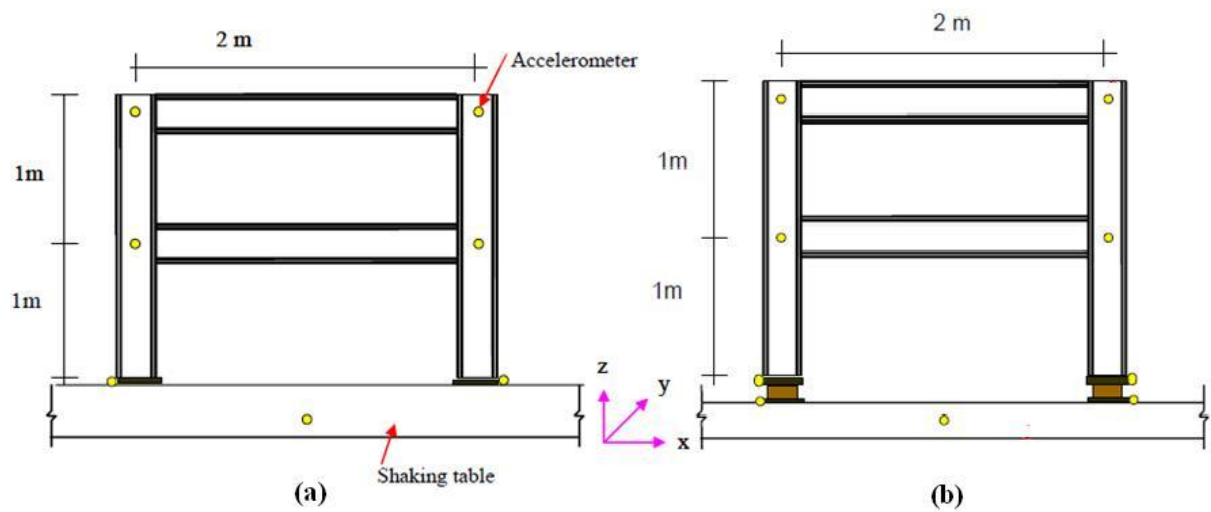


Figure 9. Monitoring Instrumentation for (a) FBS and (b) BISRB or BIHRB.

Table 3. Specifications of Accelerometer and Data Logger.

Accelerometer		Data Logger	
Measuring Range	±50g	Nos. of Channel	80
Sensitivity	100.8mV/g	Sampling Rate	500Hz
Transverse Sensitivity	1.0%		
Resonant Frequency	22kHz		
Temperature	0-65 <sup>0</sup> C		

### 3. RESULTS

Observations and data analysis of rubber bearing testing are presented in this section, separated particularly into (a) quasi-static testing of individual base isolator as well as (b) integrated shake table testing, respectively.

#### 3.1. Dynamic Properties of Rubber Bearing

The single cycle hysteresis load-displacement loops of SRB and HRB are presented in Figure 10. It is observed that under vertical compression of 25kN, the 150% shear strain lateral loading has forced the rubber bearing to

behave nonlinearly. The hysteresis loops obtained from 5 cycles lateral loading are illustrated in Figure 11. The values of effective horizontal stiffness  $K_{eff}$  and equivalent viscous damping  $\zeta$  of the rubber bearing are computed from the hysteresis curves by referring to Equation 5 and Equation 6. Graphical plot of the results is presented in Figure 12. The effective stiffness depends on peak loading ( $F_{max}$ ,  $F_{min}$ ) and maximum displacement ( $d_{max}$ ,  $d_{min}$ ). The area enclosed by hysteresis loop ( $W_D$ ) equals energy dissipation capability of the rubber bearings. Another important parameter which influences the computation of  $\zeta$  is the rubber bearing's elastic strain



energy,  $W_s$  (Equation 7).

$$K_{eff} = \frac{F_{max} - F_{min}}{d_{max} - d_{min}}$$

$$\zeta = \frac{W_D}{4\pi W_s}$$

$$W_s = \frac{1}{2} K_{eff} d_{max}^2$$

(6)

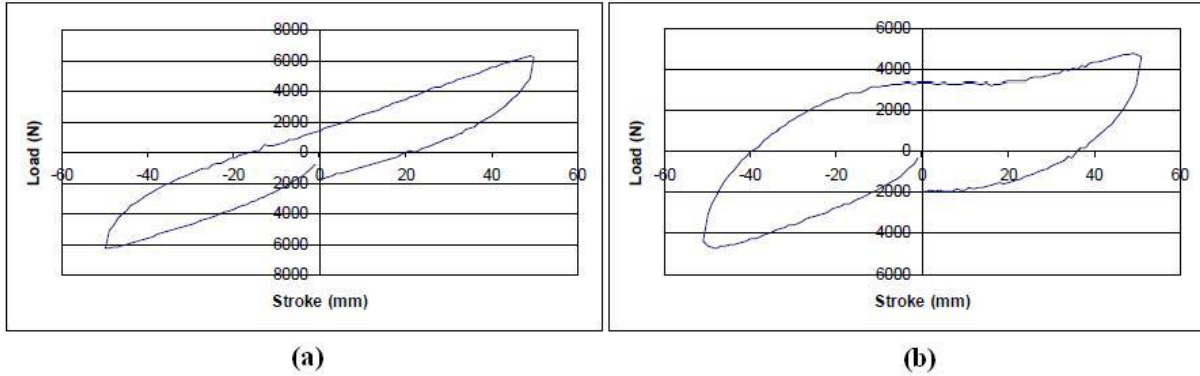


Figure 10. Hysteresis Loop of (a) SRB and (b) HRB under 1 full-cycle lateral loading.

It is noted that the nonlinear relationship between load-displacement is rather not constant during each cycle. This suggests that the preliminary designed horizontal stiffness  $K_H$  can be either overestimating or underestimating the actual stiffness of the rubber bearings due to effects of repeated loads. Percentage of difference (%) between designed lateral stiffness  $K_H$  calculated using Equation 1 compared with effective horizontal stiffness  $K_{eff}$  obtained from experimental is shown in Figure 13. From the figure, the values of effective lateral stiffness for both SRB and HRB show a decreasing trend as the numbers of load cycle increases. The minimum stiffness of SRB which occurred at the 5<sup>th</sup> loading cycle

is still however, 21.9% higher than the designed  $K_H$ . On the other hand, the lateral stiffness of HRB is observed to be lower than those calculated beginning from the 3<sup>rd</sup> loading cycle and onwards. The maximum decrement recorded is up to 5.1% lower than the designed lateral stiffness. The values of equivalent damping ratio  $\zeta$  are observed to be adequately consistent throughout the repeated cycles of loading. Nevertheless, both SRB and HRB have been observed to function safely without localized shear failure under ground motion which imposes shear strain up to 150% onto the rubber bearings.

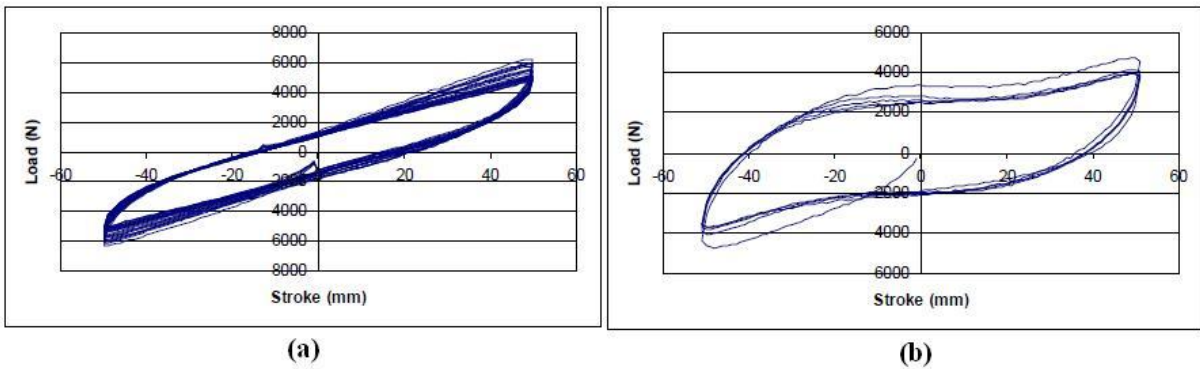


Figure 11. Hysteresis Loop of (a) SRB and (b) HRB under 5 full-cycle lateral loading.



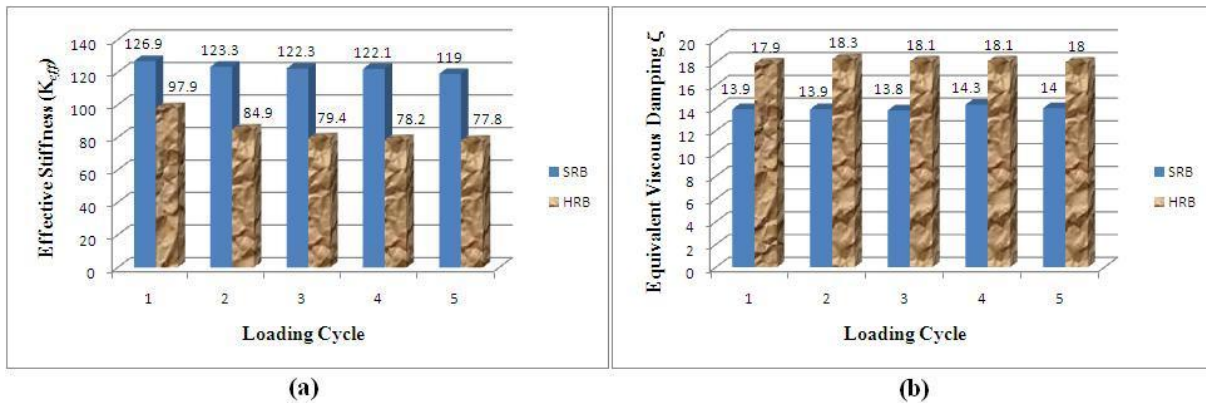


Figure 12. (a) Effective Stiffness  $K_{eff}$  and (b) Equivalent Viscous Damping  $\zeta$ .

### 3.2. Shake Table Test

The structural responses in terms of floor accelerations and displacements of FBS, BISRB and BIHRB have been analyzed to evaluate the effectiveness of the base isolation system. Figure 14 shows the response history of acceleration values recorded for FBS, BISRB and BIHRB. The peak values of these data are summarized and listed in Figure 15. Although the accelerations increased from the base level to the roof level for all three models, the difference between these values are quite significant among each types of structure. Peak accelerations recorded for FBS are 0.14g, 0.49g and

0.46g at base, floor and roof level respectively. Meanwhile, the maximum accelerations for BISRB for each storey level have been 0.11g, 0.14g and 0.15g from base to roof. It has been observed that the floor accelerations for both FBS and BISRB are varying at each storey level. Nevertheless, the acceleration response of BIHRB has been different than the previous two. Accelerations for all storey level are noted to be constant at 0.1g. This shows that the 2-storey structure responded as a rigid body. By evaluating between BISRB and BIHRB, the latter decreases maximum floor acceleration at floor level by 79.6% of FBS comparing the former which is only 71.4% (Figure 16).

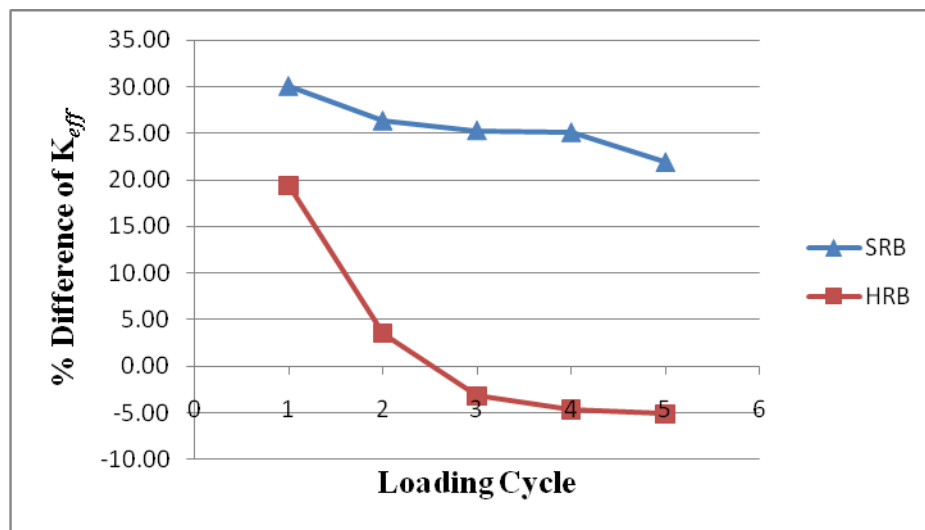


Figure 13. Percentage of Difference (%) for Effective Stiffness  $K_{eff}$ .

Maximum displacements of the three models are presented in Figure 17. The displacement patterns show good agreement with the acceleration responses. The peak displacement values have been assessed in forms of inter-storey drift, which captures the different lateral movement between each storey level. Higher inter-storey drift tends to cause nonstructural damage especially to adjacent walls. The assessment of inter-storey drift is only done between BISRB and BIHRB, excluding FBS to identify the effectiveness of HRB compared to SRB. The result is shown in Figure 18. In general, inter-storey drift

of BISRB is higher than the BIHRB, particularly at base-floor level.

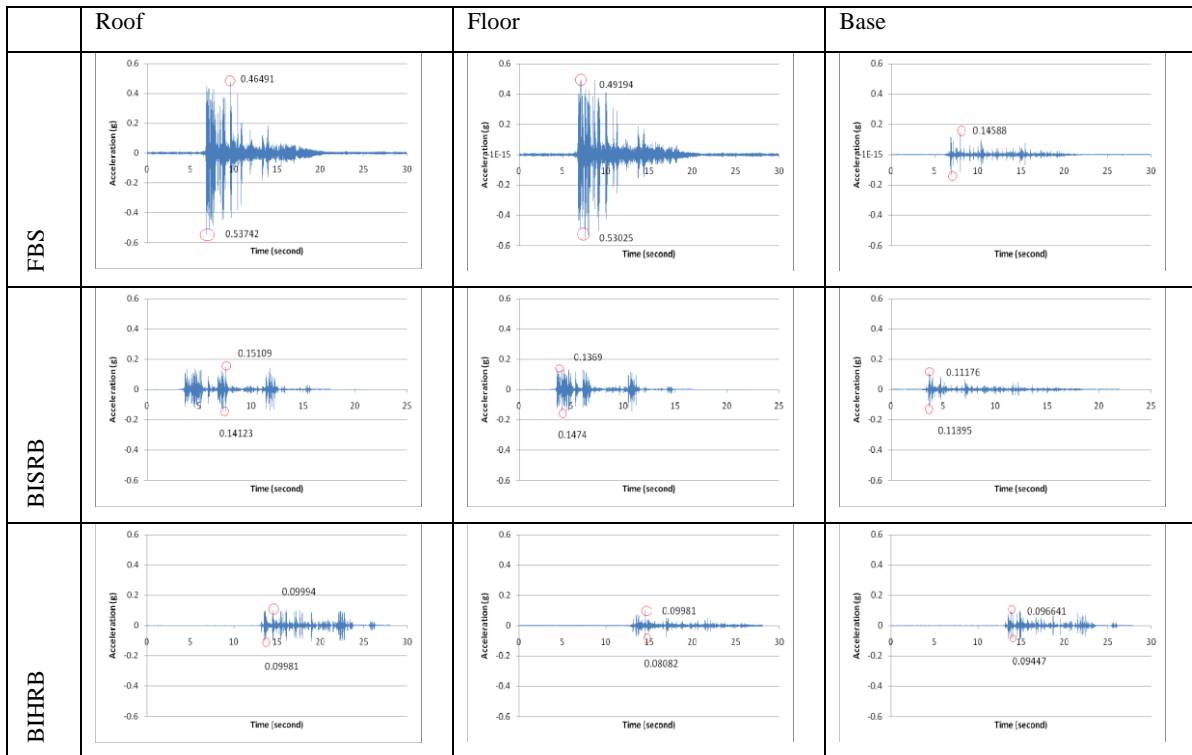


Figure 14. Response History of FBS, BISRB and BIHRB.

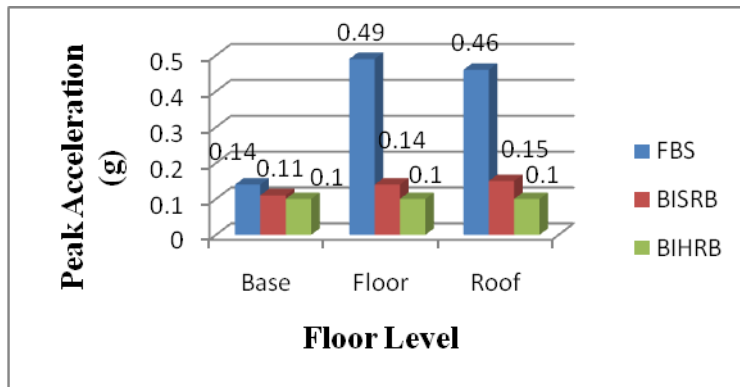


Figure 15. Peak Floor Acceleration Responses.

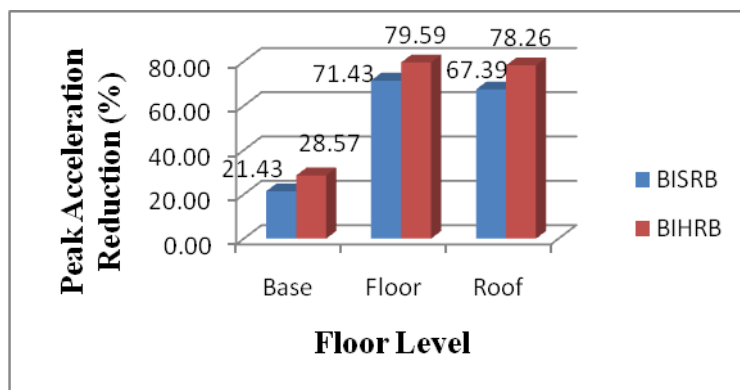


Figure 16. Maximum Floor Acceleration Reduction (%).

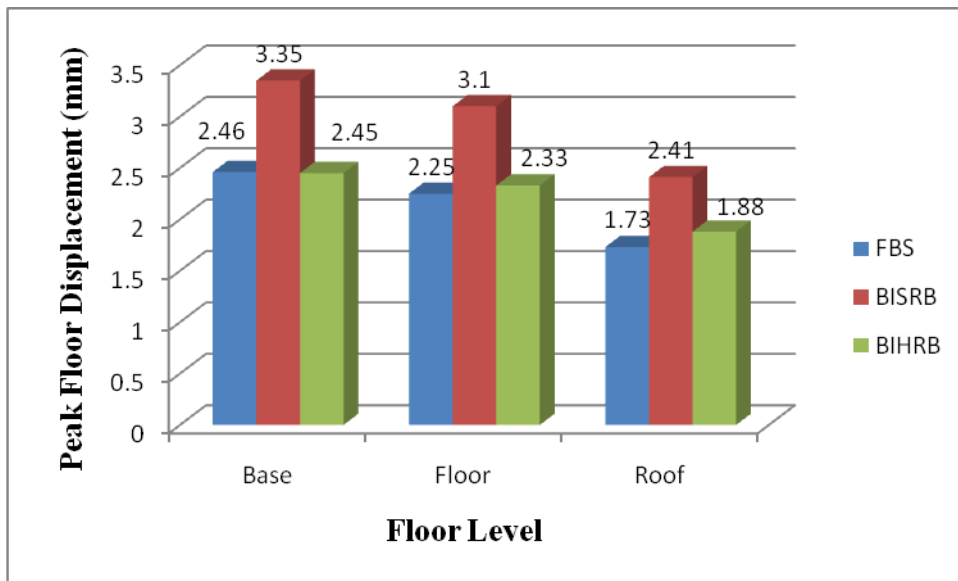


Figure 17. Peak Floor Displacement Responses.

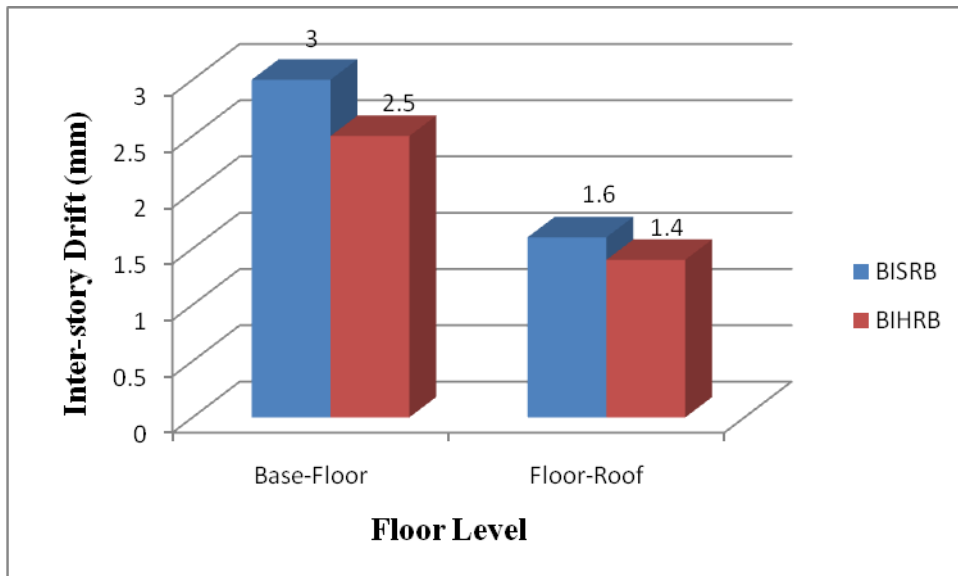


Figure 18. Inter-story Drifts.

## 5. CONCLUSION

The effectiveness of utilizing elastomeric hollow rubber bearing (HRB) as base isolator has been evaluated and compared with conventional solid rubber bearing (SRB). Besides analyzing mechanical and dynamic properties of the rubber bearings, the competency of these rubber bearings in providing seismic base isolation for moment-resisting steel frame structures have been investigated by shake table tests. From the study, following conclusions are drawn:

1. The maximum ratio of  $\phi_{in}/\phi_{out}$  allowed is 0.5 with estimated maximum rollout displacement of 86.3mm ( $\leq 88$ mm acceptable limit). However for conservative purpose, the recommended optimum diameter reduced will be 40% of the outer diameter ( $\phi_{in}/\phi_{out} = 0.4$ ).
2. Although the application of Equation 1 in estimating horizontal stiffness of SRB is noted to be acceptable, it might overestimate the actual lateral stiffness of HRB. A maximum difference of 21% lower than calculated stiffness is observed in this study. One of the reasons could be the relatively lower resistance of the HRB in defying deformation in terms of bending and elongation.
3. The equivalent viscous damping  $\zeta$  of HRB is 4% higher than SRB. The damping ratios of both types of rubber bearing are noted to be rather consistent regardless of loading cycles.
4. The BIHRB has shown better reduction of floor accelerations for each storey level compared to BISRB. Recorded floor acceleration decrements of the former are 7.1%, 8.2% and 10.9% higher for base level, floor level and roof level respectively compared to the latter. Due to relatively lower floor accelerations, inter-story drifts of BIHRB are found to be lower than BISRB correspondingly.

The study reveals the potential of utilizing HRB as alternative rubber bearing base isolator to the conventional SRB. Besides saving material cost, its lower horizontal stiffness enhances the seismic isolation capability without compromising the stability of the isolator component. This can be very much useful should the interested superstructure to be isolated happen to consist of extremely lightweight structure.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] Kelly, J.M., "Earthquake Engineering: From Engineering Seismology to Performance Based Engineering", Yousef, B., and Vitelmi, B. (ed), *CRC Press*, Florida, (2004).
- [2] ICC IBC-2000, "International Building Code",

International Code Council, (2000).

- [3] ASCE 7-05, "Minimum Design Loads for Buildings and Other Structures", *American Society of Civil Engineers*, (2006).
- [4] Mayes, R.L., Naeim, F., "The Seismic Design Handbook, 2<sup>nd</sup> ed.", Naeim, F. (ed), *Kluwer Academic Pub*, Boston, (2001).
- [5] Naeim, F., and Kelly, J.M., "Design of Seismic Isolated Structures: From Theory to Practice", *John Wiley & Sons Inc.*, New York, (1999).
- [6] Ersoy, S., Saadeghvaziri, M.A., Liu, G.Y., Mau, S.T., "Analytical and Experimental Seismic Studies of Transformers Isolated with Friction Pendulum System and Design Aspects", *Earthquake Spectra*, 17(4): 569 – 595 (2001).
- [7] Kikuchi, M., Aiken, I.D., "An Analytical Hysteresis Model for Elastomeric Seismic Isolator Bearing", *Earthquake Engineering and Structural Dynamics*, 26(2): 215 – 231(1997).
- [8] Fenves, G.L., Huang, W.H., Whittaker, A.S., Clark, P.W., Mahin, S.A., "Modeling and Characterization of Seismic Isolation Bearings", *Proceedings of the U.S.-Italy Workshop on Seismic Protective Systems for Bridges*, New York, 1 – 15(1998).
- [9] Kelly, J.M., "Analysis of Fiber Reinforced Elastomeric Isolator", *Journal of Seismology and Earthquake Engineering*, 2(1): 19 – 34(1999).
- [10] Chang, C.H., "Modeling of Laminated Rubber Bearings using an Analytical Stiffness Matrix", *International Journal of Solids and Structures*, 39(24): 6055 – 6078(2002).
- [11] Doudoumis, I.N., Gravalas, F., Doudoumis, N.I., "Analytical Modeling of Elastomeric Lead-Rubber Bearings with the use of Finite Element Micromodels", *Proceedings of the 5<sup>th</sup> GRACM International Congress on Computational Mechanics Limassol*, Cyprus, (2005).
- [12] Ravari, A.K., Othman, I., Ibrahim, Z., "Variations of Horizontal Stiffness of Laminated Rubber Bearings with Different Boundary Conditions", *Proceedings of the 11<sup>th</sup> Asia Pacific Industrial Engineering and Management Systems Conference/14<sup>th</sup> Asia Pacific Regional Meeting of International Foundation for Production Research*, Malaysia, (2010).
- [13] Derham, C.J., Kelly, J.M., Thomas, A.G., "Nonlinear Natural Rubber Bearings for Seismic Isolation", *Nuclear Engineering Design*, 84(3): 417 – 428 (1985).
- [14] Abe, M., Yoshida, J., Fujuno, Y., "Multiaxial Behavior of Lead Rubber Bearings and their Modeling, I: Experimental Study", *Journal of Structural Engineering*, 130(8): 1119 – 1132 (2004).

- [15] Burtscher, S., Dorfman, A., Bergmeister, K., "Mechanical Aspects of High Damping Rubber", Proceedings of the 2<sup>nd</sup> International PhD Symposium in Civil Engineering, Budapest, (1998).
- [16] Burtscher, S.L., Dorfman, A., "Compression and Shear Test of Anisotropic High Damping Rubber Bearing", *Engineering Structures*, 26(13): 1979 – 1991 (2004).
- [17] Pu, J.P., Tsai, C.S., Huang, J.F., Chen, B.J., Fang, Y.M., "Analysis and Experiment on the Effect of Seismic Protection of Buildings by High Damping Rubber Bearings", ASME/JSME 2004 Pressure Vessels and Piping Conference (PVP 2004), California, (2004).
- [18] Eibl, J., Hehn, K.H., Schwartz, D., "Performance Tests of High Damping Steel Laminated Seismic Isolation Bearing for LNG Storage Tanks", In: *Savidis (ed) Earthquake Resistant Construction & Design*, Rotterdam, (1994).
- [19] Taranath, B.S., "Wind and Earthquake Resistant Buildings, Structural Analysis and Design", *Marcel Dekker*, New York, (2005).
- [20] Buckle, I., Nagarajaiah, S., Ferrell, K., "Stability of Elastomeric Isolation Bearings: Experimental Study", *Journal of Structural Engineering*, 128(1): 3 – 11 (2002).
- [21] Furata, T., Furukawa, Y., Kanakubo, T., "Buckling of Rubber Bearings for Seismic Isolated Structures", Proceedings of the 5<sup>th</sup> International Congress on Advances in Civil Engineering, Istanbul, (2002).
- [22] Nagarajaiah, S., Buckle, I., "Stability of Elastomeric Isolators: Critical Load Tests and Computations", *MCEER Bulletin*, 16(1): 1 – 4 (2002).
- [23] Tsai, H.C., Kelly, J.M., "Buckling Load of Seismic Isolators Affected by Flexibility of Reinforcement", *International Journal of Solids and Structures*, 42(1): 255 – 269 (2005).
- [24] Kelly, J.M., "Discussion of Tension Buckling in Multilayer Elastomeric Bearings", *Journal of Engineering Mechanics*, 131(1): 106 – 108 (2005).
- [25] Kato, R., Oka, K., Takayama, M., "The Tensile Tests of Natural Rubber Bearings Focused on the Effect of the Steel Flange Plates", Proceedings of 2003 ASME Pressure Vessels and Piping Conference, USA, (2003).
- [26] Takhirov, S.M., and Kelly, J.M., "Numerical Study on Buckling of Elastomeric Seismic Isolation Bearings", *Proceedings of the 2006 Structures Congress*, Missouri, 1 – 10 (2006).
- [27] Warn, G.P., Whittaker, A.S., Constantinou, M.C., "Vertical Stiffness of Elastomeric and Lead-Rubber Seismic Isolation Bearings", *Journal of Structural Engineering*, 133(9): 1227 – 1236(2007).
- [28] Iiba, M., Midorikawa, M., Yamanouchi, H., Yamaguchi, S., Ohashi, Y., Takayama, M., "Shaking Table Tests on Performance of Isolators for Houses Subjected to Three Dimensional Earthquake Motions", Proceedings of the 12<sup>th</sup> World Conference on Earthquake Engineering, New Zealand, (2000).
- [29] Kang, B.S., Kang, G.J., Moon, B.Y., "Hole and Lead Plug Effect on Fiber Reinforced Elastomeric Isolator for Seismic Isolation", *Journal of Materials Processing Technology*, 140(1-3): 592 – 597 (2003).
- [30] P. Tiong. L.Y., Adnan, A., Mirasa, A.K., and A. Rahman. A.B., "Performance of IBS Precast Concrete Beam-Column Connections Under Earthquake Effects: A Literature Review", *American Journal of Engineering and Applied Sciences*, 4(1): 93 – 101, (2011).
- [31] Wu, Y.M., Samali, B., "Shake Table Testing of a Base Isolated Model", *Engineering Structures*, 24(9), 1203 – 1215, (2002).
- [32] Ponzo, F.C., Nigro, D., Dolce, M., Cardone, D., Cacosso, A., "Comparison of Different Seismic Isolation Systems through Shaking Table Tests on a Steel Structure", Proceedings of the 3<sup>rd</sup> World Conference on Structural Control, Italy, (2002).
- [33] Stewart, J.P., Conte, J.P., Aiken, I.D., "Observed Behavior of Seismically Isolated Buildings", *Journal of Structural Engineering*, 125(9): 955 – 964, (1999).
- [34] Aiken, I.D., "Testing of Seismic Isolators and Dampers – Considerations and Limitations", Proceedings of the Structural Engineering World Congress, California, (1998).
- [35] Lee, J.H., Koo, G.H., Yoo, B., "Excitation Test Response Characteristics and Simulations of a Seismically Isolated Test Structure", Proceedings of the 17<sup>th</sup> International Conference on Structural Mechanics in Reactor Technology, Czech Republic, (2003).
- [36] Taniwangsa, W., "Seismic Performance of a Base Isolated Demonstration Building", *Earthquake Spectra*, 18(4): 777 – 793 (2002).
- [37] Sunaryati, J., "Behaviour of Steel Structures with Base Isolator under Low Intensity Earthquake Effect", PhD. Thesis, *Universiti Teknologi Malaysia*, Malaysia, (2008).
- [38] BS 5950-1: 2000, "Structural Use of Steelwork in Building; Part 1: Code of Practice for Design Rolled and Welded Sections", British Standards Institution, (2001).