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DESIGN OF SEISMIC ISOLATION SYSTEM FOR SERVICED APARTMENT AT LANGKAWI

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ABSTRACT

This paper discusses the progressions in designing a seismic isolation system for a conventional RC frame moment-resisting building in Malaysia. This work covers all steps in designing the isolation system and the laminated High Damping Rubber Bearings (HDRB). The decision to isolate, despite low seismic risk is discussed in the context of history and design philosophy.

Four types of HDRB have been designed to suit the anticipated seismic criteria. The design inputs include identification of the design spectrum, and of relevant building parameters such as dimensions and mass distribution. The HDRB designs in term of vertical load capacity, lateral deflection and capacity are than derived from these inputs. The actual testing of HDRB agrees closely to the behaviour predicted from the design.

INTRODUCTION

The Malaysian Rubber Board (MRB) has commissioned a 10-storey building consisting of offices, serviced apartments, training banquet and recreational facilities in Kuah, Langkawi. The decision to consider seismic hazard was made during the design phase and hence, a seismic isolation concept has been designed and proposed. Building construction was started in early 2013.

From the Global Seismic Hazard Map (www.seismo.ethz.ch/GSHAP/), the peak ground acceleration (PGA) for a return period of 475years at Langkawi, an island on the west of the Malay peninsular close to the Thai border, lies in the band 0.8 to 1.6ms^{-2}. This suggests a somewhat greater risk of lateral loading than that from the wind, but Malaysia has no current requirement to consider seismic risk. In fact, this hazard band is shared with Lambesc, France and Lisbon, Portugal. Lambesc is the only location in France where an earthquake has resulted in a recorded loss of life – 46 died and 2000 buildings were damaged in the 1909 earthquake – and also the location of the only isolated building in France, the secondary school built in 1979. The Great Lisbon Earthquake of 1755 claimed tens of thousands of lives, resulting in great religious and philosophical trauma throughout Europe and the birth of seismology. Discussion of seismic hazard has begun in Malaysia, and designers of tall chimneys already use a self-imposed target to design for a lateral acceleration of 0.1g.

Seismic isolation, based on natural rubber (NR), was pioneered by three research teams: Delfosse, at Marseille, leading to isolation of the Lambesc school; the DSIR, New Zealand, leading to the William Clayton Building in Wellington in 1983 – the first building isolated on lead plug bearings - and TARRC (a research centre of MRB in the UK), leading to the Foothills Community Law and Justice Centre in California in 1985, the first building isolated with high damping NR (HDNR) bearings. From this background, it was natural for MRB to not only consider seismic risk for its

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project in Kuah, Langkawi, but to see base isolation on HDNR bearings as a natural solution should analysis show there to be a risk to be met.

Seismic Risk

A seismic hazard map of Peninsular Malaysia has been produced following a study conducted by SEER UTM. The map gives the Peak Ground Acceleration (PGA, ms^{-2}) values around Peninsular Malaysia resulting from a probabilistic seismic hazard study.

Figure 1 shows that the horizontal peak acceleration a_g for 475-year return period event is between 0.04g to 0.06g. This hazard is almost entirely contributed by large earthquakes occurring at the Sumatran Fault (~500km away) or Sumatran Trench (~800km away) according to Adnan et al. (2004). Identification of a_g=0.05g ($0.5ms^{-2}$) PGA is sufficient to merit seismic consideration although not specific stipulations according to Eurocode 8. Type I is the appropriate spectrum to be used for a distant earthquake with high magnitude ($M_w \geq 5.5$).

The establishment of the soil classification has been derived from Eurocode 8 Clause 3.1.2. From the borehole data on site, the soil is made of deposits of dense and medium-dense sand, gravel and stiff clay. The Standard Penetration Test (SPT) borehole data suggests a classification of Ground Type C according to Table 3.1 of Eurocode 8 Part 1.

An elastic design spectrum of spectral acceleration $S_a(T)$ versus period (T) for the site has been obtained from Table 3.2 of Eurocode 8 Part 1 with the criteria;

soil factor S = 1.15
periods T_B, T_C, T_D = 0.2s, 0.6s, and 2s respectively

and using Eq 3.2 to 3.5 (Clause 3.2.2.2);

$$0<T<T_B \qquad S(T)=\left[1+\left(2.5\eta-1\right)\frac{T}{T_B}\right]\cdot a_g \cdot S \tag{1}$$

$$T_B<T<T_C \qquad S(T) = 2.5\eta.a_g.S \tag{2}$$

$$T_C<T<T_D \qquad S(T) = 2.5\eta.\frac{T_C}{T_B}.a_g.S \tag{3}$$

$$T_D<T<4s \qquad S(T) = 2.5\eta.\frac{T_C T_D}{T^2}.a_g.S \tag{4}$$

and

$$\eta = max\left(\sqrt{\frac{10}{5+\xi}},0.55\right) \tag{5}$$

where ξ is the equivalent damping coefficient expressed as a percentage, normally taken as 5% or, for typical base isolated buildings, 10%. Elastic design spectra for these two levels of damping are shown in Figure 3.

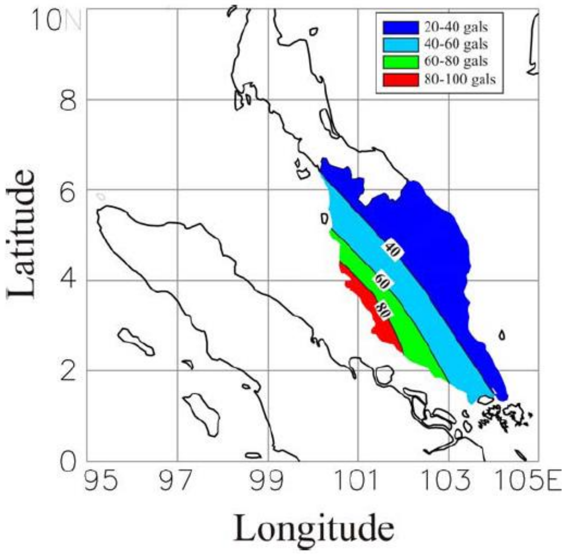

Figure 1 PGA map for 10% Probability of Exceedence in 50 years or equals to 475 years return period

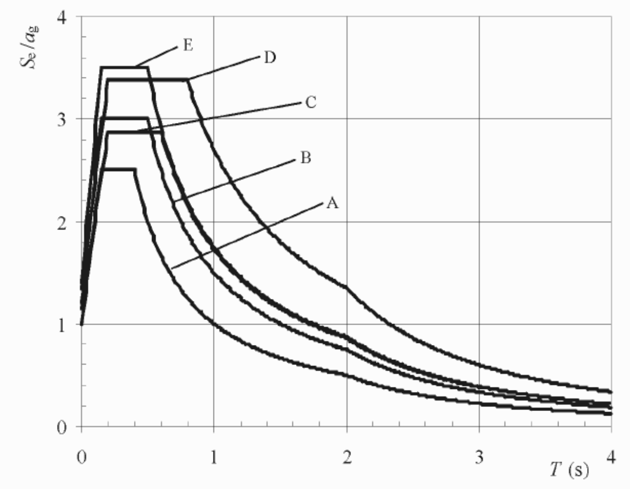

Figure 2 Eurocode 8 Type I design spectra for 475 year return period events (A, rock; B very stiff soil; C medium soil; D soft to medium soil; E up to 20m medium soil underlain by rock)

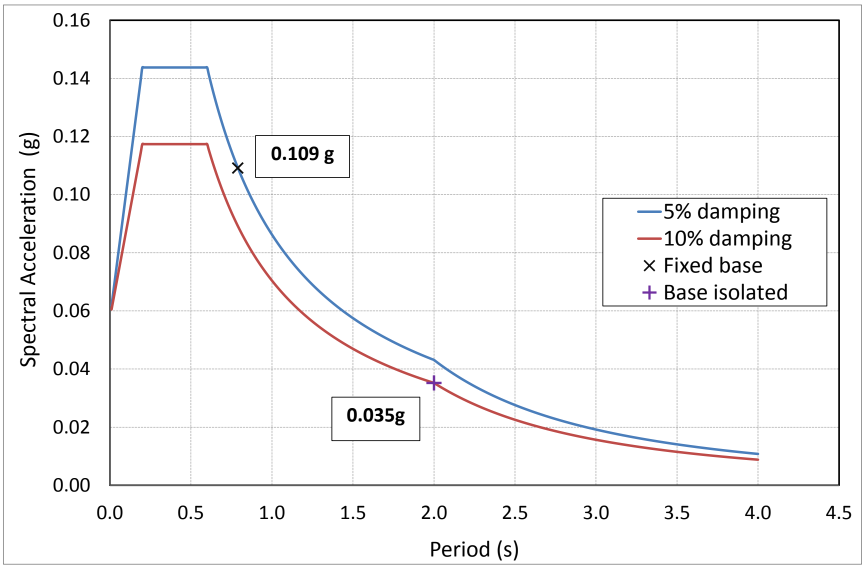

Figure 3 Kuah Langkawi elastic design spectra [Eurocode 8: Type I; 475 year return period events; C medium soil; $a_g = 0.05g$]

Eurocode 8 Part 1 Clause 3.2.1 spells out the role of National Authorities in deciding seismic zones for their country and whether or not seismic design need be considered. The Note in Clause 3.2.1 (5)P recommends that sites be deemed as very low seismicity if the ground acceleration $a_g < 0.39\ \mathrm{ms}^{-2}$ or $S.a_g < 0.49\ \mathrm{ms}^{-2}$, i.e. the provisions of Eurocode 8 need not be observed. For Ground Type C, the soil factor S is 1.15 (see Table 3.2 of Eurocode 8) so that for the MRB site this gives the "very low seismicity" criterion PGA $< 0.49\ \mathrm{ms}^{-2}/1.15 = 0.43\ \mathrm{ms}^{-2}$.

Similarly, the Note in Eurocode 8 Clause 3.2.1 (4) recommends a threshold value of ~0.8 ms^{-2} for low seismicity, below which simplified seismic design procedures may be used. Since the site PGA is $0.5\mathrm{ms}^{-2}$ it can be designated low seismicity, and this stipulation applies.

According to Eurocode 8 Clause 4.3.3.5.2 the vertical component of seismic action need only be considered if $a_{vg} > 2.5\ \mathrm{ms}^{-2}$. Table 3.4 recommends, for Type I, $a_{vg}/a_g = 0.9$, so that there is no need to consider vertical seismic action. If, nevertheless, the vertical action is needed, the elastic spectrum may be constructed using the same equations as for the horizontal, but substituting a_{vg} for a_g and 3 for the numerical factor 2.5.

Clause 3.2.2.5 of Eurocode 8 Part 1 provides rules for constructing a "design spectrum", from the elastic spectrum discussed above, with reduced spectral accelerations according to the "behaviour factor" q which accounts for the increase in energy dissipation associated with inelastic structural deformation. In this way, explicit inelastic structural analysis is avoided in design.

SUPERSTRUCTURE DESIGN

Effect of isolation

According to Eurocode 8 Clause 4.3.3.2.2, the fundamental period of a building (other than a space frame) may be estimated from;

$$T_1 \approx 0.05H^{0.75} \tag{6}$$

where H is the building height in metres from the foundation or from the top of a rigid basement.
The total height of the building, H=39.6m corresponds to T_1 = 0.79s which is only slightly greater than the cut off T_C = 0.6s of the constant acceleration (maximum amplification) part of the elastic design spectrum; the 5% spectral acceleration is ~0.109g, an amplification of 2.18 times that of the local ground. On the other hand, if the building is isolated using T = 2s and ζ = 10%, the spectral acceleration would be reduced to around 0.035g, around 32% of the fixed base value and 70% of the site ground acceleration. These points on the elastic design spectra are included in Figure 3.

In comparison, the spectral acceleration S_e (2s, 10% damping) for the isolated UNIDO demonstration building on a rock site near Pelabuhan Ratu, Indonesia, is 0.10g, again nearly 60% of the site ground acceleration. In its case the return period was taken as 200 years, in accord with the Indonesian Code in force at that time (Muhr, 1994).

From Newton's second law, the spectral relative displacement may be calculated from the spectral acceleration (ms^{-2}) by multiplying by $(T/2\pi)^2$ ~ $0.1s^2$, giving 35mm. For a detailed design of the isolators their maximum displacement needs to be considered. For this, the displacement would need to be adjusted upwards by the factor 1.044 to allow for the uncorrelated orthogonal component of seismic excitation and by a factor for the effect of eccentricity of the building, the minimum permitted value being 1.1 (Muhr, 1994), giving 40.2mm. It is interesting to note that the seismic gap for the Lambesc secondary school is 50mm as measured by one of the authors (Muhr) during a site visit.

Structural dimensions

Incorporating a seismic isolation system will introduce a horizontal compliance at the plane of the isolator bearings. With this compliance the columns will have to be tied together and the provision of a diaphragm, connecting all the columns just above the plane of the isolators, is crucial.

The MRB building has been designed with a basement. Immediately above it is the ground floor, which consists of beams supporting floor slabs and will thus behave as a diaphragm. For such a structure incorporation of isolation does not entail the substantial additional cost of adding an extra floor structure, on top of the cost of the isolators.

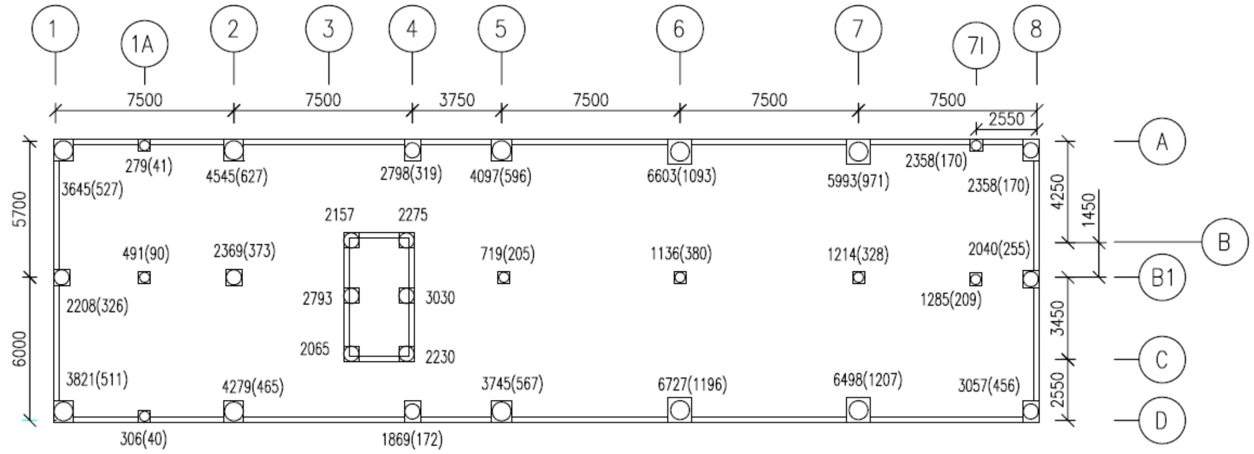

Figure 4 Plan view of column locations and the mass borne (live load in parentheses)

DESIGN OF THE ISOLATION SYSTEM

The design of the isolation system has been found to be straightforward in the method of arriving at the important parameters of bearing deflection and shear stiffness. The fundamental strategy of base isolation is to decouple the structure from the horizontal components of the earthquake ground motion by a mechanism that, while it carries the vertical load of the building, greatly reduces the transmission of horizontal load into the structure.

Two main features of a base isolation system are 1) an increase in the natural period with a corresponding decrease in the spectral acceleration and 2) a predominant rigid body translational motion in the horizontal direction, with very little amplification of the acceleration at the higher storeys.

The equation for the natural period of an undamped single degree of freedom (SDOF) system is shown below, in which M and K are the mass and shear stiffness respectively.

$$T = 2\pi\sqrt{\frac{M}{K}} \tag{7}$$

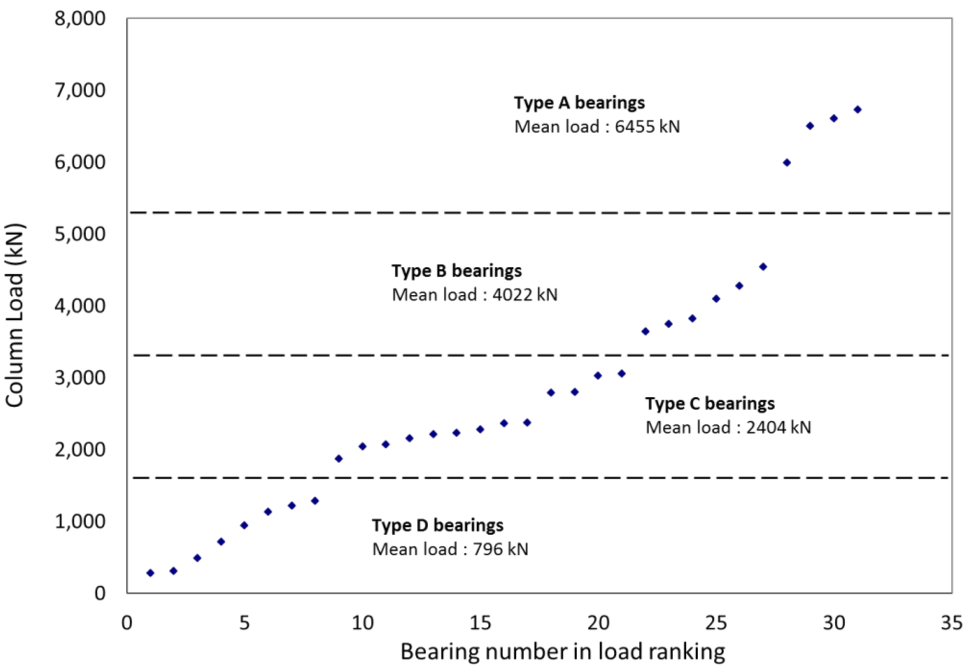

Figure 5 Distribution of column loads

The columns bear the load of the building, so their bases are also the ideal location for the isolation bearings, minimizing the need for structural modification. The column loads thus also provide the specification for the loads on individual bearings. The distribution of column loads is shown in Figure 5 above. Four bearing designs were proposed, each corresponding to the mean load of a subset of the column loads, so as to control the deviation of the loads within each set. The smallest column size is 500x550mm and the biggest is 1010x1010mm in plan, size correlating with load. The properties of all four types of bearing are shown in Table 1.

Bearing positioning and torsion effect

The MRB building is nearly symmetrical in plan hence the effect of eccentricity can be easily dealt with. Design of the isolation system has to ensure that the Center of Stiffness (CS) is coincident or as close as possible to the structure's Center of Mass (CM). The convergence of the CS and CM for an asymmetric building may pose a challenge to the design and could possibly be managed by a correct positioning and the use of more than one type of bearing, differing in stiffness. The near-coincidence of CS and CM of the MRB building is shown in Figure 6.

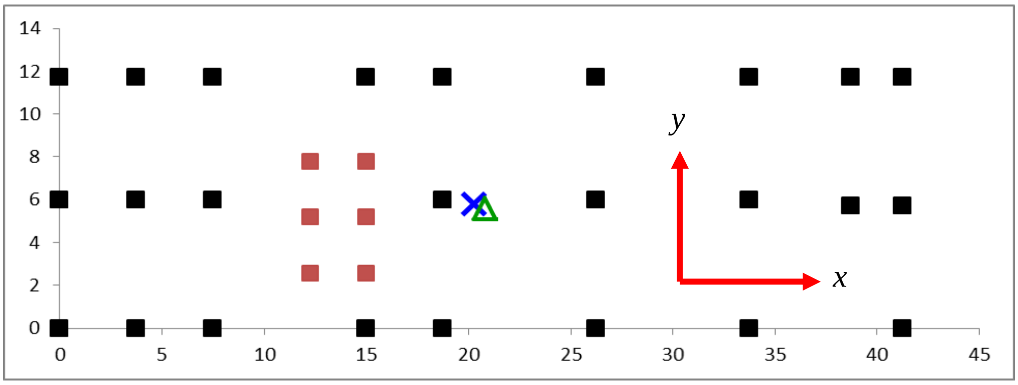

Figure 6 Distribution of bearings' Center of Stiffness (X) coinciding with the structure's Center of Mass (Δ).

The position vector of CM is given by;

$$CM_{x,y} = \Sigma m_i r_i / M \tag{8}$$

with r is position vector of ith column in x and y direction, m_i is the individual column load and M is the total mass of t the building.
Alternatively, the position vector of CS is given by;

$$CS_{x,y} = \Sigma k_i r_i / K \tag{9}$$

where k_i is the individual bearing stiffness and K is the total bearing stiffness.

The static column load is calculated by taking the mass at the surround region of the columns. Each column will support each respective area bounded by a region perpendicular to adjacent columns. The Center of Mass (CM) of the building in elevation is calculated by the same approach as for the plan area's CM. The distance in y-direction is determined from the calculation of CM of plan area, while the distance in z-direction is calculated from the multiplication of the height of each floor by its respective load. The calculated CM in elevation is shown in Figure 7.

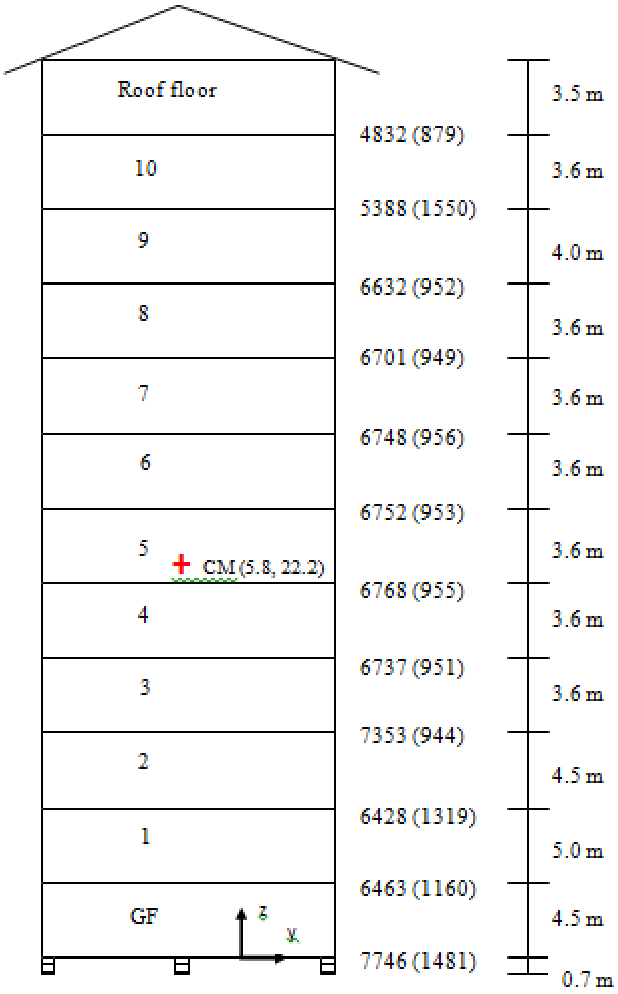

Figure 7: Elevation view of building with CM shown as + . The distribution of loads at every floor with Dead Load (DL) and Live Load (LL in parentheses) shown.

Table 1 Specification of bearing properties

Property	Type-A	Type-B	Type-C	Type-D
Shear stiffness (kN/mm)	6.08	3.80	2.18	0.73
Vertical design load (kN)	6495	4022	2404	796
Design shear deflection (mm)	45			
Lateral displacement capacity	54			
Damping ratio (%)	10			
Shear modulus of rubber (N/mm)	0.8	0.5		
Radius of reinforcing plate (mm)	330		250	145
Thickness of rubber layer (mm)	7.5@6 = 45			
Thickness of reinforcing plate (mm)	3@5 = 15			

Design of HDRB and connection details

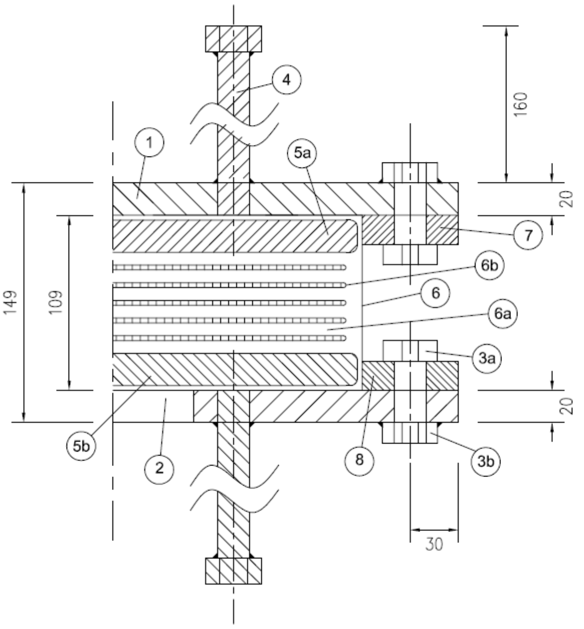

Figure 8 Bearing section with the connection detail adopted

Figure 9 Bearing mounted on a concrete pedestal

The connection method of the bearings has been designed so it would be economical and yet easy for handling at site. Recess rings bolted to the anchor plates have been adopted for connecting the bearings at each designated column. The anchor plate is cast to the concrete pedestal with the anchor rods embedded in and jointed to the column rebar.

The adoption of recess rings results in less mechanical bolting work and also enables future bearing replacement. The appropriate capacity of connection details can be achieved by ensuring the bolts connection and recess plate are sufficient against the shear force expected from the bearing shear deflection. This detail waa also used for the isolated building near Pelabuhanratu, Indonesia (Muhr, 1994).

TESTING OF THE BEARINGS

Rubber compound properties

The rubber compound has to conform to a specification for it to be considered as a valid base material for the bearings. Among the crucial test is the double shear test which provides stress-strain data, enabling the estimation of the final bearing's properties in stiffness and damping. The sample result is shown in Figure 10 below.

Referring to Figure 10, Compound 1 is represented by solid marker while Compound 2 by the empty marker. It shows that the test strain affects the shear modulus G (segmented line) and the damping (solid line) of the material. The modulus for Compound 1 is targeted to be 0.8 MPa and Compound 2 at 0.5 MPa. Both compounds are designed to provide a nominal damping ratio of 10%.

The physical test done on both compound were found to be satisfactorily passed all the specifications underlined in EN15129:2009 standard. A summary of the tests is shown in Table 2.

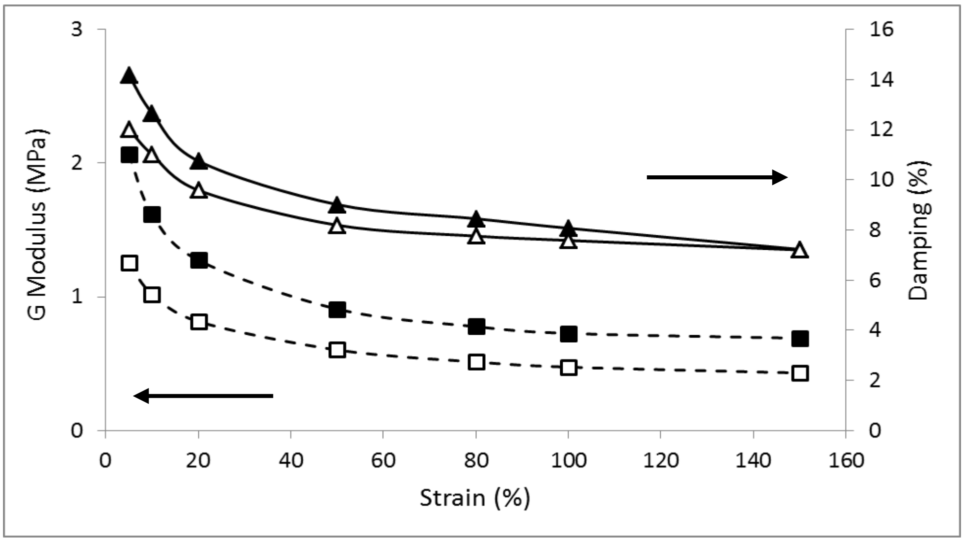

Figure 10 Effect of strain on compound shear modulus G (segmented line) and damping (solid line). The test temperature and frequency were 25^{o}C and 0.5Hz respectively.

Table 2 Physical Properties of High Damping Rubber for Compound 1 and Compound 2.

Property	**Test Results**		**Test Method**
	Compund 1	**Compund 2**	
Tensile strength, MPa	22	20	ISO 37 Type 2
Elongation at break, %	649	555	
Tear resistance, kN/m	28	24	ISO 34a Method A
Compression set 70^{o}C, 24h, max	32	32	ISO 815 Type A 25% compression
Ozone resistance Elongation 30% - 96h 40°C ± 2°C Concentration: 25pphm	No cracks	No cracks	ISO 1431/1

Accelerated air oven ageing 7 days at 70°C			ISO 188, Method A
Maximum change from unaged value:			
Hardness (IRHD)	+3	+5	ISO 48
Tensile strength (%)	-10	-11	ISO 37 Type 2
Elongation at break (%)	+14	+12	ISO 37 Type 2

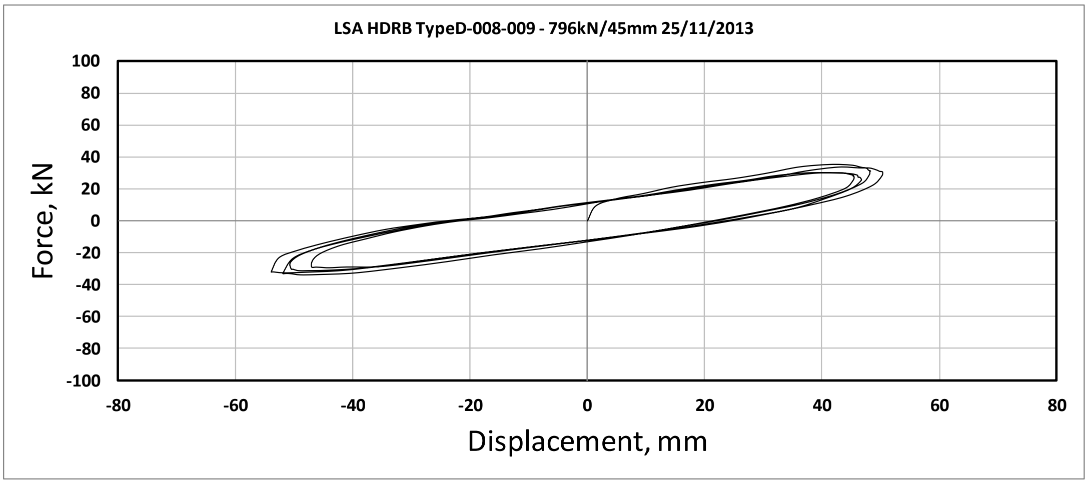

Figure 11 Force-displacement loop for the tested bearing Type-D

Figure 11 shows hysteresis loops from a double-shear stiffness test on a pair of Type-D bearing tested to 45mm displacement. A triangular waveform was applied to the bearings for a total of 4 cycles while maintaining a compression load as specified according to the type of bearings. The shear stiffness, K_s was calculated using the following equation;

$$K_s = \frac{F^+ - F^-}{d^+ - d^-} \tag{10}$$

where F^+ and F^- are the maximum and minimum values of the horizontal shear force and d^+ and d^- are the maximum and minimum values of displacement of the cycle. The damping ratio of the bearing, ζ_b, is calculated using the following relationship;

$$\zeta_b = \frac{2H}{\pi K_b \left(d^+ - d^-\right)^2} \tag{11}$$

where H is the area of the hysteresis.The test result for production bearing tests has been factored with a frequency correction factor. The frequency correction factor is determined from the ratio of the shear modulus obtained from bearing test machine at its operating frequency for a complete test cycle, and the shear modulus of the double shear rubber test piece tested at known 0.5Hz frequency of the machine.

DISCUSSION AND CONCLUSIONS

Although the site is classified as low seismicity by Eurocode 8, the hazard is of a rather awkward kind, similar to that faced by Lisbon: resulting from very infrequent but very large events a long way away. The Malaysian Rubber Board (MRB) feels that the small premium for providing a seismic isolation system would protect the structure together with the occupants, as well as seeing it as a demonstration for the seismic isolation concept. Having made this decision, a method of arriving at a seismic isolation system has been presented.

The isolation design adheres to standard design requirements as stipulated in EN15129:2009. It has been shown that the estimation based on the displacement spectrum is sufficient to specify the bearing deflection. Such bearings are readily designed, and their performance confirmed by test. It is shown in this practice that the design of the seismic isolation system is straightforward from knowledge of the mass, the coordinates of the center of mass, the plan dimensions of the structure and the design spectrum. This MRB building will be the first commercial building in Malaysia that uses High Damping Rubber Bearings.

REFERENCES

Adnan, A., Hendriyawan, & Irsyam, M. (2002). The Effect of the November 2 , 2002 Sumatran Earthquake to Peninsular Malaysia. *Journal of Civil Engineering, 15*(2003), 89–90.

Adnan, A., Marto, A., & Hendriyawan. (2004). Lesson Learned From the Effect of Recent Far Field Sumatra Earthquakes to Peninsular Malaysia. In WCEE (Ed.), *13th World Conference on Earthquake Engineering, Vancouver Canada* (pp. 1–10). Vancouver.

Muhr, A. (1994). Design of the Isolation System for the Demonstration Building at Tenjo Resmi. *UNIDO Workshop on The Use of Natural-Rubber Based Bearings for Earthquake Protection of Small Buildings, Jakarta, 1994* (pp. 1–28). London.

EN 15129:2009, Anti-seismic devices

EN 1998-1:2004, Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings.