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Design and characteristics of high damping natural rubber bearings for base isolation

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Abstract

High damping natural rubber bearings are effective in providing protection to structures from damaging effects of an earthquake. There are many buildings around the world which are mounted on rubber bearings and these buildings as expected were not damaged during the recent Kobe and Northridge earthquakes in 1995 and 1994 respectively. Although the Peninsular Malaysia is generally considered as seismically stable, the state of Sabah in the eastern part of Malaysia is not. Recently a 3-story reinforced concrete frame building mounted on high damping natural rubber bearings was constructed in Sabah. This paper describes the design of the isolation system and the individual bearings. The properties of the rubber and the bearings are presented.

1 Introduction

To many structural engineers, the conventional approach to protect buildings from the destructive forces of earthquakes is to increase the strength of the buildings so that they do not collapse during such events. This approach is not entirely effective in terms of protection afforded to the contents and occupants as a result of the amplification of the forces transmitted into the building. Since the motion of earthquakes is vibrational in nature, the principle of vibration isolation [1] can be utilized to protect a building. In this approach, commonly known as base isolation, a building is decoupled from the horizontal components of the earthquake ground motion by mounting rubber bearings between the building and its foundation. Such a system not only provides protection to the building but to its contents and occupants as well [2].

Among the numerous designs of base isolation system, the high damping (HDNR) [3] steel-laminated natural rubber bearings offer perhaps the simplest and the most cost effective method of isolation and are relatively easy to manufacture as compared to lead-plug laminated rubber bearings [2]. HDNR steel-laminated rubber bearings have advantages over the lead-plug rubber bearings in that the later induce higher modes response [2]. At present more than 2000 structures (buildings and bridges) in the world's seismically-prone areas (USA, Japan, Italy and New Zealand) have been installed with HDNR and lead-plug bearings. The effectiveness of the laminated rubber bearings was clearly demonstrated by the 1994 Northridge and 1995 Kobe devastating earthquakes where base-isolated buildings performed very well as compared to conventionally-built structures which were either destroyed or suffered serious damage. For example, a base-isolated University of Southern California Hospital, showed a reduction in the acceleration in the 7th floor by a factor of 5 when compared to the ground acceleration. In Kobe, the sixth floor of a base-isolated West Japan Postal Service Computer Centre showed a reduction in the acceleration by a factor of 10 when compared to an equivalent conventionally-built building nearby. After the Kobe temblor the demand for base isolation system skyrocketed in Japan especially in bridges where 99% of the newly-built bridges are now using base isolation as compared to 5% before Kobe earthquake.

As part of a continuous programme to promote HDNR bearings and as a service to humanitarian causes, the Malaysian Rubber Board (MRB) was involved with the United Nation Industrial Development Organisation (UNIDO) in three projects to demonstrate feasibility of utilizing HDNR bearings for base isolation of public dwellings in developing countries. In 1993, the MRB participated in an UNIDO programme to encourage the extension of base-isolation using HDNR bearings to ordinary dwellings, particularly public housing, in developing countries which are earthquake-prone. The first project involved the construction of two identical 8-storey demonstration apartments in Shantou, China which was completed in 1994. One of the apartments was base-isolated with HDNR bearings. The second project was the construction of a base-isolated 4-storey demonstration building at Pelabuhan Ratu in Indonesia which was completed in 1994. The third project was retrofitting an existing 5-storey unreinforced masonry apartment block in Vanadzor, Armenia which was completed in 1996 and the apartment sits on 30 HDNR bearings.

While Malaysia may be regarded as seismically stable, nevertheless it is at a close proximity with the seismically-active Sumatra faults. The massive destruction suffered by Mexico in 1985 was due to an earthquake whose epicenter was in an ocean some 400km away. Earthquakes have also occurred in areas traditionally regarded as safe, for example, Newcastle in Australia in 1991 and Maharastra in India in 1993. In addition, based on the Indonesian Earthquake Study (1979-1981) [4], Sabah, a state in the eastern part of Malaysia, falls within a seismically active region designated as zone 5. Therefore it is felt that seismic awareness in Malaysia and the necessary precautions ought to be given some prominence by constructing a building isolated with rubber bearings in Sabah. This report describes the design procedure to establish the dimensions and properties of the rubber bearings.

2 Design of isolation system

In October 1999 the MRB and the Malaysian Palm Oil Board (MPOB) signed a memorandum to jointly construct two identical 3-story reinforced concrete frame office buildings at the MPOB research station in Lahad Datu, Sabah. One of the buildings is installed with rubber bearings and the other is conventionally built. Figure 1 shows that the construction of the two buildings is almost completed, and the building on the right is base-isolated. Figure 2 shows the installed bearings.

In order to design appropriate bearing dimensions, the maximum displacement response of a structure was deduced from the Indonesian Earthquake Study [4] which gives simplified structural response spectra of six seismic zones for earthquake return periods of 20, 200 and 1000 years. Sabah falls in zone 5 and according to the Study, the peak displacement values for different return periods is shown in Table 1.

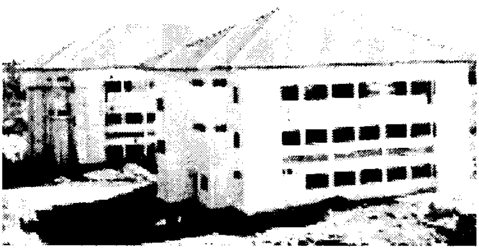

Figure 1: The two buildings in the process of completion, the one on the right is base-isolated.

Figure 2: Installed bearings underneath the building.

Generally the 200-year return period spectrum is used for the design purpose for an isolated building. Since the soil at the site was found to be firm, the building and the isolation system should be designed such that no irreversible damage occurs for horizontal deflections up to 91mm that is expected in the design earthquake. In addition the building is also expected not to fail catastrophically in the event of 1000-year return period earthquake (maximum probable earthquake) that is at a horizontal deflection of 218mm which includes allowance for torsion. The isolation system has to be designed with the rubber compound having about 10% of critical damping otherwise the maximum displacement will be higher and this means larger bearings have to fabricated.

Table 1: Peak displacement for Indonesian seismic zone 5 on hard and soft ground

Earthquake return period year	Displacement (5% damping) mm		Displacement (Corrected to 10% damping) mm	
	Hard	Soft	Hard	Soft
20	15	50	12.5	12
200	109	188	91	157
1000	227	317	218	304

From a structural point of view, a practical and convenient way to incorporate the isolation system is to locate one bearing under each load-bearing column. Since there are 28 columns in the building, this lead to 28 isolation bearings supporting a significant load variation from 313kN to 1360kN. In order to provide an approximate match of column load to horizontal stiffness, two types of bearings of different hardness (different shear modulus) were used but the dimension of the bearings are the same so that fabrication could be made from the same mould. In addition the same size bearings would ensure that the height drop of all bearings will be similar and the use of stiffer rubber compound would be much easier to control damping than if only the soft compound is used. The details of the axial load on each 28 columns are given in Table 2 and on the basis of these loads, it was decided that the number of soft bearings would be 12 and supporting nominal load of 450kN. In addition the number of hard bearings would be 16 supporting nominal load of 1,120kN.

One of the main prerequisites for effective performance of base isolation is that the horizontal stiffness is sufficiently low to achieve isolation, i.e., the natural frequency of the system is well below (one third or less) the predominant frequency of the earthquake. In this case an isolation frequency of 0.5 Hz was chosen and to achieve this the required properties of the bearings are summarized in Table 3. The dimensions and the details of the required soft and hard bearings are given in Table 4.

The thick end-plates of the bearings are required for installation where the bearings are located in upper and lower recesses in the form of annular steel rings bolted to outer steel which are connected to the reinforcement in the upper beams and lower foundation pedestal as shown in Figure 2. This method of connection helps to minimize the cost of the bearings and simplifies their installation on site, and also enables the bearings to be easily removed should this ever be necessary. Under large deflections these end-plates are free to bend and this helps to relieve local hydrostatic tensions which might otherwise lead to cavitation in the rubber [5] (as would be the case if a bearing is bolted to the structure).

Table 2: Axial load for each column

No	Axial Loads (kN)	No	Axial Loads (kN)	No	Axial Loads (kN)	No	Axial Loads (kN)
1	453	8	354	15	1,112	22	1,337
2	453	9	1,041	16	1,078	23	1,159
3	313	10	1,358	17	1,078	24	910
4	313	11	1,358	18	1,112	25	544
5	354	12	1,041	19	1,112	26	491
6	544	13	1,078	20	1,078	27	491
7	544	14	1,112	21	910	28	544
Total building weight 23,262 kN							

Table 3: Design parameters for the hard and soft bearings

Type of bearings	Soft bearing	Hard bearing
Vertical design load (kN)	450	1120
Nominal shear stiffness (kN/mm)	0.58	1.0
Nominal vertical stiffness (kN/mm)	349	639
Nominal vertical natural frequency (Hz)	12.1	11.1
Safety factor	5.7	6.2
Critical load (kN)	2565	6944
Rollout instability (mm)	432	432
Maximum vertical load (kN)	544	1360
Maximum compressive stress (MPa)	3	7.5
Nominal compressive stress (MPa)	2.5	6.2

Table 5 shows the building overall properties. The two types of bearings consisting of 16 hard and 12 soft, will produce a horizontal natural frequency of the building of 0.5 Hz and a vertical natural frequency of 12.4Hz. Since the vertical natural frequency is about 25 times higher than the horizontal's, rocking of the building is expected to be very minimal.

The high damping rubber used here are non-linear (Figure 3) and the bearings would be stiffer at low amplitude and this is an added advantage to the building because the movement due to wind forces is prevented without the necessity of additional devices. Figure 4 shows the damping characteristics of the hard and soft rubber compounds used in the fabrication of the bearings.

Table 4: Dimensions of the bearings

Soft bearing	Hard bearing
11 rubber layers; 11.35mm thick	12 rubber layers, 10.16mm thick
10 reinforcing plates; 3mm thick, 480mm diameter	11 reinforcing plates; 3mm thick, 480mm diameter
Rubber cover layer (side); 10mm thick	Rubber cover layer (side); 10mm thick
2 endplates; 20mm thick, 494mm diameter	2 endplates; 20mm thick, 494mm diameter
2 end cover layer; 2mm thick	2 end cover layer; 2mm thick
Overall dimensions; 199mm high, 500mm diameter	Overall dimensions; 199mm high, 500mm diameter

Table 5: Building's overall properties

Weight of the building	23,275 kN
Total number of bearings: 28	16 hard bearing and 12 soft bearings
Total vertical stiffness; 16x639 kN/mm + 12x341N/mm	14316 kN/mm
Building's vertical natural frequency	12.4 Hz
Total horizontal stiffness; 16x1.0 kN/mm + 12x0.58 kN/mm	23.0 kN/mm
Building's horizontal natural frequency	0.5 Hz
Design force at 91mm deflection on the building	1046 kN
Maximum probable force on the building at 218mm deflection for the building	2507kN
Design force at 91mm deflection on the structure below the bearings	2093 kN
Maximum probable force at 218mm deflection below the bearings	5014 kN

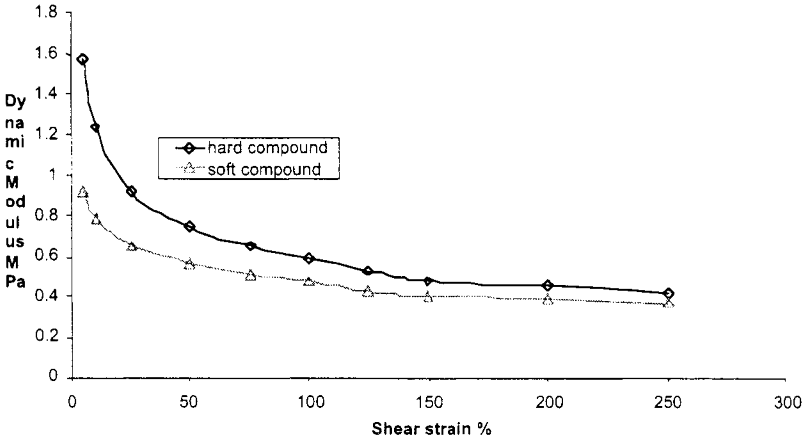

Figure 3: Effect of strain amplitude on shear modulus.

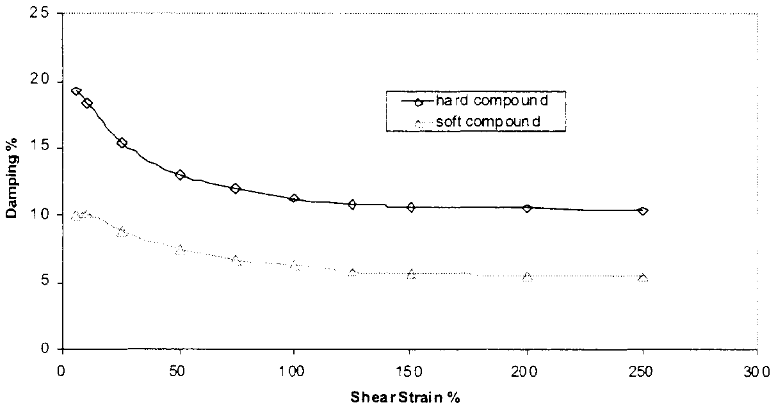

Figure 4: Effect of strain amplitude on damping.

3 Manufacture and testing of the bearings

Before the actual production of the 28 bearings, two prototype bearings were fabricated. The prototype bearings were tested and they were within the designed specifications. Figure 5 is one of the bearings with the outer rubber skin removed showing the thickness uniformity of the rubber layers, and the parallelism between the metal plates and the rubber layers which are crucial in the effective performance of the bearings. The bonding between the rubber layers and the metal plates were also tested and it was well above the minimum

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required values. Only after the completion of the test on the prototype bearings and the results were within the designed values that the actual production of 28 bearings began. All the completed 28 bearings were tested and Figure 6 shows two bearings being tested under a combined vertical and horizontal loads at 100% shear deflection (122 mm deflection) with no damage to the bearings and no occurrence of rollout. In fact it is predicted that the rollout will only occur at 432mm deflection which is well above even for a 1000 year earthquake return period (218mm). The testing could not be done higher than 122mm deflection because of the limitation of testing equipment. The bearings were designed to be able to deform horizontally up to about 200% well above the 1000 year return period. The predicted shear stiffness values of the bearings are 0.58kN/mm and 1.0kN/mm respectively for soft and hard bearings. The measured values for these 28 bearings were on average within 5% of the predicted values.

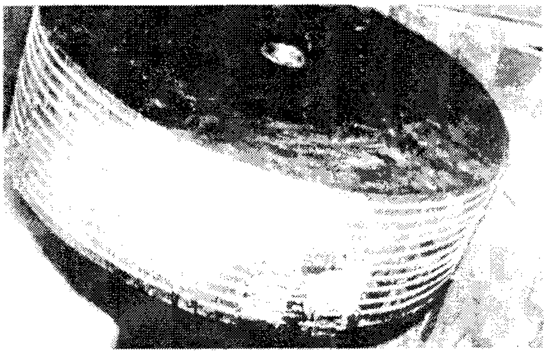

Figure 5: The first prototype bearing with the outer rubber cover removed to show a uniform thickness of rubber layers and parallelism between metal plates and rubber layers.

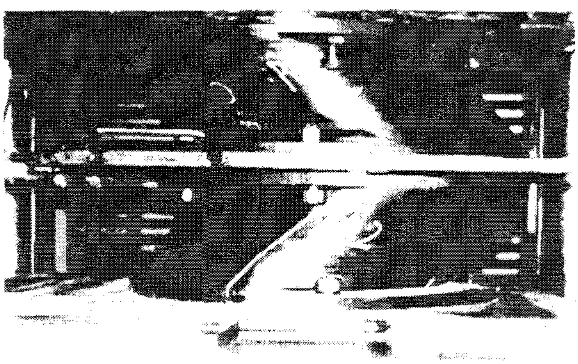

Figure 6: Two bearings being tested under combined shear and vertical loads at a maximum of 100% shear deflection and these bearings so no sign of damage and their stiffness were within 4% of the predicted values.

4 Conclusions

Base isolation is an effective and proven technique to protect buildings from an earthquake. A 3-story base-isolated building was successfully constructed in Sabah and hopefully this will increase the Malaysian public awareness of the seismic risks in Malaysia. The rubber bearings were designed and fabricated at the MRB and they were tested and were well within the designed specifications.

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