Seismic Protection Of 2nd Penang Crossing Using High Damping Natural Rubber Isolators

Kamarudin Ab-Malek, H.R. Ahmadi, A.H. Muhr, I.J. Stephens, J. Gough, & J.K. Picken
Tun Abdul Razak Research Centre, Brickendon Lane, Hertford, UK

Lee Jian Jun & Muhammad Umar Zulkefli
Rubber Technology Centre, RRIM Research Station, Sungai Buloh, Malaysia

Ismail M. Taib,
Jambatan Kedua Sdn Bhd, Bukit Damansara, Kuala Lumpur, Malaysia

SUMMARY:
The Second Penang Bridge will connect mainland Malaysia to Penang Island. The total length of the bridge is 24km, making it the longest in Malaysia and Southeast Asia. The paper will address the seismic risk to this major new structure from large far field events. High Damping Natural Rubber (HDNR) isolators are used for the seismic protection of the sea section as well as the land expressway part of the bridge. The creep and shrinkage of the precast sections of the deck for the sea section posed a challenge to the design and installation of the isolation bearings. A total of 1352 HDNR bearings are required for the sea section and 882 for the land expressway. The bearings have been manufactured in Malaysia under the supervision of the Malaysian Rubber Board and tested in accordance with international standards at the local manufacturer's testing facility.

Keywords: High Damping Natural Rubber, base isolation, seismic isolator, vibration isolator, Penang Bridge.

1. INTRODUCTION

Base isolation provides earthquake protection of the structure by shifting its fundamental resonant frequency away from earthquake ground motion frequencies. Damping is needed to control the resonant response of the structure. Bridge seismic isolation involves the replacement of conventional bridge bearings by seismic isolators, which then perform two roles, that of the conventional bridge bearing (controlling loads transmitted to the piers due to thermal expansion/contraction of the deck) and seismic isolation. Bridge natural periods are often in the range 0.2 to 1.2 seconds (Kunde 2003). A significant body of work published on base isolation of bridges shows considerable advantages over conventional fixed design (Kunde 2003). By 1996, 255 seismically isolated bridges had been built; Iceland -5; New Zealand -49; Japan -12; USA -21 and Italy -168. (Kunde 2003, Priestley 1996). With the exception of Italy most bridges were isolated using lead rubber bearings whereas in Italy sliders and dampers were common.

2. DETAILS OF THE STRUCTURE

The structure when complete will be the longest bridge in Malaysia and Southeast Asia. It traverses the sea between Batu Kawan (joining the North-South Expressway) on mainland Malaysia and Batu Maung (for the Bayan Lepas Expressway) on Penang Island. It will be 23.6km long.

The bridge is split into three work packages- see Fig. 1:

- Package 1 is the foundation piling and pier construction for the 16.9km Sea Section.
- Package 2 consists of the HDNR isolators and the superstructure of the Sea Section.

- Package 3 covers the sub and super structure (including the HDNR isolators) for the 6.8km land connections.

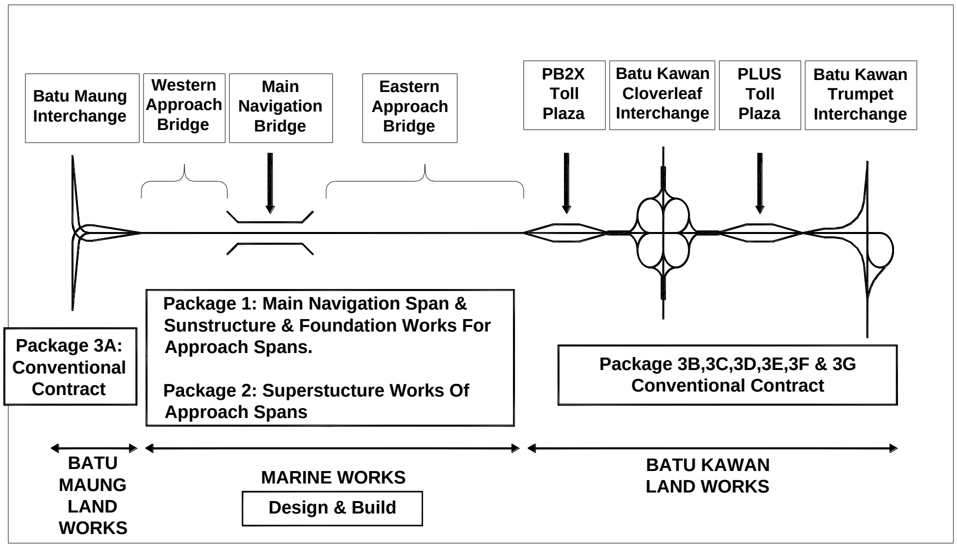

Figure 1. Second Penang Bridge work packages

The Sea section, Package 2 viaducts are twin prestressed concrete box girder structures constructed using precast prestressed concrete segments and erected using the whole span segmental construction method. Spans are nominally 55m. There are 44 viaduct modules of six spans each and five viaduct modules each with five spans. Expansion joints are located between adjacent modules. The piers for the viaduct consist of a reinforced concrete pier head on raked pile foundations. Bearings connect the superstructure and substructure (see Fig. 2). The pile foundation consists of 1m diameter spun piles of 60m long with a bore pile diameter of 2.3m.

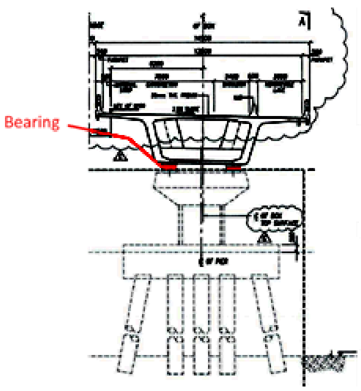

Figure 2. The location of the bearings in relation to the superstructure and the sub-structure.

Package 3 is divided into six sections (3A to 3G) of which only packages 3A and 3B are required to be isolated. Package 3A is the Land Expressway section of the bridge covering Batu Maung interchange on the island of Penang. The base isolated part of this package consists of 13 modules two of which are curved ramps using cast-in-situ concrete box girder beam for the deck supported by two bearings on each piers. The decks for the remaining 11 modules are "T" beam and slab design. The number of precast "T" section beams across the piers of the modules varies from 5 to 10 (see Fig. 3). Each T section beam is supported by two bearings mounted on the piers as shown in Figure 3.

Package 3B1 consists of 3 spans of 34 meter length at the Batu Kawan (the mainland) side of the bridge connecting the end of the sea section (package 2) to the land. The mode of construction of package 3B1 is similar to package 3A with each deck supported typically by 7 bearings. Similarly

Package 3B2 consists of 11 spans crossing over River Tengah in the Batu Kawan land expressway section.

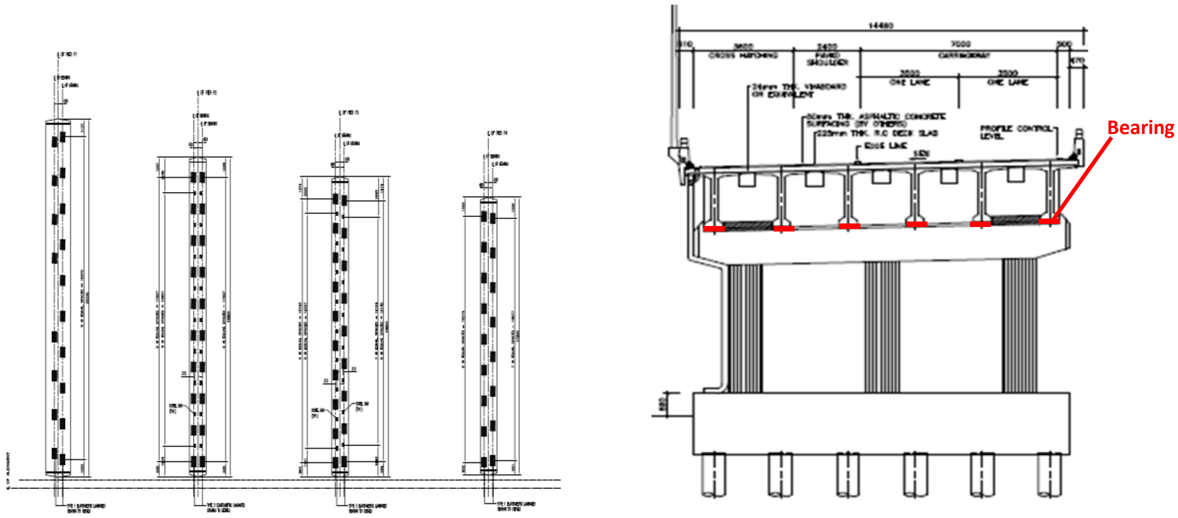

Figure 3. Example of isolation bearings layout plan (bearings are shown in black squares) and section through package 3 T section and slab deck , piers and pier cap and piles and pile cap.

3. SEISMIC ANALYSIS

Although Peninsular Malaysia is located in the stable Sunda Shelf with low to medium seismic activity level, tremors due to Sumatra earthquakes have been reported several times. For instance, two large earthquakes near Sumatra occurred at the end of 2002 (Movement Magnitude Scale, Mw = 7.4) and early 2003 (Mw = 5.8). Following these two far field events it was considered essential to carry out the first seismic hazard assessment for Malaysia in order to be assured of adequate performance during potential large earthquakes that may occur in the future.

The University Technologi Malaysia (UTM) appointed by the Construction Industry has carried out a number of studies aimed at developing the first macrozonation map for Peninsular Malaysia (Adnan et al, 2005). Following this analysis UTM was asked to carry out a seismic hazard assessment of the Second Penang Bridge and produce the Site Specific Design Spectra. The two events were:
i) Design Earthquake: 475 years return period (TR475) earthquake, under which bridge structures may have minor and repairable damages.
ii) Maximum Credible Earthquake: 2500 years return period (TR2500) earthquake should result in no collapse of the bridge.
Peak bedrock accelerations (PBA) for TR 475 and TR2500 earthquakes were 0.056 g and 0.11g respectively.

For the sea section (package 2), the nonlinear time history seismic analysis results revealed overstressing of the pilings in the absence of isolators, but showed that by adopting high damping rubber bearings, the effect of TR2500 seismic forces to the approach span substructures can be greatly reduced (Kamarudin et al, 2011). The existing pile foundations in both longitudinal and transverse directions are then found to be structurally adequate under the seismic action and ensure the structural adequacy of approach bridge pilings under the 2500 year return earthquake. Based on the above analyses a decision was made to use High Damping Natural Rubber (HDNR) bearings to base isolate the sea section as well as parts of the land expressways that are above the water.

For the land expressway, the stiffness of the bearings was set to achieve an isolation period of 2 seconds. The seismic actions on the bearings were arrived at using dimensional modal analysis using the Site Specific Design Spectra adjusted to the isolation system damping of 12% of critical.

4. CHARACTERISTICS OF THE ISOLATION SYSTEM

4.1 Sea Section

Four potential types of bearings were required for each 6 span module depending upon the location within the module. These are labelled E1, E2, E3 and E4 (see Fig. 4). Bearings E1, E2 and E4 are identical but are expected to withstand different shear deformations due to shrinkage and creep of the deck. These are called Type 1. The piers at each end of the module carry two sets of E3 bearings and therefore in order to reduce the shear loads imposed on the end pier, E3 (referred to as Type 2) bearings were approximately half the shear stiffness of Type 1.

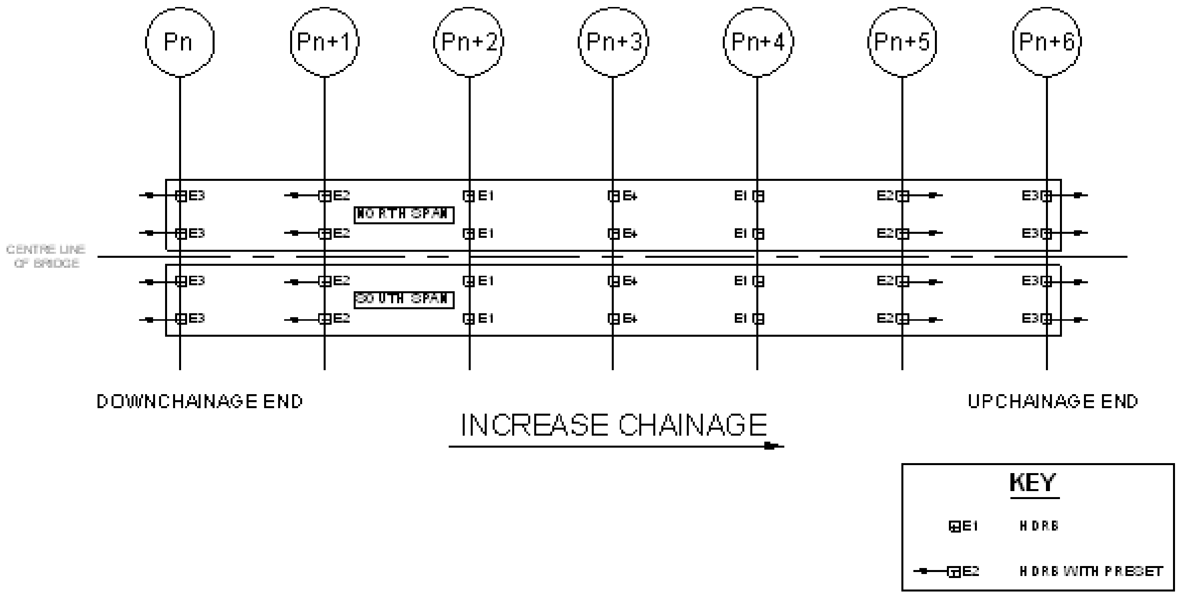

Figure 4. Location of the bearings within the 6-span module.

4.1.1 SLS non-seismic actions - conformance with BS5400

Historical precedence shows that conformance with BS5400 Part 9 ensures a very long maintenance-free lifetime, and a sufficiently conservative design to meet scenarios for non-seismic ULS actions. EN1337-3 is intended to be consistent with BS5400 part 9, but because the emphasis was shifted from SLS-based non-seismic design of the rubber bearings to nominal ULS-based design, the local total strain criterion was adjusted upwards from 5 (BS5400 part 9.1 clause 10.6) to 7 (EN1337-3 clause 5.3.3).

4.1.2 SLS non-seismic actions simultaneous with a 2500-year return period seismic event - conformance with EN15129

Seismic Standard EN15129 for laminated rubber bearings was chosen because it calls up EN1337-3 for non-seismic actions, which, being nearly equivalent to BS5400 part 9, relates better to the BS5400 based approach adopted for the design of the overall crossing structure. The horizontal stiffnesses for the bearings used in the time history analyses conform approximately to the usual choice of a natural period for an isolated structure of approximately 2.1s. Historical precedent on base isolated buildings has demonstrated that this feature of the behaviour of high damping rubber bearings works well in controlling the response of the buildings due to wind loading. For the purpose of predicting displacement of the bearings due to wind loading the relationship of:

$$F = 42\text{kN}.(d/1\text{mm})^{0.5532} \quad (4.1)$$

was used for the nonlinear load, *F*, versus the shear deflection deflection, *d*, for the bearings.

MRB was asked to check the conformance of the design also for the 475year return period earthquake. Since the deflection (44mm) under the 475 year period event is less than half that for the of the 2500 year earthquake (102mm) this is assured.

Table 1 shows the horizontal creep and shrinkage values estimated for 330m six span decks. These are 140mm at each end of the module, location of E3 bearings, reducing to 100mm for piers with bearing E2 and 50mm at E1 piers. Due to lack of available space on the piers and the need to avoid jacking up the decks after the completion of the shrinkage process it was decided that bearings E3 and E2 would be delivered locked to a preset shear deformation. The magnitude of the horizontal preset deformation for bearings E3 and E2 was chosen to be half of the predicted maximum shrinkage at those location i.e. 70 and 50mm respectively. No preset was required for bearings E1 as their predicted final deformation due to shrinkage was similar to the preset for bearing E2, i.e. half the final deformation due to creep and shrinkage. Table 2 shows the ULS loads and actions under the TR2500 seismic event as stipulated by the structural engineer. The dimensions of the bearings and some of their properties are given in Table 3.

Table 1. SLS applied loads, movements and rotations.

Bearing Identification mark				E1	E2	E3	E4
Loads [KN]	Vertical		Permanent G	6800	7000	3400	6900
			Live Qv	6700	6950	4600	6700
			Maximum	13500	13950	8000	13600
			Minimum	5000	5300	2150	5100
	Transverse		Wind Wt	330	330	180	330
			Traffic Qt	100	100	100	100
	Longitudinal		Wind Wt	215	215	108	215
			Traffic Qt	125	125	125	125
Translat-ions [mm]	Vertical	Irreversible	Permanent	2	2	2	2
		Reversible	Live	2	2	2	2
	Transverse	Reversible	Wind	50	50	50	50
		Reversible	Traffic	15	15	20	15
	Longitudinal	Reversible	Wind	20	20	20	20
		Reversible	Traffic	10	10	10	10
		Reversible	Temperature	10	15	20	5
		Irreversible	Creep & shrink	50	100	140	5
		Irreversible	Preset	0	- 50	- 70	0
Rotation [radian]	Longitudinal		Permanent	+ 0.004	+ 0.004	+ 0.009	+ 0.004
			Live	+ 0.004	+ 0.004	+ 0.005	+ 0.004
				– 0.002	– 0.002	– 0.002	– 0.002
	Transverse		Live	+ 0.002	+ 0.002	+ 0.002	+ 0.002
				– 0.002	– 0.002	– 0.002	– 0.002

An innovative system of plates patented by MRB was designed for locking the bearings in their preset deformation at the Doshin factory following the characterisation tests. Fig. 6 shows the preset plates installed in position on the testing rig, while Fig. 5 shows the two end bearings (E3) of the adjacent modules installed on the pier with the locking plates still in position. The locking system decouples the horizontal and vertical deflection of the bearing i.e. as the vertical load on the bearing changes the two locking plates slide past each other allowing for the change in the height of the bearing while the shear deflection in the bearing is unchanged. The bearings are installed in position when the ambient temperature is at its lowest. As the temperature rises the deck extends resulting in the separation of the upper and lower locking plates. This then provides a safe opportunity for the removal of the plates.

Table 2. ULS (2500) applied loads, movements and rotations.

Bearing Identification mark			E1	E2	E3	E4
Loads [KN]	Vertical	Max	2200	2200	1100	2200
		Min	-2200	-2200	-1100	-2200
	Transverse		600	600	300	600
	Longitudinal		600	600	300	600
Translation [mm]	Vertical	Max	+2	+2	+2	+2
		Min	-1	-1	-1	-1
	Transverse		100	100	100	100
	Longitudinal		100	100	100	100
Rotation [radian]	Longitudinal		0.010	0.010	0.012	0.010
	Transverse		0.001	0.001	0.001	0.001

Figure 5. Left: the two end bearings (E3) of the adjacent modules installed on the pier with the locking plates in position. Right: bearing in the foreground has had the locking plates removed after being connected to structure.

Table 3- Package 2 bearing dimensions and properties.

	E4	**E1**	**E2**	**E3**
Length (mm)	1050	1050	1050	850
Width (mm)	850	850	850	700
Height (mm)	350	350	350	350
Preset Displacement (mm)	locked	0	50	70
Shear Stiffness 44% strain (kN/mm)	5.0	5.0	5.0	3.3
Nominal Vertical Stiffness (MN/mm)	3.2	3.2	3.2	1.7
Shape Factor	14.4	14.4	14.4	11.7

Figure 6. Tests in double shear configuration: a) Left: bearings without preset plates, b) Right: bearings with preset plates installed after test.

4.2 Land Expressways (packages 3A, 3B1&2)

Bearings designed for Packages 3A, 3B1 and 3B2 are in general much smaller than Package 2 isolators as, with the exception of the curved ramps which have box girder decks, the land expressways are T beam and slab design. The T beams are supported by two rows of bearings on each pier. The curved ramps however are supported by two bearings on each pier. The stiffness of the bearings on the end piers are set to about half of the intermediate piers bearings.

Table 4- Package 3 bearing dimensions and properties.

	T1	**T2**	**Curved ramps End bearings**	**Curved ramps intermediate bearings**	**Pier 292 outer bearings**	**Pier 292 inner bearings**
Length (mm)	374	374	425	580	432	432
Total Height (mm)	287	265	203	188	224	269
Number, thickness of rubber layer (mm)	24, 5.5	23, 5	12, 9	9, 12	9. 16	18, 8
Shear Stiffness at 100% strain (kN/mm)	1.18	1.15	1.86	3.70	1.14	1.14
Nominal Vertical Stiffness (MN/mm)	0.96	1.12	0.90	2.04	0.24	0.72
Shape Factor	16.5	18.2	11.3	12.1	6.4	12.9

The bearing design process involved the receipt, from structural engineers responsible for non-seismic and seismic analysis of the structure, of the loads and actions on every bearing of the land expressway under the 475 and 2500 year return period seismic events. The proposed bearings design were then verified according to BS5400 and EN15129 standards against the predicted loads/actions for each bearing, rather than based on the maximum of the load/action imposed on all the bearings. One reason for this approach was the lack of space on the piers to accommodate one bearing design that can sustain the maximum conditions throughout the modules of packages 3. In addition, some of the bearings were predicted to experience tension during the TR2500 event. The design process resulted in two bearing designs (T1 and T2) capable of meeting the requirements of most of the package 3 piers. There were however, a few piers (e.g. pier 292 interface pier between the sea section and the land expressway) that required 2 additional bearing designs as the magnitude of the displacements for these piers were much higher. Table 4 shows the characteristics of the bearings designed for package 3. There different high damping natural rubber compounds were used to achieve the required performance from the bearings. This is in contrast with package 2 where only one compound was utilised.

4.3 Isolator Tests

Quasi-static and dynamic tests of the prototype and production bearings for package 2, stipulated by BS5400 and EN15129 standards were carried out on the manufacturer's bi-axial testing facility having vertical and horizontal load capacities of 2000ton and 200ton respectively. The compression-shear tests were performed on two bearings, in a double shear configuration- see Fig. 6.. The dynamic properties of the prototype bearings for packages 2 and 3 are shown in figures 7 and 8.

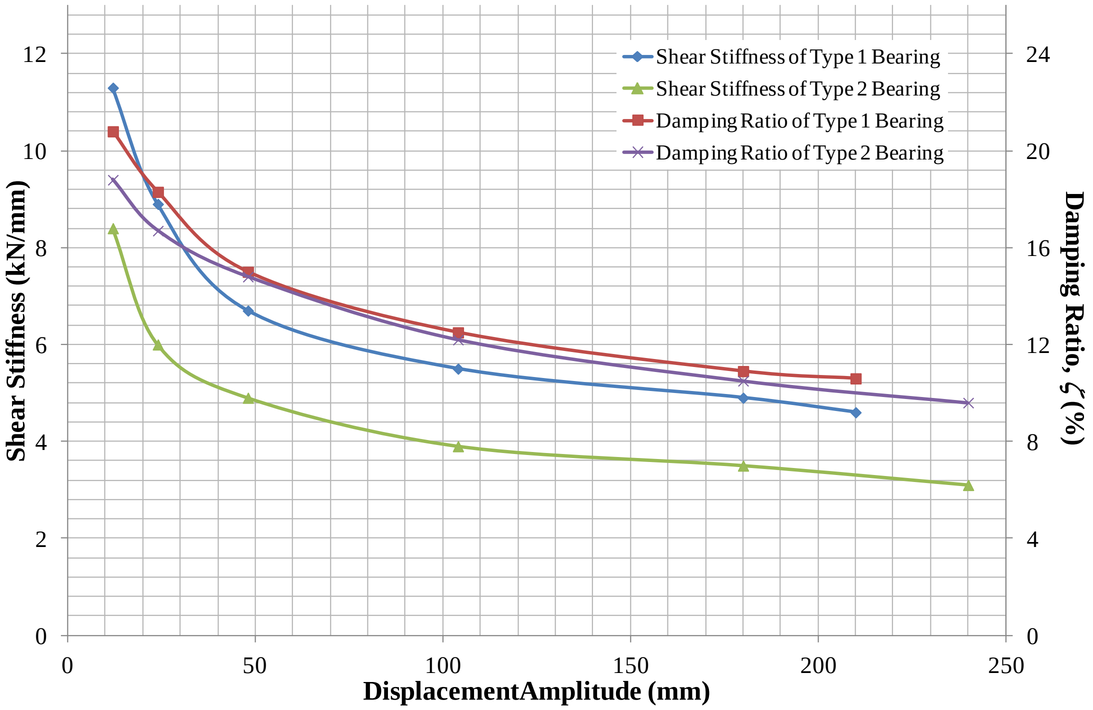

Figure 7. Shear Stiffness and Damping Ratio of Type 1 and Type 2 prototype HDNR bearings.

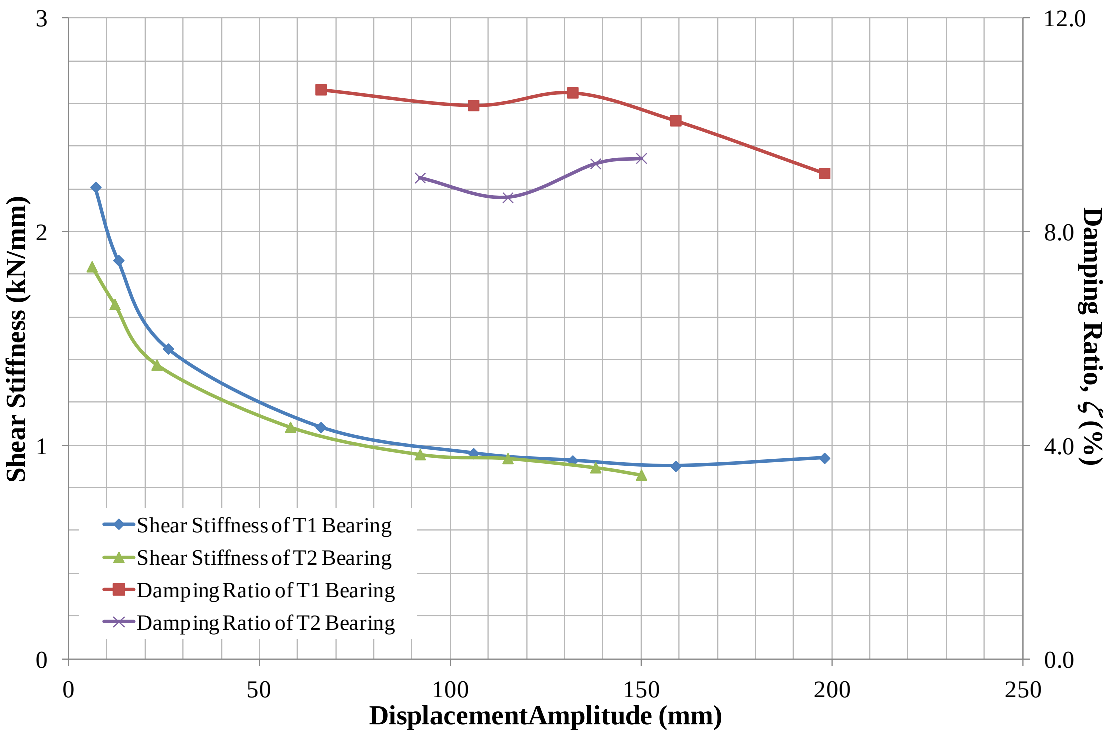

Figure 8 Shear Stiffness and Damping Ratio of T1 and T2 prototype HDNR bearings.

All the prototype and production bearings were tested under the supervision of MRB research officers. In all tests, visual inspections were made for any damage/defects on the bearings. Pictorial and numerical data were recorded by MRB officers present during the tests. The quality control reports stipulated by the EN15129 and BS5400 standards were prepared and approved by MRB and dispatched to Doshin Rubber for submission to their client.

4.4 Elastomer Tests

Each batch of rubber mixed for the production of the bearings were tested according to EN15129 and relevant parts of BS5400 standards at the Physical Testing Unit of the Rubber Technology Centre of MRB in Sungai Buloh, Selangor. The experimental data checked by MRB was then used to prepare Quality Test reports for each rubber batch.

4.5 Production inspection

The manufacture process used for the production of prototype and production bearing was supervised by MRB officers to ensure that the production control is of highest quality.

5. CONCLUSIONS

The paper shows the application of base isolation in eliminating the risk of damage to the piling foundation of the Second Penang Bridge as a result of seismic loads due to the 2500 year return period seismic event. High Damping Natural Rubber (HDNR) isolators chosen for the seismic protection of the sea section were shown to offer a lower cost solution compared to the major remedial action that would have been required to eliminate the seismic risk to this important structure. The creep and shrinkage of the precast sections of the deck for the sea section posed a challenge to the design and installation of the isolation bearings. An innovative locking plate system has shown to meet this, offering a simple and safe to use solution. Recent communications with the site engineers have confirmed this was indeed their experience.

REFERENCES

Kunde, M.C. and Jangid, R.S. (2003). Seismic behaviour of isolated bridges: A-state-of-the-art review. *Electronica Journal of Structural Engineering* **3**: 140-170.

Priestley, M.J.N.; Seible, F. and Calvi, G.M. (1996). Seismic Design and Retrofit of Bridges. John Wiley and Sons, New York.

Adnan, A., Hendriyawan, Marto, A., and Irsyam, M. (2005). Seismic hazard assessment for Peninsular Malaysia using Gumbel distribution method. *Jurnal Teknologi* **42**:57-73.

Kamarudin.Ab-Malek, Ahmadi, H.R., Muhr, A.H., Stephens, I.J., Gough, J., Picken, J., Lee, J.J. and Muhammad Umar, Z. (2011). High Damping Rubber Bearing Design for Approach Bridge. *1st International Seminar on the design and construction of the Second Penang Bridge*, *Kuala Lumpur*.