Seismic Performance of East Malaysia Bridge under Sulawesi subduction zone and shallow crustal zone

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Abstract

The code of practice for the design of bridge bearings (BS 5400 Part 9.1) and the specification for materials, manufacture, and installation of bridge bearings (BS 5400 Part 9.2) are still being widely used amongst Malaysian bridge designers. The shift of the design practices from conventional British Standard to Eurocode provides awareness on the earthquake effects. Eurocode 8 introduces the adoption of seismic isolation in the design of bridges for earthquake resistance (BS EN 1998-2005 Part 2). At the same time, the effects of earthquake from North Sulawesi Subduction zone (Megathrust), Palu-Koro (zones 1, 2, and 3), Sulu, Tarakan Basin, Kutai, Melange (zones 1, and 2), Mamuju, Matano, and Sangkulirang have been frequently felt in the East Malaysia. The adoption of the new design practice may affect the installation and the construction costs in total. The objectives of the study had been to look into the performances of an East Malaysia bridge with the previously designed rubber bearing under the Sulawesi subduction zone and the shallow crustal zone. The study attempted to examine the effectiveness of the use of rubber bearings on the bridge that will be built with expected design earthquakes in the probability of occurrence of an earthquake 500 years and 2500 years return period. The results were compared with a bridge without any bearing consideration (fix-based).

Keywords : Bridge, BS 5400, Eurocode 8, Sulawesi Subduction, rubber bearing

I. Introduction

Finite element analysis and modelling have been used extensively by many researchers to study earthquake effects on steel and concrete girder bridges. However, most researchers generally use computer programmes that are not widely available. This significantly limits the structural analysis capabilities of practicing engineers who are more interested in implementing finite element analysis with readily available software in the market. As such, practicing engineers have often faced problems with verifying the accuracy of their structural analysis results using commercially-available programmes that are generally limited to linear elastic analysis. Bridge engineering in Malaysia commonly practices the BS 5400 Part 9.1 and the specification for materials, manufacture, and installation of bridge bearings (BS 5400 Part 9.2) in the design. However, the adoption of seismic isolation for bridge under earthquake resistance (BS EN 1998-2005 Part 2) in the recent design practice requires knowledge in finite element analysis.

The objectives of the study were to evaluate the performances of a bridge in the East Malaysia that will be built under the Sulawesi subduction zone and the shallow crustal zone. The bridge will be located in the east coast of Sabah, Malaysia, on the island of Borneo. The bridge will connect the mainland to the island and its length is expected to reach as far as 1.4km. The bridge is designed to have 25 spans and is divided into three different segmentals: (1) the middle part with 7 main spans of variable depth segmental box girder, (2) the first approach of the bridge from the mainland, and (3) the second approach of the bridge to the island. In this study, only the second part of the bridge was studied. The total length of the approach of the bridge with consistent depth segmental box girder was 60 meters and 50 meters in length for each span with its pier design as a single column. This study attempted to examine the effectiveness of the use of rubber bearings on the bridge that will be built with expected design earthquakes in the probability of occurrence of an earthquake 500 years and 2500 years return period.

II. The Bridge

The study of the approach of the bridge under earthquake loadings is more meaningful compared to the middle span of the bridge, where it is usually very high and flexible (high natural period). The selected approach of the bridge consisted of 7 spans with 50 and 60 meters in length for each span. The bridge has some skew at the beginning and 4% slope consistently. The configuration of the bridge is shown in Figure 1.

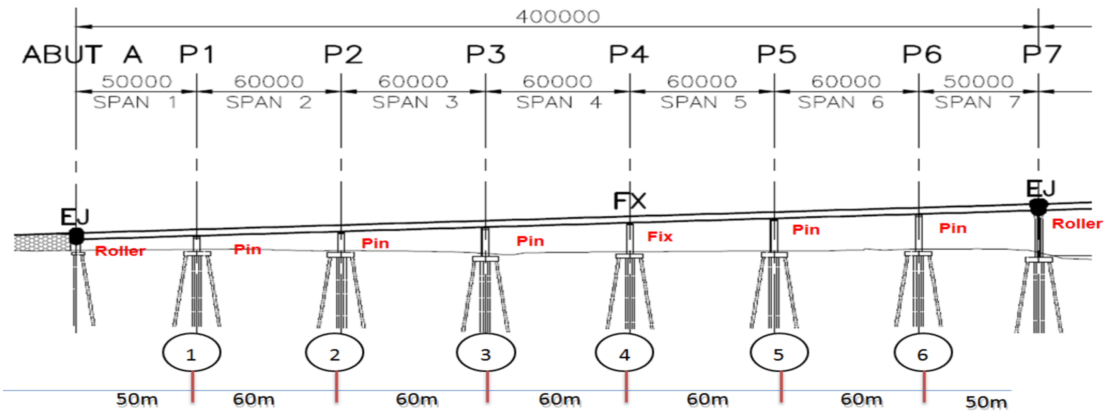


Figure 1: Bridge layout arrangement

In finite element, the deck is modelled as a beam (frame) element with consistent depth along the spans. The analysis was done from the expansion joint (EJ) to another EJ and it consisted of 7 spans in total. The effects of the middle span bridge are not included in this analysis. Furthermore, the points at both EJs were considered as abutments with a roller joint in the longitudinal direction. One point at the middle was defined as fix bearing and the others were considered pinned. This bearing condition is normally used in bridge design practices, and in this study, it was categorised under fixed-base analysis. The un-deform shapes of the extrude model with various view directions in Finite element modelling are clearly shown in Figure 2.

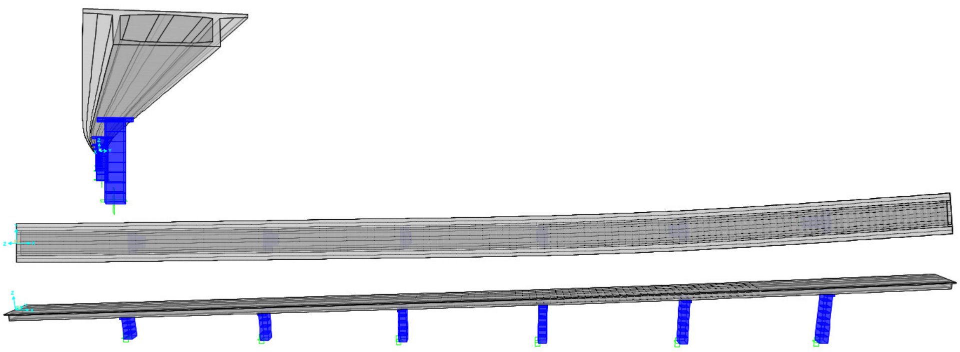


Figure 2: The extrude view of the beam model

In this study, the bridge was modelled under two bearing conditions: (1) fixed-base model, and (2) rubber bearing model. Both models are described below.

A. *Fixed base model*

This model reflects directly to the normal practices in design and analysis of bridge. Normally, the engineers necklace the effects of rubber bearing located between the beam and the bridge girder in their preliminary analysis and the design of the bridge. The bearing or joint is considered as roller, fix, and pin, as described earlier and as shown in Figure 1.

B. *Rubber Bearing Model*

This model normally reflects the actual condition of the bridge with the consideration of the existing bridge bearing. Therefore, in this study, the rubber bearings were used as the bridge bearings. The bearings were designed using normal practice design standards of BS 5400 Part 9.1 and Part 9.2. As for the rubber bearing model, the vertical and horizontal stiffness was required in the analysis. The formulas used to calculate the vertical or compressive (K_c) and horizontal or shear (K_s) stiffness of the bearings are given below:

i) Vertical Stiffness, Kc

$$K_c = \frac{3AG}{H}\left[1 + kS^2 \right] \tag{1}$$

ii) Horizontal Stiffness, Ks

$$K_s = \frac{AG}{H} \tag{2}$$

Where A is the area of the elastomer, G is the shear modulus of the elastomer, H is the total thickness of the bearing, K is the empirical constant dependent on elastomer hardness, and S is the weighted shape factor for bearing (ratio of one bonded area of block to the force free area). The link element was used to model the rubber bearing and the location of the bridge bearing is illustrated in Figure 3. Table 1 shows the bearing design parameter used for design purposes. The loading calculation was verified between the manual calculation and the joint reaction from dead load in the preliminary bridge model analysis. Table 2 indicates the summary of both vertical and horizontal stiffness used in the rubber bearing model analysis.

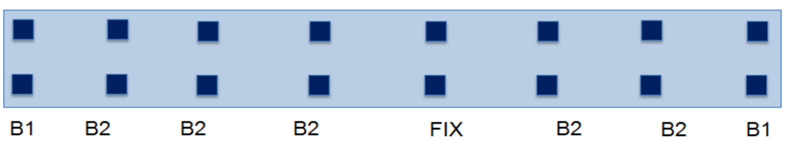


Figure 3: The bearing locations and numberings (plan view)

Table 1: Bearing design parameter

Bearing Identification Mark		B1	B2
Loads [kN]	Vertical	5,000	11,000
Translation [mm]	Transverse	50	50
	Longitudinal	150	150
Rotation [Radians]	Transverse	+-0.002	+-0.002
	Longitudinal	+-0.008	+-0.004

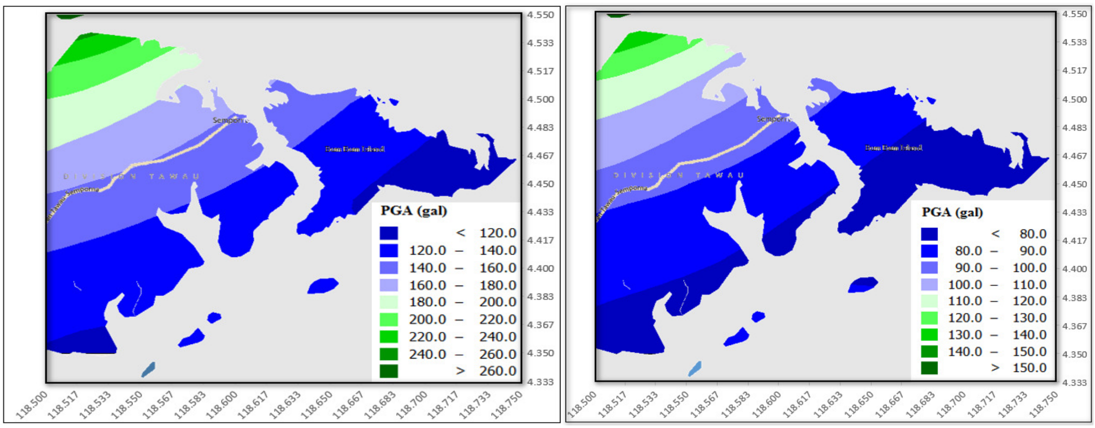
Table 2: Rubber bearing stiffness

Direction	B1	B2
Vertical Stiffness (kN/mm)	1,672	3,739
Horizontal Stiffness (kN/mm)	2.8125	4.500

III. East Malaysia Seismic Hazard

Azlan et al. (2005) carried out a seismic hazard analysis of Peninsular Malaysia for two hazard levels; 10% and 2% probabilities of exceedance in 50 years for bedrock. Based on the analysis, the peak ground acceleration (PGA) across Peninsular Malaysia presented a range between 10 gal and 25 gal for 10% probability of exceedance in 50 years hazard levels or 500(475) year return period (TR) of earthquake and between 15 gal and 35 gal for 2% in 50 year hazard levels or 2500(2475) year TR of earthquake.

The seismic hazard in East Malaysia also was examined via probabilistic study. The summation of all the probabilities was plotted into a contour map of PGA. The hazard map was depicted in terms of PGA at bedrock level for 2% and 10% probabilities of exceedance in 50 year. These correspond to TRs of 2500 and 500 years, respectively. Figures 4 (a) and (b) show the seismic hazard map for east coast of Sabah for TR=2500 and TR=500.



(a) (b)

Figure 4: (a) 2% probability of exceedance with 2,500 years TR; and (b) 10% probability of exceedance with 500 years TR

This study also presented the response spectral acceleration on rock site of the east coast of Sabah region with 2% and 10% probabilities of exceedance in 50 years exposure time (i.e., 500 and 2,500 years TR, respectively). The response spectral curves are shown in Figure 5.

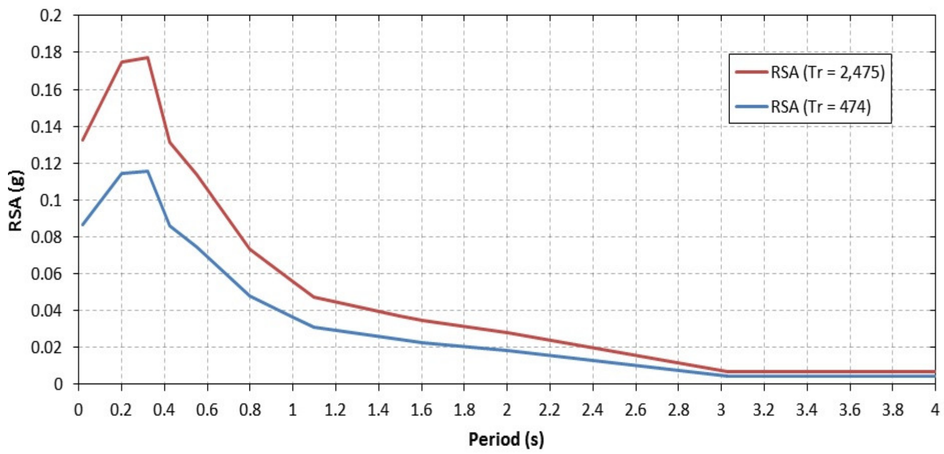


Figure 5: Response spectral acceleration on rock site of the east coast of Sabah Region with 2,500 and 500 years TR

IV. The Analysis

The modal analysis or also known as free vibration analysis (FVA) was used in this study and the frequency of the bridge was observed easily. The frequency of the free-vibration is the "inherent natural frequency". As for applications considered by many researchers, they assume that the natural frequency is constant for a given system and the mode of vibration. The FVA was recognized as an eigenvalue analysis in CsiBridge, as a tool in this study. This analysis produced the undamped free vibration mode shapes and frequencies of the structural system, which were needed for the seismic analysis by using response spectra.

A. Fixed base model

This model was analysed to reflex to the normal practice in designing and analysis of the bridge. In normal practice, the effect of bridge bearing is neglected because the purpose of the design of the bearing is normally just to accommodate the vertical load and some horizontal movement due to shrinkage, temperature, and vehicle. Figure 1 shows the bearing arrangement that consists of roller, pin, and fix support. The model is dominant in static and has a dynamic response, especially in lateral direction. The use of 65 modes provides high modal mass participation ratios up to 90% in every direction. Selected important three mode shapes based on the direction of dominance are shown in Figure 6.

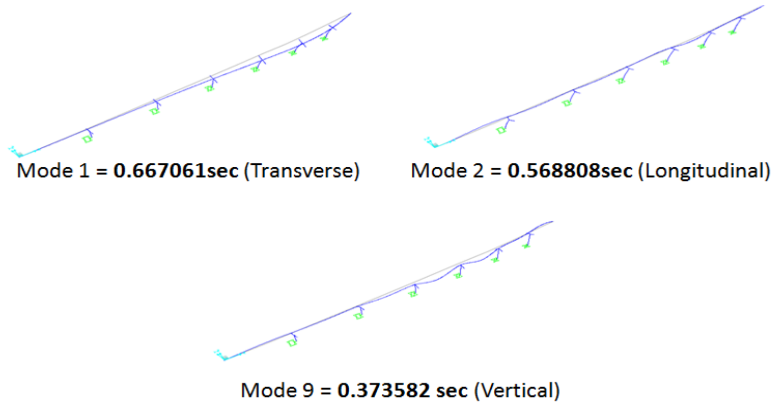
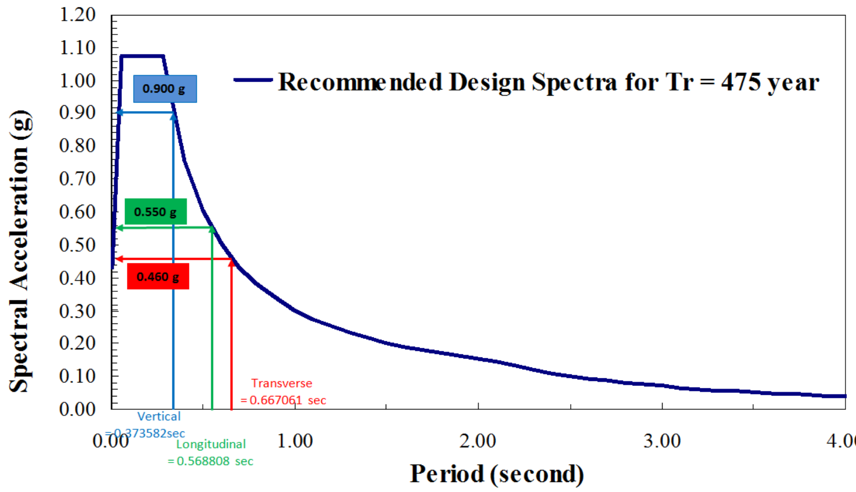
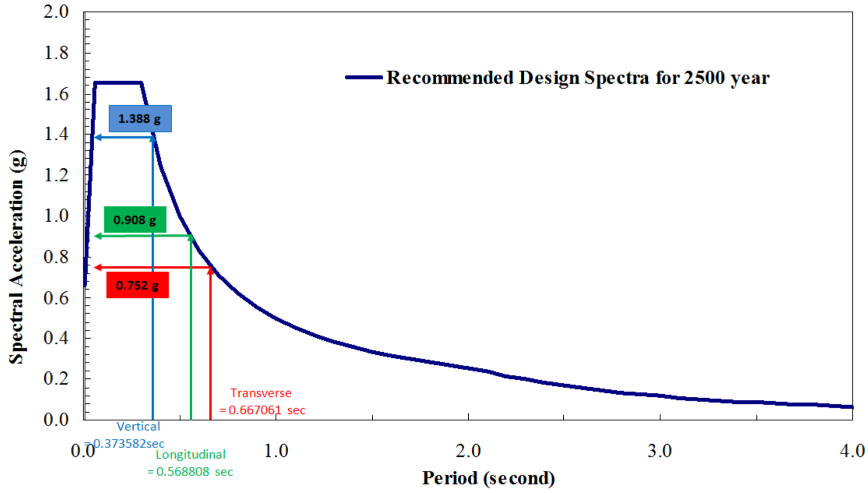


Figure 6: Response for analytical bridge model (fix-based model)

With the results of bridge period, the estimation of ground acceleration (a_g) for the bridge can be observed. For that purpose, a designer can refer to the recommended design response spectra for the proposed bridge project in 475TR and 2500TR, as given before. Figures 7 (a) and (b) 10 show the estimation of design ground acceleration based on the findings of bridge period for both 475TR and 2500TR respectively.



(a)



(b)

Figure 7: The estimation of design ground acceleration based on the finding of bridge period for fix-based model (a) 475TR and (b) 2500TR

The design response spectrum observed from the previous seismic hazard assessment and site specific study showed that the PGA and a_g were 0.430g for 475TR, and 0.660g for 2500TR. The amplification of the acceleration occurred based on this bridge's natural period and provided larger design value for the designer to design the bridge element.

Table 3: Design ground acceleration for Semporna bridge (fix-based model)

Direction	Period (Sec)	Response (Spectral Acceleration)			
		TR=475 (a_g=0.430g)		TR=2500 (a_g=0.660g)	
		a_g	Amplify (%)	a_g	Amplify (%)
Vertical	0.37358	0.900g	+109.3%	1.388g	+110.3%
Longitudinal	0.56881	0.550g	+27.9%	0.908g	+37.6%
Transverse	0.66706	0.460g	+7.0%	0.752g	+13.9%

Table 3 indicates the percentages of amplification of the bridge due to the structural period obtained from FVA.

B. *Rubber Bearing Model*

The analysis of this model was to reflex the actual condition of the bridge with the consideration of rubber bearing. Figure 8 shows the rubber bearing arrangement with the centre bridge bearing that are considered as fixed support. The stiffness of the bearing had been already observed before and listed in table 2.

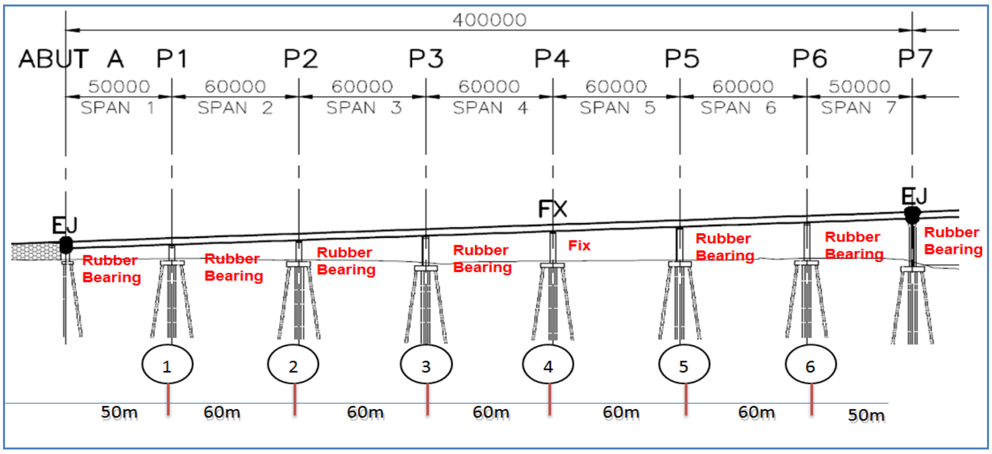


Figure 8: Bearing arrangement for rubber bearing model

The model is dominant in static and has a dynamic response, especially in the lateral direction. The use of 65 modes provides high modal mass participation ratios up to 90% in every direction. The major three mode shapes based on the direction of dominance are shown in Figure 9. The transverse natural period of 0.66706 sec for fixed-base model was already lengthened to 2.3242 sec. The longitudinal natural period was also lengthened from 0.56881 sec to 1.35667 sec and vertical direction from 0.37358 sec to 0.58416 sec.

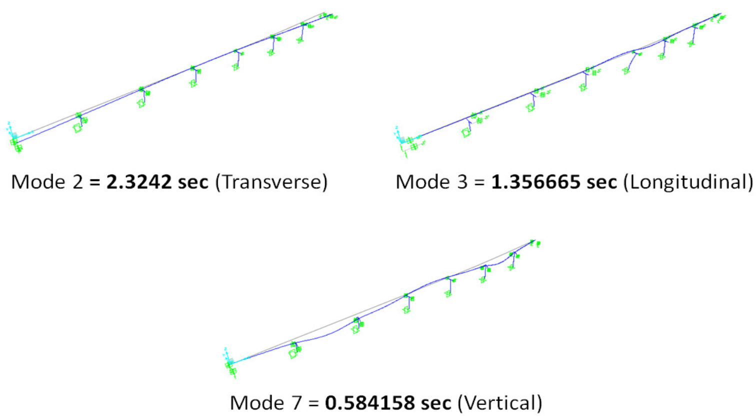
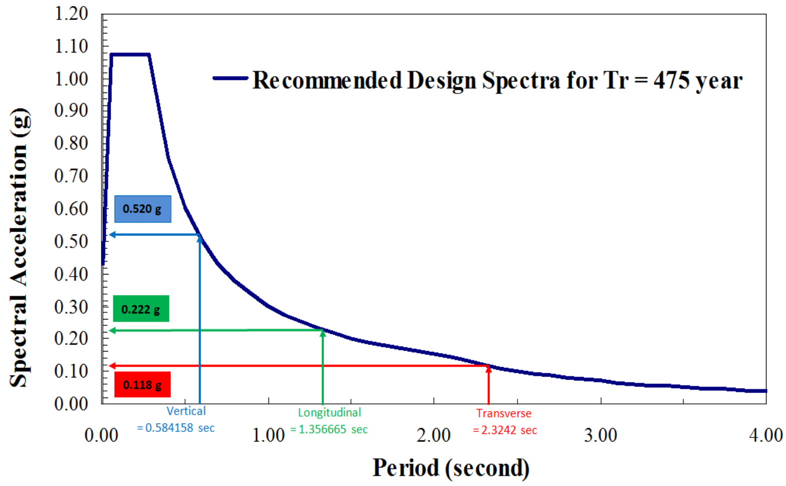
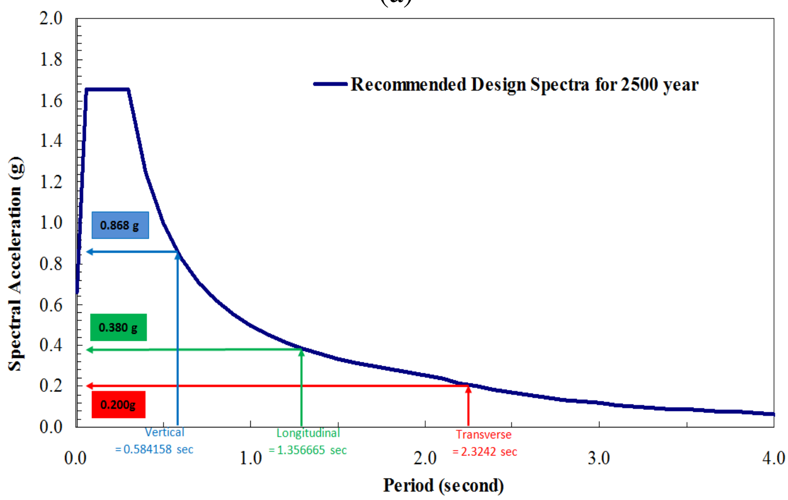


Figure 9: Response for analytical bridge model (rubber bearing model)

With the result of bridge period, the designer also can estimate the design ground acceleration for the bridge. For that purpose, the designer can refer to the recommended design response spectra for the proposed bridge project in 500 years return period (475TR) and 2500 years return period (2475TR), as given before. Figures 10 (a) and (b) show the estimation of design ground acceleration based on observed bridge period for both 475TR and 2500TR respectively.



(a)



(b)

Figure 10: The estimation of design ground acceleration based on the finding of bridge period for rubber bearing model (a) 475TR and (b)2500TR

The design response spectrum observed from previous seismic hazard assessment and site specific study showed that the PGA and ag were 0.430g for 475TR, and 0.660g for 2500TR. The amplification of acceleration had different behaviour compared to the previous analysis using fixed-base model. The longitudinal and transverse directions of the acceleration were reduced up to 72.6% and it gave a small value of design acceleration for bridge designer. Table 4 indicates the overall percentages of amplification of the bridge due to the structural period obtained from the FVA.

Table 4: Design ground acceleration for Semporna bridge (rubber bearing model)

Direction	**Period (Sec)**	**Response (Spectral Acceleration)**			
		TR=475 (a_g=0.430g)		TR=2500 (a_g=0.660g)	
		a_g	Amplify (%)	a_g	Amplify (%)
Vertical	0.58416	0.520g	+20.9%	0.868g	+31.5%
Longitudinal	1.35667	0.222g	-48.4%	0.380g	-42.4%
Transverse	2.3242	0.118g	-72.6%	0.200g	-69.7%

V. Conclusion

The study evaluated the performance of the proposed bridge using the finite element modelling technique. With this technique, the behaviour of the bridge under seismic loading was determined to utilise the geometric shape of bearing based on the displacement, periods, frequencies, and bearing stiffness. Hopefully, these basic guidelines are valuable for the bridge designer, especially when seismic factor is considered in their analysis.

The approach of the bridge had more risks to the seismic load compared to the middle span of the bridge. The middle span of the bridge had a long span and a long period like a high-rise building and it had low-risk to seismic. The horizontal or shear bearing stiffness gave dominant effects in the overall bridge performance compared to the vertical or compressive stiffness. Therefore, in the design of the rubber bearing to resist seismic load, the horizontal stiffness should be given more importance. The analysis that considered the rubber bearing stiffness factor improved the overall performance of the bridge based on the FVA. The usage of rubber bearing gave larger effect for the approach of the bridge, and thus the usage of rubber bearing is highly recommended to this bridge.

The finite element modelling has been the best way to study the performance of the structure, especially in bridge dynamic analysis. CsiBridge may be used to study the structure under seismic analysis because of its efficiency of running the programmes. The FVA has been useful to study the structural performance of bridges, especially in seismic analysis. Hence, Malaysian designers should not only study the seismic isolation system, but also look into the seismic design guidelines and codes that are suitable to our country, which is located in the low intensity seismic region.

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