

Seismic Performance of Laminated Rubber Bearing Bridges Subjected to High Intensity Earthquake Time-History Loading

Wan Noor Azhar Wan Sulaiman and Norliyati Mohd Amin

Abstract Malaysia needs to be more aware of the seismic effect on the infrastructure facilities especially on the bridge structure located in the dense population which is prone to the earthquake especially in Peninsular Malaysia. If the bridges fail in the event of earthquake, the rescue and relief effort will be halted. The most common strategy to enable the bridge sustain under the seismic loading is by using base isolator. Base isolator will reduce the reaction of the seismic force to the bridge. At present, the studies of the numerical modeling using 3D solid element are minimal. In this paper, the Finite Element Analysis using 3D solid element was chosen because it increases the accuracy of analysis result. In order to obtain the details response of the laminated rubber bearing (LRB), transient analysis was done under Kobe earthquake excitation. Structural damage in the form of permanent deformation is unavoidable. The failure of the laminated rubber bearing will made the superstructure's weight disable to provide a reasonable balance between shear force transmitted to the pier and displacement of the bridge deck. It was also found that the high value of displacement occurred at the elastomer in the laminated rubber bearing under Kobe earthquake excitation.

1 Introduction

Malaysia is bordered by Sumatra and Philippines, which are the seismic sources zone. Malaysia has felt tremors several times due to the earthquake event originated from both countries especially in Peninsular Malaysia region.

W. N. A. W. Sulaiman (✉)

Faculty of Civil Engineering, University Technology MARA, Shah Alam, Selangor, Malaysia

e-mail: 2011386711@isiswa.uitm.edu.my

N. M. Amin

Institute for Infrastructure Engineering and Sustainable Management IIESM, University Technology MARA, Shah Alam, Selangor, Malaysia

e-mail: norli830@salam.uitm.edu.my

The earthquake event is originated from the intersection areas of Eurasian plate and Indo-Australian plate near Sumatra. Relatively, Malaysia is far away from seismic Sumatra zone but it is recorded that the nearest earthquake epicenter from Malaysia is approximately 350 km. The distance of the epicenter is almost same with the Mexico City earthquake in 1985 which it caused seriously damaged to the Mexico City. The 8.1 magnitude of the quake struck the Mexico City. The effects of the quake were particularly devastating because the city sits atop a combination of dirt and sand. These combinations are much less stable than bedrock and quite volatile during an earthquake occurred. Almost Klang Valley areas also sit atop of filling area which comprised of sand. Due to the above fact, Malaysia needs to be more aware to the seismic effect on the infrastructure facilities especially bridge structure at the location of high population. The bridge acts as an important link in transportation network. If the bridges fail due to the earthquake event, the relief and rehabilitation work will cripple. There are many cases the failure of bridges around the world such as Santa Clara River Bridge pounding damage in 1994 Northridge earthquake, Nishinomiya-ko Bridge due to the Hyogo-Ken Nanbu earthquake in 1995 and the Kobe earthquake in 1995 lead to destructive damage to the highway bridge.

2 Overview

Dynamic analysis is the main analysis in order to know the behavior of the structural subjected to earthquake excitation. Earthquake is classified as the non-periodical loading because the loading in irregular condition. The loading vary with time induced from ground motion. Ground motion is represented by the time history or seismograph in terms of acceleration, velocity and displacement for a specific location during an earthquake. Time history can be plotted in three dimension x , y and z . From the analysis, it can provide several informations that significant for design. For example, value of forces, moment and displacement will be obtained from the structural analysis. There are several methods in the dynamic analysis that suitable for the bridge structure under earthquake excitation. However, the time-history method was used in this study by using the actual earthquake time-history. The time-history method is a numerical step-by-step integration of equations of motion. It is usually required for critical or important or geometrically complex bridges.

Based on Powel [1], the selection of the analysis method is depending on the effective design decision. The selection must be suitable with complexity of bridge structure besides the local condition of the site. Therefore, for this study, time-history method of analysis is considered. This is because this study involving investigation of bridge element response in x , y and z direction subjected to Kobe earthquake time-history loading.

3 Transient Analysis

Since this study is related to the time-history analysis, it involved a method of analysis so called transient dynamic analysis. A transient dynamic analysis is a technique which is used to determine the time history dynamic response of a structure to arbitrary forces varying in time. On the right hand side of Eq. (1) any function for the load vector may be specified, i.e. $\mathbf{p}(t) = \mathbf{p}(t)$. This type of analysis yields the displacement, strain, stress and force time history response of a structure to any combination of transient or harmonic loads. To obtain a solution for the equation of motion (1) time integration has to be performed.

$$m\ddot{u}_t + c\dot{u} + ku = -mu_g \quad (1)$$

where k is the spring constant; \ddot{u}_t is the acceleration; \dot{u} is the velocity; u is the displacement; u_g is the ground acceleration; c is the damping ratio and m is the mass of dynamic system.

They can be broadly classified into implicit and explicit methods. Considering the stability of these two types of integration methods we notice that implicit methods are usually unconditionally stable which means that different time step sizes can be chosen without any limitations originating from the method itself.

Explicit methods on the other hand are only stable if the time step size is smaller than a critical one which typically depends on the largest natural frequency of the structure. Due to the small time step necessary for stability reasons explicit methods are typically used for short-duration transient problems in structural dynamics [2].

Based on the facts, implicit method has been used whereby there is no limitation to choose different time steps size for load vector input. The reason is because the load vectors input for this study represent the earthquake excitation with uncertainty different time step size.

Newmark's Method is used as numerical evaluation of dynamic response. This method is developed by N. M. Newmark in 1959. The method involved a family of time-stepping methods based on the following equations:

$$\dot{u}_{i+1} = \dot{u}_i + [(1 - \gamma)\Delta t]\ddot{u}_i + (\gamma\Delta t)\ddot{u}_{i+1} \quad (2)$$

$$u_{i+1} = u_i + [\Delta t]\dot{u}_i + \left[(0.5 - \beta)(\Delta t)^2 \right] \ddot{u}_i + \beta(\Delta t)^2 \ddot{u}_{i+1} \quad (3)$$

The parameter of β and γ define the variation of acceleration over a time step and determine the stability and accuracy characteristics of the method. Typical selection for γ is $1/2$ and $1/6 \leq \beta \leq 1/4$ is satisfactory from all points of view including that of accuracy. These two equations are combined with Eq. (1) at the end of the time step. It provide the basis for computing u_{i+1} , \dot{u}_{i+1} , \ddot{u}_{i+1} at time $i + 1$.

This method is very useful in order to determine the deformation response of the bridge structural element in x , y and z direction subjected to Kobe earthquake

Fig. 1 Girder falling in Lauhan bridge [4]



time-history loading. Newmark's Method is known as implicit method as the current time i is used at the end of the time step.

4 Earthquake Damage to Bridge

As bridge element is the vital link in transportation system, earthquake damage to bridge caused severe consequence. Therefore, understanding of the causes of damage is very important in order to overcome the damages through analysis and design consideration. Three general types of damages normally occur to the bridge due to the earthquake:

- a. Displacement in all direction (transverse, longitudinal and vertical)
- b. Exceeded reaction forces at connection system, and
- c. Inelastic structural response to the bridge components.

The most destructive of the bridge damages is the bridge deck collapse from the pier. Superstructures are designed to support service gravity load and lateral load for earthquake excitation. The superstructure is supported by bearing and pier. Superstructure consists of post stress beam and slab. The combination between those elements is called bridge deck. The bridge deck collapse or unseating from the pier and abutment is because of the relative displacement between bridge deck and pier. Figure 1 shows the example of how the bridge deck collapse.

The movement of the superstructure leads to failure of the bearing. When the bearing fails the superstructure tend to rotate and collapse. This can be seen as in Fig. 2 Nishinomiya-ko bridge bearing failure in the 1995 HyogoKen Nanbu earthquake.

Some bridges, the bearing is used to sustain with the force in one or two directions. At the same time it allows the movement in one or two direction. Therefore, when the bearing failed in an earthquake as in Fig. 3 it caused the

Fig. 2 Nishinomiya-ko bridge bearing failure in the 1995 HyogoKen Nanbu earthquake [5]



Fig. 3 The rubber bearing pad is dislocated [4]



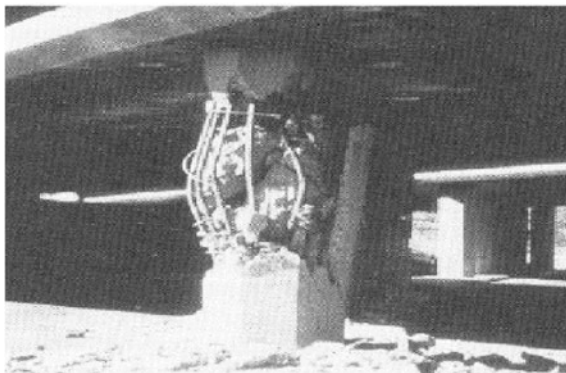
distribution of internal force between superstructure and substructure in unbalance condition.

The reinforcement ratio of stirrup is not enough, and the buckling of the main steel will result in the crushing of core concrete, then the pier could not be able support the upper loads from the bridge deck. This condition can be seen in Fig. 4.

5 Bridge Model

The existing bridge has been selected in order to investigate the capability of LRB that has been used in bridge subject to earthquake loading. The Kajang-Seremban Highway bridge is selected for this study to represent bridge model to conduct a linear dynamic time history. The bridge used Laminated Rubber Bearing which is

Fig. 4 Pier failure of viaduct in Northridge Earthquake [4]



aligned with this study to investigate the displacement of the LRB subjected to the Malaysia earthquake time-history loading. The bridge is selected also due to the availability of structural drawing and mechanical properties of structural elements.

The details of the bridge structural elements as in Fig. 5. The bridge is simply supported bridge using post stress beam. The abutment type is seat abutment. It is single span with length of 44,000 mm. However, the abutment is formed with column and crosshead beam. The Laminated Rubber Bearing is used with dimension 400×400 mm. The width of the deck is 15,300 mm where by it can be considered as R5 road geometry class. All the design consideration is based on BS 5400:2006.

The entire structural model is based on the existing bridge. The materials properties of the bridge as in Tables 1 and 2.

Kobe Time History loading was used in this study because the magnitude of quake is 7.0 M and availability of the earthquake data. The form of earthquake loads depends on the type of analyses. In this study, one synthetic sample of time history in x, y and z axis has been used. The data will be applied for the time-history analysis using Ansys software for this study. The time—history data is in acceleration versus time as in Fig. 6. The data is obtained from the Pacific Earthquake Engineering Research Centre (PEER).

6 Finite Element Analysis

The seismic analysis of Kajang—Seremban Highway is implemented by using Finite Element software in three dimensional modelling. All the structural members are used 3D solid element types hexahedral elements as in Fig. 6. The total Hexahedral elements that have been applied in the model are 67,000 elements (Fig. 7).

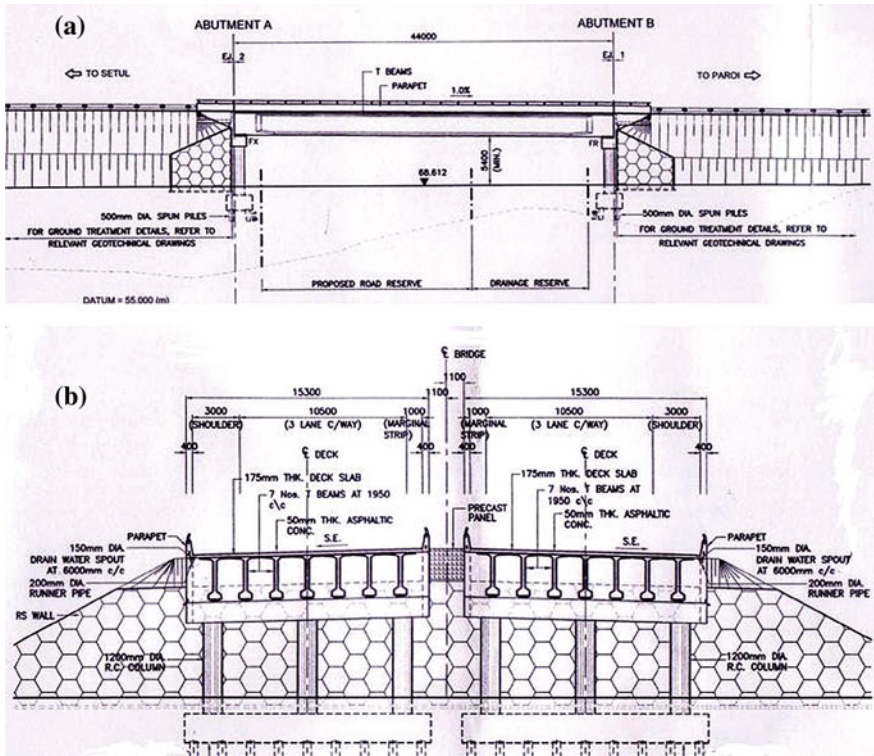


Fig. 5 The details of the bridge structural elements. a Elevation view. b Section view

Table 1 Material properties of each element in bridge model

Types of material	Young's modulus (kN/mm ²)	Poisson's ratio	Density (kg/m ³)
Post stress concrete	34	0.15	7,874
Rubber	0.01	0.4999	910
Reinforced concrete	31	0.15	2,400

All the elements in the model are using linear elastic properties. The bridge superstructure including the post stress beam and concrete deck were presented using linear elastic elements. Nominal properties were used for both post stress beam and concrete deck with the post stress beam having a modulus of elasticity of 34 kN/mm² and concrete deck having a modulus equal to 31 kN/mm².

Substructure elements were included in the computational models. Included in the substructure models were the abutment, column, crosshead beam and footing. Modulus of elasticity that has been assigned to the substructure elements is 31 kN/mm². The piles are not considered in this analysis. Fixed support is assigned at the bottom of footing. Soil—structure interaction was not considered at the behind of abutment since this study limited to the linear analysis.

Table 2 Laminated rubber bearing properties

Types	Dimension $L \times B \times t$ (mm)	Compressive stiffness (kN/mm)	Shear stiffness (kN/ mm)	Natural rubber thickness		Steel plate		Shape factor, S
				Inner slab t_1 (mm)	Outer slab t_0 (mm)	Nos	Thickness t_s (mm)	
Laminated rubber bearing	$400 \times 400 \times 50$	67	0.9	12	6	3	2	6.07

Fig. 6 Time-history Kobe earthquake

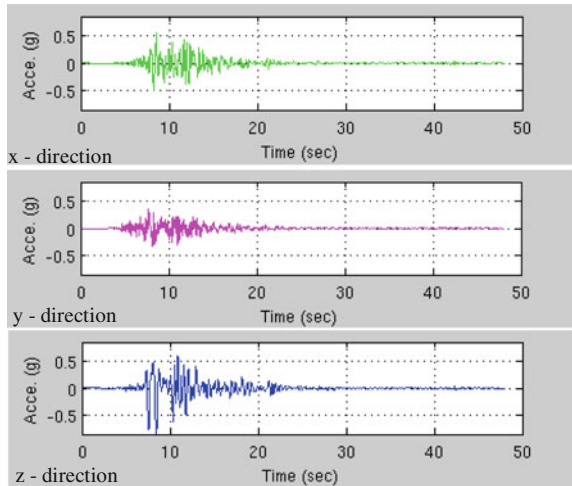
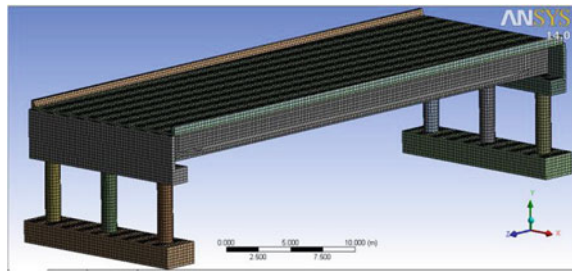


Fig. 7 Finite element modelling



Laminated Rubber Bearing also was modelled using solid element. The elastomer is modelled by using modulus of elasticity of 0.01 kN/mm^2 . While steel shims inside the elastomer using a modulus equal to 210 kN/mm^2 .

Figure 8 shown the numbers of degree of freedom is increased at the laminated rubber bearing in order to obtain the approximate result of the deformation under seismic loading.

Full transient analysis has been done in this study to define the behaviour of bearing under specified time history earthquake loading. However, modal analysis still needed in order to find the Rayleigh Damping for the bridge model. The purpose to conduct modal analysis is to obtain the natural frequency of the bridge and the mode shape. These two data are useful to find the value of Rayleigh Damping. Since the value of damping ratio is difference between of the other system or bridge therefore damping could be idealised as proportional to the stiffness of the structure. It is assumed that a portion of the energy is lost due to the deformation of the structure.

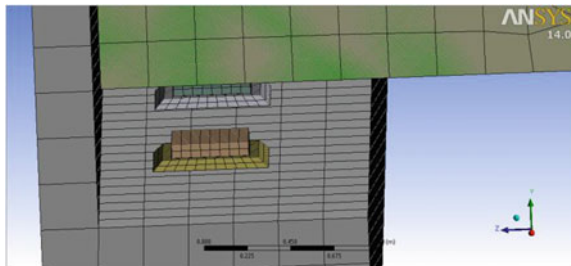
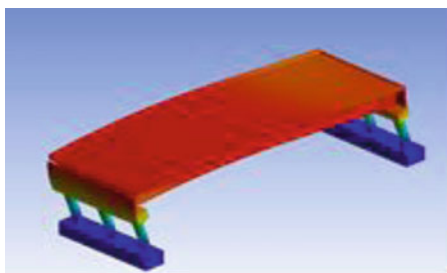


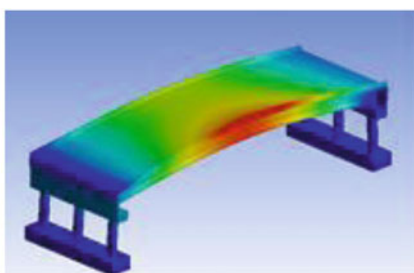
Fig. 8 Increasing discretisation of elements at the laminated rubber bearing

Table 3 Modes and frequency of the bridge

Modes	Frequency (Hz)
1	7.5756
2	8.1896
3	9.1494
4	12.153
5	16.176
6	16.344



Mode Shape 1



Mode Shape 2

Fig. 9 Mode 1 and 2

Damping is accounted for the model using 1.3 % [3]. Modal analysis was done by using Ansys software. The frequency and mode shape gave result as in Table 3. The analysis considered six modes. The shapes of the modes are as in Figs. 9, 10 and 11.

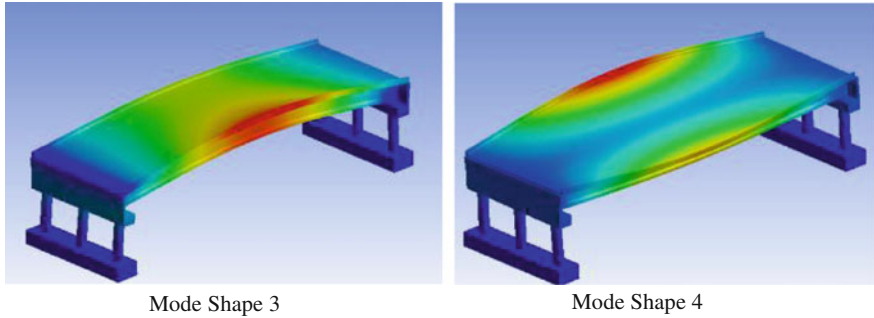


Fig. 10 Mode 3 and 4

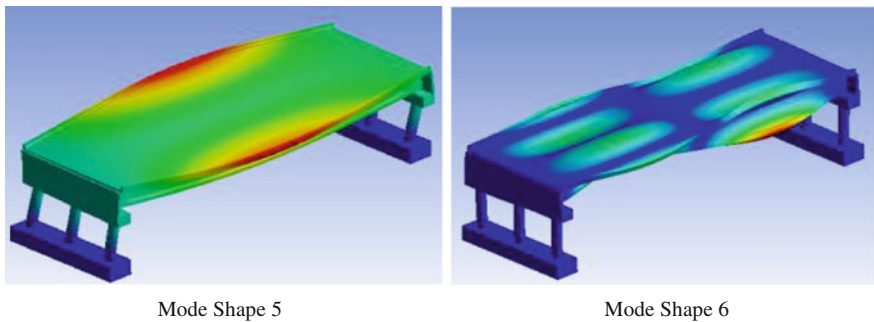


Fig. 11 Mode 5 and 6

7 Displacement Response

From the time-history analysis, displacement response of the bridge has been simulated. The graph displacement responses versus time were generated. Response of the bridge structural element can be observed from the graph based on the time-history earthquake excitation. It was found that the displacement response under Kobe is bigger since the bridge is not applied seismic design. The displacement response (in mm unit) of the laminated rubber bearing can be seen through the graph as in Fig. 12. The displacement in z direction gave the biggest value.

The maximum horizontal displacement is 381.29 mm under Kobe earthquake excitation. The Table 4 show the result has been obtained. The existing of LRB is designed to sustain with limit of displacement 34.92 mm in z direction. Based on the result, the LRB could not be able to sustain under the earthquake excitation (Fig. 13).

Laminated Rubber Bearing deformed to the maximum level under Kobe earthquake excitation. The deformation occurred due to the overturning of the structure.

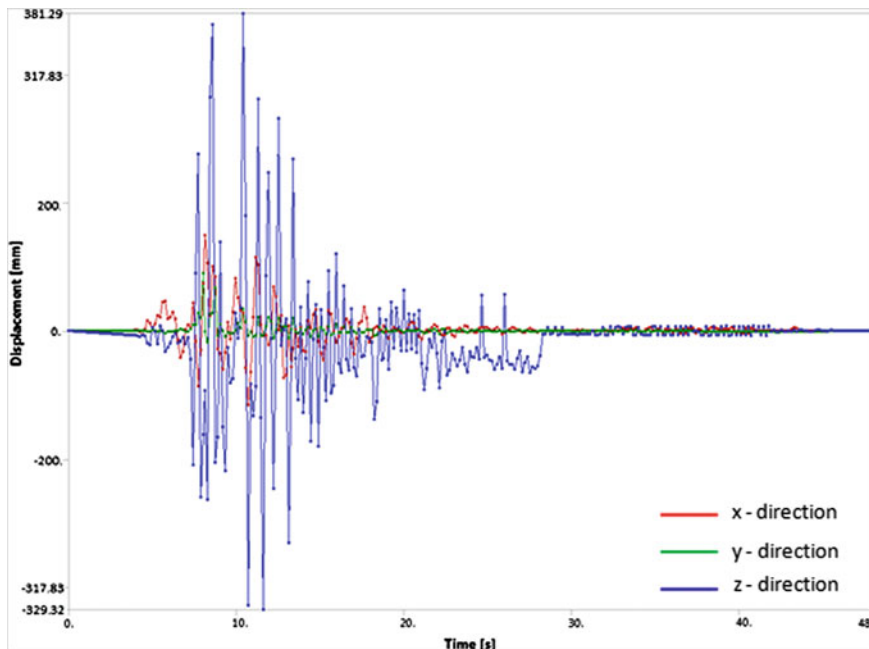


Fig. 12 Displacement responses of laminated rubber bearing subjected to Kobe earthquake time-history loading

Table 4 The result for the maximum displacement of the LRB in x, y and z direction subjected to Kobe earthquake loading intensity

Earthquake loading	Laminated rubber bearing displacement response (x-axis) (mm)	Laminated rubber bearing displacement response (y-axis) (mm)	Laminated rubber bearing displacement response (z-axis) (mm)
Kobe	189.46	101.23	381.29

It was also accompanied by the lateral shear exist between the steel plate and elastomer. Since the shear deformation is high it induce top of LRB to move upward by larger displacement. The LRB totally failed as the designed displacement value is only 1.59 mm in y-direction. The failure of the laminated rubber bearing will made the superstructure’s weight disable to provide a reasonable balance between shear force transmitted to the pier and displacement of the bridge deck. As a result the superstructure is dislocated or pounding from the abutment as in Fig. 1.

The Von Mises stresses is adopted to define the behaviour at pier. Time step at 10.4 s generates the high value of stress response. Based on Fig. 14, high stress occurred at the bottom of the pier. That was occurred when the laminated rubber bearing disable to provide a reasonable balance between shear forces transmitted to the pier and displacement of the bridge deck.

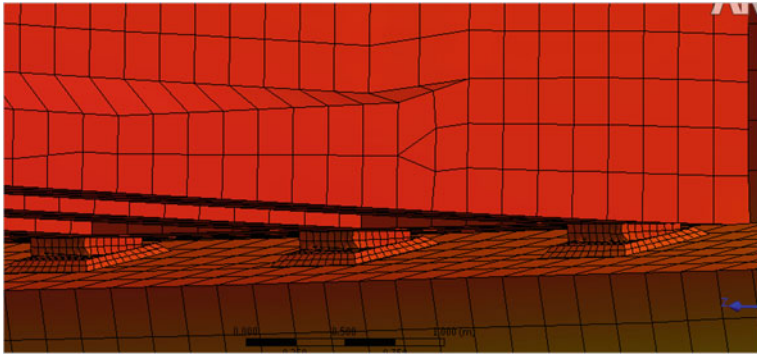


Fig. 13 The laminated rubber bearing deformed under Kobe earthquake excitation

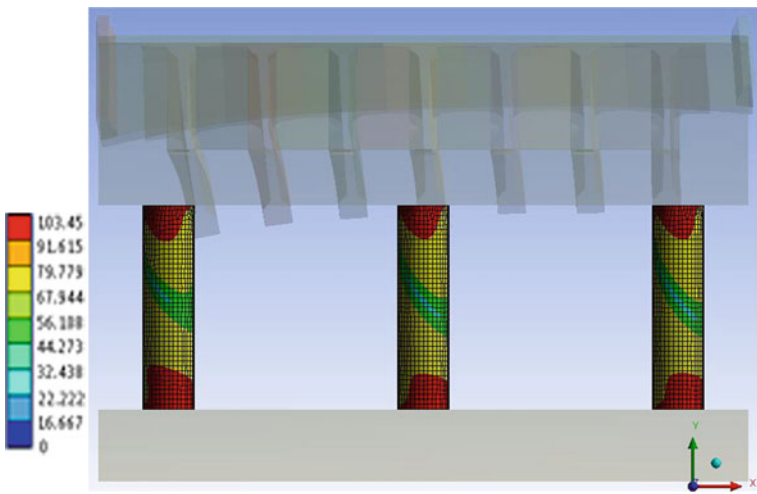


Fig. 14 Von Mises stress response (MPa) at pier subjected to Kobe earthquake at time step 10.4 s

8 Conclusion

A details study on rubber bearing is needed in earthquake engineering and bridge study to define the behaviour of bearing under ground motion. All direction of rubber bearing displacement can be studied by using 3D solid elements. A time-history analysis using Newmark's Method is very useful in order to obtain the response of rubber bearing and the whole structure for a specified time history of excitation.

From the analysis, several conclusions can be made regarding to the displacement behaviour of the rubber bearing such as listed below:

- a. The selected bridge can sustain under earthquake up to time step at 7.2 s.
- b. The maximum displacement of the laminated rubber bearing occurred at time step 10.4 s.
- c. The high stress of pier occurred at time step 10.4 s.
- d. The displacement of rubber bearing can be studied at specified time history earthquake loading through time history analysis.

Acknowledgments The authors wish to acknowledge the support of the University of Technology MARA (UiTM) and Faculty of Mechanical (UiTM). This work was done under the Exploratory Research Grant Scheme (ERGS), Ministry Higher Education Malaysia (MOHE). McMaster University.

References

1. G.H. Powell, Concept and principles for the application of nonlinear structural analysis in bridge design. Report No. UCB/SEMM-97/08, Department of Civil Engineering, University of California, Berkeley, 1997
2. E. Wang, T. Nelson, *Structural Dynamic Capabilities of Ansys* (CADFEM GmBH, Germany, 2002)
3. T. Katayama, A review of theoretical and experimental investigation of damping in structures. UNICIV Report No. 1–4, University of New South Wales, Sydney, Australia, 1965
4. W. Zhang, L. Yang, Analysis and inspiration on typical damage characteristic of bridges. *Appl. Mech. Mater.* **147**, 315–319 (2012)
5. W.F. Chen, L. Dan, *Bridge Engineering Seismic Design*, (CRC Press, Boca Raton, 2003)