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Seismic Response of a Base Isolated Cable-Stayed Bridge Under Near-Fault Ground Motion Excitations

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ABSTRACT

Nowadays, development of cable-stayed bridges is increasing around the world. The mitigation of seismic forces to these bridges are obligatory to prevent damages or failure of its structural members. Herein, this paper aimed to determine the near-fault ground motion effect on an existing cable-stayed bridge equipped with lead-rubber bearing. In this context, Shipshaw cable-stayed bridge is selected as the case study. The selected bridge has a span of 183.2 m composite deck and 43 m height of steel tower. 2D finite element models of the non-isolated and base isolated bridges are modelled by using SAP2000. Three different near-fault ground motions which are Tabas 1978, Cape Mendocino 1992 and Kobe 1995 were subjected to the 2D FEM models in order to determine the seismic behaviour of the bridge. The near-fault ground motions were applied to the bridge in the longitudinal direction. Nonlinear dynamic analysis was performed to determine the dynamic responses of the bridge. Comparison of dynamic response of non-isolated and base isolated bridge under three different near-fault ground motions were conducted. The results obtained from numerical analyses of the bridge showed that the isolation system lengthened the period of bridge and minimised deck displacement, base shear and base moment of the bridge. It is concluded that the isolation system significantly reduced the destructive effects of near-fault ground motions on the bridge.

Keywords: *cable-stayed bridges, seismic isolation, nonlinear dynamic analysis, seismic performance*

INTRODUCTION

Ground motions or earthquake cause severe problems to the structures such as dams, bridges, buildings, infrastructures and others [1–3]. In addition, many researchers had investigated the effect of earthquakes on the structures and attempted to mitigate the destructive force of earthquake through seismic control systems [4–7]. In recent years, cable-stayed bridges are the key in transportation networks, and gained popularity due to longer span, appealing aesthetics values, economical and faster construction [6]. These bridges are associated with high flexibility, low damping and long fundamental periods [8], which make them susceptible to high amplitude oscillation under earthquake ground motions [9]. Seismic response of structures under near-fault motion are different as compare to far-field ground motion [10].

The characteristics of near-fault ground motions are: i) large long-period spectral component in normal direction of fault; ii) large-short period spectral component, parallel to fault direction; iii) high peak ground velocities and long-duration pulses of ground displacement. Seismic response of structure under near-fault ground motions significantly increase as compare to typical far-field ground motion, which are the resultant of higher spectral components in near-fault ground motions. Several studies dealt with isolation techniques of cable-stayed bridges to improve their performance under earthquake excitation [11–14].

Cable-stayed bridges are highly sensitive under large amplitude long-period ground motions, also associate with multi modes in the dynamic responses, this make the use of seismic isolation obligatory to prevent the damages under near-fault ground motions and keep the bridge in service after the earthquake [15-16].

METHODOLOGY

Shipshaw Cable-stayed Bridge

Shipshaw cable-stayed bridge used for the case study is a double-plane fan-type cable bridge. It consists of a double leg steel tower and two box girders which support a composite steel deck as shown in Figure 1. Overall length of the bridge is 183 m with four identical spans and 4% downward slope from the East to the West abutment along deck. The bridge support is founded on rock. The tower bearings are hinged and allow to rotate along their axes. The abutment bearings are roller supported to prevent the uplifting force generated by the cable forces.

The deck is 11 m wide and composed of concrete deck thickness of 165 mm with two non-structural precast parapets. In addition, the deck is supported by five longitudinal stringers spaced equally at 2.4 m interval in longitudinal direction. Floor beams transfer the stringer loads to box girders and spaced equally at 7 m interval in transverse direction. The box girder dimension is 1.5 m x 2.4 m with web and flange thickness of 50 mm. The tower is 43 m tall with two 1.5 m x 2.4 m rectangular box steel with flange and web thickness of 50 mm. Steel Grade 330 is used for box tower and box girder. Four cables are connected from each tower to the top flange of box girders. Each cable consists of nine strands with each strand cross sectional area of 65.1 mm^2. The cables have the modulus of elasticity 175 GPa, yield strength of 1500 MPa and the ultimate strength of 1725 MPa [17].

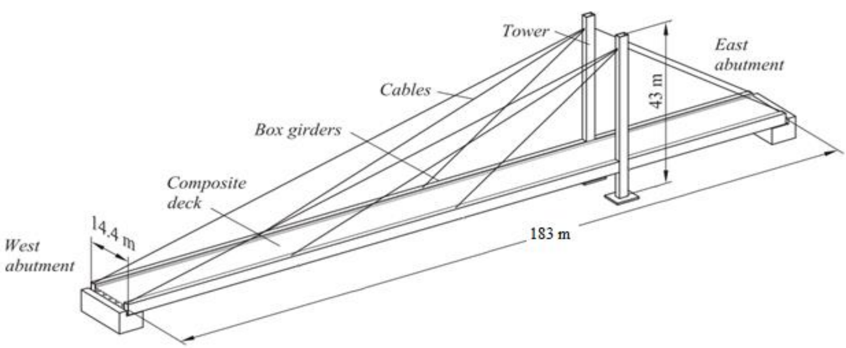


Figure 1: Detailing of Shipshaw Cable-stay Bridge

Numerical Modelling

The nonlinear dynamic response of non-isolated and isolated cable-stayed bridge subjected to longitudinal near-fault ground motions were performed in SAP2000. The bridge was modelled in two dimensions, consisted of one tower, one main box girder and four sets of cables as shown in Figure 2. Material properties used in the model are as described in previous section. The pretension forces in each cable is calculated based on the unit load method. The pretension force prevent the box girder from deflecting under its self-weight [18]. A lead rubber bearing is designed based on AASHTO specification [19-20]. The isolator device was placed at the base of pylon since the abutments are roller supporter and provide free horizontal movement of the deck. The initial stiffness of the lead rubber bearing is 15000 kN/m. The characteristics of the lead rubber bearing were input in SAP2000. Figure 3 shows the ideal force-deformation behaviour of the lead rubber bearing.

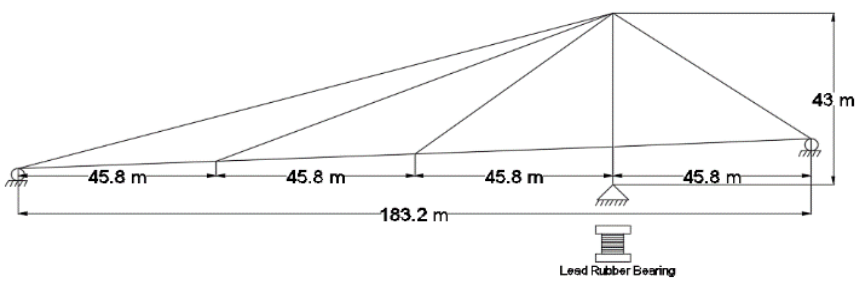


Figure 2: Bridge Model in SAP2000

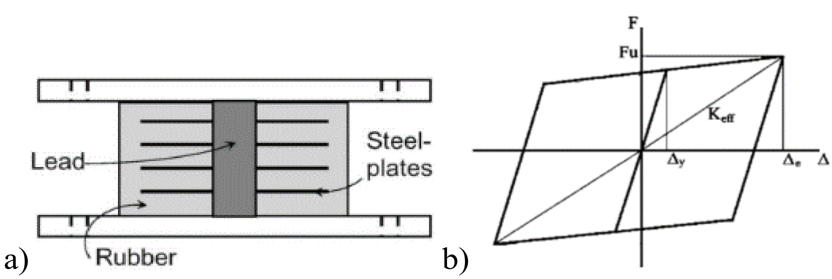


Figure 3: a) Schematic Diagrams and b) Ideal Force-Deformation Behaviour of the Lead Rubber Bearing

Near-fault Ground Motions

The seismic response of the cable-stayed bridge was studied using three near-fault ground motion records. The data and characteristics of these records are listed in Table 1 [21]. These near-fault ground motions are applied to the bridge in longitudinal direction only. A total time of ten seconds of each record was used.

Table 1: Main Characteristics of The Near-Fault Ground Motions Used in This Study [21]

No.	Earthquake name	Year	Magnitude	Distance (km)	Peak Acceleration	
					PGA (g)	Time (s)
1	Tabas	1978	7.4	1.2	0.900	10.66
2	Cape Mendocino	1992	7.1	8.5	0.655	3.60
3	Kobe	1995	6.9	3.4	0.575	4.66

NUMERICAL RESULTS AND DISCUSSION

Natural Time Period of Bridge

Table 2 shows the natural time period from the previous experimental investigation and the numerical analysis [22]. There is a reasonable agreement between three natural time periods of the longitudinal bending modes which are computed experimentally and numerically.

Table 2: Natural Time Period of Shipshaw Cable-Stay Bridge

Mode No.	Mode Type	T, Experimental (s)	T, Numerical (s)	Error (%)
1	Longitudinal bending	1.85	1.58	14.5
2	Longitudinal bnding	0.85	0.70	17.6
3	Longitudinal bending	0.57	0.43	24.5

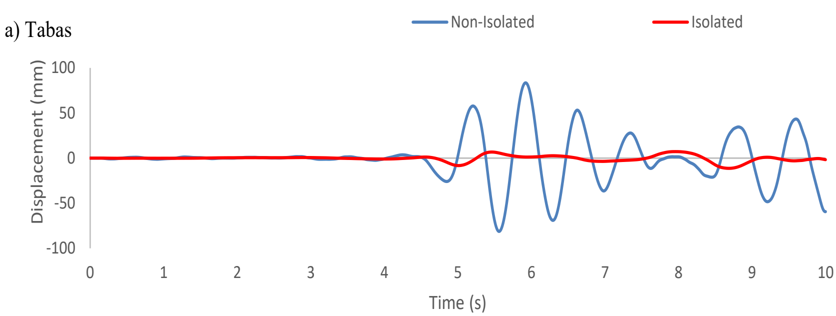
After the implementation of the base isolator in numerical model, the natural time periods are increased significantly, as shown in Table 3. In addition, the effective modal participating mass of the first mode became 98% of the total mass of the isolated bridge which makes the first longitudinal mode as governing mode of the bridge.

Table 3: Natural Time Period of Non-Isolated and Isolated Cable-Stayed Bridge

Mode No.	Period (s)	
	Non-Isolated Bridge	Isolated Bridge
1	1.58	5.50
2	0.70	1.68
3	0.43	0.75

Deck Displacement

The maximum horizontal relative displacements of the deck for three near-fault ground motions are shown in Figure 4. The relative deck displacements are taken at the node where the box girder and the tower intersected with each other. The maximum deck displacement in non-isolated bridge is 160.56 mm under Cape Mendocino ground motion. However, after the implementation of the isolation device, it is decreased to 30.10 mm. Figure 4 indicates that the based isolator device significantly reduced the deck displacements. In addition as shown, the oscillation of the deck displacement in isolated bridge is relatively smaller than that of the non-isolated bridge, which enhances the stability of the bridge under serviceablity during earthquakes.



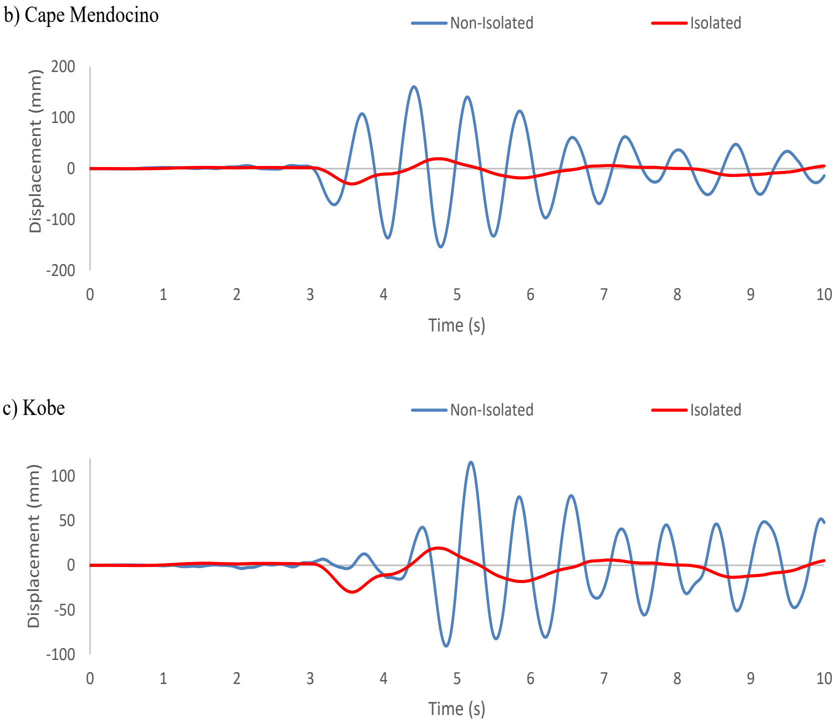


Figure 4: Deck Displacements Response Due to Near-Fault Ground Motions; a) Tabas; b) Cape Mendocino and c) Kobe

Tower Base Shear

The maximum base shear was computed at the tower support as shown in Figure 5. The base shear variation over total time of each earhquake is less varying and reduced significanlty. The maximum base shear is 10983.4 kN under Cape Mendocino ground motion for non-isolated bridge and after installation of isolator device, the base shear is reduced to 1666.03 kN. As resultant, the isolator significantly decreased the base shear force of the tower.

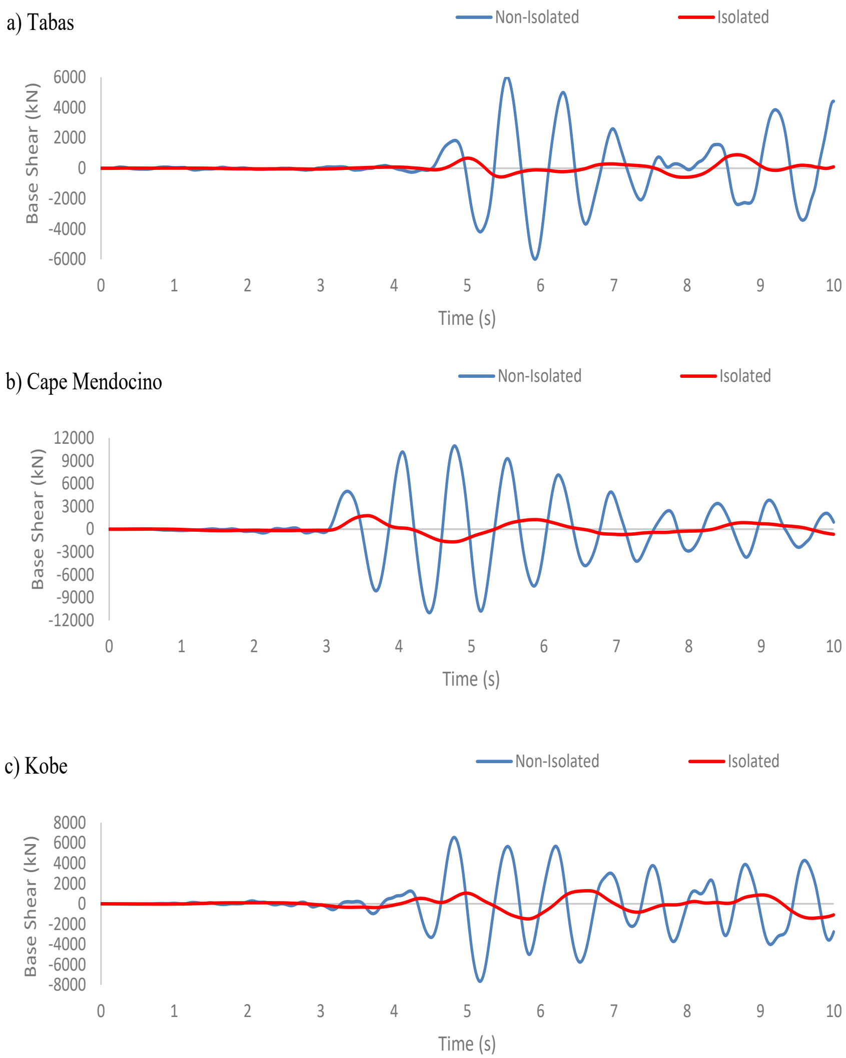


Figure 5 : Tower Base Shear Response Due to Near-Fault Ground Motions; a) Tabas b) Cape Mendocino and c) Kobe

Tower Bending Moment

The maximum bending moments of the tower for three near-fault ground motions are given in Figure 6. The maximum tower bending moments are taken at the deck level. The maximum of tower bending moments of non-isolated and isolated bridge are 0.69 kNmm and 0.1017 kNmm, respectively during Cape Mendocino earthquake. As indicated in the figure, the bending moment of the tower reduced significantly under all the ground motions when the base isolation is implemented.

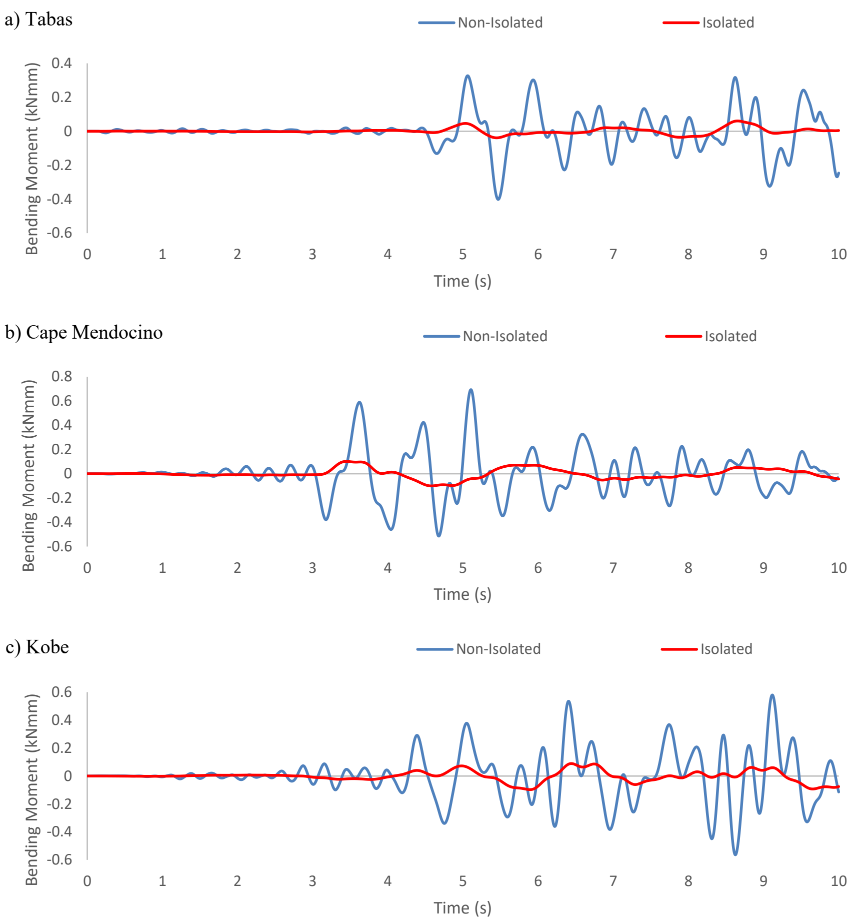


Figure 6: Tower Base Bending Moment Due to Near-Fault Ground Motions; a) Tabas b) Cape Mendocino and c) Kobe

As the comparative study, the overall seismic response of the bridge is summarised in Table 4. The percentage reduction of displacements for Tabas, Cape Mendocino and Kobe earthquake ground motions are 86.40%, 81.25%, and 73.96%, respectively. In addition, the base shear reduction percentage of the tower is 85.20%, 84.83%, and 80.56%, due to Tabas, Cape Mendocino and Kobe near-fault ground motions respectively. Furthermore, the bending moment of the tower reduced by 84.89%, 85.26%, and 83.24% under Tabas, Cape Mendocino and Kobe near-fault ground motions, respectively.

Table 4: Overall Peak Responses of The Bridge Under Different Near-Fault Earthquakes

Ground Motion	Bridge Configuration	Deck Displacement (mm)	Base Shear (kN)	Base Moment (kN-mm)
Tabas	Non-isolated	83.4	6029.5	0.401
	Isolated	11.3	891.9	0.061
Cape Mendocino	Non-isolated	160.6	10983.4	0.692
	Isolated	30.1	1666.0	0.102
Kobe	Non-isolated	115.7	7641.7	0.579
	Isolated	30.1	1486.1	0.097

CONCLUSION

In general, the base isolation system of the bridge is placed below the deck. Nonetheless, in this case study, the isolator device was implemented between the tower and foundation. The isolated and non-isolated cable-stayed bridge were modeled by using SAP2000. The nonlinear dynamic response of the bridge was performed to investigate the effectiveness of the isolation system. The main conclusions of this investigation are summarised as follows:

- Implementation of the isolation device lengthened the bridge time periods, hence, decreasing the transferred acceleration and the reduction of internal forces in the bridge.

- The horizontal deck displacement, base shear and bending moment of the tower decreased significantly, after the implementation of the base isolator in cable-stayed bridge.
- The lead-rubber bearing offered some advantages for the internal force on the base isolated bridge compare to non-isolated bridge.
- The isolated bridge remained elastic under all near-fault ground motions. This abled the bridge to remain in service after strong near-fault ground motions.

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