Comparison of Different Types of Pylon Shapes on Seismic Behaviour of Cable-Stayed Bridges

Chapter · January 2020

DOI: 10.1007/978-981-15-1404-3_7

3 authors:

Govardhan Polepally
Mahindra University

Venkata Dilip Kumar Pasupuleti
Mahindra University École Centrale School of Engineering

Archanaa Dongre
Veermata Jijabai Technological Institute

Comparison of Different Types of Pylon Shapes on Seismic Behaviour of Cable-Stayed Bridges

Govardhan Polepally, Venkata Dilip Kumar Pasupuleti and Archanaa Dongre

Abstract Cable-stayed bridges are the most flexible bridges and getting popularity because of its economy for longer spans and aesthetics. This study focuses on the effect of the shape of the pylon on the seismic response of cable-stayed bridge. For this study, complete geometry, material properties, loads and boundary conditions of the Quincy Bayview Bridge are considered from the past published literature. The bridge span dimension and other parameters are kept constant, and the only shape of the pylon is varied viz. A type, H type, inverted Y shapes. The height of the pylon is kept constant for all the numerical models for comparison purposes. The 3D bridge model is modeled using SAP 2000 software and analyzed for three earthquake ground motions Bhuj 2001, Loma Prieta 1989 and El Centro earthquake 1940. The seismic response of bridge at various locations are considered and compared. The study shows that the shape of the pylon has got great influence on the seismic behavior of cable-stayed bridge.

Keywords Quincy Bay view bridge · Cable-stayed bridge · Pylon shape · Time history analysis

1 Introduction

Cable-stayed bridges have gained a lot of popularity in the last few decades, especially in developed countries, though this practice has raised, there are few parameters like wind loads, seismic loads, impact loads and other natural dynamic loads are

G. Polepally (✉)
Vidya Jyothi Institute of Technology, Hyderabad, Telangana, India
e-mail: polepallygovardhan@gmail.com

V. D. K. Pasupuleti
College of Engineering, Mahindra Ecole Centrale, Hyderabad, Telangana, India
e-mail: venkata.pasupuleti@mechyd.ac.in

A. Dongre
Northcap University, Gurgaon, Haryana, India
e-mail: archanaadongre@ncuindia.edu

K. Ganesh Babu et al. (eds.), *Emerging Trends in Civil Engineering*,
Lecture Notes in Civil Engineering 61,
https://doi.org/10.1007/978-981-15-1404-3_7

still a concern to structural designers, maintenance and construction community. A few of the primary reasons for the increase of cable-stayed bridges all over the world are their structural efficiency, aesthetic appeal, enhanced stiffness compared to suspension bridges, ease of construction, large spans and small size of substructures. Primarly it would be of highest advantage were a large cantilever is needed for a span of the bridge and that point suspension bridge would be uneconomical. There are different types of cable-stayed bridges built based on variations like side-spar cable-stayed bridge, cantilever spar cable-stayed bridge, multi-span cable-stayed bridge, extra dosed bridge and cable-stayed cradle-system bridge apart from four classes of rigging on cable-stayed bridges harp, mono, star and fan. The structural components of a cable-stayed system behave in the following manner: The stiffening girder transmits the load to the tower through cables, which are always in the tension. The stiffening girder is subjected to bending and axial loading. The tower transmits the load to the cable-stayed bridges; their form and configuration depend on the way individual wires are assembled. A strand is generally composed of seven-wires, helically formed around a center wire and its diameter ranges from 3–7 mm. As cables are the most important elements in cable-stayed bridges; they carry the load from the super structure to the tower and to the backstay cable anchorages. In addition to high tensile strength, they must also have high fatigue resistance and corrosion protection. This study mainly focuses on the dynamic analysis of different types of pylon shapes of cable-stayed bridge to understand the effect of span length.

2 Literature

The concept of cable-stayed bridges was first proposed in the seventeenth century [1], however, the modern cable-stayed bridge began with the Stralsund Bridge, which was completed in 1956 in Sweden with a main span length of 183 m [2]. Cable-stayed bridges, due to their large dimensions and flexibility, usually experience long fundamental periods, aspect that makes the difference with respect to other structures, and of course, that affects their dynamic behavior. However, their flexibility and dynamic characteristics depend on several parameters such as the main span length, stay system and their layout, support conditions and many other things [3]. And modal analysis results on cable-stayed bridges are discussed in many papers, with emphasis on the seismic behavior. First vibration modes show a very long period, in the order of several seconds, and they are fundamentally deck modes. They are followed by cable vibration modes, coupled with the deck. The tower modes are usually of higher-order, which can be coupled with the deck depending on the support conditions. Undoubtedly, the modes are very difficult to separate when they are sufficiently coupled [4]. An exact analysis of natural frequencies and modal shapes on cable-stayed bridges is very important, not only for the study of the seismic response but also for wind action and traffic loads [5]. Shah et al., studied the seismic response of bridge considering different shapes of pylon and soil structure interaction [6]. Sarhang thesis mainly concentrated on comparison of three different types of cable stayed bridges using structural optimization and found to be very useful in optimization of complete structure [7]. Similarly, linear and non-linear dynamic analysis of cable stayed bridges were also carried out to understand the dynamic behavior and for possible failure locations [8, 9].

3 Modeling and Analysis

Cable-stayed bridge can be divided into three primary categories, cables, pylons and bridge deck. The Quincy Bay view bridge consists of 56 cables in two planes along the bridge deck, twenty-eight of them are in main span and the rest of the cables are in the side spans. The total length of the bridge is 541.8 m, the main span is 285.8 m and the two side spans are 128.1 m respectively as shown in Fig. 1a. The bridge deck is made up of concrete with thickness of 0.230 m and the bridge deck consists of two steel composite girders with the total height of 3 m. Two H type pylons support the bridge deck and the cables. The height of the pylons from the piers is 79 m and pylon also consists of two struts, the upper strut and lower strut. The lower strut supports the bridge deck. The cable connections at the pylons are starting at top of the pylons

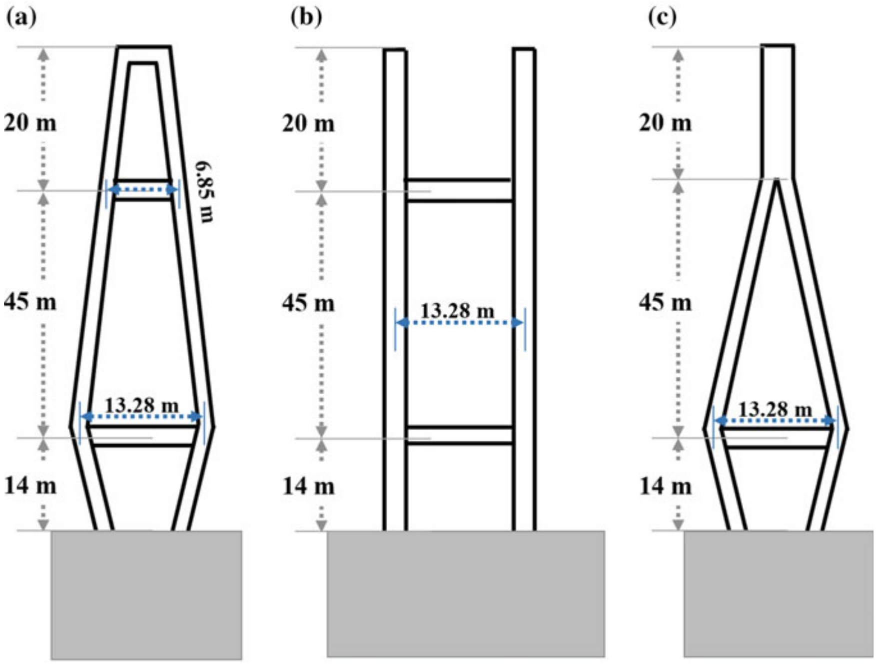

Fig. 1 Schematic diagram of 3 different types of pylon shapes of cable-stayed bridge **a** ‘A’ shape. **b** ‘H’ shape. **c** Inverted ‘Y’ shape

Table 1 Material properties considered for this study and same for all three scenarios

Bridge Parameter	Definition	Value
A_d	The cross-section area of the deck	2.806 m^2
$^E ds$	The modulus of elasticity of the deck	3.8e08 kN/m^2
$^E cs$	The modulus of elasticity of the cables	2.100e8 kN/m^2
$^F ue$	The effective tensile stress of the cables	4.9e5 kN/m^2
W_{cs}	The weight per unit length of the cables	76.9729 kN/m^2
E_c	The modulus elasticity of the concrete	3.8e7 kN/m^2
D	Diameter of the cable	0.146

and each cable is a parted by 2.5 m from the first cable. The lower ends of the cables support the bridge deck and the upper end of the cables connects at the top of pylon with fan type and diameter of the cable is 0.146 m. Rest of models are same as Quincy Bay view bridge but only difference is pylon shape, reaming all are constant including material and geometrical properties. Complete schematic diagram of the mentioned cable-stayed bridges are shown in Fig. 1 with dimensions. As for the modeling and analysis of the bridges, a finite element based software SAP2000 [10] is used. Most of the studies have similar software for effective and faster computations. Material properties assigned for different components explained above are given in Table 1. The bridge is assumed to be a composite structure consisting steel and concrete as prescribed in the past literature. Detailed sections modeled in SAP2000 for pylon and deck are mention in the Fig. 1. Boundary conditions at the bottom of the pylons are considered to be fixed and two edges of the bridge deck are considered to be simply supported. For modeling of cables, this study directly uses the cable element and their attachments to the pylon and deck are considered to be rigidly connected.

3.1 Case Studies

As discussed earlier, in this study three distinct cases have been considered with varying pylon shapes without changing other parameters.

4 Modal Analysis

Dynamics of any structure is governed by a simple equation of motion mention in the (Eq. 1), assuming the damping coefficient to be zero.

$$\mathrm{MU} + \mathrm{KU} = \mathrm{F}(t) = 0 \tag{1}$$

Above basic equation would give mode shapes based on the degree of freedom. Modal analysis is also very important in understanding the boundary conditions and modeling accuracy by seeing the frequencies obtained. Modal analysis is carried for three scenarios to calculate the frequencies and time periods. The obtained mode shapes for A shape, H shape and inverted Y shape pylons are shown in the Figs. 2, 3 and 4 respectively. And comparative modal analysis results for three cases are given in Table 2, where, column 1 represents mode shape number, column 2, column 3 and column 4 represents time period in seconds of A shape, H shape and inverted Y shape pylons respectively. Figure 5 shows developed three dimensional models with different pylon shapes.

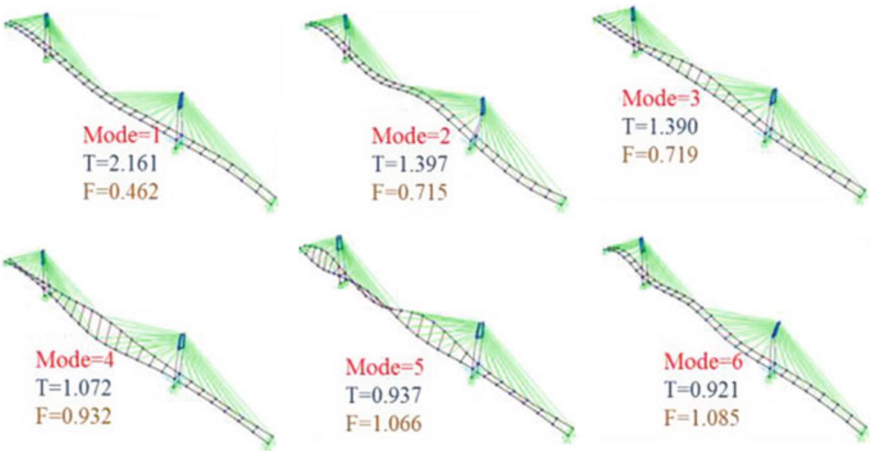

Fig. 2 First six mode shapes of A shape pylon cable-stayed bridge

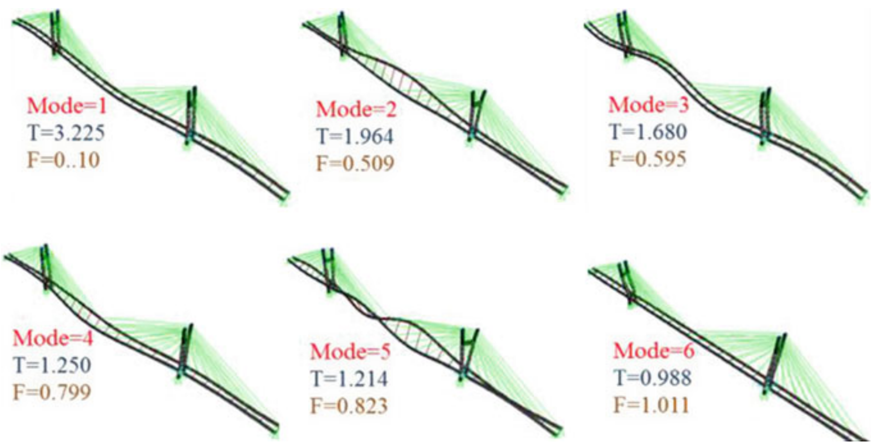

Fig. 3 First six mode shapes of H shape pylon cable-stayed bridge

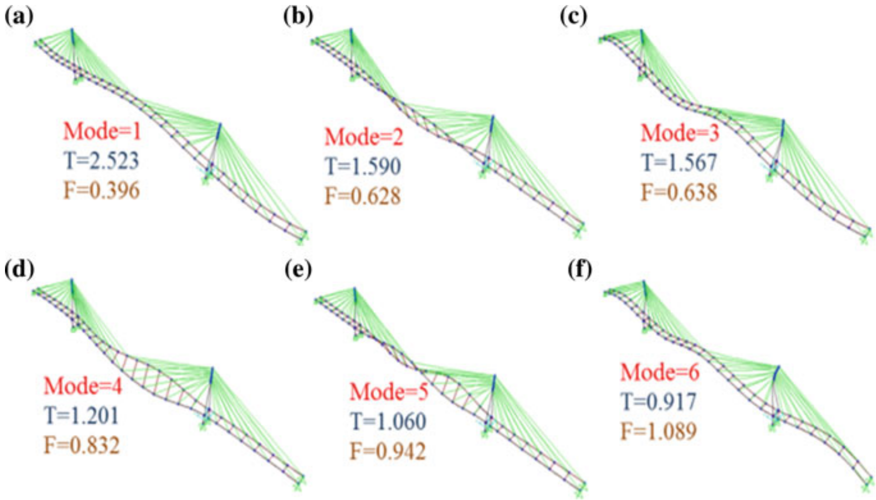

Fig.4 First six mode shapes of inverted Y shape pylon cable-stayed bridge

Table 2 Comparative time periods of different modes of three scenarios

Mode Shape No.	A Shape	H Shape	Inverted Y Shape
	Time Period (s)	Time Period (s)	Time Period (s)
1	2.16015	3.22565	2.5239
2	1.39768	1.96470	1.59021
3	1.39019	1.68051	1.56731
4	1.0729	1.25017	1.20145
5	0.93735	1.21440	1.06089
6	0.92124	0.98868	0.91754
7	0.86907	0.98807	0.85717
8	0.76588	0.93314	0.69984
9	0.75987	0.8324	0.67937
10	0.75891	0.79381	0.66509
11	0.67264	0.76301	0.64585
12	0.63634	0.65200	0.62510

Modal analysis play a vital role in understanding the possible behavior of any structure and its frequency or time period directly gives an ideal idea about the exactness of numerical model and its boundary conditions. In fact parametric studies are most needed for robust conclusions.

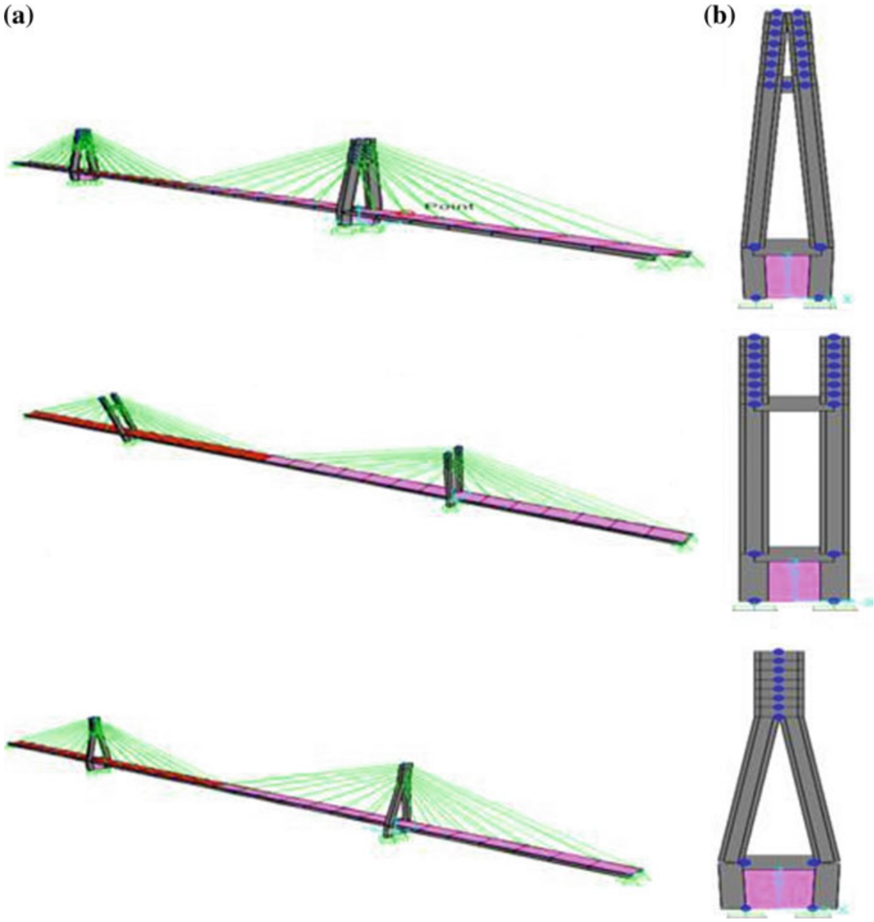

Fig. 5 Different views of developed 3D model of **a** 'A' shape. **b** 'H' shape. **c** Inverted 'Y' shape of cable-stayed bridge in SAP2000

5 Dynamic Linear Analysis

To understand the dynamic behavior of the bridge, three major earthquake ground motions of Loma Prieta, Bhuj earthquake and Elcentro earthquake ground motions have been considered, which are different in their nature of predominant frequencies. Dynamic linear analysis will give the basic idea in understanding the behavior of cable-stayed bridge under the action of wind or earthquake ground motions. This study mainly concentrated on understanding characteristic behavior using modal analysis and linear behavior is calculated using earthquake ground motions. Consideration of seismic effects in the design of any bridge is almost a mandatory step for long life of the structure. As long as all the components of the bridge are lower than the yield values, linear analysis is the most suitable analysis. Once the effects grow larger, geometric non-linear inclusion needs to be considered for large deformations and material non-linear to be considered for individual member failures. In this study P-Delta effect has been considered as the bridge can undergo very large deformations.

The following analysis results for three cases have been presented to discuss the effect of each earthquake ground motion on the three scenarios. Obtained results have showed different behavior than what is expected logically. This study has also limited itself to the discussion based only on the maximum displacements. For example, obtained plots are divided into ‘a’ and ‘b’. (a) Shows the time history response on top of the pylon in the ‘x’ and ‘y’ direction, whereas figure (b) shows the time history response at the mid of the deck in both the directions.

5.1 Behavior Due to Loma Prieta Earthquake Ground Motion

Loma Prieta earthquake has occurred on the San Andreas Fault system and has generated peak acceleration of 0.65 g at the epicenter. This ground motion was applied to all the three case studies and obtained responses at the mid of the deck and top of the pylon are shown in the Fig. 6a, b, respectively and respective peak values at both mid of the deck and top of the pylon for three cases are presented in Table 3, where third, fourth column represent maximum responses at mid and fifth, sixth column represents at the top of pylon.

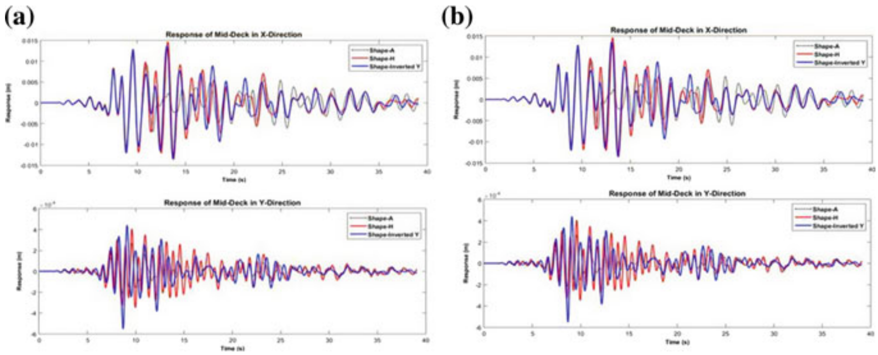

Fig. 6 Response of the bridges suspected to Loma Prieta earthquake ground motion **a** at the mid of the bridge deck. **b** at the top of pylon

Table 3 Maximum responses for Loma Prieta earthquake ground motion of the cable-stayed bridges at the mid of the deck and at the top of the pylon for three scenarios

Case	Loma U_x	Loma U_y	Loma U_x	Loma U_y
	(m)	(m)	(m)	(m)
A Shape	0.012	0.01048	0.01048	0.00269
H Shape	0.01466	0.01298	0.01298	0.00293
Inverted Y shape	0.01365	0.0062	0.0062	0.00335

5.2 *Behavior Due to Bhuj Earthquake Ground Motion*

One of the most powerful earthquakes occurred on 26 January 2001 of magnitude 7.9 in India and resulted in lot of research thereafter. This earthquake has not only damaged the traditional mud and masonry structures but also new reinforced concrete structures that were constructed questioning the durability of ongoing construction practices. Figure 7 shows the responses of three different pylon shape bridges subjected to Bhuj earthquake ground motion and in Table 4, column 2, column 3 represents the peak values obtained at the mid of the deck and column 4, column 5 represents peak values obtained at the top of the deck.

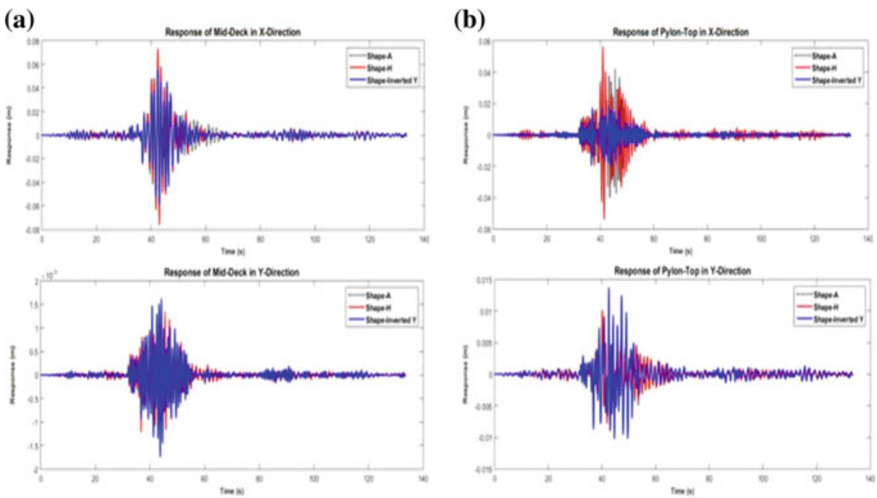

Fig. 7 Response of the bridges suspected to Bhuj earthquake ground motion **a** at the mid of the bridge deck. **b** at the top of pylon

5.3 Behavior Due to El Centro Earthquake Ground Motion

El Centro earthquake was one of the devastating earthquakes in 1940 and affected the USA and Mexico. The north–south component ground motion is considered and applied to all the three scenarios, obtained responses at the mid of the are shown in Fig. 8a and responses obtained at the top of the pylon are shown in Fig. 8b. Table 5 shows the peak responses obtained at the top of the pylon and Table 6 shows the peak values obtained at the mid of the deck.

Table 4 Maximum responses for Bhuj earthquake ground motion of the cable-stayed bridges at the mid of the deck for three scenarios

Case no.	Bhuj U_x(m)	Bhuj U_y(m)	Bhuj U_x(m)	Bhuj U_y(m)
A Shape	0.04796	0.00111	0.04222	0.01108
H Shape	0.07346	0.00135	0.05673	0.01164
Inverted Y shape	0.0556	0.00163	0.01881	0.01383

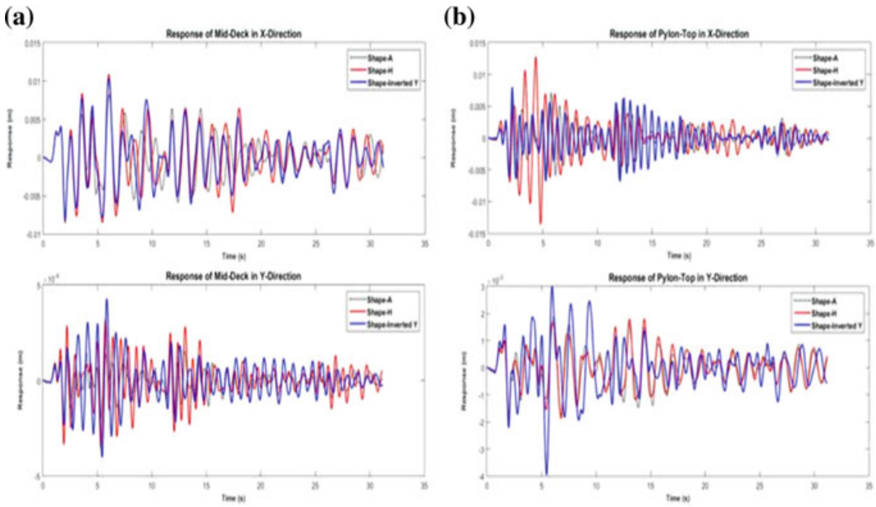

Fig. 8 Response of the bridges suspected to El Centro earthquake ground motion **a** at the mid of the bridge deck. **b** at the top of pylon

Table 5 Maximum responses for El Centro earthquake ground motion of the cable-stayed bridges at the top of the pylon for three scenarios

Case	El Centro U_x(m)	El Centro U_y(m)
A Shape	0.00825	0.000207
H Shape	0.0109	0.000322
Inverted Y shape	0.01033	0.000428

Table 6 Maximum responses for El Centro earthquake ground motion of the cable-stayed bridges at the mid of the deck for three scenarios

Case	El Centro U_x(m)	El Centro U_y(m)
A Shape	0.00825	0.000207
H Shape	0.0109	0.000322
Inverted Y shape	0.01033	0.000428

6 Conclusions

Civil engineering projects always have a shortcoming of understanding through actual scaled experimental models either due to their scale, cost or time taking process. So, largely numerical models play a vital role due to their ease in modeling, computations and faster parametric studies. In this study, the most important key design considerations for cable-stayed bridges under gravity loads and earthquake loads are discussed. The numerical model of a cable-stayed bridge is formulated for single plane of cables with global coordinates for bridges having three different pylon shapes. Different parameters are considered to get the influence of the principal characteristics which are layout of the stays, the inertia of deck and pylons.

Few key observations from this study are time period of the bridge with A-shaped pylon is less when compared to other two pylon shapes, and inverted-Y shaped pylon have a larger time period. And as the numbers of cables are increased, the time period has also increased, but the difference in time period between 6 cables and 7 cables is very high compared to increase in time period between 7 cables and 8 cables bridge for all kinds of pylon shapes. And from time history analysis, the maximum responses obtained for all the bridges are dependent on the type of ground motion they are subjected to. It is observed that the Inverted-Y shape pylon bridge has less response for Loma and Bhuj ground motion, whereas A-shape pylon bridge has less response for Elcentro earthquake when compared other pylon-shaped bridges.

References

1. Leonhardt, F., & Zellner, W. (1991). Past, present and future of cable-stayed bridges. In M. Ito, Y. Fujino, T. Myiata, & N. Narita (Eds.), *Cable-stayed bridge: Recent development and their future* (pp. 1–33). New York: Elsevier.
2. Hongwei, C., & Amjad, J. A. (2014).Three-dimensional geometric nonlinear analysis of composite cable-stayed bridges using a refined double-beam model. *Journal of Bridge Engineering*, *19*(6), 04014017.
3. Walther, R. (1999). *Cable-stayed bridges* (2nd ed.). London, UK: Thomas Telford.
4. Morgenthal, G. (1991). *Cable-stayed bridges—Earthquake response and passive control* (MSc dissertation). Civil Engineering Department, Imperial College of Science, Technology and Medicine, London, UK.
5. Valdebenito, G. E., Aparicio, A. C., & Alvarez. J. J. (2012). Seismic response of cable-stayed bridges for different layout conditions: A comparative analysis. In *Proceedings of 15th world conference on earthquake engineering*. Lisboa, Portugal.

6. Shah, S. G., Desai, J. A., & Solanki, C. H. (2010). Effect of pylon shape on seismic response of cable stayed bridge with soil structure interaction. *International Journal of Civil & Structural Engineering*, *1*(3), 667–682.
7. SarhangZadeh, O. (2012). *Comparison between three types of cable stayed bridges using structural optimization* (Electronic Thesis and Dissertation Repository. Paper 897).
8. Egeseli E. A. (1975). *The nonlinear dynamic response of a cable stayed girder bridge to various loadings* (Ph.D. Dissertation), Department of civil engineering, university of Pittsburgh.
9. Fleming, J. F., & Egeseli, E. A. (1980). Dynamic behavior of a cable stayed bridge. *Journal of Earthquake Engineering and Structural Dynamics*, *8*(1), 1–16.
10. Computers and Structures. (2007). *SAP2000 V. 18.0—Integrated software for structural analysis & design*. Berkeley, CA.