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Original Research Article

Seismic response characteristics of a base isolated cable-stayed bridge under moderate and strong ground motions

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ABSTRACT

In this study, the seismic behavior of an existing steel cable-stayed bridge equipped with lead-rubber bearing subjected to moderate and strong earthquakes is investigated. The bridge is located at high seismic zone and experienced an earthquake in 1988 which caused the failure of one of its anchorage plate of the support. Herein, the bridge was modeled in three dimensions and the base isolators implemented at the abutments and deck-tower connection. The bridge seismic responses were evaluated through nonlinear dynamic time-history analysis. The comparative analysis confirmed that the base isolation system was an effective tool in reducing seismic force transmit from substructure to superstructure. Furthermore, the overall seismic performance of cable-stayed bridge significantly enhanced in longitudinal and transverse directions. However, it is observed that the axial force of the tower in substructure increased due to the isolation system induced torsional deformation to the superstructure under transverse seismic loads.

1. Introduction

In recent years the application of cable-stayed bridges has risen significantly around the globe due to their advantages, i.e. appealing esthetics, longer span length, light weight and small structural members and efficient in load resistance. However, they are characterized by longer natural time period and low structural damping which make them highly flexible and susceptible to large amplitude oscillation under seismic loadings [1,2]. They are required to stay in service after earthquakes for emergency cases. Several researches have studied the static and dynamic behavior of cable-stayed bridges [3–8]. Wang and Yang [9] elaborated that the main sources of geometric nonlinearity in cable-stayed bridges, which were the beam-column effect, the cable sag effect and the large displacement effect (P-delta). The cable sag effect led to substantial nonlinearity in cable-stayed bridges. These identified nonlinearities were highly influenced on the dynamic performance of cable-stayed bridges. Au et al. [10] developed the constitutive model for the cables for determination of natural frequencies and modes shapes of the bridge accurately. The deck connection between tower and piers greatly affected the seismic performance of the cable-stayed

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List of notation

A, β, γ	dimensionless quantities
B_L	damping coefficient
d	initial displacement
d_{isol}	isolator displacement
d_{sub}	substructure displacement
d_y	isolator yield displacement
F_i	force mobilized in isolators in the i direction
F_{isol}	isolator shear force
f_y	steel tensile stress
f'_c	compressive strength of concrete
F^Y	yield force
k_d	post-yield stiffness of isolator
K_{isol}	effective stiffness of isolator
K_u	loading and unloading stiffness (elastic stiffness)
PGA	peak ground acceleration
Q_d	characteristics strength
S_{D1}	design spectral displacement
T_{eff}	effective time period
$U_{2,3}$	bearing displacement in the 2 and 3 directions
$U_{X,Y,Z}$	support translation in the X, Y and Z directions
W	superstructure weight
Y	yield displacement
$Z_{2,3}$	hysteretic dimensionless quantity in the 2 and 3 directions
α	ratio of post-yield stiffness to pre-yield stiffness
ξ	viscous damping

bridges [3]. The rigid connection of deck and tower limited the horizontal deck displacement under earthquake excitation and led to transmission of forces from superstructure to substructure, and hence increased the base shear of the tower [11,12]. On the other hand, the movable or floating configuration had higher deck flexibility and enlarged the horizontal deck displacement under service loadings [13]. In addition, shape and height of the tower, substantially affected the dynamic response of the cable-stayed bridge [7,14,15].

Seismic control of the cable-stayed bridge has brought several authors attention [16–19]. Ali and Abdel-Ghaffar [16] constructed the constitutive model for passive seismic control of a cable-stayed bridge, in order to optimize the mechanical properties and location of the bearings. The passive control system could be used as an alternative in retrofitting strategy for the exiting cable-stayed bridges [19]. Wesolowsky and Wilson [20] evaluated the base shear reduction of isolated cable-stayed bridges for near-field ground motions and also stated that the characteristics of near-field ground motions have to be consider when the base isolators are designed. Seismic isolation is an effective tool for protection of new or retrofit of existing bridges as the isolation retrofitting is found to be more economical than conventional retrofitting of bridges in seismic zones [21,22]. Nonetheless, there is a lack of research on the seismic response behavior of isolated cable-stayed bridges with unique characteristics such as geometry irregularity and elevation difference of abutments [23–25].

This paper attempts to investigate the seismic behavior of an existing steel cable-stayed bridge equipped with base isolators under bidirectional moderate and strong earthquakes. The bridge experienced an earthquake of $M_L = 6.0$ magnitude in 1988 with peak ground acceleration (PGA) of $0.15 \times g$ in horizontal direction. It was confirmed that one of the four anchorage plates which connected the steel box girders to the abutment failed due to high stress concentrations under dead load and stresses produced by seismic loads [26,27]. The bridge was closed immediately for repairing. Furthermore, this bridge is characterized by its asymmetric geometry and 7.3 m elevation difference between the West and the East abatements. Hereupon, the base isolation system is utilized to protect the superstructure from seismic loads and minimized the damage to the bridge. In line with this, the lead-rubber bearings (LRB) are implemented at abutments and deck-tower connection. The isolators are designed based on AASHTO [28,29] and with bidirectional interaction. Full scale three-dimensional (3D) finite element (FE) model of the bridge is developed with all source of nonlinearities and then verified with the previous field experiment for consistency. The nonlinear seismic behavior of the bridge is studied through time-history analysis in longitudinal and transverse directions.

2. Methodology

2.1. *Description of Shipshaw cable-stayed bridge*

Shipshaw bridge is a non-symmetric double-plane fan-type cable-stayed bridge over Saguenay River near Jonquiere Quebec. The bridge is consisted of a double leg steel tower and two parallel box girders supporting a composite deck. The bridge has four identical spans of 45.8 m with a total length of 183.2 m. Further, the bridge has 4% downward slope from the East to the west abutment. The bridge support system is founded on rock. The tower bearings are hinged and allowed to rotate in transverse axis. The abutment bearings are roller supported which only allow the longitudinal movement and prevent the uplifting of the deck which is generated by cable forces. Meanwhile, the deck-tower connection is considered as a rigid connection.

The deck with 11 m breadth is made of concrete deck with thickness of 165 mm and has two non-structural precast parapets at each side. Furthermore, the deck is supported by five longitudinal stringers which placed equally at 2.4 m interval. Floor beams are spaced at 7 m interval in transverse direction. The floor beams transfer the stringer loads to box girders. The box girder dimension is 1.5 m $\times$ 2.4 m with web and flange thickness of 50 mm. The tower height is 43 m which consisted of two 1.5 m $\times$ 2.4 m steel boxes with flange and web thickness of 50 mm. Four cables are connected from top of the tower to the box girders. Each cable consists of nine strands with cross-sectional area of 65.1 mm^2. The detail of the bridge is shown in Fig. 1.

2.2. *Numerical bridge modeling*

Since cable-stayed bridges are complex structures with high degree of redundancy and have a large number of degrees of freedom [6,7,30], the simplification of the model leads to