Engineering Structures 99 (2015) 232–252

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A case study on the application of passive control and seismic isolation techniques to cable-stayed bridges: A comparative investigation through non-linear dynamic analyses

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ARTICLE INFO

Article history:
Received 30 September 2014
Revised 16 March 2015
Accepted 28 April 2015
Available online 18 May 2015

Keywords:
Cable-stayed bridges
Dampers
Seismic isolation
Passive control
Strength degradation
Non-linear dynamic analysis
Seismic performance
Supplemental damping

ABSTRACT

This paper investigates the seismic performance of an existing steel cable-stayed bridge located in a high seismic zone. In 1988 the structure experienced the failure of one of its anchorage plates needing closure and structural repair as a consequence of seismic activity. In this study, the possibility of retrofitting the original bridge with different passive supplemental damping and seismic isolation systems is proposed and assessed, in order to improve the response of the structure in its longitudinal direction. To this end a Finite Element model of the bridge is developed and the structural response is evaluated through non-linear dynamic response analyses under a set of historical ground motions of different intensities, including a near field record. Strength degradation capabilities are introduced in the model, allowing the occurrence of brittle failure in all the members. Seismic performance indices referred to the dynamic response of the unretrofitted structure and to the results of a pushover analysis are defined and used to compare the proposed innovative solutions. The major improvement on the overall response of the bridge is shown and conclusions regarding the most appropriate retrofit alternative for the particular case study are determined.

1. Introduction

In the last decades cable-stayed bridges have gained popularity throughout the world for spans up to approximately 1 km due to their appealing aesthetics, fast construction, efficient use of structural materials leading to small structural members and light appearance, and increased stiffness when compared to suspension bridges. This type of structure, characterized by a long fundamental period, large flexibility, light weight and low structural damping [1,2], is quite vulnerable to large amplitude oscillations when excited by earthquake ground motions [3–6]. A number of studies have been performed in the past related to the seismic behaviour of cable-stayed bridges [5,7–9]. The seismic response of a cable-stayed bridge depends to a great extent on how the bridge deck is connected to the tower and the piers. Rigid connections limit the deck horizontal displacements under earthquake action but unavoidably increase the transmitted forces between the superstructure and the substructure. There is a general agreement in the convenience of permitting certain relative movement of the deck at the pier and tower locations, to reduce the internal forces at the base of these elements but, due to the low inherent damping, important horizontal displacements are to be expected in that location. This behaviour suggests seismic control techniques, i.e. passive, active or semi-active control, as possible alternatives to improve the performance of cable-stayed bridges under strong earthquake ground motions [10].

This particular study is focusing on an existing metallic 183 m long cable-stayed bridge located in a high seismic zone (Fig. 1). A past inspection of the bridge revealed the complete failure of one of the four anchorage plates connecting the deck steel girders to one abutment. The bridge was closed and immediately repaired. The investigation that followed this event [11,12], confirmed that the failure had been the result of a $M_L = 6.0$ magnitude earthquake, during which peak horizontal ground accelerations of approximately 0.15 g were recorded in the epicentral region. The original rigid welded connection of the bridge tower to the box girder at the deck level, along with the high levels of longitudinal vibration evidenced from previous studies, suggest that the introduction of supplemental dampers, the application of base isolation

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http://dx.doi.org/10.1016/j.engstruct.2015.04.048
0141-0296/

Fig. 1. Bridge under study.

techniques or a combination of both could effectively improve the seismic performance of this particular bridge structure.

In a mitigation design (or redesign) context, two main objectives are pursued: (i) to increase the structure fundamental period, and therefore reduce the spectral acceleration demand levels and, (ii) to enhance the energy dissipation capabilities of the bridge and, thereby, increase damping. In this regard, three approaches may be adopted: (i) introducing dampers that, taking advantage of the structure motion during the earthquake, transform the input seismic energy into heat i.e. fluid viscous dampers (FVDs), metallic or friction dampers (MDs, FDs), shape memory alloys (SMAs); or into kinetic energy i.e. tuned mass dampers (TMDs); (ii) isolating totally or partially the bridge deck from the substructure, leading to minimum member forces but maximum deck horizontal displacements; or (iii) a combination of (i) and (ii) which would take the advantages of seismic isolation but while also controlling the level of displacements through supplemental damping. In this particular study, passive devices with and without isolation systems are considered, as opposed to active or semi-active techniques, as they do not require external energy and therefore, if properly installed and maintained, may constitute reliable, robust, simple and economic alternatives.

The first studies dealing with the application of seismic isolation techniques to improve the seismic performance of cable-stayed bridges were conducted by Ali and Abdel-Ghaffar [2,3]. The authors evaluated the seismic isolation of cable-stayed bridges using elastomeric and lead-rubber bearings (LRBs), focusing on the devices most appropriate constitutive models for analysis and their optimal location and mechanical properties. Constantinou et al. [13,14] proposed and evaluated experimentally a seismic isolation system for bridges consisting on multidirectional Teflon disc bearings and displacement control devices. The former accommodated thermal movements and provided isolation while the latter introduced a restoring force for re-centring the bridge during the earthquake and for providing additional energy dissipation capacity and rigidity for service loading. Iemura and Padrono [15] investigated the seismic performance of a cable-stayed bridge isolated by means of elastomeric and hysteretic bearings, incorporating passive linear and semi-active dampers. Casciati et al. [16] evaluated the dynamic performance of the ASCE benchmark problem of a cable-stayed bridge isolated with elastomeric LRBs by means of fragility curves. Weselowsky and Wilson [17] examined the seismic response of cable-stayed bridges isolated by means of LRBs under the action of near field earthquake records. The authors concluded that there is an optimal amount of isolation that will maximize the benefits of reducing seismic forces and limiting the seismically-induced displacements. Soneji and Jangid [18] compared the effectiveness of three systems i.e. high damping rubber bearings (HDRBs), LRB and a friction pendulum system (FPS) on the isolation of cable-stayed bridges, finding the optimal amount of yield strength of LRBs and frictional coefficient of FPS leading to the maximum reduction in the tower base shear, while keeping the maximum displacement of the superstructure to a minimum. They also proposed to combine isolation techniques with passive dampers to enhance the control of the maximum displacement in isolated structures.

Apart from the studies dedicated to seismic isolation, other works have been conducted on the introduction of passive control systems with and without seismic isolation. In particular, regarding the application of metallic or friction devices, Nihihara et al. [19] analysed the seismic performance of cable-stayed bridges retrofitted with yielding MDs, considering different deck-tower connections. The authors detected an important reduction of the maximum displacements in the harp cable-system arrangement case. Vader and McDaniel [20] compared the effectiveness of FDs and FVDs with that of a new shear-link protection system for cable-supported bridges. More recently, Camara [5] investigated the possibility of introducing yielding MDs to control the transverse response of the towers in cable-stayed bridges.

As for the effectiveness of improving the seismic performance of cable-stayed bridges with passive FVDs, most of the limited studies done in this regard considered hybrid control systems as well. That is the case of Soneji and Jangid [21], who compared the seismic performance of cable-stayed bridges with isolation systems with and without passive hybrid systems, combining elastomeric or sliding isolation systems in association with FVDs. He and Agrawal [22] evaluated the effectiveness of passive FVDs and a hybrid control system, consisting of passive FVDs installed in parallel with semi-active dampers under a large number of near field records. The semi-active dampers are only triggered in the case of short duration pulses in order to protect the passive dampers, resulting in a hybrid system quite capable of reducing peak response quantities of the bridge. Valdebenito [23] analysed the important role of the damping constant in the seismic performance cable-stayed bridges retrofitted with FVDs.

Only a few authors have evaluated the possibility of introducing shape memory alloy based devices in cable-stayed bridges. Sharabash and Andrawes [10] pointed out the re-centring capabilities, strain hardening for high strain levels and stress plateau limiting the forces transmitted to the structure as clear advantages. TMDs have also been considered as a possible measure to control seismic induced vibrations in bridges. Koh et al. [24] investigated the effect of installing several tuned liquid dampers in a simplified model of a suspension bridge. The authors focussed on the spatial distribution of the devices and its effect in controlling the response of multiple modes.

In recent years, innovative passive and semi-active devices have been investigated for the same application. Domaneschi and Martinelli [25] compared the performance of a refined version of the ASCE cable-stayed bridge benchmark model retrofitted with electro-inductive devices, idealized by the Bouc–Wen hysteretic law, with classical MDs. Ha et al. [26] proposed a complex damper system combining a velocity dependent oil damper, for frequent and small vibration amplitudes, and a displacement dependent elasto-plastic damper, which activates for large amplitude vibration pulses. The authors show that the proposed system could significantly improve the seismic performance of long span cable-stayed bridges.

Despite that the first studies on passive isolation of cable-stayed bridges date back 20 years, there is a clear need for research on passive protection systems applied to this type of structures [4], along with the development of regulations and normative support