Engineering Structures 112 (2016) 287–294

Contents lists available at ScienceDirect

Engineering Structures

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

Structural impact mitigation of bridge piers using tuned mass damper

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ARTICLE INFO

Article history:
Received 11 August 2015
Revised 24 November 2015
Accepted 31 December 2015
Available online 3 February 2016

Keywords:
Collision forces
Structural impact
Vessel collision
Tuned mass damper (TMD), and structural control
Optimization

ABSTRACT

This paper proposed the application of tuned mass damper (TMD) systems to bridge piers for structural impact damage mitigation to reduce the risk of collapses. A bridge superstructure and substructure were designed in accordance with The American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications (BDS) (2012). A variety of vessel collision forces were obtained from collision testing of a scaled reinforced concrete pier. The optimal parameters of TMD systems were determined such that the drift and displacement of the bridge superstructure were minimized for various impact scenarios. Structural impact mitigation performance of the pier equipped with the proposed optimal TMD system was compared with four different TMD systems employing the benchmark TMD optimal parameters. The uncontrolled responses were used as a baseline. It was demonstrated from the extensive simulations that the control effectiveness of the proposed TMD system was 25% better than all of the existing TMD models in reducing the response of the structure.

1. Introduction

1.1. Background

In the United States, in the period of 1989–2000, there were 503 bridge failures: 13.73% were directly related to the collisions of vehicle/barge/ship/tanker to bridges, causing fatalities [29] Although AASHTO LRFD BDS [6] 3.14 addresses bridge pier design to protect against vessel collisions, these provisions simply lead to a higher load carrying capacity for the pier so that the vessel does not cause the collapse of the bridge [4,5,1,2,17]. Other methods to protect bridge pier structure against vessel collision include installing artificial islands; and employing guide structures [27]. These methods, however, either cause damage to the structure beyond repair or are expensive and suitable for significant bridges. The use of a vibration absorber such as tuned mass damper (TMD) is one of the alternative solutions to this problem that has not yet been researched or implemented.

TMD refers to a type of vibration absorber that consists of a mass that is able to move freely relative to the primary structure [23]. TMDs are used to reduce the amplitude of structure vibrations caused by an excessive force. The connection between the mass and the structure is usually an elastic spring with a specific stiffness and damping. The mass, stiffness, and damping of the TMD are designed in such a way that the TMD acts to mitigate the amplitude of the structural vibrations by dissipation of energy. Design of TMDs with optimum parameters go back to 1950s [13]. As the dynamic systems get more complex, Hartog's formulations have also been updated for different cases [28,25,21].

Many TMD systems have been proposed for building structures subject to earthquake and wind forces. The actual use of TMD systems is a relatively new concept in civil engineering dating back to just 1976 when a passive TMD system was placed on the CN Tower TV antenna in Toronto, Canada. The TMD on the John Handcock Building in Boston, Massachusetts, with the two 270,000 kg (300 t) steel blocks, was first installed to reduce discomfort for residents but then found to also reduce wind response by up to 40% [15]. The largest TMD currently in use is in the Taipei 101 building in Taipei, Taiwan which, until 2010, was the world's tallest building [10].

TMDs have been applied to footbridges to dampen the vibrations due to pedestrian loads [12]. The most famous example of a TMD application in pedestrian bridges is arguably the Millennium Bridge in London, England [12]. TMD systems can mitigate bridge vibrations and displacements, keeping primary structural members elastic under extreme loads, and therefore reducing downtime for maintenance [16]. A TMD system on a bridge pier can mitigate the response of the bridge to collisions, and decrease bridge cross

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http://dx.doi.org/10.1016/j.engstruct.2015.12.041
0141-0296/

section and save materials, as long as the local damage at the impact location is tolerated.

1.2. Aim and scope

Despite TMDs' wide use in buildings and infrastructures and well known effect of vibration reduction, there is no research on the application of TMDs to bridge piers under vessel collision events. This paper is the first to investigate the use of TMDs to reduce damage and to prevent collapse of bridges due to vessel collisions to bridge piers. It acts as a proof of concept for the effectiveness of TMDs under a potential dynamic excitation that has never been investigated before. This would lead to creation of other exciting research topics that are needed to be considered including structure impact modeling and simplification, TMD parameters searching algorithms that work for this type of model and input excitation. This is mainly because the time scale for the TMD system for seismic response controls (on the order of ~1 s) is not suitable for an TMD for high impact hazard mitigation (on the order of ~1 ms), i.e., a vessel collision force is an extremely fast and high impulse-type excitation. Hence it is logically clear that a TMD model with different parameters is needed to mitigate the impact hazard of bridge piers. The main contributions of this paper, therefore, are the proposal of a new design for TMDs for such scenarios and comparison of the performance of the new system with the ones of the existing TMD. The organization of this paper is as follows: The approach for modeling a bridge structure is presented in Section 2. The determination of parameters in the proposed model is described in Section 3. The optimal design of the bridge equipped with TMD systems and the simulation results are shown in Section 4. Finally, Section 5 includes the conclusion remarks and suggestions for future studies.

2. System modeling

In this paper, a lumped mass bridge pier-deck-TMD model is investigated to demonstrate the effectiveness of the proposed TMD system in mitigating the structural impact response of bridge structures. The TMD is integrated into the bridge pier model discussed in Section 2.1.

2.1. Bridge pier model

A bridge pier is modeled after Yuan [30]. In this model, a reinforced concrete bridge pier is excited by a 15-barge flotilla. The model predicts reliable time-history response of kinetic energy during collision with 95% accuracy in comparison with the simulation results obtained from a full-scale finite element model. In this paper, the vessel impact forces are replaced by the time-history of impact forces measured using a high impact testing facility, and the total number of degree of freedoms (DOF) of the Yuan model is reduced to 2.

The bridge pier substructure and superstructure are modeled with 2 lumped masses as shown in Fig. 1. The 1st lumped mass includes the substructure from the base of the pier to the point of impact, and the 2nd lumped mass is the remaining part of the substructure from the point of the impact to the top of the deck.

Initially, each lump mass had 2 DOFs: 1 lateral and 1 rotational displacement. The initial stiffness equation of this 4 DOF-system is then converted to a 2 DOF model (1 DOF for each lumped mass) by the static condensation. The new stiffness matrix K is obtained:

$$K = \frac{3}{L_2^2\left(3L_1 + 4L_2 + \frac{k_\theta L_2(L_1+L_2)}{EI}\right)}\begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \tag{1}$$

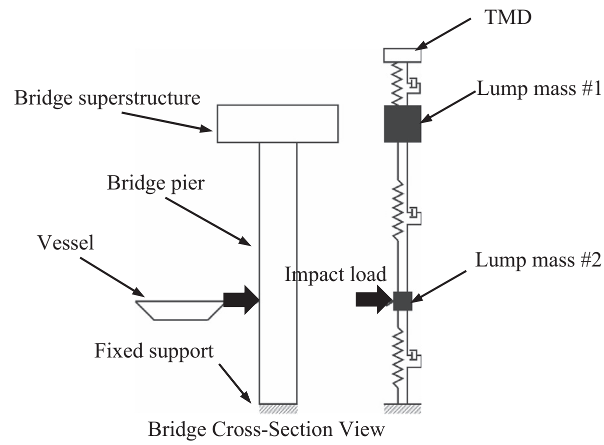

Fig. 1. Lumped model of the bridge pier employing a TMD.

where

$$k_{11} = \left(1 + \frac{L_2}{L_1}\right)^3 (4EI + (L_1 + L_2)k_\theta) \tag{2}$$

$$k_{22} = 4EI + (L_1 + 4L_2)k_\theta + L_2^2(3L_1 + 4L_2)\frac{k_x}{3} + L_2^3\frac{(L_1 + L_2)k_x k_\theta}{3EI} \tag{3}$$

$$k_{12} = k_{21} = -2\left(2 + \frac{3L_2}{L_1}\right)EI - \left(1 + \frac{3L_2}{L_1}\right)(L_1 + L_2)k_\theta \tag{4}$$

where k_θ is the rotational stiffness, k_x is the lateral stiffness, I is the moment of inertia, L_i is height of the ith component of the structure. The mass matrix is calculated according to the equations:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \tag{5}$$

where

$$m_1 = 0.5(L_1 + L_2) = 0.5L\overline{m} \tag{6}$$

$$m_2 = m_s + 0.5L_2\overline{m} \tag{7}$$

where $\overline{m}$ is the average mass of the pier (mass per length), m_s is the mass of the super structure. Using these parameters to solve for eigenvalues with the assumption that the damping ratio is not too high to affect the natural frequencies, the two natural frequencies are computed as:

$$\omega_{2,1}^2 = R\left(2\lambda^3 + 2\mu\left(1 + 4\kappa + \frac{3\kappa}{\lambda - 1}\right)\right) \pm \sqrt{\left(2\lambda^3 - 2\mu\left(1 + 4\kappa + \frac{3\kappa}{\lambda - 1}\right)\right)^2 + 4\mu(-3\lambda + 1)^2} \tag{8}$$

where

$$\lambda = \frac{L}{L_1}, \quad \mu = \frac{M_1}{M_2}, \quad \kappa = \frac{L_2^3 k}{12EI}, \quad R = \frac{3EI}{M_1(3L_1 + 4L_2)L_2^2} \tag{9}$$

Finally, damping matrix is defined using Rayleigh's approximation.

2.2. Bridge pier equipped with a TMD

The TMDs should be installed in the location that has the most vibration [16]. Therefore, the TMD is installed on the 2nd lumped mass. After the installation of the TMD, the system becomes a 3-DOF mass-spring system in which the 3rd lumped mass is the TMD. As a result, the new stiffness, mass and damping matrices after static condensation are defined as: