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Disaster protection of coastal bridge with cable restrainer under hurricane-induced waves

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ABSTRACT

Huge waves in hurricane would generate significant vertical and horizontal wave forces on the bridge superstructures, consequently resulting the movement, even unseating, of the superstructure. This paper presents a prior investigation on using cable restrainer to connect the superstructure and substructure for mitigating the wave-induced damage of coastal bridges. To achieve this purpose, a 3D finite element model, considering the nonlinear pier behavior and soil effects, was built by using OpenSees software package. The structural responses of the coastal bridge are analyzed under wave forces for the bridge with and without the cable restrainers. The analyzed results indicated that cable restrainer could significantly reduce not only the maximum transversal displacement of bridge deck but also the residual displacement. Furthermore, compared to other countermeasures, the cable restrainer would also induce much lower damage on the substructures of the coastal bridge.

1. INTRODUCTION

Extreme events have caused significant damage to coastal bridges. During Hurricanes Ivan in 2004 and Katrina in 2005, at least 11 highway and railroad bridges along the U.S. Gulf Coast were damaged by a combination of storm surge and wave action (Padgett et al., 2008). Surveys of the damaged bridges suggested that the connection failure between bent-cap and superstructure was the main reason for the overall failure (Douglass et al., 2004). Since then, lots of research has been conducted to figure out the mechanism of wave-structure interaction. Bradner et al. (2011) performed an experiment with a 1:5-scale reinforced concrete model of the I-10 bridge over Escambia Bay to investigate the wave action acting on the bridge under regular and random waves. A small-scale experiment of tsunami loads on coastal bridge decks was conducted by Lukkunaprasit et al. (2011) to study the effect of perforations in the

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girders on the horizontal loads due to tsunami. Guo et al. (2015) conducted an experiment on periodic wave loads on a 1:10-scale specimen, which is a full bridge model with superstructure, substructure and neighboring segments.

Advances have also been made in theoretical works and numerical simulations. Douglass et al. (2006) introduced a simple and conservative equation to estimate wave loads on coastal bridge decks. Base on the Morison equation, Marin (2010) developed a theoretical model to estimate wave forces with the parameters determined by a series of hydrodynamic tests on slab decks and girder-slab decks. Basing on experimental data, Mazinani et al. (2016) provided a computational model, named Extreme Learning Machine predictive model, to estimate tsunami bore forces on coastal bridges.

Until present, much efforts have made to understand the wave-structure interaction mechanism. However, appropriate disaster mitigation approach is also an important issue to protect the safety of the structures. Cable restrainer is a wide-used earthquake unseating prevention device for bridges with insufficient seat width. According to the disaster mitigation principal, this type of device has the possibility to be employed to reduce the wave-induced damage of the coastal bridges under hurricane. The feasibility of applying cable restrainer in mitigating the wave-induced damage of coastal bridges was investigated. A 3D finite element model was built and the analyzed results indicated that cable restrainer could significantly reduce the displacement of bridge deck.

2. MODEL CONFIGURATION

A 3D finite element model was built by using OpenSees software package (Mazzoni et al. 2006) with a prototype coming from the I-10 bridge over Escambia bay, as shown in Fig. 1. It is a 5-span simply supported beam bridge, containing three 6.64 m long middle spans and two 8.32 m long side spans. The superstructures consist of 5 AASHTO type III girders and a 10.0 m width slab. Each full length span weighs 242.0 t. The 2-column bents contain of two circular piers with a diameter of 1.5 m and a height of 6.1 m, spaced at 2.58 m on center. In analysis, we only focus on the center span and the third span, while other spans were merely built to ensure the force transmits to 2 middle piers being right.

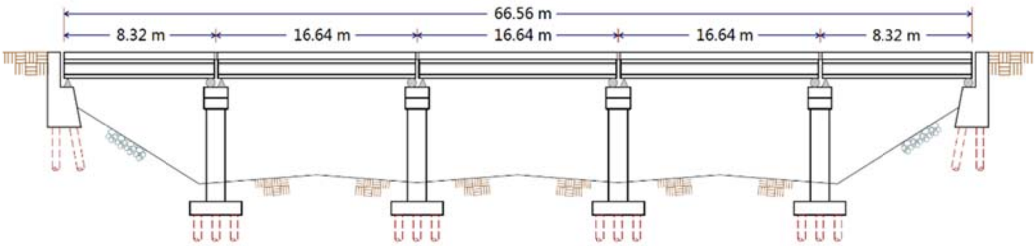


Fig. 1 Bridge configuration

2.1 Model modifications

In most earthquakes, horizontal acceleration plays a critical role and the vertical forces are always ignorable. Many numerical simulations and shake-table tests applied a constant vertical force to save time and reduce procedures. But storm wave is far different from earthquake. The features of vertical wave forces affecting on the bridge can be summarized as:

(1) Cause anchorage broke.
(2) Change constraint condition of bridge deck.
(3) Change the behavior of piers.

The problem of changing vertical force and complex interaction between deck and bent-cap can be solved by utilizing Flat Slider Bearing Element, which is a built-in element in OpenSees software package. As shown in Fig. 2, the element is defined by two nodes, with zero length or finite length. The element can modify the specified Uniaxial Material to no-tension material automatically to capture the uplift behavior.

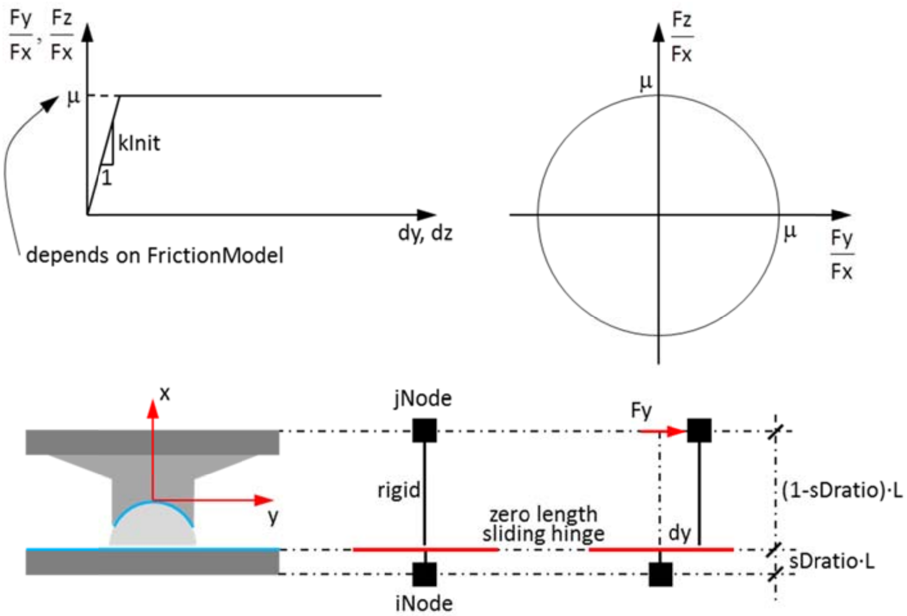


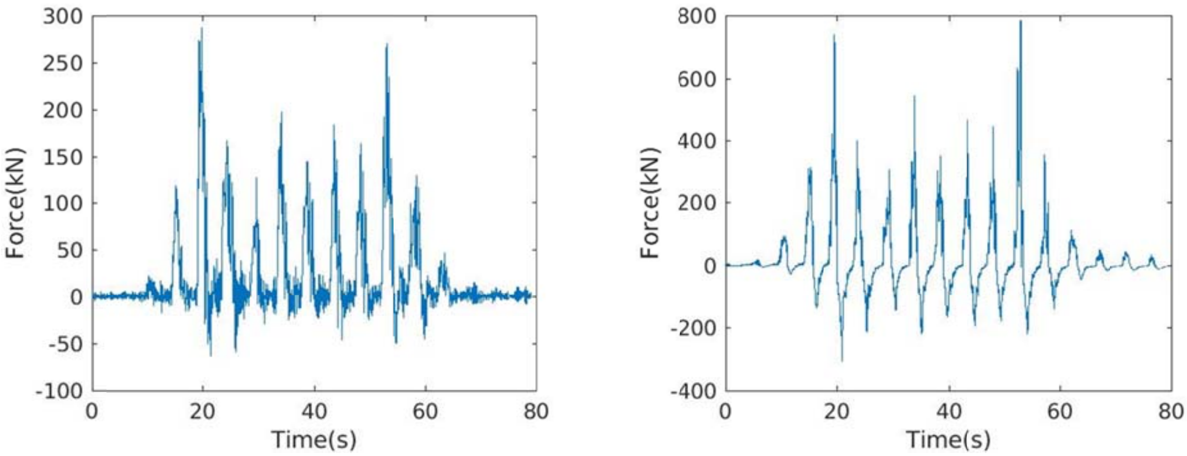
Fig. 2 Flat slider bearing element in OpenSees

2.2 Source of wave force

Test data of a hydrodynamic experiment on bridge decks is used as the input force in this study. The experiment was conducted in the Wind Tunnel and Wave Flume test facility at the Harbin Institute of Technology in China. The horizontal and vertical wave forces acting on the bridge model were measured by using four three-component underwater load cells installed between the girders and beam caps. The case we selected has 2cm deck clearance from still water level, 1.5 s wave period and 20 cm wave height. The test data should be converted according to Froude scaling laws. Fig. 3 shows the time series of wave forces used in this study. We applied the force acquired by each load cell back to the position it was placed.

3. RESULTS

Three different constraint conditions were discussed in this section, including free, equipped with cable restrainers and equipped with shear keys. Because of the limited

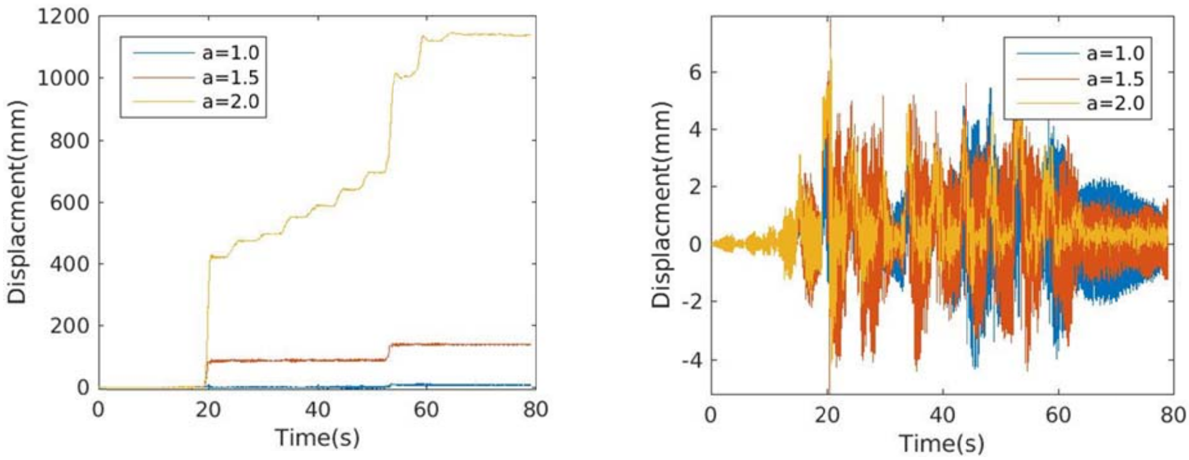


a) Horizontal wave force b) Vertical wave force

Fig. 3 Wave force time series used in simulation

capacity of wave maker, the waves action on the structure can hardly achieve the ultimate bearing capacity of the bridge. In the following analysis, the wave forces were multiplied by several amplification factors, 1.0, 1.5, 2.0 and 2.5, respectively to achieve the simulation purpose.

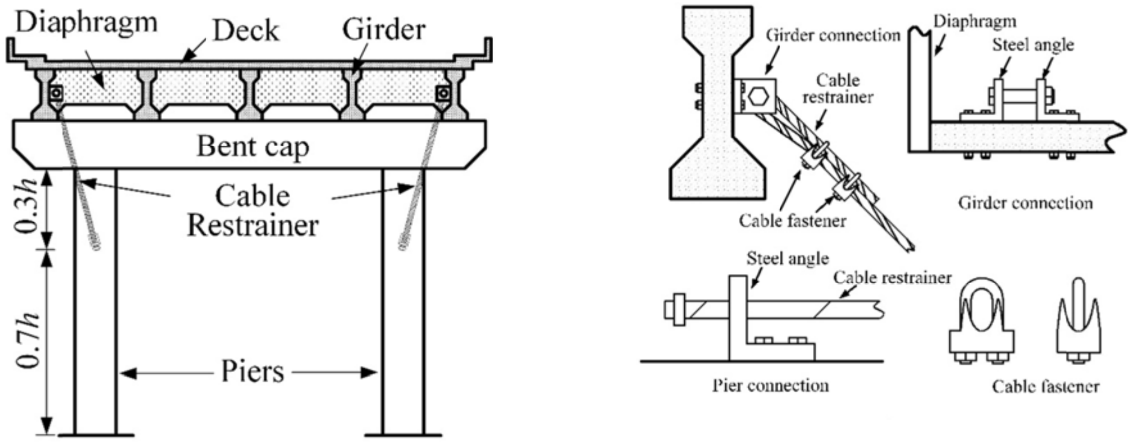
Fig. 4 shows the displacement response of bridge versus different amplification factors. It should be mentioned that bridge bearings were broken and superstructure can sway freely in these situations. In this figure, there is a sudden rise of transversal displacement at 21 s, accompanied with a peak in vertical displacement. At this moment, the superstructure was lifted up and the frictional force between deck and bentcap became 0. A relatively small horizontal force then caused a large displacement, accounting for about 40% of the total displacement. Vertical constraints can prevent bridge deck from lifting up, thus reduce the horizontal displacement.



a) Displacement of deck b) Displacement of Pier

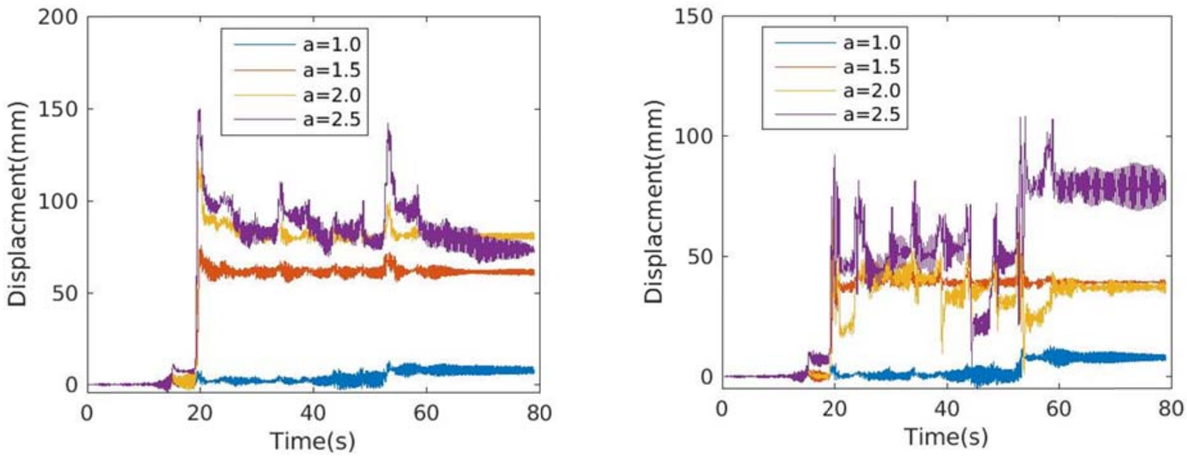
Fig. 4 Transversal displacement of bridges without additional constraint

Cable restrainer is the retrofit method which we focus on with a comparison with shear key. Fig. 5 shows the connection details of cable restrainer. Fig. 6 shows the displacement responses of bridge decks equipped with cable restrainer and shear key, respectively. It illustrated that the cable restrainer could reduce the residual displacement by 90% compared with cases without constraint. Fig. 7 shows the displacement response of bridge pier under different conditions. For bridges equipped with shear key, there was a 50 mm deformation at the top of pier as the amplification factor setting to 2.5. Meanwhile, bridge equipped with cable restrainer have its piers remained elastic. Although shear key achieved a better displacement control at deck, cable restrainer induced a much lower damage to pier. Repairing piers cost more than replacing decks for coastal bridges, so cable restrainer is preferred in this situation.



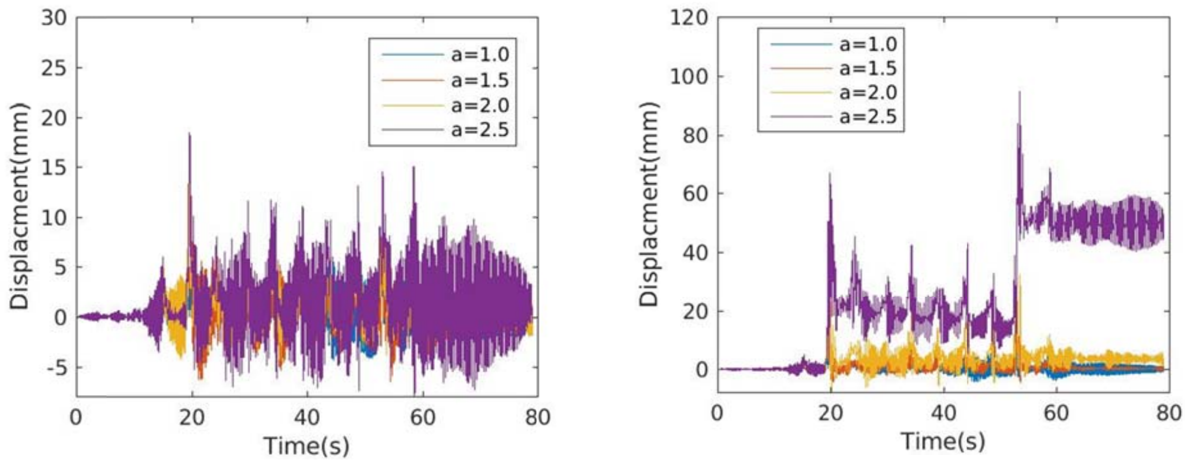
a) Bridge retrofitted with restrainer b) Connection details

Fig. 5 Configuration of cable restrainer



a) Retrofitted with restrainer b) Retrofitted with shear key

Fig. 6 Transversal displacements of bridge decks retrofitted with different devices



a) Retrofitted with restrainer b) Retrofitted with shear key

Fig. 7 Transversal displacements of bridge piers retrofitted with different devices

CONCLUSIONS

This paper aims at investigating the practical potential and effectiveness of the cable restrainer in mitigating the dynamic responses of coastal bridges when it subjected to extreme wave forces. A five-span highway bridge was selected as the prototype structure to establish the numerical model by using the OpenSees. The simulation results showed that the cable restrainer is a reasonable retrofit method for mitigating wave induced disasters. It also demonstrated that the cable restrainer can reduce the displacement significantly while inducing much lower damage on the substructures of the coastal bridge compared to other retrofit methods.

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