

# **Bridge Earthquake Resistance and Vibration Analysis**

Bridge local damage and global collapse induced by earthquake, passing vehicle, vehicle collision, and ship collision are generally observed. Transient vibration analysis and vibration resistance design is critical for ensuring life-cycle performance of bridges and structures. Recent research works in BE at Tongji University that address bridge earthquake resistance and vibration analysis include: Seismic isolator design and performance analysis; Dynamic response analysis of deep water bridge piers subjected to earthquake excitation; Double deck bridge behavior analysis under seismic loads; Vibration and noise reduction analysis for rail bridges; Ship-impact analysis of bridges; Seismic performance analysis of hollow rectangular bridge piers.

# **Analysis of the dominant vibration frequencies of rail bridges for structure-borne noise using a power flow method**

Many field tests and numerical simulations have shown that both the vibration of a bridge and the bridge-borne noise low-frequency dominated. Using the concept of mobility and power-flow analysis in the frequency domain, the aim of this study was to identify the dominant vibration frequencies of a concrete bridge in the frequency range from 20 to 200 Hz by considering the vehicle, track and bridge subsystems as a coupled system.

**Objective:** The use of concrete bridges in urban rail transit systems has raised many concerns regarding low-frequency (20-200 Hz) structure-borne noise due to the vibration of bridges when subjected to moving trains. Understanding the mechanism that determines the dominant frequencies of bridge vibrations is essential for both vibration and noise reduction.

**Approach:** This paper presents a general procedure based on the force method to obtain the power flows within a coupled vehicle-track-bridge system, the point mobility of the system and the dynamic interaction forces connecting various components. The general coupling system consists of multi-rigid-bodies for the vehicles, infinite Euler beams representing the rails, two-dimensional or three-dimensional elements of the concrete bridges, and spring-dashpot pairs to model the wheel-rail contacts, the vehicle suspensions, the rail pads and the bridge bearings. The dynamic interaction of the coupled system is solved in the frequency domain by assuming the combined wheel-rail roughness moves forward relative to the stationary vehicles. The proposed procedure is first applied to a rail on discrete supports and then to a real urban rail transit U-shaped concrete bridge.

**Significant Result:** The computed results show that the wheel-rail contact forces, the power flows to the rail/bridge subsystem and the accelerations of the bridge are primarily dominated by the contents around the natural frequency of a single wheel adhered to the elastically supported rail.

**Principal Investigator:** Q.Li, D.J. Wu

**Funding:** National Natural Science Foundation of China (Grant Nos. 50908178) and the Fundamental Research Funds for the Central Universities.

## **Key Publications:**

Li Q, Wu D J. Analysis of the dominant vibration frequencies of rail bridges for structure-borne noise using a power flow method[J]. Journal of Sound and Vibration, 2013, 332(18): 4153-4163.

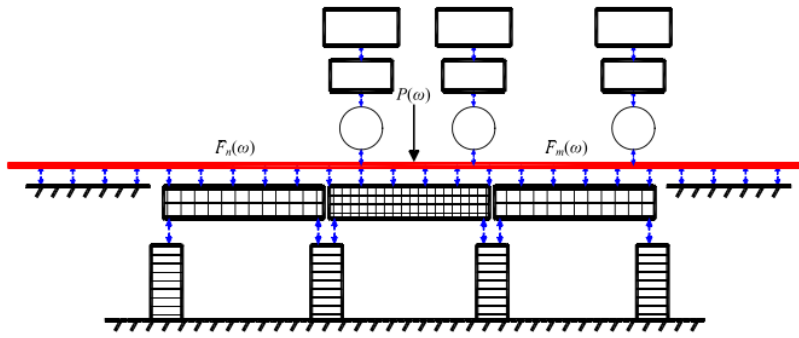


Fig. 2. Released structure of the vehicle-track-bridge system.

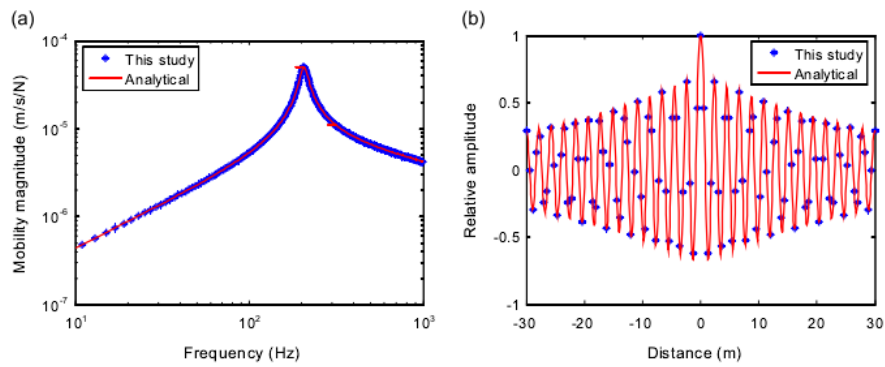


Fig. 4. Mobility of the rail on discrete supports: (a) mobility at the excitation point; (b) instantaneous relative vibration amplitude versus distance from the excitation point at a frequency of 501 Hz, showing the part that is in phase with the excitation point.

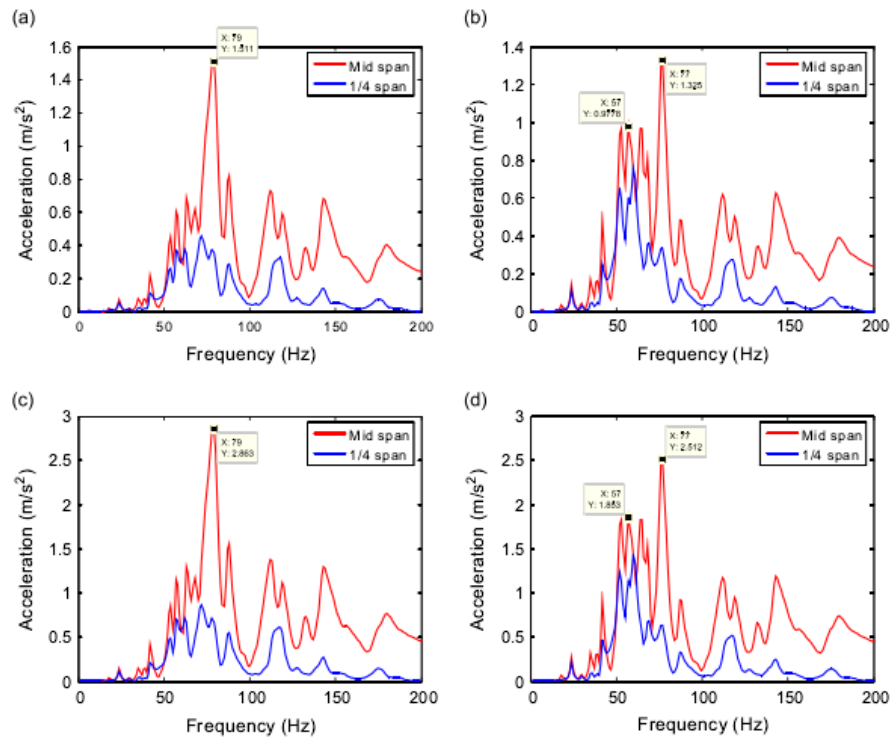


Fig. 14. Acceleration spectra of the bridge induced by the one eighth vehicle at mid span: (a) wheel mass 1150/2 kg, speed 70 km/h; (b) wheel mass 1900/2 kg, speed 70 km/h; (c) wheel mass 1150/2 kg, speed 140 km/h; (d) wheel mass 1900/2 kg, speed 140 km/h.

## Code Formulas for Ship-Impact Design of Bridges

The consideration of ship collisions at bridges crossing waterways is a core component of a design process. First, the lateral impact loads by ships need to be quantified. At present, bridge design codes generally provide simplified procedures for deciding equivalent static loadings (ESLs) in the design of a bridge against ship collisions. In this paper, the code formulas are reviewed, the FEM is used to compute the impact forces of example ships, and comparisons and discussions are presented.

**Objective & Approach:** Four finite-element models of ships with deadweight tonnage varying from 3,000 to 50,000 t are developed for numerical collision simulation. The time histories of ship collisions against rigid walls are obtained using the software LS-DYNA. Equivalent static loading is determined, and simplified formulas are developed through a fitting procedure as indicated by the data from the numerical simulations. Codified formulations from AASHTO and other design specifications are compared with the simplified formulas. The geometric effects of the bridge foundation on the ship impact force are investigated with an example pile cap.

**Significant Result:** A geometric modification factor is proposed for an ideal rectangular block to modify ship impact forces estimated by code formulas.

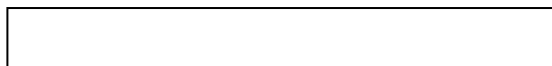
### **Principal Investigator:**

Junjie Wang, Lingtao Bu and Conghui Cao

### **Funding:**

### **Key Publications:**

Wang J, Bu L, Cao C. Code Formulas for Ship-Impact Design of Bridges[J]. Journal of Bridge Engineering, 2011, 17(4): 599-606.



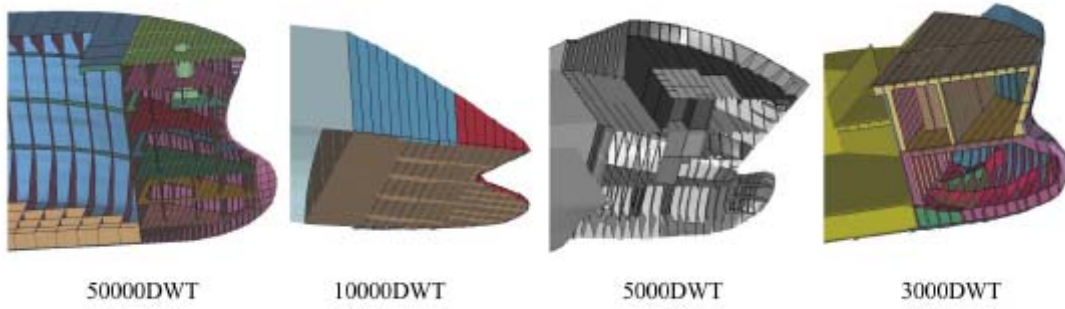


Fig. 3. FEM of example ships (inside view)

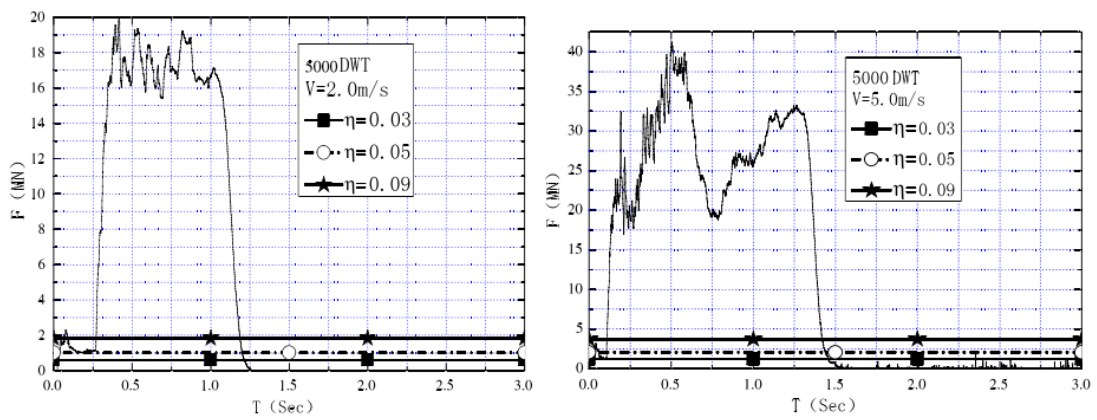


Fig. 5. The  $T_{eff}$  for various values of  $\eta$

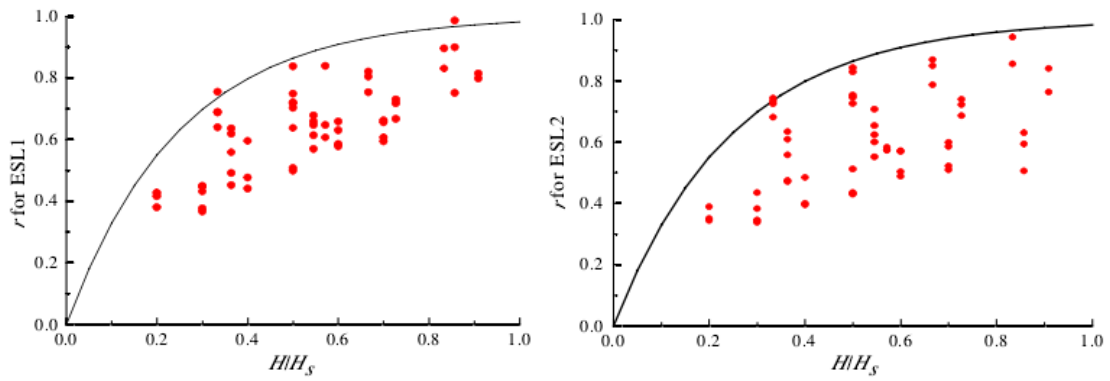


Fig. 14. Discrete values and modification function of  $r$

## **Development and mechanical performance of a new kind of bridge seismic isolator for low seismic regions**

The existing elastomeric isolators include lead rubber bearings, high damping rubber bearings and common laminated rubber bearings. Compared with the large amount of theoretical and experimental researches, FEM researches are relatively fewer. Most of the researches in the past were based on the fiber fabric which is relatively rigid in tension and relatively flexible in bending. Three specimens were manufactured to study the mechanical performance of this new kind of isolator by conducting vertical and horizontal tests.

**Objective & Approach:** The concept of fiber-reinforced plate elastomeric isolator (FRPEI) is introduced firstly in this paper. Three FRPEI specimens have been constructed to evaluate the mechanical performance of the isolators by performing vertical and horizontal tests. The research focuses on the compression stiffness, the shear stiffness, the hysteretic characteristic and the vertical bearing capacity of the isolators.

**Significant Result:** The experimental results show that the mechanical performance of FRPEIs can meet the requirements of bridge rubber bearings and the energy dissipation capacity is better than that of general laminated rubber bearings. Therefore, it is feasible to use FRPEIs in seismic isolation of short span bridges in low seismic regions. Theoretical and finite element methods have also been employed and the deformation assumptions applied in the theoretical method are also verified by FEM. By comparing the differences of the results of different methods, the effectivenesses of the theoretical and finite element methods are evaluated and some considerations on isolator design are proposed.

**Principal Investigator:**

H. Zhang, J. Li and T. Peng

**Funding:**

**Key Publications:**

Zhang H, Li J, Peng T. Development and mechanical performance of a new kind of bridge seismic isolator for low seismic regions[J]. Shock and Vibration, 2013, 20(4): 725-735.



Fig. 1. Fiber fabric.



Fig. 2. Lay down glass fiber fabric and release fabric.

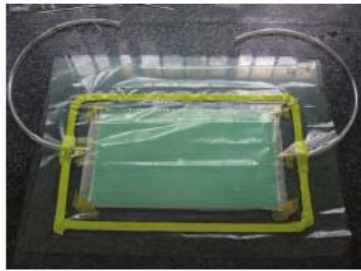


Fig. 3. Lay pipes and vacuum bag.

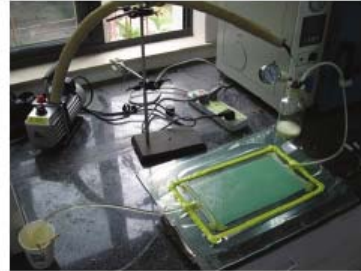


Fig. 4. Pump the formulated resin.

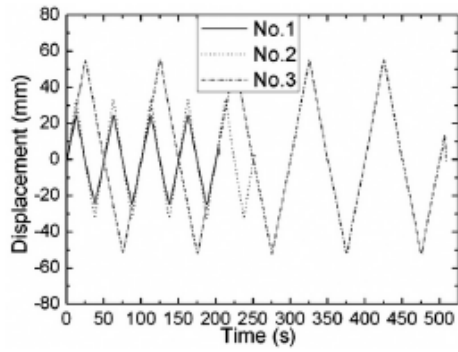


Fig. 8. Horizontal cyclic loading applied to each specimen.

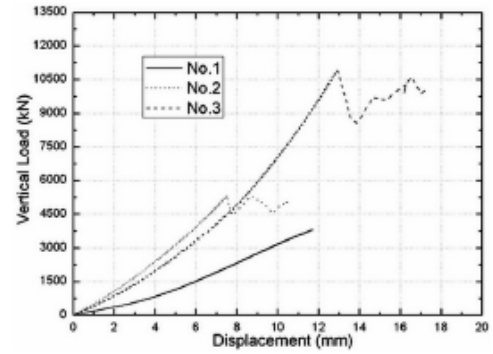
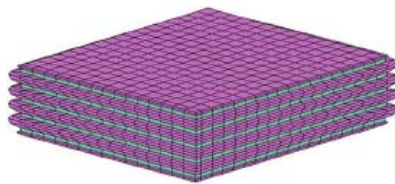
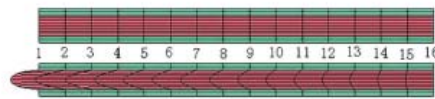


Fig. 9. Vertical tests of FRPEI specimens.

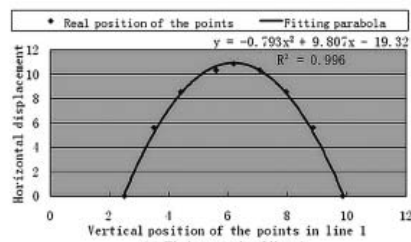


(a) View from the symmetry axis

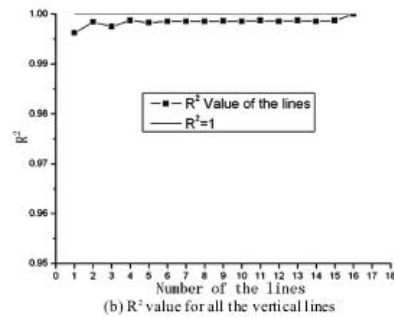


(b) Comparison before and after loading

Fig. 14. Deformation condition of an FRPEI under pressure.



(a) Fitting result of line 1



(b) R<sup>2</sup> value for all the vertical lines

Fig. 15. Fitting of the vertical lines.

## **Double deck bridge behavior and failure mechanism under seismic motions using nonlinear analyzes**

For the double deck bridge, which consists of two stories, it is desirable to design the bridge as a strong beam-weak columns system for seismic resistance. Few studies have been conducted on double deck bridges and most focus on the reasons for past earthquake collapses and the retrofit it methods of the beam-column connections were shown to be one of the major reasons for the failures of the old bridges. The aim of this study is to investigate the seismic response of a new double deck bridge designed with many irregularities, and to detect the effect of different parameters on its response through nonlinear time history analysis.

**Objective:** This paper investigates the behavior and the failure mechanism of a double deck bridge constructed in China through nonlinear time history analysis.

**Approach:** A parametric study was conducted to evaluate the influence of different structural characteristics on the behavior of the double deck bridge under transverse seismic motions, and to detect the effect of bidirectional loading on the seismic response of this type of bridge. The results showed that some characteristics, such as the variable lateral stiffness, the foundation modeling, and the longitudinal reinforcement ratio of the upper and lower columns of the bridge pier bents have a major impact on the double deck bridge response and its failure mechanism under transverse seismic motions.

**Significant Result:** It was found that the soft story failure mechanism is not unique to the double deck bridge and its occurrence is related to some conditions and structural characteristics of the bridge structure. The analysis also showed that the seismic vulnerability of the double deck bridge under bi-directional loading was severely increased compared to the bridge response under unidirectional transverse loading, and out-of-phase movements were triggered between adjacent girders.

### **Principal Investigator:**

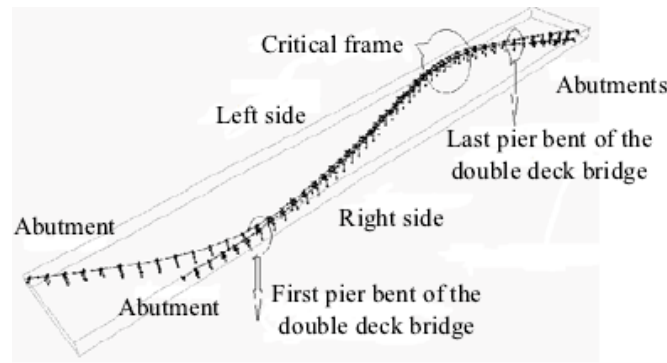
Shirin Alali, Li Jianzhong and Guo Guanzhong

### **Funding:**

### **Key Publications:**

Alali S, Li J, Guo G. Double deck bridge behavior and failure mechanism under seismic motions using nonlinear analyzes[J]. Earthquake Engineering and Engineering Vibration, 2013, 12(3): 447-461.

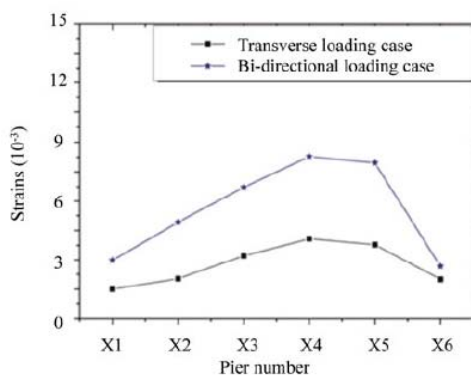




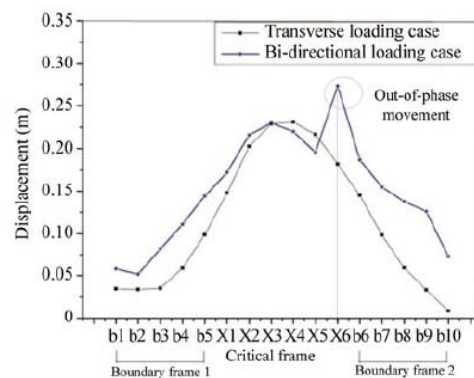
**Fig. 1 Bridge layout**

**Table 4 Nonlinear time history analysis case studies**

Group number	Bridge parameters under consideration	Case studies	Soil- structure interaction (SSI) modelling	Seismic motion intensity
Group 1	Length of the pier bent columns	1-real bridge case 2-long lower columns case 3-equal upper/ lower columns case 4-long upper columns case	Flexible foundations	Transverse loading 0.345 g, 0.6 g, 0.95 g
Group 2	Foundation conditions	1-real bridge case, flexible foundations 2- equal foundations stiffness case, flexible foundations 3- fixed foundations case	1-flexible foundations 2-fixed foundations	Transverse loading, 0.345 g
Group 3	Longitudinal reinforcement ratio of the pier bent columns	1- real bridge case 2-upper level- half steel ratio case 3-lower level- half steel ratio case 4-upper/lower levels- half steel ratio case	Flexible foundations	Transverse loading, 0.345 g
Group 4	Seismic motion input	1-real bridge case, Transverse loading case 2- real bridge case, Bi-directional loading	Flexible foundations	1-transverse loading, 0.345 g 2-bi-directional loading, 0.345 g



**Fig. 17 Longitudinal tensile steel strain values at the critical sections for each pier bent of the critical frame for case studies of Group 4 under 0.345 g seismic motion**



**Fig. 19 Displacement shapes at peak response for the uni-directional and bi-directional response, calculated as the vector sum of the displacements in the transverse and longitudinal directions**

# **Experimental and Numerical Assessment of the Three-Dimensional Modal Dynamic Response of Bridge Pile Foundations Submerged in Water**

The dynamic response of a deep water bridge subjected to earthquake excitation depends on the dominant period of the seismic input and the vibration periods of the bridge-foundation-water system along various modes. The main purpose of this work is to assess the modal dynamic response of bridge foundation piles surrounded by water. The scope of the paper does not address the effect of dynamic forces such as wave loads and is restricted to the assessment of the modal dynamic response of the tested bridge foundation piles in terms of vibration frequencies and modal hydrodynamic pressure distributions.

**Objective:** This paper describes an experimental program conducted to investigate the effects of fluid-structure interaction on the modal dynamic response of three reduced-scale bridge pile foundations submerged partially or totally in water.

**Approach:** The vibration periods of the specimens are measured for the two lateral modes and first torsional mode using ambient and forced vibration tests. The results are presented and discussed as a function of surrounding water levels and the number and geometrical patterns of the piles. Three-dimensional (3D) finite-element models of the tested specimens surrounded by different water levels are built, and the results are successfully validated against the obtained experimental data. The built numerical models are used to compute 3D modal hydrodynamic pressures. A systematic analysis of the period ratios and 3D hydrodynamic loads is presented to characterize the effects of pile cap, water height, and the number and geometrical pattern of the piles on dynamic response.

**Significant Result:** The experimental and numerical results of this research allow a better understanding of the complex dynamically induced fluid-structure interaction effects in the response of deep water bridge pile foundations.

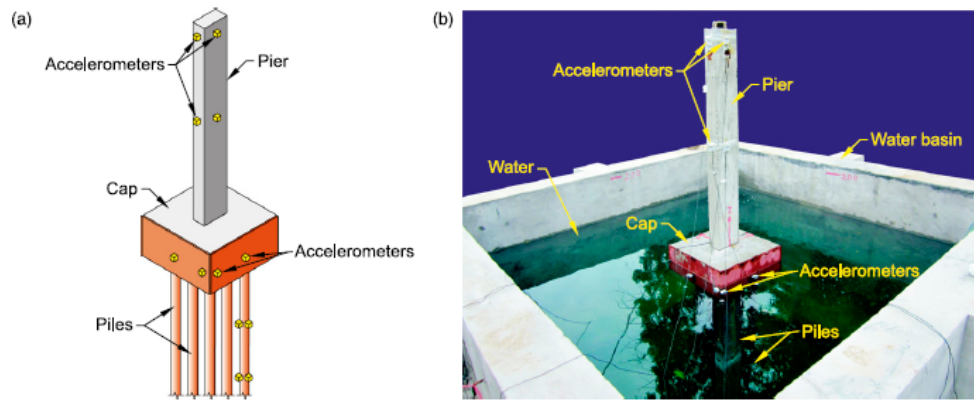
## **Principal Investigator:**

Kai Wei, Wancheng Yuan, Najib Bouaanani

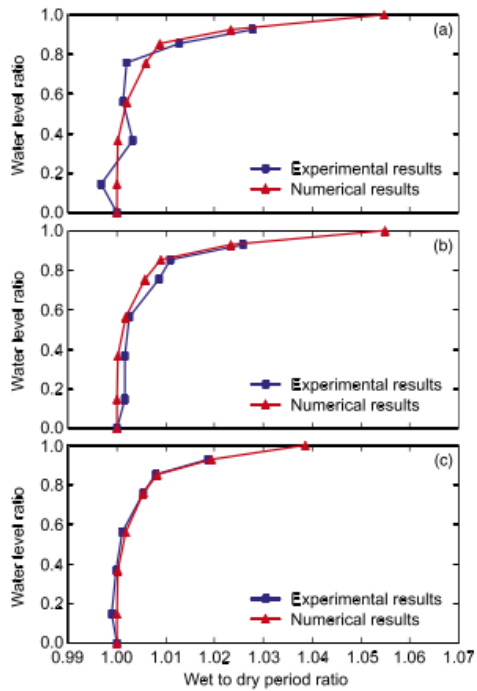
**Funding:** National Natural Science Foundation of China (Grant No. 50978194 and 90915011)

## **Key Publications:**

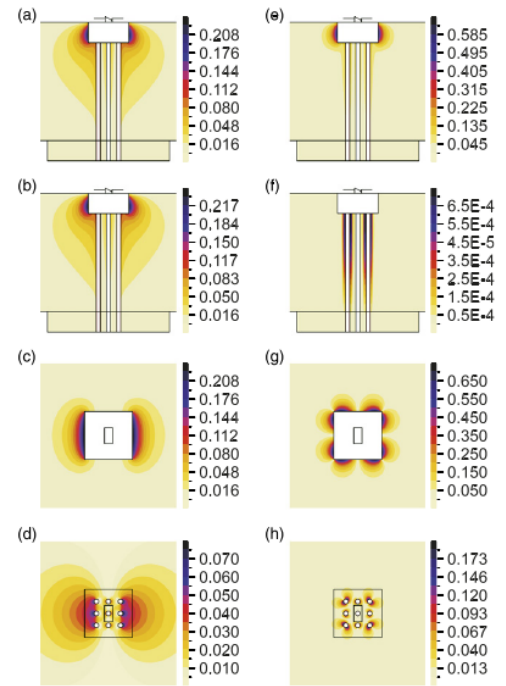
Wei K, Yuan W, Bouaanani N. Experimental and numerical assessment of the three-dimensional modal dynamic response of bridge pile foundations submerged in water[J]. *Journal of Bridge Engineering*, 2012, 18(10): 1032-1041.



**Fig. 5.** Experimental setup: (a) positions of the 12 accelerometers fixed on the cap, pier, and piles of the tested specimens; (b) global view of the specimen and testing setup



**Fig. 11.** Measured and computed wet-to-dry period ratios for the four-pile foundation specimen as a function of water level: (a) first lateral vibration mode; (b) second lateral vibration mode; (c) torsional mode



**Fig. 12.** Nondimensional modal hydrodynamic pressures on the nine-pile foundation specimen for a water level,  $H_w$ , of 20.5 m; first lateral mode along cutting planes (a)  $x = -0.15$  m, (b)  $x = 0$  m, (c)  $z = 1.90$  m, and (d)  $z = 1.35$  m; torsional mode along cutting planes (e)  $x = -0.15$  m, (f)  $x = 0$  m, (g)  $z = 1.90$  m, and (h)  $z = 1.35$  m

## **Experimental and numerical investigation of the seismic performance of hollow rectangular bridge piers constructed with and without steel fiber reinforced concrete**

SFRC is a multi-phase composite material in which short steel fibers are distributed in random directions in conventional reinforced concrete (RC). The objective of this study is to evaluate the effect of steel fiber reinforcement on the seismic behavior of hollow rectangular piers, through comparative analysis of a normal RC pier and an otherwise identical SFRC pier. The lateral cyclic loading history and constant axial loading were applied in testing the specimens.

**Objective:** The seismic performance of reinforced concrete and steel fiber reinforced concrete rectangular hollow piers is evaluated through model tests and numerical simulations.

**Approach:** Two large-scale pier specimens, with small amounts of transverse reinforcement, were modeled and tested under a combination of reversed cyclic lateral loading and constant axial loading. One specimen was made of conventional reinforced concrete, while the other was made of steel fiber reinforced concrete – with steel fiber volume fraction of 1.0%. Seismic behavior of the test specimens, including the failure mode, hysteretic characteristics, ductility, stiffness degradation and energy dissipation capacity were investigated. The corresponding finite element simulations, using Open Sees, were carried out and the results are compared with the experimental results. In addition, the parametric analyses of the seismic performance of hollow piers, varying the steel fiber content and transverse reinforcing ratio, were conducted based on the Open Sees analysis platform.

**Significant Result:** The finite element analysis results agree well with the experimental data. The results indicate that the hysteretic characteristics, ductility and energy dissipation capacity of hollow concrete piers are improved by the addition of steel fibers, and that the steel fibers can substitute part of the transverse reinforcement in hollow piers for seismic design.

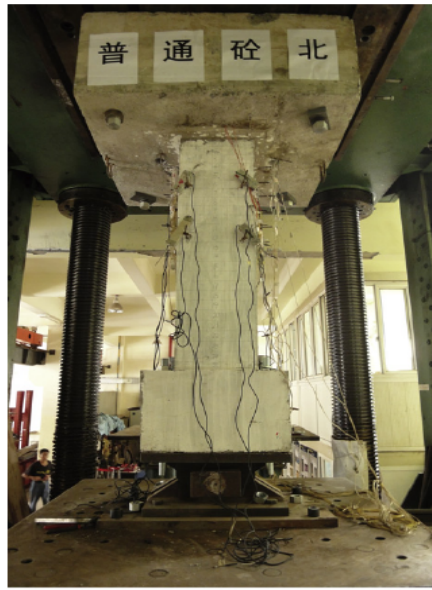
### **Principal Investigator:**

Yu-ye Zhang, Kent A. Harries, Wan-cheng Yuan

**Funding:** the National Nature Science Foundation of China (Grants Nos. 50978194, 51278376 and 90915011) and the Ministry of Science and Technology of China (Grant No. SLDRCE09-B-08)

### **Key Publications:**

Zhang Y, Harries K A, Yuan W. Experimental and numerical investigation of the seismic performance of hollow rectangular bridge piers constructed with and without steel fiber reinforced concrete[J]. *Engineering Structures*, 2013, 48: 255-265.

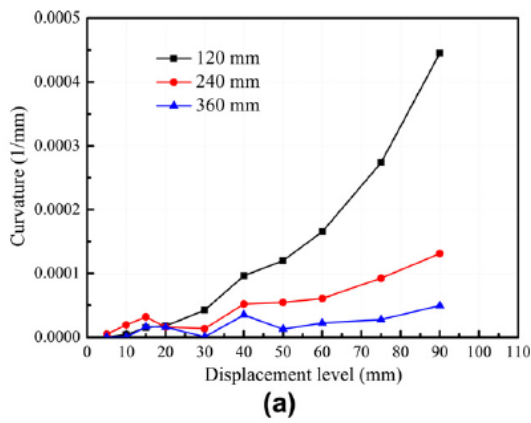


(a)

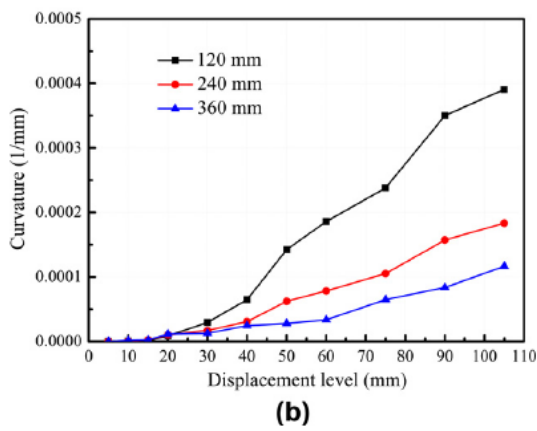


(b)

Fig. 3. Photos of specimens installed in the test system: (a) RC pier and (b) SFRC pier.



(a)



(b)

Fig. 9. Curvature in plastic hinge region of specimens: (a) RC pier and (b) SFRC pier.

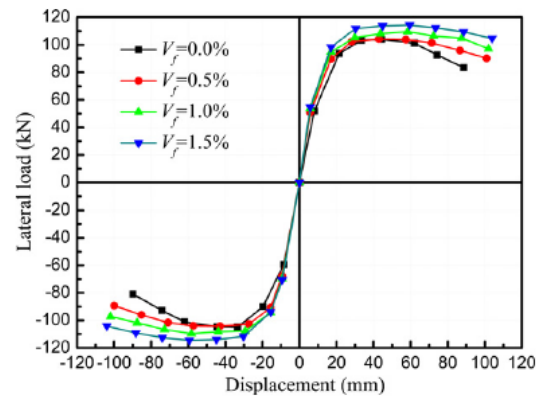


Fig. 16. Skeleton curves with different  $V_f$ .

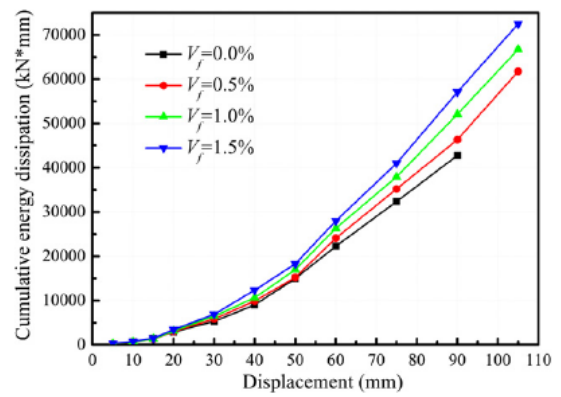


Fig. 17. Cumulative energy dissipation with different  $V_f$ .