Seismic Fragility Based Optimum Design of LRB for Isolated Continuous Girder Bridge

X. H. Long, J. Fan, F. F. Nie, and Y. T. Zhang
School of Civil Engineering and Mechanics, Hubei key Laboratory of Control Structure, Huazhong University of Science and Technology, Wuhan, China
E-mail: {xhlong, sufeinie, sufeinie, zyt1965}@hust.edu.cn, fan-jian@126.com

***Abstract*—The mechanical properties of the isolation bearings have a significant effect on the damage probability of the isolated bridges. In this paper a RC seismic isolated continuous highway bridge is selected, and a 3D finite element model is established by OpenSees software. In order to investigate the isolation bearing mechanical parameters on the effect of bridge seismic fragility, the seismic fragility functions of bridge components under certain limit state and different isolation bearing parameters were obtained. The multi-objective functions of the series bridge system and weighted bridge system are found based on the seismic fragility of bridge components and are solved by the Multi-Objective Genetic Algorithm (MOGA). The results showed that the selection of isolation bearing parameters has a great influence on the seismic fragility of the whole bridge. The optimum isolation bearing parameters for the series system and weighting system can both improve the bridge seismic fragility. However, the isolation bearing parameters from the bridge series system model improve seismic performance more effectively.**

***Index Terms*—isolated continuous bridge, seismic fragility, optimum design, MOGA**

I. Introduction

Bridges are the key components of transportation networks. When the bridges damage under major earthquakes, these will cause significant direct or indirect economic impact. In recent year, seismic isolation bearings have been used to improve the seismic response and reduce seismic damage. For seismic-isolated bridge it has a big influence on the selection of the isolation device parameters. However, isolation devices possess various mechanical properties and their behavior is often highly nonlinear. A lot of work has been done on the influence of the isolation design parameters on the seismic response. Jangid [1] researched on the multilayer isolation building under the earthquake action near fault. If the minimum value of the top story acceleration and the bearing displacement are taken as the optimization goal, the optimum shear strength of the lead rubber bearing should be 10%-15% of the total weight of the structure. Christian Bucher [2] studied the optimum design of the friction pendulum isolation structure based on dynamic reliability analysis. The weighted linear combination of the dynamic reliability indexes (bearing displacement and story drift of the upper structure) are taken as objective function. The optimal radius and friction coefficient of the friction pendulum bearing are 3.3m and 0.27 respectively by using multi-objective genetic algorithm (GA). Zhang [3] studied on the seismic fragility of a highway bridge, and considering geometric parameters and the earthquake response of the bridge put forward isolation bearing parameter optimization methods. Li [4] simulated the nonlinear behavior of the isolated-bridge ductile plastic hinge with nonlinear horizontal and rotational springs. The influence of various lead distributions of the pier and abutment was analyzed. However, it should be noted that currently isolation performance evaluation is based on single seismic response index or when discussing certain index fixing other index. In fact, the response indexes of the isolated-bridge design are contradictory. Isolation bearing design should strike a balance among the indicators which is a multi-objective optimization problem. The RC isolated continuous girder bridge is taken as research object in this paper. The nonlinear time history method is applied to calculate the average ground motion intensity of bridge components that reach a certain limit state under different bearing parameters (pre-yielding stiffness and yielding shear). The multi-objective optimization equations of whole bridge system are established in series bridge system or weighted bridge system according to seismic fragility functions of the bridge components. The genetic algorithm is used to solve and obtain the optimal bearing parameters.

II. Seismic Fragility Analyses and MOGA Method

A. Probabilistic Seismic Demand Analysis

Probabilistic Seismic Demand Model (PSDM) is used to derive analytical fragility functions. To establish PSDM is mainly research on statistical relationship between structural seismic demand parameters (EDP) and the ground motion Intensity Measure (IM). PSDA is the commonly used seismic demand model analysis method. The PSDA method utilizes regression analysis to obtain the mean and standard deviation for each limit state by assuming the logarithmic correlation between median EDP and an appropriately selected IM:

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$$\ln(EDP) = \ln a + b\ln(IM) \quad (1)$$

where the parameters a and b are regression coefficients obtained from the response data of nonlinear time history analysis. The standard deviation can be estimated as:

$$\xi_{EDP/IM} = \sqrt{\frac{\sum_{i=1}^{n}[\ln(EDP_i) - (\ln a + b\ln IM_i)]^2}{n-2}} \quad (2)$$

Bridge structure Seismic fragility functions describe the conditional probability of reaching a certain limit states (LS) under different seismic IM. The damage probability of certain LS can be written as Eq. (3):

$$P_f = P(D \geq LS / IM) = \Phi\left(\frac{\ln(aIM^b) - \ln(LS)}{\xi_{EDP/IM}}\right) \quad (3)$$

where $\xi_{EDP/IM}$ is the standard deviation of the logarithmic distribution that computed from Eq. (2), and $\Phi(\cdot)$ is the standard normal distribution function.

TABLE I. DAMAGE INDEX AND CORRESPONDING LSS FOR CONCRETE PIERS AND BEARINGS

Bridge component	Damage Index	Slight LS=1	Moderate LS=2	Extensive LS=3	Collapse LS=4
Piers	A. section ductility μ_k	$\mu_\kappa > 1$	$\mu_\kappa > 2$	$\mu_\kappa > 4$	$\mu_\kappa > 7$
Bearings	B. shear strain γ	$\gamma > 100\%$	$\gamma > 150\%$	$\gamma > 200\%$	$\gamma > 250\%$

A. Choi et al[5]; B. Jian Zhang, Yili Huo[3]

B. Damage Index and Limit States

In seismic fragility analysis the bridge components of seismic resistance can be defined as the damage states that the bridge reaches when the components loss certain function. Table I summarizes the definitions of various damage states and corresponding damage index (DI) criteria available in literature. In this paper the curvature ductility is adopted as DI of bridge pier, and the shear strain is utilized to capture the damage states of bearing.

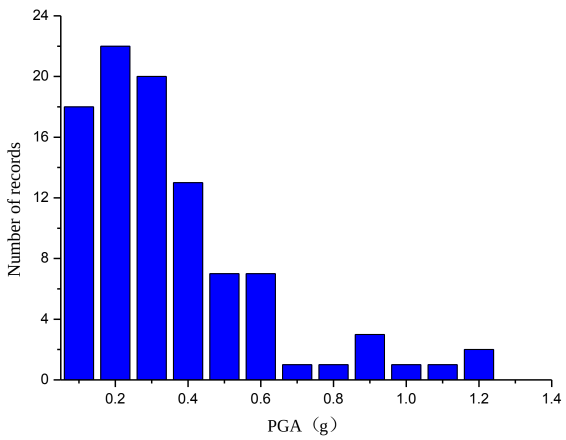


Figure 1. PGA distribution of selected earthquake records

C. Selection of Earthquake Wave

Earthquake selection method is based on design response spectrum: (1) the selected response spectrums of the ground motion records are close to the design response spectrum. (2) the ground motion records whose acceleration response spectrums (after amplitude modulation) are approaching to the design response spectrum at short period (e.g. [0.1s, T_g]) and fundamental period ([T_1 -ΔT_1 , T_1 +ΔT_2]) are selected. The limition the seismic information and stations such as site condition, magnitude and epicentral distance is not considered. Where T_g is the site characteristics period, T_1 is the structural fundamental period, ΔT_1 and ΔT_2 is the period control range. In this paper, 100 ground motion records are selected from the Pacific Earthquake Engineering Research Center (PEER) [6]. Fig. 1 is the seismic Peak Ground Acceleration (PGA) distribution of the selected 100 ground motion records.

D. Solution of Multi-Objective Function

Multi-objective optimization problem is a hot issue in the field of science and engineering, because many of the projects itself is a multi-objective optimization problems [7], [8]. In this paper the seismic fragility functions of the piers and bearings in isolated continuous girder bridge are taken as sub-objective functions, and then multi-objective optimization problem of the series bridge system or the weighted bridge system are built. The bearing parameters multi-objective optimization problem of isolated continuous girder bridge system can be expressed as follows:

$$y = \min[f_1(x,y), f_2(x,y),..., f_6(x,y), g_1(x,y), g_2(x,y),..., g_6(x,y)] \quad (4)$$

where $f_1(x,y), f_2(x,y),..., f_6(x,y)$ are six seismic fragility functions of isolation bearing in the bridge system. $g_1(x,y), g_2(x,y),..., g_6(x,y)$ are six seismic fragility functions of piers in the bridge system.

For obtaining the Pareto optimal solutions of multi-objective optimization problem there are many methods based on genetic algorithm. The weighted coefficient of transformation method is adopted to solve multi-objective problems in this paper. The multi-objective optimum equation can be expressed as.

$$y = \sum_{i=1}^{n}\omega_i f_i(x) \quad (6)$$

where $\sum_{i=1}^{n}\omega_i = 1$ and $f_i(x), i = 1,2,...n$ are sub-objective functions. Assume that the linear weighted function is taken as evaluation function of the multi-objective optimization problem. So the multi-objective optimization problem can be transformed into single objective optimization problem, and single objective optimization problem can be directly used genetic algorithm to solve.

III. Optimum Design of LRB for Isolated Continuous Girder Bridges

A. Finite Element Modeling

The bridge, located in western part of China, is a reinforcement concrete isolated continuous bridge with five equal spans and 100-meter overall length. The layouts and sections of the bridge are plotted in Fig. 2(a) and Fig. 2(b), respectively. The seismic isolation bearing LRB500 is used to connect the girder and the top of the piers. Expansion joints of this bridge are set on the proscenium of both sides and the girder supported by the abutment at the end which is gravity U-shaped abutment with the expansion base [9]. In addition, the seismic fortification intensity of this site is 9 degrees; site classification type is II; the characteristic period of site is 0.4s. The peak acceleration of earthquake ground motion is 0.40g in the horizontal direction of the bridge.

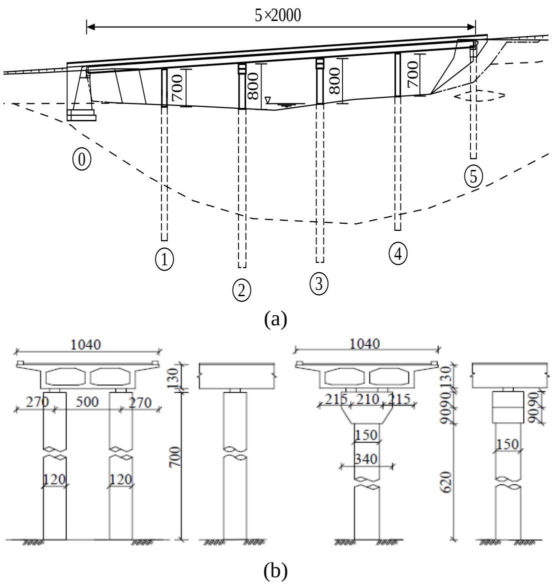


Figure 2. Elevation view of continuous girder bridge

In order to model the nonlinear action of the column piers, the fiber bridge piers are established with nonlinear beam elements in OpenSees (Fig. 3). A linear torsional spring and a linear shear spring are aggregated with the fiber elements to stand for the torsional and shear load carrying properties of the columns. Fig. 4 is the material model of concrete and rebar.

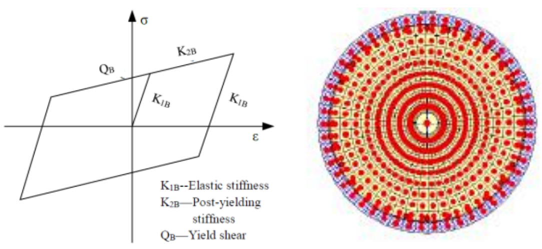


Figure 3. Sketch and bilinear modeling of LRB and fiber element of pier section.

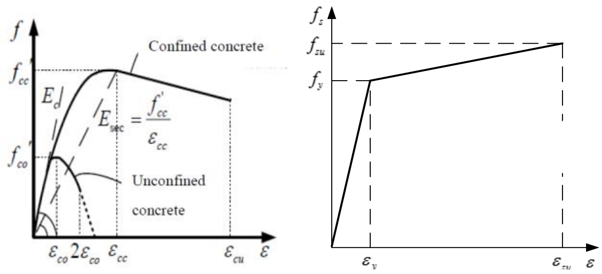


Figure 4. Material model of concrete (left) and rebar (right)

Fig. 5 is the force-displacement relationship of the piers 1# and 2# (pier 4# is the same with 1# and pier 3# is the same with 2#) respectively derived from the pushover analysis. The force-displacement relationship of the column can be roughly approximated by a bilinear curve, which is fully defined by three parameters, namely the elastic stiffness, yield shear, and post-yielding stiffness, which are obtained from the bilinear regression analysis minimizing the difference area between the two curves.

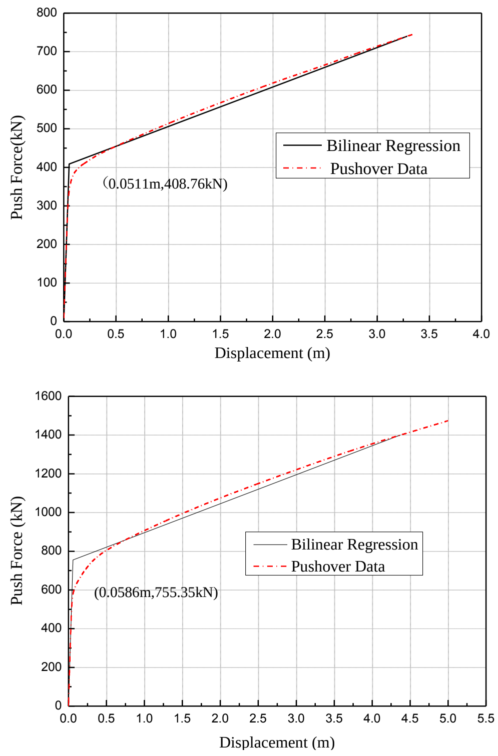
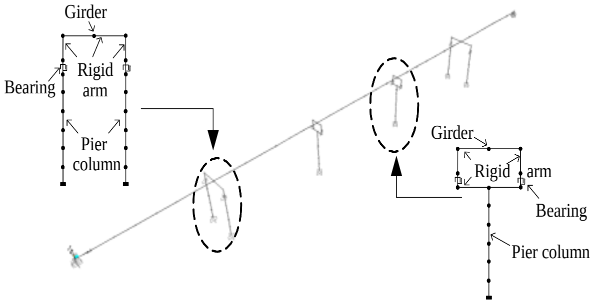


Figure 5. Force-displacement pushover curves of 1# (left) and 2# piers (right)

Based on the finite element analysis software OpenSees, box section girder is modeled with the elastic beam-column element, while the nonlinear beam-column element is adopted in the finite element modeling. Isolation bearing is simulated by combining the zero-length element with uniaxial material model in OpenSees. Set K_2=0.1$K_1$when defining parameters of material models. Rigid arm is used to connect the bearing and girder, which is simulated with elastic beam-column element and the stiffness are set to infinity. Finite element model of the bridge in OpenSees is shown in Fig.

6. Further modal analysis is made using Ritz vector method for the model to acquire dynamic characteristics of the structure.



(c)

Figure 6. Finite element model of continuous girder bridge

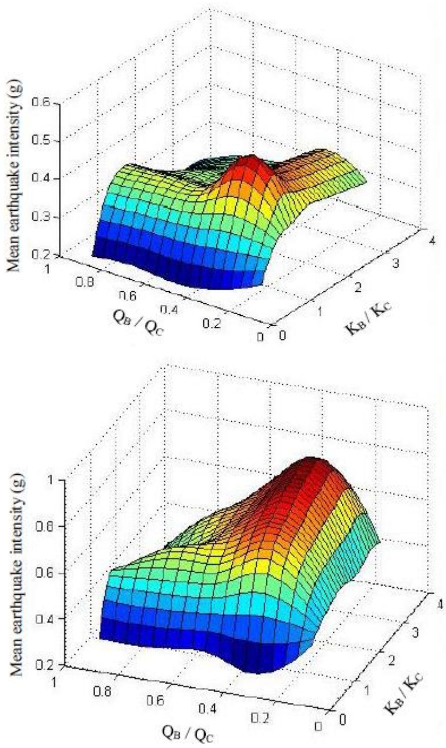


Figure 7. Slight (up) and moderate (down) damage states of the series bridge system

B. Influence of Bearing Parameters on Seismic Fragility of Bridge System

Under ground motion the piers and isolation bearing of the bridge structure will experience different damage state. That only use damage state of one component to describe the damage state of the whole bridge structure is so difficult. For a bridge system under the same earthquake wave the damage probability is higher than a single component. So it is necessary to do some research on the seismic fragility analysis of whole bridge system. From Eq. (1) and Eq. (2), the seismic fragility curve of the whole bridge system is derived. Fig. 1 plots the mean value of the ground motion to reach the slight and moderate damage state for the series bride system. Fig. 3 plots the mean value of the ground motion to reach the slight and moderate damage state for the weighted bride system. The Fig. 7 and Fig. 8 show that there are peak points among the mean value of the earthquake intensity to reach different damage states under the given range of bearing parameter. The peak points on the contours represent the largest mean values of the earthquake intensity required to reach the specified damage states, which also correspond to the best structural performance. The bearing parameters at these peak points therefore represent the optimal design.

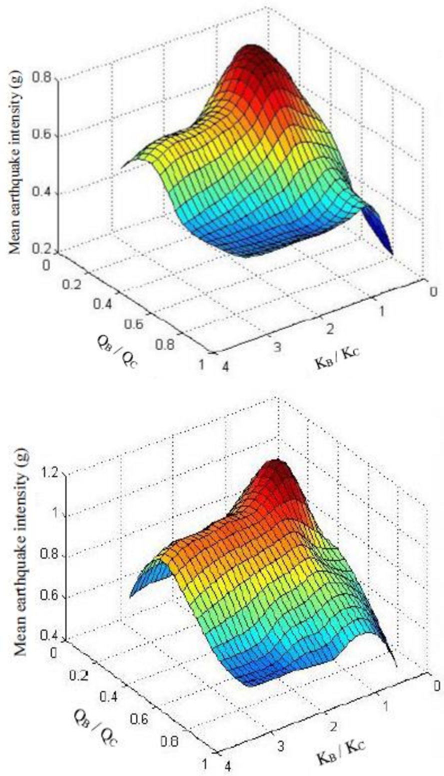
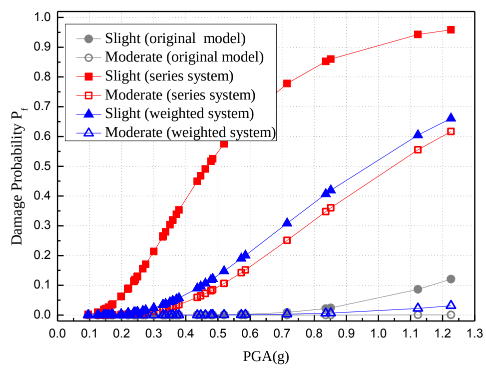


Figure 8. Slight (up) and moderate (down) damage states of the weighted bridge system

C. Application of the Optimum Bearing Parameters

In this section the optimum bearing parameters that were obtained with Multi-objective optimization genetic algorithm will be applied in the isolated continuous girder bridge. The seismic fragility theory will be employed to evaluate the best bearing parameters.

The seismic fragility of bridge piers under isolation continuous girder bridges series model and weighted model are plot as Fig. 9. The maximum horizontal displacement of box-section beam under 50 earthquake records are plot as Fig. 10.



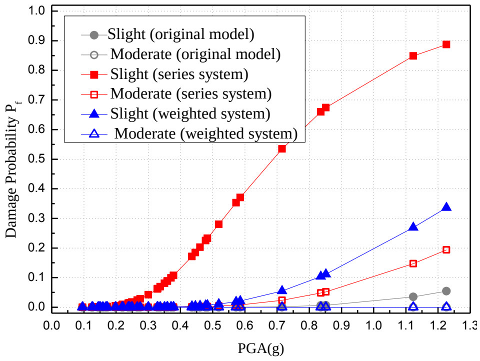
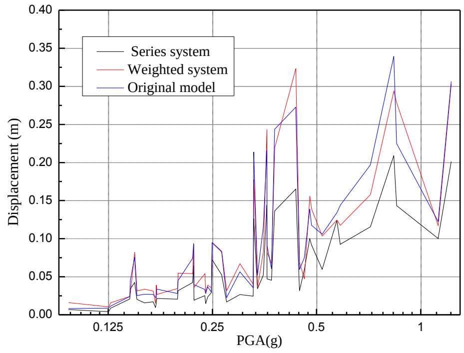


Figure 9. The 1 # pier (left) and 2 # pier (right) seismic fragility curve under different isolation bearing parameter



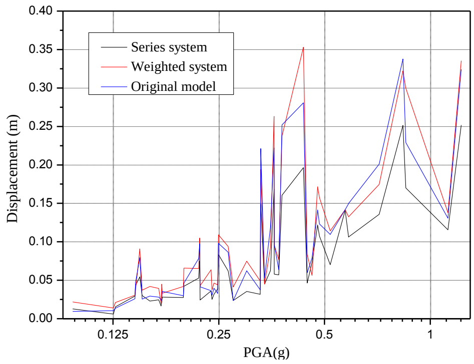
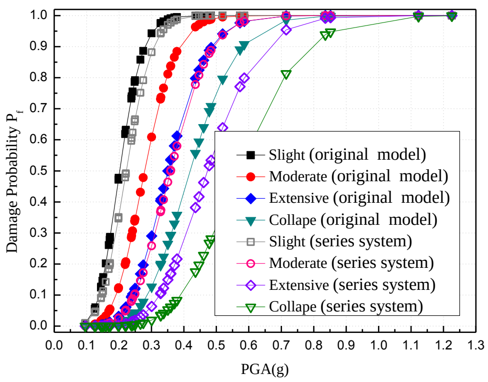


Figure 10. The maximum relative horizontal displacement of the box section girder on 1 # pier (left) and 2 # pier (right) under seismic action

The Fig. 11 shows that the optimum isolation bearing parameters of the series system model can effectively improve the failure probability of bridge system under the earthquake action. However, the seismic fragility of weighting bridge system is similar to original bridge system.



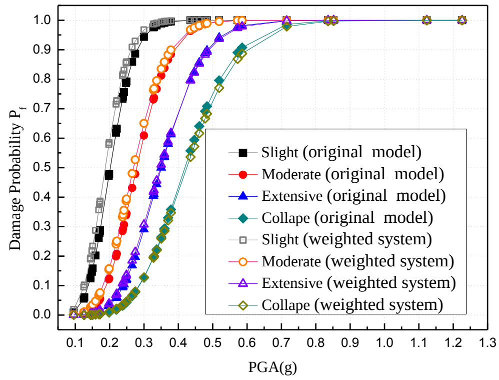


Figure 11. Seismic fragility of series bridge system (up) or weighted bridge system (down) compared to original bearing model

IV. Conclusions

Nonlinear time history analyses are used to investigate the influence of isolation bearing parameters on the seismic fragility of bridge piers and bearings by OpenSees software. The seismic fragility surfaces among bearing parameters, pier features and earthquake intensity are plot. And then least square method is employed to find the fitting polynomial equations of the bridge components seismic fragility surface of which isolation bearing parameters are taken as variables. Using genetic algorithm solved multi-objective optimization equations that are based on series bridge system and weighted bridge system. The conclusions are as following.

(1) This paper uses the least square method to obtain the fitting seismic fragility equation. Using high order polynomial fitting effect would be better, but that will be a big amount of calculation. So the binary quadratic polynomial is adopted for surface fitting in this paper.

(2) Bearing parameters of series system improve the bridge pier participation under earthquake action, and reduce the failure probability of the bridge system effectively. So the optimum isolation bearing parameters of series bridge system can improve the seismic behavior of the continuous girder bridge.

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Xiaohong Long was born in Hubei province of China in 1975. He earned the Ph.D. degree from Huazhong University of Science and Technology (HUST). He is currently an associate professor in school of civil engineering and mechanics at HUST. For the past ten years, he has carried out lots of works in earthquake engineering and seismic base-isolation structures in civil engineering.

Jian Fan was born in Hunan province of China in 1969. He earned the Ph.D. degree from Huazhong University of Science and Technology (HUST). He is currently an associate professor in school of civil engineering and mechanics at HUST. For the past twenty years, he has carried out lots of works in earthquake engineering and seismic base-isolation structures in civil engineering.

Sufei Nie was born in Hubei province of China in 1972. She earned the Ph.D. degree from Huazhong University of Science and Technology (HUST). She is currently a lecturer in school of civil engineering and mechanics at HUST. For the past twenty years, she has carried out lots of works in steel structure.

Yaoting Zhang was born in Hubei province of China in 1965. He earned the Ph.D. degree from Huazhong University of Science and Technology (HUST). He is currently a professor in school of civil engineering and mechanics at HUST. For the past twenty years, he has carried out lots of works in prestressed concrete structure and structure seismic.