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Hysteresis behavior of reinforced concrete bridge pier: A review

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ABSTRACT: Bridge piers which are the bridging point between the superstructure and substructure are vulnerable in earthquakes. Deformation of the bridge piers directly affects seismic performance of bridge structures. Usually, nonlinear hysteretic behavior of the RC bridge pier is the focus issue for seismic analysis of bridge structures. Since RC bridge piers are made of reinforcing bars and concrete, cyclic constitutive relation of both steel and concrete are responsible to determine the overall behavior of reinforced concrete bridge piers. The structural strength and stiffness are influenced by the results of RC material nonlinearity, opening and closing of cracks in concrete, pulling out of steel reinforcement from the concrete matrix, etc., which lead to the complex characteristics of the force-displacement hysteretic curves of the RC piers. In this study a review of hysteresis/seismic behavior of reinforced concrete bridge piers has been made describing different models and experimental tests on different RC bridge piers with different cross sectional shape available in the literature. How different non-linear behavior of structural elements like stiffness degradation, strength degradation, pinching effects, energy dissipation of RC piers and yield strength of longitudinal bars and concrete compressive strength affect the overall seismic performances of bridge are pointed out.

1 INTRODUCTION

A bridge pier is a sort of structure that prolong to the earth below or into the water. It is used to support bridge superstructure and transfer the loads to the foundation. The bridge piers can be constructed to be substantially attractive and strong in order to withstand both vertical and horizontal loads. It also does not hinder water flow or tide if the bridge spans the water.

Bridge piers, acting as the important bridge component supporting the superstructure and transferring the upper load to the foundation, are vulnerable in earthquakes. So the bearing capacity and deformation of the bridge piers directly affect seismic performance of bridge structures. Especially, how to exactly describe the nonlinear hysteretic behavior of the RC bridge pier is the focus issue for seismic analysis of bridge structures. The structural strength and stiffness are influenced by the results of RC material nonlinearity, opening and closing of cracks in concrete, pulling out of steel reinforcement from the concrete matrix, etc., which lead to the complex characteristics of the force-displacement hysteretic curves of the RC piers (Han et al., 2014).

It has been shown by dynamic analyses that the theoretical response inertia loads of structures responding elastically to severe earthquake ground motions are significantly greater than the static design lateral loads. However, it would be very uneconomical to design structures to respond elastically to such high inertia loads. Hence, if the structures are to survive through such severe earthquakes, some means of energy dissipation need to be provided. So, unless devices such as mechanical energy dissipators are incorporated in the design, the structures must possess sufficient ductility so that seismic energy can be absorbed and dissipated by some form of post-elastic deformation (Ang, 1981).

In Japan, Kawashima and others have tested around 50 concrete bridge columns using quasi staticmethods. The purpose of testing has been related to various objectives such as the effect of loading hysteresis on ductility, effect of interlocking ties on strength and ductility, verifying plastic hinge lengths, etc (Bechtoula et al. 2014).

As concrete is a mixture of different materials and there is micro-crack in nature, the damage mechanism of concrete is inherently initiated from micro crack developing to macro-crack, and eventually from macro-crack developing to material failure. In the past experiments, it has been found that the skeletal of the stress-strain curve of concrete is very close to its uniaxial stress-strain curve (Li and Li, 2007).

To ensure that the seismic performance of the structure meets the design requirements, the engineering designer must apply a strict elasto-plastic calculation analysis of the structures. As the basis of elasto-plastic calculation analysis, the hysteresis model that can accurately reflect the strength and stiffness degradation, deformation performance, and energy dissipation capacity of structures and members under cyclic repeated loading is required (Wang et al. 2019).

Dissipation of hysteresis energy in the isolator of the base isolated structure under seismic excitation is investigated in many literatures. The hysteresis force-deformation characteristics of the base isolator is specified by a nonlinear differential equation. The parameters of the equation can be adjusted to obtain various types of hysteresis models of the isolator including the elasto-plastic type. The variation of hysteretic energy dissipated in the isolators is obtained for both harmonic and EI Centro 1940 earth quake ground motion for a set of important parameters. They include time period of superstructure, ratio of superstructure mass to base mass, level to yield strength of the isolator, post to pre-yielding stiffness ratio, and the ratio of harmonic excitation frequency to base isolation frequency. It is shown that the dissipation of hysteretic energy in the isolator is significantly influenced by the above parameters (Jangid and Datta, 1996).

The purpose of this review paper is to show the importance to understand the hysteresis behavior of reinforced concrete bridge pier, the parameters affecting the hysteresis behavior and its influence on the seismic performance of bridge.

2 LITERATURE REVIEW

In this section different experimental tests, numerical and analytical studies, review papers from available literature are described where different non linear behavior, hysteretic energy dissipation, influence of constitutive relation of steel and concrete on the behavior of reinforced concrete members are reflected**.**

Kawashima and Koyama (1988) conducted a series of dynamic loading tests with use of three different symmetrical loading hysteresis with loading velocity of 2.4 mm/sec over five large-size specimens with shear-span ratio of 6.8, which failed in flexure to study the effect of loading hysteresis on strength and energy dissipation capability of reinforced concrete bridge piers. Based on the test results the conclusions were - (1) Effects of loading hysteresis are less significant on the maximum load, and equivalent stiffness of the specimens. However, energy dissipation capabilities in terms of accumulated energy dissipation and equivalent hysteretic damping ratio depends on the loading hysteresis. (2) Progress of failure which was caused by the previous load reversals is not significantly developed unless the loading displacement is larger than that of the previous one. (3) Skeleton curve of the hysteresis loop depends on the loading path. Consequently, prediction of the time at which the peak response displacement is developed is quite important for nonlinear response of reinforced concrete bridge piers.

Pandey et al. (2004) revealed that the unbonded columns showed larger seismic displacement than that of ordinary RC column due to smaller amount of energy absorption. The main purposes of this study was to investigate the possible enhancement of seismic performance of RC columns by controlling bond of longitudinal reinforcement and to analyze seismic response behavior of RC columns with unbonded reinforcement.

Ongsupankul et al. (2007) studied the behavior of six bridge pier column models with different amount and arrangement of tie bars subjected to constant axial load and cyclic lateral load experimentally. The cyclic loading tests and verification by fiber element analysis were conducted. It was found that increasing the amount of tie bars does not affect the maximum lateral load force and the yield lateral force. Increasing the amount of tie bars increases the maximum deflection and ductility ratios of the specimens.

Han et al. (2014) developed an improved nonlinear hysteresis model for RC bridge piers considering stiffness and strength degradation and pinching effect based on classical Bouc-Wen model. The various controlling parameters for the improved model were determined, and the improved model can be carried out to predict the nonlinear hysteresis behavior of RC bridge piers and various failure modes using MATLAB/Simulink program. The results of cyclic tests of bridge column specimens with different failure modes showed force-displacement relationship hysteresis curves of bridge column specimens derived from theoretical analysis are well agree with experimental results.

It is found from Chowdhury and Hassan (2014) that in order to get real response of seismic analysis of RC structures reinforced with high-strength steel, it is necessary to implement appropriate steel model with cyclic constitutive characteristics in the RC model and cyclic test of RC members to know the hysteretic energy dissipation and drift.

Pahwa and Gupta (2014) found that unexpected vulnerability in the bridge structures is due to considerable damages in their reinforced concrete piers, which implies that the non-linear behavior of these structural elements during intense earthquakes remains an important issue, both for designers and researchers.

Kehila et al. (2015) found that loading history and axial load intensity had a great influence on the performance of piers, especially concerning strength and stiffness degradation as well as the energy dissipation. Controlling these parameters is one of the keys for an ideal seismic performance for a given structure during an eventual seismic event.

Rong et al. (2015) investigated four rectangular reinforced concrete bridge piers, including one common reinforced concrete bridge pier specimen and three specimens with HRB500 steel. The effect of axial compression ratio, the longitudinal reinforcement and the stirrup strength grade on specimens' hysteretic behavior were analyzed. The findings were - high strength stirrup and longitudinal reinforcement can improve the hysteretic behavior of bridge piers and reducing the axial compression ratio has a good effect on the hysteretic behavior of the bridge pier.

Wang et al. (2019) tested eight Steel Reinforced Concrete (SRC) frame column specimens under combined axial compression and lateral cyclic load. Based on the test results, a hysteresis model was developed to simulate the hysteresis behavior of the SRC frame columns, and conclusions were obtained as follows: (1) In the elastic stage, the hysteresis behavior of the SRC frame columns is similar to the reinforced concrete frame columns but in the inelastic stage, due to the mutual constraint between steel and concrete, the bearing capacity of steel and concrete is improved. (2) With the increase of the axial compression ratio and steel ratio, the seismic performance of the frame column is enhanced. The stirrups ratio has the little effect on the seismic performance of the frame column before the peak load. However, after the peak load, the energy dissipation capacity and the ductility of the members is enhanced with the increase of the stirrups ratios.

To investigate the influence of yield strength of longitudinal steel bars and concrete compressive strength on the seismic performance of reinforced concrete (RC) bridge piers, Su et al. (2019) performed cyclic loading tests of ten large scale RC bridge piers of circular section and rectangular section with different longitudinal steel bars grades and concrete compressive strengths. The test results indicated that all RC bridge piers showed typical flexural failure mode while circular piers showed better deformability and hysteretic energy dissipation than rectangular piers. Replacing conventional steel bars with same amount of high-strength longitudinal steel bars (i.e. equivalent volume replacement) increased the lateral bearing capacity, the yield displacement and the total deformation. Due to the increase in yield displacement, the displacement ductility, the viscous damping ratio and the residual displacement reduced to some extent. Still, the RC piers reinforced with high-strength steel bars (HSSB) showed larger plastic deformation and hysteretic energy dissipation because of greater total deformation and bearing capacity. The transverse reinforcement configurations of circular section provide better restraint to the buckling of longitudinal steel bars than rectangular section, thereby RC bridge piers with circular section show better deformability and hysteretic energy dissipation than rectangular section. The increase in concrete compressive strength reduces the yield displacement, thus enhances the hysteretic energy dissipation and viscous damping ratio at same total deformation. It was also found that the effect of concrete compressive strength on the seismic performance of rectangular section is more remarkable than circular section. Replacing conventional longitudinal steel bars with reduced amounts of high-strength steel bars (i.e. equivalent strength replacement) provided comparable flexural strength and deformation capacity, but reducing the residual displacement and hysteretic energy dissipation.

3 CONCLUSIONS

Nonlinear hysteretic behavior of the RC bridge pier is the focus issue for seismic analysis of bridge structures. The structural strength and stiffness are influenced by the results of RC material nonlinearity, opening and closing of cracks in concrete, pulling out of steel reinforcement from the concrete matrix, etc., which lead to the complex characteristics of the force-displacement hysteretic curves of the RC piers. Under severe earthquakes to survive bridge structures some means of energy dissipation need to be provided. In this study, different cyclic experimental tests, numerical and analytical models of Reinforced Concrete Bridge Piers from available literature is described and it is concluded that internal energy dissipation of the structure depends on the hysteresis loops of the bridge piers, cyclic constitutive relation of Steel and Concrete. Along with energy dissipation, also non-linear behavior of structural elements like stiffness degradation, strength degradation, pinching effects, yield strength of longitudinal bars and concrete compressive strength influence the overall seismic performances of bridge. For this reason non-linear behavior of such structural elements during earthquakes is an important issue for designers as well as researchers.

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