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Research Paper

A STUDY ON SEISMIC BEHAVIOR OF REINFORCED CONCRETE BRIDGE PIERS

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A bridge is a structure built to span physical obstacles such as a body of water, valley, or road, for the purpose of providing passage over the obstacle. The function of a structure during and after an earthquake usually dictates the methodology employed in the design of the structure. Lifeline structures, such as bridges, are assigned a much higher "importance" factor in the design process since these structures are "essential facilities" necessary for emergency operations subsequent to an earthquake. Such structures should resist minor earthquakes without damage, moderate earthquakes without significant structural damage, and in the case of a major earthquake, some structural and non-structural damage is allowed, but it does not affect the functioning of the structure after the earthquake. The 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. A study is carried out for the seismic performance of reinforced concrete bridge piers.

Keywords: Bridge, Bridge Piers, Non-linear behavior, Seismic performance, Inelastic flexural behavior

INTRODUCTION

The function of a structure during and after an earthquake usually dictates the methodology employed in the design of the structure. Lifeline structures, such as bridges, are assigned a much higher "importance" factor in the design process since these structures are "essential facilities" necessary for emergency operations subsequent to an earthquake. Such structures should resist minor earthquakes without damage, moderate earthquakes without significant structural damage, and in the case of a major earthquake, some structural and non-structural damage is allowed, but it does not affect the functioning of the structure after the earthquake (Sashi *et al.,* 1997).

A bridge is a structure built to span physical obstacles such as a body of water, valley, or road, for the purpose of providing passage over the obstacle. There are many different designs that all serve unique purposes and apply to different situations. Designs of bridges

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vary depending on the function of the bridge, the nature of the terrain where the bridge is constructed and anchored, the material used to make it, and the funds available to build it.

Single-span bridges have abutments at each end that support the weight of the bridge and serve as retaining walls to resist lateral movement of the earth enfill of the bridge approach. Multi-span bridges require piers to support the ends of spans between these abutments. In cold climates the upstream edge of a pier may include a starkwater to prevent accumulation of broken ice during peak snowmelt flows. The starkwater has a sharpened upstream edge sometimes called a cutwater. The cutwater edge may be of concrete or masonry, but is often capped with a steel angle to resist abrasion and focus force at a single point to fracture floating pieces of ice striking the pier. In cold climates the starling is typically sloped at an angle of about 45° so current pushing against the ice tends to lift the downstream edge of the ice translating horizontal force of the current to vertical force against a thinner cross-section of ice until unsupported weight of ice fractures the piece of ice allowing it to pass on either side of the pier.

Bridges

A bridge is a structure providing passage over an obstacle without closing the way beneath. The required passage may be for a road, a railway, pedestrians, a canal or a pipeline. The obstacle to be crossed may be a river, a road, railway or a valley. In other words, bridge is a structure for carrying the road traffic or other moving loads over a depression or obstruction such as channel, road or railway. A bridge is an arrangement made to cross an obstacle in the form of a low ground or a stream or a river without closing the way beneath.

Components of Bridges

The bridge structure comprises of the following parts.

Superstructure or Decking

This includes slab, girder, truss, etc. This bears the load passing over it and transmits the forces caused by the same to the substructures.

Bearings

The bearings transmit the load received from the decking on to the substructure and are provided for distribution of the load evenly over the substructure material which may not have sufficient bearing strength to bear the superstructure load directly.

Substructure

This comprises piers and abutments, wing walls or returns and their foundation.

- **Piers and Abutments:** These are vertical structures supporting deck/bearing provided for transmitting the load down to the bed/earth through foundation.
- **Wing walls and Returns:** These are provided as extension of the abutments to retain the earth of approach bank which otherwise has a natural angle of repose.
- **Foundation:** This is provided to transmit the load from the piers or abutments and wings or returns to and evenly distribute the load on to the strata. This is to be provided sufficiently deep so that it is not affected by the scour caused by the flow in the river and does not get undermined. While the above mentioned are structurally operational parts,

for safety hand rails or parapets, guard rails or curbs are provided over the decking in order to prevent vehicle or user from falling into the stream or for the separation of traffic streams.

Bridge Piers

A pier is an intermediate substructure unit located between the ends of a bridge. Its function is to support the bridge at intermediate intervals with minimal obstruction to the flow of traffic or water below the bridge. Piers provide vertical supports for spans at intermediate points and perform two main functions: transferring superstructure vertical loads to the foundations and resisting horizontal forces acting on the bridge. Although piers are traditionally designed to resist vertical loads, it is becoming more and more common to design piers to resist high lateral loads caused by seismic events. Even in some low seismic areas, designers are paying more attention to the ductility aspect of the design. Piers are predominantly constructed using reinforced concrete. Steel, to a lesser degree, is also used for piers. Steel tubes filled with concrete (composite) columns have gained more attention recently.

Pier is usually used as a general term for any type of substructure located between horizontal spans and foundations. However, from time to time, it is also used particularly for a solid wall in order to distinguish it from columns or bents. From a structural point of view, a column is a member that resists the lateral force mainly by flexure action whereas a pier is a member that resists the lateral force mainly by a shear mechanism. A pier that consists of multiple columns is often called a bent.

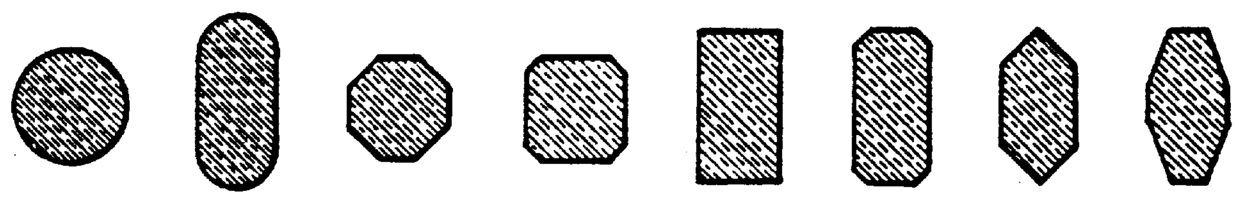
There are several ways of defining pier types. One is by its structural connectivity to the superstructure: monolithic or cantilevered. Another is by its sectional shape: solid or hollow; round, octagonal, hexagonal, or rectangular. It can also be distinguished by its framing configuration: single or multiple column bent; hammerhead or pier wall.

Design Loads

Piers are commonly subjected to forces and loads transmitted from the superstructure, and forces acting directly on the substructure. Some of the loads and forces to be resisted by the substructure include:

1. Dead loads.
2. Live loads and impact from the superstructure.
3. Wind loads on the structure and the live loads.
4. Centrifugal force from the superstructure.
5. Longitudinal force from live loads.

Typical Cross-section Shapes of Piers for Overcrossings or Viaducts on Land



6. Drag forces due to the friction at bearings.
7. Earth pressure.
8. Stream flow pressure.
9. Ice pressure.
10. Earthquake forces.
11. Thermal and shrinkage forces.
12. Ship impact forces.
13. Force due to prestressing of the superstructure.
14. Forces due to settlement of foundations.

The effect of temperature changes and shrinkage of the superstructure needs to be considered when the superstructure is rigidly connected with the supports. Where expansion bearings are used, forces caused by temperature changes are limited to the frictional resistance of bearings (WISDOT Manual).

LITERATURE REVIEW

The construction of reinforced concrete bridges has become widely used in many countries. Researches on the seismic behavior of reinforced concrete bridge piers are described below:

"Cumulative Seismic Damage of Reinforced Concrete Bridge Piers", Sashi K Kunnath, Ashraf El-Bahy, Andrew W Taylor, William C Stone, investigated the cumulative damage in reinforced concrete circular bridge piers. Twelve identical quarter-scale bridge columns, designed and fabricated in accordance with current AASHTO specifications, were tested in two phases. Phase-I testing consisted of benchmark tests to establish the monotonic force-deformation envelop, the energy capacity under standard cyclic loads, and constant amplitude tests to determine the low-cycle fatigue characteristics of the bridge column. Phase-II testing was composed of a series of analytically predicted displacement amplitudes representing the bridge response to typical earthquakes. The results of phase-I testing provided information on the fatigue behavior of reinforced concrete and phase-II provided data on the effects of load path on cumulative damage.

Test observations indicate two potential failure modes: low cycle fatigue of the longitudinal reinforcing bars and confinement failure due to rupture of the confining spirals. The former failure mode is associated with relatively large displacement amplitudes in excess of 4% lateral drift while the latter is associated with a large number of smaller amplitude cycles. The results of the testing were also used in an analytical study of cumulative damage. It was observed that the energy dissipation capacity of members is path-dependent, hence, models of seismic damage that rely on measures of energy dissipation cannot predict failure if it is not related to ductility.

"The Behavior of Reinforced Concrete Piers Under Strong Seismic Actions", Luca Martinelli, formulated the finite element model for the pier end zones to capture interaction between shear resistance and inelastic flexural behavior in reinforced concrete bridge piers, subjected to seismic excitation. In the following, the element kinematics, the modelling of the shear resisting mechanisms together with material models and some comparison with experimental results are presented.

When subjected to strong cyclic horizontal loading, Reinforced Concrete (RC) bridge piers can suffer from many different possible failures. Among these, as it has been recently recognized, shear failure deserves particular care, not only for its brittle character, but also because shear resistance is due to the interaction of several different mechanisms: beam action, arch action and truss action. The proposed model has been able to reproduce the behavior of structural members strongly influenced by shear; simplifications of adopted material models appear possible. In this respect a simpler uniaxial constitutive law for concrete able to model crack bridging is highly desirable. Among the possible applications, the model will be used to study the dynamic behavior of complete 3-D bridges having non slender piers.

"Seismic Behavior of R/C Bridge Piers: Numerical Simulation and Experimental Validation", Rui Faria, Nelson Vila Pouca and Raimundo Delgado, presented a constitutive model suitable for reproducing the seismic behavior of hollow section bridge piers. They described a numerical model suitable for simulating the non-linear behaviour of reinforced concrete under seismic loading. Basically a recent constitutive model founded on Damage Mechanics is used for the concrete itself, incorporating two independent scalar damage variables to reproduce degradation produced under tensile or compressive stress conditions.

According to this research in the recent Los Angeles and Kobe earthquakes most of the unexpected vulnerability was 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. For validation descritized 2D finite element models were analyzed. A validation of the model devised for the analysis of R/C bridge piers under cyclic loading will be based on a 'case study' pier, whose performance during pseudodynamic tests is reported in (Guedes, 1997). This pier was firstly submitted to a monotonic loading in order to evaluate the static horizontal collapse load, and afterwards to a cyclic loading, in order to assess its dissipative behavior. The comparison of the model predictions with the available experimental results showed a very good agreement, and evidenced the ability of the proposed R/C model to simulate the seismic behaviour of this kind of bridge piers.

"Seismic Damage Mitigation of Reinforced Concrete Bridge Piers By Unbonding Longitudinal Reinforcements", 13th World Conference on Earthquake Engineering, Vancouver, BC., Canada, August 1-6, 2004, revealed that the unbonded columns show larger seismic displacement than that of ordinary RC column due to smaller amount of energy absorption. The main purposes of this study are 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.

According to this research, the recent major earthquakes such as Hyogo-ken Nanbu earthquake in 1995 (hereafter Kobe Earthquake) showed that most of the fatal collapses of RC structures were caused by shear failure. Design codes in Japan, subsequently revised, demand a large quantity of shear reinforcement to prevent shear failure and to maintain sufficient ductility. The resulting design comprises of the shear reinforcements with a very high volumetric ratio, which creates negative impact both in terms of constructability and economy. In an attempt to find some alternative methods to handle this issue without the conventional reliance on shear reinforcements alone, an investigation was carried out to examine the enhancement of seismic performance of reinforced concrete columns such as shear strength and ductility by controlling bond of longitudinal reinforcements. Six 300 x 300 mm square RC columns were tested under reversed cyclic loading. Three different bond conditions varying from the perfect bond with the use of ordinary deformed bars to the perfect unbond by completely eliminating bond between steel and concrete were employed in the experiment. Test results showed that this method is very effective in completely altering the failure mode at the ultimate state from shear to flexure. This method was also found to produce remarkable improvement in the ductility of RC columns.

"Behavior of Reinforced Concrete Bridge Pier Columns Subjected to Moderate Seismic Load", Sumnieng Ongsupankula, Torkul Kanchanalaib and Kazuhiko Kawashimac, reported the strength and ultimate displacement of the square columns having different amount and arrangement of tie bars. This research investigated the behavior of typical reinforced concrete bridge piers of six 400 mm × 400 mm square columns. The columns were subjected to constant axial load and cyclic lateral load. The tests were conducted at Kawashima laboratory of department of civil engineering, Tokyo institute of technology. The fiber element inelastic analyses were conducted and compared with the experiment results. 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 was studied experimentally. The cyclic loading tests and verification by fiber element analysis were conducted. It can be 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. The criterion of limiting lateral strain in inner core gave satisfactory estimate of the column deflection. Further analytical study of six specimens with the tie reinforcement ratios varying in the range of 0.19% to 0.56% and subjected to varying cyclic loads was conducted.

"Residual Seismic Performance of Reinforced Concrete Bridge Piers After Moderate Earthquakes", Young-Soo Chung, Chang Kyu Park, and Christian Meyer, conducted an investigation to evaluate the seismic ductility of previously damaged concrete columns. Eight circular concrete columns 600 mm (23.6 in.) in diameter and 1500 mm (59.0 in.) in height were constructed with three test parameters: confinement ratio, lap-splice of longitudinal steel, and retrofitting

Fiber-Reinforced Polymer (FRP) materials. The objective of this research was to subject Reinforced Concrete (RC) bridge piers to artificial earthquake motions using a Pseudo-Dynamic Test (PDT), and then to examine their seismic performance in a Quasi Static Test (QST). Test results showed that RC bridge piers damaged during a series of probable earthquake ground motions of the pseudodynamic test retain good residual seismic resistance and that retrofitting them with fiber composite wraps in the potential plastic hinge region is an effective way of enhancing their flexural ductility even for a flexural shear failure mode. Lapspliced RC piers are especially vulnerable and need to be retrofitted to secure good seismic performance in subsequent earthquakes. The eight scale-model tests of RC bridge piers reported herein permit to draw the following conclusions:

1. During earthquake motions with 0.22 g PGA in a PDT, all test specimens behaved almost linear elastically with minor damage.
2. Ordinary RC bridge piers with lap-spliced longitudinal reinforcement in the plastic hinge region, that is, without regard for seismic design provisions, exhibited much lower displacement and curvature ductilities than those without such splices.
3. Retrofitting measures considerably increased the lateral strength and ductility of test specimens to values comparable with those of specimens designed for limited seismic response.

"Inelastic Seismic Response Analyses of Reinforced Concrete Bridge Piers With Three-Dimensional FE Analysis Method", Guangfeng Zhang, Shigeki Unjoh, provided an analysis method for simulating the seismic behavior of a RC pier under multi-directional seismic excitation. Three-dimensional elasto-plastic finite element method was adopted with a purpose to make it possible to consider the failure mode of flexure-shear failure at the termination location of the main rebar. Two RC pier specimens, in which one failed in flexure failure at the base of the pier and the other failed in flexure-shear failure at the main rebar termination location, were analyzed and the validity of the analysis method was discussed. Discussion results show that the analyses provided a successful identification of the failure mode and a good simulation of the seismic behavior before the effect of concrete cover spalling over the responses become dominant.

An analysis method for simulating the seismic behavior of a RC pier under multi-directional seismic excitation was proposed based on three-dimensional FEM in this paper. Two RC pier specimens, in which one without main rebar termination failed in flexure failure at the base of the pier in test and the other with main rebar termination failed in flexure-shear failure at the main rebar termination location, were analyzed and the validity of the analysis method was confirmed by comparing the natural period of the test system, response displacement and damage progression of the piers.

Discussion results show that the analyses provided a successful identification of the failure mode and a good simulation of the seismic behavior before the effect of concrete cover spalling over the responses become dominant. However, the final failure stage involving concrete cover spalling off and shear failure initiated from the main rebar termination location can not be simulated by the current method. This becomes an issue in the next research stage.

"Design and Construction Highway Piers with Interlocking Hoops in Japan", Kazuyuki Mizuguchi, Norimasa Higashida, Koji Osada, Gaku Ohashi, presented a summary of experimental results carried out by J H and others, and analyzes the applicability of bridge piers with interlocking hoops to typical expressways in Japan in terms of cost performance, constructability, and application range. The construction of interlocking four hoops is introduced.

Bridge piers with interlocking hoops offer high restraining effects and help reduce the volume of reinforcing steel as well as enhance constructability. Starting around the mid-1970's, bridge piers having interlocking hoops appeared in California, USA, and the interlocking hoop reinforcement system was adopted by AASHTO in its standards in 1977 and by CALTRANS in 1990.

In Japan, a study on interlocking-hoop bridge piers began around 1997. In 1997, bridge piers with two interlocking hoops were built for the first time in Japan for the Trans Chubu Expressway constructed by the Japan Highway Public Corporation (JH). In 2001, reinforcement using four interlocking hoops was applied to wall bridge piers at the third work section in expressway construction. With the demand for lower cost and higher concrete quality getting greater, more use of interlocking hoops in bridge piers is expected.

"Experimental Study on Seismic Performance of a Precast Reinforced Concrete Bridge Pier", Satoru Nonaka, Masahiro Nakai, Shigeki Unjoh, Junichi Sakai, conducted a shake table test to investigate the dynamic behavior of a precast RC pier during earthquakes. The experimental result showed that the precast RC pier performed similar to a conventional RC pier in the viewpoint on hysteresis and energy-absorbing capacity. Nonlinear dynamic analysis was conducted to simulate the behavior of the test specimen. The analytical result calculated by using the same model of conventional RC piers showed good correlation with the test result. From these results, it was concluded that the dynamic behavior of the precast RC piers with structural conditions proposed in this study can be simply evaluated using a similar method to that used for conventional RC piers. The construction steps of the method proposed in this research is as follows:

1. Precast segment produced at the factory is transported to the construction site.
2. Precast segment is piled up. Epoxy resin is spread on the bonded surface between segments.
3. Prestressing force necessary to push and to expand epoxy resin between the segments is applied.
4. The high strength mortar is grouted into the sheath.
5. Longitudinal reinforcing bars are inserted into the sheath to connect the piled up segments.

Following conclusions were made from the analysis:

1. The hystereses of precast RC pier showed similar properties to conventional RC piers. The lateral force was larger than the calculation result based on 2002 JRA design specifications. Moreover, even when the response displacement was exceeded the displacement capacity, the lateral force did not decrease.
2. The analytical result which used the same model of conventional RC piers showed good correlation with the test result. From these results, it was concluded that dynamic behavior of precast RC pier and conventional RC pier can be evaluated in a similar method.

Authors View: From the past experiences it is observed that there are some important deficiencies in the behavior of bridges. Most of this unexpected vulnerability was due to considerable damages in their reinforced concrete piers, which implies that the non-linear behaviour of these structural elements during intense earthquakes remains an important issue, both for designers and researchers. To overcome from this issues strut and tie model is proposed by some researchers. Further the study to validate this remedial measure can be performed and can improve the performance of bridge piers.

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