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Seismic inspection and seismic strengthening method of reinforced concrete bridge piers

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ABSTRACT : This paper presents an experimental study on seismic inspection and seismic strengthening methods for reinforced concrete bridge piers with termination of the main reinforcement at mid-height without enough anchorage length. The effect of the anchorage length of main reinforcement was studied through dynamic loading tests of 13 reinforced concrete pier specimens. A seismic inspection method to evaluate the vulnerability to developing serious damage at termination zone is proposed. In order to develop a seismic strengthening method using a steel jacket for vulnerable reinforced concrete bridge piers, the effect of the length of a steel jacket and the effect of injection material were also experimentally studied.

1 INTRODUCTION

During recent earthquakes including the Miyagi-ken-oki Earthquake of 1978 and the Urakawa-oki Earthquake of 1982, reinforced concrete piers of highway bridges have suffered serious damage at mid-height. The importance for this type of damage became apparent when a bridge was critically damaged during the Urakawa-oki Earthquake in 1982. The Shizunai bridge which is of five-span continuous girders and reinforced concrete piers suffered destructive damage at the pier as shown in Photo 1. Significant shear failure was developed at mid-height of reinforced concrete piers, where half of main reinforcement was terminated without enough anchorage length.

Before the Design Specifications of Highway Bridges were revised in 1980, anchorage length of main reinforcement terminated at tension zone was only 20 - 30 times a diameter of reinforcing bars. Longer length of either 20 times the diameter plus effective width of the piers or the length up to the point where the stress of the reinforcing bar becomes half of the allowable stress is now taken as the anchorage length.

In order to develop a seismic inspection method and a seismic strengthening method for reinforced concrete bridge piers which have high vulnerability to develop serious damage due to such termination of main reinforcement, a series of dynamic loading tests was conducted at the Public Works Research Institute.

This paper proposes a seismic inspection method and a seismic strengthening method for reinforced concrete piers with termination of main reinforcement at mid-height.

2 TEST SPECIMENS AND LOADING CONDITIONS

2.1 Test Specimens

Thirteen specimens were constructed for verifying the vulnerability. The scale of the specimens is assumed to be about 1/5 of a prototype pier.

Among 13 specimens, 11 specimens were for square sections of 50cm × 50cm. The shear span ratio was assumed as 5.4 (4 specimens), 9.9 (3 specimens) and 5.6 (6 specimens). Two more specimens were constructed to study the effect of cross sectional shape. One is for circular hollow section with an outer diameter of 60cm and an inner diameter of 41.6cm. The shear span ratio is 4.9. The other is for wall type section of 40cm× 160cm. The shear span ratio is 7.1. Anchorage lengths of main reinforcement terminated at mid-height, axial force and main reinforcement ratio are varied in these specimens.

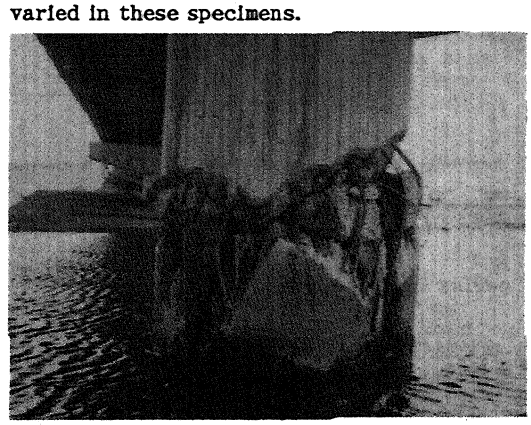

Photo 1 Damage of Shizunai Bridge during Urakawa-oki Earthquake in 1982

Eleven more specimens were constructed for verifying the effectiveness of a steel jacket for seismic strengthening. Tests were made for circular hollow (4 specimens), square (4 specimens) and wall type (3 specimens) piers. Parameters considered in the tests are lengths of steel jacket and injection material between steel jacket and concrete.

2.2 Loading Conditions

Specimens were laterally loaded at the top with the footing being fixed to a test floor. They were subjected to an axial loading as shown in **Photo 2**. An electro-hydraulic dynamic actuator and a static jack were used for the lateral loading and axial loading, respectively.

The specimens were subjected to a reversed cyclic lateral loading under displacement control as shown in **Fig.1**. The displacement developed at the pier crest when the main reinforcement yielded at the base is defined hereinafter as the yield displacement $\delta_{\square}$.

Extensive electric instrumentation was used to measure and record the basic deformation parameters such as the strain in the main and tie reinforcement as well as the displacement and acceleration at the loading point.

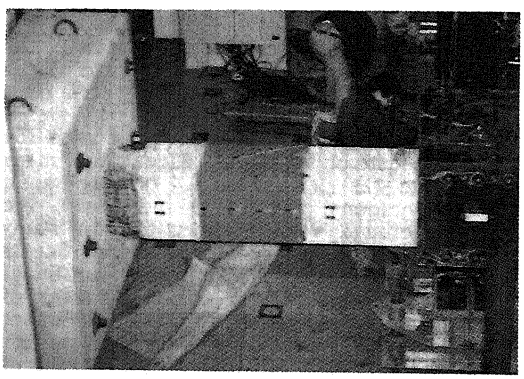

Photo 2 Loading Tests of Reinforced Concrete Pier with Termination of Main Reinforcement at Mid-Height (Square Section)

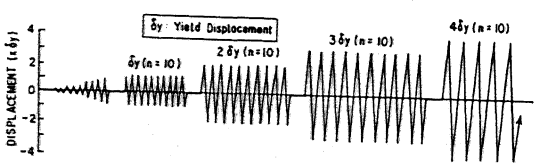

Fig.1 Step-wise Increasing Symmetric Loading Displacement

3 VULNERABILITY OF REINFORCED CONCRETE PIERS WITH INADEQUATE ANCHORAGE LENGTH

Because failure process of all 13 specimens cannot be presented here, description is given only for 4 specimens (Specimens P-10, P-14 ~ P-16) which have a square section of 50cm × 50cm and a shear span ratio of 5.4. They gives the typical failure mechanism of the reinforced concrete bridge piers with inadequate anchorage length at termination zone. Only anchorage length was varied among the 4 specimens as shown in **Fig.2** with other conditions being the same. Forty deformed reinforcing bars with a diameter of 13mm and yield strength of 3,000kgf/cm^2 were placed as main reinforcement so that main reinforcement ratio is 2.03% at the base. Round reinforcing bars with a diameter of 9mm and yield strength of 2,400kgf/cm^2 were placed every 25cm as tie reinforcement. The tie reinforcement ratio was 0.1%.

In Specimen P-10, all reinforcements are continuous from the base to the top without termination at mid-height. In Specimen P-14, the main reinforcement is terminated at the point where the stress induced in the reinforcement becomes one half of the allowable stress. Therefore, no anchorage length was provided in Specimen P-14. On the other hand, Specimens P-15 and P-16 were constructed with the anchorage length of D/2 and D, respectively, in which D represents the width of the cross section (D = 50cm).

Fig.3 shows the failure mode of the specimens. In Specimen P-10, flexural cracks were firstly developed at the base. As the loading increased, the cracks progressed and spalling-off of the cover concrete developed. The specimen failed finally in flexure at the base.

In Specimen P-14, which had zero anchorage length, flexural cracks were firstly developed at the termination zone. The flexural cracks progressed and the specimen failed finally in shear at the termination zone.

In Specimen P-15, which had an anchorage length of D/2, flexural cracks were developed at both the termination zone and the base of the pier. As the loading increased, the cracks at the base progressed significantly, and the specimen failed finally in flexure at the base.

In Specimen P-16, which had an anchorage length of D, the failure mode was almost the same with that of Specimen P-10. The anchorage length of D was considered to be sufficient to prevent failure at the termination zone.

Based on the test results of 4 specimens, the location where the cracks firstly occurred is closely related with the location where failure would eventually occur.

Fig.4 compares the envelopes of load-displacement hysteresis loop. It is obvious that the lateral load resistance of Specimen P-14, which failed at the termination point, is considerably smaller than that of other specimens.

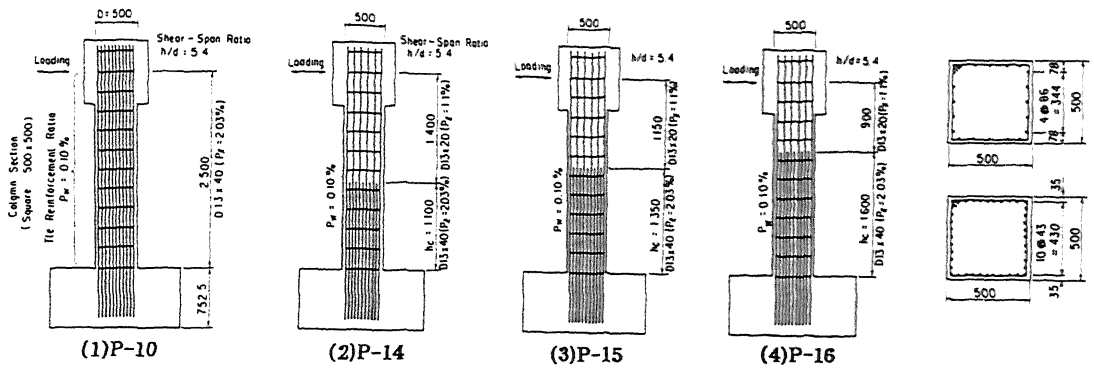

Fig.2 Reinforced Concrete Pier Specimens with Shear Span Ratio of 5.4 to study Effect of Anchorage Length of Main Reinforcement

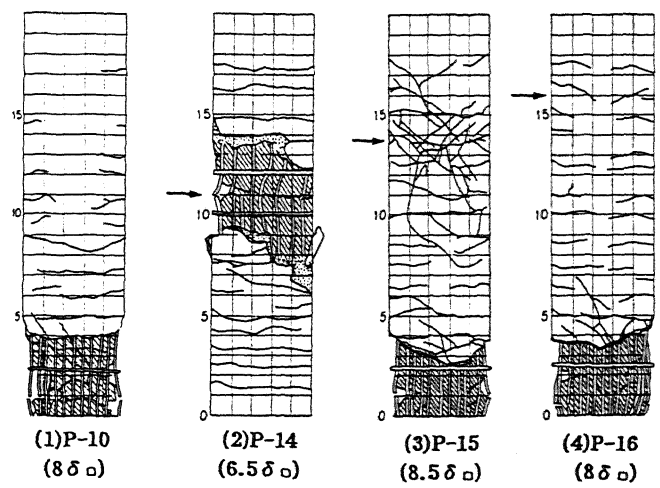

Fig.3 Failure Mode for Specimens with Shear Span Ratio of 5.4

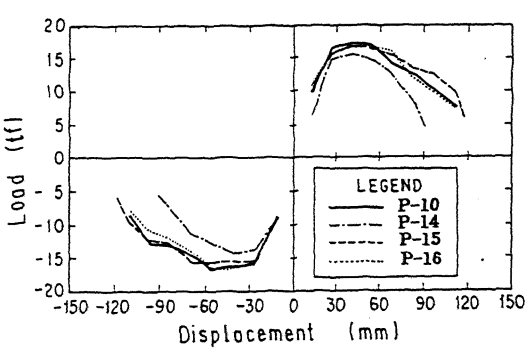

Fig.4 Envelope of Load-Displacement Hysteresis Loops for Specimens with Shear Span Ratio of 5.4

4 PROPOSED SEISMIC INSPECTION METHOD

Fig.5 shows a method proposed based on the tests for identifying the vulnerability at the termination zone. Tests results for all 13 specimens were used for the inspection method proposed. The inspection is made by two parameters, i.e., failure mode factor S_y and safety factor at termination point F_y^T, which are defined as

$$S_y = F_y^T / F_y^B \quad (1)$$

$$F_y^T = M_y^T / M^T \quad (2)$$

$$F_y^B = M_y^B / M^B \quad (3)$$

where

S_y : failure mode factor

F_y^T, F_y^B : safety factor representing strength of pier in terms of bending moment at termination point and base, respectively

M^T, M^B : bending moment developed at

termination point and base, respectively, when the pier is subjected to a lateral inertia force during earthquakes (tf·m)

M_y^T, M_y^B : yielding bending moment at termination point and base, respectively (tf·m)

In Eqs.(1) and (2), the failure mode S_y is used to identify where failure is likely developed firstly at either termination zone or base, and safety factor F_y^T represents redundancy to failure at the termination zone. With use of S_y and F_y^T, the decision is made in accordance with **Table 1** following the flow chart as shown in **Fig.5**. Check of shear stress is also made as shown in **Fig.5**.

Fig.6 shows the effectiveness to identify where the failure is developed by means of the failure mode factors S_y. Failure is likely to be developed at the termination zone when $S_y \leq 0.9$, while flexural failure at the base tends to be developed when $S_y \geq 1.1$ as shown in **Table 1**.

Fig.7 shows how the safety factor F_y^T is effective to assess the damage degree. The damage degree is defined here as the failure which is possibly developed at the loading stage of 5 times the yielding displacement (5 δ_0). From **Fig.7**, it is clear that significant failure including rapture of main reinforcement tends to be developed when $F_y^T < 1.2$.

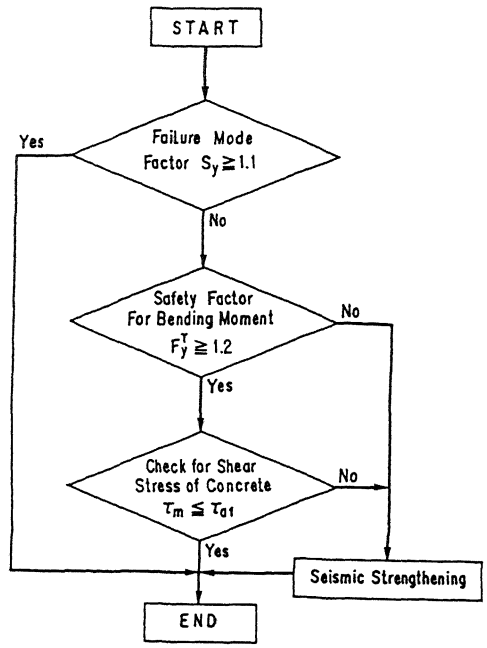

Fig.5 Seismic Inspection for Reinforced Concrete Piers with Termination of Main Reinforcement at Mid-Height

Table 1 Estimation of Seismic Vulnerability on the Strength of Termination Zone by Failure Mode Factor S_y and Safety Factor F_y^T

(a) Estimation of Failure Mode

Failure Mode Factor Sy	Failure Mode
$Sy \geq 1.1$	Flexural Failure at Base
$Sy < 1.1$	Vulnerable to Failure at Termination Zone

(b) Estimation of Damage Degree (In Case of $Sy < 1.1$)

Safety Factor F_y^T	Damage Degree at Termination Zone at the Loading Displacement of $5\delta y$
$F_y^T < 1.2$	Rupture and Serious Buckling of Main Reinforcement
$F_y^T \geq 1.2$	Diagonal Cracks, Spalling-off of Cover Concrete, Slight Buckling of Main Reinforcement

5 SEISMIC STRENGTHENING BY MEANS OF A STEEL JACKET

Effectiveness of seismic strengthening by means of a steel jacket is presented here for only 4 specimens (Specimens from R-9 to R-12) because they show the typical failure mode of the specimens strengthened. They have a square section of 50cm × 50cm and a shear span ratio of 5.6 as shown in **Fig.8**. Forty-six deformed reinforcing bars with a diameter of 10mm and yield strength of 3,000kgf/cm^2 were placed as main reinforcement. The main reinforcement ratio is 1.31% at the base. Round reinforcing bars with a diameter of 6mm and yield strength of 2,400kgf/cm^2 were placed every 25cm as tie reinforcement. The tie reinforcement ratio is 0.05%.

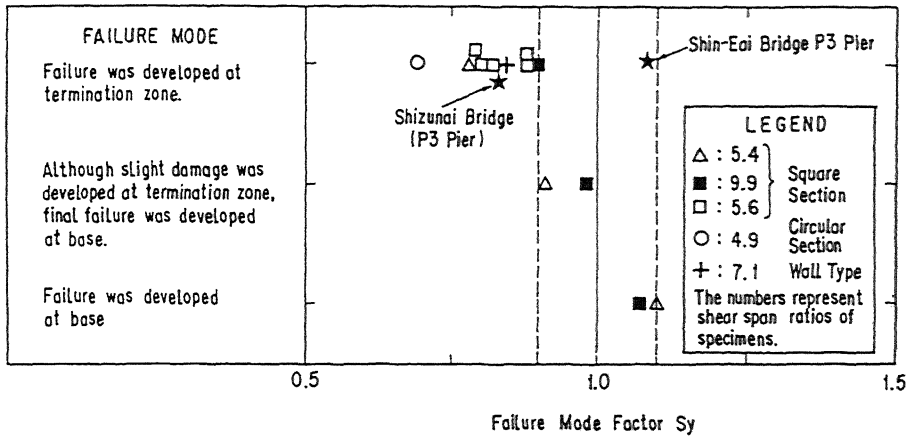

Fig.6 Estimation of failure Mode by S_y

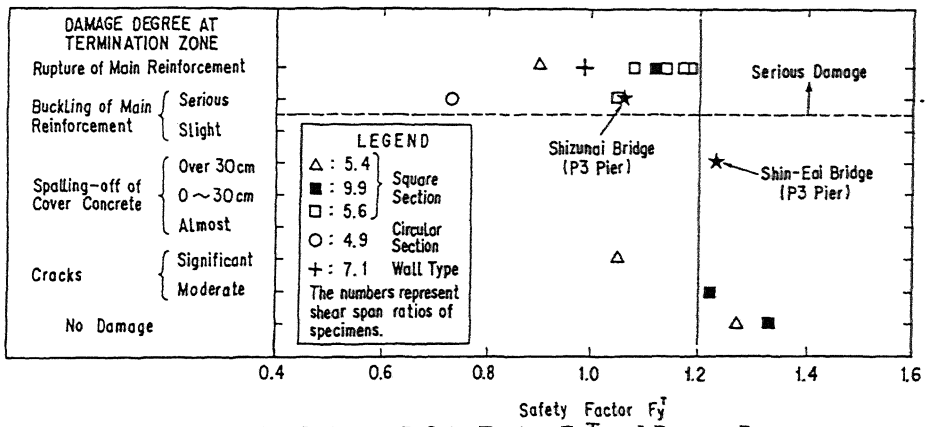

Fig.7 Relation between Safety Factor F_y^T and Damage Degree at the Loading Displacement of $5\delta_0$

The effectiveness of a 1mm thick steel jacket with the length of 1D was studied in Specimens R-9 and R-10. The steel jacket was placed at the termination zone so that it covered the region of D/2 above and below the termination point. Two types of material were injected between the steel jacket and the surface of existing concrete piers to investigate their effectiveness. They were concrete mortar (Specimen R-9) and epoxy resin (Specimen R-10). Because the length of a steel jacket of 1D was not enough to prevent the failure at the termination zone, it was elongated to 1.5D for Specimen R-11. The steel jacket was placed over the region D above and D/2 below the termination point, respectively.

Fig.9 shows how failure was developed in the 4 specimens. In Specimen R-12 which was not strengthened, flexural cracks were firstly developed at the termination zone. The flexural cracks progressed and the specimen failed finally in shear at the termination zone. On the other hand, in Specimen R-9 (concrete mortar) and Specimen R-10 (epoxy resin), which were strengthened with 1D long steel jackets, flexural cracks were developed at the base. As the loading increased, the cracks progressed, and the specimens failed finally in flexure at the base. However, diagonal shear cracks were found at the termination zone of Specimens R-9 and R-10. In Specimen R-11, flexural cracks were developed at the base. The specimen failed finally in flexure at the base and no damage was found at the termination zone.

Epoxy resin was better than the concrete mortar in this test because separation of the steel jacket from the concrete surface did not occur. However, the effectiveness of such injection materials has to be evaluated from other viewpoints such as durability for long-term use.

According to the above tests, steel jackets were effective to strengthen piers vulnerable to shear failure at the termination zone. The minimum length of the steel jacket may be 1.5 to 2.0 times the pier width D.

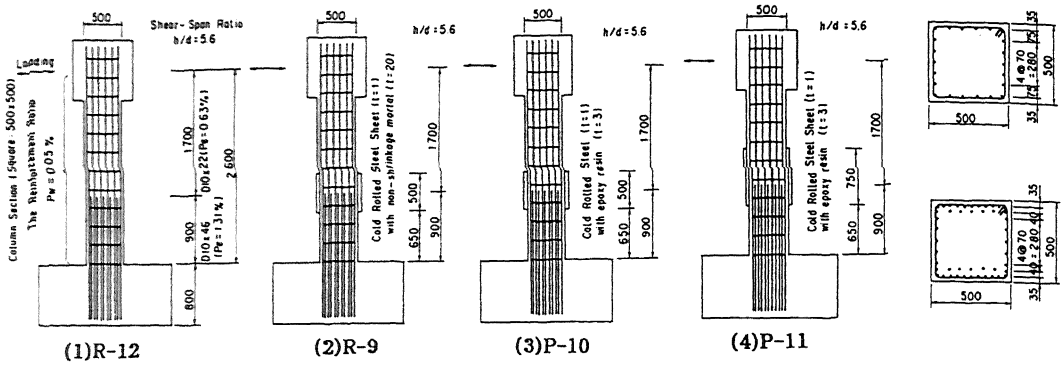

Fig.8 Reinforced Concrete Square Pier Specimens with Shear Span Ratio of 5.6 to study Strengthening Method by Means of A Steel Jacket

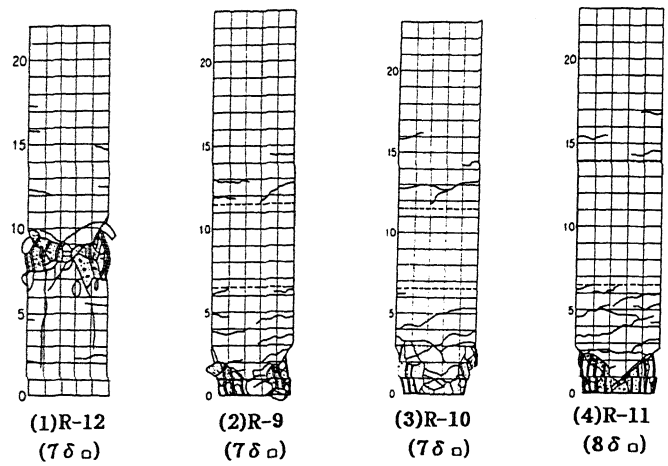

Fig.9 Failure Mode Jacket for Square Specimens with Shear Span Ratio of 5.6

6 CONCLUDING REMARKS

For evaluating seismic vulnerability of reinforced concrete bridge piers which have termination of main reinforcement with inadequate anchorage length and for evaluating effectiveness of strengthening by means of steel jackets, a series of dynamic loading tests was made on specimens with square, circular hollow and wall type sections. Based on the test results presented herein, the following conclusions may be deduced:

1) For preventing shear failure at the termination zone, the anchorage length of main reinforcement should be longer than 1D, where D is the width of the cross section.

2) Whether shear failure at the termination zone is developed or not may be evaluated by the failure mode factor S_v defined by Eq. (1). If the failure mode factor S_v is smaller than 1.1, shear failure is likely to be developed at the termination zone. When the failure mode factor S_v is larger than or equal to 1.1, flexural failure at the base tends to be developed.

3) Steel jackets can be used to strengthen piers vulnerable to shear failure at the termination zone. The minimum length of the steel jacket may be from 1.5 to 2.0 times the pier width D.

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