Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 73/1/73/2 (1995)

Artikel: Research on seismic damage of reinforced concrete bridge piers

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DOI: https://doi.org/10.5169/seals-55248

Research on Seismic Damage of Reinforced Concrete Bridge Piers

Recherche sur les dommages sismiques des piles de pont en béton armé

Forschung über Erdbebenschäden an Stahlbetonbrückenpfeilern

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SUMMARY

In this paper, seismic damage of reinforced concrete bridge piers is discussed. The paper presents experimental research on the damage to reinforced concrete bridge piers subjected to reversed cyclic lateral loading, as well as on the damage mechanism of reinforced concrete bridge piers. A modified low-cycle fatigue damage model combined excessive deformation and low-cycle fatigue influence. Variables included confinement reinforcement and shear span ratio. Test results indicate that failure modes mainly depend upon shear span ratio, and increasing confinement reinforcement can improve the ductility of reinforced concrete bridge piers. Besides, crack propagation is related to the deterioration of strength and stiffness.

RÉSUMÉ

L'auteur présente une recherche expérimentale menée sur les dommages subis par les piles de pont en béton armé, soumises à des efforts horizontaux cycliques et alternés; il fournit aussi des informations sur les mécanismes significatifs de dégradation. Il expose un modèle pour étudier la fatigue sous faible cycles de charges combinée aux effets d'une déformation extrême. Ce modèle prend en compte deux variables, les armatures de frettage et le rapport portée-cisaillement. Les résultats montrent que le mode de rupture dépend essentiellement du rapport portée-cisaillement, et que l'augmentation du pourcentage d'armatures de frettage améliore la ductilité des piles en béton armé.

ZUSAMMENFASSUNG

Der Beitrag berichtet über experimentelle Forschung an Stahlbetonbrückenpfeilern unter zyklischer Horizontalbelastung und über die relevanten Schädigungsmechanismen. Ein modifiziertes Schädigungsmodell für Ermüdung unter wenigen Zyklen mit extremer Deformation wurde entwickelt, in das als Variablen die Umschnürungsbewehrung und das Schubspannweitenverhältnis eingehen. Die Versuchsergebnisse zeigen, dass die Versagensform vor allem vom Schlussspannweitenverhältnis abhängt, während die Duktilität mit dem Gehalt der Umschnürungsbewehrung zunimmt.

1. RESEARCH SIGNIFICANCE

The experimental research presented in this paper provides design information for earthquake-resistant RC bridge piers. The aim of theoretical work is to study the method which can evaluate the behaviour of RC bridge piers in earthquake. Improvements for seismic performance of RC bridge piers are also discussed.

2. EXPERIMENTAL PROGRAM AND RESULTS

2.1 Description of Test Piers

The test bridge piers were about one-third scale model of practical bridge piers designed in accordance with China Railway Bridge Design Code ,TBJ2-85, and constructed with ready-mixed concrete using pea gravel in practical environment. Test piers were representative of a column between the foundation and the lateral loading point. Fig.1 illustrates the pier geometry. The strength of longitudinal and transverse steel are 395.9 and 235MPa, respectively. A summary of test piers properties is presented in Table 1.

Test piers	Concrete strength, (MPa)	Transverse steel		Height (m)
		Percent (%)	Spacing (mm)	
P-1	27.9	0.26	80	1.5
P-2	30.9	0.21	100	2.0
P-3	30.3	0.21	100	2.5
P-4	32.9	0.26	80	2.0
P-5	39.4	0.33	50	2.0

Table 1 Properties of test piers

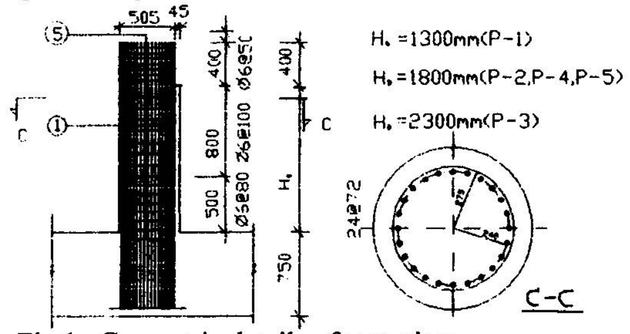

Fig.1 Geometric details of test piers

Test variables included confinement reinforcement and shear span ratio. According to the two variables, the piers were divided into two groups. The first group contained piers labeled as P-1, P-2 and P-3, respectively. Their effective heights were 1.5, 2.0 and 2.5 meter,respectively. The second group contained piers labeled as P-2, P-4 and P-5, respectively. They had same effective height 2.0 meter, but the spacings of confinement reinforcements were 100, 80 and 50 millimeter, respectively. All test piers had a 550 millimeter diameter and 1.14% longitudinal steel ratio.

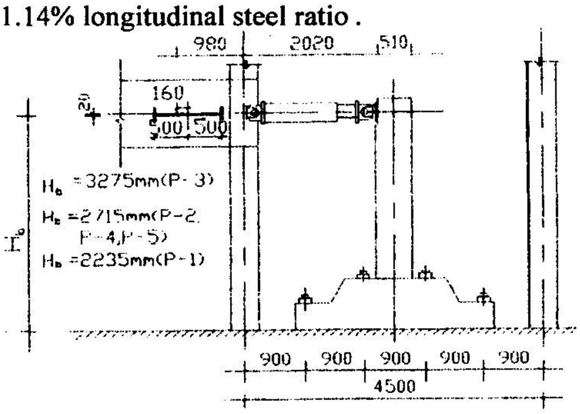

Fig.2 Test setup

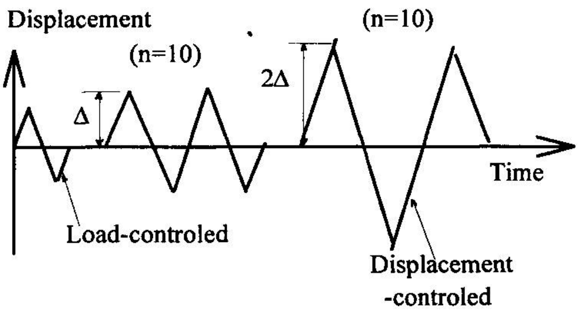

Fig.3 Load history

2.2 Test Setup and Testing Procedure

In this test program, the test setup was used to apply the lateral load by a 200KN capacity actuator. Fig.2 illustrates the test setup. No axial load was applied in this test program . The foundations of piers were fixed on the laboratory floor. The foundations were constructed having very high stiffness to assure no rotation occurrence during loading.

The piers were instrumented for deflection and steel strain measurements. The steel strains were measured by using dynamic electrical resistance strain gages. The top deflection and applied load can be measured by automatic data acquisition system. The load history adopted in the test is shown in Fig.3, it consists of two stages. In the first cycle, the piers were subjected to load-controlled lateral load reversals. It is used to determine the yield displacements (referred to as Δ_y throughout this paper) experimentally. In the following cycles, cyclic lateral displacements were increased by multiples of Δ_y . The lateral load was applied at the top of the pier, and the cycling was performed under displacement control. Pier failure was defined as the point at which the extreme tensile longitudinal bar fractured or the extreme compressed longitudinal bar buckled.

2.3 Test Results and Discussion

As expected, the failure mode for Model P-3 (shear span ratio 4.8) was a typical flexural failure. Horizontal flexural cracks were formed in the plastic hinge region, followed by gradual extension of the cracks around the circumference of the model pier. The increased lateral displacement resulted in spalling of concrete at the base of the column to a height of approximately one pier diameter. At the end, external longitudinal reinforcement fractured in the plastic hinge region.

The failure mode for Models P-2, P-4 and P-5 (shear span ratio 3.9) was similar to that for the flexural pier (P-3), except that the extensive diagonal cracks formed on the sides of piers in the plastic hinge region prior to spalling. Despite the presence of diagonal cracking, the pier shear span ratio of 3.9 was not sufficiently low to permit a true shear failure. The effection of transver bar spacing to ductility was remarkable. Ductility of P-5 (spaing of transver bar was 50mm) was 1.4 times of P-2 (spaing of transver bar was 50mm).

The failure mode for Model P-1 (shear span ratio 2.9) was a typical shear failure. Following side concrete spalling in plastic hinge region, the pier broke along a main diagonal crack, very large shear deformation was observed. The final damage states of model piers are illustrated in Fig.4.

The overall performance of each pier was measured by plotting the lateral displacement at the top of the pier as a function of the lateral load,as shown in Fig.5. The load-deflection curves exhibited stable behavior until the strength and stiffness deterioration were serious. Seismic properties of test piers are given in table 2.

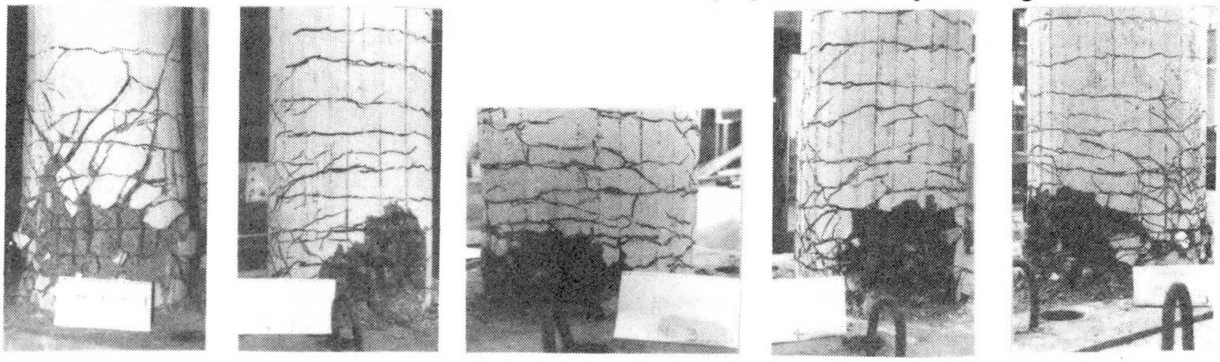

Fig.4 Final damage states of test piers .

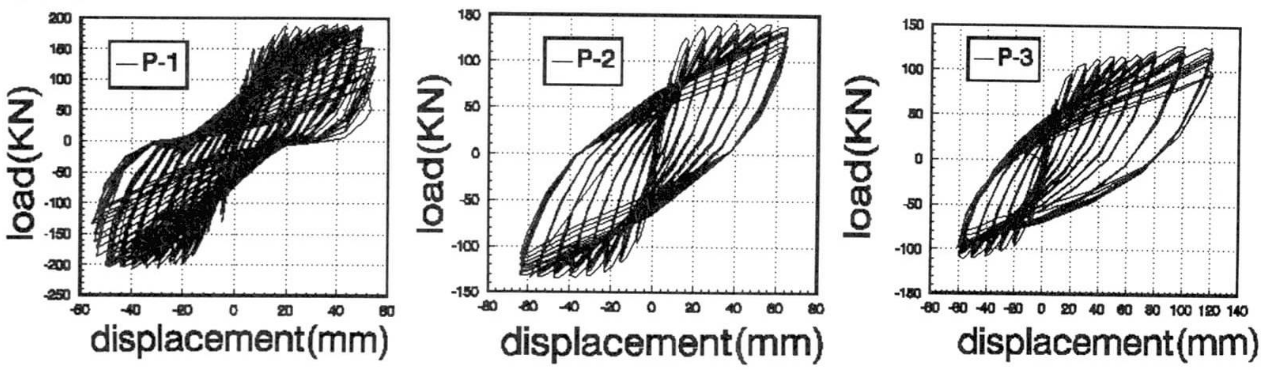

Fig. 5 Load-displacement curves(P-1 ~ P-3)

Test piers	Δ_y mm	P_y KN	Δ_u mm	P_u KN	Δ_u / Δ_y	P_u / P_y	Absorbed energy(KN-M)	s, mm	height m
P-1	9	135.87	52.6	187.63	5.85	1.38	513.294	80	1.5
P-2	13.7	118.37	64.7	140.48	4.72	1.18	393.102	100	2.0
P-3	19.4	96.48	120.2	128.55	6.2	1.33	572.31	100	2.5
P-4	13.7	118.4	*	*	*	*	*	80	2.0
P-5	13.3	110.46	81.3	132.9	6.11	1.20	583.159	50	2.0

Table 2 Seismic properties of test piers(* represents that no data was recorded.)

3. DAMAGE MECHANISM OF RC BRIDGE PIERS

3.1 General Discussion

Conventionally, the energy-absorption capacity for RC member is measured by ultimate ductility, but the index of ductility is not sufficient as a damage indicator for evaluating the damage sustained by RC members in earthquake. The main reason is that ductility index only reflects the influence of the amplitude of earthquake acceleration, the effect of earthquake duration is not considered. Hence, many damage models were proposed , some of them are tied to the dissipated energy during cyclic loading[1], others are based on the stiffness deterioration or accumulation of plastic deformation[3], and again others employ a linear combination of dissipated energy and normalized displacement[4],etc. The effect of duration to damage sustained by RC structure is commonly considered as "low-cycle fatigue". Because of the hysteretic behaviour of RC material, there is even less justification to apply Miner's hypothesis to reinforced concrete. The displacement at which energy dissipation reaches a maximum value is referred to as Displacement Barrier of low-cycle fatigue.

3.2 A New Damage Definition

The damage index is defined as the ratio of strength drop Δf_i at a specific deformation level to the elastic strength f_i at same deformation level (see Fig. 6). According to this definition, the damage index D_s can be expressed in the form

$$D_s = 1 - \frac{k_i}{k_y} \tag{1}$$

where $k_i = P_i / \delta_i$ is equivalent stiffness and $k_y = P_y / \Delta_y$ is elastic stiffness.

Defining $D_s = 1$ is corresponding failure, some normalized factor had to be introduced. Let $k_i = k_f$ (see Fig.6) be corresponding $D_s = 1$ in equation 1, the normalized factor λ is obtained in the form

$$\lambda = \frac{k_y}{k_y - k_f} \tag{2}$$

The stiffness-based damage index is defined as

$$D_s = \lambda(1 - \frac{k_i}{k_y}) \tag{3}$$

3.3 A Modified Low-Cycle Fatigue Damage Model

The damage index D_e proposed by Chung, Meyer and Shinozuka [2] is defined as

$$D_e = \sum_i \sum_j (\alpha_{ij}^+ \frac{n_{ij}^+}{N_i^+} + \alpha_{ij}^- \frac{n_{ij}^-}{N_i^-}) \tag{4}$$

where i: indicator of different displacement or curvature levels, j: indicator of cycle number for a given load i, N_i : number of cycles (with curvature level i) to cause failure, n_{ij} : number of cycles (with curvature level i) actually applied, α_{ij}: damage accelerator, and +, - : indicator of loading sense.

The main problem of damage index in Eq.4 is that assuming the beginning-point of low-cycle fatigue is at yield point. This assumption is not corresponding to the experimental results of model piers. In fact, the damage sustained by model piers under cyclic reversed load mainly depends upon the maximum displacement experienced by model piers in large range of displacement (generally three or four times Δ_y). When the displacement exceeds a specified value called the barrier of low-cycle fatigue, the cyclic effect become remarkable. The influence of load history is considered by introducing a so-called damage-factor α. The damage-factor α is defined as

$$\alpha = 1 - \frac{|\delta_{max}|}{\delta_f} \tag{5}$$

If ΔP_i denotes the strength drop in one load cycle for given displacement level, and it can be expressed as

$$\Delta P_i = pk_y(\delta_f - \delta_y)\left(\frac{\delta_i - \delta_y}{\delta_f - \delta_y}\right)^{\omega} \tag{6}$$

ω is a constant number, P_{fi} denotes the failure strength for different displacement levels , and it is defined as(Fig.7)

$$P_{fi} = P_f \frac{2\Delta_i}{\Delta_i - 1.0} \tag{7}$$

where P_i: failure strength for monotonic loading, $\Delta_i = \delta_i / \delta_f$: displacement ratio; δ_f: failure displacement for monotonic loading. Finally, the damage index of modified low-cycle fatigue is defined as

$$D_m = \frac{|\delta_{max}|}{\delta_f} + \sum_i \sum_j \alpha \frac{n_{ij}}{N_i} \tag{8}$$

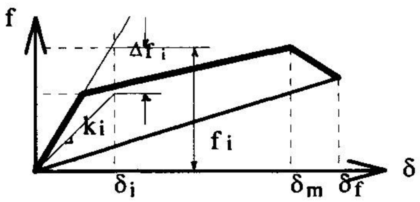

Fig. 6. Stiffness-based damage index

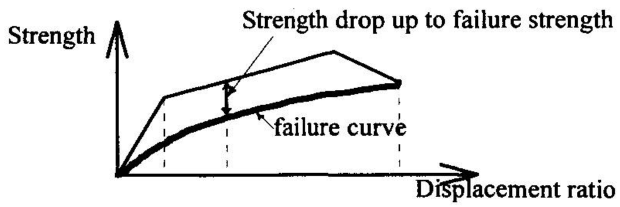

Fig.7 Definition of failure curve

We use Eq.3, Eq.4 and Eq.8 to calculate the damage index of model pier P-2 under cyclic reversed lateral load, the results are summarized in Table 3

Amplitude		Maximum displacement (m m)	Minimum displacement (mm)	Maximum load (KN)	Minimum load (KN)	D_e(Eq.3)	D_e(Eq.4)	D_e(Eq.8)
$2\delta_0$	n=1	16.6	-15.2	122.493	-116.37	0.157	0.0000	0.2024
	n=10	16.9	-15.2	111.050	-108.89	0.248	0.0000	0.2061
$3\delta_0$	n=1	24.6	-23.5	132.813	-127.14	0.450	0.0004	0.3002
	n=10	24.8	-23.3	121.229	-117.93	0.510	0.0037	0.3076
$4\delta_0$	n=1	32.7	-31.5	136.948	-131.39	0.620	0.0076	0.4013
	n=10	32.7	-31.4	123.583	-121.14	0.670	0.0435	0.4129
$5\delta_0$	n=1	40.6	-39.3	140.478	-131.78	0.727	0.0603	0.5120
	n=10	40.7	-39.1	127.17	-122.79	0.765	0.2185	0.5525
$6\delta_0$	n=1	49.1	-47.6	137.917	-133.86	0.810	0.2728	0.6598
	n=10	48.6	-47.2	127.463	-124.92	0.835	0.7493	0.7372
$7\delta_0$	n=1	57.0	-55.5	141.155	-132.60	0.863	0.8946	0.8497
	n=10	56.7	-55.0	129.661	-124.18	0.885	2.1849	1.0135
$8\delta_0$	n=1	64.7	-63.7	137.747	-131.77	0.909	2.5373	1.1065
	n=10	64.4	-63.8	122.599	-109.39	0.960	2.2432	1.3139

Table 3 Test results and damage index of model pier P-2

As shown in Table 3, the results given by the damage index of modified low-cycle fatigue coincide with the results given by the stiffness-based damage index very well.

4. CONCLUSIONS

According to experimental results and theoretical analysis, the following conclusions are obtained:

(1) The failure modes mainly depend upon the shear span ratio ;

(2) Increasing amount of confinement reinforcement in plastic hinge region can improve the ductility of RC bridge piers;

(3) The damage sustained by RC bridge piers under cyclic reversed load is related to the stiffness deterioration;

(4) Modified low-cycle fatigue damage is suited for quantifying the damage sustained by RC bridge piers in earthquake.

ACKNOWLEDGMENT

This study is supported by the Science Foundation of State Education Commission of China.

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