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DETERIORATION OF EQUIVALENT STIFFNESS OF REINFORCED CONCRETE COLUMNS SUBJECTED TO INELASTIC LOAD REVERSALS

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SUMMARY

Presented in this paper is a method to evaluate degradation of restoring force and equivalent stiffness of reinforced concrete bridge piers subjected to a series of step-wise increasing symmetric load reversals. Decreasing rate of equivalent stiffness at each loading step is defined as a ratio of equivalent stiffness of i-th load reversal divided by that of first load reversal. Approximating the decreasing rate of equivalent stiffness by introducing a coefficient (reduction coefficient), effect of shear span ratio, longitudial reinforcement ratio, loading velocity, tie reinforcement ratio, spiral and diagonal reinforcement on the reduction coefficient was studied with use of loading test results of twenty reinforced concrete cantilever models simulating bridge piers.

INTRODUCTION

Because bridge piers subjected to strong ground motion shows significant inelastic behavior, it is extremely important to prevent significant deterioration even during strong shaking. Various studies have been made to study inelastic behavior of reinforced concrete bridge piers subjected to a strong earthquake, and specimens simulating reinforced concrete bridge piers have been tested under various loading conditions (Ref.1). Loads are generally step-wise increased monotonically up to failure, in which at each step several cycles of symmetrical load reversals with same displacement amplitude are applied. Number of the load reversals at each step significantly affects ductility capability (Ref.2). Restoring force at each step also decreases in accordance with increase of the number of load reversals. Because bridge response represented in terms of response spectra highly depends on number of response cycles (Ref.3), degradation of restoring force during load reversals is of particular importance to study seismic stability of bridge piers subjected to a strong earthquake. For aiming to determine limit state of ductility capability of bridge piers in seismic design, this paper presents a method to evaluate decreasing rate of restoring force of bridge piers subjected to load reversals.

DEFINITION OF REDUCTION FACTOR OF EQUIVALENT STIFFNESS

Hysteretic behavior of reinforced concrete bridge piers subjected to a series of step-wise increasing symmetric load reversals as shown in Fig.1 may be represented as shown in Fig.2. Due to degradation of pier, peak restoring force decreases as the number of loading reversal increases. Because loading displa-

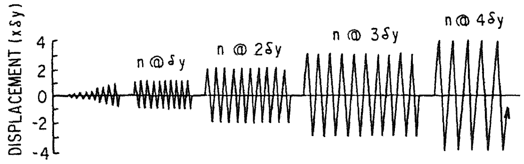


Fig. 1 Loading Hysteresis

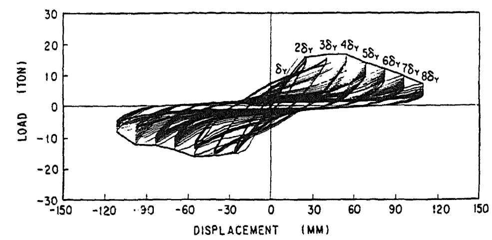


Fig. 2 Hysteresis Loop for Specimen No.10

cement is same during each loading step, decrease of the peak restoring force may be represented in terms of decrease of equivalent stiffness, which is defined as a secant stiffness between two points on loading hysteresis where the loading displacement takes the maximum and minimum values (refer to Fig.3).

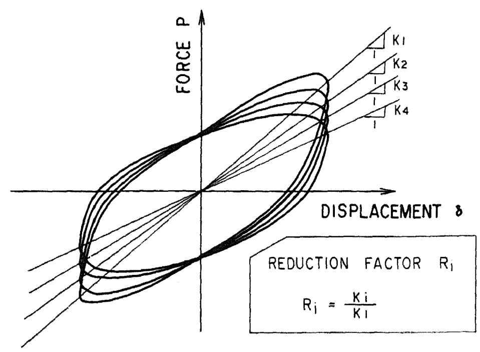


Fig. 3 Definition of Reduction Factor of Equivalent Stiffness

Decreasing rate of the equivalent stiffness in accordance with increase of the number of load reversals at each step may be represented as

$$R_i = K_i / K_1 \qquad (1)$$

where K_i represents the equivalent stiffness at i-th loading reversals, and R_i represents a factor expressing the degrading rate which is defined here as a reduction factor.

LOADING TEST RESULT STUDIED

Loading test results for twenty specimens simulating cantilever bridge piers were used for the study of the reduction factor. Specimen numbers presented in Table-1 show those to identify specimens in a series of dynamic loading tests conducted at the Public Works Research Institute, Japan. The cantilever pier was framed into massive reinforced concrete footing which was anchored to a test floor by means of post tentioned rods. The specimens have cross sections of 40 x 80 cm, 50 x 50 cm and ϕ 50.4 cm with shear span ratio ranging from 1.9 to 6.9.

All specimens were subjected to ten cycles of loading with the same displacement amplitude at each step. The step size was determined by increasing the displacement in each step by a displacement ductility factor of one. Yield displacement δ_y corresponding to one ductility factor was defined as the displacement at loading point at which reinforcing bars at the extreme tension fiber firstly reached yield strain. Loading velocity was taken as either 25 cm/sec^2 or 0.25 cm/sec^2.

STIFFNESS DEGRADATION IN TERMS OF REDUCTION FACTOR

Definition of Reduction Coefficient Fig.4 shows the reduction factor R_i defined by Eq.(1) for a specimen No.10, in which the reduction factor R_i approximated by Eq.(2), which will be described later, is also presented. It is apparent that the reduction factor R_i decreases as the number of load reversal i and that the decreasing rate of the reduction factor increases as the loading

Table 1 Specimens Used for Analysis

Model No.	Cross Section D×W [cm]	Covering Depth of Concrete [cm]	Effective Height [cm]	Shear-Span Ratio h/d	Longitudinal Reinforcing Bar (Deformed Bar)			Hoop Tie			Concrete		Loading Velocity [cm/sec.]
					Material and Diameter ϕ [mm]	Ratio of Reinforcement [%]	Yield Strength σ_{sy} [kgf/cm²]	Material and Diameter ϕ [mm]	Ratio of Reinforcement [%]	Yield Strength σ_{sy} [kgf/cm²]	Max Grain Size of Aggregate [mm]	Uni-Axial Strength [kgf/cm²]	
P- 4	40×80	5	240	6.9	SD30,19	1.79	3792	SR24,9	0.08	3660	20	290	0.25
P- 5	40×80	5	240	6.9	SD30,19	1.79	3792	SR24,9	0.08	3660	20	258	25
P- 6	40×80	5	240	6.9	SD30,16	0.87	3625	SR24,9	0.08	3660	20	290	0.25
P- 7	40×80	5	240	6.9	SD30,16	0.87	3625	SR24,9	0.08	3660	20	258	25
P- 8	40×80	5	240	6.9	SD30,13	0.48	3704	SR24,9	0.08	3660	20	290	0.25
P- 9	40×80	5	240	6.9	SD30,13	0.48	3704	SR24,9	0.08	3660	20	258	25
P-10	50×50	3.5	250	5.4	SD30,13	2.03	3144	SR24,9	0.1	2776	10	319	25
P-11	50×50	3.5	250	5.4	SD30,13	2.03	3144	SR24,9	0.1	2776	10	327	25
P-12	50×50	3.5	250	5.4	SD13,13	2.03	3144	SR24,9	0.1	2776	10	321	25
P-13	50×50	3.5	250	5.4	SD30,13	2.03	3144	SR24,9	0.1	2776	10	334	25
P-17	50×50	3.5	175	3.8	SD30,13	2.03	3144	SR24,9	0.1	2776	10	338	25
P-18	50×50	3.5	100	2.2	SD30,13	2.03	3144	SR24,9	0.1	2776	10	334	25
P-25	50×50	3.5	116	2.5	SD30,13	2.03	3144	SR24,9	0.51	3494	10	390	25
P-26	50×50	3.5	116	2.5	SD30,13	2.03	3144	SR24,9	1.02 (Spiral)	3494	10	390	25
P-27	50×50	3.5	116	2.5	SD30,13	2.03	3144	SR24,9	0.1 Diagonal Reinforcement with an amount of 1/4 of Main Reinforcement	3494	10	390	25
P-28	ϕ56.4	3.5	250	4.7	SD30,13	2.03	3144	SR24,9	0.1	3494	10	406	25
P-29	ϕ56.4	3.5	175	3.3	SD30,13	2.03	3144	SR24,9	0.1	3949	10	406	25
P-30	ϕ56.4	3.5	100	1.9	SD30,13	2.03	3144	SR24,9	0.1	3494	10	406	25
P-31	ϕ56.4	3.5	250	4.7	SD30,13	2.03	3144	SR24,9	1.02 (Spiral)	3494	10	406	25
P-32	ϕ56.4	3.5	175	3.3	SD30,13	2.03	3144	SR24,9	1.02 (Spiral)	3494	10	406	25

amplitude increases. Because the reduction factor decreases monotonically with increasing the number of load reversal i, it seems reasonable to approximate it in a form

$$R_i = \frac{1}{1 + a\,(i - 1)} \tag{2}$$

in which a is a coefficient representing the decreasing rate of the reduction factor R_i, which is to be determined for each loading step. The coefficient a is defined here as reduction coefficient. Dotted lines in Fig.4 represent that the

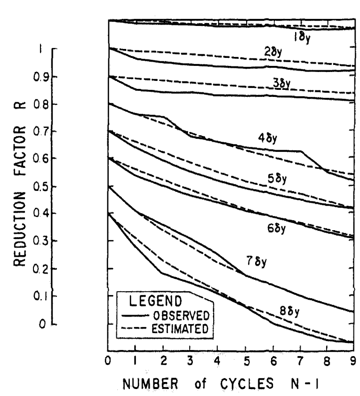


Fig. 4 Reduction Factor for Specimen No.10

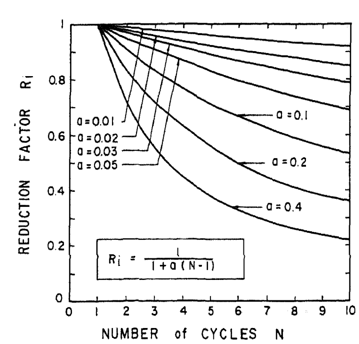
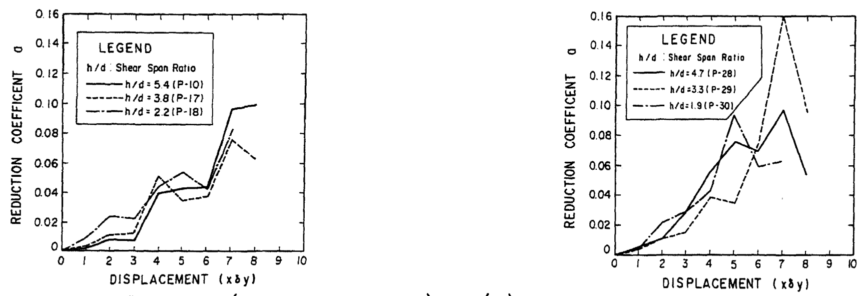


Fig. 5 Reduction Factor Represented in terms of Reduction Coefficient

approximation by Eq.(2) is reasonably accurate. Fig.5 shows the decreasing rate of the reduction factor R_i in terms of the reduction coefficient a.

Effect of Shear Span Ratio   Fig.6 shows an effect of shear span ratio on the stiffness degradation in terms of the reduction coefficient. It should be noted that speciments No.18 (rectangular section) and No.30 (circular section) failed in shear, while the other specimens failed in flexure. In the specimens with square section, the reduction coefficient takes a value from 0.01 to 0.02 until 3 δ_y. It suddenly increases to about 0.04 from 4 δ_y and again increases to more larger value from 7 δ_y Such displacements where sudden increase of the reduction coefficient occures are designated herein as first and second critical loading displacement. The second critical loading displacement is unclear in some specimens although the first critical loading displacement can be observed in most of specimens.

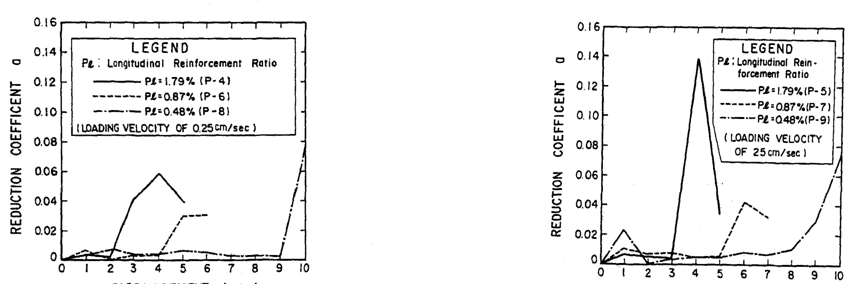
Although the effect of shear span ratio can been seen between 1 δ_y and 3 δ_y, in which the reduction coefficient is larger in the specimen with smaller shear span ratio, it is less significant. Similar results can been seen in the specimens with circular section.



(a) Rectangular Section (Specimen No.18)   (b) Circular Section (Specimen No.30)

Fig. 6 Effect of Shear Span Ratio

Effect of longitudinal Reinforcement Ratio and Loading Velocity   Fig.7 shows an effect of longitudinal reinforcement ratio P_ℓ (P_ℓ = 1.79 - 0.48 %). An effect of loading velocity is also presented. In both cases of the loading velocity, longitudinal reinforcement ratio P_ℓ shows significant effect to the reduction coefficient. In the specimens with larger longitudinal reinforcement ratio, the reduction coefficient takes large value from smaller loading displacement. It should be noted here that in the specimens presented in Fig.7, only longitudinal reinforcement ratio was varied as a parameter to be studied by tie reinforcement ratio being the constant as 0.08%. Fig.7 gives a credit that early deterioration of the equivalent stiffness occures in the specimens which have large longitudinal reinforcement ratio in spite of small tie reinforcement ratio.



(a) Loading Velocity of 0.25 cm/sec   (b) Loading Velocity of 25 cm/sec

Fig. 7 Effect of Longitudinal Reinforcement Ratio and Loading Velocity

Effect of loading velocity can be seen by comparing Fig.7 (a) and Fig.7 (b). It affects the first critical loading displacement, i.e., the first critical loading dispacement is $3\delta_y$ (P_ℓ = 1.79 %) and $5\delta_y$ (P_ℓ = 0.87 %) in the specimens subjected to loading velocity of 0.25 cm/sec, whereas it increases to $4\delta_y$ (P_ℓ = 1.79 %) and $6\delta_y$ (P_ℓ = 0.87 %) in the specimens subjected to loading velocity of 25 cm/sec. Loading with higher velocity seems to makes the first critical loading displacement large with an amount of one δ_y.

Effect of Tie Reinforcement Ratio Fig.8 shows an effect of tie reinforcement ratio P_w (P_w = 0.1 % - 0.31 %) for the specimens with shear span ration of 5.4, which failed in flexure. The effect of tie reinforcement ratio is less significant until the first critical loading displacement, and over this loading displacement it affects slightly for reducing the reduction coefficient.

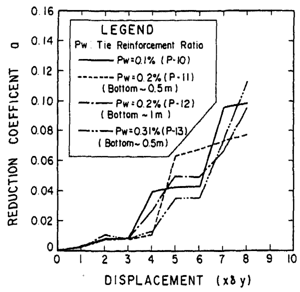


Fig. 8 Effect of Tie Reinforcement Ratio

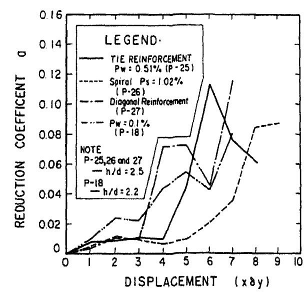


Fig. 9 Effect of Spiral and Diagonal Reinforcement

Effect of Spirals and Diagonal Reinforcement Fig.9 shows an effect of spirals (tie reinforcement ratio P_w = 1.02 %) and diagonal reinforcement (diagonal reinforcement with an amount of 25 % of longitudinal reinforcement in tension zone) for specimens with shear span ratio of 2.5. The reduction coefficients for the specimen No.25, which has a dense tie reinforcement ratio of 0.51 %, and the specimen No.18 with tie reinforcement ratio of 0.1 % are also presented in Fig.9 for comparison. Longitudinal reinforcement ratio was 2.03 % for all specimens. Shear failure was not developed in three specimens excluding the specimen No.18, and failures concentrated at bottom of the pier at final stage.

Spiral is extremely effective for reducing the reduction coefficient. The reduction coefficient takes 0.01 even at the loading displacement of $5\delta_y$. The diagonal reinforcement is also effective for reducing the reduction coefficient up to $3\delta_y$. However, the reduction coefficient increases suddenly from 0.01 to 0.07 at $4\delta_y$, which corresponds to critical deterioration of the diagonal reinforcement. Increase of tie reinforcement up to 0.51 % shows remarkable effect for reducing the reduction coefficient up to $4\delta_y$.

Fig.10 also shows an effect of spiral for specimens (circular section) with shear span ratio of 3.3 and 4.7, which failed in flexure. The effect of spiral for increasing the first critical loading displacement is apparent.

Averaged Reduction Coefficient Fig.11 shows an averaged reduction coefficient over twenty specimens presented in Table 1. Deviations from the mean value are also presented. The mean reduction coefficient may be represented as

$$a = \begin{cases} 0.01 & \delta \leqq 3\delta y \\ 0.04 & 4\delta y \leqq \delta \leqq 6\delta y \\ 0.08 \text{ or larger} & 7\delta y \leqq \delta \end{cases} \qquad (3)$$

It should be noted that the first and the second critical loading displace-

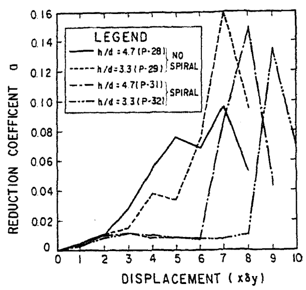


Fig.10 Effect of Spiral for Specimens with Circular Section

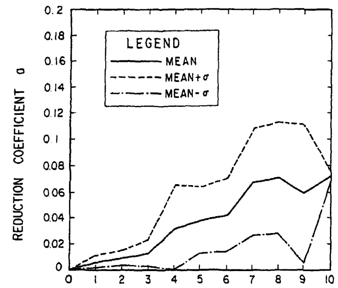


Fig.11 Averaged Reduction Coefficient

ments of 4 δ_y and 7 δ_y correspond approximately to the displacement at which spalling-off of cover concrete and rupture of longitudinal reinforcement are developed.

CONCLUSION

To study degradation of equivalent stiffness of reinforced concrete bridge pier specimens subjected to alternative lateral loading, a reduction factor R_i was proposed by Eq.(1) and it was approximated introducing a reduction coefficient a by Eq.(2). From the results presented herein, the deterioration of equivalent stiffness in terms of the reduction coefficient may be summalized as :

1) Longitudinal reinforcement ratio, spiral and diagonal reinforcement are the major factors affecting the reduction coefficient. Effect of shear span ratio (h/d = 1.6 - 6.9), loading velocity (v = 0.25 - 25cm/sec) and tie reinforcement ratio (P_w = 0.1 - 0.31 %) is less significant.

2) The overall feature of the reduction coefficient may be represented by Eq.(3). Sudden increase of the reduction coefficient occures at about 4 δ_y and 7 δ_y, which corresponds to spalling-off of cover concrete and rupture of longitudinal reinforcement. These loading displacement may be regraded as a limit state of reinforced concrete bridge piers in terms of deterioration of restoring force subjected to inelastic load reversals.

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