[2117] 鉄筋コンクリート橋脚における鉄筋の座屈モデル

MODELING FOR BUCKLING OF REINFORCEMENT IN REINFORCED CONCRETE PIER

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ABSTRACT

Deformational capacity of reinforced concrete pier undergoing reversed cyclic loading was studied by carrying out experimental work of modeled piers. It was observed that for specimens which failed in bending, buckling of the reinforcement induced degradation of the load carrying capacity. A model to predict the buckling point in the load-deformation historic curve of the modeled piers was proposed. Buckling of the reinforcement is supposed to occur when the compressive stress of the reinforcement at the compressive side of the pier section exceeds the buckling stress as well as the main crack at the footing top is open. In the analysis, the parameters such as concrete strength, steel strength, size of reinforcement and stirrup interval can be taken into account.

1. INTRODUCTION

One of the analytical problem dealing with the deformational capacity of structures is to determine the ultimate state that is the situation before which the structure exhibits prominent capacity drop. Fig.1 expresses the ultimate point, U, as well as the corresponding ultimate load and ultimate deformation denoted by P_u and D_u, respectively. This ultimate point can not be worked out in the analysis utilizing currently available material constitutive laws unless there is a pertinent failure criteria for each type of structure and loading. This is because more complicated behaviour usually arises in reinforced concrete structures than those of the concrete and reinforcement themselves.

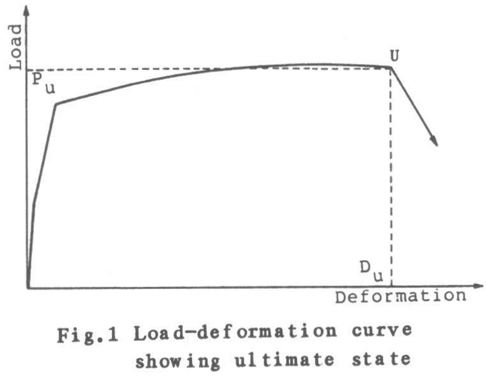

Fig.1 Load-deformation curve showing ultimate state

For a modeled pier under action of reversed cyclic load, it was found that the ultimate state was induced by buckling of the reinforcement if the failure was bending type. In other words, buckling caused the decrease in load carrying capacity for a pier having bending type of failure. Therefore, this study was aimed to determine the buckling point in the load-deformation curve. A model was established as a criteria for buckling of the reinforcement in reinforced concrete pier undergoing load reversal and

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failed in bending. By adopting the proposed buckling model in the computor analysis, buckling points in the load-deformation curves of the modeled piers were determined. These analysis results were also compared satisfactorily with the test results.

2. EXPERIMENTAL OUTLINE

2.1 Specimens

Table.1 summarizes properties of the tested specimens. The details of specimen are given in Fig.2. The parameter $V_u a/M_u$ was introduced for the design of specimen since it included the effect of all other parameters. It was considered that if the behavior of specimen was not controlled by shear strength, the specimen with higher shear strength to flexural strength ratio would be more ductile than that of the lower.

Table 1 Properties of specimens

specimen	section (cm)	ρ_s(%)	ρ_h(%)	a/d	f'_c	$V_u a/M_u$
No.1	40×40×90	1.42	0.215	4.72	320	1.76
No.2	30×40×90	1.89	0.259	4.17	255	1.47
No.3	40×40×90	1.77	0.215	3.61	230	1.22

ρ_s : main reinforcement ratio
ρ_h : transverse reinforcement ratio
a/d : shear span/depth ratio
f'_c : compressive strength of concrete
$V_u a/M_u$: shear strength to flexural strength ratio

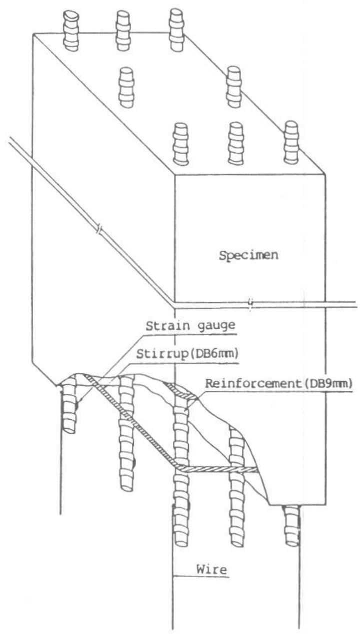


Fig.2 Specimen

2.2 Experiment

Fig.3 illustrates setup of the experimental apparatus which consists of steel footing and upper steel column. This set of apparatus enables us to cast only the critical portion of the pier as a specimen. Detail 1 and 2 show treatment of connection between concrete specimen and steel apparatus. The deflection at 1.75d, 2.0d and 2.25d from the footing top were measured to obtain the rotation at 2.0d (d : effective depth). Loading pattern was controlled by deflection at loading position. Loading history was such that

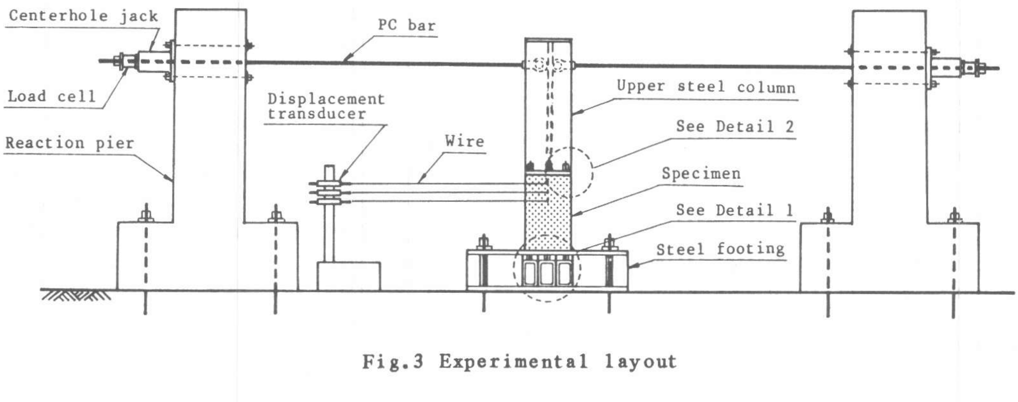
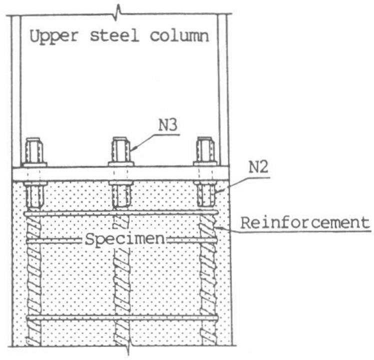
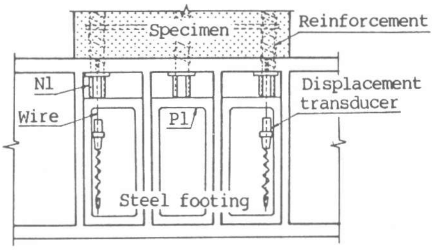


Fig.3 Experimental layout

the top deflection reached δ_y, $2\delta_y$, $3\delta_y$, until failure was reached (δ_y : measured deflection when the average of measured strains in tensile reinforcing bars reached yield strain). Three cycles of repetition were operated at each deflection level. The intensive detail of experimental manipulation has been given in reference 1.



detail 1



detail 2

3. EXPERIMENTAL RESULTS

Fig.4, Fig.5 and Fig.6 show the moment-total rotation curves at 2.0d of specimen No.1, No.2 and No.3, respectively. Specimen No.1 and No.2 share the same pattern of moment-total rotation curves and is distinct from that of specimen No.3. That is to say, rotation of specimen No.1 and No.2 keep on increasing even their load carrying capacity decrease. On the contrary, specimen No.3 has reduction of rotation after the load carrying capacity has dropped. This can be clearly observed if the envelopes of moment-total rotation curve, in Fig.7, of the three specimens are compared. These indicate different types of failure between specimen No.1, No.2 and that of specimen No.3. Specimen No.1 and No.2 failed in bending with diminutive amount of shear deflection. Conversely, shear slip caused reduction of rotation when failure occured for specimen No.3. As a consequence, the shape of moment-rotation envelope can be used to identify failure type of the specimens clearly. For specimens No.1 and No.2, after the specimens were loaded upto a certain step, load carrying capacity dropped. It was firstly supposed that buckling of reinforcement had taken place and the specimens lost their load carrying capacity [2]. However, the specimens still could resist load after the reinforcement had buckled because before closing of cracks, hoop reinforcement

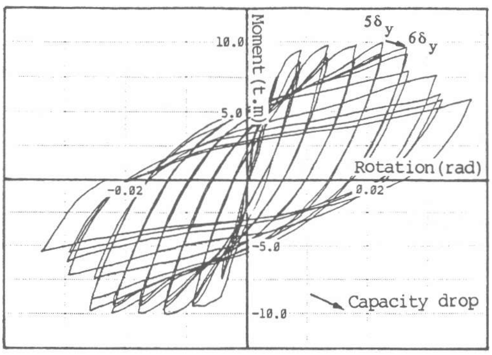


Fig.4 Moment-rotation curve of specimen No.1

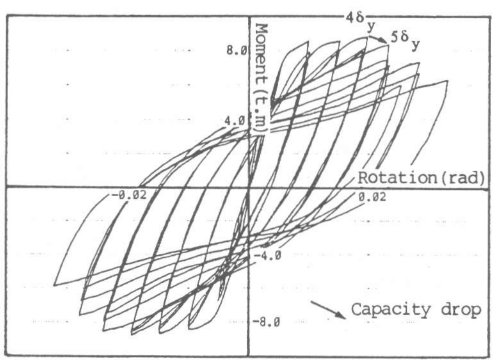


Fig.5 Moment-rotation curve of specimen No.2

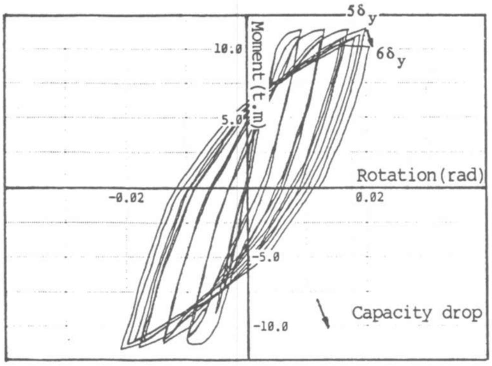


Fig.6 Moment-rotation curve of specimen No.3

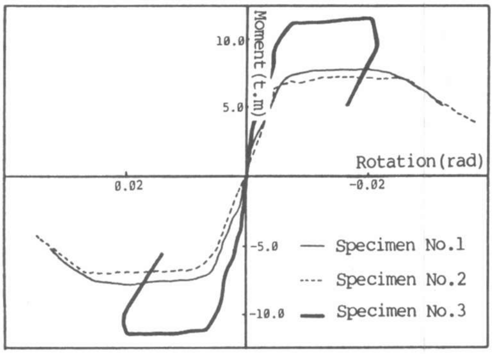


Fig.7 Envelopes of moment-rotation curve

prevented sudden stability loss of reinforcement and after the cracks closed, concrete at the compression side gave contribution to the load resisting mechanism. Usually concrete covering the reinforcement resists buckling of the reinforcement. However, combination of horizontal and vertical cracks weaken the resistance so that buckling can take place.

4. IDEA OF THE BUCKLING CRITERIA

It was realized from the tests that buckling of the reinforcement in the specimens No.1 and No.2, having bending type of failure,occurred when both of these following conditions were present simultaneously,

1) The average compressive stress of the reinforcement at the footing top exceeded the buckling stress

$$f_s - f_b > 0 \qquad (1)$$

where f_s is the average compressive stress of reinforcement at the footing top and is computed when external load and properties of the pier section are given. f_b is the buckling stress determined by modelling the reinforcement between two consecutive stirrups nearest to the footing top as column with fixed end at the bottom and roller end at the top of the column. Finally, buckling stress is derived by modifying Euler's formula as

$$f_b = \frac{2.25 \ E_t I}{A_s l^2} \qquad (2)$$

where E_t is tangential modulus of reinforcement at each step of loading, I is moment of inertia of the reinforcement. A_s is cross sectional area of the reinforcement and l is buckling length taken as spacing of stirrup.

2) The crack at the footing top is open. In other words, the crack width at the top of footing has positive value. This crack width can be determined as follows,

$$w = s_f + s_p \qquad (3)$$

where w is crack width, s_f is slip of the reinforcement from the footing and it is measured from the test directly because the footing is made of steel, s_p is slip of the reinforcement from the pier body and it can be obtained from elongation of the reinforcement between two cracks nearest to the footing top as follows,

$$s_p = \int_{x1}^{x2} \varepsilon_s \, dx \qquad (4)$$

where ε_s is strain in reinforcement at distance x from the footing top. Fig.8a shows strain distribution of the reinforcement at the critical portion. However, s_p is idealized as illustrated in Fig.8b [3]. Consequently, s_p is simply derived as follows,

$$s_p = 0.75\varepsilon'_s l_c \qquad (5)$$

where ε'_s is the strain in reinforcement at the footing top, l_c is the distance between two cracks nearest to the footing top.

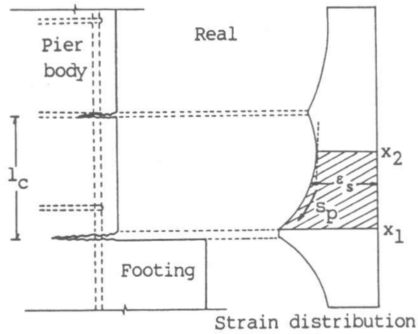


Fig.8a

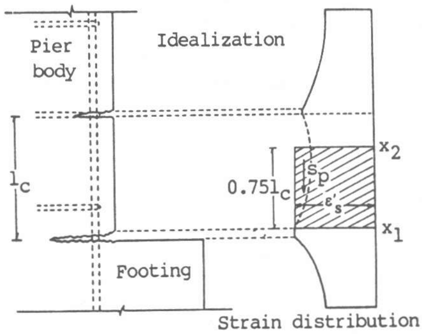


Fig.8b

Fig.8 Strain distribution of reinforcement

5. ANALYTICAL RESULTS

Generally, in the seismic resistance analysis, the system of force acting on structure is computed from seismic data. In case of bridge pier, this force corresponds to the one acting at the top of pier. When this force is determined, behaviour of the pier under influence of this force can be investigated. In this study, the analysis was carried out under the system of statically cyclic load which is supposed to be the idealization of force system derived from seismic resistance analysis. The value of idealized cyclic load handled in the experiment were used as the input data in the computor program to work out the buckling point in the load-deformation curve. The critical section at the top of footing was analysed, using the discrete element technique, by

-assumimg plane section remains plane to derive strain compatibility.
-determining internal forces by introducing MAEKAWA's model [3] and KATO's model [4] for constitutive laws of concrete and steel, respectively.
-employing iteration method to satisfy equilibrium of internal forces.
-checking discrepancy between internal moment derived from internal forces and external moments obtained from the applied load data by iteration process.
-using buckling criteria at each loading step to detect buckling point.

It is a difficult task to measure the exact point of buckling from the experiment. Therefore, in order to compare the analytical results from the proposed model with the experimental results, a definition of buckling in the experimental load-deformation curve has to be given. Buckling of the reinforcement is considered to take place at the loading path of the load-deformation curve when the pier specimen is loaded to the new deflection level where there is a decrease in load carrying capacity.

The points of buckling of specimen No.1 and No.2. from the analyses are plotted in the experimental results by square dots in Fig.9 and Fig.10,

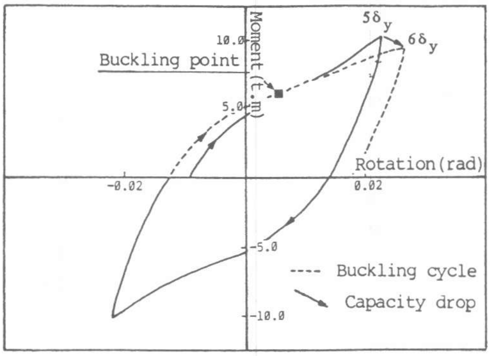


Fig.9 Analytical buckling point of specimen No.1

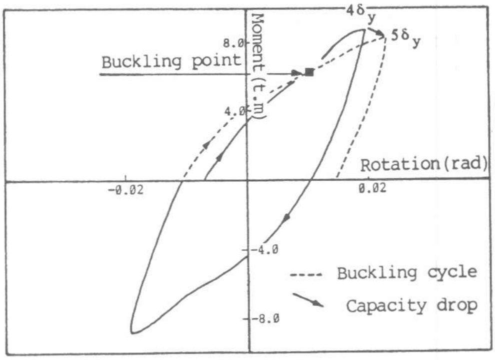


Fig.10 Analytical buckling point of specimen No.2

respectively. Specimen No.1 was predicted to have buckling of reinforcement when it was being loaded to $6\delta_y$. For specimen No.2, buckling point was found when the specimen was being loaded to $5\delta_y$. If the definition of buckling given previously and the experimental results given in Fig.4 and Fig.5 are considered, buckling should be anticipated when specimen No.1 and No.2 were on the way of being loaded to $6\delta_y$ and $5\delta_y$ since load carrying capacity of specimen No.1 and No.2 dropped when they had been loaded to $6\delta_y$ and $5\delta_y$, respectively. This is congruent to the analytical results.

Generally in practice, shear failure is unfavourable for design of the reinforced concrete structures. Therefore, this research is useful to work out the ultimate state of the reinforced concrete piers of which their sectional properties and the pattern of load are given.

6. CONCLUSION

A model for predicting the buckling point in the load-deformation historic curve of reinforced concrete pier under reversed cyclic loading was proposed. The model can reliably predict the point of load carrying capacity drop of the tested specimens.

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