REDUCED RESIDUAL DISPLACEMENTS OF PARTIALLY PRESTRESSED CONCRETE BRIDGE PIERS

Wael A ZATAR[1] And Hiroshi MUTSUYOSHI[2]

SUMMARY

In the Hyogo-Ken Nanbu 1995 earthquake, many RC bridge piers suffered from severe damage as well as high residual displacements. A reduction in residual displacements is necessary to achieve seismic resistant bridges. It was intended herein to find a way to reduce such residual displacements. Consequently, the objectives of this study are to investigate the effectiveness of partially prestressed concrete (hereafter known as PRC) to reduce such residual displacements of bridge piers and to obtain an accurate restoring hysteretic force model that can simulate their behavior. A series of experiments was carried out using small-scaled pier specimens. The experimental program basically verified the effectiveness of using PRC to reduce residual displacements after earthquake excitations. Based on experimental cyclic test results, a new hysteretic restoring force model for PRC piers was proposed. Results of response analyses conducted using the proposed model verified its applicability, in terms of both residual displacements and dissipated energy, to be implemented in dynamic analyses.

INTRODUCTION

Highway and railway concrete bridges commonly consist of prestressed concrete (PC) girders and reinforced concrete (RC) piers. The mechanical benefits of the RC piers are to obtain high-energy dissipation characteristics and high ductility factors during earthquake excitations. Conversely, some RC bridge piers suffered from severe damage and high residual displacements [Shiramama et al. 1998 and Ito et al. 1997] due to the Hyogo-Ken Nanbu 1995 earthquake. Current seismic codes for RC piers specify that residual displacement should not exceed allowable limits; otherwise the usability of the bridge could be prevented. Therefore, a reduction in residual displacements is necessary to achieve seismic resistant bridges. Studies have hardly been conducted yet in order to clarify how residual displacements of bridge piers can be reduced after earthquakes.

On the other hand, PC is known for its ability to have an elastic recovery, during unloading, even after high inelastic deformations, its low energy absorption characteristic and its reduced ductility factor [Thompson and Park 1980 and Zatar et al. 1997]. As a consequence, a new technique is being implemented in this study in which the idea of PPC [Ikeda 1998] was introduced to RC piers (hereafter known as PRC piers) in such a way to examine its effectiveness to reduce the residual displacements after earthquake excitations [Zatar and Mutsuyoshi 1998a]. Nevertheless, The applicability of PRC piers depends mainly on accurate identification of their characteristic behavior during simulated earthquake excitations. Different restoring force models for PC members, to be implemented in response analyses, have been previously presented. In general, those models could result in good prediction of accumulated dissipated energy though they deficit accurate estimations of residual displacements after simulated earthquake excitations.

Therefore, the objectives of this study are to clearly identify the characteristic behavior of such PRC piers, to identify how much reduction in the residual displacements can be achieved and to obtain an accurate hysteretic restoring force model that can accurately assist in predicting residual displacements for PRC piers. Consequently, a series of experiments was carried out using small-scaled pier specimens [Zatar et al. 1999a]. RC

[1] *Research Ass., D. Eng., Dept. of Civil and Env. Eng., Saitama University, Japan, Email: wael@mtr.civil.saitama-u.ac.jp*
[2] *Prof., D. Eng., Dept. of Civil and Env. Eng., Saitama University, Japan, Email: mutuyosi@mtr.civil.saitama-u.ac.jp*

control specimens as well as PRC specimens with different ratios of PC tendons to rebars were tested. Statically reversed cyclic loading tests were conducted in which multiple integers of the yielding displacements were used. Additionally, two specimens were tested using pseudo-dynamic (PSD) testing technique in which amplified excitations of the 1995 Hyogo-Ken Nanbu earthquake (NS direction) were carried out. Experimental results in terms of hysteretic load-deformation behavior and time histories were obtained. The plastic deformability in terms of ductility factor was also examined. A comparison between the inelastic response behavior of both RC and PRC bridge piers was also conducted. Eventually, based on the experimental results, a hysteretic restoring force model was proposed and its accuracy to predict residual displacements was examined.

EXPERIMENTAL PROGRAM

Prc pier specimen variables

Seven small-scaled pier specimens were tested under Prestressed Concrete Pier Research Project [Zatar and Mutsuyoshi 1998a and JPCEA 1998]. Specimens have strength ratios, which are ratios of shear capacities to flexural capacities of about 1.50 to ensure final flexural failure modes. Specimens have upper parts that represent bridge piers connected to lower parts that represent footings. Specimens have cross sections of 40x40 cm with a/d ratios of 4.0. Details of specimens are shown in Figure 1. An axial stress of 1 MPa was imposed to specimens. Nominal compressive strength of concrete is 35 MPa. Yielding stresses of reinforcement are 401 MPa for D13 and 360 MPa for D10 while the yielding stresses of prestressing tendons SWPR7Bϕ12.7 and SWRP19ϕ17.8 are 1421 MPa and 1205 MPa, respectively. One experimental variable was the mechanical prestressing ratio (λ), which is defined as the contribution of PC tendons in the overall cross sectional capacity. Values of λ ranged from 0.0 for RC specimen S-1 to 0.86 for PRC specimen S-5. Another variable was the usage of ungrouted PC tendons (specimens S-4, S-7). The last experimental variable was the testing type. Five specimens were tested under statically reversed cyclic loading. The objectives are to identify the inelastic behavior characteristics, to examine the effectiveness of PRC piers to reduce residual displacements and to obtain an accurate restoring force model for PRC piers. The last two specimens were tested using pseudo-dynamic testing technique [Zatar and Mutsuyoshi 1998a]. Elastic natural periods of specimens S-6 and S-7 are 0.3 sec. Details concerning specimens are shown in Table 1 while full description and instrumentation can be found elsewhere [Zatar and Mutsuyoshi 1998a, JPCEA 1998 and Zatar and Mutsuyoshi 1998b].

Table 1: Details of specimens

Spec. No.	Reinforcing Bars		Prestressing Tendons		Shear Reinforcement		Mechanical Prestressing Ratio (λ)	Test Type
	Rein.	(As/bd) %	Tendons	(Aps/bd) %	Hoops	(Ash/bs) %		
S-1	32D13	2.65	---------	---------	D6@3 cm	0.47	0.00	Cyclic
S-2	16D13	1.41	4 SWPR7B ϕ12.7	0.33	D6@3 cm	0.47	0.33	Cyclic
S-3	16D10	0.79	8 SWPR7E ϕ12.7	0.63	D6@3 cm	0.47	0.64	Cyclic
S-4	16D10	0.79	8 SWPR7E ϕ12.7	0.63	D6@3 cm	0.47	0.64	Cyclic
S-5	8D10	0.42	8 SWPR19 ϕ17.8	1.32	D10@4 cm	0.98	0.86	Cyclic
S-6	32D13	2.65	---------	---------	D6@3 cm	0.47	0.00	PSD
S-7	16D10	0.79	8 SWPR7B ϕ12.7	0.63	D6@3 cm	0.47	0.64	PSD

Experimental procedures

In the statically reversed cyclic loading test, the first displacement amplitude was the cracking displacement followed by the first yielding displacement. Then, consecutive multiple integers of the yielding displacements were applied. In the PSD tests, load was applied quasi-statically during the test and the restoring force was measured directly from the loading test system. The used ground acceleration was the modified Hyogo-Ken Nanbu 1995 (NS direction) earthquake excitation. Time scale was the same as per the original one while the maximum acceleration was 563 gal and 474 gal for S-6 and S-7, respectively. The time interval was taken as 0.01 second. The used testing system consisted of the specimen, loading actuator, loading jack, loading cell, displacement transducers, data logger, personal computer that analyzes the inelastic earthquake response and controls the input data and another personal computer that controls the output data.

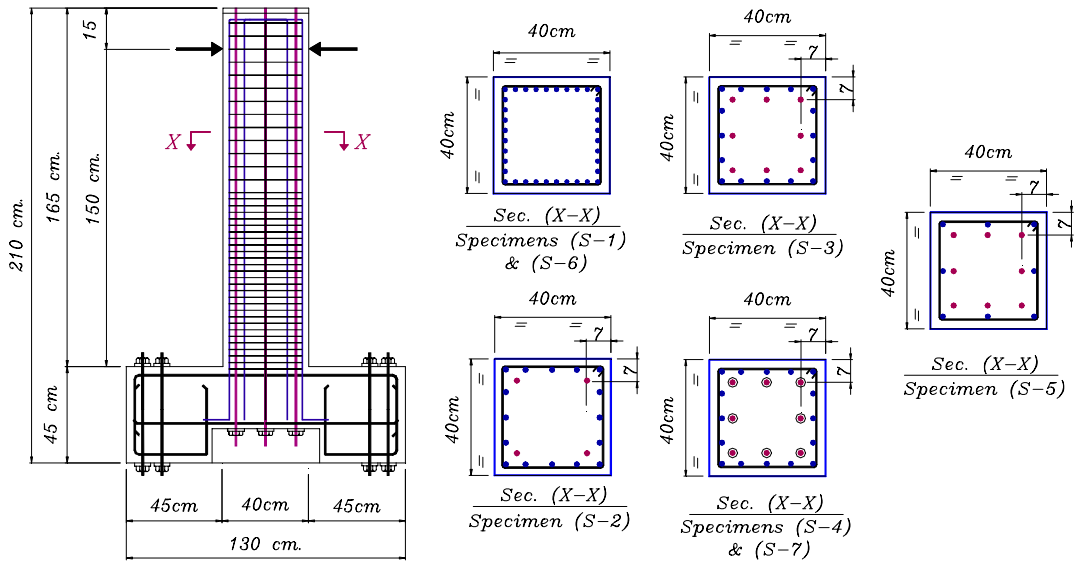
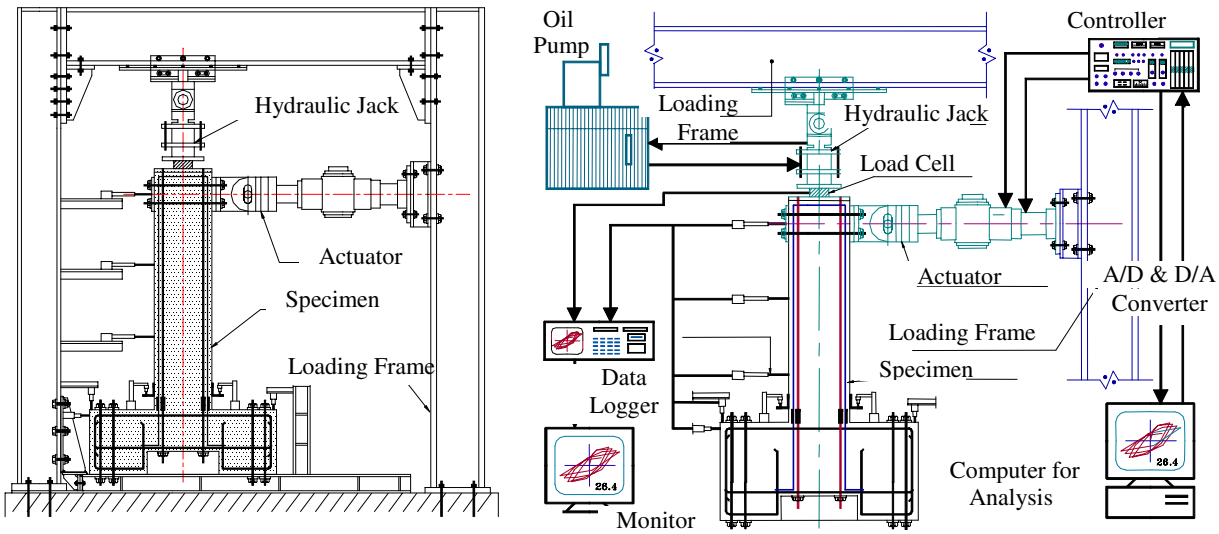


Figure 1 : Details of test specimens.



a) General loading setup.

b) Instrumentation details.

Figure 2: Loading setup and instrumentation details.

cyclic test results

Behavior of specimens is presented graphically in the form of column shear force versus tip deflection relationships. For all specimens, failure occurred at expected plastic hinges located nearby the footings. First sign of distress in specimens were flexural cracks formed in the expected plastic hinge locations. Ductility factor is defined here as the displacement corresponding to either P_y or 80% of P_u, whichever is smaller, divided by yield displacement (where, P_u is the ultimate load while P_y is the yielding load). For ductility considerations, the yield displacement is defined as the intersection of stiffness after cracking and stiffness after yielding (in the strain-hardening portion). Because of the existence of closely-spaced transverse ties, crushing was delayed inside core concrete and buckling of rebars occurred only between two successive ties in the plastic hinge regions.

Because of space limitation and since the main objective of the reversed cyclic loading tests is to show the effectiveness of using prestressing tendons to reduce the residual displacements, only the results of PRC specimen S-4 with ungrouted tendons (λ = 0.64) are compared with those of RC specimen S-1. Other

experimental results can be found elsewhere [Zatar 1999b and JPCEA 1998]. It was found, for RC specimen S-1 that fat hysteretic load-displacement curve was obtained allowing for high-energy dissipation during loading cycles. No pinching was recorded and very stable loops were obtained. Almost no strength degradation was observed as can be seen in Figure 3. Ductility factor at both directions of loading was as high as 8.5.

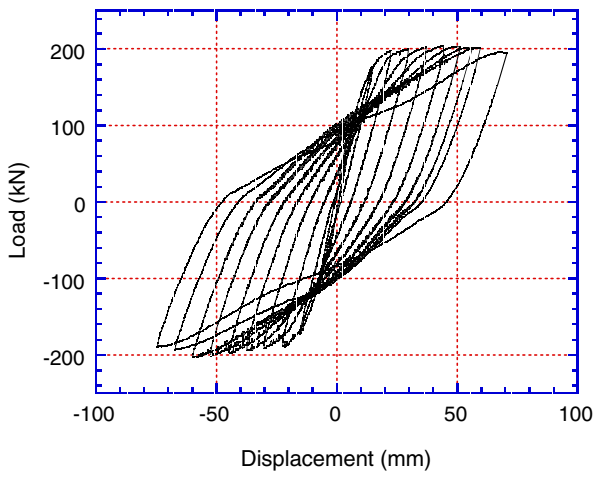


Fig. 3: Hysteretic load-displacement relationship of RC specimen S-1.

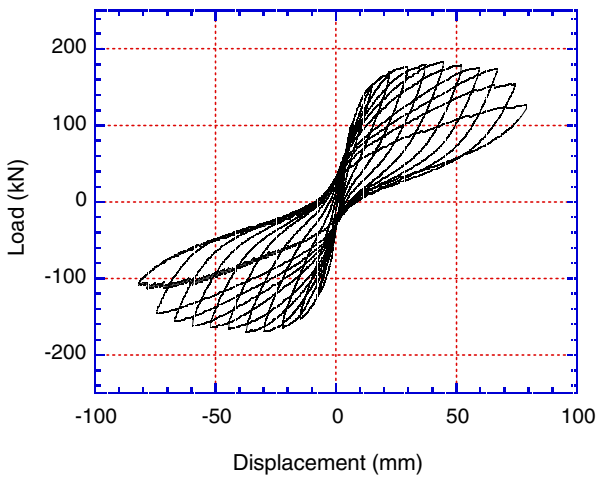


Fig. 4: Hysteretic load-displacement relationship of PRC specimen S-4.

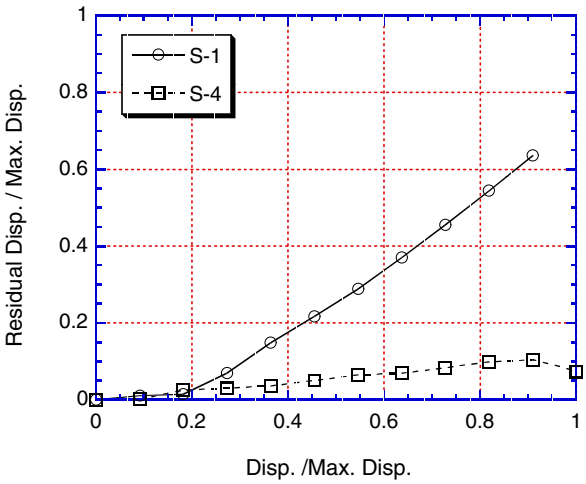


Fig. 5: Residual displacement / max. displacement versus displacement / max. displacement.

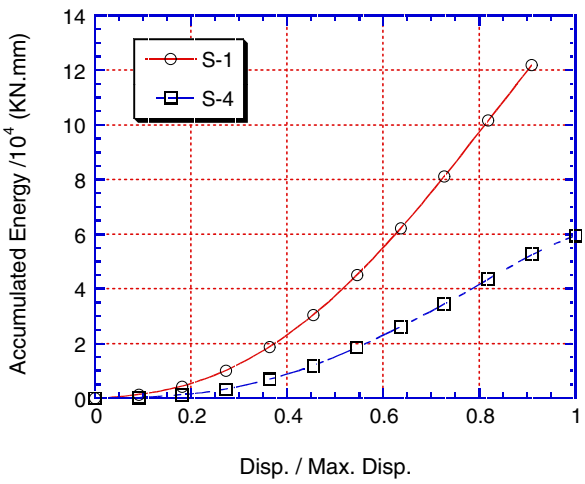


Fig. 6: Accumulated absorbed hysteretic energy versus displacement / max. displacement.

Figure 4 shows the hysteretic load-displacement curve of specimen S-4. Pinching [Saatcioglu 1991] manifested in marked change of slope during reloading was clear. Pinching can be attributed to the fact that prestressing tendons showed marked elastic recovery even after considerable inelastic deformations. Consequently, the energy absorbed during test cycles was less than that of RC specimen S-1. Residual tensile forces in PC tendons enabled to close previously opened cracks. Flexural crack widths were lower than those of specimen S-1 that can be considered as a merit of using such PRC piers. The PC tendons yielded in the plastic hinge location when the tip displacement was equal to 68 mm after which strength degradation was clearly pronounced. Maximum attained ductility factor was about 7.05 that is lower than that of specimen S-1. Ductility factor reduction for specimen S-4 can be attributed to the existence of low ratio of non-prestressing reinforcement. A comparison between S-1 and S-4 in terms of residual displacements and accumulated absorbed hysteretic energy was conducted (Figure 5 and Figure 6). Figure 5 shows that the use of PC tendons can reduce the residual displacements at various loading stages. As a consequence and in order to eventually attain seismic resistant bridge piers, the implemented mechanical prestressing ratio should be carefully chosen in such a way that allows

having a compromise between the merits and demerits encountered in using PRC in bridge piers. Similar observations were found from all the other tested specimens, depending on the mechanical prestressing ratios, thus encouraging, in principal, for future implementation of PC tendons to bridge piers to overcome problems encountered with excessive residual displacements.

3. EXISTING RESTORING FORCE MODELS

Thompson and Park [1980] developed an idealization for moment-curvature characteristics of PRC members under reversed cyclic loading by combining responses of PC modified idealization, presented by Blakelay, and Rambörg Osgood idealization. The model is quite useful since it can cover the whole range of concrete from fully PC members to RC members. It was reported by Nishiyama et al. [1993] that the model has two defects. In large ductility ranges, the PC model shows more pinched hysteresis than the actual one. Also, flexural cracking can not be explicitly defined in the RC model. Another disadvantage for a section with small λ is that loops, especially for small displacement amplitudes, are based on Rambörg Osgood idealization while it is believed that Takeda's one [1970] is a better idealization. Nishiyama et al. [1993] presented a modification for the model by Thompson and Park to overcome the difference in predicting the pinching hysteresis in large ductility ranges. Unfortunately, this model could not overcome the other disadvantages. Okada et al. [1993] proposed a restoring force model with rather complicated equations for PC members. Okada et al. commented that the model could give good conformity with experimental results though some differences were observed in the residual displacements. Okamoto and Kato [1993] presented a perfect model for PC members after cracking and before yielding. The model can efficiently estimate the accumulated absorbed energy though it deficit good prediction of the residual displacement especially at high displacement amplitudes.

A PROPOSED HYSTERETIC RESTORING FORCE MODEL FOR PRC PIERS

Basic features

In order to accurately simulate cases of grouted or ungrouted PRC piers and to obtain a better estimation of residual displacements than those to be obtained using the pre-mentioned models, a new hysteretic restoring force model is proposed. The model can, almost, capture the exact behavior since it accounts for changes in stiffness during unloading by considering two unloading stiffnesses. One of the advantages of the proposed model is that it can overcome the deficiency of not accounting for effect of area and arrangement of PC tendons and non-prestressing reinforcement for cases of PRC piers. The proposed model can account for such shortcoming through the calculation of λ as a function of actual stress of each PC tendons and non-prestressing reinforcement as shown in Eq. 1. Stress values are to be calculated based on having a concrete strain of 0.0035 (Figure 7). The model has the same characteristics and basic rules of Takeda's tri-linear model [1970] except it permits having two unloading stiffnesses (named K_{r1}, K_{r2}) (Figure 8). The use of two unloading stiffnesses in the proposed model allows accounting for the actual absorbed energy at small displacement amplitudes. The proposed model can also account for cases of PC members having any value of λ. The turning point (T_p) about which the second unloading stiffness commences is a function of λ as well as the previous maximum load as shown in Eq. 2. Value of K_{r1} can be obtained from Eq. 3 based on having a constant unloading parameter α of 0.4. Value of K_{r2} can be obtained from Eq. 4 based on unloading parameter β, which is a function of λ. Based on experimental results of the specimens shown in Table 1 and on others [JPCEA 1998], the relationship between λ and unloading parameter β was obtained (Figure 9). It can be seen that this relationship is linear until λ=0.4 after which β has a constant value of 1.15. In case of PRC piers having ungrouted tendons, values of β should be increased by 10% over those values shown in Figure 9. In case of RC piers, the two parameters α and β are identical and equal to 0.4.

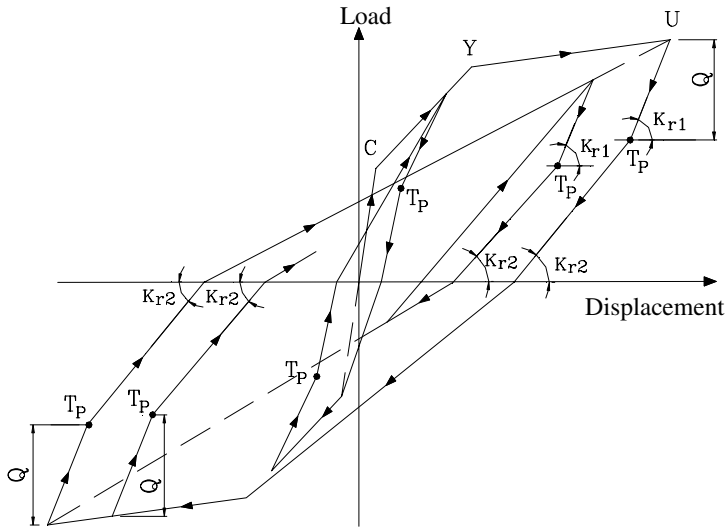
$$\lambda = \sum_{i=1}^{n} (A_{ps_i}.F_{p_i}) / (\sum A_{s_i}.F_{s_i} + \sum A_{ps_i}.F_{p_i}) \quad (1)$$

$$Q = Q_{max.}\ (1 - \lambda) \tag{2}$$

$$K_{r1} = (Q_c + Q_y) / (D_c + D_y)\ (D_y / D_m)^{\alpha} \tag{3}$$

$$K_{r2} = (Q_c + Q_y) / (D_c + D_y)\ (D_y / D_m)^{\beta} \tag{4}$$

where: A_{ps_i} = area of each layer of PC tendons, F_{p_i} = stress of each layer of PC tendons, A_{s_i} = area of each layer of reinforcing bars, F_{s_i} = stress of each layer of reinforcing bars, Q_c = cracking load of the pier, Q_y = yielding load of the pier, K_{r1} = first unloading stiffness, K_{r2} = second unloading stiffness, D_c = cracking displacement of the pier, D_y = yielding displacement of the pier, D_m = maximum displacement at the current cycle and α, β = unloading stiffness parameters.



where: K_{r1} and K_{r2} are unloading stiffnesses.
α and β are unloading stiffness parameters.

Figure 8: Hysteretic rules for load-displacement relationship of the proposed model.

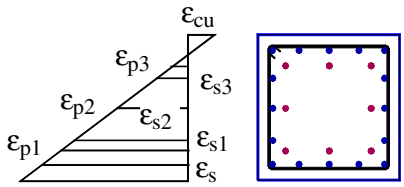


Figure 7: Basis for consideration of PC tendons location.

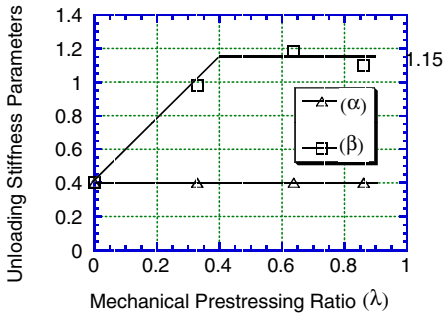


Figure 9: λ versus unloading stiffness parameters (α, β).

VERIFICATION OF THE PROPOSED RESTORING FORCE MODEL

In order to verify the accuracy of the proposed model to be implemented in PRC piers and because of space limitations, only experimental results of specimens S-6 and S-7 were compared with results obtained by the proposed hysteretic restoring force model.

Figure 10 shows the hysteretic load-displacement curve of RC specimen S-6. A comparison between the hysteretic load-displacement curves obtained experimentally and using the proposed model showed a general good accuracy in terms of the maximum displacement and the overall hysteretic behavior. Also, the use of the proposed model resulted in an accurate prediction of the residual displacement. Based on the obtained good accuracy, the model can be used for RC and PRC piers with low values of λ.

Figure 11 shows the hysteretic load-displacement curve of ungrouted PRC specimen S-7. A comparison between the hysteretic load-displacement curves obtained experimentally and using the proposed model showed an overall good accuracy in terms of the maximum displacement and the overall hysteretic behavior. Also, a considerable accurate prediction of residual displacements, as can be seen in the displacement-time histories in Figure 12, confirmed the applicability of the proposed model. Based on the obtained good accuracy, the model can be used for PRC piers with ungrouted tendons and with relatively high λ values.

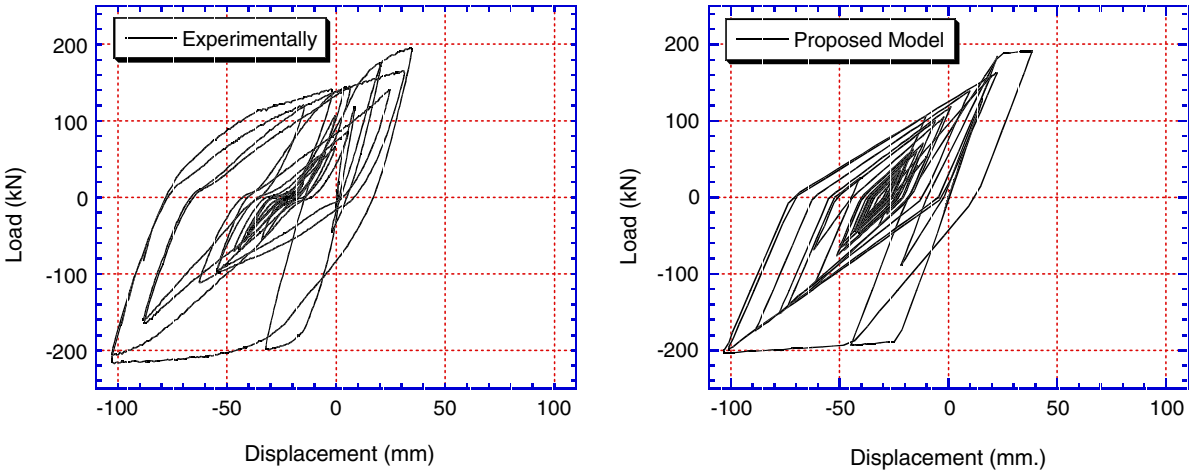


Figure 10: Verification of the proposed hysteretic restoring force model for specimen S-6.

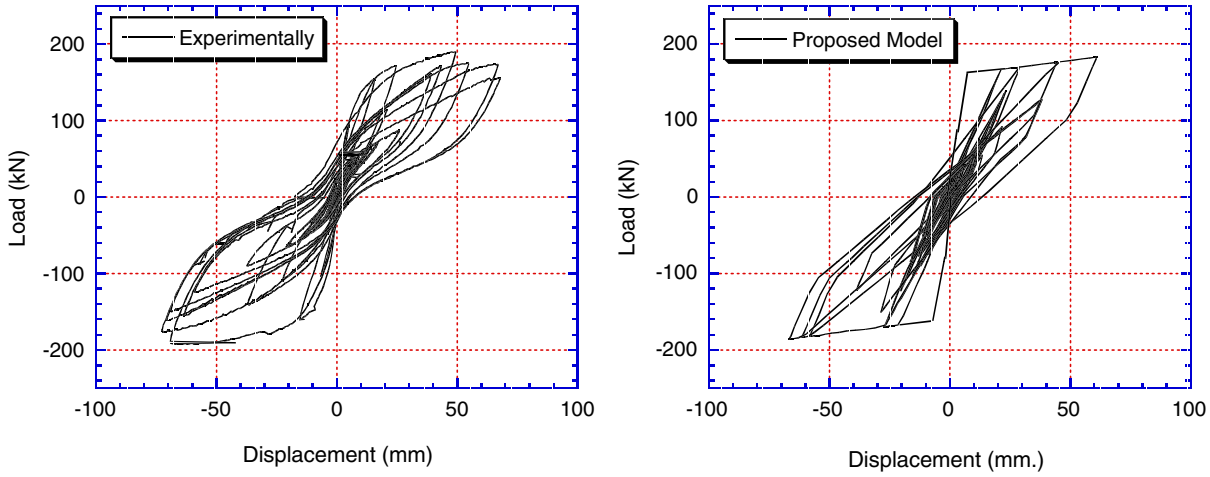


Figure 11: Verification of the proposed hysteretic restoring force model for specimen S-7.

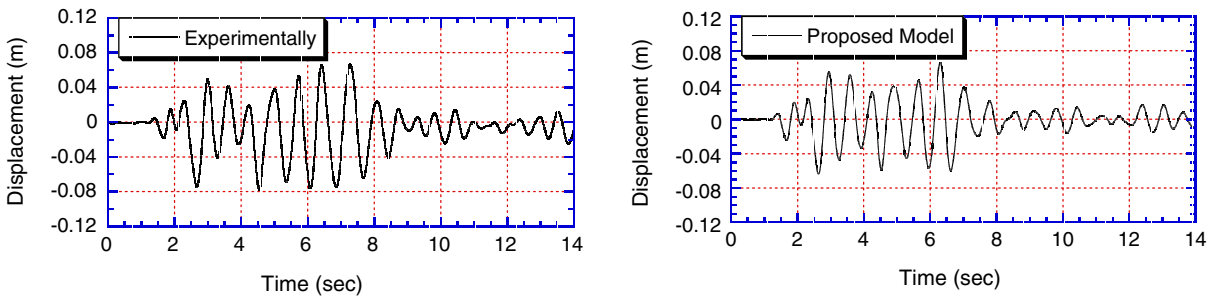


Figure 12: Displacement time-histories of RC specimen S-7.

CONCLUSIONS

In order to clarify the inelastic response behavior of partially prestressed concrete (PRC) piers under severe earthquake, experimental program was carried out using small-scaled specimens. It can be concluded that the usage of PRC piers has the following merits and demerits; a) It showed superior restoration characteristics and small residual displacements thus encouraging its implementation in actual bridge piers, b) The residual cracking

patterns of PRC piers, after earthquake excitation, are better than those of ordinary RC piers. Reduced cracking widths could be obtained when higher values of prestressing tendons were used, and c) A lower energy dissipation capacity, depending on the mechanical prestressing ratios, was obtained. Consequently, such ratio should be chosen in such a way that balances the merits and demerits.

Additionally, a hysteretic restoring force model that can capture these characteristics was proposed and its accuracy was verified thus allowing for its future implementation in dynamic analyses. The proposed restoring force model has the following advantages; a) It allows for a superior prediction of residual displacements after simulated earthquake excitations, b) The whole range of concrete members from fully PC to RC members could be covered, c) Cases when unbonded PC tendons exist could be accounted for, and d) Changes in area and arrangement of PC tendons and non-prestressing reinforcement could be taken into consideration.

ACKNOWLEDGEMENT

This research work has been conducted under Prestressed Concrete Pier Research Project (Chairman: Prof. S. Ikeda) established in Japan Prestressed Concrete Engineering Association. The authors would like to acknowledge the co-operation of the members of RC laboratory of Saitama University.

REFERENCES

Ikeda, S. (1998), "Seismic Behavior of Reinforced Concrete Columns and Improvement by Vertical Prestressing", *Proceedings of the 13th FIP Congress on Challenges for Concrete in the Next Millennium*, Vol. 2, pp.879-884.

Ito, T. Yamaguchi, T. and Ikeda, S. (1997), "Seismic Performance of Reinforced Concrete Piers Prestressed in Axial Direction", *Proc. of J*CI, Vol. 19, No. 2, pp.1197-1202.

JPCEA (Japan Prestressed Concrete Engineering Association), (1998), "*A Report on Seismic Behavior of Prestressed Concrete Pier"*, March.

Nishiyama, M. Ohta, Y. Watanabe, F. and Muguruma, H. (1993), "Seismic Response of Prestressed, Partially Prestressed and Reinforced Concrete Building Frames", *FIP' 93 Symposium of Modern Prestressing Techniques and their Applications*, Vol. 1, pp.65-72.

Okada, M. Hamahara, M. Suetsugu, H. and Motooka, J. (1993), "Effect of Prestressing Force and Mode of Mechanism on Hysteretic Behavior of Prestressed Concrete Frames", *FIP' 93 Symposium of Modern Prestressing Techniques and their Applications*, Vol. 1, pp.219-226.

Okamoto, S. and Kato H. (1993), "Nonlinear Analytical Study on Precast Prestressed Concrete Frame Building", *FIP' 93 Symposium of Modern Prestressing Techniques and their Applications*, Vol. 1, pp.49-56.

Priestley, M. J. N., Seible, F. and Calvi, G. M. (1996), "*Seismic Design and Retrofit of Bridges*", John Wiley & Sons Inc.

Saatcioglu, M. (1991), "Modeling Hysteretic Force-Deformation Relationship for Reinforced Concrete Elements, Earthquake Resistant Concrete Structures," *Inelastic Response and Design, ACI SP-127-5*, pp.153-198.

Shiramama, H. Yamaguchi, T. and Ikeda, S. (1998), "Seismic Response Behavior of Concrete Piers Prestressed in Axial Direction", *Proc. of JCI*, Vol. 20, No. 3, pp.745-750.

Takeda, T. Sozen, M. A. and Nielsen, N. N. (1970), "Reinforced Concrete Response to Simulated Earthquake", *Journal of the Structural Division, ASCE*, Vol. 96, No. ST2, paper 7759, Dec.

Thompson, K. J. and Park, R. (1980), "Seismic Response of Partially Prestressed Concrete*", Journal of the Structural Division, ASCE*, Vol. 106, No. ST8, paper 15598, Aug. , pp.1755-1775.

Zatar, W., Mutsuyoshi, H., Tanzo, W. and Hosaka, I. (1997), "Dynamic Response Behavior of Prestressed Concrete Viaduct under Severe Earthquake", *Transactions of JCI*, Vol. 19, No. 2, pp.429-434.

Zatar, W. and Mutsuyoshi, H. (1998a), "Dynamic Response Behavior of Prestressed Concrete Piers under Severe Earthquake", *Transactions of JCI*, Vol. 20, No. 3, pp.1003-1008.

Zatar, W. and Mutsuyoshi, H. (1998b), " Seismic Behavior of Partially Prestressed Concrete Piers", *Proc. of 2nd Symposium on Ductility Design Method for Bridges*, JSCE, Dec. pp.189-192.

Zatar, W., Mutsuyoshi, H. and Koizumi, H. (1999a), "A Restoring Force Model for Partially Prestressed Concrete Piers", *Proc. of JCI*, Vol. 21, No. 3, pp.889-894.

Zatar, W. (1999b), "*Seismic Behavior of Prestressed Concrete Bridge Piers and Viaduct Structures*", Ph. D. Dissertation, Saitama University, Japan.