



MITIGATION OF RESIDUAL DISPLACEMENTS OF CIRCULAR REINFORCED CONCRETE BRIDGE COLUMNS

Junichi Sakai¹ and Stephen A. Mahin²

SUMMARY

A large ductility capacity is generally required of bridge columns located in regions of high seismicity to ensure economical designs with adequate protection against collapse. However, conventional bridge columns that develop high ductility demands tend to retain large permanent displacements. To maximize post-event operability and minimize repair costs, increased attention should be paid to reducing these residual displacements.

To minimize residual displacements in reinforced concrete columns, a design is proposed whereby longitudinal post-tensioning strands replace some of usual longitudinal mild reinforcing bars. The seismic performance of such partially prestressed, reinforced concrete columns is investigated through a series of quasistatic and dynamic analyses.

A series of quasistatic cyclic analyses is used to explore the effects of magnitude of prestressing force, amount of prestressing strands, and amount of longitudinal reinforcement on hysteretic behavior. For instance, when half of the longitudinal mild reinforcement in a conventional circular reinforced concrete column is replaced by an equal area of unbonded post-tensioning strand and a prestress equal to the axial force induced by the dead load is applied, the lateral force-lateral displacement relations for both columns are nearly identical, but the residual displacement (upon unloading that occurs from near the ultimate lateral displacement capacity) for the partially prestressed column is 86% smaller.

Based on proportioning recommendations developed, four columns with different prestressing strand configurations are designed and analyzed dynamically. For the suite of near-fault ground motions considered, the post-tensioned columns exhibit maximum displacements similar to those for conventionally reinforced concrete designs, but residual displacements are reduced by more than 50% on average. Shaking table tests of moderate-scale cantilever specimens are underway to confirm these observations and design recommendations.

¹ Postdoctoral Researcher, Pacific Earthquake Engineering Research Center, University of California at Berkeley, California, USA. Email: sakai@peer.berkeley.edu

² Byron and Elvira Nishkian Professor of Structural Engineering, Department of Civil and Environmental Engineering, University of California at Berkeley, California, USA. Email: mahin@ce.berkeley.edu

INTRODUCTION

In recent years, a high ductility capacity is expected of bridge columns located in regions of high seismicity to ensure economical designs with adequate protection against collapse during strong ground shaking [1] [2]. It has been noted, however, that bridge columns that develop high ductility demands during extreme ground shaking are likely to retain large residual displacements following the earthquake. While a large residual displacement may not endanger overall safety, it can disrupt the flow of traffic and be costly and difficult to repair. To maximize post-event operability and minimize repair costs, attention should be paid in the design process to minimizing these residual displacements.

Recent research in Japan has begun to explore methods for mitigating the post-earthquake residual displacement of reinforced concrete bridge columns [3] [4] [5]. These studies suggest that the use of prestressing tendons or unbonded high strength bars can reduce residual displacements. While results to date are promising, general recommendations have yet to be developed regarding the optimal characteristics of the column necessary to achieve desired seismic performance including reduced residual displacements.

The research presented in this paper is part of a larger experimental and analytical investigation being conducted at the Pacific Earthquake Engineering Research Center to enhance the performance of reinforced concrete bridges. A new method for reducing residual displacements of reinforced concrete bridge columns has been developed whereby a single bundle of unbonded prestressing strand is incorporated at the center of the cross-section of a lightly reinforced concrete column [6]. This paper presents a series of quasistatic analyses for the reinforced concrete columns with unbonded prestressing strands to investigate the hysteretic response of such columns, followed by a series of dynamic analyses to validate the effectiveness of this approach in improving seismic performance.

BRIDGE COLUMN ANALYZED

A circular, reinforced concrete column, designed in accordance with the Caltrans Seismic Design Criteria (SDC) [1], is considered in this study. This column is used as a reference for comparison with results obtained considering partially prestressed designs. **Figure 1** illustrates the elevation and cross section of the reference column. The diameter of the column, D , is 1.83 m, and its height from the bottom of the column to the gravity center of the superstructure, h , is 10.97 m, resulting in an effective aspect ratio of 6. The dead load, P , supported by the column is taken as 4.5 MN. For an unconfined concrete strength, f'_{co} , of 34.5 MPa, the axial load ratio, $P/f'_{co}A_g$, is 5%. The conventionally designed column is reinforced longitudinally with 48 No. 9 (29-mm diameter) deformed bars, providing for the standard case a longitudinal reinforcement ratio, ρ_l , of 1.18%. No. 5 (16-mm diameter) spirals are used to confine the concrete core, spaced at a 76-mm pitch, resulting in a volumetric ratio, ρ_s , of 0.61%. Reinforcing bars with a nominal yield strength of 420 MPa and an ultimate strain, ϵ_{su} , of 0.12 (Grade 60) are considered for both the longitudinal and spiral reinforcement. Based on the static push-over procedure suggested by the SDC, the computed lateral load capacity of the reference column is 1.29 MN and its yield and ultimate displacements are 0.11 m and 0.58 m, respectively.

Based on findings by Sakai and Mahin [6], a partially prestressed, reinforced concrete column (see **Fig. 2**) with post-tensioning strand concentrated at the center of the cross-section and debonded from adjacent concrete over the full height of the column is believed to have desirable recentering characteristics under quasi-statically loading. Grade 270 strand is considered for the prestressing strands. The essentially elastic

prestressing steel strain, $\epsilon_{ps,EE}$, the ultimate strength, $f_{ps,u}$, and the ultimate strain, $\epsilon_{ps,u}$, are 0.0086, 1860 MPa and 0.03, respectively. To prevent undesirable premature crushing of concrete due to the additional axial load by the post-tensioning strands, additional confinement is provided for the partially prestressed columns. To enhance the confinement of the core concrete, the spiral pitch is reduced from 76 mm to 38 mm. Accordingly, the denser spirals increases ρ_s to 1.22%.

As shown in **Table 1**, a series of quasistatic analyses is carried out systematically varying the following parameters: the magnitude of the prestressing force applied, P_{ps} , the areas of the strand and mild reinforcement employed. For the purposes of this study, a prestressing force ratio, α_{ps} , and a strand ratio, ρ_{ps} , are defined as:

$$\alpha_{ps} = \frac{P_{ps}}{f'_{co}A_g}; \quad \rho_{ps} = \frac{A_{ps}}{A_g} \quad (1)$$

where A_g and A_{ps} are the gross cross-sectional area and the total area of the center post-tensioning strands, respectively.

Table 1 Variables considered

Variables	Values
Prestressing force ratio, α_{ps}	0%, 2.5%, 5%, 7.5%, 10% and 15%
Strand ratio, ρ_{ps}	0.15%, 0.29%, 0.59% and 0.88%
Longitudinal reinforcement ratio, ρ_l	0.18%, 0.35%, 0.59% and 0.92%

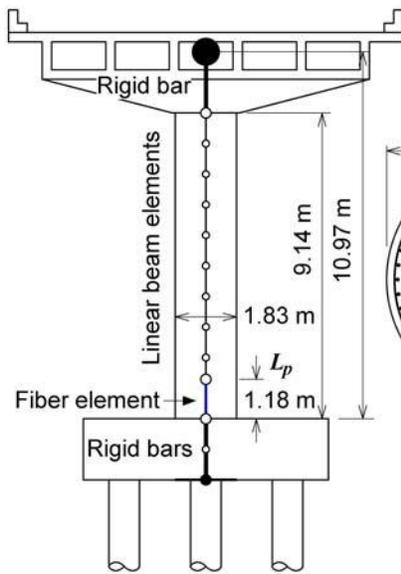


FIG. 1. Conventionally designed reinforced concrete column

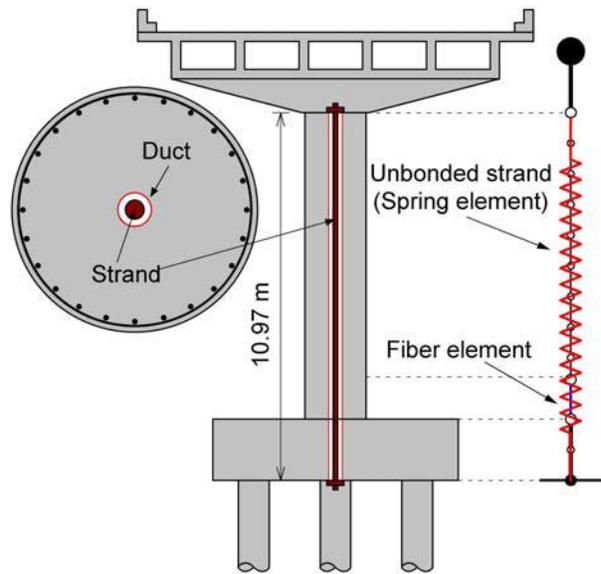


FIG. 2. Partially prestressed column

ANALYTICAL MODEL

The reference reinforced concrete bridge column and the partially prestressed columns are idealized as two-dimensional discrete models, as conceptually shown in **Figs. 1** and **2**. For sake of simplicity, the models are assumed fixed at the base and pinned at the top. The flexural hysteretic behavior of the plastic hinge region is idealized by a fiber element. The plastic hinge length is assumed to be 1.18 m, based on the equation proposed by Priestley et al. [7]. Rigid bars are used to model the footing and the region from the top of the column to the center of gravity of the superstructure. Linear beam elements with cracked stiffness properties are used for the remainder of the column. Post-tensioning strand that debonded from concrete is represented by a spring element spanning between assumed anchorage points.

Figure 3 shows the stress-strain relation assumed for the core concrete. The confinement effect of concrete is evaluated based on the model developed by Mander et al. [8]. As ρ_s is varied from 0.61% to 1.22%, the core concrete strength, f'_{cc} , the strain at peak stress, ϵ_{cc} , and the ultimate strain, ϵ_{cu} , increase from 42.4 MPa, 0.0043 and 0.014 to 49.3 MPa, 0.0063 and 0.021, respectively. Unloading and reloading paths are represented by the model proposed by Sakai and Kawashima [9]. The descending branch of the cover concrete is idealized as a linear function. Tensile stress of concrete is disregarded in this study.

The envelope curves of longitudinal mild reinforcing bars and strands are idealized as a bilinear model. The initial modulus of elasticity, the yield strength and the strain-hardening ratio are equaled to 200 GPa, 414 MPa and 2% for the mild reinforcement; 196.5 GPa, 1800 MPa and 2% are used for the strands. The modified Menegotto-Pinto model proposed by Sakai and Kawashima [6] [10] is used to represent the hysteretic behavior of the rebar and the strands to take into account the Bauschinger effect.

Predetermined cycles of displacement are imposed at the center of gravity of the superstructure. The amplitude in the first cycle is 0.127 m, which is almost the same as the yield displacement of the reference column. The lateral displacement is increased step wise up to 0.635 m, which is little over the estimated ultimate displacement of the column.

The residual displacement, d_{r-sta} , from the quasistatic cyclic analyses is defined here as the displacement at zero force following unloading from 0.635 m. This provides a general indication of the ability of the column to recenter following inelastic deformations. Later, a dynamic residual displacement is defined as the permanent displacement remaining after an earthquake excitation.

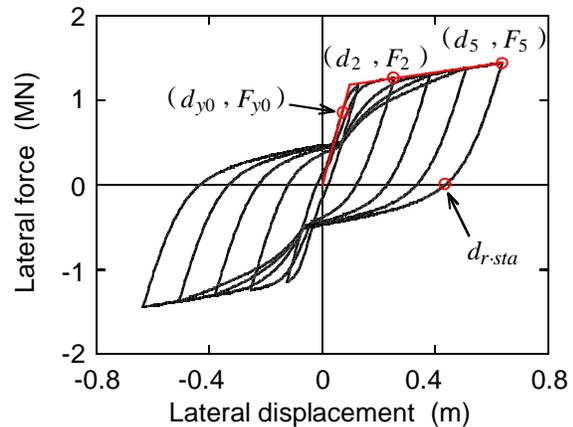
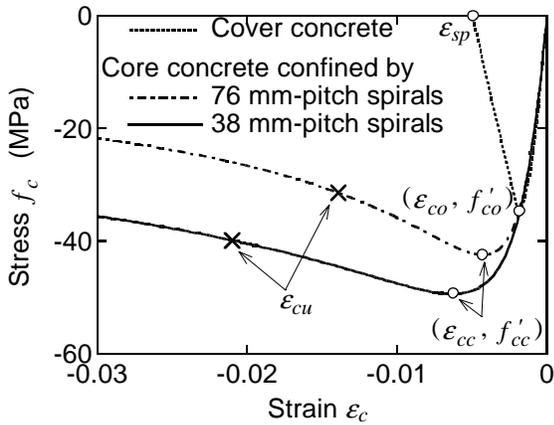


FIG. 3. Confinement effect of spirals

FIG. 4. Force-displacement hysteresis of reference column

QUASISTATIC BEHAVIOR OF COLUMNS

Reference reinforced concrete column

Figure 4 shows the lateral force versus lateral displacement hysteresis of the reference reinforced concrete column. The column yields in the first cycle and the lateral force gradually increases with positive post-yield stiffness during subsequent cycles to larger lateral displacement. The first yield force, F_{y0} , is 0.89 MN, and the lateral force increases up to $F_{max} = 1.44$ MN at displacement of 0.635 m. The static residual displacement, $d_{r.sta}$, of the reference column is 0.434 m, 68% of the peak imposed displacement. The accumulated energy dissipation through the cycles, E_D , is 3.52 MNm. The computed post-yield tangent lateral stiffness, K_2 , is 0.48 MN/m, which is 3.9% of the initial stiffness, K_1 . The initial and the post-yield stiffness is defined here as:

$$K_1 = \frac{F_{y0}}{d_{y0}}; \quad K_2 = \frac{F_5 - F_2}{d_5 - d_2} \quad (2)$$

where F_{y0} and d_{y0} are the force and displacement, respectively, at the first yielding of a reinforcing bar, F_2 and d_2 are the force and displacement at the peak displacement in the second cycle, and F_5 and d_5 are the force and displacement at the peak displacement in the fifth cycle. The skeleton curve (see **Fig. 4**) consists of lines with the initial stiffness from the origin and the post-yield stiffness through (d_2, F_2) and (d_5, F_5) .

The maximum compressive strain of the core concrete is 0.0145, which slightly exceeds the ultimate strain of concrete, ϵ_{cu} (equal to 0.014) at the maximum displacement. The maximum tensile strain of the rebar is 0.06, 50 % of the ultimate tensile strain, ϵ_{su} (equal to 0.12).

Reinforced concrete column with unbonded prestressing strand (Re-Centering RC column)

For preliminary assessment of the effect of the use of unbonded prestressing strand, half of the longitudinal reinforcement (24 29-mm diameter (No. 9) bars) is removed, and a single bundle of prestressing strand, which has an area equivalent to 24 29-mm diameter bars, is arranged at the center of the cross section. A total post-tensioning force of 4.5 MN is applied, equivalent to the axial load due to the dead load. As a consequence, a total axial load of $0.1 P/f'_{co}A_g$ is imposed. Thus, α_{ps} , ρ_{ps} , and ρ_l of this column are 5%, 0.59% and 0.59%, respectively. The denser spirals are used to prevent premature crushing of core concrete; the strand provided from the bottom of the footing to the top of the column is debonded from adjacent concrete by means of a duct. Such columns with unbonded prestressing strands are referred hereinafter as Re-Centering RC columns.

Figure 5 compares the hystereses between the conventional design and the Re-Centering RC column. The initial stiffness of the Re-Centering column is similar to that of the reference column. After yielding, the force steadily increases with the positive post-yield stiffness, reaching a maximum strength of 1.44 MN; the skeleton curve is nearly identical to that of the RC column. The use of unbonded prestressing strand significantly reduces the residual displacement upon unloading from a peak displacement. The residual displacement in the fifth cycle is 0.061 m, only 14% of the RC column. The peak strain of the strand is 0.0035, 40% of $\epsilon_{ps,EE}$. The maximum core concrete strain increases up to 0.018; however this is still 14% smaller than the ultimate strain of the concrete confined by the denser spirals. The maximum tensile strain of the rebar is 0.057.

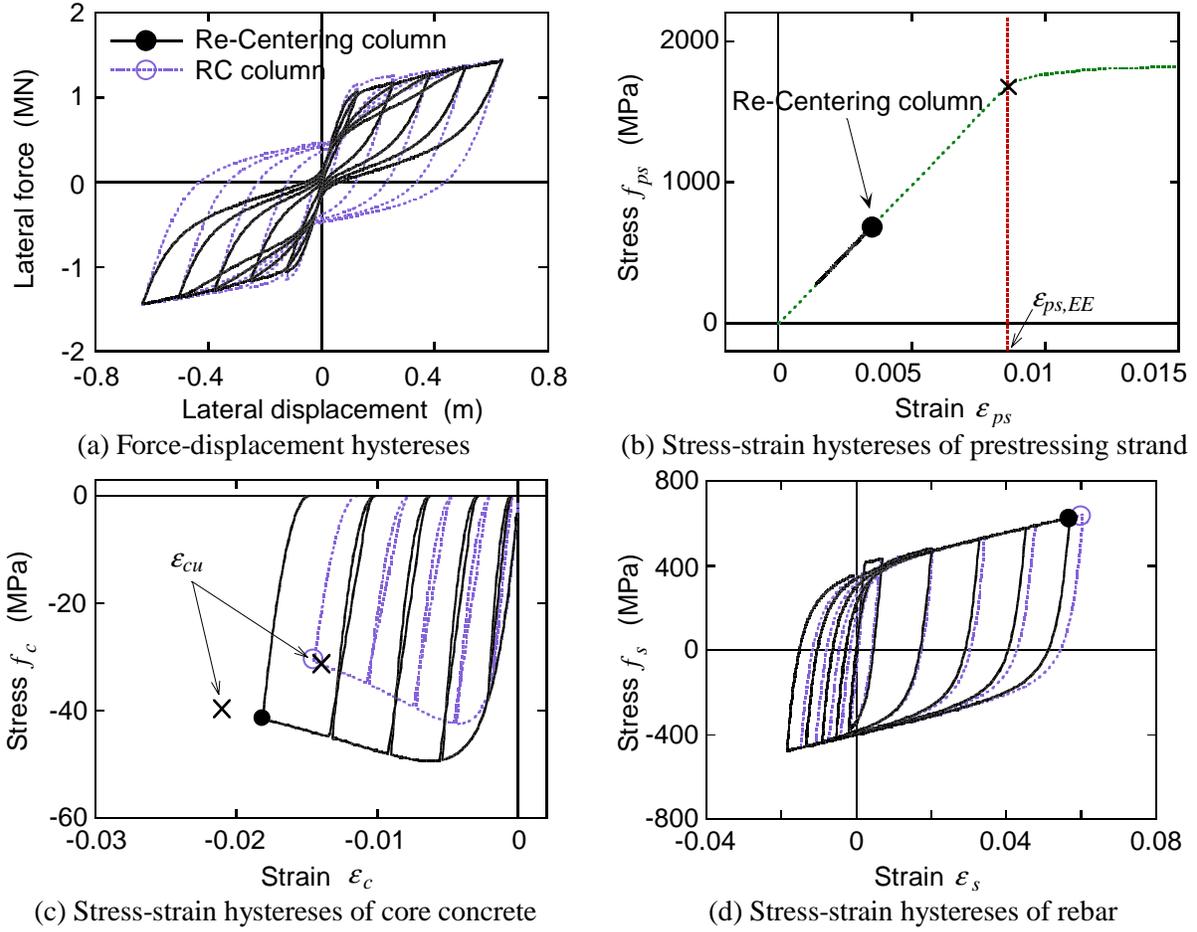


FIG. 5. Quasistatic behavior of Re-Centering RC column

Effect of magnitude of prestressing force

Figure 6 shows the sensitivity of hysteretic behavior of the columns to the magnitude of post-tensioning force. Here, ρ_{ps} and ρ_l are fixed at 0.59% and 0.59%, respectively. Cases of $\alpha_{ps} = 0\%$, 5%, 10% and 15% are shown in **Fig. 6** (a). The reference column is also shown for comparison. When the prestressing force increases by increasing the initial stress in the strand, both the first yield strength and the maximum lateral force increase. The residual displacement of the Re-Centering columns is smaller than 20% of that of the reference column except for the column without prestressing force.

To evaluate the quasistatic performance of Re-Centering RC columns, the ratios of the values of the quasistatic residual displacement, the first yield force, the flexural strength, the post-yield stiffness and the total energy dissipation between the reference column and the Re-Centering columns are computed. The maximum compressive concrete and tensile rebar strains are expressed as a percentage of the appropriate ultimate values, ϵ_{cu} and ϵ_{su} . The maximum tensile strand strain is divided by the essentially elastic strain $\epsilon_{ps,EE}$. **Figure 6** (b) shows the effect of varying the magnitude of prestressing force on the values described above. The quasistatic residual displacement decreases when, α_{ps} increases from 0% to 7.5%, and then increases as α_{ps} increases above 7.5% due to the crushing of the core concrete that occurs at

large displacements for these prestress levels. As α_{ps} increase, the first yield force and the maximum strength increase as described above, but the post-yield stiffness decrease. The total energy dissipation does not significantly depend on the magnitude of the prestressing force. **Figure 6** (b) suggests the maximum core concrete strain exceeds the ultimate concrete strain when α_{ps} exceeds 10%. As expected, the peak strain in the post-tensioning strand increases when α_{ps} increases. Nonetheless, the strand does not yield, even when α_{ps} reaches 20%.

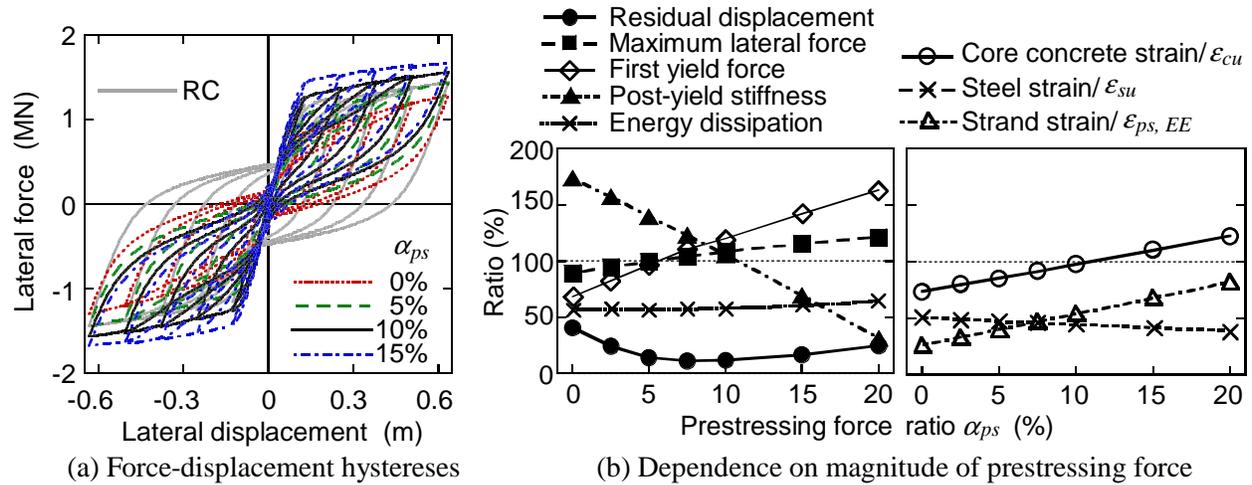


FIG. 6. Effect of magnitude of prestressing force

Effect of amount of prestressing strand provided

The area of strand provided does not significantly affect the hysteretic behavior of the column for a constant prestressing force, as shown in **Fig. 7**, where $\alpha_{ps} = 5\%$ and $\rho_l = 0.59\%$. This figure suggests that varying the area of strand is effective means of controlling the post-yield stiffness. However, the strain in the core concrete and in the post-tensioning strand should be carefully reviewed, because the concrete strain increases as the area of strand increases, and the strand are likely to yield when ρ_{ps} becomes sufficiently small.

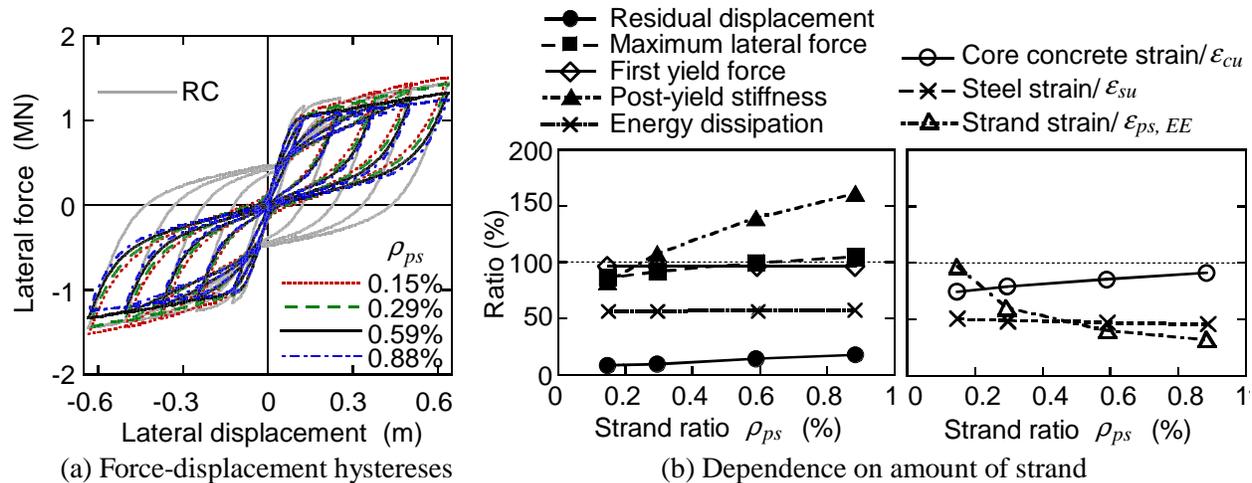


FIG. 7. Effect of amount of post-tensioning strand

Effect of area of longitudinal mild reinforcing bars

Figure 8 shows the effect of the area of longitudinal reinforcing bars on the behavior of the columns. Here, α_{ps} and ρ_{ps} are 5% and 0.59%, respectively. The residual displacement, the flexural strength, the first yield force, the post-yield stiffness, and the capacity of energy dissipation increase with increasing ρ_l . Smaller ρ_l is preferable, because it results in smaller residual displacement; however, it also leads to smaller flexural strength and energy dissipation capacity. Smaller flexural strength and energy dissipation may increase seismic demand. Therefore, the appropriate amount of longitudinal rebar should be determined based on dynamic analyses.

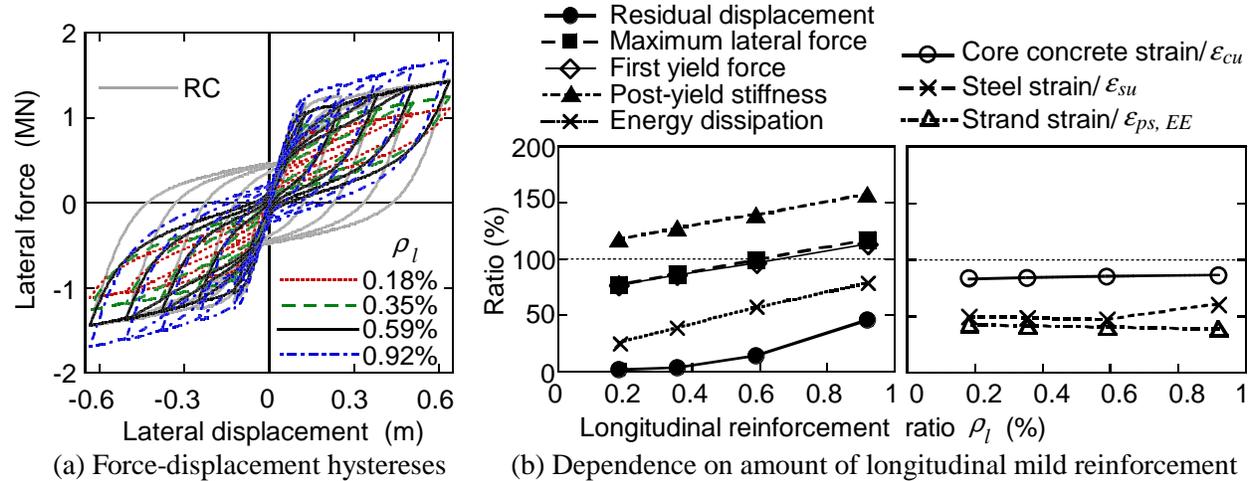


FIG. 8. Effect of amount of longitudinal mild reinforcement

DYNAMIC RESPONSE OF BRIDGES SUPPORTED BY RE-CENTERING RC COLUMNS

Selection of Re-Centering RC columns for analyses

To assess the dynamic performance of Re-Centering RC columns, several columns are subjected to an ensemble of earthquake ground motions. To select the columns used in the dynamic analyses, additional quasistatic analyses are conducted to identify specific combinations of design parameters where the columns have skeleton loading characteristics similar to the reference column, exhibit origin-oriented hysteretic properties upon unloading, and avoid excessive strains in the materials. Design variables considered are the magnitude of the prestressing force, the area of the post-tensioning strands, and the area of the longitudinal rebars.

The quasistatic analyses demonstrates that (1) a prestressing force ratio, α_{ps} , between 5% and 10% are seen to be preferable; (2) the strand ratio, ρ_{ps} , can be taken from 0.15% to 0.88%, depending on the combination with ρ_{ps} and ρ_l , but the total steel ratio, $\rho_{ps} + \rho_l$, should be larger than about 0.7%; (3) the longitudinal reinforcement ratio, ρ_l , cannot be larger than 0.59%, because increasing the amount of the longitudinal rebar results in a relatively large residual displacement.

Based on these findings, four columns shown in **Table 2** and **Figure 9** are selected. Column No.1 has almost the same skeleton curve as the reference column. Column No.2, which develops the smallest quasistatic residual displacement among the columns selected, is selected to determine the effect of

smaller energy dissipation capacity and post-yield stiffness. Column No.3 is selected to assess the effect of larger post-yield stiffness, which is 61% larger than the reference column. Column No. 4 has the largest first yield force, flexural strength, and energy dissipation capacity among the columns selected.

Table 2 Properties of Re-Centering columns used in dynamic analyses

Column ID No.	α_{ps} (%)	ρ_{ps} (%)	ρ_l (%)	$\rho_l + \rho_{ps}$ (%)	$d_{r.sta}$ (mm)	F_{max} (MN)	F_{y0} (MN)	K_2 (MN/m)	E_D (MNm)
RC	-----	-----	1.18	1.18	434	1.45	0.89	0.48	3.52
1	10	0.88	0.35	1.23	32	1.45	0.98	0.52	1.51
2	10	0.59	0.18	0.77	17	1.25	0.90	0.40	1.02
3	5	0.88	0.59	1.47	78	1.52	0.86	0.78	2.01
4	10	0.59	0.59	1.18	50	1.56	1.07	0.51	2.04

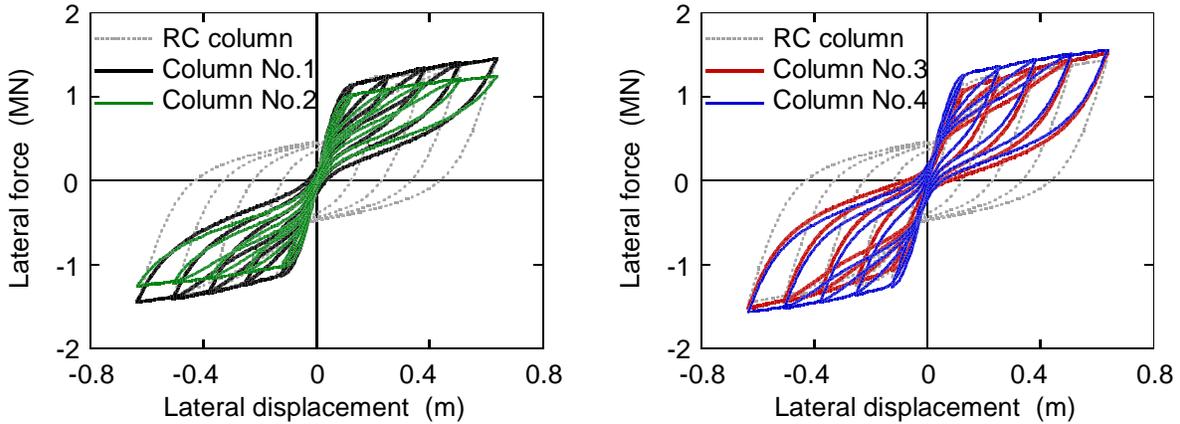


FIG. 9. Quasistatic behavior of Re-Centering RC columns selected for dynamic analyses

Analytical model and ground motions used

The two-dimensional models shown in **Figs. 1** and **2** are used for the dynamic analyses. The response of the bridges in the transverse direction is analyzed. Inertia mass for horizontal and vertical directions, and rotational moment of inertia of the superstructure for both columns are assumed to be 4.62×10^5 kg, 4.62×10^5 kg and 3.2×10^6 kg m², respectively. The models are considered fixed at the bottom of the footing, so potential soil-structure interactions are disregarded.

Based on an Eigenvalue analysis of the model assuming cracked stiffness properties for the reference column, the first, second and third modes have periods of 1.30, 0.18, and 0.05 seconds, respectively. Rayleigh damping is used to represent viscous damping. A viscous damping ratio equal to 5% of critical is assumed for the first and third modes.

An ensemble of severe near-field ground motions, listed in **Table 3** and chosen from a database compiled by the SAC Steel Project [11], is used in the dynamic analyses. Only the generally more severe fault normal component of the ground motions is used in the analyses.

Table 3 Near-field earthquake ground motion records considered

Record	Earthquake	Magnitude	Epicentral Distance	PGA (m/sec ²)	
				Normal	Parallel
Tabas	Tabas, Iran, 1978	7.4	1.2 km	8.83	9.59
Los Gatos	Loma Prieta, USA, 1989	7.0	3.5 km	7.04	4.49
Lexington Dam	Loma Prieta, USA, 1989	7.0	6.3 km	6.73	3.63
Petrolia	Cape Mendocino, USA, 1992	7.1	8.5 km	6.26	6.42
Erzincan	Erzincan, Turkey, 1992	6.7	2.0 km	4.24	4.48
Landers	Landers, USA, 1992	7.3	1.1 km	7.00	7.84
Rinaldi	Northridge, USA, 1994	6.7	7.5 km	8.73	3.81
Olive View	Northridge, USA, 1994	6.7	6.4 km	7.18	5.84
JMA Kobe	Hyogo-ken Nanbu, Japan, 1995	6.9	3.4 km	10.67	5.64
Takatori	Hyogo-ken Nanbu, Japan, 1995	6.9	4.3 km	7.71	4.16

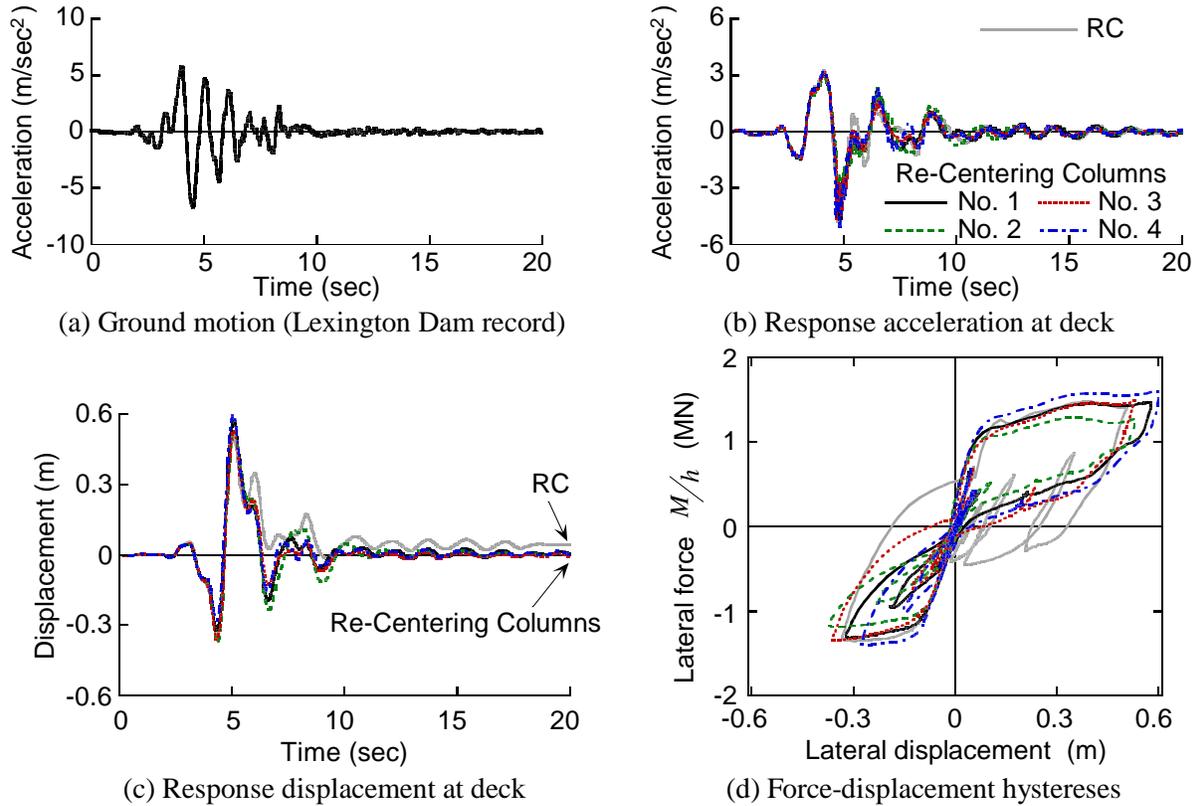


FIG. 10. Dynamic response of columns subjected to Lexington Dam record

Dynamic response

Figure 10 compares the dynamic response of the bridges supported by the Re-Centering RC columns and the reference column subjected to the Lexington Dam record obtained during 1989 Loma Prieta, California, earthquake. To draw force-displacement hysteresses, the lateral force at the center of gravity of

the superstructure is obtained by dividing the bending moment at the bottom of the column, M , by the height from the top of the foundation to the center of gravity of the superstructure, h .

The maximum response accelerations of the reference column is 4.8 m/sec^2 , while those of the Re-Centering Columns are $4.4\sim 5 \text{ m/sec}^2$. All the columns have nearly the same force-displacement characteristics when moving away from the origin as expected. The reference column has the smallest response displacement, while Column No. 4 has the largest, which is 18% larger than the reference column. The pronounced origin-oriented nature of the hysteretic loops of the Re-Centering Columns upon unloading can be clearly seen in **Fig. 10** (d).

Figure 11 compares the maximum and the residual displacements for all ten ground motions. The ultimate displacement of the reference column is also shown in **Fig. 11** (a). As a whole, the maximum responses of the Re-Centering RC columns are almost the same as that predicted for the reference column. Because of the high intensity of the ground motions considered, two of the records (Los Gatos and Takatori) cause the response to exceed the ultimate displacement capacity. Relatively large residual displacements are produced in the reference column for the Lexington Dam and Petrolia records. In contrast, the residual displacements of nearly all of the Re-Centering columns are considerably smaller than that of the reference column, with Column 3 having the smallest residual displacement. The exception is Columns No. 1 and 4 subjected to the Takatori record, where the earthquake resulted in crushing of the confined concrete core in the analyses.

Relatively small energy dissipation capacity and post-yield stiffness (Column No. 2) results in relatively large maximum response than the other Re-Centering columns although the residual displacements are about the same as the others. On the other hand, Column No. 3 performs the best overall, which has relatively large post-yield stiffness, and develops 5-10% smaller maximum displacements and 30-50% smaller residual displacements than the other Re-Centering columns.

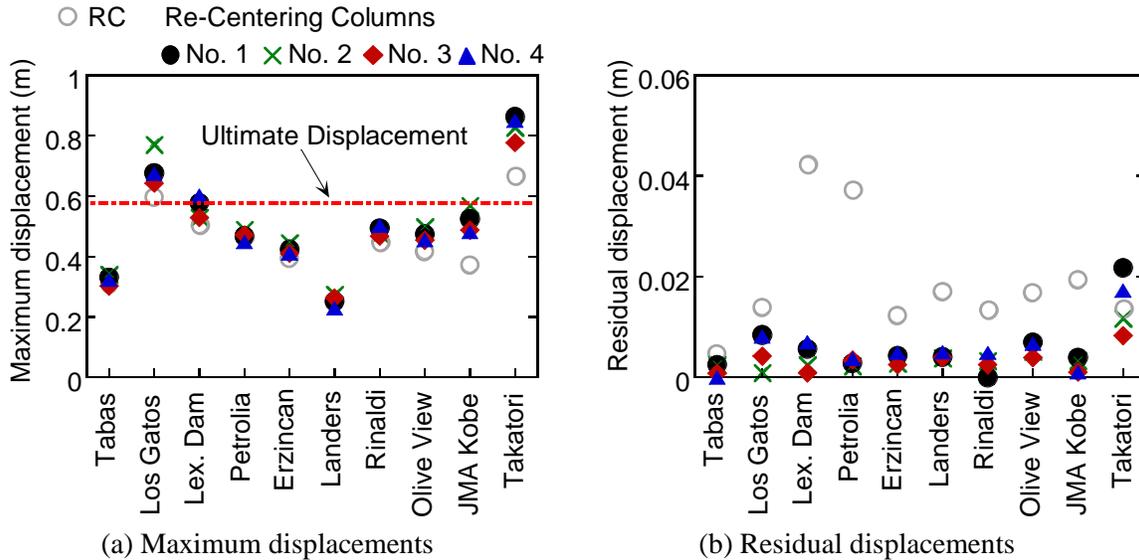
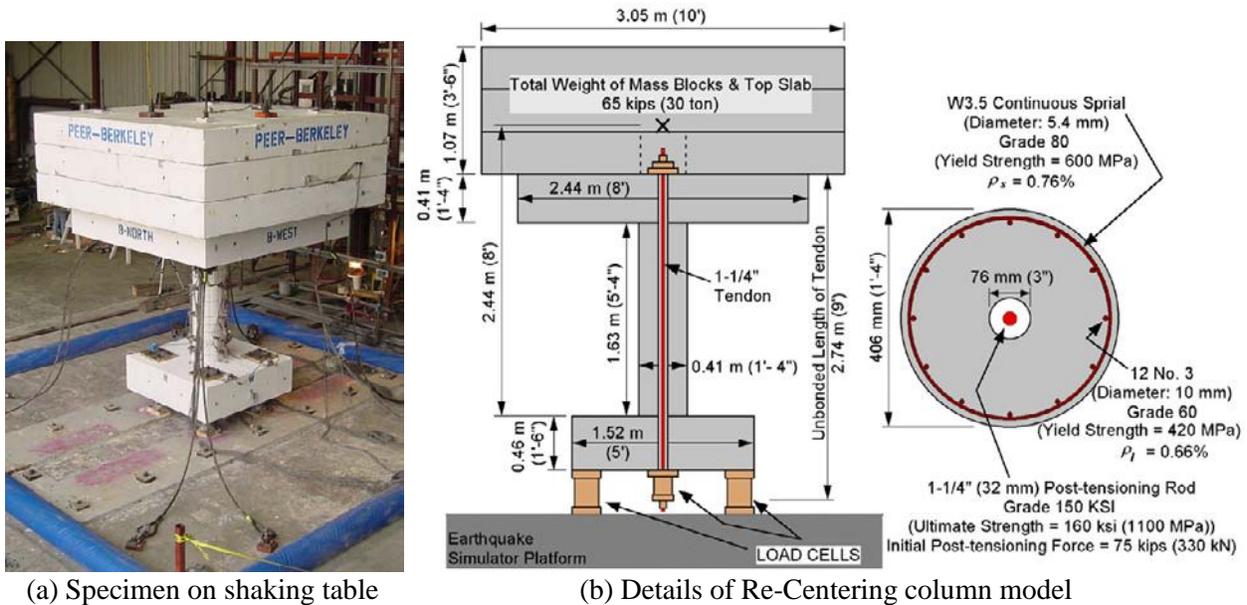


FIG. 11. Maximum and residual displacements for 10 near-field ground motions

EARTHQUAKE SIMULATION TEST FOR RE-CENTERING COLUMNS

To assess the ability of these analytical models to predict response and investigate the effect of multi-directional loading and P-delta effects, several shaking table experiments are being carried out at Berkeley. The first two specimens have been prepared. These represent simple cantilever columns like those analyzed in this paper. The specimens are approximately 1/4-scale models. One specimen is a conventional reinforced concrete specimen, while the other is a Re-centering RC column. Details of the re-centering column specimen are shown in **Fig. 12**. Comparison of the two tests with one another and with computer predictions of response will provide many suggestions for future research to enhance the performance of bridge structures.



CONCLUSIONS

To validate the effectiveness of providing unbonded prestressing strands in reinforced concrete columns on reducing residual displacements, a series of dynamic analyses as well as quasistatic analyses is conducted. Below are the conclusions determined from these analyses:

- (1) Replacing half of the longitudinal mild reinforcement with unbonded strand and applying a prestressing force equal to the axial force induced by the dead load results in 86% reduction of residual displacement when unloaded from near the ultimate displacement capacity. The restoring force characteristics of the column with unbonded prestressing strand is virtually identical to that of the conventionally designed reinforced concrete column during loading;
- (2) Results from quasistatic analyses demonstrate that prestressing force ratios between 5% and 10% are preferable. The post-yield stiffness of the Re-Centering RC column can be controlled by varying the area of post-tensioning strand incorporated into the column. Smaller amount of longitudinal mild reinforcement is preferable for reducing quasistatic residual displacement; and

- (3) Columns with unbonded prestressing strands (Re-Centering RC columns) perform very well under strong ground shaking. A column with larger post-yield stiffness shows better performance for both the residual and maximum displacements.

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