MITIGATION OF RESIDUAL DISPLACEMENTS OF REINFORCED CONCRETE BRIDGE COLUMNS

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Abstract

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 minimize such 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 and earthquake simulation tests.

Introduction

In recent years, a high ductility capacity is expected of bridge columns located in regions of high seismicity, like California and Japan, to ensure economical designs with adequate protection against collapse during strong ground shaking (California Department of Transportation, 2001; Japan Road Association, 1996). 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. To maximize post-event operability and minimize repair costs, attention should be paid in the design process to minimizing these residual displacements.

As a result of damage suffered by bridges in the 1995 Hyogo-ken Nanbu earthquake, the Japanese Design Specification of Highway Bridges was revised in 1996 and included a requirement for limiting the residual lateral displacement at the top of a column after an earthquake (Japan Road Association, 1996). The maximum allowable residual displacement is limited to 1% of the height of the column. In an effort to satisfy the specification, some research has focused on developing new systems to reduce the residual displacements of reinforced concrete bridge columns (Zatar and Mutsuyoshi, 2000; Iemura et al., 2002).

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

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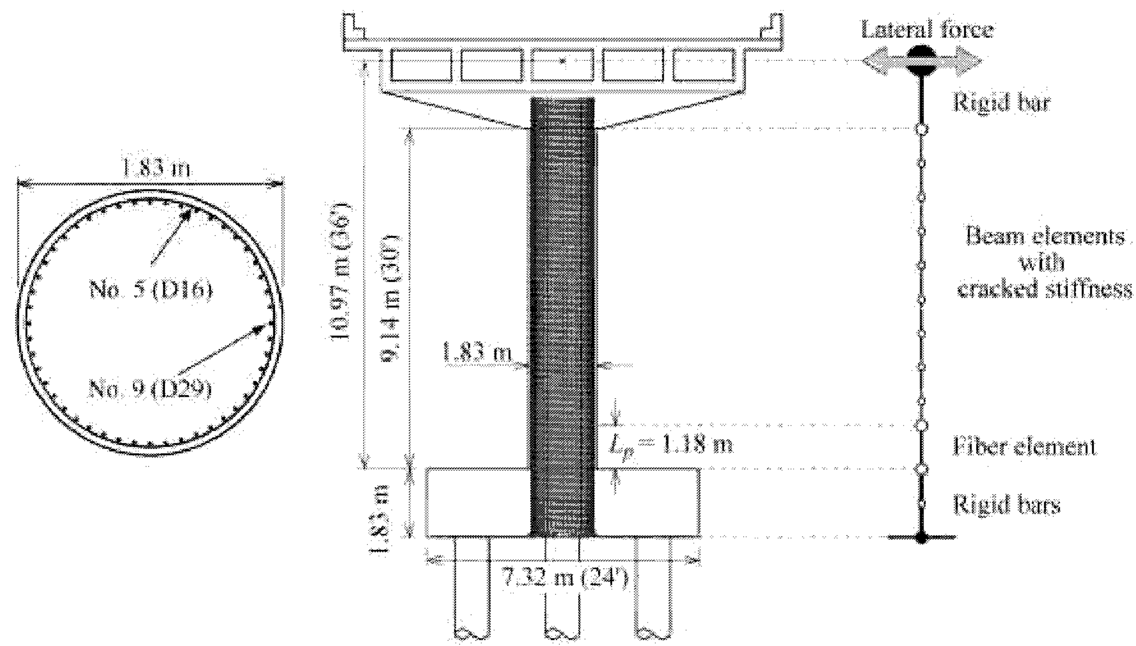
a single bundle of unbonded prestressing strand is incorporated at the center of the cross-section of a lightly reinforced concrete column (Sakai and Mahin, 2004). This paper presents a series of quasistatic and dynamic analyses for the reinforced concrete columns with unbonded prestressing strands to investigate the performance of such columns, followed by a series of earthquake simulation tests to validate the effectiveness of this approach in improving seismic performance.

Bridge Column Analyzed

A reinforced concrete bridge column designed in accordance with the Caltrans SDC (2001) is analyzed. **Figure 1** shows the dimension and the cross section of the column. The column is 1.83 m in diameter and the height from the bottom of the column to the center of gravity of the superstructure is 10.97 m, resulting in an aspect ratio of 6. The dead load supported by the column is 4.5 MN, and the unconfined concrete strength is 34.5 MPa. Thus, the ratio of axial load to axial load capacity (axial load ratio) is 5%.



(a) Cross section (b) Column (c) Analytical model

Fig. 1. Column analyzed

The column is reinforced with 48 No. 9 (29-mm diameter) deformed bars and No. 5 (16-mm diameter) spirals at 76 mm pitch. The longitudinal reinforcement ratio, ρ_l, and the volumetric ratio of spiral reinforcement, ρ_s, are 1.18% and 0.61%, respectively. Reinforcing bars with the yield strength of 420 MPa (Grade 60) are used for both longitudinal and spiral reinforcement.

The lateral load capacity of the column is 1.29 MN. The computed yield and the ultimate displacements are 0.11 m and 0.58 m, respectively, resulting in a displacement ductility capacity of 5.2.

In this paper, the reinforced concrete bridge column is idealized as a two-dimensional discrete model, as shown in **Fig. 1** (c). The flexural hysteretic behavior of the plastic hinge region is characterized in the analyses using fiber elements. The plastic hinge length is assumed to be 1.18 m based on the equation proposed by Priestley et al. (1996). The foundation and bent cap are assumed to be very stiff in comparison to the column, and therefore modeled using flexurally rigid beams. Outside of the plastic hinge length, the remainder of the column is modeled using linear elastic beam elements with cracked stiffness properties computed considering the detailing of the column and its gravity loading.

For the quasistatic analyses, 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 displacement as the yield displacement of the column. The lateral displacement is increased step wise up to 0.635 m, which slightly exceeds the estimated ultimate displacement capacity of the column.

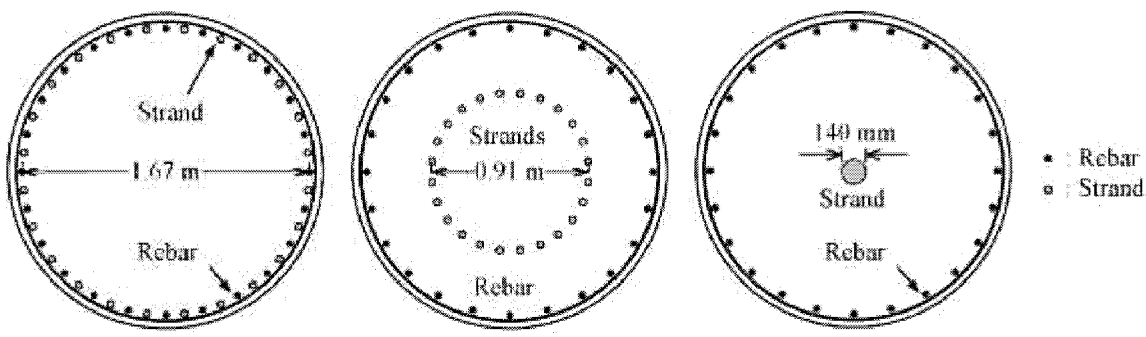
The confinement effect on concrete properties and the stress-strain envelope curve are evaluated based on the Mander model (1988). The peak stress of the core concrete, f_{cc}, the strain at the peak, ε_{cc}, and the ultimate strain, ε_{cu}, are 42.4 MPa, 0.0043, and 0.014, respectively. The descending branch of the unconfined cover concrete is idealized as a linear function. Tensile strength of concrete was disregarded in this study. The model proposed by Sakai and Kawashima (2004a) was used for the unloading and reloading paths.

The envelope curve of the reinforcing steel is idealized using a bilinear model, with the yield strength and strain-hardening ratio taken as 414 MPa and 2%, respectively. To represent the hysteretic behavior of steel, a modified Menegotto-Pinto model (Sakai and Kawashima, 2004b) is used.

Columns with Prestressing Strands

As a first step in these investigations, a series of quasistatic cyclic analyses was performed on the reinforced concrete bridge column described above to study the effects of the magnitude of axial load and the amount and type of longitudinal reinforcement on the tendency of the column to re-center following lateral displacement excursions (Sakai and Mahin, 2004). From these and other results, it was noted that reducing the amount of longitudinal reinforcement and adding axial load minimized the residual displacement following the imposition of an inelastic lateral displacement. Therefore, it was postulated that to mitigate residual displacements it might be effective to replace some reinforcing bars with prestressing strands.

To understand the consequences of adding prestressing strands, an additional series of quasi-static cyclic analyses has been conducted for columns with different arrangements of strands, as shown in **Fig. 2**. For the results presented herein, half of the rebar is removed and replaced with an equal area of prestressing strands. The strands are arranged in circular patterns, with diameters ranging from 1.67 m to 0 m; in all cases, the total area of strands is kept constant (taken equal to 24 No. 9 bars). For Column PC-A the diameter of the strand pattern is 1.67 m - the same as used for the rebar. In Column PC-B, the diameter of the strand pattern is 0.91 m (about half the column diameter). Column PC-C has one big strand, with an effective solid diameter of 140 mm, located at the center of the column (in reality, this could be a bundle of strands located at the column center).



(a) Column PC-A (b) Column PC-B (c) Column PC-C

Fig. 2. Cross sections of columns with strands

Grade 270 strands are used for the prestressing strands. The elastic modulus of the strand, E_{ps}, the essentially elastic strain, $\varepsilon_{ps,EE}$, the ultimate strain and ultimate strength are 196.5 GPa, 0.0086, 0.03 and 1860 MPa, respectively. The total prestressing force is assumed to be 4.5 MN, resulting in a total nominal axial load ratio of 10%. The stress induced in the strands by the 4.5 MN prestressing force is 293 MPa, which is only 16% of the ultimate strength of the Grade 270 strand.

To prevent undesirable premature crushing of concrete due to the additional axial load by the prestressing strands, it may be necessary to provide additional confinement for the column. To enhance the confinement of the core concrete, the spiral pitch is reduced from 76 mm to 38 mm. Accordingly, the denser spiral arrangement increased ρ_s to 1.22%. f_{cc}, ε_{cc}, and ε_{cu} of the core concrete confined by 38 mm-pitch spirals are 0.0063, 49.3 MPa and 0.021, respectively.

Yielding of the strands is another significant concern. Strands have relatively limited ability to deform inelastically, and yielding would reduce the effective prestressing force applied to the column during subsequent cycles. Therefore, strand strains are reduced for many of the post-tensioned columns considered by unbonding the strands from the concrete by means of ducts or other debonding medium. The columns presented in this study are assumed to have debonded strands from the bottom of the footing to the top of the column, as shown in **Fig. 3**. The unbonded length is thus 10.97 m; six times the column diameter. Other unbonded lengths for the post-tensioning strands have been considered, and it was noted that longer unbonded length resulted in better performance of the post-tensioned columns. The prototype column with the completely unbonded center strand and with the denser spiral arrangement is referred to in this study as the Re-Centering RC column.

To idealize columns with bonded strands for analysis, fibers including the strand's properties are added in the standard fiber elements. Unbonded strands are, on the other hand, idealized by additional longitudinal spring elements, as shown in **Fig. 3**. The stress-strain envelope curve for the strand is idealized using a bilinear model, with a yield strength of 1800 MPa, and a strain-hardening ratio of 2%; the modified Menegotto-Pinto model is used to characterize unloading and reloading paths.

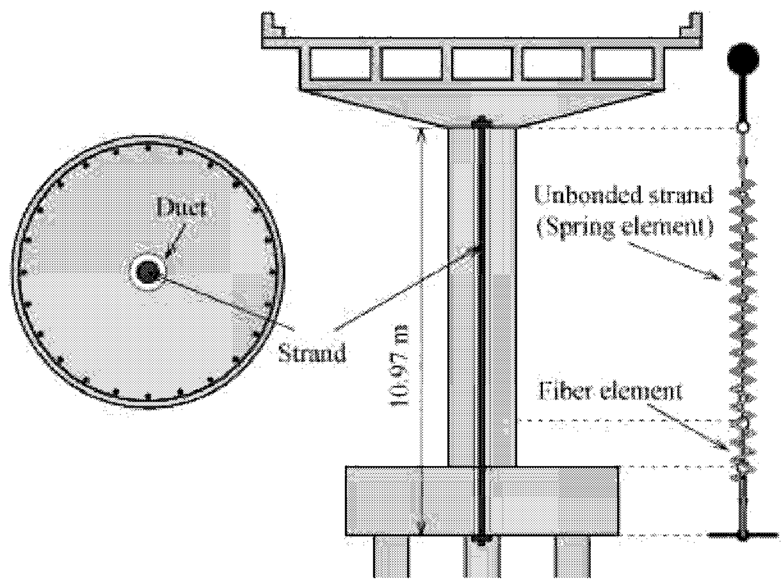


Fig. 3. Re-Centering RC column

Effect of Providing Prestressing Strands

Figure 4 compares the force versus displacement hysteresis between the RC column and three columns containing the different strand configurations. For the cases plotted, strands are bonded to the concrete and no additional confinement is provided.

In the simple configuration where half of the rebar is replaced by strands (Column

PC-A), the lateral strength goes up to 2.52 MN; this is 74% greater than that of the conventional column. Such high flexural strength is undesirable in capacity design due to the increased shear capacity required for the column, and larger design forces needed for the superstructure, footing and piles. When a single bundle of the strand is concentrated at the center of Column PC-C column, the lateral force reaches the peak strength (1.6 MN, about10% larger than the RC column) at a lateral displacement of 0.38 m, and then the lateral force decreases gradually as the lateral displacement increases.

Incorporating prestressed strands consistently results in smaller residual displacement upon unloading quasi-statically from the peak displacement reached during a cycle, but the configuration of the strands has little significant effect on the amount of reduction. The residual displacements of all three prestressed columns are approximately 25% smaller than that of the RC column.

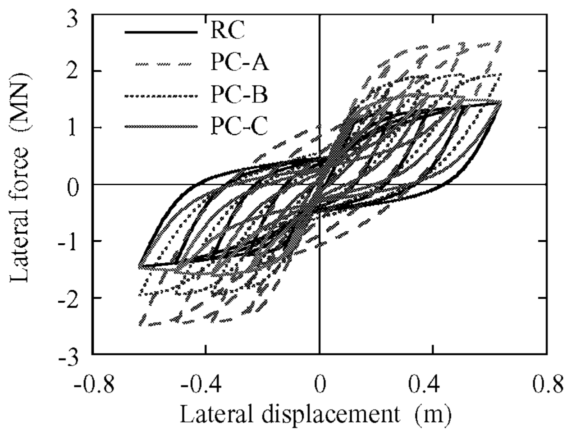
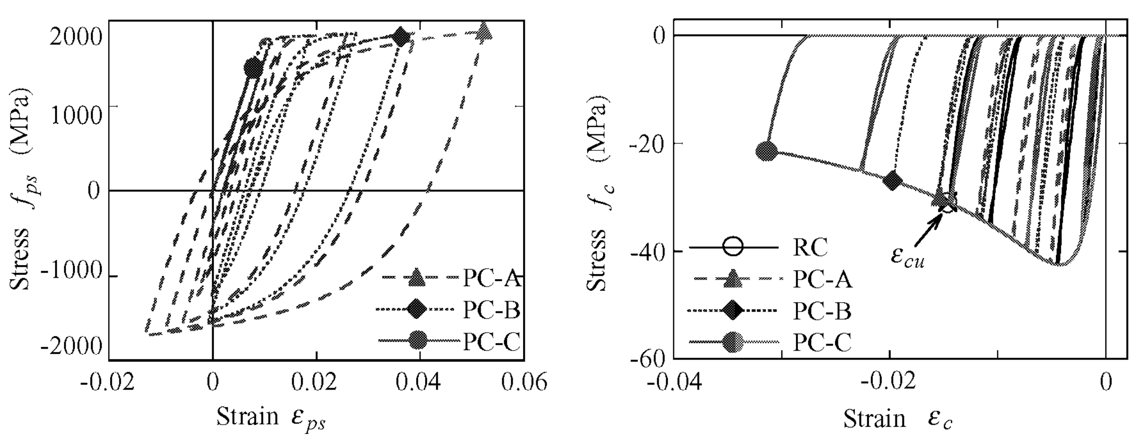


Fig. 4. Hysteresis of columns



(a) Strand (b) Core concrete

Fig. 5. Stress vs. strain hystereses of columns with prestressing strands

Figure 5 compares stress versus strain hystereses of a strand and the core concrete at the compressive edge; the hysteresis of the strand at the tension-most strand is presented for Columns PC-A and PC-B, while the hysteresis of the center strand is presented for Column PC-C. Strain induced in the tension-most strand in Columns PC-A and PC-B exceeds 3%, the ultimate strain of the strand. This is a critical problem, potentially causing fracture of the strands and significant loss of the lateral force carrying capacity of the column. Although the strand at the center of Column PC-C does not yield, the maximum strain induced is 0.0074, and the core concrete strain computed is more than twice the estimated ultimate strain.

Based on the previous results, it is decided that the prestressed columns need additional confinement for the core concrete and that the strands should be unbonded. Because Column PC-C shows better performance, i.e., desirable flexural strength, ease of construction and smaller strand strain, results presented hereinafter focus on Column PC-C with an unbonded center strand and with 38-mm pitch spirals (the Re-Centering RC column).

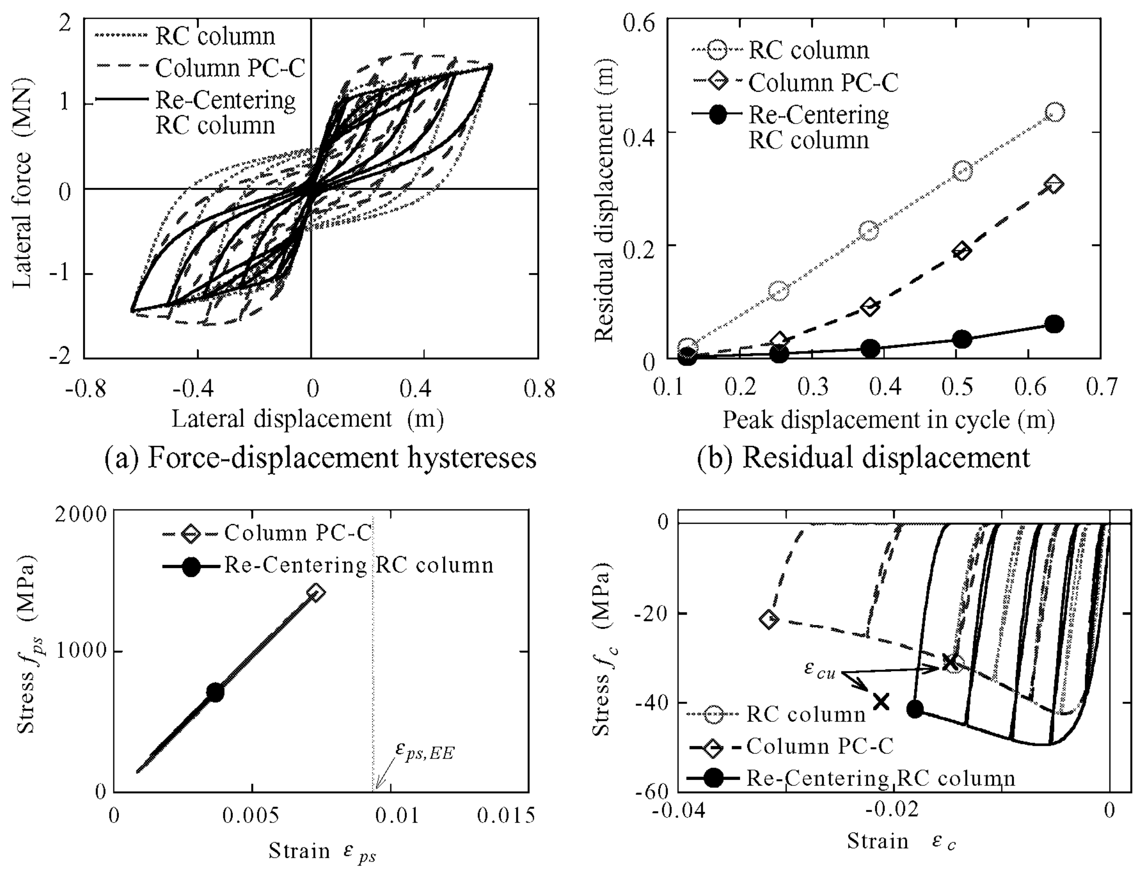


Fig. 6. Quasistatic behavior of Re-Centering RC column

Figure 6 shows quasistatic hysteretic behavior predicted for the Re-Centering RC column. The stiffness of the Re-Centering RC column changes sharply when the rebar begins yielding in tension. After yielding, the force steadily increases with the positive post-yield stiffness, reaching a maximum strength of 1.44 MN: the skeleton curve is almost the same as that of the RC column. Unbonding of the central strand significantly affects the residual displacement upon unloading from a peak displacement. The residual displacement in the fifth cycle is 0.061 m, which is only 14% of that of the conventional RC column.

The peak strain of the strand is only 0.0035, 40% of $\varepsilon_{ps,EE}$ when it is unbonded. Furthermore, the maximum core concrete strain is reduced to 0.018, which is 14% smaller than ε_{cu} .

Dynamic Response of Columns with Unbonded Prestressing Strands

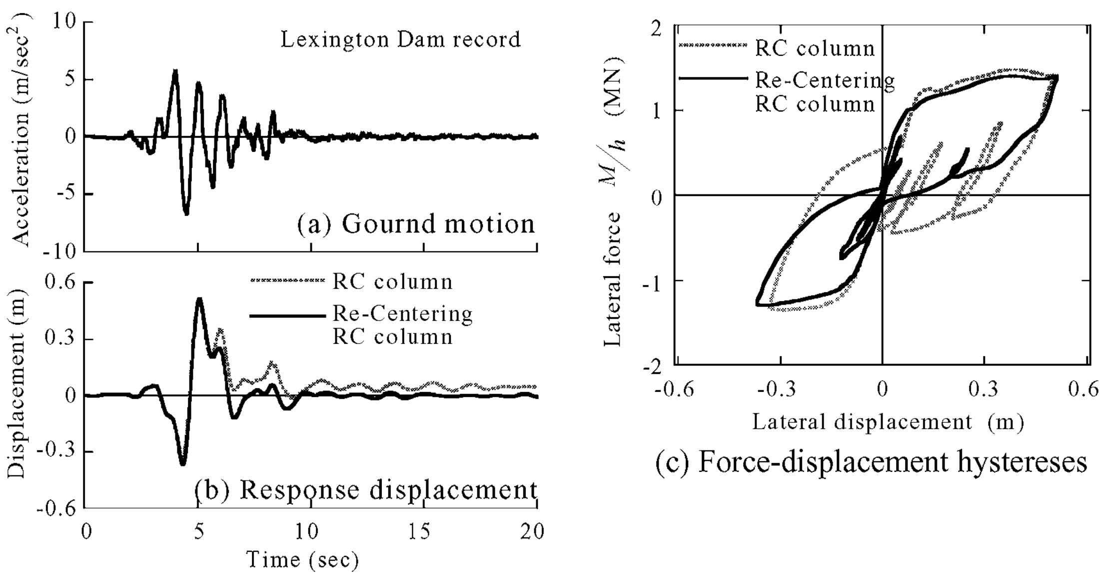
The two-dimensional models shown in **Figs. 1** and **3** are used to carry out dynamic analyses of the columns. The models are fixed at the bottom of the footing and the soil-structure interaction is disregarded. The natural period of the 1st mode is 1.30 seconds, based on the Eigenvalue analysis of the model considering cracked stiffness properties of the column. The SAC impulsive near-field ground motions (Somerville et al., 1998), listed in **Table 1**, are used for the dynamic analyses. Results are presented herein only for the more damaging, fault-normal component of the motions.

Table 1 Near-Field Earthquake Ground Motions

No.	Record	Earthquake	M	Δ	PGA
1	Tabas	Tabas, Iran, 1978	7.4	1.2	8.83
2	Los Gatos	Loma Prieta, USA, 1989	7.0	3.5	7.04
3	Lexington Dam	Loma Prieta, USA, 1989	7.0	6.3	6.73
4	Petrolia	Cape Mendocino, USA, 1992	7.1	8.5	6.26
5	Erzincan	Erzincan, Turkey, 1992	6.7	2.0	4.24
6	Landers	Landers, USA, 1992	7.3	1.1	7.00
7	Rinaldi	Northridge, USA, 1994	6.7	7.5	8.73
8	Olive View	Northridge, USA, 1994	6.7	6.4	7.18
9	JMA Kobe	Hyogo-ken Nanbu, Japan, 1995	6.9	3.4	10.67
10	Takatori	Hyogo-ken Nanbu, Japan, 1995	6.9	4.3	7.71

M : Magnitude, Δ : Epicentral Distance (km)
PGA: Peak Ground Acceleration (m/sec^2)

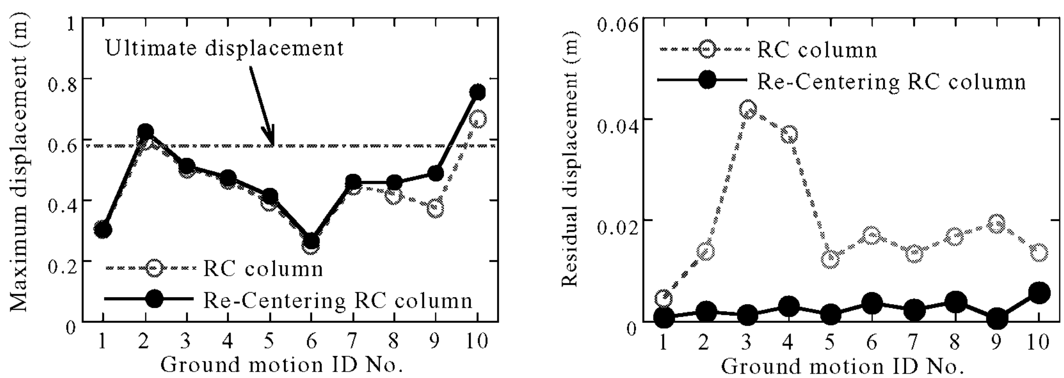
Figure 7 compares the dynamic response of the Re-Centering RC column and the conventional RC column subjected to the Lexington Dam record obtained during the 1989 Loma Prieta earthquake. Both the columns have nearly the same force-displacement characteristics when moving away from the origin. The pronounced origin-oriented nature of the hysteretic loops of the Re-Centering column upon unloading can be clearly seen in **Fig.** 7 (c). The maximum response displacement of the Re-Centering RC column is almost the same as that of the RC column. However, the residual displacement of the Re-Centering RC column is only 0.0013 m, while that of the RC column is 0.042 m.



(c) Force-displacement hystereses

Fig. 7. Dynamic response of Re-Centering RC column

Figure 8 compares the maximum and residual displacements of the columns for all the ten ground motions. As a whole, the maximum response displacements of the Re-Centering RC column are almost the same as those predicted for the conventional RC column. When either column is subjected to the Los Gatos Record or the Takatori record, the responses exceeds the ultimate displacement. The residual displacements of the Re-Centering RC column are on average only about 10% of those of the RC column.



(a) Maximum displacement (b) Residual displacement

Fig. 8. Maximum and residual displacement

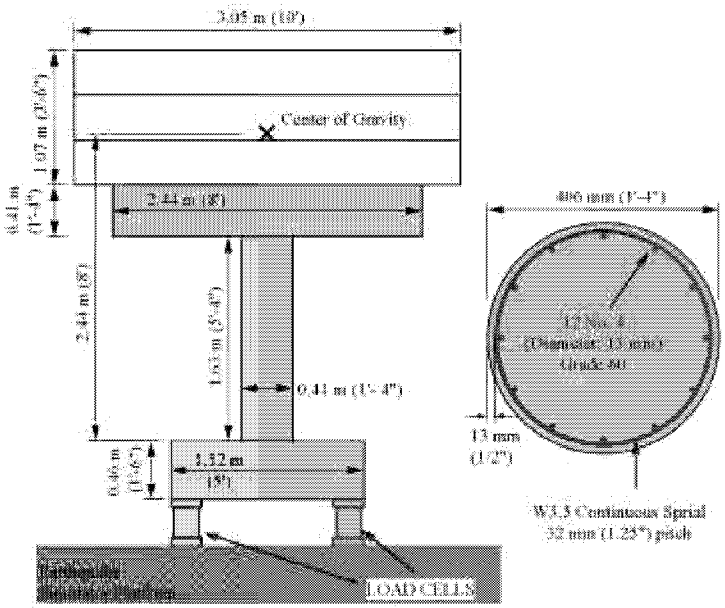
Specimens and Ground Motions for Earthquake Simulation Test

To assess the ability of these analytical models to predict response and investigate the effect of multi-directional loading and P-delta effects, earthquake simulation tests have been conducted on the shaking table of University of California, Berkeley. The specimens represent simple cantilever columns like those analyzed in this paper. These are 1/4.5-scale models. One specimen was a conventional reinforced concrete specimen, while the other was a Re-Centering RC column.

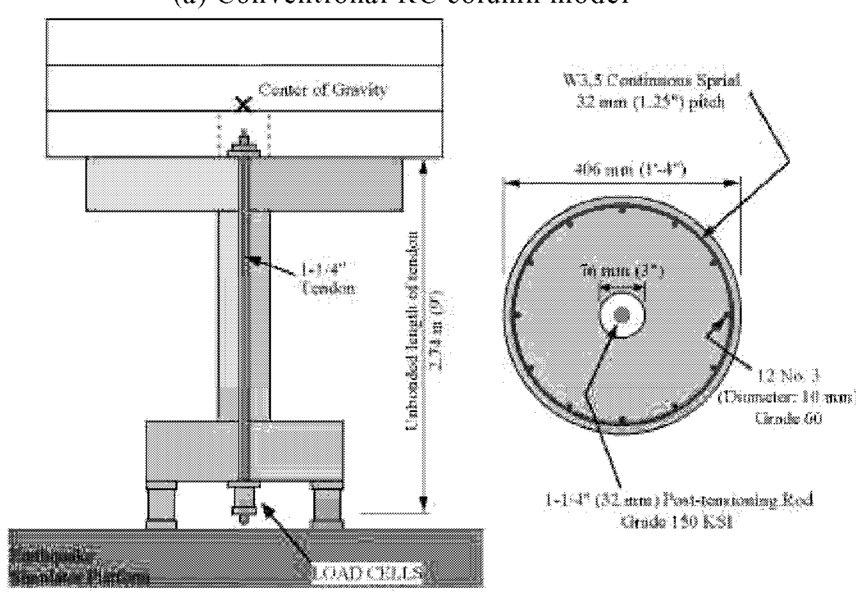
Figure 9 shows the test specimens. The diameter of the specimens was 406 mm, and its height from the bottom of the column to the center of gravity of the superstructure was 2.44 m, resulting in an effective aspect ratio of 6. The concrete strength was 35 MPa. Three concrete blocks were placed on the top slab of each specimen to idealize an inertia mass of the superstructure of a bridge and dead load due to the superstructure. The total inertia mass of the concrete blocks-top slab assembly was 29 ton, and the axial load ratio at the bottom of the conventional model was 6.3%. The conventionally designed model was reinforced longitudinally with 12 No. 4 (13-mm diameter) deformed bars, providing for a longitudinal reinforcement ratio, ρ_l, of 1.2%. W3.5 (5.4-mm diameter) spirals were used to confine the concrete core, spaced at a 32-mm pitch, resulting in a volumetric ratio, ρ_s, of 0.61%. Grade 60 bars were used for the longitudinal bars, while Grade 80 wire (f_y = 600 MPa) was used for the spirals. The No. 4 bars had a yield strength of 455 MPa, and an ultimate strength of 662 MPa. The yield displacement of the conventional column was estimated by a moment-curvature analysis to be 26 mm.

Based on findings from the analytical investigation shown above, a partially prestressed, reinforced concrete column with posttensioning strand concentrated at the center of the cross-section and debonded from adjacent concrete over the full height of the column was constructed as a Re-Centering RC column model (see **Fig. 9** (b)). A series of quasistatic analyses was conducted to explore the best combination of design variables such as longitudinal reinforcement ratio, size of prestressing tendon and magnitude of prestressing force to obtain similar skeleton curve of the lateral force-lateral displacement hystereses to the conventional column model and yet much smaller residual displacement. Based on the results, 12 No. 3 (10-mm diameter) deformed bars and 32-mm diameter prestressing tendon were selected for the Re-Centering column model. The yield strength of the steels was 424 MPa and 1000 MPa, respectively. The longitudinal mild reinforcement ratio was 0.66%, which was 55% of that of the conventional one. The prestressing force induced was 390 kN, providing a total axial load ratio of 15%. The same spiral arrangement of the conventional model was used for the Re-Centering column model.

Using the 10 ground motions shown in **Table. 1**, a series of bi-directional dynamic analyses for the models were conducted prior to the tests, and this had resulted in selection of Los Gatos records from the 1989 Loma Prieta, California, earthquake as the input ground motion for the tests. The ground motion that has stronger intensity, which was fault normal component, was used for X direction, the motion with the weaker intensity (fault parallel component) was used for Y direction. The records were first scaled down in time using a time scale factor equal to the square root of the length scale (= 2.12), and then, band pass filtered to remove low and high frequency components. The filter used had cutoff frequencies of 0.4 Hz and 15 Hz with corner frequencies of 0.5 Hz and 12 Hz.



(a) Conventional RC column model



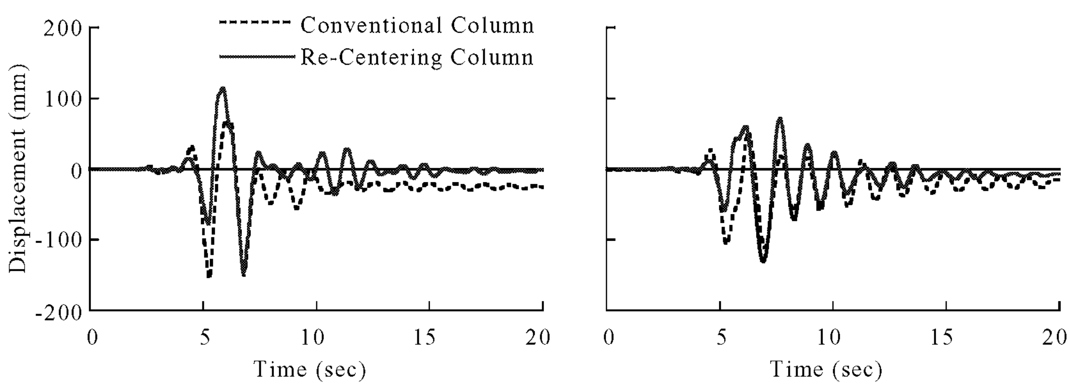
(b) Re-Centering RC column model

Fig. 9. Test specimens

In the earthquake simulation test program, the ground motion intensity was increased by four steps; each step were named an elastic, a yield, a design and a maximum level run. The ground motion intensity of each run was predetermined based on the results from the dynamic analyses. The first level was intended to check the instrumentations and the data acquisition system, in which the records were scaled down to 7%. The second one was used to check the dynamic initial stiffness of the models, in which the records were scaled down to 10%. The third and forth runs were the actual runs to investigate nonlinear dynamic response of the specimens. For the design level run, which was 70% of the original record intensity, the columns were expected to endure a response ductility of 4-6. For the maximum level run, which was 100% of the records, the columns were expected to experience a response ductility of 8-10.

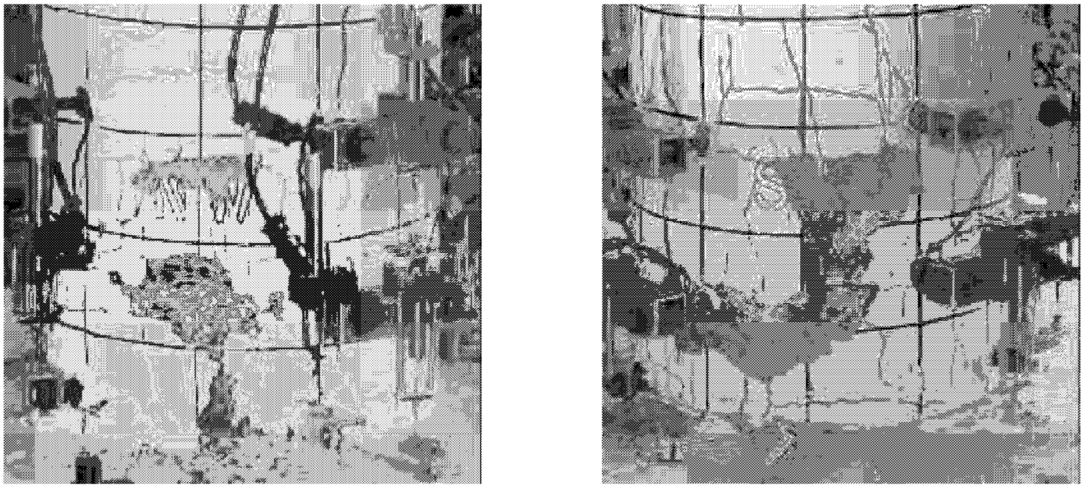
Dynamic Performance of Re-Centering RC Column

Figure 10 compares the displacement response at the center of gravity of the top mass subjected to the design level ground motion. While the both columns showed similar response in Y direction, the conventional model had the maximum response at 5.2 seconds during the first big pulse; the Re-Centering column model showed relatively smaller response during the first pulse, which in turn leaded to larger response in the positive direction, and then reached the maximum response in the negative direction. The maximum responses of the columns were 155 mm and 147 mm for the conventional and Re-Centering columns, respectively, which were about 6 of the response ductility. Although the both columns had similar peak during the second pulse in the negative direction, the conventional column had a residual displacement of 25 mm, which was equivalent of the yield displacement of the column and more than 1% of the effective column height, whereas the Re-Centering column showed a residual displacement of only 2 mm. **Figure 11** shows local damage of the columns after the design level run. Minor damage such as spalling off of the cover concrete was observed in the plastic hinge region of both the columns.



(a) X direction (b) Y direction

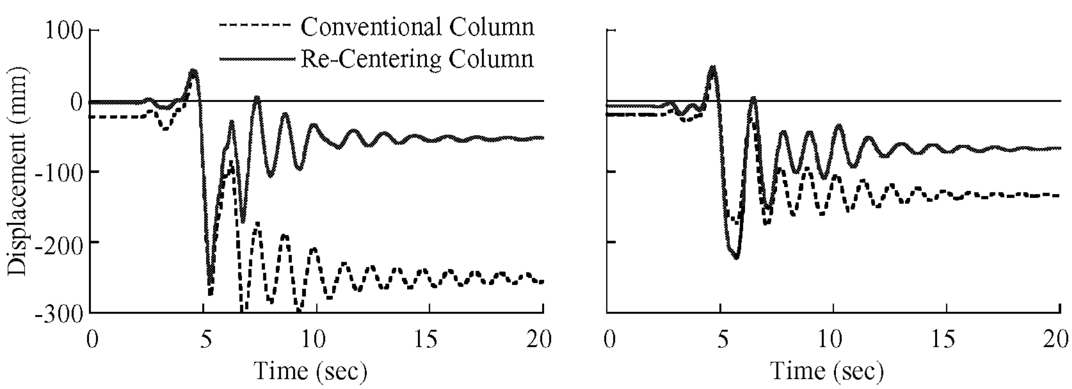
Fig. 10. Response Displacement at the center of gravity of top mass



(a) Conventional column (b) Re-Centering column

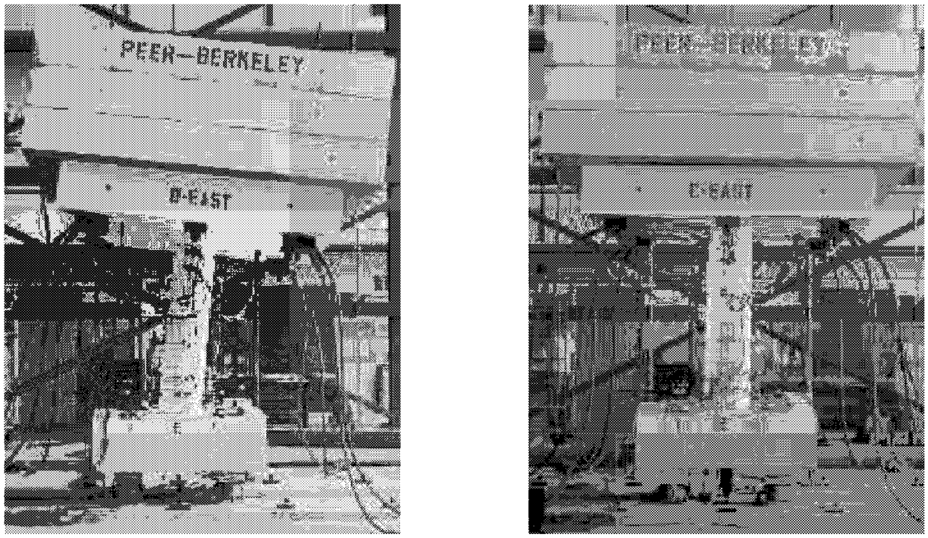
Fig. 11. Local damage after design level run

Figure 12 compares the dynamic response of the columns subjected to the maximum level ground motion. Although the response displacement of the both columns in X direction reached similar peak (= about 250 mm; a response ductility of 10) at 5.3 sec, the response after the peak was quite different. The conventional column never went back to the original position and the residual displacement was accumulated, which resulted in 252 mm as the residual displacement; on the other hand, the Re-Centering column went back close to the original position and the residual displacement after the run was 53 mm, which was only 21% of that of the conventional one. The Re-Centering column showed larger residual displacement in Y direction than in X direction; however the displacement was still about 50% of that of the conventional one in Y direction. The residual displacement and the effect of providing the unbonded prestressing tendon can be clearly seen in **Figure 13**.



(a) X direction (b) Y direction

Fig. 12. Response Displacement at the gravity center of the top mass



(a) Conventional column (b) Re-Centering column

Fig. 13 Residual displacement of columns after maximum level run

Note that even though the conventional column suffered such a large residual displacement, no major damage such as crushing of the core concrete, buckling or fracture of the longitudinal or spiral reinforcement was observed. Besides, the Re-Centering column model had a similar damage, which indicates that higher axial load ratio is not a significant factor to determine its design when a certain degree of confinement is provided.

Conclusions

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

(1) For the column geometry and material properties considered, replacing half of the rebar with unbonded strand and applying prestressing force that is equivalent to the axial load due to the dead load results in a 86% reduction in the residual displacement upon quasistatic unloading from a peak inelastic displacement compared to the conventional reinforced concrete column.

(2) Dynamic analyses indicate that the column with the unbonded center strand (Re-Centering RC column) performs very well under strong ground shaking. The predicted residual displacements of the Re-Centering RC column are only about 10% of those of the conventional column, while the maximum response displacements of the Re-Centering RC column are virtually the same as those of the RC column.

(3) The earthquake simulation tests validate the effect of providing unbonded prestressing

strand at the center of the cross section. After a design level ground motion, the residual displacement of the conventional design model was more than 1% of the column height while that of the Re-Centering column model was only less than 0.1% of the column height; the maximum responses of the columns were similar.

Acknowledgments

Support for this work was provided in part by the Earthquake Engineering Research Centers Program of the National Science Foundation, under Award Number EEC-9701568, through the Pacific Earthquake Engineering Research Center (PEER). Additional support has been provided by the Japan Society for the Promotion of Science in the form of a post-doctoral fellowship to the second author. The findings, observations and conclusions contained herein, however, are those of the authors and do not necessarily represent those of the sponsoring organizations.

The thoughtful help and advice provided by the staff of the Pacific Earthquake Engineering Research Center and by Andres Espinoza, a Ph. D. student carrying out companion tests, are gratefully appreciated.

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