EARTHQUAKE SIMULATOR TESTS ON THE MITIGATION OF RESIDUAL DISPLACEMENTS OF REINFORCED CONCRETE BRIDGE COLUMNS

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Abstract

To minimize residual displacements in reinforced concrete columns, a design is proposed whereby a longitudinal post-tensioning tendon replaces some of usual longitudinal mild reinforcing bars. The seismic performance of such partially prestressed, reinforced concrete columns is investigated through a series of earthquake simulator tests. The effects of unbonding of longitudinal mild reinforcement and providing a steel jacket are also investigated. The partially prestressed, reinforced concrete columns studied perform remarkably well under strong ground excitations. Very small permanent deformations are observed after the tests, especially when the longitudinal mild reinforcement is unbonded and a steel jacket is provided.

Introduction

In recent years, reinforced concrete bridge columns with high ductility capacity are designed and constructed in regions of high seismicity to avoid collapse of the supported bridge during strong ground shaking (California Department of Transportation, 2001; Japan Road Association, 2002). While such conventionally designed reinforced concrete bridge columns are likely to ensure life safety, large residual displacements may exist following extreme earthquakes, necessitating long-term closure of highways while expensive repairs or even complete replacement is carried out. Thus, mitigation of post-earthquake residual displacements of bridge columns has become a major concern.

A recent analytical study conducted by the authors (Sakai and Mahin, 2004a & 2004b) proposed a new method to reduce residual displacements by incorporating an unbonded prestressing tendon at the center of a lightly reinforced concrete column. The study demonstrates that (1) incorporating an unbonded prestressing strand at the center of a lightly reinforced concrete cross section can achieve restoring force characteristics similar to a conventionally designed column upon loading, but with substantially less residual displacement upon unloading; (2) such self-centering columns perform very well under uni-directional earthquake excitation; predicted residual displacements of the proposed columns are only about 10% of those of conventionally detailed columns while the peak responses are virtually identical; and (3) unbonding of longitudinal mild reinforcing bars enhances the origin-oriented tendency of the column's hysteresis.

Experimental studies have been conducted following the analytical study to assess the effectiveness of this approach. This paper presents a series of earthquake simulator tests

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carried out to investigate the seismic behavior of the proposed columns. The effects of locally unbonding longitudinal mild reinforcement and providing a steel jacket in the plastic hinge region are also explored experimentally.

Specimens

Table 1 and **Figures 1** and **2** show the specimens tested in this study. **Figure 3** shows the test setup. A scaling factor of 4.5 is assumed for the specimens. The diameter of all specimens is 406 mm, and the height from the bottom of the column to the center of gravity of the top mass is 2.44 m, resulting in an effective aspect ratio of 6. The design concrete strength is 34.5 MPa.

Table 1 Specimens

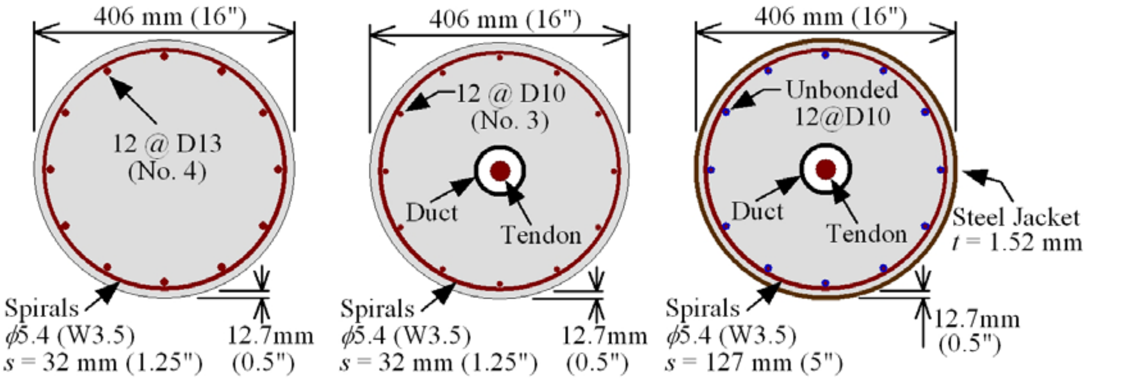
No.	Specimen	Description	f'_{co} (MPa)	P_{ps} (kN)	α_{total} (%)	Tendon Size
1	RC	Reinforced concrete column	41.7	-----	5.4	-----
2	PRC	Partially prestressed reinforced concrete column	41.7	379	12.4	32 mm (1-1/4")
3	PRC-2	Partially prestressed reinforced concrete column	32.6	220	11.0	36 mm (1-3/8")
4	PRC-U	PRC-2 with unbonded mild reinforcing bars	32.2	207	10.8	36 mm (1-3/8")
5	PRC-U2	PRC-U with larger prestressing force	32.5	347	14.0	36 mm (1-3/8")
6	PRC-UJ	PRC-U with steel jacketing	32.1	217	11.1	36 mm (1-3/8")

As shown in **Fig. 3**, the first two specimens have a top slab to support the concrete blocks used to idealize the inertia mass and dead load from the bridge's superstructure. The total inertia mass of the concrete blocks-top slab assembly was 29,200 kg, and the dead load applied to the column, P, was 291 kN including the column weight. To facilitate construction, the other four specimens do not have a top slab, but use reusable steel brackets to support the top blocks. The total inertia mass and dead load of these specimens are 14 % smaller than for the first two specimens (24,500 kg and 245 kN, respectively).

The first two specimens included a conventionally designed specimen (Specimen RC) and a partially prestressed, reinforced concrete specimen (Specimen PRC). They were tested in 2004 to investigate the effectiveness of providing an unbonded prestressing tendon in a lightly reinforced concrete column to reduce residual displacements.

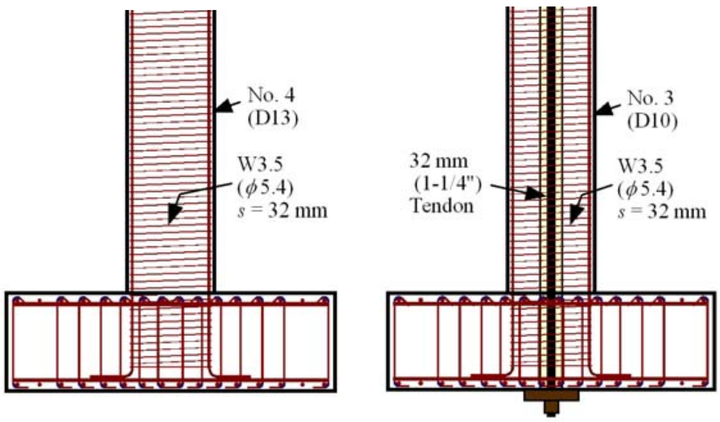
Specimen RC represents at reduced scale a reinforced concrete bridge column, as commonly constructed in California. The specimen is reinforced longitudinally with 12 No. 4 (13-mm diameter) deformed bars, providing a longitudinal reinforcement ratio, ρ_l, of 1.19%. W3.5 (5.4-mm diameter) spirals are used to confine the concrete core, spaced at a 32-mm pitch, resulting in a volumetric ratio, ρ_s, of 0.76%. Grade 60 bars are used for the mild longitudinal reinforcement, while Grade 80 wire (f_y = 607 MPa) is used for the spirals.

The Grade 60 No. 4 bars have a yield strength of 491 MPa, and an ultimate strength of 728 MPa. The actual concrete strength, f'_{co}, was 41.2 MPa.

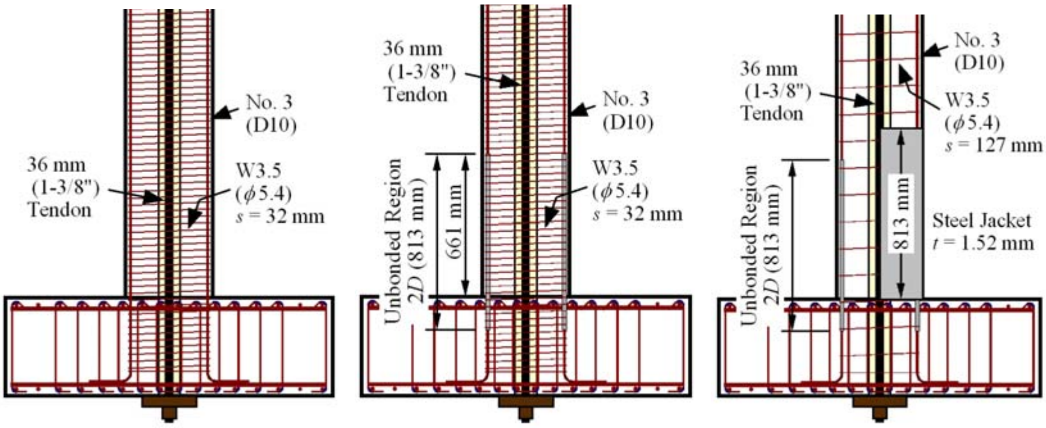


(a) RC specimen (b) PRC specimens (c) PRC specimen with jacketing

Fig. 1. Cross sections



(a) Specimen RC (b) Specimen PRC



(c) Specimen PRC-2 (d) Specimens PRC-U/U2 (e) Specimen PRC-UJ

Fig. 2. Reinforcement details of specimens at plastic hinge regions

(a) Specimens tested in 2004

(b) Specimens tested in 2005

Fig. 3. Test setup

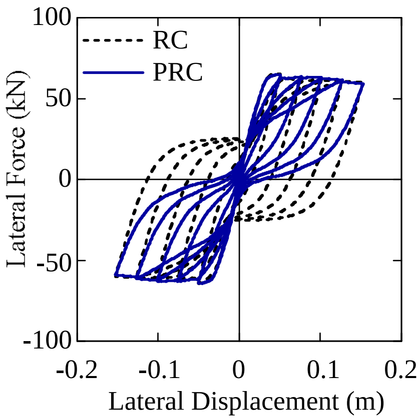


Fig. 4. Expected hystereses

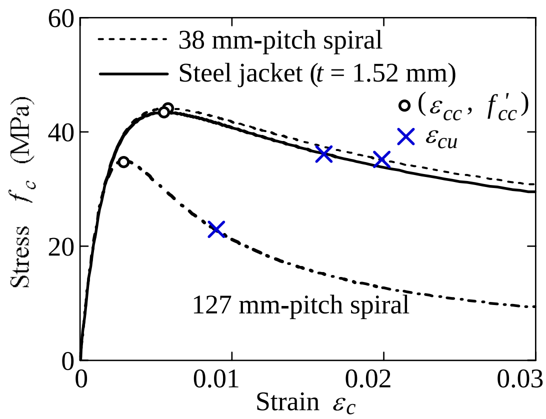


Fig. 5. Confinement effects of spirals and steel jacket

The design parameters for Specimen PRC were based on results of a series of quasistatic analyses. Specimen PRC is reinforced longitudinally with 12 No. 3 (10-mm diameter) deformed bars and a 32-mm diameter prestressing tendon. The same spiral reinforcement used for Specimens RC and PRC. To debond the tendon from the concrete, the tendon is installed in a duct going through the center of the cross section from the bottom to the top of the specimen. A prestressing force of 379 kN is applied to the column, resulting in a total axial force ratio, α_{total}, which is defined in Eq. (1), of 12.4%.

$$\alpha_{total} = \frac{P + P_{ps}}{f'_{co} A_g} \tag{1}$$

where P_{ps} is the prestressing force, and A_g is the gross section area. The yield and ultimate strength of the Grade 60 No. 3 bars are 488 MPa and 792 MPa, respectively. Those of the tendon are 1024 MPa and 1169 MPa, respectively.

Figure 4 shows computed quasi-static hystereses of the specimens when they are loaded uni-directionally. The PRC specimen is expected to have a strongly origin-oriented tendency upon unloading.

Four more partially prestressed, reinforced concrete specimens were tested in 2005 to investigate the effects on seismic behavior of (a) the magnitude of the imposed prestressing force, (b) local unbonding of the longitudinal mild reinforcement in the plastic hinge region and (c) adding steel jacketing near the base of the column. The basic design of these specimens is similar to that of Specimen PRC. The first specimen (the 3rd one in **Table 1**) is basically the same as Specimen PRC, but has several minor adjustments based on observations from the test of Specimen PRC: tendon area, prestressing force, P_{ps}, conduit diameter, concrete strength, f'_{co}, and test protocol. This specimen provides a baseline for evaluating the effects of unbonding of longitudinal mild reinforcement, steel jacketing and prestress force, and is designated Specimen PRC-2. The fourth specimen is similar to Specimen PRC-2, but all the longitudinal mild reinforcing bars are coated with wax and covered with a plastic sheath to debond the bars from the concrete. The unbonded length is 2 times the diameter (813 mm) of the column. The unbonded region begins 152 mm below the footing surface, as shown in **Fig. 2**. This specimen is called Specimen PRC-U. The fifth specimen, PRC-U2, is similar to PRC-U, but the applied prestressing force is 68% larger. The sixth specimen, PRC-UJ, is similar to PRC-U, but a steel jacket with a thickness of 1.52 mm (16 gage) is provided at a potential plastic hinge region, and spiral pitch is increased from 32 mm to 127 mm throughout the column. Only a very narrow gap is provided between the bottom of the jacket and the top of the footing. The jacket thickness and spiral pitch are determined so that the confinement effect of the jacket on the concrete is similar to that expected in the other columns, as shown in **Fig. 5**. The jacket is used as part of the formwork and left in place to provide lateral confinement.

The actual concrete strength, f'_{co}, for the second series of specimens is about 32 MPa, which was 23% smaller than that for the first series. These specimens are reinforced longitudinally with 12 No. 3 (10-mm diameter) deformed bars like Specimen PRC, but a 36-mm diameter prestressing tendon is used. The yield and ultimate strength of the Grade 60 No. 3 bars are 477 MPa and 627 MPa, respectively. Those of the tendon are 913 MPa and 1113 MPa, respectively. ASTM A36 steel or similar is used for the jacket.

Ground Motions and Test Sequence

The two horizontal components of a modified motion recorded in Los Gatos during the 1989 Loma Prieta, California, earthquake (Somerville et al., 1997) are selected for the test input signals, based on the large residual displacements predicted for the RC specimen by nonlinear dynamic analyses. The stronger ground motion component (fault normal) is used for the X direction, and the weaker component (fault parallel) is applied in the Y direction. Both records are scaled using a time scale factor equal to the square root of the length scale factor (= 2.12), and then, because of the performance characteristics of the earthquake simulator, both are band pass filtered to remove low and high frequency components. The filter used has cutoff frequencies of 0.4 Hz and 15 Hz, with corner frequencies of 0.5 Hz and 12 Hz.

In the earthquake simulator test program, four intensities of ground motion are imposed. These levels are denoted herein as elastic, yield, design and maximum level tests. The first two test levels are intended to check the instrumentation and data acquisition system, and provided information on the dynamic response of the specimens under excitations representative of moderate earthquakes and aftershocks. The design and maximum level tests investigate nonlinear dynamic response of the specimens. The intensity of the excitations are set to develop a displacement ductility of about 4 during the design level tests, and a displacement ductility of 8 during the maximum level test (approximately the deformation capacity of the specimen).

The intensities of ground shaking were determined based on results of dynamic analyses carried out prior to the first test series in 2004. However, these specimens experience a larger response than predicted for the design and maximum level tests. Thus, the intensities used for the tests conducted in 2005 are adjusted to better achieve the targeted displacement ductility levels. **Table 2** summarizes amplitude scaling factors used for the ground motions in the two test series.

Table 2 Scaling factors for ground motion intensities

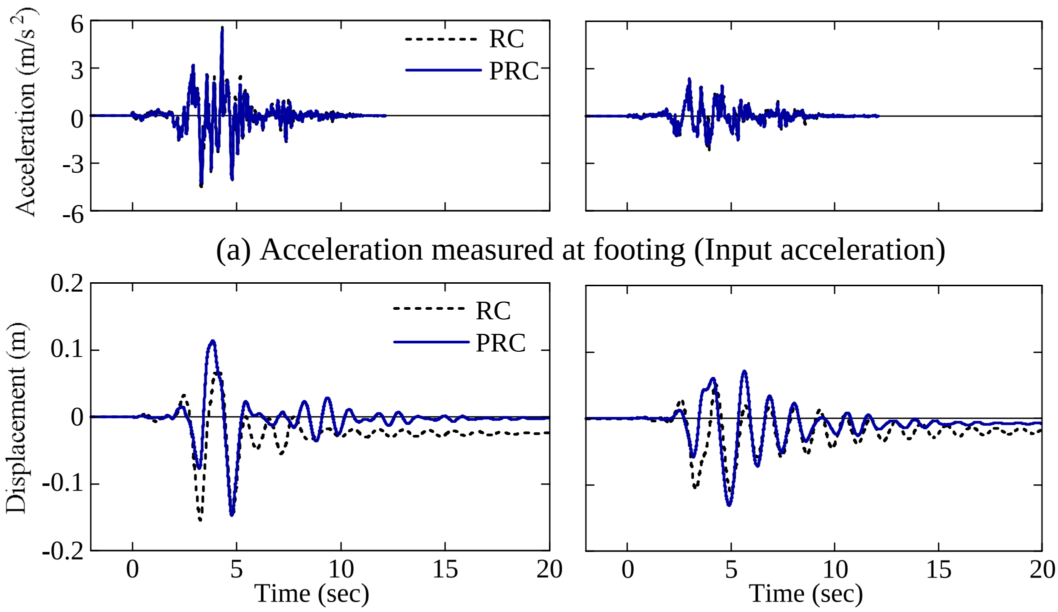
Intensity level	Test Level	Tests in 2004 (RC, PRC)	Tests in 2005 (PRC-2, PRC-U, PRC-U2, PRC-UJ)
1	Elastic	7%	10%
2	Yield	10%	25%
3	Design	70%	50%
4	Maximum	100%	75%

Dynamic Response of Specimens RC and PRC

Figure 6 compares the displacement response at the center of gravity of the top mass subjected to the design level ground motion, and **Table 3** shows maximum and residual displacements during the high level tests. The displacements are expressed as distances from the origin in **Table 3** while the displacements are shown in each principal direction in **Fig. 6**. The maximum displacements in the X direction of the specimens are 0.155 m and 0.147 m, respectively, which occurs around 4.8 seconds. About the same time, the specimens reach the maximum distances from the origin, which are 0.187 m and 0.189 m (ductilities of about 7.5). Although both specimens have similar peaks, Specimen RC has a residual displacement of 0.031 m, which is more than 1% drift, whereas Specimen PRC has a residual displacement of only 0.008 m (a drift ratio of 0.3%). The physical damage in both columns was minor after these tests, consisting of moderate spalling of the concrete covers.

Table 3 Maximum and residual distances of Specimens RC and PRC

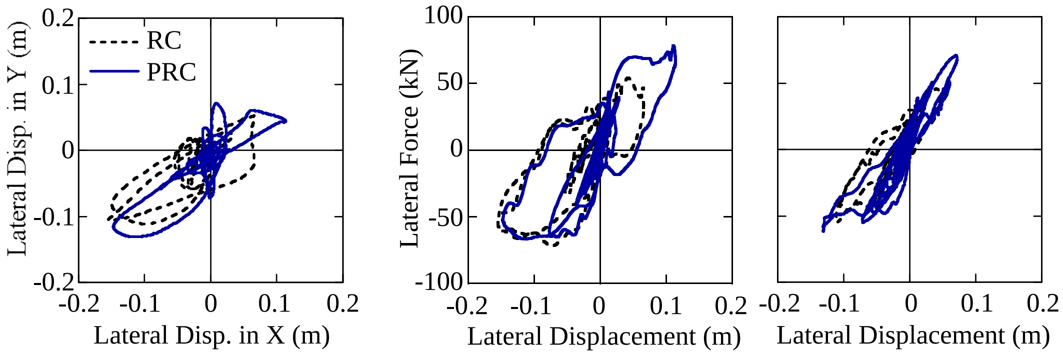
Specimen	Design Level (70%)		Maximum Level (100%)	
	Maximum Response	Residual Deformation	Maximum Response	Residual Deformation
RC	0.187 m	0.031 m	0.349 m	0.285 m
PRC	0.189 m	0.008 m	0.323 m	0.107 m



(b) Displacement response at center of gravity of top blocks

(1) X direction (2) Y direction

Fig. 6. Input acceleration and response displacement (Design level test)

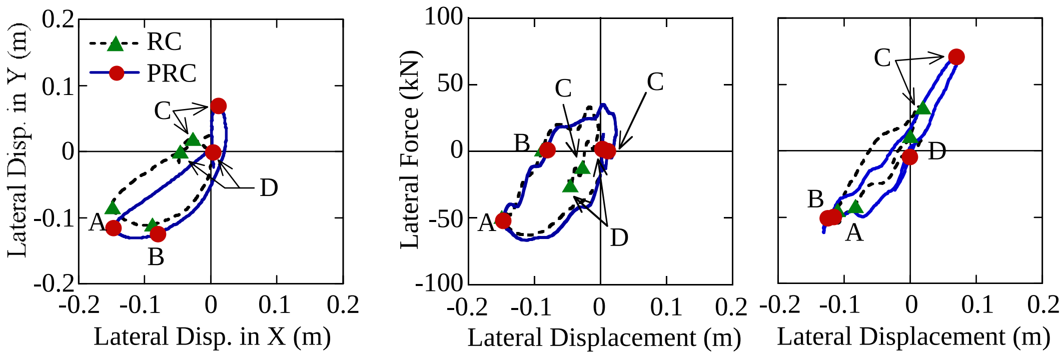


(a) Displacement orbits (i) X direction (ii) Y direction

(b) Lateral force-lateral displacement hystereses

Fig. 7. Orbits and lateral force-lateral displacement hystereses (Design level test)

Figure 7 shows orbits of displacements along with the lateral force versus lateral displacement hystereses. Displacements are plotted for the center of gravity of the top mass blocks. Both sets of hystersis loops exhibit similar skeleton curves as they move away from the origin, as expected from the analytical results shown in **Fig. 4**. However, they have similar unloading curves as well, which is inconsistent with the origin-oriented loops predicted for Specimen PRC during unidirectional cyclic loading. Nonetheless, hysteresis loops for Specimen PRC in the Y direction are origin-oriented, although response displacements are smaller than those in the X direction.



(a) Displacement orbits (i) X direction (ii) Y direction

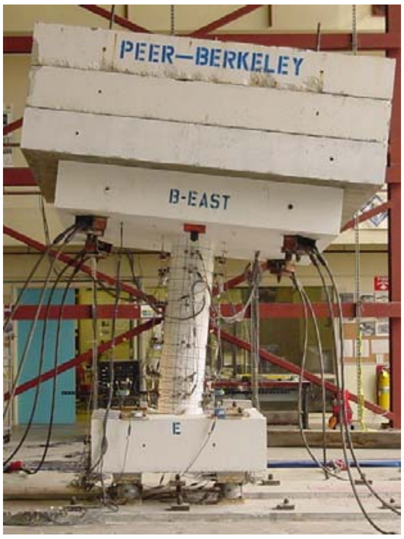
(b) Lateral force-lateral displacement hystereses

Fig. 8. Response during main pulses (Design level test)

In spite of the lack of consistent origin-oriented hysteresis (**Fig. 7**), Specimen PRC achieves a small residual displacement. To figure out the reason for this behavior, response during the main pulses is examined in detail. **Figure 8** shows orbits of displacements and lateral force versus lateral displacement hystereses between 4.4 and 6 seconds. Points A to D in **Fig. 8** denote the response of the specimens at common times. For example, while the specimens move from Points A to B, it is clear from **Fig. 8** (a) that the displacement vectors for both specimens are similar and not directed towards the origin. During this time interval, the X-component of force decreases significantly, the Y-component of force increases slightly, and the hysteresis loops for both specimens are similar. On the other hand, between the Points C and D, the displacement vector is directed towards the origin and the hysteresis of Specimen PRC has an origin-oriented hysteresis in the Y direction. From these observations (and additional analyses (not presented here)), it appears that when the displacement vector is not directed towards the origin, Specimen PRC does not exhibit its characteristic pinched origin-oriented hysteresis; however, when the displacement vector points towards the origin, Specimen PRC shows such a hysteresis. At the end of the shaking, while the response damps out in both directions, the displacement vector of Specimen PRC is likely directed to the origin, and thus unlike Specimen RC the residual displacement of Specimen PRC tends to decrease.

Figure 9 shows residual displacements of the specimens after the maximum level test. The maximum displacement ductility factors attained by Specimens RC and PRC are 14 and 13, respectively. These are very large, exceeding the computed capacities. The residual drift of Specimen RC is more than 10%, while that of Specimen PRC is 3%. Even though Specimen RC 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. Nonetheless, it was believed unsafe to continue testing.

After the maximum level test, Specimen PRC did not show severe damage or as large of permanent deformation as Specimen RC, even though the ductility demand exceeded its theoretical capacity. As such, it was subjected to the design level ground motion again. During the second main pulse, 6 of the 12 longitudinal reinforcing bars fractured, resulting in a significant loss of restoring force, and collapse of the specimen.



(a) Specimen RC

(b) Specimen PRC

Fig. 9 Residual displacements of specimens after maximum level test

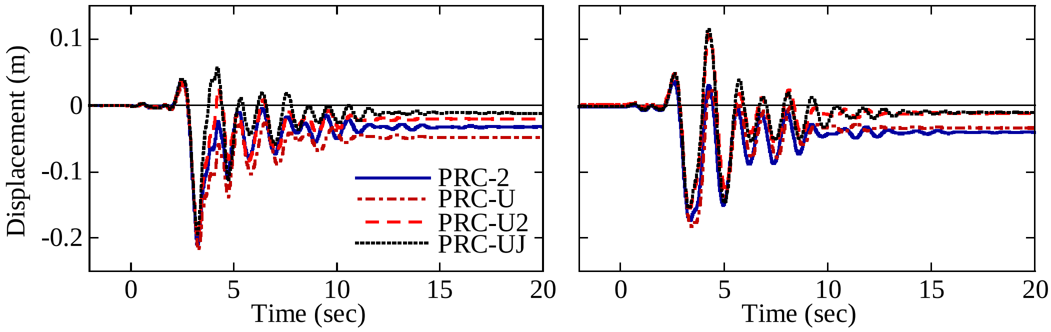
Effects of Unbonding of Mild Reinforcement and Using Steel Jacketing

In the second series of tests, efforts were made to reduce the susceptibility of Specimen PRC to fracture of the longitudinal mild reinforcement and crushing of the confined core. To reduce the maximum strain induced in the bars, the mild reinforcement in the vicinity of the expected plastic hinge is unbonded from the concrete in three of the specimens. In this manner, strains in the bars tend to distribute over the unbonded length rather than localizing near large cracks that form during the maximum level events. Buckling of longitudinal bars also accelerates their fracture. Decreasing the pitch of the already closely spaced spiral reinforcement is not a practicable solution here. As such, steel jacketing was provided in one specimen. This jacket reduces the need for spiral reinforcement in the column, and is expected to prevent spalling of the concrete cover, thereby obviating the need for, or further reducing the cost of, post-earthquake repair. Because excessive compression forces in the confined concrete can also trigger failures, one test is carried out considering a larger prestressing force.

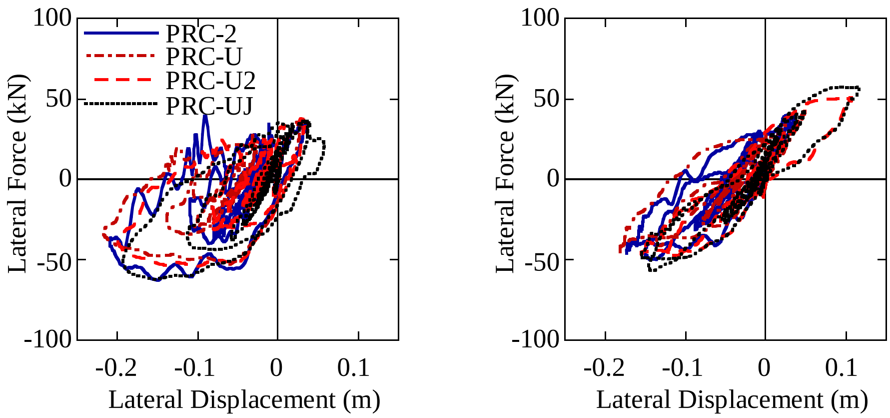
Table 4 summarizes the maximum and residual displacements at the center of gravity of the top mass block for all of the 2005 tests. The values are shown as distances from the origin. These specimens exhibit similar response during the first design level excitation. For example, the peak distances are 0.117 m, 0.124 m, 0.119 m and 0.123 m for Specimens PRC-2, PRC-U, PRC-U2 and PRC-UJ, respectively, which correspond to a displacement ductility of about 5. All the specimens demonstrate an impressive ability to re-center. The residual displacements for all these specimens are smaller than 10% of the yield displacement and a drift of 0.1%. The physical damage consists of moderate spalling of the concrete cover, except for the steel jacketed column, for which only very minor buckling of the jacket is observed at one side of the column.

Table 4 Maximum and residual distances of PRC specimens

Specimen	Design Level (50%)		Maximum Level (75%)	
	Maximum Response	Residual Deformation	Maximum Response	Residual Deformation
PRC-2	0.117 m	0.002 m	0.269 m	0.052 m
PRC-U	0.124 m	0.002 m	0.278 m	0.058 m
PRC-U2	0.119 m	0.001 m	0.251 m	0.023 m
PRC-UJ	0.123 m	0.001 m	0.245 m	0.015 m



(a) Displacement response at center of gravity of top blocks



(b) Lateral force - lateral displacement hystereses

(1) X direction (2) Y direction

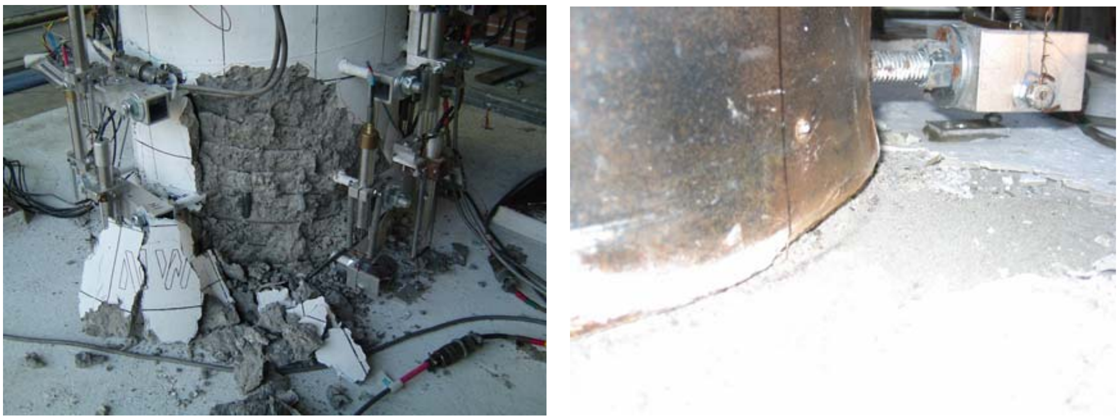
Fig. 10. Dynamic response of PRC specimens during maximum level test

By increasing ground motion intensity by 150% to the maximum level, some differences in behavior among the specimens can be detected. **Figure 10** compares the displacement response and the lateral force versus lateral displacement hystereses at the center of gravity of the top mass of all of the 2005 specimens subjected to the maximum level input. All the specimens reach the maximum response at around 3.3 seconds during the first main pulse in both directions. Specimen PRC-U has the largest response, while specimen PRC-UJ has the smallest, when evaluated as distances from the origin. The maximum response displacements correspond to a ductility of about 10. The residual displacements increase for this severe excitation, but are all less than 0.06 m (< 2.5% drift).

By using unbonded mild reinforcement, the maximum as well as residual displacements increase compared to PRC-2 due to smaller flexural strength and even negative post-yield stiffness (as can be seen in **Fig. 10** (b)); however by increasing the prestressing force in Specimen PRC-U2, the residual displacement reduce to only 43% of that for Specimen PRC-U, which is 55% smaller than that of Specimen PRC-2. The maximum tensile strains in the reinforcement (measured 0.1 m above the top of the footing) are generally lower for Specimens PRC-U and PRC-U2 than PRC-2, but the maximum width of the cracks at the bottom of the column are larger. Importantly, the maximum level excitation results in increased spalling and buckling of the longitudinal reinforcement in Specimens PRC-2, PRC-U and PRC-U2. Damage in the specimens with unbonded reinforcement concentrates close to the base of the column, whereas the worst damage is located somewhat higher in Specimen PRC-2. Compared to Specimens PRC-2 and PRC-U, Specimen PRC-U2 (with the higher prestressing force) shows smaller crack opening, more concrete crushing, and more bar buckling. For Specimen PRC-U, three bars buckled, whereas half of the reinforcement (6 bars) buckled for specimen PRC-U2.

When a steel jacket is provided, the peak displacement decreases from 0.278 m (PRC-U) to 0.245 m (PRC-UJ). Similarly, the residual displacement of Specimen PRC-UJ is only 0.015 m (0.6% drift), less than a quarter of that measured for PRC-U. Fig. 10(b) shows Specimen PRC-UJ has larger strength and slightly positive post-yield stiffness.

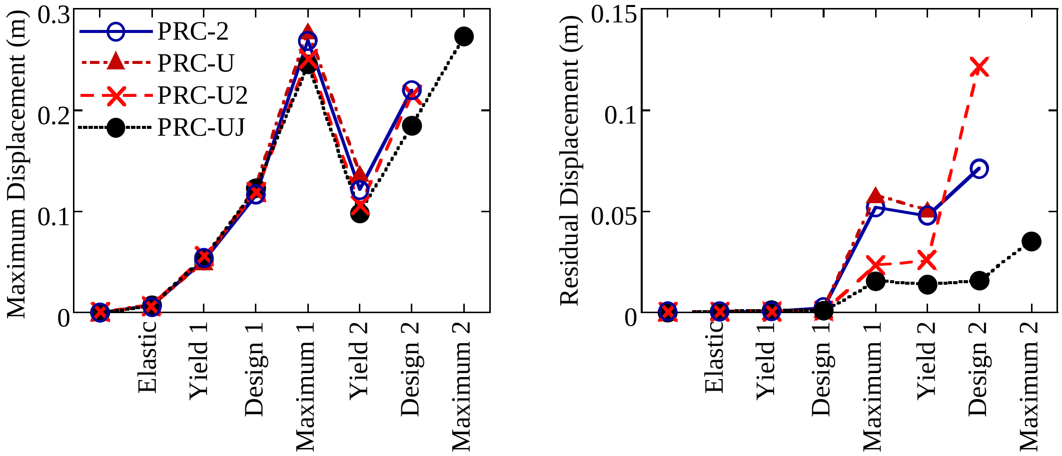
The photographs in **Fig. 11** depict the local damage at the bottom of Specimens PRC-U and PRC-UJ following the maximum level test. The improved behavior of Specimen PRC-UJ at this stage relative to the specimens without steel jackets is believed to be associated with the absence of spalling and, especially, bar buckling. On the other hand, the peak crack opening at the bottom of the jacket is larger than for any of the other specimens tested. In addition, moderate "elephant foot" buckling is observed intermittently along the bottom of the steel jacket. To mitigate such buckling, a larger gap than provided in the test specimen between the top of the footing and the bottom of the jacket is recommended (as commonly done in California bridge design practice).



(a) PRC-U (NW side) (b) PRC-UJ (NW side)

Fig. 11. Local Damage (After maximum level test)

Following the tests described above, the specimens are subjected to a second yield level, design level and maximum level excitations to assess the effects of cumulative damage and the column's ability of to sustain significant aftershocks. **Figure 12** illustrates that the second yield level and design level events induce larger peak responses compared to the first excursions. Residual displacements did not change significantly for the second yield level excursions, but during the second design level excitation increased significantly for Specimens PRC-2 and PRC-U2 while specimen PRC-UJ shows no increase in residual displacement. Only Specimen PRC-UJ is subjected to the second maximum level test, since the other specimens suffer substantial damage and residual deformation after the second design level tests. During the second maximum level test, Specimen PRC-UJ develops about the same peak displacement as measured during the first excursion to this level, but the residual displacement increases. Nonetheless, the residual displacement is still smaller than for the other self-centering columns during the first maximum excursion, except PRC-U2. Upon removal of the steel jacket at the end of testing, it was noted that in spite of this good behavior four of the longitudinal bars buckled and two fractured.



(a) Maximum response (b) Residual deformation

Fig. 12. Maximum and residual distances

Analytical Simulation

Nonlinear dynamic analyses are performed to simulate the behaviors of the test specimens. Hysteretic behavior of the reinforced concrete at plastic hinge region is idealized with fiber elements. The unbonded tendon is idealized with a spring element. Details of the analytical models and assumptions can be found in the report by the authors (Sakai and Mahin, 2004a). Rayleigh viscous damping is assumed in the analyses. Damping ratios and frequencies used to determine the coefficients required for the Rayleigh damping assumption are based on the test results. Measured accelerations at the footing during the tests are used as input for the analyses.

Figure 13 compares displacement time histories for the tests and analyses during the design and maximum level tests of Specimens RC and PRC. The analyses for Specimen RC predict 20-30% smaller maximum response, and 80-90% smaller residual displacements. Those for Specimen PRC provide better agreements for the maximum response; however, the computed residual displacements are more than twice the observed test results. Work is continuing to improve the accuracy of predictions of the details column response, especially residual displacements.

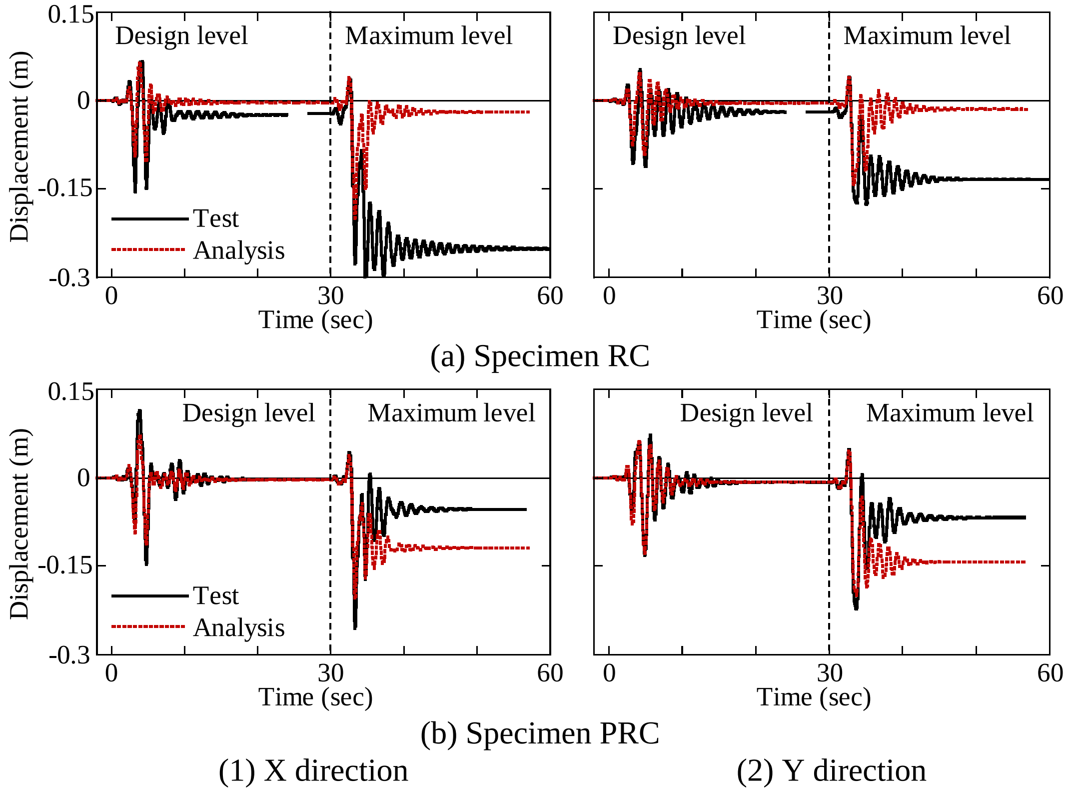


Fig. 13. Analytical simulation

Conclusions

To investigate the seismic behavior of bridge columns developed to mitigate post-earthquake residual displacements, a series of earthquake simulator tests and analyses have been conducted. Below are the conclusions determined from the study:

(1) The earthquake simulator tests confirm the self-centering benefit of providing an unbonded prestressing tendon at the center of the column cross-section. After a design level ground excitation, the residual drift index of the conventionally designed RC specimen is more than 1%, while that for the self-centering, partially prestressed, reinforced concrete specimens was 0.1% or less. The peak displacement response of RC and PRC specimens are similar for the same shaking.

(2) Using unbonded mild reinforcement in a partially prestressed, reinforced concrete column slightly increases maximum and residual displacements due to smaller flexural strength. However, by providing a larger prestressing force, maximum and residual displacements can be reduced.

(3) A confining steel jacket with a partially prestressed, reinforced concrete column with

locally unbonded mild reinforcement prevents any significant observable damage, throughout the entire testing regime. For the design level excitation, the residual ductility of Specimen PRC-UJ was less than 0.1%, and it remained less than 0.6%, even for the maximum level test. This test program demonstrates the substantial benefits of partially prestressed, reinforced concrete columns with locally unbonded mild reinforcement and a steel jacket.

(4) Analytical simulation currently does not provide sufficient accuracy, especially with respect to predicting residual displacement, for either Specimens RC or PRC. The analyses predict 90% smaller residual displacement for Specimen RC, while more than 100% larger ones for Specimen PRC.

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