The Effect of Load History on Performance Limit States of Circular Bridge Columns

Test 12 Summary – Japan 2011 Earthquake Load History

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The Load History research program includes an experimental component that consists of several large scale bridge columns with identical geometry and reinforcement subjected to different load histories. The goal of the physical tests is to investigate the impact of load history on the relationship between strain and displacement and the strain limits themselves. The first six test specimens were constructed by a local contractor with transverse steel detailing errors which affected the column’s displacement capacity. In an effort to isolate the effect of load history, the next six columns were constructed by the research team with proper detailing. The first of these columns, with new steel and concrete properties, was tested under a symmetric three cycle set load history to determine the yield displacement and to help establish a displacement level to scale future time history based tests. The effects of welding on the strain capacity for this batch of longitudinal steel became apparent when five reinforcing bars ruptured before buckling ever occurred.

For the remaining columns, a new instrumentation scheme was implemented using two Optotrak position sensors and target markers directly applied to the reinforcing bars without welded posts. For the first six tests, a displacement ductility of ten produced buckling for specimens with transverse steel spacing in the plastic hinge region closest to 2”. The Chile 2010 load history from the eighth test was scaled to a peak displacement consistent with the strain at ductility ten which was used to scale earthquake records in the first six tests. The peak displacement of 7.25” (displacement ductility 8.7) failed to produce buckling during the Chile load history. Since a reliable method of scaling earthquake time histories could not be formulated based on the results of Tests 7 and 8, a second symmetric three cycle set load history was chosen for Test 9. The peak strain from the Chile load history, scaled to ductility 8.7 without buckling, matched the peak strain from the symmetric three cycle set load history from Test 9 which produced buckling on both sides of the specimen during ductility eight.

To determine possible effects of different load history characteristics on the relationship between strain and displacement, an asymmetric displacement history from the 1999 Chichi earthquake in Taiwan was chosen for Test 10. The Chichi record produced a one sided response with a displacement ductility demand of 8.9 in one direction of loading and a ductility demand of only 2.5 in the opposing direction. Large concrete compressive strains during the peak cycle lead to excessive yielding of the transverse steel which decreased its effectiveness as a boundary condition restraining buckling during latter cycles of loading. A scaled version of the 1995 Japanese Kobe earthquake was selected for Test 11 since it contained a near monotonic cycle to the peak displacement in one direction followed by the largest reversal to the peak cycle in the opposing direction of loading. A load history from the recent Japan 2011 earthquake was chosen for the twelfth test because it characterizes a large subduction event with many cycles before the peak and high ductility cycles after the peak displacement. The Chile 2010 record, also a large subduction event, contained more high ductility cycles before the peak displacement compared to the Japan 2011 earthquake. Overall, the Japan 2011 record contains more reversals of loading with higher ductility demands after the peak cycles compared to the Chile 2010 load history.
The test specimen was designed to represent a single degree of freedom bridge column subjected to lateral and axial load. The 2’ diameter column contains 16 #6 (A706) bars for longitudinal reinforcement \( (A_{st}/A_g = 1.6\%) \) and a #3 (A706) spiral at 2” pitch for transverse reinforcement \( (4A_{sp}/(D’s) = 1\%) \). The test specimen consists of a footing, column, and loading cap. The footing is a capacity protected member which secures the specimen to the lab strong floor using post tensioned bars. The 220 kip hydraulic actuator applies lateral load to the loading cap of the specimen. A spreader beam with two hydraulic jacks and a load cell is placed above the loading cap for axial load application (170 kips, \( (P/(f’cA_g) = 6.2\%) \) through bars running beneath the lab strong floor.

![Figure 1 - Cross Section Bar Designation – North reinforcement is placed into tension during push cycles while South reinforcement is placed into tension during pull cycles (Photo taken from the back side of the specimen)](image)

**Test Setup:**

A unique instrumentation system (Optotrak) was utilized in the plastic hinge region to obtain strains in the inelastic range. The Optotrak camera system can read the location of target markers placed on the specimen in three dimensional space in real time during a test. By calculating the change in three dimensional distances between target markers, strains can be determined from the target marker locations with respect to their original unloaded gage lengths. For the first seven tests, target markers were placed on small steel posts which were tig welded to the longitudinal reinforcement at approximate 2” spacing. The improved instrumentation scheme utilizes two Optotrak position sensors (cameras) directly facing the North and South extreme fiber regions of the column where target markers are directly adhered to the longitudinal reinforcement. The dual camera and direct application instrumentation method provides more accurate strain data since the values are not affected by small rotations in the steel posts and the reinforcement material properties are free from the possible effects of tack welds. Together, the strips of target markers placed on the reinforcement can be used to generate vertical and horizontal strain and curvature profiles as well as strain hysteresis for individual gage lengths. Additional target markers were placed on angles attached to the top of the footing to capture possible joint rotations and strains due to strain penetration into the footing.

Traditional instrumentation was also utilized in the test setup. The top column displacement was obtained through a string potentiometer placed at the center of loading. An inclinometer was placed on the cap in the longitudinal direction of loading to obtain top column rotations caused by the lateral load.
Similarly, a transverse inclinometer was placed to capture any out of plane rotation. The lateral load and stroke of the 220 kip hydraulic actuator were measured through an integrated load cell. An axial load cell measured the contribution of one hydraulic jack to the total axial load of the column.

Figure 2 – Dual Optotrak Position Sensors with Direct Application of Target Markers to Reinforcement

Figure 3 - Peak Displacement Cycle of Japan 2011 Load History at ($\mu_{48.62} = 8.22''$)
Load History:

The first yield force for the tested material and geometric properties was determined using moment curvature analysis (Test 12: Cumbia $F_y' = 46.87$ kips with $f'c = 6100$ psi) compared to (Test 9: Cumbia $F_y' = 46.87$ kips with $f'c = 6814$ psi). The first yield displacement for the ninth test was obtained as an average for the first yield push and pull cycles ($\Delta_y' = 0.625''$). The equivalent yield displacement, used to determine the displacement ductility levels ($\mu_{\Delta_1} = 1 \cdot \Delta_y$), is then calculated as $\Delta_y = \Delta_y'(M_n/M_y') = 0.84''$ for the material properties of Test 9. Since the material properties are similar with the exception of the concrete compressive strength due to separate casting of columns 10-12 and 7-9, the same equivalent yield displacement from Tests 7-9 was used to define displacement ductility levels in Tests 10-12.

The analytical top column displacement history for the scaled Japan 2011 earthquake, which appears in Figure 4, was determined using fiber-based numerical simulation in OpenSees. A 1.25x scaled version of the 2011 Japan earthquake was selected to reach a displacement ductility of ten during the largest cycle. In previous time history based tests, buckling did not occur during the Chile or Chichi records scaled to displacement ductility 8.7 and 8.9 respectively. The results from the Chichi and Kobe records suggest that high ductility cycles can decrease the effectiveness of transverse steel as a boundary condition restraining the longitudinal steel. A peak displacement ductility level of ten was chosen to increase the level of tension strain in the steel to evaluate the steel tensile strain limit which leads to buckling of longitudinal steel upon reversal of loading. The initial portion of the Japan 2011 earthquake contained many reversals of loading around ductility one which should not have a large impact on the relationship between strain and displacement at higher ductility cycles. The portion of the load history recreated in Test 12 appears in Figure 6, the cycles with the black circle markers show peak cycles included in the experimental test.
Figure 4 - Japan 2011*1.25 Top Column Displacement History

Figure 5 - Chile 2010 Load History from Test 8 (large subduction event comparison)
Figure 6 - Portion of Japan 2011 Load History Selected for Experimental Test

Figure 7 - Force vs. Displacement Response with Monotonic Moment Curvature Prediction
Test 12 Observations:

The first cycle for the experimental test reached a lateral displacement of -0.26”, displacement ductility of -0.3, and occurred 43.98 seconds into the earthquake as shown by the first black circle on Figure 6. The form of the displacement ductility label utilized in the rest of this report is \( \mu_{0.3}^{43.99} = -0.26" \). The first cracks on the South side of the specimen were measured at 0.1mm at a lateral force of -24.63 kips which is over half of the first yield force. The load history prior to this point contained many cycles of loading around a displacement ductility of one, which were not included in the experimental test. The beginning cycles omitted from the experimental displacement history should not have a large impact on the relationship between strain and displacement or damage within the section. Cracks measuring 0.2mm on the North side of the specimen were measured during the second half cycle of the load history at \( \mu_{0.5}^{44.26} = 0.39" \) with a lateral force of 35.69 kips which is around 75% of the first yield force.

Cracks on the South side of the specimen were measured at 0.4mm during \( \mu_{1.3}^{47.53} = -1.10" \) as shown in the left photo of Figure 8. The crack distribution on the North side of the specimen during \( \mu_{2.1}^{48.83} = 1.77" \) appears in the middle and right photos of Figure 8. Crack widths on the North side of the specimen measured 2mm and the cover concrete on the South side of the specimen began to crush as shown in the left photo of Figure 9. The extent of crushing on the South side of the specimen extended 10” above the footing during \( \mu_{2.4}^{61.36} = 2.02" \), while crack widths on the North side of the column measured 2.5mm. Crushing usually begins after a visual flaking and vertical cracking which was observed on the North side of the specimen during \( \mu_{2.2}^{61.80} = -1.85" \) as shown in the right photo of Figure 9. The extent of crushing on the North side of the specimen extended 7” above the footing during \( \mu_{2.1}^{65.83} = -1.71" \) as shown in the right photo of Figure 10.

The largest cycle in the pull direction of loading occurred during \( \mu_{-7.9}^{66.88} = -6.53" \) with additional crushing on the North side of the specimen, see Figure 11. The peak cycle in the push direction at \( \mu_{0.9}^{68.62} = -8.22" \) was concluded without visible buckling on the South side of the specimen as shown in Figure 3 and Figure 12. A peak lateral load of 72.1 kips was recorded during the peak cycle of the Japan 2011 load history. Upon reversal of loading from \( \mu_{0.9}^{68.62} = 8.22" \), which placed the North side of the specimen under large tensile strains, the extreme fiber North reinforcing bar N3 buckled on the way to \( \mu_{-2.0}^{68.95} = 1.68" \) as shown in the left photo of Figure 13. Even though the reversal only brought the specimen to a lower ductility in the same direction of loading as the peak cycle, a lateral load of -27.40 kips was recorded due to hysteretic offset from the peak displacement cycle. Therefore, visible buckling was observed while the cracks on the North side of the specimen remained open and the North reinforcement was the sole source of compression zone stability. After a small push cycle to \( \mu_{-1.4}^{69.12} = 2.80" \), a second reinforcing bar N4 on the North side of the specimen buckled on the way to \( \mu_{-1.4}^{69.41} = -1.14" \) as shown in the right photo of Figure 13. The rest of the load history progressed without any additional buckled reinforcement or rupture of buckled reinforcement. The deformation in the previously buckled bars increased and the core concrete over the North buckled region began to deteriorate as the load history progressed, see Figure 14. Visible buckling of the South reinforcement was never observed, although very slight deformation over the bottom three transverse steel spacing was noticed. This deformation never visibly increased with additional cycles, so the research team did not attribute this to bar buckling.
Figure 8 - (Left) South Crack Distribution during $\mu_{1,3}^{47.53} = -1.10^\circ$ and (Middle & Right) North Crack Distribution during $\mu_{2,1}^{49.83} = 1.77^\circ$.

Figure 9 - First Signs of Crushing (Left) South Side of the Specimen during $\mu_{2,1}^{49.83} = 1.77^\circ$ and (Right) North Side of the Specimen during $\mu_{2,2}^{61.00} = -1.85^\circ$.

Figure 10 – (Left) Crushing on the South side of the specimen during $\mu_{2,4}^{64.36} = 2.02^\circ$ and (Right) Crushing on the North side of the specimen during $\mu_{2,1}^{65.83} = -1.71^\circ$. 
Figure 11 Peak Pull Cycle at ($\mu_{7.9} = -6.53^\circ$) - (Left) Back Side of the Specimen, (Middle) South Side of the Specimen, and (Right) North Side of the Specimen

Figure 12 - Peak Push Cycle in the Japan 2011 Load History at ($\mu_{9.9} = 8.22^\circ$)
Figure 13 - (Left) Buckling of Extreme Fiber Bar N3 at ($\mu_{x_{0.05}} = 1.68''$) and (Right) Buckling of Bar N4 at ($\mu_{x_{-1.4}} = -1.14''$)

Figure 14 - Increased Deformation in the Buckled Bars toward the End of the Load History
Strain Data Summary for Test 12:

North Reinforcement:

The tensile vertical strain profile for North extreme fiber bar N3 appears in Figure 17. Bar N3 buckled after reversal from a peak tensile strain of 0.058 measured 3.57” above the footing during the peak push cycle ($\mu_{4.9}^{6.62} = 8.22$”). The compressive vertical strain profile for bar N3 appears in Figure 18. The peak compressive strain of -0.021 measured 3.57” above the footing during ($\mu_{7.9}^{6.88} = -6.53$”) preceded the peak tensile cycle which caused buckling upon reversal of loading. The location of the largest tensile and compressive strains coincides with the location of the latter outward buckling of the reinforcing bar. The relationship between tensile strain and displacement from when the column was vertical to the peak of push cycles for extreme fiber bar N3 appears in Figure 19. All of the push cycles produce a similar relationship between tensile strain and displacement which falls below the moment curvature prediction by an increasing margin at higher ductilities. This same phenomenon has been observed for all of the tests with the improved instrumentation method. The relationship between compressive strain and displacement from when the column was vertical to the peak of pull cycles for bar N3 appears in Figure 22. During initial pull cycles, the moment curvature prediction matches the recorded compressive strains well, but during the peak pull cycle ($\mu_{7.9}^{6.88} = -6.53$”) the recorded strain begin to exceed the moment curvature prediction at an increasing rate.

The strain hysteresis for the buckled region of extreme fiber reinforcing bar N3, 3.75” above the footing, appears in Figure 24 with an earthquake time colorbar to track the progression of the test. The peak tensile and compressive strains for bar N3 were measured over this gage length during the largest push and pull cycles respectively. The transverse steel strain gage hysteresis over the North buckled region appears in Figure 25. The strain in the transverse steel went into the inelastic range during the largest pull cycle ($\mu_{7.9}^{6.88} = -6.53$”) which placed the longitudinal reinforcement and concrete in compression. A data label is placed at the displacement upon reversal from the peak cycle ($\mu_{4.9}^{6.62} = 8.22$”) where the strain in the transverse steel began to increase sharply indicating an increased demand by the outward deformation of the buckled extreme fiber reinforcing bar, as shown in Figure 25. A data label at the same displacement is provided on the strain hysteresis for the longitudinal bar in Figure 24. Longitudinal steel strains past this point no longer represent engineering strain, but are included to illustrate that buckling occurred. The transverse steel strains quickly go off scale and no longer represent accurate strains once the reinforcing bar buckled.

South Reinforcement:

The compressive vertical strain profile for extreme fiber bar S3 for push cycles appears in Figure 15. A peak compressive strain of -0.032 was measured 7.88” above the footing. The original Mander model ultimate concrete compressive strain for the column is -0.0187. Past research has shown that the Mander model is consistently around 50% conservative which leads to an assessment value for the ultimate concrete compression strain around -0.028 which was exceeded during the largest push cycle. After the largest push cycle the vertical strain profile changes shape which may be due to one of two reasons: (1) buckling of the North reinforcement changed the demands on the other side of the specimen, or (2) there was some amount of measurable deformation over the bottom three layers of transverse steel which was not visibly discernable during the test. The tensile vertical strain profile for extreme fiber bar S3 for pull cycles appears in Figure 16. The effects of possible deformation over the “buckled region” of
extreme fiber bar S3 appears to not affect the tensile vertical strain profiles in the same manner as the compressive profiles. The relationship between compressive strain and displacement from when the column was vertical to the peak of push cycles appears in Figure 20 for extreme fiber bar S3. The recorded compressive strains match up well with the moment curvature prediction up to the peak cycle at $\mu_{4,9}^{68.62} = 8.22^\circ$. Past this point the relationship between compressive strain and displacement clearly changes for this individual gage length. At the same level of displacement a much larger compressive strain is observed which could be due to measurable deformation over multiple gage lengths. This particular gage length decreased as the bar deformed while other gage lengths over the outward “buckled” region increased. The relationship between tensile strain and displacement from when the column was vertical to the peak of pull cycles appears in Figure 21. Prior to the peak cycle in the push direction which may have caused deformation in the bar, the relationship between tensile strain and displacement matched the same trends described for the North reinforcing bar. The recorded tensile strains fall below the moment curvature prediction in an increasing manner at higher ductilities. After the peak cycle the relationship seems to be affected since they no longer follow the trend of previous cycles.

The strain hysteresis for extreme fiber bar S3 appears in Figure 26 with an earthquake time colorbar to track the progression of the test. The transverse steel strain hysteresis over the South “buckled region” appears in Figure 27. The transverse steel strain sharply increased during the largest push cycle at $\mu_{4,9}^{68.62} = 8.22^\circ$. Since visible buckling was not observed for the South reinforcement, it is difficult to know if this sharp increase is due to deformation in the reinforcing bar or due to large compressive concrete strains in the region. Figure 20 would suggest that the deformation occurred after the peak pull cycle since the relationship between strain and displacement matches previous cycles and the moment curvature prediction at this time. A data label was placed at the location where the transverse steel strain begins to increase after reversal from a pull cycle which placed bar S3 in tension. Presumably, the transverse steel strain would increase during the time it was restraining the reinforcing bars while the cracks were closing. If a similar data label is placed on the strain hysteresis for bar S3, it becomes easier to see that the bar did indeed buckle over this region. After the data label the reinforcement over this gage length is never placed back into compression strain due to outward deformation during push cycles. This cannot be visually verified by test results, but upon comparison of the strain hysteresis for bars S3 and N3 I believe we have sufficient evidence of buckling of bar S3.
Figure 15 - South Extreme Fiber Bar S3 Compressive Vertical Strain Profiles during Push Cycles

Figure 16 - South Extreme Fiber Bar S3 Tensile Vertical Strain Profiles during Pull Cycles
Figure 17 - North Extreme Fiber Bar N3 Tensile Vertical Strain Profiles during Push Cycles

Figure 18 - North Extreme Fiber Bar N3 Compressive Vertical Strain Profiles during Pull Cycles
Figure 19 - Extreme Fiber Bar N3 Push Tensile Strains (dashed lines are reversals)

Figure 20 - Extreme Fiber Bar S3 Pull Compressive Strains (dashed lines are reversals)
Figure 21 - Extreme Fiber Bar S3 Pull Tensile Strains (dashed lines are reversals)

Figure 22 - Extreme Fiber Bar N3 Pull Compressive Strains (dashed lines are reversals)
Vertical Curvature Profiles:

The vertical curvature profile for push cycles of the Japan 2011 load history appears in Figure 28. Early cycles in the load history at smaller ductilities have more jagged curvature profiles, and as the crack distribution forms the curvature distributions smooth out. Following the same trends observed in curvature profiles for previous tests, the extent of plasticity increases at higher ductilities and the distribution of plastic curvature is nearly linear. This forms a triangular distribution of curvature that shifts upward and outward with increasing ductility. The same discussion can be made for the vertical curvature profiles for pull cycles of the Japan 2011 load history which appear in Figure 29.

For comparison, the vertical curvature profiles for push and pull cycles for the symmetric three cycle set load history of Test 8 appear in Figure 33 and Figure 34. The small dashed lines are the moment curvature analysis predicted base curvature at each displacement ductility level. In these vertical curvature profiles, it becomes clear that the extent of plastic deformation increases with increasing ductility and a constant plastic hinge length for all ductility levels may give accurate displacements, but will not necessarily give accurate tensile strains at that displacement. The linear distribution of curvature shifts upward and outward with increasing ductility. This is further evident when you consider that the relationship between tensile strain and displacement is over predicted by an increasing margin at higher ductilities in moment curvature analysis. This is likely due to the use of a constant plastic hinge length, whereas if the extent of curvature increased with increasing ductility the predicted strain at a given displacement would be lower. Presumably, the curvature profiles for many tests could be used to determine a more appropriate distribution of curvature for moment curvature analysis.
Figure 24 – North Extreme Fiber Bar N3 Strain Hysteresis (1.56” above the footing)

Figure 25 - Transverse Steel Strain Hysteresis over North Buckled Region
Figure 26 - South Extreme Fiber Bar S3 Strain Hysteresis (4.03” above the footing)

Figure 27 - Transverse Steel Strain Gage Hysteresis over South "Buckled Region" – Buckling Not Visibly Observed
Figure 28 - Vertical Curvature Profiles for Push Cycles

44.85 sec: Ductility 0.6
48.83 sec: Ductility 2.1
61.36 sec: Ductility 2.4
63.71 sec: Ductility 3.2
65.37 sec: Ductility 3.9
68.62 sec: Ductility 9.9

Figure 29 - Vertical Curvature Profiles for Pull Cycles

44.53 sec: Ductility -0.7
49.08 sec: Ductility -1.6
61.80 sec: Ductility -2.2
62.60 sec: Ductility -2.5
66.88 sec: Ductility -7.9
Figure 30 - Strain Comparison for Peak Displacement Cycles (dashed lines are reversals – if bar buckled upon reversal they no longer represent engineering strain)

Figure 31 – Vertical Tensile Strain Profile Comparison for Peak Cycles
Figure 32 - Vertical Curvature Profile Comparison for Peak Cycles

Figure 33 - Test 8 Three Cycle Set Curvature Distribution for Push Cycles (dashed lines are Cumbia base curvatures at each ductility level)
Strain Data Comparison:

The relationship between tensile strain and displacement for recent tests which utilized the improved instrumentation method appears in Figure 30. The relationship between tensile strain and displacement does not seem to be affected by load history once the crack distribution is in place. The largest push cycle of the Kobe load history was a near monotonic push to the peak displacement without cyclic ramp up to set in place a crack distribution. Since the cracks were being distributed during the peak cycle, the relationship between strain and displacement is initially different than the values recorded in other tests. Slightly higher strains at a given displacement were measured during the symmetric three cycle set load history compared to the other earthquake time histories. The tensile vertical strain profile for each of the peak displacement cycles appears in Figure 32. Considering that the peak cycles for each perspective test did not reach the same value of displacement, the vertical strain profiles are surprisingly similar. The same can be said for the vertical curvature profile comparison shown in Figure 32.

The series of three graphs show that load history does not seem to affect the relationship between strain and displacement, distribution of tensile strain, or the distribution of curvature during the peak cycle. A comparison for other levels of ductility or cycles after the peak displacement has not been made at this time. Load history does have an impact on buckling of longitudinal steel as suggested by the peak displacement ductility of eight before buckling during a three cycle set load history compared to a displacement ductility of ten for the Kobe and Japan 2011 load histories. Furthermore, the Chichi and Chile load histories scaled to ductility 8.9 and 8.7 respectively did not produce buckling. The balanced repeated cycles of increasing ductility of the symmetric three cycle set load history seem to be more damaging than the load histories produced by historical earthquake records.