BEHAVIOR, DESIGN, AND ANALYSIS OF UNBONDED POST-TENSIONED PRECAST CONCRETE COUPLING BEAMS

VOLUME III

A Dissertation

Submitted to the Graduate School
of the University of Notre Dame
in Partial Fulfillment of the Requirements
for the Degree of

Doctor of Philosophy

by

Brad D. Weldon

Yahya C. Kurama, Director

Graduate Program in Civil Engineering and Geological Sciences
Notre Dame, Indiana
April 2010
CONTENTS

VOLUME III

FIGURES ........................................................................................................................ cix
TABLES .......................................................................................................................... cxxv

CHAPTER 7:

POST-VIRGIN BEAM SUBASSEMBLY EXPERIMENTAL RESULTS .......................519

7.1 Test 3A ...................................................................................................................519
  7.1.1 Test Photographs ............................................................................................522
  7.1.2 Beam Shear Force versus Chord Rotation Behavior .................................526
  7.1.3 Beam End Moment Force versus Chord Rotation Behavior ......................529
  7.1.4 Beam Post-Tensioning Forces ...................................................................530
  7.1.5 Angle-to-Wall Connection Post-Tensioning Forces .................................535
  7.1.6 Vertical Forces on Wall Test Region .........................................................539
  7.1.7 Beam Vertical Displacements ....................................................................540
  7.1.8 Beam Chord Rotation ...............................................................................545
  7.1.9 Local Beam Rotations ..............................................................................547
  7.1.10 Load Block Displacements and Rotations ............................................549
  7.1.11 Reaction Block Displacements and Rotations .......................................557
  7.1.12 Contact Depth and Gap Opening at Beam-to-Wall Interfaces ..................562
  7.1.13 Wall Test Region Local Concrete Deformations .................................573
7.2.18 Wall Test Region Confined Concrete Strains ...........................................666
7.2.19 Wall Test Region Confinement Hoop Strains .......................................667
7.2.20 Crack Patterns .......................................................................................667
7.3 Test 4A ............................................................................................................668
7.3.1 Test Photographs .......................................................................................669
7.3.2 Beam Shear Force versus Chord Rotation Behavior ..............................673
7.3.3 Beam End Moment Force versus Chord Rotation Behavior .................676
7.3.4 Beam Post-Tensioning Forces ...............................................................677
7.3.5 Angle-to-Wall Connection Post-Tensioning Forces ..............................681
7.3.6 Vertical Forces on Wall Test Region .......................................................681
7.3.7 Beam Vertical Displacements ...............................................................682
7.3.8 Beam Chord Rotation ............................................................................687
7.3.9 Local Beam Rotations ............................................................................689
7.3.10 Load Block Displacements and Rotations ...........................................691
7.3.11 Reaction Block Displacements and Rotations .....................................699
7.3.12 Gap Opening and Contact Depth at Beam-to-Wall Interfaces .............704
7.3.13 Wall Test Region Local Concrete Deformations .................................715
7.3.14 Beam Looping Reinforcement Longitudinal Leg Strains ....................717
7.3.15 Beam Transverse Reinforcement Strains .............................................724
7.3.16 Beam Confined Concrete Strains ..........................................................728
7.3.17 Beam End Confinement Hoop Strains ..................................................732
7.3.18 Wall Test Region Confined Concrete Strains .......................................736
7.3.19 Wall Test Region Confinement Hoops Strains .....................................737
7.3.20 Crack Patterns .......................................................................................737
7.4 Test 4B........................................................................................................................................738

7.4.1 Test Photographs..............................................................................................................739
7.4.2 Beam Shear Force versus Chord Rotation Behavior ..............................................743
7.4.3 Beam End Moment Force versus Chord Rotation Behavior ............................746
7.4.4 Beam Post-Tensioning Forces .................................................................................747
7.4.5 Angle-to-Wall Connection Post-Tensioning Forces ...........................................752
7.4.6 Vertical Forces on Wall Test Region .......................................................................755
7.4.7 Beam Vertical Displacements....................................................................................756
7.4.8 Beam Chord Rotation ............................................................................................760
7.4.9 Local Beam Rotations ...........................................................................................762
7.4.10 Load Block Displacements and Rotations ..........................................................765
7.4.11 Reaction Block Displacements and Rotations .....................................................773
7.4.12 Contact Depth and Gap Opening at Beam-to-Wall Interfaces ............................778
7.4.13 Wall Test Region Local Concrete Deformations .................................................789
7.4.14 Beam Looping Reinforcement Longitudinal Leg Strains ..................................791
7.4.15 Beam Transverse Reinforcement Strains .............................................................798
7.4.16 Beam Confined Concrete Strains ..........................................................................801
7.4.17 Beam End Confinement Hoop Strains ..................................................................806
7.4.18 Wall Test Region Confined Concrete Strains .......................................................811
7.4.19 Wall Test Region Confinement Hoops Strains ....................................................812
7.4.20 Crack Patterns .......................................................................................................812
FIGURES

VOLUME III

CHAPTER 7:

Figure 7.1: Test 3A angle – (a) hole pattern and locations; (b) photograph of angle..... 521

Figure 7.2: Test 3A overall photographs – (a) pre-test undisplaced position;
   (b) \( \theta_b = 3.33\% \); (c) \( \theta_b = -3.33\% \); (d) \( \theta_b = 5.0\% \); (e) \( \theta_b = -5.0\% \); (f) final post-test
   undisplaced position............................................................................................ 524

Figure 7.3: Test 3A beam south end photographs – (a) pre-test undisplaced position;
   (b) \( \theta_b = 3.33\% \); (c) \( \theta_b = -3.33\% \); (d) \( \theta_b = 5.0\% \); (e) \( \theta_b = -5.0\% \); (f) final post-test
   undisplaced position............................................................................................ 525

Figure 7.4: Test 3A south beam end damage propagation – positive and negative
   rotations............................................................................................................... 526

Figure 7.5: Test 3A coupling beam shear force versus chord rotation behavior – (a) using
   beam displacements; (b) using load block displacements. ................................. 528

Figure 7.6: Test 3A angle fracture – (a) side view; (b) front view ......................... 529

Figure 7.7: Test 3A \( M_b-\theta_b \) behavior. ................................................................. 530

Figure 7.8: Test 3A beam post-tensioning strand forces – (a) strand 1; (b) strand 2;
   (c) strand 3. ......................................................................................................... 532

Figure 7.9: Test 3A \( F_{LC}-\theta_b \) behavior – (a) strand 1; (b) strand 2; strand 3............ 533

Figure 7.10: Test 3A beam post-tensioning force versus chord rotation behavior –
   (a) using beam displacements; (b) using load block displacements. ............... 534

Figure 7.11: Test 3A south end top angle-to-wall connection strand forces – (a) east
   strand; (b) west strand........................................................................................ 536

Figure 7.12: Test 3A south end top angle-to-wall connection strand forces versus beam
   chord rotation – (a) \( F_{LC3}-\theta_b \); (b) \( F_{LC4}-\theta_b \)......................................................... 537

   cix
Figure 7.13: Test 3A south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand. ................................................................. 537

Figure 7.14: Test 3A south end seat angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LCS-\theta_b}$; (b) $F_{LCS-\theta_b}$. ................................................................. 538

Figure 7.15: Test 3A south end total angle-to-wall connection strand forces versus beam chord rotation – (a) top connection; (b) seat connection. .......................... 538

Figure 7.16: Test 3A vertical force on wall test region, $F_{wt}$ – (a) $F_{wt}$-test duration; (b) $F_{wt-\theta_b}$. ................................................................. 540

Figure 7.17: Test 3A south end beam vertical displacements – (a) measured, $\Delta_{DT9}$; (b) adjusted, $\Delta_{DT9,y}$; (c) difference, $\Delta_{DT9,y}-\Delta_{DT9}$. ........................................... 542

Figure 7.18: Test 3A north end beam vertical displacements – (a) measured, $\Delta_{DT10}$; (b) adjusted, $\Delta_{DT10,y}$; (c) difference, $\Delta_{DT10,y}-\Delta_{DT10}$. ........................................... 543

Figure 7.19: Test 3A percent difference between measured and adjusted displacements versus beam chord rotation – (a) south end, DT9; (b) north end, DT10. ....... 544

Figure 7.20: Test 3A beam vertical displacements versus beam chord rotation – (a) $\Delta_{DT9-\theta_b}$; (b) $\Delta_{DT10-\theta_b}$. ................................................................. 544

Figure 7.21: Test 3A beam chord rotation – (a) $\theta_b$ from $\Delta_{DT9}$ and $\Delta_{DT10}$; (b) $\theta_{b,lb}$ from $\Delta_{LB_9}$. ................................................................. 545

Figure 7.22: Test 3A percent difference between $\theta_b$ and $\theta_{b,lb}$. ........................................ 546

Figure 7.23: Test 3A difference between $\theta_b$ and $\theta_{b,lb}$. ........................................ 546

Figure 7.24: Test 3A beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. ................................................................. 548

Figure 7.25: Test 3A difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape. ........................................... 549

Figure 7.26: Test 3A load block horizontal displacements – (a) measured, $\Delta_{DT3}$; (b) adjusted, $\Delta_{DT3,y}$; (c) percent difference. ................................................................. 552

Figure 7.27: Test 3A load block north end vertical displacements – (a) measured, $\Delta_{DT4}$; (b) adjusted, $\Delta_{DT4,y}$; (c) percent difference. ................................................................. 553

Figure 7.28: Test 3A load block south end vertical displacements – (a) measured, $\Delta_{DT5}$; (b) adjusted, $\Delta_{DT5,y}$; (c) percent difference. ................................................................. 554

Figure 7.29: Test 3A percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5. ................................................................. 554
Figure 7.30: Test 3A load block displacements versus beam chord rotation – (a) $\Delta DT4-\theta_b$; (b) $\Delta DT3-\theta_b$; (c) $\Delta DT3_x-\theta_b$.

Figure 7.31: Test 3A load block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements.

Figure 7.32: Test 3A load block centroid displacements versus beam chord rotation – (a) x-displacement-\(\theta_b\); (b) y-displacement-\(\theta_b\); (c) rotation-\(\theta_b\).

Figure 7.33: Test 3A reaction block displacements – (a) $\Delta DT6$; (b) $\Delta DT7$; (c) $\Delta DT8$.

Figure 7.34: Test 3A reaction block displacements versus beam chord rotation – (a) $\Delta DT7-\theta_b$; (b) $\Delta DT8-\theta_b$; (c) $\Delta DT6-\theta_b$.

Figure 7.35: Test 3A reaction block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements.

Figure 7.36: Test 3A reaction block centroid displacements versus beam chord rotation – (a) x-displacements; (b) y-displacements; (c) rotation.

Figure 7.37: Test 3A beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta DT11$; (b) adjusted, $\Delta DT11_x$; (c) percent difference.

Figure 7.38: Test 3A beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta DT12$; (b) adjusted, $\Delta DT12_x$; (c) percent difference.

Figure 7.39: Test 3A beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta DT13$; (b) adjusted, $\Delta DT13_x$; (c) percent difference.

Figure 7.40: Test 3A beam-to-reaction-block interface LVDT displacements versus beam chord rotation – (a) $\Delta DT11-\theta_b$; (b) $\Delta DT13-\theta_b$; (c) $\Delta DT12-\theta_b$.

Figure 7.41: Test 3A contact depth at beam-to-reaction-block interface – (a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT1, DT11, and DT13; (c) method 3 using RT1 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.

Figure 7.42: Test 3A gap opening at beam-to-reaction-block interface – (a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT1, DT11, and DT13; (c) method 3 using RT1 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.

Figure 7.43: Test 3A gap opening at beam-to-reaction-block interface using method 4.

Figure 7.44: Test 3A contact depth at beam-to-reaction-block interface – (a) method 4 using $\Delta DT12$ and $\theta_b$; (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord rotation cycle.
Figure 7.45: Test 3A wall test region concrete deformations – (a) DT14; (b) DT15 .... 574

Figure 7.46: Test 3A wall test region concrete deformations versus beam chord rotation – (a) $\Delta x_{DT14}-\theta_b$; (b) $\Delta x_{DT15}-\theta_b$. ............................................................................................................. 574

Figure 7.47: Test 3A beam looping reinforcement top longitudinal leg strains –
(a) $e_{6(1)T-E}$; (b) $e_{6(1)T-W}$; (c) $e_{6(2)T-E}$; (d) $e_{6(2)T-W}$; (e) $e_{6(3)T-E}$; (f) $e_{6(3)T-W}$; (g) $e_{6MT-E}$; (h) $e_{6MT-W}$. ............................................................................................................. 576

Figure 7.48: Test 3A beam looping reinforcement bottom longitudinal leg strains –
(a) $e_{6(1)B-E}$; (b) $e_{6(1)B-W}$; (c) $e_{6(2)B-E}$; (d) $e_{6(2)B-W}$; (e) $e_{6(3)B-E}$; (f) $e_{6(3)B-W}$; (g) $e_{6MB-E}$; (h) $e_{6MB-W}$. ............................................................................................................. 577

Figure 7.49: Test 3A beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) $e_{6(1)T-E}-\theta_b$; (b) $e_{6(1)T-W}-\theta_b$; (c) $e_{6(2)T-E}-\theta_b$; (d) $e_{6(2)T-W}-\theta_b$; (e) $e_{6(3)T-E}-\theta_b$; (f) $e_{6(3)T-W}-\theta_b$; (g) $e_{6MT-E}-\theta_b$; (h) $e_{6MT-W}-\theta_b$. ............................................................................................................. 579

Figure 7.50: Test 3A beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $e_{6(1)B-E}-\theta_b$; (b) $e_{6(1)B-W}-\theta_b$; (c) $e_{6(2)B-E}-\theta_b$; (d) $e_{6(2)B-W}-\theta_b$; (e) $e_{6(3)B-E}-\theta_b$; (f) $e_{6(3)B-W}-\theta_b$; (g) $e_{6MB-E}-\theta_b$; (h) $e_{6MB-W}-\theta_b$. ............................................................................................................. 580

Figure 7.51: Test 3A beam looping reinforcement vertical leg strains – (a) $e_{6SE(E)-E}$; (b) $e_{6SE(W)-E}$; (c) $e_{6SE(E)-E}$; (d) $e_{6SE(W)-E}$. ............................................................................................................. 583

Figure 7.52: Test 3A beam looping reinforcement vertical leg strains versus beam chord rotation – (a) $e_{6SE(E)-E}-\theta_b$; (b) $e_{6SE(W)-E}-\theta_b$; (c) $e_{6SE(E)-E}-\theta_b$; (d) $e_{6SE(W)-E}-\theta_b$. ............................................................................................................. 584

Figure 7.53: Test 3A beam midspan transverse hoop reinforcement strains – (a) $e_{MH-E}$; (b) $e_{MH-W}$. ............................................................................................................. 584

Figure 7.54: Test 3A beam midspan transverse hoop reinforcement strains versus beam chord rotation – (a) $e_{MH-E}-\theta_b$; (b) $e_{MH-W}-\theta_b$. ............................................................................................................. 585

Figure 7.55: Test 3A No. 3 top hoop support bar strains – (a) $e_{3THT-(1)}$; (b) $e_{3THB-(1)}$; (c) $e_{3THT-(2)}$; (d) $e_{3THB-(2)}$. ............................................................................................................. 586

Figure 7.56: Test 3A No. 3 bottom hoop support bar strains – (a) $e_{3BHB-(1)}$; (b) $e_{3BHT-(1)}$; (c) $e_{3BHB-(2)}$; (d) $e_{3BHT-(2)}$. ............................................................................................................. 587

Figure 7.57: Test 3A No. 3 top hoop support bar strains versus beam chord rotation –
(a) $e_{3THT-(1)}-\theta_b$; (b) $e_{3THB-(1)}-\theta_b$; (c) $e_{3THT-(2)}-\theta_b$; (d) $e_{3THB-(2)}-\theta_b$. ............................................................................................................. 588

Figure 7.58: Test 3A No. 3 bottom hoop support bar strains versus beam chord rotation –
(a) $e_{3BHB-(1)}-\theta_b$; (b) $e_{3BHT-(1)}-\theta_b$; (c) $e_{3BHB-(2)}-\theta_b$; (d) $e_{3BHT-(2)}-\theta_b$. ............................................................................................................. 589

Figure 7.59: Test 3A beam end confinement hoop east leg strains – (a) $e_{1HB-E}$; (b) $e_{2HB-E}$; (c) $e_{3HB-E}$; (d) $e_{4HB-E}$. ............................................................................................................. 590
Figure 7.60: Test 3A beam end confinement hoop west leg strains – (a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$.

Figure 7.61: Test 3A beam end confinement hoop east leg strains versus beam chord rotation – (a) $\varepsilon_{1HBE-\theta_b}$; (b) $\varepsilon_{2HBE-\theta_b}$; (c) $\varepsilon_{3HBE-\theta_b}$; (d) $\varepsilon_{4HBE-\theta_b}$.

Figure 7.62: Test 3A beam end confinement hoop west leg strains versus beam chord rotation – (a) $\varepsilon_{1HBW-\theta_b}$; (b) $\varepsilon_{2HBW-\theta_b}$; (c) $\varepsilon_{3HBW-\theta_b}$; (d) $\varepsilon_{4HBW-\theta_b}$.

Figure 7.63: Test 3B overall photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 8.0\%$; (e) $\theta_b = -8.0\%$; (f) final post-test undisplaced position.

Figure 7.64: Test 3B beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 8.0\%$; (e) $\theta_b = -8.0\%$; (f) final post-test undisplaced position.

Figure 7.65: Test 3B beam south end damage propagation – positive and negative rotations.

Figure 7.66: Test 3B angle fracture – (a) side view; (b) isometric view.

Figure 7.67: Test 3B angle-to-wall connection plates.

Figure 7.68: Test 3B coupling beam shear force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements.

Figure 7.69: Test 3B $M_b-\theta_b$ behavior.

Figure 7.70: Test 3B beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3.

Figure 7.71: Test 3B $F_{LC-\theta_b}$ behavior – (a) strand 1; (b) strand 2; (c) strand 3.

Figure 7.72: Test 3B beam post-tensioning force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements.

Figure 7.73: Test 3B south end top angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.74: Test 3B south end top angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC3-\theta_b}$; (b) $F_{LC4-\theta_b}$.

Figure 7.75: Test 3B south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.76: Test 3B south end seat angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC5-\theta_b}$; (b) $F_{LC6-\theta_b}$.
Figure 7.77: Test 3B south end total angle-to-wall connection strand forces versus beam chord rotation – (a) top connection; (b) seat connection. ................................................. 612

Figure 7.78: Test 3B vertical force on the wall test region, $F_{wt}$ – (a) $F_{wt}$-test duration; (b) $F_{wt}$-$\theta_b$. ............................................................................................................ 613

Figure 7.79: Test 3B south end beam vertical displacements – (a) measured, $\Delta DT9$; (b) adjusted, $\Delta DT9_y$; (c) difference, $\Delta DT9_y$-$\Delta DT9$. ........................................................................ 615

Figure 7.80: Test 3B north end beam vertical displacements – (a) measured, $\Delta DT10$; (b) adjusted, $\Delta DT10_y$; (c) difference, $\Delta DT10_y$-$\Delta DT10$. ......................................................... 616

Figure 7.81: Test 3B percent difference between measured and adjusted displacements versus beam chord rotation – (a) south end, DT9; (b) north end, DT10. ............ 617

Figure 7.82: Test 3B beam vertical displacements versus beam chord rotation – (a) $\Delta DT9$-$\theta_b$; (b) $\Delta DT10$-$\theta_b$. ..................................................................................... 617

Figure 7.83: Test 3B beam chord rotation – (a) $\theta_b$ from $\Delta DT9$ and $\Delta DT10$; (b) $\theta_b,lb$ from $\Delta LB, y$. ............................................................................................................. 618

Figure 7.84: Test 3B percent difference between $\theta_b$ and $\theta_b,lb$. ........................................ 619

Figure 7.85: Test 3B difference between $\theta_b$ and $\theta_b,lb$. ........................................................................... 619

Figure 7.86: Test 3B beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. ............................................................................. 621

Figure 7.87: Test 3B difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape. ......................... 622

Figure 7.88: Test 3B load block horizontal displacements – (a) measured, $\Delta DT3$; (b) adjusted, $\Delta DT3,x$; (c) percent difference. .............................................................. 625

Figure 7.89: Test 3B load block north end vertical displacements – (a) measured, $\Delta DT4$; (b) adjusted, $\Delta DT4,y$; (c) percent difference. ......................................................... 626

Figure 7.90: Test 3B load block south end vertical displacements – (a) measured, $\Delta DT5$; (b) adjusted, $\Delta DT5,y$; (c) percent difference. ......................................................... 627

Figure 7.91: Test 3B percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5. ......................................................... 627

Figure 7.92: Test 3B load block displacements versus beam chord rotation – (a) $\Delta DT4$-$\theta_b$; (b) $\Delta DT5$-$\theta_b$; (c) $\Delta DT3,x$-$\theta_b$. ................................................................. 628

Figure 7.93: Test 3B load block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements. ........................................ 629
Figure 7.94: Test 3B load block centroid displacements versus beam chord rotation –
(a) x-displacement-\(\theta_b\); (b) y-displacement-\(\theta_b\); (c) rotation-\(\theta_b\). ............................ 630

Figure 7.95: Test 3B reaction block displacements – (a) \(\Delta DT6\); (b) \(\Delta DT7\); (c) \(\Delta DT8\). 632

Figure 7.96: Test 3B reaction block displacements versus beam chord rotation –
(a) \(\Delta DT7\)-\(\theta_b\); (b) \(\Delta DT8\)-\(\theta_b\); (c) \(\Delta DT6\)-\(\theta_b\). ............................ 633

Figure 7.97: Test 3B reaction block centroid displacements – (a) x-y displacements;
(b) rotation; (c) x-displacements; (d) y-displacements. ............................ 634

Figure 7.98: Test 3B reaction block centroid displacements versus beam chord rotation –
(a) x-displacements; (b) y-displacements; (c) rotation. ............................ 635

Figure 7.99: Test 3B beam-to-reaction-block interface top LVDT displacements –
(a) measured, \(\Delta DT1\); (b) adjusted, \(\Delta DT1, x\); (c) percent difference. ............................ 637

Figure 7.100: Test 3B beam-to-reaction-block interface middle LVDT displacements –
(a) measured, \(\Delta DT1,2\); (b) adjusted, \(\Delta DT1,2, x\); (c) percent difference. ............................ 638

Figure 7.101: Test 3B beam-to-reaction-block interface bottom LVDT displacements –
(a) measured, \(\Delta DT1,3\); (b) adjusted, \(\Delta DT1,3, x\); (c) percent difference. ............................ 639

Figure 7.102: Test 3B beam-to-reaction-block interface LVDT displacements versus
beam chord rotation – (a) \(\Delta DT1\)-\(\theta_b\); (b) \(\Delta DT1,3\)-\(\theta_b\); (c) \(\Delta DT1,2\)-\(\theta_b\). ............................ 640

Figure 7.103: Test 3B contact depth at beam-to-reaction-block interface – (a) method 1
using \(\Delta DT1, DT12\), and \(\Delta DT1,3\); (b) method 2 using RT1, DT11, and DT13; (c)
method 3 using RT1 and DT12; (d) method 4 using \(\Delta DT12\) and \(\theta_b\); (e) method 5
using \(\theta_b\), DT11, and DT13. ............................ 643

Figure 7.104: Test 3B gap opening at beam-to-reaction-block interface – (a) method 1
using \(\Delta DT1, DT12\), and \(\Delta DT1,3\); (b) method 2 using RT1, DT11, and DT13; (c)
method 3 using RT1 and DT12; (d) method 4 using \(\Delta DT12\) and \(\theta_b\); (e) method 5
using \(\theta_b\), DT11, and DT13. ............................ 644

Figure 7.105: Test 3B gap opening at beam-to-reaction-block interface method 4. ............................ 645

Figure 7.106: Test 3B contact depth at beam-to-reaction-block interface – (a) method 4
using \(\Delta DT12\) and \(\theta_b\); (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord
rotation cycle. ............................ 645

Figure 7.107: Test 3B wall test region concrete deformations – (a) DT14; (b) DT15. 647

Figure 7.108: Test 3B wall test region concrete deformations versus beam chord rotation
– (a) \(\Delta DT14\)-\(\theta_b\); (b) \(\Delta DT15\)-\(\theta_b\). 647
Figure 7.109: Test 3B beam looping reinforcement top longitudinal leg strains –
(a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$;
(h) $\varepsilon_{6MT-W}$ ............................................................................................................ 649

Figure 7.110: Test 3B beam looping reinforcement bottom longitudinal leg strains –
(a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$; (f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MB-E}$;
(h) $\varepsilon_{6MB-W}$ ............................................................................................................ 650

Figure 7.111: Test 3B beam looping reinforcement top longitudinal leg strains versus beam chord rotation –
(a) $\varepsilon_{6(1)T-Eb}$; (b) $\varepsilon_{6(1)T-Wb}$; (c) $\varepsilon_{6(2)T-Eb}$; (d) $\varepsilon_{6(2)T-Wb}$; (e) $\varepsilon_{6(3)T-Eb}$; (f) $\varepsilon_{6(3)T-Wb}$; (g) $\varepsilon_{6MT-Eb}$; (h) $\varepsilon_{6MT-Wb}$ ............................................................................................................ 652

Figure 7.112: Test 3B beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation –
(a) $\varepsilon_{6(1)B-Eb}$; (b) $\varepsilon_{6(1)B-Wb}$; (c) $\varepsilon_{6(2)B-Eb}$; (d) $\varepsilon_{6(2)B-Wb}$; (e) $\varepsilon_{6(3)B-Eb}$; (f) $\varepsilon_{6(3)B-Wb}$; (g) $\varepsilon_{6MB-Eb}$; (h) $\varepsilon_{6MB-Wb}$ ............................................................................................................ 653

Figure 7.113: Test 3B beam looping reinforcement vertical leg strains – (a) $\varepsilon_{6SEE(E)-E}$;
(b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(E)-E}$; (d) $\varepsilon_{6SE(E)-W}$ .................................................................. 656

Figure 7.114: Test 3B beam looping reinforcement vertical leg strains versus beam chord rotation –
(a) $\varepsilon_{6SE(E)-Eb}$; (b) $\varepsilon_{6SE(E)-Wb}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$ .................................................................. 657

Figure 7.115: Test 3B beam midspan transverse hoop reinforcement strains – (a) $\varepsilon_{MH-E}$;
(b) $\varepsilon_{MH-W}$ .................................................................................................................. 657

Figure 7.116: Test 3B beam midspan transverse hoop reinforcement strains versus beam chord rotation –
(a) $\varepsilon_{MH-Eb}$; (b) $\varepsilon_{MH-Wb}$ .......................................................................................... 658

Figure 7.117: Test 3B No. 3 top hoop support bar strains – (a) $\varepsilon_{3THT-(1)}$; (b) $\varepsilon_{3THT-(1)}$;
(c) $\varepsilon_{3THT-(2)}$; (d) $\varepsilon_{3THT-(2)}$ ................................................................................. 659

Figure 7.118: Test 3B No. 3 bottom hoop support bar strains – (a) $\varepsilon_{3BHT-(1)}$; (b) $\varepsilon_{3BHT-(1)}$;
(c) $\varepsilon_{3BHT-(2)}$; (d) $\varepsilon_{3BHT-(2)}$ .................................................................................. 660

Figure 7.119: Test 3B No. 3 top hoop support bar strains versus beam chord rotation –
(a) $\varepsilon_{3THT-(1)b}$; (b) $\varepsilon_{3THT-(1)b}$; (c) $\varepsilon_{3THT-(2)b}$; (d) $\varepsilon_{3THT-(2)b}$ ........................................................................ 661

Figure 7.120: Test 3B No. 3 bottom hoop support bar strains versus beam chord rotation –
(a) $\varepsilon_{3BHT-(1)b}$; (b) $\varepsilon_{3BHT-(1)b}$; (c) $\varepsilon_{3BHT-(2)b}$; (d) $\varepsilon_{3BHT-(2)b}$ ........................................................................ 662

Figure 7.121: Test 3B beam end confinement hoop east leg strains – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$;
(c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$ ........................................................................................ 663

Figure 7.122: Test 3B beam end confinement hoop west leg strains – (a) $\varepsilon_{1HB-W}$;
(b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$ ..................................................................................... 664

Figure 7.123: Test 3B beam end confinement hoop east leg strains versus beam chord rotation –
(a) $\varepsilon_{1HBE-b}$; (b) $\varepsilon_{2HBE-b}$; (c) $\varepsilon_{3HBE-b}$; (d) $\varepsilon_{4HBE-b}$ ........................................................................ 665

CXVI
Figure 7.124: Test 3B beam end confinement hoop west leg strains versus beam chord rotation – (a) $\varepsilon_{IHBW}$-$\theta_b$; (b) $\varepsilon_{2HBW}$-$\theta_b$; (c) $\varepsilon_{3HBW}$-$\theta_b$; (d) $\varepsilon_{4HBW}$-$\theta_b$. ........................................ 666

Figure 7.125: Test 4A angle with short tapered horizontal leg................................. 669

Figure 7.126: Test 4A overall photographs – (a) pre-test undisplaced position; (b) $\theta_b$ = 3.33%; (c) $\theta_b$ = –3.33%; (d) final post-test undisplaced position. ............. 671

Figure 7.127: Test 4A beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b$ = 3.33%; (c) $\theta_b$ = –3.33%; (d) final post-test undisplaced position. ........ 672

Figure 7.128: Test 4A beam south end damage propagation – positive and negative rotations........................................................................................................... 673

Figure 7.129: Test 4A coupling beam shear force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements. .............. 675

Figure 7.130: Test 4A $M_b$-$\theta_b$ behavior. ................................................................. 676

Figure 7.131: Test 4A beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3. ............................................................................................................ 678

Figure 7.132: Test 4A $F_{LC}$-$\theta_b$ behavior – (a) strand 1; (b) strand 2; (c) strand 3. .... 679

Figure 7.133: Test 4A beam post-tensioning force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements. ............ 680

Figure 7.134: Test 4A vertical force on the wall test region, $F_{wt}$ – (a) $F_{wt}$-test duration; (b) $F_{wt}$-$\theta_b$. ............................................................................................................ 682

Figure 7.135: Test 4A south end beam vertical displacements – (a) measured, $\Delta DT9$; (b) adjusted, $\Delta DT9,y$; (c) difference, $\Delta DT9,y-\Delta DT9$. .............................................. 684

Figure 7.136: Test 4A north end beam vertical displacements – (a) measured, $\Delta DT10$; (b) adjusted, $\Delta DT10,y$; (c) difference, $\Delta DT10,y-\Delta DT10$. .................................................... 685

Figure 7.137: Test 4A percent difference between measured and adjusted displacements – (a) south end, DT9; (b) north end, DT10. ......................................................... 686

Figure 7.138: Test 4A beam vertical displacement versus beam chord rotation – (a) $\Delta DT9$-$\theta_b$; (b) $\Delta DT10$-$\theta_b$. ............................................................................................................ 686

Figure 7.139: Beam chord rotation – (a) $\theta_b$ from $\Delta DT9$ and $\Delta DT10$; (b) $\theta_{b,lb}$ from $\Delta LB,y$. ... 688

Figure 7.140: Test 4A percent difference between $\theta_b$ and $\theta_{b,lb}$. ........................................ 688

Figure 7.141: Test 4A difference between $\theta_b$ and $\theta_{b,lb}$. ................................................................. 689
Figure 7.142: Test 4A beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. ................................................................. 690

Figure 7.143: Test 4A difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape. .................. 691

Figure 7.144: Test 4A load block horizontal displacements – (a) measured, $\Delta DT3$; (b) adjusted, $\Delta DT3,x$; (c) percent difference. ........................................ 694

Figure 7.145: Test 4A load block north end vertical displacements – (a) measured, $\Delta DT4$; (b) adjusted, $\Delta DT4,y$; (c) percent difference. ...................... 695

Figure 7.146: Test 4A load block south end vertical displacements – (a) measured, $\Delta DT5$; (b) adjusted, $\Delta DT5,y$; (c) percent difference. ...................... 696

Figure 7.147: Test 4A percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5. .................. 696

Figure 7.148: Test 4A load block displacements versus beam chord rotation – (a) $\Delta DT4$-$\theta_b$; (b) $\Delta DT5$-$\theta_b$; (c) $\Delta DT3,x$-$\theta_b$. ........................................ 697

Figure 7.149: Test 4A load block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements......................... 698

Figure 7.150: Test 4A load block centroid displacements versus beam chord rotation – (a) x-displacement-$\theta_b$; (b) y-displacement-$\theta_b$; (c) rotation-$\theta_b$. .................. 699

Figure 7.151: Test 4A reaction block displacements – (a) $\Delta DT6$; (b) $\Delta DT7$; (c) $\Delta DT8$. ...... 701

Figure 7.152: Test 4A reaction block displacements versus beam chord rotation – (a) $\Delta DT7$-$\theta_b$; (b) $\Delta DT8$-$\theta_b$; (c) $\Delta DT6$-$\theta_b$. ........................................ 702

Figure 7.153: Test 4A reaction block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements......................... 703

Figure 7.154: Test 4A reaction block centroid displacements versus beam chord rotation – (a) x-displacements; (b) y-displacements; (c) rotation. .............. 704

Figure 7.155: Test 4A beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta DT11$; (b) adjusted, $\Delta DT11,x$; (c) percent difference. ............... 706

Figure 7.156: Test 4A beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta DT12$; (b) adjusted, $\Delta DT12,x$; (c) percent difference. ............... 707

Figure 7.157: Test 4A beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta DT13$; (b) adjusted, $\Delta DT13,x$; (c) percent difference .......... 708

Figure 7.158: Test 4A beam-to-reaction-block interface LVDT displacements versus beam chord rotation – (a) $\Delta DT11$-$\theta_b$; (b) $\Delta DT12$-$\theta_b$; (c) $\Delta DT12$-$\theta_b$. .................. 709
Figure 7.159: Test 4A contact depth at beam-to-reaction-block interface – (a) method 1 using $\Delta DT_{11}$, $\Delta DT_{12}$, and $\Delta DT_{13}$; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using $\Delta DT_{12}$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13. ................................................................. 712

Figure 7.160: Test 4A gap opening at beam-to-reaction-block interface – (a) method 1 using $\Delta DT_{11}$, $\Delta DT_{12}$, and $\Delta DT_{13}$; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using $\Delta DT_{12}$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13. ................................................................................. 713

Figure 7.161: Test 4A gap opening at beam-to-reaction-block interface using method 4. ............................................................................................................................. 714

Figure 7.162: Test 4A contact depth at beam-to-reaction-block interface – (a) method 4 using $\Delta DT_{12}$ and $\theta_b$; (b) 0.75% beam chord rotation cycle; (c) 3.33% beam chord rotation cycle. ...................................................................................................... 714

Figure 7.163: Test 4A wall test region concrete deformations – (a) DT14; (b) DT15. ............................................................................................................................. 716

Figure 7.164: Test 4A wall test region concrete deformations – (a) $\Delta DT_{14}-\theta_b$; (b) $\Delta DT_{15}-\theta_b$. ............................................................................................................................. 716

Figure 7.165: Test 4A beam looping reinforcement top longitudinal leg strains – (a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$; (h) $\varepsilon_{6MT-W}$ ................................................................. 719

Figure 7.166: Test 4A beam looping reinforcement bottom longitudinal leg strains – (a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$; (f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MB-E}$; (h) $\varepsilon_{6MB-W}$ ........................................................................................................................................ 720

Figure 7.167: Test 4A beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)T-E}-\theta_b$; (b) $\varepsilon_{6(1)T-W}-\theta_b$; (c) $\varepsilon_{6(2)T-E}-\theta_b$; (d) $\varepsilon_{6(2)T-W}-\theta_b$; (e) $\varepsilon_{6(3)T-E}-\theta_b$; (f) $\varepsilon_{6(3)T-W}-\theta_b$; (g) $\varepsilon_{6MT-E}-\theta_b$; (h) $\varepsilon_{6MT-W}-\theta_b$. ................................................................. 721

Figure 7.168: Test 4A beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)B-E}-\theta_b$; (b) $\varepsilon_{6(1)B-W}-\theta_b$; (c) $\varepsilon_{6(2)B-E}-\theta_b$; (d) $\varepsilon_{6(2)B-W}-\theta_b$; (e) $\varepsilon_{6(3)B-E}-\theta_b$; (f) $\varepsilon_{6(3)B-W}-\theta_b$; (g) $\varepsilon_{6MB-E}-\theta_b$; (h) $\varepsilon_{6MB-W}-\theta_b$. ................................................................. 723

Figure 7.169: Test 4A beam looping reinforcement vertical leg strains – (a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$. ........................................................................................................................................ 726

Figure 7.170: Test 4A beam looping reinforcement vertical leg strains versus beam chord rotation – (a) $\varepsilon_{6SE(E)-E}-\theta_b$; (b) $\varepsilon_{6SE(E)-W}-\theta_b$; (c) $\varepsilon_{6SE(I)-E}-\theta_b$; (d) $\varepsilon_{6SE(I)-W}-\theta_b$. ........................................................................................................................................ 727

Figure 7.171: Test 4A beam midspan transverse hoop reinforcement strains – (a) $\varepsilon_{MH-E}$; (b) $\varepsilon_{MH-W}$. ........................................................................................................................................ 727
Figure 7.172: Test 4A beam midspan transverse hoop reinforcement strains versus beam chord rotation – (a) $\varepsilon_{MH-E}-\theta_b$; (b) $\varepsilon_{MH-W}-\theta_b$. ................................. 728

Figure 7.173: Test 4A No. 3 top hoop support bar strains – (a) $\varepsilon_{3THT-(1)}$; (b) $\varepsilon_{3THB-(1)}$; (c) $\varepsilon_{3THT-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. ......................................................... 729

Figure 7.174: Test 4A No. 3 bottom hoop support bar strains – (a) $\varepsilon_{3BHB-(1)}$; (b) $\varepsilon_{3BHT-(1)}$; (c) $\varepsilon_{3BHB-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. ...................................................................................... 730

Figure 7.175: Test 4A No. 3 top hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3THT-(1)}-\theta_b$; (b) $\varepsilon_{3THB-(1)}-\theta_b$; (c) $\varepsilon_{3THT-(2)}-\theta_b$; (d) $\varepsilon_{3BHT-(2)}-\theta_b$. .......................... 731

Figure 7.176: Test 4A No. 3 bottom hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3BHB-(1)}-\theta_b$; (b) $\varepsilon_{3BHT-(1)}-\theta_b$; (c) $\varepsilon_{3BHB-(2)}-\theta_b$; (d) $\varepsilon_{3BHT-(2)}-\theta_b$. .......................... 732

Figure 7.177: Test 4A beam end confinement hoop east leg strains – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$. ............................................................................................ 733

Figure 7.178: Test 4 beam end confinement hoop west leg strains – (a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$. ........................................................................................... 734

Figure 7.179: Test 4A beam end hoop confinement hoop east leg strains versus beam chord rotation – (a) $\varepsilon_{1HB-E}-\theta_b$; (b) $\varepsilon_{2HB-E}-\theta_b$; (c) $\varepsilon_{3HB-E}-\theta_b$; (d) $\varepsilon_{4HB-E}-\theta_b$. ............................ 735

Figure 7.180: Test 4A beam end hoop confinement hoop west leg strains versus beam chord rotation – (a) $\varepsilon_{1HB-W}-\theta_b$; (b) $\varepsilon_{2HB-W}-\theta_b$; (c) $\varepsilon_{3HB-W}-\theta_b$; (d) $\varepsilon_{4HB-W}-\theta_b$. ............................ 736

Figure 7.181: Test 4B overall photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 6.4\%$; (e) $\theta_b = -6.4\%$; (f) final post-test undisplaced position................................................................. 741

Figure 7.182: Test 4B beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 6.4\%$; (e) $\theta_b = -6.4\%$; (f) final post-test undisplaced position................................................................. 742

Figure 7.183: Test 4B beam south end damage propagation – positive and negative rotations........................................................................................................... 743

Figure 7.184: Test 4B coupling beam shear force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements. ......................... 745

Figure 7.185: Test 4B failure........................................................................................................... 746

Figure 7.186: Test 4B $M_b-\theta_b$ behavior. .................................................................................. 747

Figure 7.187: Test 4B beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3; (d) strand 4. ..................................................................................... 749

cxx
Figure 7.188: Test 4B $F_{LC} \cdot \theta_b$ behavior – (a) strand 1; (b) strand 2; (c) strand 3; (d) strand 4. ................................................................. 750

Figure 7.189: Test 4B beam post-tensioning force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements. ................. 751

Figure 7.190: Test 4B south end top angle-to-wall connection strand forces – (a) east strand; (b) west strand. ........................................................................ 753

Figure 7.191: Test 4B south end angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC3} \cdot \theta_b$; (b) $F_{LC4} \cdot \theta_b$. .............................................................. 753

Figure 7.192: Test 4B south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand. ........................................................................ 754

Figure 7.193: Test 4B south end angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC5} \cdot \theta_b$; (b) $F_{LC6} \cdot \theta_b$. .............................................................. 754

Figure 7.194: Test 4B south end total angle-to-wall connection strand forces versus beam chord rotation – (a) top connection; (b) seat connection. ......................... 755

Figure 7.195: Test 4B vertical force on the wall test region, $F_{wt}$ – (a) $F_{wt}$-test duration; (b) $F_{wt} \cdot \theta_b$. ..................................................................................... 756

Figure 7.196: Test 4B south end beam vertical displacement – (a) measured, $\Delta DT9$; (b) adjusted, $\Delta DT9,y$; (c) difference, $\Delta DT9,y-\Delta DT9$. .................................................. 758

Figure 7.197: Test 4B north end beam vertical displacement – (a) measured, $\Delta DT10$; (b) adjusted, $\Delta DT10,y$; (c) difference, $\Delta DT10,y-\Delta DT10$. .............................................. 759

Figure 7.198: Test 4B percent difference between measured and adjusted displacements – (a) south end, DT9; (b) north end, DT10. ........................................................... 759

Figure 7.199: Test 4B beam vertical displacements versus beam chord rotation – (a) $\Delta DT9 \cdot \theta_b$; (b) $\Delta DT10 \cdot \theta_b$. ........................................................................................................ 760

Figure 7.200: Test 4B beam chord rotation – (a) $\theta_b$ from $\Delta DT9$ and $\Delta DT10$; (b) $\theta_{b,lb}$ from $\Delta LB,y$. ............................................................................................... 761

Figure 7.201: Test 4B percent difference between $\theta_b$ and $\theta_{b,lb}$................................................................. 762

Figure 7.202: Test 4B percent difference between $\theta_b$ and $\theta_{b,lb}$................................................................. 762

Figure 7.203: Test 4B beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. ................................................................. 764

Figure 7.204: Test 4B difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape. ........................................ 765
Figure 7.205: Test 4B load block horizontal displacements – (a) measured, $\Delta DT_{3}$; 
(b) adjusted, $\Delta DT_{3,x}$; (c) percent difference……………………………………. 768

Figure 7.206: Test 4B load block north end vertical displacements – (a) measured, $\Delta DT_{4}$; 
(b) adjusted, $\Delta DT_{4,y}$; (c) percent difference……………………………………. 769

Figure 7.207: Test 4B load block south end vertical displacements – (a) measured, $\Delta DT_{5}$; 
(b) adjusted, $\Delta DT_{5,y}$; (c) percent difference……………………………………. 770

Figure 7.208: Test 4B percent difference between measured and adjusted displacements 
versus beam chord rotation – (a) DT4; (b) DT5. ................................................ 770

Figure 7.209: Test 4B load block displacements versus beam chord rotation – (a) $\Delta DT_{4}$-\(\theta_b\); 
(b) $\Delta DT_{5}$-\(\theta_b\); (c) $\Delta DT_{3,x}$-\(\theta_b\). .................................................................. 771

Figure 7.210: Test 4B load block centroid displacements – (a) x-y displacements; 
(b) rotation; (c) x-displacements; (d) y-displacements…………………………….. 772

Figure 7.211: Test 4B load block centroid displacements versus beam chord rotation – 
(a) x-displacement-\(\theta_b\); (b) y-displacement-\(\theta_b\); (c) rotation-\(\theta_b\). ....................... 773

Figure 7.212: Test 4B reaction block displacements – (a) $\Delta DT_{6}$; (b) $\Delta DT_{7}$; (c) $\Delta DT_{8}$. ...... 775

Figure 7.213: Test 4B reaction block displacements versus beam chord rotation – 
(a) $\Delta DT_{7}$-\(\theta_b\); (b) $\Delta DT_{8}$-\(\theta_b\); (c) $\Delta DT_{6}$-\(\theta_b\). ................................................ 776

Figure 7.214: Test 4B reaction block centroid displacements – (a) x-y displacements; 
(b) rotation; (c) x-displacements; (d) y-displacements…………………………….. 777

Figure 7.215: Test 4B reaction block centroid displacements versus beam chord rotation 
– (a) x-displacement-\(\theta_b\); (b) y-displacement-\(\theta_b\); (c) rotation-\(\theta_b\). ....................... 778

Figure 7.216: Test 4B beam-to-reaction-block interface top LVDT displacements – 
(a) measured, $\Delta DT_{11}$; (b) adjusted, $\Delta DT_{11,x}$; (c) percent difference. .......... 780

Figure 7.217: Test 4B beam-to-reaction-block interface middle LVDT displacements – 
(a) measured, $\Delta DT_{12}$; (b) adjusted, $\Delta DT_{12,x}$; (c) percent difference. .......... 781

Figure 7.218: Test 4B beam-to-reaction-block interface bottom LVDT displacements – 
(a) measured, $\Delta DT_{13}$; (b) adjusted, $\Delta DT_{13,x}$; (c) percent difference. .......... 782

Figure 7.219: Test 4B beam-to-reaction-block interface LVDT displacements versus 
beam chord rotation – (a) $\Delta DT_{11}$-\(\theta_b\); (b) $\Delta DT_{13}$-\(\theta_b\); (c) $\Delta DT_{12}$-\(\theta_b\). .......... 783

Figure 7.220: Test 4B contact depth at beam-to-reaction-block interface – (a) method 1 
using DT11, DT12, and DT13; (b) method 2 using RT2, DT11, and DT13; (c) 
method 3 using RT2 and DT12; (d) method 4 using DT12 and \(\theta_b\); (e) method 5 
using \(\theta_b\), DT11, and DT13. ................................................................................. 786
Figure 7.221: Test 4B gap opening at beam-to-reaction-block interface – (a) method 1 using \( \Delta_{DT11}, \Delta_{DT12}, \) and \( \Delta_{DT13}; \) (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using \( \Delta_{DT12} \) and \( \theta_b; \) (e) method 5 using \( \theta_b, \) DT11, and DT13. ............................................................................................................. 787

Figure 7.222: Test 4B gap opening at beam-to-reaction-block interface using method 4. ....................................................................................................................................... 788

Figure 7.223: Test 4B contact depth at beam-to-reaction-block interface – (a) method 4 using \( \Delta_{DT12} \) and \( \theta_{b,lb}; \) (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord rotation cycle.................................................................................................................. 788

Figure 7.224: Test 4B wall test region concrete deformations – (a) DT14; (b) DT15. ............................................................................................................. 790

Figure 7.225: Test 4B wall test region concrete deformations versus beam chord rotation – (a) \( \Delta_{DT14}-\theta_b; \) (b) \( \Delta_{DT15}-\theta_b. \) .......................................................................................................................... 790

Figure 7.226: Test 4B beam looping reinforcement top longitudinal leg strains – (a) \( \varepsilon_{6(1)T-E}; \) (b) \( \varepsilon_{6(1)T-W}; \) (c) \( \varepsilon_{6(2)T-E}; \) (d) \( \varepsilon_{6(2)T-W}; \) (e) \( \varepsilon_{6(3)T-E}; \) (f) \( \varepsilon_{6(3)T-W}; \) (g) \( \varepsilon_{6MB-E}; \) (h) \( \varepsilon_{6MT-W}. \) ............................................................................................................. 792

Figure 7.227: Test 4B beam looping reinforcement bottom longitudinal leg strains – (a) \( \varepsilon_{6(1)B-E}; \) (b) \( \varepsilon_{6(1)B-W}; \) (c) \( \varepsilon_{6(2)B-E}; \) (d) \( \varepsilon_{6(2)B-W}; \) (e) \( \varepsilon_{6(3)B-E}; \) (f) \( \varepsilon_{6(3)B-W}; \) (g) \( \varepsilon_{6MB-E}; \) (h) \( \varepsilon_{6MB-W}. \) ............................................................................................................. 794

Figure 7.228: Test 4B beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) \( \varepsilon_{6(1)T-E}-\theta_b; \) (b) \( \varepsilon_{6(1)T-W}-\theta_b; \) (c) \( \varepsilon_{6(2)T-E}-\theta_b; \) (d) \( \varepsilon_{6(2)T-W}-\theta_b; \) (e) \( \varepsilon_{6(3)T-E}-\theta_b; \) (f) \( \varepsilon_{6(3)T-W}-\theta_b; \) (g) \( \varepsilon_{6MT-E}-\theta_b; \) (h) \( \varepsilon_{6MT-W}-\theta_b. \) ............................................................................................................. 795

Figure 7.229: Test 4B beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) \( \varepsilon_{6(1)B-E}-\theta_b; \) (b) \( \varepsilon_{6(1)B-W}-\theta_b; \) (c) \( \varepsilon_{6(2)B-E}-\theta_b; \) (d) \( \varepsilon_{6(2)B-W}-\theta_b; \) (e) \( \varepsilon_{6(3)B-E}-\theta_b; \) (f) \( \varepsilon_{6(3)B-W}-\theta_b; \) (g) \( \varepsilon_{6MB-E}-\theta_b; \) (h) \( \varepsilon_{6MB-W}-\theta_b. \) ............................................................................................................. 796

Figure 7.230: Test 4B beam looping reinforcement vertical leg strains – (a) \( \varepsilon_{6SE(E)}-\varepsilon_{E}; \) (b) \( \varepsilon_{6SE(W)}-\varepsilon_{E}; \) (c) \( \varepsilon_{6SE(I)}-\varepsilon_{E}; \) (d) \( \varepsilon_{6SE(I)}-\varepsilon_{W}. \) ............................................................................................................. 799

Figure 7.231: Test 4B beam looping reinforcement vertical leg strains versus beam chord rotation behavior – (a) \( \varepsilon_{6SE(E)}-\varepsilon_{E}-\theta_b; \) (b) \( \varepsilon_{6SE(E)}-\varepsilon_{W}-\theta_b; \) (c) \( \varepsilon_{6SE(I)}-\varepsilon_{E}-\theta_b; \) (d) \( \varepsilon_{6SE(I)}-\varepsilon_{W}-\theta_b. \) ............................................................................................................. 800

Figure 7.232: Test 4B beam midspan transverse hoop reinforcement strains – (a) \( \varepsilon_{MH-E}; \) (b) \( \varepsilon_{MH-W}. \) ............................................................................................................. 801

Figure 7.233: Test 4B beam midspan transverse hoop reinforcement strains versus beam chord rotation behavior – (a) \( \varepsilon_{MH-E}-\theta_b; \) (b) \( \varepsilon_{MH-W}-\theta_b. \) ............................................................................................................. 801

Figure 7.234: Test 4B No. 3 top hoop support bar strains – (a) \( \varepsilon_{3THT-(1)}; \) (b) \( \varepsilon_{3THB-(1)}; \) (c) \( \varepsilon_{3THT-(2)}; \) (d) \( \varepsilon_{3THB-(2). \) ............................................................................................................. 803
Figure 7.235: Test 4B No. 3 bottom hoop support bar strains – (a) $\varepsilon_{3BHB-(1)}$; (b) $\varepsilon_{3BHT-(1)}$; (c) $\varepsilon_{3BHB-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. ................................................................. 804

Figure 7.236: Test 4B No. 3 top hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3THT-(1)}-\theta_b$; (b) $\varepsilon_{3THB-(1)}-\theta_b$; (c) $\varepsilon_{3THT-(2)}-\theta_b$; (d) $\varepsilon_{3THB-(2)}-\theta_b$.............................. 805

Figure 7.237: Test 4B No. 3 bottom hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3BHB-(1)}-\theta_b$; (b) $\varepsilon_{3BHT-(1)}-\theta_b$; (c) $\varepsilon_{3BHB-(2)}-\theta_b$; (d) $\varepsilon_{3BHT-(2)}-\theta_b$.............................. 806

Figure 7.238: Test 4B beam end hoop confinement strains (east legs) – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$. ................................................................. 808

Figure 7.239: Test 4B beam end hoop confinement strains (west legs) – (a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$. ................................................................. 809

Figure 7.240: Test 4B beam end hoop confinement strains (east legs) versus beam chord rotation – (a) $\varepsilon_{1HB-E}-\theta_b$; (b) $\varepsilon_{2HB-E}-\theta_b$; (c) $\varepsilon_{3HB-E}-\theta_b$; (d) $\varepsilon_{4HB-E}-\theta_b$.............................. 810

Figure 7.241: Test 4B beam end hoop confinement strains (west legs) versus beam chord rotation – (a) $\varepsilon_{1HB-W}-\theta_b$; (b) $\varepsilon_{2HB-W}-\theta_b$; (c) $\varepsilon_{3HB-W}-\theta_b$; (d) $\varepsilon_{4HB-W}-\theta_b$.............................. 811
TABLES

VOLUME III

CHAPTER 7:

Table 7.1  Ruler Measurements of Gap Opening at South Beam End............................573
Table 7.2  Ruler Measurements of Gap Opening at South Beam End............................646
Table 7.3  Ruler Measurements of Gap Opening at South Beam End............................715
Table 7.4  Ruler Measurements of Gap Opening at South Beam End............................789
CHAPTER 7

POST-VIRGIN BEAM SUBASSEMBLY EXPERIMENTAL RESULTS

This chapter presents the results from Tests 3A, 3B, 4A, and 4B in which Beams 3 and 4 are re-tested as part of a parametric investigation on the behavior of the coupling beam specimens from Chapter 6. These tests are referred to as the “post-virgin” beam tests in this dissertation. The chapter is divided into the following sections: (1) Test 3A; (2) Test 3B; (3) Test 4A; and (4) Test 4B. A comparison, summary, and overview of all virgin and post-virgin subassembly experimental results are given in Chapter 8.

Note that while the beam post-tensioning strands remain the same in all tests within each test series using the same beam specimen, the top and seat angles and the angle-to-beam/wall connections are renewed for each post-virgin test. The load block is re-used in all of the subassembly experiments presented in this dissertation and the reaction block is re-used in all experiments except for Test 1. Note also that the strain gauge measurements from the post-virgin beam tests should be used with caution since these strain gauges had previously been used as part of the virgin beam tests.

7.1 Test 3A

The beam used in Test 3A (i.e., Beam 3) has the following properties: (1) beam depth, $h_b = 14$ in. (356 mm); (2) beam width, $b_b = 7.5$ in. (191 mm); (3) mild steel
reinforcement of two No. 6 bars looping around the beam vertical perimeter along its length; (4) No. 3 full-depth rectangular hoops [6.125 in. by 12.675 in. (156 mm by 322 mm)] placed at a nominal 7.0 in. (178 mm) spacing to provide transverse reinforcement in the beam midspan region; (5) No. 3 partial-depth rectangular hoops [6.125 in. by 4.375 in. (156 mm by 111 mm)] placed at a 1.5 in. (38 mm) spacing to provide concrete confinement at the beam ends; (6) a beam post-tensioning tendon comprised of three 0.6 in. (15 mm) nominal diameter high-strength strands with a total area of \( A_{bp} = 0.651 \text{ in.}^2 \) (420 mm\(^2\)); (7) average initial beam post-tensioning strand stress of \( f_{bpi} = 0.34 f_{bpu} \), where \( f_{bpu} = 270 \text{ ksi (1862 MPa)} \) is the design maximum strength of the post-tensioning steel; (8) total initial beam post-tensioning force of \( P_{bi} = 60.4 \text{ kips (269 kN)} \); (9) initial beam concrete nominal axial stress (based on actual cross-sectional area with beam post-tensioning duct removed) of \( f_{bc} = 0.59 \text{ ksi (4.1 MPa)} \); and (10) two top and two seat angles (L8x8x1/2) with length, \( l_a = b_b = 7.5 \text{ in. (191 mm)} \). In each angle, a series of seven 0.50 in. (13 mm) diameter holes were drilled at the two expected plastic hinge locations of the angle vertical leg [at distances of 1.125 in. (29 mm) and 4.125 in. (105 mm) from the angle heel, see Figure 7.1].

The primary parameter difference of Test 3A from Test 3 is the use of full-length angles with holes drilled in the vertical leg. In addition, there was a small reduction in the initial beam post-tensioning strand stress, \( f_{bpi} \), and the resulting initial beam concrete nominal axial stress, \( f_{bc} \) due to the post-tensioning losses that occurred in Test 3. Note that the part of the wall test region that was damaged in Test 3 was patched using a high-strength fiber-reinforced grout. The same displacement loading history from Test 3 was also used for Test 3A.
Figure 7.1: Test 3A angle – (a) hole pattern and locations; (b) photograph of angle.
7.1.1 Test Photographs

Photographs of the original and displaced subassembly configurations from Test 3A are shown in Figures 7.2 and 7.3. Figures 7.2(a) through 7.2(f) show overall subassembly photographs as follows: (a) pre-test undisplaced position; (b) displaced to $\theta_b = 3.33\%$; (c) displaced to $\theta_b = -3.33\%$; (d) displaced to $\theta_b = 5.0\%$; (e) displaced to $\theta_b = -5.0\%$; and (f) final post-test undisplaced position. Similarly, Figures 7.3(a) through 7.3(f) show close-up photographs of the south end of the beam at the beam-to-reaction-block interface. The accumulation of damage at the south end of the beam is shown in more detail in Figure 7.4.

The wall test region of the reaction block, including the patched concrete, did not receive any additional damage (no cracking and/or spalling of the cover concrete) during the test. No additional damage to the beam was observed throughout the duration of the test. The ultimate failure of the specimen occurred due to the fracture of the top and seat angles during the first cycle to 5.0% rotation.

The angle-to-wall connections performed well with no yielding in the connection strands and no damage to the wall concrete. No slip in the angle-to-beam connections was observed during the test. Slip between the coupling beam and the walls did not occur demonstrating that the friction resistance due to the post-tensioning force provided adequate vertical support to the beam together with resistance from the top and seat angles. Similar to Tests 2 and 3, premature wire fracture in the post-tensioning strands did not occur in Test 3A.

Gap opening formed on both sides of the fiber-reinforced grout column throughout the test as a result of the bond being broken between the grout and the beam
ends in Test 3. While this is not the desired mode of behavior for the structure as
described in Chapter 3, it did not change the behavior of the system or cause any
problems with the performance of the grout. No significant crushing of the grout at the
beam-to-wall interfaces was observed throughout the test. Note that the grout column was
left approximately 0.25 in. (6.4 mm) short of the beam depth at the top and bottom, as
was done in Tests 2 and 3.
Figure 7.2: Test 3A overall photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 5.0\%$; (e) $\theta_b = -5.0\%$; (f) final post-test undisplaced position.
Figure 7.3: Test 3A beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 5.0\%$; (e) $\theta_b = -5.0\%$; (f) final post-test undisplaced position.
7.1.2 Beam Shear Force versus Chord Rotation Behavior

Figure 7.5(a) shows the hysteretic coupling beam shear force, $V_b$ versus chord rotation, $\theta_b$ behavior from Test 3A, where $V_b$ and $\theta_b$ are calculated from Equations 5.5 and 5.35, respectively. For comparison, Figure 7.5(b) plots the $V_b$-$\theta_{b,lb}$ behavior, where $\theta_{b,lb}$ is the beam chord rotation determined from the vertical ($y$-direction) displacement of the load block centroid using Equation 5.36. As shown in Figure 7.5, the structure was able to sustain three cycles at 3.33% rotation with approximately 4.9% loss in shear.
resistance. The subassembly was then able to undergo one cycle at 5.0% beam chord rotation at which time angle fracture occurred and the test was stopped.

Looking at the hysteresis loops, it can be seen that the specimen was able to dissipate a considerable amount of energy. Most of this energy dissipation occurred due to the yielding of the top and seat angles. The beam had a sufficient amount of restoring force to yield the tension angles back in compression and close the gaps at the beam-to-wall interfaces upon unloading, resulting in a large self-centering capability. During the three cycles at 3.33% beam chord rotation, a loss in the lateral resistance of the beam is observed, which occurred due to the initiation of angle fracture. The angle fracture was observed between several drilled holes in the layer of holes closest to the angle heel in all four top and seat angles as shown in Figure 7.6.
Figure 7.5: Test 3A coupling beam shear force versus chord rotation behavior –
(a) using beam displacements; (b) using load block displacements.
7.1.3 Beam End Moment Force versus Chord Rotation Behavior

Figure 7.7 shows the hysteretic coupling beam end moment, $M_b$ versus chord rotation, $\theta_b$ behavior from Test 3A, where $M_b$ is calculated from Equation 5.6 as described in Chapter 5. Since the beam end moment is calculated from the beam shear force, the results shown in Figure 7.7 are directly related to the results in Figure 7.5; and thus, no further discussion is provided herein.
 Beam Post-Tensioning Forces

The coupling beam post-tensioning strand forces from the test are measured using load cells LC15 – LC17 mounted at the dead ends of the three strands (see Chapter 5). The forces from the three load cells, $F_{LC15}$, $F_{LC16}$, and $F_{LC17}$ are shown in Figure 7.7, and are plotted against the beam chord rotation, $\theta_b$ in Figure 7.8. Figure 7.9 shows the total beam post-tensioning tendon force, $P_{bp}$ (sum of the forces in the three strands) normalized with the total design ultimate strength of the tendon, $\Sigma a_{bp} f_{bpu}$. The total initial beam post-tensioning tendon force is equal to 60.4 kips (269 kN), resulting in an initial beam concrete nominal axial stress of $f_{bci} = 0.59$ ksi (4.1 MPa). Note that the initial beam post-tensioning tendon force in Test 3A is slightly lower than the final beam post-
tensioning tendon force in Test 3 [62.6 kips (278 kN)] indicating that there may have been some relaxation in the post-tensioning strands after Test 3.

As the structure is displaced and gap opening occurs at the beam ends, the post-tensioning strands elongate and the post-tensioning forces increase. Since the strands are unbonded over the entire length of the subassembly, the nonlinear straining of the post-tensioning steel is significantly delayed. Note that the continuously occurring post-tensioning losses observed up through 5.0% beam chord rotation in Test 3 are not seen in Test 3A due to the fact that the same post-tensioning strands were used in both tests and no additional concrete damage occurred in Test 3A. Therefore, most or all of the anchor seating, nonlinear straining of the strands, and beam/wall concrete damage had already occurred in Test 3. The steps taken in Test 3 to help prevent premature wire fracture of the post-tensioning strands (i.e., the use of reduced initial post-tensioning stresses and the use of extra anchor barrels to reduce strand “kinking” inside the anchor wedges) were successful to achieve satisfactory performance of the strand/anchor system during Test 3A.
Figure 7.8: Test 3A beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3.
Figure 7.9: Test 3A $F_{LC}-\theta_b$ behavior –
(a) strand 1; (b) strand 2; strand 3.
Figure 7.10: Test 3A beam post-tensioning force versus chord rotation behavior –
(a) using beam displacements; (b) using load block displacements.
7.1.5 Angle-to-Wall Connection Post-Tensioning Forces

The beam south end (i.e., reaction block end) angle-to-wall connection post-tensioning strand forces, $F_{LC3} - F_{LC6}$, measured using load cells LC3 – LC6, respectively, are shown in Figures 7.10 through 7.13. The target initial force for each connection strand is 20 kips (89 kN); whereas, the measured initial forces in the four strands are $F_{i,LC3} = 17.3$ kips (119 kN), $F_{i,LC4} = 22.6$ kips (156 kN), $F_{i,LC5} = 27.5$ kips (190 kN), and $F_{i,LC6} = 26.5$ kips (183 kN). A significant variation is observed in the initial connection strand forces since even a slight difference in the amount of anchor wedge seating has a large effect on the initial force (due to the short length of the strands).

Figures 7.14(a) and 7.14(b) show the total forces in the south top and south seat angle connection strands, respectively, plotted against the beam chord rotation, $\theta_b$. The connection forces are normalized with the total design ultimate strength of the strands, $P_{abu} = \sum a_p f_{apa}$, where $f_{apa} = 270$ ksi (1862 MPa). The expected behavior of the strands is that as the structure is displaced and the angles are pulled in tension, the connection forces increase; and upon unloading, the connection forces return more or less back to the initial forces with possibly some losses occurring due to additional seating of the anchor wedges and any permanent deformations in the concrete (note that the nonlinear straining of the post-tensioning steel is prevented since the strands are left unbonded). The increase in the angle-to-wall connection force with increasing rotation is seen in the top angle load cell, LC4; however, the measurements also show a significant loss in the connection force upon unloading, which could have occurred due to deterioration of the patched concrete in the wall test region. None of the other connection strand forces show the expected behavior. This could have been due to the malfunctioning of the load cells.
under the non-uniform loads applied on the load cells during the prying deformations of the angles.

Figure 7.11: Test 3A south end top angle-to-wall connection strand forces – (a) east strand; (b) west strand.
Figure 7.12: Test 3A south end top angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC3} - \theta_b$; (b) $F_{LC4} - \theta_b$.

Figure 7.13: Test 3A south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand.
Figure 7.14: Test 3A south end seat angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LCS} - \theta_b$; (b) $F_{LCO} - \theta_b$.

Figure 7.15: Test 3A south end total angle-to-wall connection strand forces versus beam chord rotation – (a) top connection; (b) seat connection.
7.1.6 Vertical Forces on Wall Test Region

Load cells LC7 – LC14 are used to measure the forces in the eight vertical bars applying axial compression forces to the wall test region of the reaction block and anchoring the block to the strong floor. The total vertical force, $F_{wt}$ is determined as described in Chapter 5, with the target initial total force ranging between 150 – 160 kips (667 – 712 kN). Figure 7.15(a) shows $F_{wt}$ for the duration of the test and Figure 7.15(b) plots $F_{wt}$ against the beam chord rotation, $\theta_b$. The initial total force, $F_{wt,i}$ is 125 kips (558 kN), somewhat below the target force range. Note that the initial force in Test 3A is slightly smaller than the force at the end of Test 3 indicating that there may have been some relaxation in the bars after Test 3. The initial force was not adjusted before Test 3A. As the beam is displaced in the positive (i.e., clockwise) direction with the load block moving down, $F_{wt}$ decreases since the beam applies a downward force on the reaction block. Similarly, as the beam is displaced in the negative (i.e., counterclockwise) direction, $F_{wt}$ increases since the beam applies an upward force on the reaction block. Note that, as described in Chapter 5, the amount of variation in $F_{wt}$ during the cyclic displacements of the beam is relatively small as compared with the expected variation of axial forces in the wall pier coupling regions of a multi-story coupled wall system. Upon unloading, $F_{wt}$ returns more or less to its initial value.
7.1.7 Beam Vertical Displacements

The vertical displacements $\Delta DT_9$ and $\Delta DT_{10}$ at the south and north ends of the beam are measured using string pots DT9 and DT10, respectively. These displacements are used to calculate the beam chord rotation, $\theta_b$. As described in Chapter 5, as the subassembly is displaced, the transducer string undergoes a change of angle, which can be “adjusted” to give the vertical displacements in the $y$-direction. Figures 7.16 and 7.17 show the measured displacements, $\Delta DT_9$ and $\Delta DT_{10}$, respectively, the corresponding adjusted $y$-displacements $\Delta DT_{9,y}$ and $\Delta DT_{10,y}$, respectively, and the difference between the measured and adjusted displacements for the duration of the test. Note that similar to Test 3, the displacement measurement $\Delta DT_9$ displays an downward shift from the origin in Figure 7.16(a). This shift, which is very small [0.03 in. (0.8 mm)] and negligible, occurs early during the test and then remains relatively constant. Thus, it is not expected that the measured shift in $\Delta DT_9$ is an indication of slip between the beam and the reaction block.
It can be seen from Figures 7.15 and 7.16 that $\Delta_{DT9}$ and $\Delta_{DT10}$ are close to $\Delta_{DT9,y}$ and $\Delta_{DT10,y}$, respectively, with the difference being less than 0.0025 in. (0.06 mm). Figure 7.18 plots the percent difference between the measured and adjusted displacements versus the beam chord rotation, $\theta_b$. The results indicate that the largest percent differences occur when the beam chord rotation is close to zero; however, these differences are not significant since the corresponding measurements are very small and are mostly outside of the sensitivity of the transducers. As the structure is displaced, the measurements from DT9 require larger adjustments than those from DT10, since corresponding to a given $\theta_b$, $\Delta_{DT9}$ is smaller than $\Delta_{DT10}$. It is also observed that for negative rotations, DT9 displays larger percent errors than under positive rotations because the measured displacements under negative rotations are smaller (possibly due to the drift in the data) than the measured displacements under positive rotations. Therefore, similar differences between the measured and adjusted displacements under the negative and positive directions result in larger percent errors in the negative direction. Since the adjustments described in Chapter 5 require certain assumptions and approximations and since the amplitude differences (which are more important than percent differences for the calculation of the beam chord rotation) between the measured and adjusted displacements remain small, these differences are ignored and the measurements from DT9 and DT10 are used as the vertical $y$-displacements of the beam throughout this dissertation. Figure 7.19 plots the measured data from DT9 and DT10 against the beam chord rotation, $\theta_b$. 
Figure 7.17: Test 3A south end beam vertical displacements – (a) measured, $\Delta DT9$; (b) adjusted, $\Delta DT9,y$; (c) difference, $\Delta DT9,y - \Delta DT9$. 
Figure 7.18: Test 3A north end beam vertical displacements – (a) measured, $\Delta DT_{10}$; (b) adjusted, $\Delta DT_{10,y}$; (c) difference, $\Delta DT_{10,y} - \Delta DT_{10}$. 

North Beam Vertical Displacement

North Adjusted Beam Vertical Displacement

Difference
Figure 7.19: Test 3A percent difference between measured and adjusted displacements versus beam chord rotation – (a) south end, DT9; (b) north end, DT10.

Figure 7.20: Test 3A beam vertical displacements versus beam chord rotation – (a) $\Delta DT9 - \theta_b$; (b) $\Delta DT10 - \theta_b$. 
7.1.8 Beam Chord Rotation

The beam chord rotation is defined as the relative vertical displacement of the beam ends divided by the beam length. The beam chord rotation $\theta_b$ determined based on the $\Delta_{DT9}$ and $\Delta_{DT10}$ measurements in Test 3A is shown in Figure 7.20(a). For comparison, Figure 7.20(b) shows the load block beam chord rotation, $\theta_{b,lb}$ calculated using $\Delta_{LB,y}$, and Figure 7.21 shows the percent difference between $\theta_b$ and $\theta_{b,lb}$ plotted against $\theta_b$. It can be seen that there is a large percent difference for small beam chord rotations; with the difference dropping down to less than 10% at larger beam rotations. Figure 7.22 plots the beam chord rotation, $\theta_b$ and the load block beam chord rotation, $\theta_{b,lb}$ against the beam chord rotation, $\theta_b$. The results show that the two rotations are nearly identical for both positive and negative rotations.

![Beam Chord Rotation from Beam Displacements](a)

![Beam Chord Rotation from Load Block Displacements](b)

Figure 7.21: Test 3A beam chord rotation –
(a) $\theta_b$ from $\Delta_{DT9}$ and $\Delta_{DT10}$; (b) $\theta_{b,lb}$ from $\Delta_{LB,y}$. 

545
Figure 7.22: Test 3A percent difference between $\theta_b$ and $\theta_{b,lb}$.

Figure 7.23: Test 3A difference between $\theta_b$ and $\theta_{b,lb}$. 
7.1.9 Local Beam Rotations

Local beam rotations were measured using two rotation transducers (inclinometers); one near the south end of the beam (RT1) and the other near the midspan (RT2). Figure 7.24 shows the rotation time history results, $\theta_{RT1}$ and $\theta_{RT2}$ from these transducers, and Figures 7.25(a) and 7.25(b) compare $\theta_{RT1}$ and $\theta_{RT2}$, respectively, with the beam chord rotation, $\theta_b$. The rotation measurements are positive when the load block is displaced in the downward direction (i.e., clockwise beam rotation). Note that, as a result of the bending deformations over the length of the beam, it may be expected that the midspan rotation, $\theta_{RT2}$ is larger than the chord rotation, $\theta_b$, and that the chord rotation is larger than the end rotation, $\theta_{RT1}$ [see Figure 7.25(c)]. However, since the nonlinear lateral displacements of the beam are primarily governed by the gap opening at the ends, the differences in the measured end, midspan, and chord rotations for the test beams are in general too small to make conclusive comparisons, and the different instruments utilized for the chord rotation measurements (using displacement transducers) and for the beam end and midspan rotation measurements (using rotation transducers) further make these comparisons difficult.
Figure 7.24: Test 3A beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$.
Figure 7.25: Test 3A difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape.

7.1.10 Load Block Displacements and Rotations

String pots DT3 – DT5 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the load block. Similar to the vertical beam displacements, as the load block is displaced, the strings of the load block displacement transducers undergo a change in angle; and thus, their measurements may need to be adjusted to give the $x$- and $y$-displacements of the load block as described in Chapter 5.

Figures 7.25 through 7.27 show the measured displacements $\Delta_{DT3}$, $\Delta_{DT4}$, and $\Delta_{DT5}$, respectively, the corresponding adjusted displacements $\Delta_{DT3,x}$, $\Delta_{DT4,y}$, and $\Delta_{DT5,y}$, respectively, and the percent differences between the measured and adjusted
displacements. Note that, as described in Chapter 5, the negative $\Delta_{DT3}$ and $\Delta_{DT3,x}$ measurements indicate the movement of the load block in the north direction, away from the reaction block. It can be seen that the difference between $\Delta_{DT3}$ and $\Delta_{DT3,x}$ is well over 10% for much of the duration of the test; and thus, adjustments need to be applied to the measurements from DT3. In comparison, the adjustments needed for the vertical displacement measurements from DT4 and DT5 remain small throughout the test with the largest differences being less than 0.4% and 5.0%, respectively. Figure 7.28 shows the percent difference between the measured and adjusted displacements for DT4 and DT5 plotted against the beam chord rotation, $\theta_b$. It can be seen that away from the origin, the maximum differences between the unadjusted and adjusted measurements from DT4 and DT5 remain less than 0.25%.

The measurements from DT3 require larger adjustments than those from DT4 and DT5 since the changes in the string angle for DT3, which occur due to the applied vertical displacements of the structure, are much larger than the changes in the string angles for DT4 and DT5, which occur due to the gap opening displacements at the beam ends. In evaluating the results from Test 3A, adjusted measurements are used for $\Delta_{DT3}$; however, the measurements for $\Delta_{DT4}$ and $\Delta_{DT5}$ are not adjusted. Figure 7.29 plots $\Delta_{DT4}$, $\Delta_{DT5}$, and $\Delta_{DT3,x}$ against the beam chord rotation, $\theta_b$, respectively. It can be seen in Figures 7.29(a) and 7.29(b) that the vertical displacements of the load block at the north and south ends are nearly the same.

Combining these displacements, the $x$-displacement, $y$-displacement, and rotation of the load block centroid can be determined as described in Chapter 5 and shown in Figures 7.30 and 7.31. Figure 7.30(a) plots the $y$-displacement versus the $x$-displacement
showing the path of the load block centroid during the test. As the subassembly is displaced under positive (i.e., clockwise) and negative (i.e., counterclockwise) rotations, the load block is pushed north in the $x$-direction (away from the reaction block) due to the gap opening at the beam ends. After each cycle, the load block returns to its initial position with minimal residual displacements. Figures 7.30(a) and 7.31(a) show that the $x$-direction displacements of the load block centroid are slightly smaller during the negative rotations of the subassembly as compared to the displacements during the positive rotations, which is possibly due to any unsymmetric loading and/or behavior of the structure. In the $y$-direction, the load block displaces symmetrically during the positive and negative rotations as shown in Figures 7.29(a), 7.29(b), 7.30(d), and 7.31(b). Finally, the rotation of the load block is shown to remain small throughout the duration of the test as plotted in Figures 7.30(b) and 7.31(c). The load block rotation remains below 0.003 radians indicating that the two hydraulic actuators moved near simultaneously.
Figure 7.26: Test 3A load block horizontal displacements – (a) measured, $\Delta DT_3$; (b) adjusted, $\Delta DT_{3,x}$; (c) percent difference.
Figure 7.27: Test 3A load block north end vertical displacements –
(a) measured, $\Delta_{DT4}$; (b) adjusted, $\Delta_{DT4,y}$; (c) percent difference.
Figure 7.28: Test 3A load block south end vertical displacements – (a) measured, $\Delta DT5$; (b) adjusted, $\Delta DT5,y$; (c) percent difference.

Figure 7.29: Test 3A percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5.
Figure 7.30: Test 3A load block displacements versus beam chord rotation –
(a) $\Delta_D T_4$-$\theta_b$; (b) $\Delta_D T_5$-$\theta_b$; (c) $\Delta_D T_{3, x}$-$\theta_b$. 
Figure 7.31: Test 3A load block centroid displacements – (a) x-y displacements; (b) rotation; (c) x-displacements; (d) y-displacements.
Figure 7.32: Test 3A load block centroid displacements versus beam chord rotation – (a) $x$-displacement-\(\theta_b\); (b) $y$-displacement-\(\theta_b\); (c) rotation-\(\theta_b\).

7.1.11 Reaction Block Displacements and Rotations

String pots DT6 – DT8 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the reaction block. Figure 7.32 shows the measurements from DT6 – DT8 for the duration of the test. Since the reaction block is tied to the strong floor, the measured displacements remain very small throughout the test. Due to these small displacements and the use of lead cables for each string pot, the change in angle that the string undergoes during testing is very small. Thus, it can be assumed that no
adjustments are needed for the displacements measured from the reaction block displacement transducers. Figure 7.33 plots the measurements from DT6 – DT8 against the beam chord rotation.

The $x$-displacement, $y$-displacement, and rotation of the reaction block centroid can be determined (see Chapter 5) as shown in Figure 7.34 and plotted against the beam chord rotation in Figure 7.35. It is concluded that the vertical displacements of the reaction block do not have a significant effect on the displacements of the test structure (e.g., the beam chord rotation), and the test results are evaluated with the reaction block displacements taken as zero (i.e., the measured displacements of the reaction block are ignored in investigating the response of the subassembly). Note that the horizontal displacements of the reaction block are significant when determining the total elongation of the post-tensioning tendon; and thus, are included in those calculations.
Figure 7.33: Test 3A reaction block displacements – (a) $\Delta DT_6$; (b) $\Delta DT_7$; (c) $\Delta DT_8$. 
Figure 7.34: Test 3A reaction block displacements versus beam chord rotation –
(a) \( \Delta DT7 - \theta_b \); (b) \( \Delta DT8 - \theta_b \); (c) \( \Delta DT6 - \theta_b \).
Figure 7.35: Test 3A reaction block centroid displacements –
(a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
Figure 7.36: Test 3A reaction block centroid displacements versus beam chord rotation – (a) $x$-displacements; (b) $y$-displacements; (c) rotation.

7.1.12 Contact Depth and Gap Opening at Beam-to-Wall Interfaces

The beam contact depth and gap opening displacements are measured at the beam-to-reaction-block interface using displacement transducers DT11 – DT13. Note that these transducers were initialized and zeroed prior to the application of the beam post-tensioning force at the beginning of the virgin Test 3. Since the beam post-tensioning tendon in Test 3A was the same as that in Test 3, the contact depth and gap opening transducers were not re-zeroed at the beginning of Test 3A. As described in Chapter 5,
these LVDTs rotate with the beam; and thus, their measurements may need to be adjusted to determine the gap opening displacements in the horizontal $x$-direction.

Figures 7.36 through 7.38 plot the measured displacements $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$, respectively, the corresponding adjusted $x$-displacements $\Delta_{DT11,x}$, $\Delta_{DT12,x}$, and $\Delta_{DT13,x}$, respectively, and the percent differences between the measured and adjusted displacements. The results indicate that the adjusted measurements are less than 0.15\% different from the original measurements; and thus, $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$ can be taken as the displacements in the $x$-direction. Figure 7.39 plots the measured data from DT11, DT12, and DT13 against the beam chord rotation.

The maximum average concrete compressive strain in the beam-to-wall contact regions can be calculated by dividing the measured displacements from DT11 and DT13 with the gauge length (i.e., the distance from the LVDT ferrule insert in the beam to the reaction plate ferrule insert in the wall test region; see Chapter 5). For Test 3A, the maximum average compressive strain is 0.0098. Note that this measurement includes the compressive strain occurring in the fiber-reinforced grout at the beam-to-wall interface as well as the patched concrete deformations in wall test region of the reaction block.
Figure 7.37: Test 3A beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta DT11$; (b) adjusted, $\Delta DT11,x$; (c) percent difference.
Figure 7.38: Test 3A beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta DT12$; (b) adjusted, $\Delta DT12,x$; (c) percent difference.
Figure 7.39: Test 3A beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta DT13$; (b) adjusted, $\Delta DT13,x$; (c) percent difference.
Using the measured data, the contact depth and the largest (i.e., at the beam top and bottom) gap opening displacements at the beam-to-reaction-block interface can be determined following the procedures in Chapter 5. Figures 7.40(a) and 7.41(a) show the results based on the measured data from DT11 – DT13 (method 1); Figures 7.40(b) and 7.41(b) show the results based on the measured data from RT1, DT11, and DT13 (method 2); Figures 7.40(c) and 7.41(c) show the results based on the measured data from RT1 and DT12 (method 3); Figures 7.40(d) and 7.41(d) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT12 (method 4); and Figures
7.40(e) and 7.41(e) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT11 and DT13 (method 5). Each ○ marker indicates the contact depth or gap opening displacement at the peak of a loading cycle up to a beam chord rotation of 5.0%. Note that, as described in Chapter 5, the contact depth and gap opening results from methods 1, 3, and 4 are valid only when $\Delta_{DT12}$ is positive (i.e., the gap extends beyond the level of DT12 and the contact depth is less than $h_b/2$). Figures 7.40 and 7.42 show the results within the validity range of these methods.

Looking at Figure 7.40, it can be stated that the contact depth results obtained using the five methods are somewhat different (possibly because of small differences in the measurements used in the different methods, especially since the contact depth calculations are sensitive to these measurement differences) but show similar trends. There is a rapid reduction in the contact depth up to a beam chord rotation of about 2.0%. After this rotation, the contact depth remains relatively stable due to nonlinear behavior of the concrete in compression. In comparison, the gap opening results obtained using the five methods in Figure 7.41 are reasonably similar and the increase in gap opening with the rotation of the beam is very close to linear.

Figure 7.42 shows a continuous plot of the largest gap opening displacements determined from method 4 (using the beam chord rotation and DT12) against the beam chord rotation. Similarly, Figure 7.43(a) plots the beam contact depth from method 4 against the beam chord rotation as continuous data. Furthermore, Figures 7.43(b) and 7.43(c) show continuous plots of the contact depth during the 2.25% and 5.0% beam chord rotation cycles, respectively. Note that method 3 (using the measured data from RT1 and DT12) can also be used to obtain the continuous plots above; however, the
measurements from RT1 were found to be not always reliable (especially at small rotations); and thus, method 4 is used instead. The gap opening and contact depth plots in Figures 7.43 and 7.44 could have been affected by the use of $\theta_b$ (i.e., chord rotation) instead of $\theta_{RT1}$ (i.e., local rotation) to determine the behavior of the south end of the beam. The use of the beam midheight transducer DT12 instead of the extreme beam top or bottom transducer (DT11 or DT13) may also have affected the results, especially the contact depth plots in Figure 7.44 during small beam rotations, which are very sensitive to the measurements. Thus the estimated contact depths at small beam rotations ($\theta_b < 0.25\%$) should be used with caution. It can be seen that the contact depth behavior in Test 3A is similar to the behavior in Test 3.

Unlike Test 3 in Chapter 6, no ruler measurements of the gap opening displacements were taken during Test 3A (Table 7.1).
Figure 7.41: Test 3A contact depth at beam-to-reaction-block interface –
(a) method 1 using $\Delta DT_{11}$, $\Delta DT_{12}$, and $\Delta DT_{13}$; (b) method 2 using RT1, DT11, and DT13; (c)
method 3 using RT1 and DT12; (d) method 4 using $\Delta DT_{12}$ and $\theta_b$; (e) method 5 using $\theta_b$,
DT11, and DT13.
Figure 7.42: Test 3A gap opening at beam-to-reaction-block interface – (a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT1, DT11, and DT13; (c) method 3 using RT1 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.43: Test 3A gap opening at beam-to-reaction-block interface using method 4.

Figure 7.44: Test 3A contact depth at beam-to-reaction-block interface – (a) method 4 using $\Delta_{DT12}$ and $\theta_b$; (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord rotation cycle.
TABLE 7.1
RULER MEASUREMENTS OF GAP OPENING AT SOUTH BEAM END

<table>
<thead>
<tr>
<th>Nominal Rotation (%)</th>
<th>Gap Opening, $\Delta g$ [in. (mm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no measurements taken</td>
<td></td>
</tr>
</tbody>
</table>

7.1.13 Wall Test Region Local Concrete Deformations

The reaction block confined concrete deformations near the beam-to-wall interface of the wall test region are measured using displacement transducers DT14 and DT15. Figure 7.44 plots the time history results from the top (DT14) and bottom (DT15) transducers and Figure 7.45 plots the measured data from DT14 and DT15 against the beam chord rotation. As expected, the concrete deformations are mostly compressive (negative), due to the compression stresses that are transferred through the contact region from post-tensioning.

From Figure 7.45, the maximum average concrete compressive strain in the wall test region can be calculated by dividing the measured deformations with the gauge length (i.e., the distance from the LVDT ferrule insert in the wall test region to the reaction plate; see Chapter 5). For Test 3A, the maximum average concrete compressive strain is 0.002, which is less than the expected unconfined (cover) concrete crushing strain of 0.004. This finding is in accordance with the visual observation that no concrete
spalling occurred in the wall test region during the test. Note that most of the compressive strains in the wall test region occurred in the patched concrete.

![Diagram of Reaction Block LVDT Displacement](a)

![Diagram of Reaction Block LVDT Displacement](b)

Figure 7.45: Test 3A wall test region concrete deformations – (a) DT14; (b) DT15.

![Diagram of Beam Chord Rotation](a)

![Diagram of Beam Chord Rotation](b)

Figure 7.46: Test 3A wall test region concrete deformations versus beam chord rotation – (a) $\Delta DT14 - \theta_b$; (b) $\Delta DT15 - \theta_b$. 
7.1.14 Beam Looping Reinforcement Longitudinal Leg Strains

Figures 7.46 and 7.47 show the strain gauge measurements for the top and bottom horizontal legs of the east and west No. 6 mild steel looping reinforcing bars in the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3 (since the beam post-tensioning tendon in Test 3A was the same as that in Test 3). Note that these initial strain values do not include any reduction in strain due to relaxation losses (between the end of Test 3 and the beginning of Test 3A) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.1.4) and their effects on the strain measurements are expected to be negligible. Upon lateral loading of the subassembly, the largest tensile strains occur, as expected, in the gauges closest to the angle-to-beam connection bolts [i.e., gauges 6(1)T-E, 6(1)T-W, 6(1)B-E, and 6(1)B-W]. The measurements in the gauges away from the angle-to-beam connection decrease with distance from this critical location.

To provide a better understanding of the strain measurements in the horizontal legs of the beam looping reinforcement, the Δ and □ markers in Figures 7.46(a) and 7.46(b) for gauges 6(1)T-E and 6(1)T-W correspond to positive and negative chord rotation peaks for the beam, respectively, and the ○ markers indicate zero rotation positions. To provide further insight into the results, Figures 7.48 and 7.49 show the strains plotted against the beam chord rotation. In the positive (i.e., clockwise) rotation direction, the strains in the top bars increase in tension as the gap opens at the top south corner of the beam and the top angle is pulled in tension. In the negative (i.e.,
counterclockwise) direction, the strains in the bottom bars increase in tension and the top bars go into compression due to the closing of the gap.

The maximum strains in the four gauges closest the critical section (i.e., angle-to-beam connection) remain well below the yield strain of the longitudinal steel ($\varepsilon_{ly} = 0.00283$) from the material tests in Chapter 4; and thus, it is concluded that the amount of mild steel reinforcement used to transfer the angle forces into the beam is adequate.

Figure 7.47: Test 3A beam looping reinforcement top longitudinal leg strains –
(a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$; (h) $\varepsilon_{6MT-W}$. 
Figure 7.47 continued.

(continued)

Figure 7.48: Test 3A beam looping reinforcement bottom longitudinal leg strains –
(a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$; (f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MBE-E}$; (h) $\varepsilon_{6MB-W}$. 
no data collected from strain gauge 6(2)B-E

no data collected from strain gauge 6(2)T-W

c (d)

\[ \text{strain, } \varepsilon_{6(3)B-E} \]

\[ \text{test duration} \]

\[ -0.001 \]

\[ 0 \]

\[ 0.0008 \]

\( e (f) \)

\[ \text{strain, } \varepsilon_{6(3)B-W} \]

\[ \text{test duration} \]

\[ -0.001 \]

\[ 0 \]

\[ 0.0008 \]

\( g (h) \)

no data collected from strain gauge 6MB-E

no data collected from strain gauge 6MB-W

Figure 7.48 continued.
Figure 7.49: Test 3A beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)T-E} - \theta_b$; (b) $\varepsilon_{6(1)T-W} - \theta_b$; (c) $\varepsilon_{6(2)T-E} - \theta_b$; (d) $\varepsilon_{6(2)T-W} - \theta_b$; (e) $\varepsilon_{6(3)T-E} - \theta_b$; (f) $\varepsilon_{6(3)T-W} - \theta_b$; (g) $\varepsilon_{6MT-E} - \theta_b$; (h) $\varepsilon_{6MT-W} - \theta_b$. 
Figure 7.49 continued.

Figure 7.50: Test 3A beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)B-E} - \theta_b$; (b) $\varepsilon_{6(1)B-W} - \theta_b$; (c) $\varepsilon_{6(2)B-E} - \theta_b$; (d) $\varepsilon_{6(2)B-W} - \theta_b$; (e) $\varepsilon_{6(3)B-E} - \theta_b$; (f) $\varepsilon_{6(3)B-W} - \theta_b$; (g) $\varepsilon_{6MB-E} - \theta_b$; (h) $\varepsilon_{6MB-W} - \theta_b$. 

580
7.1.15 Beam Transverse Reinforcement Strains

Figure 7.50 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3. Note that the replacement of the top and seat angles in Test 3A may have affected the

---

Figure 7.50 continued.

---

7.1.15 Beam Transverse Reinforcement Strains

Figure 7.50 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3. Note that the replacement of the top and seat angles in Test 3A may have affected the

---

7.1.15 Beam Transverse Reinforcement Strains

Figure 7.50 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3. Note that the replacement of the top and seat angles in Test 3A may have affected the
initial strains in the transverse legs of the looping reinforcing bars; however, this effect is expected to be small. To give more insight into the measurements, Figure 7.51 plots the strain data against the beam chord rotation. It can be seen that the strain gauge readings remain well below the yield strain of the reinforcing steel ($\varepsilon_{y} = 0.00283$, see Chapter 4) throughout the test, demonstrating that the design of the transverse reinforcement at the beam end is adequate. Note that the angle-to-beam connection bolts may also have acted as transverse reinforcement in the beam; however, this could not be confirmed from the test results since the connection bolts were not instrumented.

No strain measurements were collected from gauges MH-E and MH-W placed on the vertical legs of the No. 3 transverse hoop at the beam midspan (Figures 7.52 and 7.53). However, the strain gauge results from Tests 1 and 2 and visual observations from Tests 3 and 3A indicate that the use of nominal transverse reinforcement within the span of the beam is adequate.
strain gauge 6SE(E)-E removed from Beam #3

strain gauge 6SE(E)-W removed from Beam #3

(a) (b)

Figure 7.51: Test 3A beam looping reinforcement vertical leg strains –
(a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$.
strain gauge 6SE(E)-E removed from Beam #3

strain gauge 6SE(E)-W removed from Beam #3

(a) (b)

Figure 7.52: Test 3A beam looping reinforcement vertical leg strains versus beam chord rotation – (a) $\varepsilon_{6SE(E)-E} - \theta_b$; (b) $\varepsilon_{6SE(E)-W} - \theta_b$; (c) $\varepsilon_{6SE(I)-E} - \theta_b$; (d) $\varepsilon_{6SE(I)-W} - \theta_b$.

(c) (d)

no data collected from strain gauge MH-E

no data collected from strain gauge MH-W

(a) (b)

Figure 7.53: Test 3A beam midspan transverse hoop reinforcement strains – (a) $\varepsilon_{MH-E}$; (b) $\varepsilon_{MH-W}$. 584
7.1.16 Beam Confined Concrete Strains

Figures 7.54 and 7.55 show the measurements from the strain gauges placed on the No. 3 support bars inside the hoop confined concrete at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3 (since the beam post-tensioning tendon in Test 3A was the same as that in Test 3. Note that the initial strains are close to zero. Note also that these initial strain values do not include any reduction in strain due to relaxation losses in the beam post-tensioning tendon force; however, these losses are small (see Section 7.1.4) and their effects on the strain measurements are expected to be negligible. For further insight into the strain gauge readings, Figures 7.56 and 7.57 plot the strain data against the beam chord rotation. As the beam is rotated in the positive (i.e., clockwise) direction, the compression strains in the bottom bars increase due to the transfer of the contact stresses to the bottom corner of the beam. In the opposite (i.e., counterclockwise)
direction, the strains in the top and bottom bars reverse due to the reversal of the load. It can be seen that the strain gauge measurements from the support bars remain below the yield strain $\varepsilon_{\text{hy}} = 0.00240$ of the No. 3 support bars in tension and below the expected crushing strain $\varepsilon_{\text{cu}} = 0.004$ of the unconfined concrete in compression.

Figure 7.55: Test 3A No. 3 top hoop support bar strains – (a) $\varepsilon_{3\text{THT-(1)}}$; (b) $\varepsilon_{3\text{THB-(1)}}$; (c) $\varepsilon_{3\text{THT-(2)}}$; (d) $\varepsilon_{3\text{THB-(2)}}$. 
Figure 7.56: Test 3A No. 3 bottom hoop support bar strains – (a) $\varepsilon_{3BHB-(1)}$; (b) $\varepsilon_{3BHT-(1)}$; (c) $\varepsilon_{3BHB-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. 

strain gauge 3BHT-(1) removed from Beam #3

strain gauge 3BHT-(2) removed from Beam #3
strain gauge 3THT-(1) removed from Beam #3

strain gauge 3THB-(1) removed from Beam #3

strain gauge 3THT-(2) removed from Beam #3

strain gauge 3THB-(2) removed from Beam #3

(a)  (b)

(c)  (d)

Figure 7.57: Test 3A No. 3 top hoop support bar strains versus beam chord rotation –
(a) $\varepsilon_{3THT-(1)} - \theta_b$; (b) $\varepsilon_{3THB-(1)} - \theta_b$; (c) $\varepsilon_{3THT-(2)} - \theta_b$; (d) $\varepsilon_{3THB-(2)} - \theta_b$. 
Beam End Confinement Hoop Strains

Figures 7.58 and 7.59 show the measurements from the strain gauges placed on the vertical legs of the bottom layer No. 3 confinement hoops at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3A and the “initial” strains were assumed to be equal to the final strains from Test 3. Note that the replacement of the top and seat
angles in Test 3B may have affected the initial strains in the beam end confinement hoops; however, this effect is expected to be small. For further insight into the measurements, Figures 7.60 and 7.61 plot the strain data against the beam chord rotation. Throughout the test, the measured confinement hoop strains remain small and mostly tensile as also observed in Test 3.

Figure 7.59: Test 3A beam end confinement hoop east leg strains –
(a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$. 
Figure 7.60: Test 3A beam end confinement hoop west leg strains –
(a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$.
Figure 7.61: Test 3A beam end confinement hoop east leg strains versus beam chord rotation – (a) $\varepsilon_{1HB-E}-\theta_b$; (b) $\varepsilon_{2HB-E}-\theta_b$; (c) $\varepsilon_{3HB-E}-\theta_b$; (d) $\varepsilon_{4HB-E}-\theta_b$. 

no data collected from strain gauge 3HB-E
Figure 7.62: Test 3A beam end confinement hoop west leg strains versus beam chord rotation – (a) $\varepsilon_{1HB,W} - \theta_b$; (b) $\varepsilon_{2HB,W} - \theta_b$; (c) $\varepsilon_{3HB,W} - \theta_b$; (d) $\varepsilon_{4HB,W} - \theta_b$.

7.1.18 Wall Test Region Confined Concrete Strains

As described previously, the strain gauge wires coming out of the reaction block used in Tests 2 through 4B were all severed during the removal of the steel casting mold. Thus, no measurements were recorded for the wall test wall region confined concrete strains in Test 3A.
7.1.19 Wall Test Region Confinement Hoop Strains

Similar to above, no measurements were recorded for the wall test region confinement hoop strains in Test 3A since the strain gauge wires were severed.

7.1.20 Crack Patterns

Cracks were not marked for Test 3A due to the damage that occurred previously in Test 3.
7.2 Test 3B

The beam used in Test 3B (i.e., Beam 3) has the following properties: (1) beam depth, \(h_b = 14\) in. (356 mm); (2) beam width, \(b_b = 7.5\) in. (191 mm); (3) mild steel reinforcement of two No. 6 bars looping around the beam vertical perimeter along its length; (4) No. 3 full-depth rectangular hoops [6.125 in. by 12.675 in. (156 mm by 322 mm)] placed at a nominal 7.0 in. (178 mm) spacing to provide transverse reinforcement in the beam midspan region; (5) No. 3 partial-depth rectangular hoops [6.125 in. by 4.375 in. (156 mm by 111 mm)] placed at a 1.5 in. (38 mm) spacing to provide concrete confinement at the beam ends; (6) a beam post-tensioning tendon comprised of three 0.6 in. (15 mm) nominal diameter high-strength strands with a total area of \(A_{bp} = 0.651\) in.\(^2\) (420 mm\(^2\)); (7) average initial beam post-tensioning strand stress of \(f_{bpi} = 0.34f_{bpu}\), where \(f_{bpu} = 270\) ksi (1862 MPa) is the design maximum strength of the post-tensioning steel; (8) total initial beam post-tensioning force of \(P_{bi} = 59.5\) kips (265 kN); (9) initial beam concrete nominal axial stress (based on actual cross-sectional area with beam post-tensioning duct removed) of \(f_{bc_i} = 0.58\) ksi (4.0 MPa); and (10) two top and two seat angles (L8x8x1/2) comprised of 2 – 2.5 in. (64 mm) long angle strips resulting in a total angle length of \(l_a = 5.0\) in. (127 mm).

The primary parameter difference of Test 3B from Test 3 is the use of angle-to-wall connection plates behind the angle vertical legs as described later. In addition, there was a small reduction in the initial beam post-tensioning strand stress, \(f_{bpi}\), and the resulting initial beam concrete nominal axial stress, \(f_{bc_i}\) due to the post-tensioning losses.
that occurred in Test 3. The same displacement loading history from Test 3 was also used for Test 3B.

7.2.1 Test Photographs

Photographs of the original and displaced subassembly configurations from Test 3B are shown in Figures 7.63 and 7.64. Figures 7.63(a) through 7.63(f) show overall subassembly photographs as follows: (a) pre-test undisplaced position; (b) displaced to $\theta_b = 3.33\%$; (c) displaced to $\theta_b = -3.33\%$; (d) displaced to $\theta_b = 8.0\%$; (e) displaced to $\theta_b = -8.0\%$; and (f) final post-test undisplaced position. Similarly, Figures 7.64(a) through 7.64(f) show close-up photographs of the south end of the beam at the beam-to-reaction-block interface. The accumulation of damage at the south end of the beam is shown in more detail in Figure 7.65.

Up through a beam chord rotation of $\theta_b = 3.33\%$, there was only a small amount of additional cover concrete spalling at the beam ends. As the beam chord rotation increased beyond 3.33\%, the beam ends suffered additional damage, which influenced the behavior of the beam as described later. The ultimate failure of the specimen occurred due to the fracture of the top and seat angles. The first full angle fracture occurred during the third cycle to 6.4% rotation on the horizontal leg of the northwest seat angle strip. This was followed by the fracture of the horizontal leg of the northeast seat angle strip (see Figure 7.66) during the third cycle to 8.0% rotation, and then the fracture of the vertical leg of the southwest seat angle strip during the third cycle to -8.0% rotation.

The angle-to-wall connections performed well with no yielding in the connection strands and no damage to the wall concrete. Unlike Test 3, the wall test region of the
reaction block did not receive any additional damage (no cracking and/or spalling of the cover concrete) during Test 3B even though the same type of angle strips was used in the two tests. This is because of the angle-to-wall connection plates (see Figure 7.67), which helped distribute the connection forces into the concrete. The use of the angle-to-wall connection plates did not affect the behavior of the angles. A small amount of slip in the angle-to-beam connections was observed during the test, most likely due to the loss of force in the angle-to-beam connection bolts caused by the deterioration of the concrete at the beam ends. Slip between the coupling beam and the walls did not occur demonstrating that the friction resistance due to the post-tensioning force provided adequate vertical support to the beam together with resistance from the top and seat angles. Similar to Tests 2, 3, and 3A, premature wire fracture in the beam post-tensioning strands did not occur in Test 3B.

Gap opening formed on both sides of the fiber-reinforced grout column throughout the test as a result of the bond being broken between the grout and the beam ends in Tests 3 and 3A. While this is not the desired mode of behavior for the structure as described in Chapter 3, it did not change the behavior of the system or cause any problems with the performance of the grout. No significant crushing of the grout at the beam-to-wall interfaces was observed throughout the test. Note that the grout column was left approximately 0.25 in. (6.4 mm) short of the beam depth at the top and bottom, as was done in Tests 2, 3, and 3A.
Figure 7.63: Test 3B overall photographs –
(a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 8.0\%$;
(e) $\theta_b = -8.0\%$; (f) final post-test undisplaced position.
Figure 7.64: Test 3B beam south end photographs –
(a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 8.0\%$;
(e) $\theta_b = -8.0\%$; (f) final post-test undisplaced position.
Figure 7.65: Test 3B beam south end damage propagation – positive and negative rotations.

Figure 7.66: Test 3B angle fracture – (a) side view; (b) isometric view.
7.2.2 Beam Shear Force versus Chord Rotation Behavior

Figure 7.68(a) shows the hysteretic coupling beam shear force, $V_b$ versus chord rotation, $\theta_b$ behavior from Test 3B, where $V_b$ and $\theta_b$ are calculated from Equations 5.5 and 5.35, respectively. For comparison, Figure 7.68(b) plots the $V_b$-$\theta_{b,lb}$ behavior, where $\theta_{b,lb}$ is the beam chord rotation determined from the vertical ($y$-direction) displacement of the load block centroid using Equation 5.36. As shown in Figure 7.68, the structure was able to sustain three cycles at 8.0% rotation with approximately 18% loss in shear resistance. Note that during the first cycle at 5.0% beam chord rotation, there is a “bulge” in the unloading portion of the curve. This was caused by pieces of concrete spalling at the beam ends and falling between the angle-to-wall connection plates and the seat angles. After the first cycle at 5.0% rotation, the pieces were removed.
Looking at the hysteresis loops, it can be seen that the specimen was able to dissipate a considerable amount of energy. Most of this energy dissipation occurred due to the yielding of the top and seat angles. The beam had a sufficient amount of restoring force to yield the tension angles back in compression and close the gaps at the beam-to-wall interfaces upon unloading, resulting in a large self-centering capability. Beginning at a chord rotation of 3.33%, a loss in the lateral resistance of the beam is observed in each subsequent cycle at that rotation, which occurred due to the initiation of angle fracture. The angle fracture was observed in all top and seat angle strips.
Figure 7.68: Test 3B coupling beam shear force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements.
7.2.3 Beam End Moment Force versus Chord Rotation Behavior

Figure 7.69 shows the hysteretic coupling beam end moment, $M_b$, versus chord rotation, $\theta_b$, behavior from Test 3B, where $M_b$ is determined from Equation 5.6 as described in Chapter 5. Since the beam end moment is calculated from the beam shear force, the results shown in Figure 7.69 are directly related to the results in Figure 7.68; and thus, no further discussion is provided herein.

![Figure 7.69: Test 3B $M_b$-$\theta_b$ behavior.](image)
7.2.4 Beam Post-Tensioning Forces

The coupling beam post-tensioning strand forces from the test are measured using load cells LC15 – LC17 mounted at the dead ends of the three strands (see Chapter 5). The forces from the three load cells, $F_{LC15}$, $F_{LC16}$, and $F_{LC17}$ are shown in Figure 7.69, and are plotted against the beam chord rotation, $\theta_b$ in Figure 7.70. Figure 7.71 shows the total beam post-tensioning tendon force, $P_{bp}$ (sum of the forces in the three strands) normalized with the total design ultimate strength of the tendon, $\Sigma a_{bp}f_{bpu}$. The total initial beam post-tensioning tendon force is equal to 59.5 kips (265 kN), resulting in an initial beam concrete nominal axial stress of $f_{bcf} = 0.58$ ksi (4.1 MPa). Note that the initial beam post-tensioning tendon force in Test 3B is slightly lower than the final beam post-tensioning tendon force in Test 3A [60.6 kips (270 kN)] indicating that there may have been some relaxation in the post-tensioning strands after Test 3A.

As the structure is displaced and gap opening occurs at the beam ends, the post-tensioning strands elongate and the post-tensioning forces increase. Since the strands are unbonded over the entire length of the subassembly, the nonlinear straining of the post-tensioning steel is significantly delayed. Due to the accumulation of damage at the beam ends, a loss of post-tensioning force is seen at large rotations of the beam. Note that the post-tensioning strands were not replaced after Test 3 or Test 3A; and thus, most of the post-tensioning losses in Test 3B occurred after 5.0% rotation, which is the largest rotation reached in Tests 3 and 3A. The steps taken in Test 3 to help prevent premature wire fracture in the post-tensioning strands (i.e., the use of reduced initial post-tensioning stresses and the use of extra anchor barrels to reduce strand “kinking” inside the anchor
wedges) were successful to achieve satisfactory performance of the strand/anchor system during Test 3B.

Figure 7.70: Test 3B beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3.
Figure 7.71: Test 3B $F_{LC}$-$\theta_b$ behavior – (a) strand 1; (b) strand 2; (c) strand 3.
Figure 7.72: Test 3B beam post-tensioning force versus chord rotation behavior –
(a) using beam displacements; (b) using load block displacements.
7.2.5 Angle-to-Wall Connection Post-Tensioning Forces

The beam south end (i.e., reaction block end) angle-to-wall connection post-tensioning strand forces, $F_{LC3} - F_{LC6}$, measured using load cells LC3 – LC6, respectively, are shown in Figures 7.73 through 7.76. The target initial force for each connection strand is 20 kips (89 kN); whereas, the measured initial forces in the four strands are $F_{i,LC3} = 22.4$ kips (100 kN), $F_{i,LC4} = 33.2$ kips (148 kN), $F_{i,LC5} = 30.8$ kips (137 kN), and $F_{i,LC6} = 23.1$ kips (103 kN). A significant variation is observed in the initial connection strand forces since even a slight difference in the amount of anchor wedge seating has a large effect on the initial force (due to the short length of the strands).

Figures 7.77(a) and 7.77(b) show the total forces in the south top and south seat angle connection strands, respectively, plotted against the beam chord rotation, $\theta_b$. The connection forces are normalized with the total design ultimate strength of the strands, $P_{abu} = \Sigma a_{up} f_{up}$, where $f_{up} = 270$ ksi (1862 MPa). The expected behavior of the strands is that as the structure is displaced and the angles are pulled in tension, the connection forces increase; and upon unloading, the connection forces return more or less back to the initial forces with possibly some losses occurring due to additional seating of the anchor wedges and any permanent deformations in the concrete (note that the nonlinear straining of the post-tensioning steel is prevented since the strands are left unbonded). These trends are not observed in the connection forces in Test 3B. This could have been due to the malfunctioning of the load cells under the non-uniform loads applied during the prying deformations of the angles.
Figure 7.73: Test 3B south end top angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.74: Test 3B south end top angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC3} - \theta_b$; (b) $F_{LC4} - \theta_b$. 
Figure 7.75: Test 3B south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.76: Test 3B south end seat angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC5}-\theta_b$; (b) $F_{LC6}-\theta_b$. 
Figure 7.77: Test 3B south end total angle-to-wall connection strand forces versus beam chord rotation – (a) top connection; (b) seat connection.

7.2.6 Vertical Forces on Wall Test Region

Load cells LC7 – LC14 are used to measure the forces in the eight vertical bars applying axial compression forces to the wall test region of the reaction block and anchoring the block to the strong floor. The total vertical force, $F_{wt}$ can be determined as described in Chapter 5, with the target initial total force ranging between 150 – 160 kips (667 – 712 kN). Figure 7.78(a) shows $F_{wt}$ for the duration of the test and Figure 7.78(b) plots $F_{wt}$ against the beam chord rotation, $\theta_b$. The initial total force, $F_{wt,i}$ is 124 kips (552 kN), below the target force range. Note that the initial force in Test 3B is slightly smaller than the force at the end of Test 3A indicating that there may have been some relaxation in the bars after Test 3A. The initial force was not adjusted before Test. As the beam is displaced in the positive (i.e., clockwise) direction with the load block moving down, $F_{wt}$ decreases since the beam applies a downward force on the reaction block. Similarly, as the beam is displaced in the negative (i.e., counterclockwise) direction, $F_{wt}$ increases...
since the beam applies an upward force on the reaction block. Note that, as described in Chapter 5, the amount of variation in $F_{wt}$ during the cyclic displacements of the beam is relatively small as compared with the expected variation of axial forces in the wall pier coupling regions of a multi-story coupled wall system. Upon unloading, $F_{wt}$ returns more or less to its initial value.

![Vertical Force on Wall Test Region](image)

Figure 7.78: Test 3B vertical force on the wall test region, $F_{wt}$ – (a) $F_{wt}$-test duration; (b) $F_{wt}$-$\theta_b$.

7.2.7 Beam Vertical Displacements

The vertical displacements $\Delta_{DT9}$ and $\Delta_{DT10}$ at the south and north ends of the beam are measured using string pots DT9 and DT10, respectively. These displacements are used to calculate the beam chord rotation, $\theta_b$. As described in Chapter 5, as the subassembly is displaced, the transducer string undergoes a change of angle, which can be “adjusted” to give the vertical displacements in the $y$-direction. Figures 7.79 and 7.80 show the measured displacements at $\Delta_{DT9}$ and $\Delta_{DT10}$, respectively, the corresponding
adjusted $y$-displacements $\Delta_{DT9,y}$ and $\Delta_{DT10,y}$, respectively, and the difference between the measured and adjusted displacements for the duration of the test. In Figure 7.79, it can be seen that there is an upward shift from the origin in the measured data from DT9, which was caused by the loosening of the ferrule insert as damage accumulated at the beam ends.

It can be seen from Figures 7.79 and 7.80 that $\Delta_{DT9}$ and $\Delta_{DT10}$ are close to $\Delta_{DT9,y}$ and $\Delta_{DT10,y}$, respectively, with the difference being less than 0.03 in. (0.76 mm). Figure 7.81 plots the percent difference between the measured and adjusted displacements versus the beam chord rotation, $\theta_b$. The results indicate that the largest percent differences occur when the beam chord rotation is close to zero; however, these differences are not significant since the corresponding measurements are very small and are mostly outside of the sensitivity of the transducers. As the structure is displaced, the measurements from DT9 require larger adjustments than those from DT10, since corresponding to a given $\theta_b$, $\Delta_{DT9}$ is smaller than $\Delta_{DT10}$. It is also observed that for negative rotations, DT9 displays larger percent errors than under positive rotations because the measured displacements under negative rotations are smaller (possibly due to the drift in the data) than the measured displacements under positive rotations. Therefore, similar differences between the measured and adjusted displacements under the negative and positive directions result in larger percent errors in the negative direction. Since the adjustments described in Chapter 5 require certain assumptions and approximations and since the amplitude differences (which are more important than percent differences for the calculation of the beam chord rotation) between the measured and adjusted displacements remain small, these differences are ignored and the measurements from DT9 and DT10 are used as the
vertical $y$-displacements of the beam throughout this dissertation. Figure 7.82 plots the measured data from DT9 and DT10 against the beam chord rotation, $\theta_b$.

![Graphs](https://example.com/graphs.png)

Figure 7.79: Test 3B south end beam vertical displacements – (a) measured, $\Delta_{DT9}$; (b) adjusted, $\Delta_{DT9,y}$; (c) difference, $\Delta_{DT9,y} - \Delta_{DT9}$. 

615
Figure 7.80: Test 3B north end beam vertical displacements – (a) measured, $\Delta_{DT10}$; (b) adjusted, $\Delta_{DT10,y}$; (c) difference, $\Delta_{DT10,y} - \Delta_{DT10}$. 
Figure 7.81: Test 3B percent difference between measured and adjusted displacements versus beam chord rotation – (a) south end, DT9; (b) north end, DT10.

Figure 7.82: Test 3B beam vertical displacements versus beam chord rotation – (a) $\Delta_{DT9} - \theta_b$; (b) $\Delta_{DT10} - \theta_b$. 
7.2.8 Beam Chord Rotation

The beam chord rotation is defined as the relative vertical displacement of the beam ends divided by the beam length. The beam chord rotation $\theta_b$ determined based on the $\Delta_{DT9}$ and $\Delta_{DT10}$ measurements in Test 3B is shown in Figure 7.83(a). For comparison, Figure 7.83(b) shows the load block beam chord rotation, $\theta_{b,lb}$ calculated using $\Delta_{LB,y}$, and Figure 7.84 shows the percent difference between $\theta_b$ and $\theta_{b,lb}$ plotted against $\theta_b$. It can be seen that there is a large percent difference for small beam chord rotations; with the difference dropping down to less than 10% at larger beam rotations. Figure 7.85 plots the beam chord rotation, $\theta_b$ and the load block beam chord rotation, $\theta_{b,lb}$ against the beam chord rotation, $\theta_b$. The results show that the two rotations are nearly identical for both positive and negative rotations.

![Beam Chord Rotation from Beam Displacements](image)

![Beam Chord Rotation from Load Block Displacements](image)

Figure 7.83: Test 3B beam chord rotation – (a) $\theta_b$ from $\Delta_{DT9}$ and $\Delta_{DT10}$; (b) $\theta_{b,lb}$ from $\Delta_{LB,y}$.  

618
Figure 7.84: Test 3B percent difference between $\theta_b$ and $\theta_{b,lb}$.

Figure 7.85: Test 3B difference between $\theta_b$ and $\theta_{b,lb}$. 
7.2.9 Local Beam Rotations

Local beam rotations were measured using two rotation transducers (inclinometers); one near the south end of the beam (RT1) and the other near the midspan (RT2). Figure 7.86 shows the time history results, $\theta_{RT1}$ and $\theta_{RT2}$ from these two rotation transducers, and Figures 7.25(a) and 7.25(b) compare $\theta_{RT1}$ and $\theta_{RT2}$, respectively, with the beam chord rotation, $\theta_b$. Note that the measurements from RT2 show some shift in the data. The cause of this shift is not clear. Both rotation measurements are positive when the load block is displaced in the downward direction (i.e., clockwise beam rotation). Note that, as a result of the bending deformations over the length of the beam, it may be expected that the midspan rotation, $\theta_{RT2}$ is larger than the chord rotation, $\theta_b$, and that the chord rotation is larger than the end rotation, $\theta_{RT1}$ [see Figure 7.87(c)]. However, since the nonlinear lateral displacements of the beam are primarily governed by the gap opening at the ends, the differences in the measured end, midspan, and chord rotations for the test beams are in general too small to make conclusive comparisons, and the different instruments utilized for the chord rotation measurements (using displacement transducers) and for the beam end and midspan rotation measurements (using rotation transducers) further make these comparisons difficult.
Figure 7.86: Test 3B beam inclinometer rotations –
(a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. 
Figure 7.87: Test 3B difference between beam inclinometer rotations and beam chord rotations – (a) RT1; (b) RT2; (c) beam deflected shape.

7.2.10 Load Block Displacements and Rotations

String pots DT3 – DT5 are used to measure the vertical \( y \)-displacements and the horizontal \( x \)-displacement of the load block. Similar to the vertical beam displacements, as the load block is displaced, the strings of the load block displacement transducers undergo a change in angle; and thus, their measurements may need to be adjusted to give the \( x \)- and \( y \)-displacements of the load block as described in Chapter 5.
Figures 7.88 through 7.90 show the measured displacements $\Delta_{DT3}$, $\Delta_{DT4}$, and $\Delta_{DT5}$, respectively, the corresponding adjusted displacements $\Delta_{DT3,x}$, $\Delta_{DT4,y}$, and $\Delta_{DT5,y}$, respectively, and the percent differences between the measured and adjusted displacements. Note that, as described in Chapter 5, the negative $\Delta_{DT3}$ and $\Delta_{DT3,x}$ measurements indicate the movement of the load block in the north direction, away from the reaction block. It can be seen that the difference between $\Delta_{DT3}$ and $\Delta_{DT3,x}$ is well over 10% for much of the duration of the test; and thus, adjustments need to be applied to the measurements from DT3. In comparison, the adjustments needed for the vertical displacement measurements from DT4 and DT5 remain small throughout the test with the largest difference being less than 4.0%. Figure 7.91 shows the percent difference between measured and adjusted displacements for DT4 and DT5 plotted against the beam chord rotation, $\theta_b$. It can be seen that away from the origin, the maximum differences between the unadjusted and adjusted measurements from DT4 and DT5 remain less than 0.25%.

The measurements from DT3 require larger adjustments than those from DT4 and DT5 since the changes in the string angle for DT3, which occur due to the applied vertical displacements of the structure, are much larger than the changes in the string angles for DT4 and DT5, which occur due to the gap opening displacements at the beam ends. In evaluating the results from Test 3B, adjusted measurements are used for $\Delta_{DT3}$; however, the measurements for $\Delta_{DT4}$ and $\Delta_{DT5}$ are not adjusted. Figure 7.92 plots $\Delta_{DT4}$, $\Delta_{DT5}$, and $\Delta_{DT3,x}$ against the beam chord rotation, $\theta_b$, respectively. It can be seen in Figures 7.92(a) and 7.92(b) that the vertical displacements of the load block at the north and south ends are nearly the same.
Combining these displacements, the $x$-displacement, $y$-displacement, and rotation of the load block centroid can be determined as described in Chapter 5 and shown in Figures 7.93 and 7.94. Figure 7.93(a) plots the $y$-displacement versus the $x$-displacement showing the path of the load block centroid during the test. As the subassembly is displaced in positive (i.e., clockwise) and negative (i.e., counterclockwise) directions, the load block is pushed in north in the $x$-direction (away from the reaction block) due to the gap opening at the beam ends. After each cycle, the load block returns to its initial position with minimal residual displacements. Figures 7.93(a) and 7.94(a) show that the $x$-direction displacements of the load block centroid are slightly smaller during the negative rotations of the subassembly as compared to the displacements during the positive rotations, which is possibly due to any unsymmetric loading and/or behavior of the structure. In the $y$-direction, the load block displaces symmetrically during the positive and negative rotations as shown in Figures 7.92(a), 7.92(b), 7.93(d), and 7.94(b). Finally, the rotation of the load block is shown to remain small throughout the duration of the test as shown in Figures 7.93(b) and 7.94(c). The load block rotation remains below 0.005 radians indicating that the two hydraulic actuators moved near simultaneously.
Figure 7.88: Test 3B load block horizontal displacements – (a) measured, $\Delta DT_3$; (b) adjusted, $\Delta DT_{3,x}$; (c) percent difference.
Figure 7.89: Test 3B load block north end vertical displacements – (a) measured, $\Delta DT4$; (b) adjusted, $\Delta DT4,y$; (c) percent difference.
Figure 7.90: Test 3B load block south end vertical displacements – (a) measured, $\Delta_{DT5}$; (b) adjusted, $\Delta_{DT5,y}$; (c) percent difference.

Figure 7.91: Test 3B percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5.
Figure 7.92: Test 3B load block displacements versus beam chord rotation –
(a) $\Delta DT_4 - \theta_b$; (b) $\Delta DT_5 - \theta_b$; (c) $\Delta DT_3,x - \theta_b$. 
Figure 7.93: Test 3B load block centroid displacements –
(a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
Figure 7.94: Test 3B load block centroid displacements versus beam chord rotation – (a) $x$-displacement-$\theta_b$; (b) $y$-displacement-$\theta_b$; (c) rotation-$\theta_b$.

7.2.11 Reaction Block Displacements and Rotations

String pots DT6 – DT8 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the reaction block. Figure 7.95 shows the measurements from DT6 – DT8 for the duration of the test. Since the reaction block is tied to the strong floor, the measured displacements remain very small throughout the test. Due to these small displacements and the use of lead cables for each string pot, the change in angle that the string undergoes during testing is very small. Thus, it can be assumed that no
adjacent are needed for the displacements measured from the reaction block displacement transducers. Figure 7.96 plots the measurements from DT6 – DT8 against the beam chord rotation.

The $x$-displacement, $y$-displacement, and rotation of the reaction block centroid can be determined (see Chapter 5) as shown in Figure 7.97 and plotted against the beam chord rotation in Figure 7.98. It is concluded that the vertical displacements of the reaction block do not have a significant effect on the displacements of the test structure (e.g., the beam chord rotation), and the test results are evaluated with the reaction block displacements taken as zero (i.e., the measured displacements of the reaction block are ignored in investigating the response of the subassembly). Note that the horizontal displacements of the reaction block are significant when determining the total elongation of the post-tensioning tendon; and thus, are included in those calculations.
Figure 7.95: Test 3B reaction block displacements –
(a) $\Delta_{DT6}$; (b) $\Delta_{DT7}$; (c) $\Delta_{DT8}$.
Figure 7.96: Test 3B reaction block displacements versus beam chord rotation – (a) $\Delta DT7 - \theta_b$; (b) $\Delta DT8 - \theta_b$; (c) $\Delta DT6 - \theta_b$. 
Figure 7.97: Test 3B reaction block centroid displacements – (a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
Figure 7.98: Test 3B reaction block centroid displacements versus beam chord rotation – (a) $x$-displacements; (b) $y$-displacements; (c) rotation.

7.2.12 Contact Depth and Gap Opening at Beam-to-Wall Interfaces

The beam contact depth and gap opening displacements are measured at the beam-to-reaction-block interface using displacement transducers DT11 – DT13. Note that these transducers were initialized and zeroed prior to the application of the beam post-tensioning force at the beginning of the virgin Test 3. Since the beam post-tensioning tendon in Test 3B was the same as that in Tests 3 and 3A, the contact depth and gap opening transducers were not zeroed at the beginning of Test 3B. As described in Chapter
5, these LVDTs rotate with the beam; and thus, their measurements may need to be adjusted to determine the gap opening displacements in the horizontal $x$-direction.

Figures 7.99 through 7.101 plot the measured displacements $\Delta_{\text{DT}11}$, $\Delta_{\text{DT}12}$, and $\Delta_{\text{DT}13}$, respectively, the corresponding adjusted $x$-displacements $\Delta_{\text{DT}11, x}$, $\Delta_{\text{DT}12, x}$, and $\Delta_{\text{DT}13, x}$, respectively, and the percent differences between the measured and adjusted displacements. The results indicate that the adjusted measurements are less than 0.8% different from the original measurements; and thus, $\Delta_{\text{DT}11}$, $\Delta_{\text{DT}12}$, and $\Delta_{\text{DT}13}$ can be taken as the displacements in the $x$-direction. Figure 7.102 plots the measured data from DT11, DT12, and DT13 against the beam chord rotation.

The maximum average concrete compressive strain in the beam-to-wall contact regions can be calculated by dividing the measured displacements from DT11 and DT13 with the gauge length (i.e., the distance from the LVDT ferrule insert in the beam to the reaction plate ferrule insert in the wall test region; see Chapter 5). For Test 3B, the maximum average compressive strain is 0.0172. Note that this measurement includes the compressive strain occurring in the fiber-reinforced grout at the beam-to-wall interface as well as the patched concrete deformations in wall test region of the reaction block.
Figure 7.99: Test 3B beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta DT11$; (b) adjusted, $\Delta DT11,x$; (c) percent difference.
Figure 7.100: Test 3B beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta DT_{12}$; (b) adjusted, $\Delta DT_{12,x}$; (c) percent difference.
Figure 7.101: Test 3B beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta DT_{13}$; (b) adjusted, $\Delta DT_{13,x}$; (c) percent difference.
Figure 7.102: Test 3B beam-to-reaction-block interface LVDT displacements versus beam chord rotation – (a) $\Delta DT11 - \theta_b$; (b) $\Delta DT13 - \theta_b$; (c) $\Delta DT12 - \theta_b$.

Using the measured data, the contact depth and the largest (i.e., at the beam top and bottom) gap opening displacements at the beam-to-reaction-block interface can be determined following the procedures in Chapter 5. Figures 7.103(a) and 7.104(a) show the results based on the measured data from DT11 – DT13 (method 1); Figures 7.103(b) and 7.104(b) show the results based on the measured data from RT1, DT11, and DT13 (method 2); Figures 7.103(c) and 7.104(c) show the results based on the measured data from RT1 and DT12 (method 3); Figures 7.103(d) and 7.104(d) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT12 (method 4); and Figures
7.103(e) and 7.104(e) show the results based on the beam chord rotation, \( \theta_b \) and the measurements from DT11 and DT13 (method 5). Each ○ marker in Figures 7.103 and 7.104 indicates the contact depth or gap opening displacement at the peak of a loading cycle for each beam chord rotation. Note that, as described in Chapter 5, the contact depth and gap opening results from methods 1, 3, and 4 are valid only when \( \Delta_{DT12} \) is positive (i.e., the gap extends beyond the level of DT12 and the contact depth is less than \( h_b/2 \)). Figures 7.103 and 7.104 show the results within the validity range of these methods.

Looking at Figures 7.103, it can be stated that the contact depth results obtained using the five methods are somewhat different (possibly because of differences in the measurements used in the different methods and different amounts of loosening in the sensor inserts as damage occurred at the beam ends, especially since the contact depth calculations are sensitive to these measurements) but show similar trends. There is a rapid reduction in the contact depth up to a beam chord rotation of about 2.0%. After this rotation, the contact depth remains relatively stable due to nonlinear behavior of the concrete in compression. In comparison, the gap opening results obtained using the five methods in Figure 7.104 are reasonably similar and the increase in gap opening with the rotation of the beam is very close to linear.

Figure 7.105 shows a continuous plot of the largest gap opening displacements determined from method 4 (using the beam chord rotation and DT12) against the beam chord rotation. Similarly, Figure 7.106(a) plots the beam contact depth from method 4 against the beam chord rotation as continuous data. Furthermore, Figures 7.106(b) and 7.106(c) show continuous plots of the contact depth during the 2.25% and 5.0% beam
chord rotation cycles, respectively. Note that method 3 (using the measured data from RT1 and DT12) can also be used to obtain the continuous plots above; however, the measurements from RT1 were found to be not always reliable (especially at small rotations); and thus, method 4 is used instead. The gap opening and contact depth plots in Figures 7.105 and 7.106 could have been affected by the use of $\theta_b$ (i.e., chord rotation) instead of $\theta_{RT1}$ (i.e., local rotation) to determine the behavior of the south end of the beam. The use of the beam midheight transducer DT12 instead of the extreme beam top or bottom transducer (DT11 or DT13) may also have affected the results, especially the contact depth plots in Figure 7.106 during small beam rotations, which are very sensitive to the measurements. Thus the estimated contact depths at small beam rotations ($\theta_b < 0.25\%$) should be used with caution. It can be seen that the contact depth behavior in Test 3B is similar to the behavior in Test 3.

Unlike Test 3 in Chapter 6, no ruler measurements of the gap opening displacements were taken during Test 3B (Table 7.2).
Figure 7.103: Test 3B contact depth at beam-to-reaction-block interface – (a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT1, DT11, and DT13; (c) method 3 using RT1 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.104: Test 3B gap opening at beam-to-reaction-block interface –
(a) method 1 using $\Delta DT_{11}$, $\Delta DT_{12}$, and $\Delta DT_{13}$; (b) method 2 using RT1, DT11, and DT13; (c) method 3 using RT1 and DT12; (d) method 4 using $\Delta DT_{12}$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.105: Test 3B gap opening at beam-to-reaction-block interface method 4.

Figure 7.106: Test 3B contact depth at beam-to-reaction-block interface –
(a) method 4 using $\Delta_{DT12}$ and $\theta_b$; (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord rotation cycle.
TABLE 7.2
RULER MEASUREMENTS OF GAP OPENING AT SOUTH BEAM END

<table>
<thead>
<tr>
<th>Nominal Rotation (%)</th>
<th>Gap Opening, $\Delta_g$ [in. (mm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no measurements taken</td>
<td></td>
</tr>
</tbody>
</table>

7.2.13 Wall Test Region Local Concrete Deformations

The reaction block confined concrete deformations near the beam-to-wall interface of the wall test region are measured using displacement transducers DT14 and DT15. Figure 7.107 plots the time history results from the top (DT14) and bottom (DT15) transducers and Figure 7.108 plots the measured data from DT14 and DT15 against the beam chord rotation. As expected, the concrete deformations are mostly compressive (negative), due to the compression stresses that are transferred through the contact region from post-tensioning.

From Figure 7.108, the maximum average concrete compressive strain in the wall test region can be calculated by dividing the measured deformations with the gauge length (i.e., the distance from the LVDT ferrule insert in the wall test region to the reaction plate; see Chapter 5). For Test 3B, the maximum average concrete compressive strain is 0.001, which is less than the expected unconfined (cover) concrete crushing strain of 0.004. This finding is in accordance with the visual observation that no concrete spalling occurred in the wall test region during the test. Note that most of the compressive strains occurred in the patched concrete in the wall test region.
Figure 7.107: Test 3B wall test region concrete deformations – (a) DT14; (b) DT15.

Figure 7.108: Test 3B wall test region concrete deformations versus beam chord rotation – (a) $\Delta_{DT14}-\theta_b$; (b) $\Delta_{DT15}-\theta_b$. 
7.2.14 Beam Looping Reinforcement Longitudinal Leg Strains

Figures 7.109 and 7.110 show the strain gauge measurements for the top and bottom horizontal legs of the east and west No. 6 mild steel looping reinforcing bars in the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3B and the “initial” strains for Test 3B were assumed to be equal to the final strains from Test 3A (since the beam post-tensioning tendon in Test 3A was the same as that in Tests 3 and 3A). Note that these initial strain values do not include any reduction in strain due to relaxation losses (between the end of Test 3A and the beginning of Test 3B) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.2.4). Their effects on the strain measurements are expected to be negligible. Upon lateral loading of the subassembly, the largest tensile strains occur, as expected, in the gauges closest to the angle-to-beam connection bolts [i.e., gauges 6(1)T-E, 6(1)T-W, 6(1)B-E, and 6(1)B-W]. The measurements in the gauges away from the angle-to-beam connection decrease with distance from this critical location.

To provide a better understanding of the strain measurements in the horizontal legs of the beam looping reinforcement, the \( \Delta \) and \( \square \) markers in Figures 7.109(a) and 7.109(b) for gauges 6(1)T-E and 6(1)T-W correspond to positive and negative chord rotation peaks for the beam, respectively, and the \( \bigcirc \) markers indicate zero rotation positions. To provide further insight into the results, Figures 7.111 and 7.112 show the strains plotted against the beam chord rotation. In the positive (i.e., clockwise) rotation direction, the strains in the top bars increase in tension as the gap opens at the top south corner of the beam and the top angle is pulled in tension. In the negative (i.e.,
counterclockwise) direction, the strains in the bottom bars increase in tension and the top bars go into compression due to the closing of the gap.

The maximum strains in the four gauges closest the critical section (i.e., angle-to-beam connection) remain well below the yield strain of the longitudinal steel ($\varepsilon_{ly} = 0.00283$) from the material tests in Chapter 4; and thus, it is concluded that the amount of mild steel reinforcement used to transfer the angle forces into the beam is adequate.

![Graphs showing strain vs. test duration for different gauges](image)

**Figure 7.109**: Test 3B beam looping reinforcement top longitudinal leg strains – (a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$; (h) $\varepsilon_{6MT-W}$.
Figure 7.109 continued.

Figure 7.110: Test 3B beam looping reinforcement bottom longitudinal leg strains –
(a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$; (f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MB-E}$; (h) $\varepsilon_{6MB-W}$.
Figure 7.110 continued.
Figure 7.111: Test 3B beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)T-E}\theta_b$; (b) $\varepsilon_{6(1)T-W}\theta_b$; (c) $\varepsilon_{6(2)T-E}\theta_b$; (d) $\varepsilon_{6(2)T-W}\theta_b$; (e) $\varepsilon_{6(3)T-E}\theta_b$; (f) $\varepsilon_{6(3)T-W}\theta_b$; (g) $\varepsilon_{6MT-E}\theta_b$; (h) $\varepsilon_{6MT-W}\theta_b$.  

652
Figure 7.111 continued.

Figure 7.112: Test 3B beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\epsilon_{6(1)B-E}$-\(\theta_b\); (b) $\epsilon_{6(1)B-W}$-\(\theta_b\); (c) $\epsilon_{6(2)B-E}$-\(\theta_b\); (d) $\epsilon_{6(2)B-W}$-\(\theta_b\); (e) $\epsilon_{6(3)B-E}$-\(\theta_b\); (f) $\epsilon_{6(3)B-W}$-\(\theta_b\); (g) $\epsilon_{6MB-E}$-\(\theta_b\); (h) $\epsilon_{6MB-W}$-\(\theta_b\).
no data collected from strain gauge 6(2)B-E

no data collected from strain gauge 6(2)B-W

(c)

(d)

Figure 7.112 continued.
7.2.15 Beam Transverse Reinforcement Strains

Figure 7.113 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3B and the “initial” strains for Test 3B were assumed to be equal to the final strains from Test 3A. Note that the replacement of the top and seat angles in Test 3B may have affected the initial strains in the transverse legs of the looping reinforcing bars; however, this effect is expected to be small. To give more insight into the measurements, Figure 7.114 plots the strain data against the beam chord rotation. It can be seen that the strain gauge readings remain well below the yield strain of the reinforcing steel ($\varepsilon_{\text{yl}} = 0.00283$, see Chapter 4) throughout the test, demonstrating that the design of the transverse reinforcement at the beam end is adequate. Note that the angle-to-beam connection bolts may also have acted as transverse reinforcement in the beam; however, this could not be confirmed from the test results since the connection bolts were not instrumented.

No strain measurements were collected from gauges MH-E and MH-W placed on the vertical legs of the No. 3 transverse hoop at the beam midspan (Figures 7.115 and 7.116). However, the strain gauge results from Tests 1 and 2 and visual observations from Tests 3, 3A, and 3B indicate that the use of nominal transverse reinforcement within the span of the beam is adequate.
strain gauge 6SE(E)-E removed from Beam #3
strain gauge 6SE(E)-W removed from Beam #3

(a)  

(b)  

(c)  

(d)  

Figure 7.113: Test 3B beam looping reinforcement vertical leg strains – (a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$. 

656
Figure 7.114: Test 3B beam looping reinforcement vertical leg strains versus beam chord rotation – (a) $\varepsilon_{6SE(E)-E}$-$\theta_b$; (b) $\varepsilon_{6SE(E)-W}$-$\theta_b$; (c) $\varepsilon_{6SE(I)-E}$-$\theta_b$; (d) $\varepsilon_{6SE(I)-W}$-$\theta_b$.

Figure 7.115: Test 3B beam midspan transverse hoop reinforcement strains – (a) $\varepsilon_{MH-E}$; (b) $\varepsilon_{MH-W}$.
Figure 7.116: Test 3B beam midspan transverse hoop reinforcement strains versus beam chord rotation – (a) $\varepsilon_{MH-E} - \theta_b$; (b) $\varepsilon_{MH-W} - \theta_b$.

7.2.16 Beam Confined Concrete Strains

Figures 7.117 and 7.118 show the measurements from the strain gauges placed on the No. 3 support bars inside the hoop confined concrete at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3B and the “initial” strains for Test 3B were assumed to be equal to the final strains from Test 3A (since the beam post-tensioning tendon in Test 3A was the same as that in Tests 3 and 3A). Note that the initial strains are close to zero. Note also that these initial strain values do not include any reduction in strain due to relaxation losses (between the end of Test 3A and the beginning of Test 3B) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.2.4). Their effects on the strain measurements are expected to be negligible. For further insight into the strain gauge readings, Figures 7.119 and 7.120 plot the strain data against the beam chord rotation. As the beam is rotated in the positive (i.e., clockwise) direction, the compression strains in the bottom bars increase due to the transfer of the contact
stresses to the bottom corner of the beam. In the opposite (i.e., counterclockwise) direction, the strains in the top and bottom bars reverse due to the reversal of the load. It can be seen that the strain gauge measurements from the support bars remain below the yield strain $\varepsilon_{hy} = 0.00240$ of the No. 3 support bars in tension and below the expected crushing strain $\varepsilon_{cu} = 0.004$ of the unconfined concrete in compression.

Figure 7.117: Test 3B No. 3 top hoop support bar strains – (a) $\varepsilon_{3THT-(1)}$; (b) $\varepsilon_{3THB-(1)}$; (c) $\varepsilon_{3THT-(2)}$; (d) $\varepsilon_{3THB-(2)}$. 
Figure 7.118: Test 3B No. 3 bottom hoop support bar strains – (a) $\varepsilon_{3\text{BHB}-(1)}$; (b) $\varepsilon_{3\text{BHT}-(1)}$; (c) $\varepsilon_{3\text{BHB}-(2)}$; (d) $\varepsilon_{3\text{BHT}-(2)}$. 

strain gauge 3BHT-(1) removed from Beam #3

strain gauge 3BHT-(2) removed from Beam #3
Figure 7.119: Test 3B No. 3 top hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3THT-(1)} - \theta_b$; (b) $\varepsilon_{3THB-(1)} - \theta_b$; (c) $\varepsilon_{3THT-(2)} - \theta_b$; (d) $\varepsilon_{3THB-(2)} - \theta_b$. 
Figure 7.120: Test 3B No. 3 bottom hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3BHB-(1)} - \theta_b$; (b) $\varepsilon_{3BHT-(1)} - \theta_b$; (c) $\varepsilon_{3BHB-(2)} - \theta_b$; (d) $\varepsilon_{3BHT-(2)} - \theta_b$.

7.2.17 Beam End Confinement Hoop Strains

Figures 7.121 and 7.122 show the measurements from the strain gauges placed on the vertical legs of the bottom layer No. 3 confinement hoops at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 3B and the “initial” strains for Test 3B were assumed to be equal to the final strains from Test 3A. Note that the replacement of the
top and seat angles in Test 3B may have affected the initial strains in the beam end confinement hoops; however, this effect is expected to be small. For further insight into the measurements, Figures 7.123 and 7.124 plot the strain data against the beam chord rotation. Throughout the test, the measured confinement hoop strains remain small.

Figure 7.121: Test 3B beam end confinement hoop east leg strains – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$.
Figure 7.122: Test 3B beam end confinement hoop west leg strains –
(a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$.
Figure 7.123: Test 3B beam end confinement hoop east leg strains versus beam chord rotation – (a) $\varepsilon_{1HBE}-\theta_b$; (b) $\varepsilon_{2HBE}-\theta_b$; (c) $\varepsilon_{3HBE}-\theta_b$; (d) $\varepsilon_{4HBE}-\theta_b$. 

no data collected from strain gauge 3HBE-E
Figure 7.124: Test 3B beam end confinement hoop west leg strains versus beam chord rotation – (a) $\varepsilon_{1\text{HBW}}-\theta_b$; (b) $\varepsilon_{2\text{HBW}}-\theta_b$; (c) $\varepsilon_{3\text{HBW}}-\theta_b$; (d) $\varepsilon_{4\text{HBW}}-\theta_b$.

7.2.18 Wall Test Region Confined Concrete Strains

As described previously, the strain gauge wires coming out of the reaction block used in Tests 2 through 4B were all severed during the removal of the steel casting mold. Thus, no measurements were recorded for the wall test wall region confined concrete strains in Test 3B.
7.2.19 Wall Test Region Confinement Hoop Strains

Similar to above, no measurements were recorded for the wall test region confinement hoop strains in Test 3B since the strain gauge wires were severed.

7.2.20 Crack Patterns

Cracks were not marked for Test 3B due to the damage that occurred previously in Tests 3 and Test 3A.
7.3 Test 4A

The beam used in Test 4 (i.e., Beam 4) has the following properties: (1) beam depth, $h_b = 18$ in. (457 mm); (2) beam width, $b_b = 7.5$ in. (191 mm); (3) mild steel reinforcement of two No. 6 bars looping around the beam vertical perimeter along its length; (4) No. 3 full-depth rectangular hoops [6.125 in. by 16.675 in. (156 mm by 424 mm)] placed at a nominal 7.0 in. (178 mm) spacing to provide transverse reinforcement in the beam midspan region; (5) No. 3 partial-depth rectangular hoops [6.125 in. by 4.375 in. (156 mm by 111 mm)] placed at a 1.5 in. (38 mm) spacing to provide concrete confinement at the beam ends; (6) a beam post-tensioning tendon comprised of three 0.6 in. (15 mm) nominal diameter high-strength strands with a total area of $A_{bp} = 0.651$ in.$^2$ (420 mm$^2$); (7) average initial beam post-tensioning strand stress of $f_{bpi} = 0.39f_{bpu}$, where $f_{bpu} = 270$ ksi (1862 MPa) is the design maximum strength of the post-tensioning steel; (8) total initial beam post-tensioning force of $P_{bl} = 69.0$ kips (307 kN); (9) initial beam concrete nominal axial stress (based on actual cross-sectional area with beam post-tensioning duct removed) of $f_{bci} = 0.52$ ksi (3.6 MPa); and (10) no top and seat angles.

The primary difference of Test 4A from Test 4 is that no top and seat angles are used in the beam-to-wall connections. In addition, there was a small reduction in the initial beam post-tensioning strand stress, $f_{bpi}$, and the resulting initial beam concrete nominal axial stress, $f_{bci}$ due to the post-tensioning losses that occurred in Test 4. Note that angles with a short tapered horizontal leg, as shown in Figure 7.125, were connected to the reaction and load block at the top and seat angle locations as a precautionary measure to keep the beam from sliding vertically. These angles were not connected to the
beam and were designed to minimize contact between the angles and the beam. The same

displacement loading history from Test 4 was also used for Test 4A.

Figure 7.125: Test 4A angle with short tapered horizontal leg.

7.3.1 Test Photographs

Photographs of the original and displaced subassembly configurations from Test
4A are shown in Figures 7.126 and 7.127. Figures 7.126(a) through 7.126(f) show overall
subassembly photographs as follows: (a) pre-test undisplaced position; (b) displaced to $\theta_b$
= 3.33%; (c) displaced to $\theta_b = -3.33%$; and (d) final post-test undisplaced position.
Similarly, Figures 7.127(a) through 7.127(f) show close-up photographs of the south end
of the beam at the beam-to-reaction-block interface. The accumulation of damage at the
south end of the beam is shown in more detail in Figure 7.128.

The wall test region of the reaction block, which was damaged during
detensioning of the angle-to-wall connection strands following Test 3B, did not receive
any additional damage (no cracking and/or spalling of the cover concrete) during testing after being re-patched with a high strength fiber reinforced grout following the Test 3 series. Minimal spalling of the cover concrete at the beam ends was seen throughout the test. The test was stopped at a beam chord rotation of 3.33% so that the beam could be retested with an additional parameter variation as described in Section 7.4.

Slip between the coupling beam and the walls did not occur demonstrating that the friction resistance due to the post-tensioning force provided adequate vertical support to the beam.

Gap opening formed on both sides of the fiber-reinforced grout column throughout the test as a result of the bond being broken between the grout and the beam ends in Test 4. While this is not the desired mode of behavior for the structure as described in Chapter 3, it did not change the behavior of the system or cause any problems with the performance of the grout. No significant crushing of the grout at the beam-to-wall interfaces was observed throughout test. Note that the grout column was left approximately 0.25 in. (6.4 mm) short of the beam depth at the top and bottom as was done in the previous tests (except Test 1).
Figure 7.126: Test 4A overall photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) final post-test undisplaced position.
Figure 7.127: Test 4A beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) final post-test un-displaced position.
7.3.2 Beam Shear Force versus Chord Rotation Behavior

Figure 7.129(a) shows the hysteretic coupling beam shear force, $V_b$ versus chord rotation, $\theta_b$ behavior from Test 4A, where $V_b$ and $\theta_b$ are calculated from Equations 5.5 and 5.35, respectively. For comparison, Figure 7.128(b) plots the $V_b$-$\theta_{b,lb}$ behavior, where $\theta_{b,lb}$ is the beam chord rotation determined from the vertical ($y$-direction) displacement of the load block centroid using Equation 5.36. As shown in Figure 7.128, the structure was able to sustain three cycles at 3.33% rotation with no loss in shear resistance. The test was stopped at this point (prior to the failure of the beam) to prevent any further damage.
to the beam so that it could be reused for an additional parametric investigation in Test 4B.

Looking at the hysteresis loops, it can be seen that the specimen had very little energy dissipation due to the lack of the top and seat steel angles in the beam-to-wall connections. The behavior of the beam was very close to a nonlinear elastic behavior where the nonlinear displacements were governed primarily by the gap opening that occurred at the beam ends. The beam had a sufficient amount of restoring force to close the gaps at the beam ends upon unloading, resulting in a large self-centering capability.
Figure 7.129: Test 4A coupling beam shear force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements.
7.3.3 Beam End Moment Force versus Chord Rotation Behavior

Figure 7.129 shows the hysteretic coupling beam end moment, $M_b$ versus chord rotation, $\theta_b$ behavior from Test 4A, where $M_b$ is calculated from Equation 5.6 as described in Chapter 5. Since the beam end moment is calculated from the beam shear force, the results shown in Figure 7.129 are directly related to the results in Figure 7.128, and thus, no further discussion is provided herein.

![Figure 7.130: Test 4A $M_b$-$\theta_b$ behavior.](image)
7.3.4 Beam Post-Tensioning Forces

The coupling beam post-tensioning strand forces from the test are measured using load cells LC15 – LC117 mounted at the dead ends of the three strands (see Chapter 5). The forces from the three load cells, $F_{LC15}$, $F_{LC16}$, and $F_{LC17}$ are shown in Figure 7.130 and are plotted against the beam chord rotation, $\theta_b$ in Figure 7.131. Figure 7.132 shows the total beam post-tensioning tendon force, $P_{bp}$ (sum of the forces in the three strands) normalized with the total design ultimate strength of the tendon, $\Sigma a_{bp} f_{pu}$. The total initial beam post-tensioning tendon force is equal to 69.0 kips (307 kN), resulting in an initial beam concrete nominal axial stress of $f_{bc1} = 0.52$ ksi (3.6 MPa). Note that the initial beam post-tensioning tendon force in Test 4A is slightly lower than the final beam post-tensioning tendon force in Test 4 [76.3 kips (340 kN)] indicating that there may have been some relaxation in the post-tensioning strands after Test 4.

As the structure is displaced and gap opening occurs at the beam ends, the post-tensioning strands elongate and the post-tensioning forces increase. Since the strands are unbonded over the entire length of the subassembly, the nonlinear straining of the post-tensioning steel is significantly delayed. Note that the continuously occurring post-tensioning losses observed up through 3.33% beam chord rotation in Test 4 are not seen in Test 4A due to the fact that the same post-tensioning strands were used in both tests and no additional concrete damage occurred in Test 4A. Therefore, most or all of the anchor seating, nonlinear straining of the strands, and beam/wall concrete damage had already occurred in Test 4. The steps taken in Test 4 to help prevent premature wire fracture of the post-tensioning strands (i.e., the use of reduced initial post-tensioning stresses and the use of extra anchor barrels to reduce strand “kinking” inside the anchor
wedges) were successful to achieve satisfactory performance of the stand/anchor system during Test 4A.

Figure 7.131: Test 4A beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3.
Figure 7.132: Test 4A $F_{LC}$-$\theta_b$ behavior – (a) strand 1; (b) strand 2; (c) strand 3.
Figure 7.133: Test 4A beam post-tensioning force versus chord rotation behavior –
(a) using beam displacements; (b) using load block displacements.
7.3.5 Angle-to-Wall Connection Post-Tensioning Forces

No angles were used in the beam-to-wall connections of Test 4A.

7.3.6 Vertical Forces on Wall Test Region

Load cells LC7 – LC14 are used to measure the forces in the eight vertical bars applying axial compression forces to the wall test region of the reaction block and anchoring the block to the strong floor. The total vertical force, $F_{wt}$ is determined as described in Chapter 5, with the target initial total force ranging between 150 – 160 kips (667 – 712 kN). Figure 7.133(a) shows $F_{wt}$ for the duration of the test and Figure 7.133(b) plots $F_{wt}$ against the beam chord rotation, $\theta_b$. The initial total force, $F_{wt,i}$ is 131 kips (583 kN), somewhat below the target force range. Note that the initial force in Test 4A is slightly smaller than the force at the end of Test 4 indicating that there may have been some relaxation in the bars after Test 4. The initial force was not adjusted before Test 4A.

As the beam is displaced in the positive (i.e., clockwise) direction with the load block moving down, $F_{wt}$ decreases since the beam applies a downward force on the reaction block. Similarly, as the beam is displaced in the negative (i.e., counterclockwise) direction, $F_{wt}$ increases since the beam applies an upward force on the reaction block. Note that, as described in Chapter 5, the amount of variation in $F_{wt}$ during the cyclic displacements of the beam is relatively small as compared with the expected variation of axial forces in the wall pier coupling regions of a multi-story coupled wall system. Upon unloading, $F_{wt}$ returns more or less to its initial value.

681
7.3.7 Beam Vertical Displacements

The vertical displacements $\Delta DT9$ and $\Delta DT10$ at the south and north ends of the beam are measured using string pots DT9 and DT10, respectively. These displacements are used to calculate the beam chord rotation, $\theta_b$. As described in Chapter 5, as the subassembly is displaced, the transducer string undergoes a change of angle, which can be “adjusted” to give the vertical displacements in the $y$-direction. Figures 7.134 and 7.135 show the measured displacements, $\Delta DT9$ and $\Delta DT10$, respectively, the corresponding adjusted $y$-displacements $\Delta DT9,y$ and $\Delta DT10,y$, respectively, and the difference between the measured and adjusted displacements for the duration of the test.

It can be seen from Figures 7.134 and 7.135 that $\Delta DT9$ and $\Delta DT10$ are close to $\Delta DT9,y$ and $\Delta DT10,y$, respectively, with the difference being less than 0.005 in. (0.13 mm). Figure 7.136 plots the percent difference between the measured and adjusted displacements versus the beam chord rotation, $\theta_b$. The results indicate that the largest percent differences
occur when the beam chord rotation is close to zero; however, these differences are not significant since the corresponding measurements are very small and are mostly outside of the sensitivity of the transducers. As the structure is displaced, the measurements from DT9 require larger adjustments than those from DT10, since corresponding to a given $\theta_b$, $\Delta_{DT9}$ is smaller than $\Delta_{DT10}$. It is also observed that for negative rotations, DT9 displays larger percent errors than under positive rotations because the measured displacements under negative rotations are smaller than the measured displacements under positive rotations. Therefore, similar differences between the measured and adjusted displacements under the negative and positive directions result in larger percent errors in the negative direction. Since the adjustments described in Chapter 5 require certain assumptions and approximations and since the amplitude differences (which are more important than percent differences for the calculation of the beam chord rotation) between the measured and adjusted displacements remain small, these differences are ignored and the measurements from DT9 and DT10 are used as the vertical $y$-displacements of the beam throughout this dissertation. Figure 7.137 plots the measured data from DT9 and DT10 versus the beam chord rotation, $\theta_b$. 
Figure 7.135: Test 4A south end beam vertical displacements – (a) measured, $\Delta_{DT9}$; (b) adjusted, $\Delta_{DT9,y}$; (c) difference, $\Delta_{DT9,y} - \Delta_{DT9}$. 
Figure 7.136: Test 4A north end beam vertical displacements – (a) measured, $\Delta_{DT10}$; (b) adjusted, $\Delta_{DT10,y}$; (c) difference, $\Delta_{DT10,y} - \Delta_{DT10}$. 
Figure 7.137: Test 4A percent difference between measured and adjusted displacements –
(a) south end, DT9; (b) north end, DT10.

Figure 7.138: Test 4A beam vertical displacement versus beam chord rotation –
(a) $\Delta_{DT9}-\theta_b$; (b) $\Delta_{DT10}-\theta_b$. 
7.3.8 Beam Chord Rotation

The beam chord rotation is defined as the relative vertical displacement of the beam ends divided by the beam length. The beam chord rotation $\theta_b$ determined based on the $\Delta_DT_9$ and $\Delta_DT_{10}$ measurements in Test 4A is shown in Figure 7.138(a). For comparison, Figure 7.139(b) shows the load block beam chord rotation, $\theta_{b,lb}$ calculated using $\Delta_{LB,y}$, and Figure 7.140 shows the percent difference between $\theta_b$ and $\theta_{b,lb}$ plotted against $\theta_b$. It can be seen that there is a large percent difference for small beam chord rotations; with the difference dropping down to less than 20% at larger beam rotations. Figure 7.141 plots the beam chord rotation, $\theta_b$ and the load block beam chord rotation, $\theta_{b,lb}$ against the beam chord rotation, $\theta_b$. The results show that the two rotations are nearly identical under negative loading, but have a small difference under positive loading with $\theta_{b,lb}$ being slightly larger.
Figure 7.139: Beam chord rotation – (a) $\theta_b$ from $\Delta DT9$ and $\Delta DT10$; (b) $\theta_{b,lb}$ from $\Delta LB,y$.

Figure 7.140: Test 4A percent difference between $\theta_b$ and $\theta_{b,lb}$. 
7.3.9 Local Beam Rotations

Local beam rotations were measured using two rotation transducers (inclinometers); one near the south end of the beam (RT1) and the other near the midspan (RT2). Figure 7.141 shows the time history results, $\theta_{RT1}$ and $\theta_{RT2}$ from these transducers, and Figures 7.25(a) and 7.25(b) compare $\theta_{RT1}$ and $\theta_{RT2}$, respectively, with the beam chord rotation, $\theta_b$. The rotation measurements are positive when the load block is displaced in the downward direction (i.e., clockwise beam rotation). Note that, as a result of the bending deformations over the length of the beam, it may be expected that the midspan rotation, $\theta_{RT2}$ is larger than the chord rotation, $\theta_b$, and that the chord rotation is larger than the end rotation, $\theta_{RT1}$ [see Figure 7.142(c)]. However, since the nonlinear lateral displacements of the beam are primarily governed by the gap opening at the ends, the differences in the measured end, midspan, and chord rotations for the test beams are in
general too small to make conclusive comparisons, and the different instruments utilized for the chord rotation measurements (using displacement transducers) and for the beam end and midspan rotation measurements (using rotation transducers) further make these comparisons difficult.

Figure 7.142: Test 4A beam inclinometer rotations – (a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. 
7.3.10 Load Block Displacements and Rotations

String pots DT3 – DT5 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the load block. Similar to the vertical beam displacements, as the load block is displaced, the strings of the load block displacement transducers undergo a change in angle; and thus, their measurements may need to be adjusted to give the $x$- and $y$-displacements of the load block as described in Chapter 5.

Figures 7.143 through 7.145 show the measured displacements $\Delta_{DT3}$, $\Delta_{DT4}$, and $\Delta_{DT5}$, respectively, the corresponding adjusted displacements $\Delta_{DT3,x}$, $\Delta_{DT4,y}$, and $\Delta_{DT5,y}$,
respectively, and the percent differences between the measured and adjusted displacements. Note that, as described in Chapter 5, the negative $\Delta_{DT3}$ and $\Delta_{DT3,x}$ measurements indicate the movement of the load block in the north direction, away from the reaction block. It can be seen that the difference between $\Delta_{DT3}$ and $\Delta_{DT3,x}$ is well over 10% for much of the duration of the test; and thus, adjustments need to be applied to the measurements from DT3. In comparison, the adjustments needed for the vertical displacement measurements from DT4 and DT5 remain small throughout the test with the largest difference being less than 0.3%. Figure 7.146 shows the percent difference between the measured and adjusted displacements for DT4 and DT5 plotted against the beam chord rotation, $\theta_b$.

The measurements from DT3 require larger adjustments than those from DT4 and DT5 since the changes in the string angle for DT3, which occur due to the applied vertical displacements of the structure, are much larger than the changes in the string angles for DT4 and DT5, which occur due to the gap opening displacements at the beam ends. In evaluating the results from Test 4A, adjusted measurements are used for $\Delta_{DT3}$; however, the measurements for $\Delta_{DT4}$ and $\Delta_{DT5}$ are not adjusted. Figure 7.147 plots $\Delta_{DT4}$, $\Delta_{DT5}$, and $\Delta_{DT3,x}$ against the beam chord rotation, $\theta_b$, respectively. It can be seen in Figures 7.147(a) and 7.147(b) that the vertical displacement of the load block at the north and south ends are nearly the same.

Combining these displacements, the $x$-displacement, $y$-displacement, and rotation of the load block centroid can be determined as described in Chapter 5 and shown in Figures 7.148 and 7.149. Figure 7.148(a) plots the $y$-displacement versus the $x$-displacement showing the path of the load block centroid during the test. As the
subassembly is displaced under positive (i.e., clockwise) and negative (i.e., counterclockwise) rotations, the load block is pushed north in the x-direction (away from the reaction block) due to the gap opening at the beam ends. After each cycle, the load block returns to its initial position with minimal residual displacements. Note that similar to Test 4, Figures 7.148(a) and 7.149(a) show that the x-direction displacements of the load block centroid are symmetric during the positive and negative rotations of the subassembly. The load block displaces symmetrically in the y-direction as well as shown in Figures 7.147(a), 7.147(b), 7.148(a), and 7.149(b). Finally, the rotation of the load block is shown to remain small throughout the duration of the test as plotted in Figures 7.148(b) and 7.149(c). The load block rotation remains below 0.002 radians indicating that the two hydraulic actuators moved near simultaneously.
Figure 7.144: Test 4A load block horizontal displacements – (a) measured, $\Delta DT_3$; (b) adjusted, $\Delta DT_{3,x}$; (c) percent difference.
Figure 7.145: Test 4A load block north end vertical displacements – (a) measured, $\Delta DT4$; (b) adjusted, $\Delta DT4y$; (c) percent difference.
Figure 7.146: Test 4A load block south end vertical displacements – (a) measured, $\Delta_{DT5}$; (b) adjusted, $\Delta_{DT5,y}$; (c) percent difference.

Figure 7.147: Test 4A percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5.
Figure 7.148: Test 4A load block displacements versus beam chord rotation –
(a) $\Delta DT4-\theta_b$; (b) $\Delta DT5-\theta_b$; (c) $\Delta DT3,x-\theta_b$. 
Figure 7.149: Test 4A load block centroid displacements –
(a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
Figure 7.150: Test 4A load block centroid displacements versus beam chord rotation – (a) $x$-displacement-$\theta_b$; (b) $y$-displacement-$\theta_b$; (c) rotation-$\theta_b$.

7.3.11 Reaction Block Displacements and Rotations

String pots DT6 – DT8 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the reaction block. Figure 7.150 shows the measurements from DT6 – DT8 for the duration of the test. Since the reaction block is tied to the strong floor, the measured displacements remain very small throughout the test. Due to these small displacements and the use of lead cables for each string pot, the change in angle that the string undergoes during testing is very small. Thus, it can be assumed that no
adjustments are needed for the displacements measured from the reaction block displacement transducers. Figure 7.151 plots the measurements from DT6 – DT8 against the beam chord rotation.

The $x$-displacement, $y$-displacement, and rotation of the reaction block centroid can be determined (see Chapter 5) as shown in Figure 7.152 and plotted against the beam chord rotation in Figure 7.153. It is concluded that the vertical displacements of the reaction block do not have a significant effect on the displacements of the test structure (e.g., the beam chord rotation), and the test results are evaluated with the reaction block displacements taken as zero (i.e., the measured displacements of the reaction block are ignored in investigating the response of the subassembly). Note that the horizontal displacements of the reaction block are significant when determining the total elongation of the post-tensioning tendon; and thus, are included in those calculations.
Figure 7.151: Test 4A reaction block displacements – (a) $\Delta DT_6$; (b) $\Delta DT_7$; (c) $\Delta DT_8$. 
Figure 7.152: Test 4A reaction block displacements versus beam chord rotation – (a) $\Delta DT_7 - \theta_b$; (b) $\Delta DT_8 - \theta_b$; (c) $\Delta DT_6 - \theta_b$. 
Figure 7.153: Test 4A reaction block centroid displacements –
(a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
7.3.12 Gap Opening and Contact Depth at Beam-to-Wall Interfaces

The beam contact depth and gap opening displacements are measured at the beam-to-reaction-block interface using displacement transducers DT11 – DT13. Note that these transducers were initialized and zeroed prior to the application of the beam post-tensioning force at the beginning of the virgin Test 4. Since the beam post-tensioning tendon in Test 4A was the same as that in Test 4, the contact depth and gap opening
transducers were not re-zeroed at the beginning of Test 4A. As described in Chapter 5, these LVDTs rotate with the beam; and thus, their measurements may need to be adjusted to determine the gap opening displacements in the horizontal $x$-direction.

Figures 7.154 through 7.156 plot the measured displacements $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$, respectively, the corresponding adjusted $x$-displacements $\Delta_{DT11,x}$, $\Delta_{DT12,x}$, and $\Delta_{DT13,x}$, respectively, and the percent differences between the measured and adjusted displacements. The results indicate that the adjusted measurements are less than 0.03% different from the original measurements; and thus, $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$ can be taken as the displacements in the $x$-direction. Figure 7.157 plots the measured data from DT11, DT12, and DT13 against the beam chord rotation.

The maximum average concrete compressive strain in the beam-to-wall contact regions can be calculated by dividing the measured displacements from DT11 and DT13 with the gauge length (i.e., the distance from the LVDT ferrule insert in the beam to the reaction plate ferrule insert in the wall test region; see Chapter 5). For Test 4A, the maximum average compressive strain is 0.0059. Note that this measurement includes the compressive strain occurring in the fiber-reinforced grout at the beam-to-wall interface as well as the patched concrete deformations in wall test region of the reaction block.
Figure 7.155: Test 4A beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta_{DT11}$; (b) adjusted, $\Delta_{DT11,a}$; (c) percent difference.
Figure 7.156: Test 4A beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta DT_{12}$; (b) adjusted, $\Delta DT_{12,x}$; (c) percent difference.
Figure 7.157: Test 4A beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta DT_{13}$; (b) adjusted, $\Delta DT_{13,x}$; (c) percent difference.
Figure 7.158: Test 4A beam-to-reaction-block interface LVDT displacements versus beam chord rotation – (a) $\Delta DT11 - \theta_b$; (b) $\Delta DT13 - \theta_b$; (c) $\Delta DT12 - \theta_b$.

Using the measured data, the contact depth and the largest (i.e., at the beam top and bottom) gap opening displacements at the beam-to-reaction-block interface can be determined following the procedures in Chapter 5. Figures 7.158(a) and 7.159(a) show the results based on the measured data from DT11 – DT13 (method 1); Figures 7.158(b) and 7.159(b) show the results based on the measured data from RT2, DT11, and DT13 (method 2); Figures 7.158(c) and 7.159(c) show the results based on the measured data from RT2 and DT12 (method 3); Figures 7.158(d) and 7.159(d) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT12 (method 4); and Figures
7.158(e) and 7.159(e) show the results based on the beam chord rotation, \( \theta_b \) and the measurements from DT11 and DT13 (method 5). Each \( \circ \) marker indicates the contact depth or gap opening displacement at the peak of a loading cycle up to a beam chord rotation of 3.33%. Note that, as described in Chapter 5, the contact depth and gap opening results from methods 1, 3, and 4 are valid only when \( \Delta_{DT12} \) is positive (i.e., the gap extends beyond the level of DT12 and the contact depth is less than \( h_b/2 \)). Figures 7.158 and 7.159 show the results within the validity range of these methods.

Looking at Figure 7.158, it can be stated that the contact depth results obtained using the five methods are somewhat different (possibly because of small differences in the measurements used in the different methods, especially since the contact depth calculations are sensitive to these measurement differences) but show similar trends. There is a rapid reduction in the contact depth up to a beam chord rotation of about 1.0%. After this rotation, the contact depth remains relatively stable due to nonlinear behavior of the concrete in compression. In comparison, the gap opening results obtained using the five methods in Figure 7.159 are reasonably similar and the increase in gap opening with the rotation of the beam is very close to linear.

Figure 7.160 shows a continuous plot of the largest gap opening displacements determined from method 4 (using the beam chord rotation and DT12) against the beam chord rotation. Similarly, Figure 7.161(a) plots the beam contact depth from method 4 against the beam chord rotation as continuous data. Furthermore, Figures 7.161(b) and 7.161(c) show continuous plots of the contact depth during the 2.25% and 3.33% beam chord rotation cycles, respectively. Note that method 3 (using the measured data from RT1 and DT12) can also be used to obtain the continuous plots above; however, the
measurements from RT1 were found to be not always reliable (especially at small rotations); and thus, method 4 is used instead. The gap opening and contact depth plots in Figures 7.43 and 7.44 could have been affected by the use of $\theta_b$ (i.e., chord rotation) instead of $\theta_{RT1}$ (i.e., local rotation) to determine the behavior of the south end of the beam. The use of the beam midheight transducer DT12 instead of the extreme top or bottom transducer (DT11 or DT13) may also have affected the results, especially the contact depth plots in Figure 7.44 during small beam rotations, which are very sensitive to the measurements. Thus the estimated contact depths at small beam rotations ($\theta_b < 0.25\%$) should be used with caution. It can be seen that the contact depth behavior in Test 4A is different from the tests with top and seat angles since the beam concrete remains in contact with the wall piers throughout the test (with the exception of very small rotations for which the data is not expected to be accurate). In contrast, during the unloading of a coupling beam with top and seat angles, the tension angles need to yield back in compression for the beam concrete to come into contact with the wall piers. Depending on the beam post-tensioning force relative to the angle strength, this may result in the closing of the gap between the beam and the wall piers to be delayed, to occur partially, or not to occur at all.

Unlike Test 4 in Chapter 6, no ruler measurements of the gap opening displacements were taken during Test 4A (Table 7.3).
Figure 7.159: Test 4A contact depth at beam-to-reaction-block interface –
(a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.160: Test 4A gap opening at beam-to-reaction-block interface – (a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.161: Test 4A gap opening at beam-to-reaction-block interface using method 4.

Figure 7.162: Test 4A contact depth at beam-to-reaction-block interface – (a) method 4 using $\Delta_{DT12}$ and $\theta_b$; (b) 2.25% beam chord rotation cycle; (c) 3.33% beam chord rotation cycle.
### TABLE 7.3

**RULER MEASUREMENTS OF GAP OPENING AT SOUTH BEAM END**

<table>
<thead>
<tr>
<th>Nominal Rotation (%)</th>
<th>Gap Opening, ( \Delta_g ) [in. (mm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no measurements taken</td>
<td>no measurements taken</td>
</tr>
</tbody>
</table>

### 7.3.13 Wall Test Region Local Concrete Deformations

The reaction block confined concrete deformations near the beam-to-wall interface of the wall test region are measured using displacement transducers DT14 and DT15. Figure 7.162 plots the time history results from the top (DT14) and bottom (DT15) transducers and Figure 7.163 plots the measured data from DT14 and DT15 against the beam chord rotation. As expected, the concrete deformations are mostly compressive (negative), due to the compression stresses that are transferred through the contact region from post-tensioning.

From Figure 7.163, the maximum average concrete compressive strain in the wall test region can be calculated by dividing the measured deformations with the gauge length (i.e., the distance from the LVDT ferrule insert in the wall test region to the reaction plate; see Chapter 5). For Test 4A, the maximum average concrete compressive strain is 0.0007, which is less than the expected unconfined (cover) concrete crushing strain of 0.004. This finding is in accordance with the visual observation that no concrete spalling occurred in the wall test region during the test.
Figure 7.163: Test 4A wall test region concrete deformations – (a) DT14; (b) DT15.

Figure 7.164: Test 4A wall test region concrete deformations – (a) $\Delta_{DT14} - \theta_b$; (b) $\Delta_{DT15} - \theta_b$. 
7.3.14 Beam Looping Reinforcement Longitudinal Leg Strains

Figures 7.164 and 7.165 show the strain gauge measurements for the top and bottom horizontal legs of the east and west No. 6 mild steel looping reinforcing bars in the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4A and the “initial” strains were assumed to be equal to the final strains from Test 4 (since the beam post-tensioning tendon in Test 4A was the same as that in Test 3). Note that these initial strain values do not include any reduction in strain due to relaxation losses (between the end of Test 4 and the beginning of Test 4A) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.3.4). Their effects on the strain measurements are expected to be negligible. Upon lateral loading of the subassembly, the largest tensile strains occur, as expected, in the gauges closest to the south beam end [i.e., gauges 6(1)T-E, 6(1)T-W, 6(1)B-E, and 6(1)B-W]. The tensile strains remain nearly constant after a beam chord rotation of approximately $\theta_b = 0.125\%$. The measurements in the gauges away from the angle-to-beam connection decrease with distance from this critical location.

To provide a better understanding of the strain measurements in the horizontal legs of the beam looping reinforcement, the $\Delta$ and $\Box$ markers in Figures 7.164(a) and 7.164(b) for gauges 6(1)T-E and 6(1)T-W correspond to positive and negative chord rotation peaks for the beam, respectively, and the $\circ$ markers indicate zero rotation positions. To provide further insight into the results, Figures 7.166 and 7.167 show the strains plotted against the beam chord rotation. In the positive (i.e., clockwise) rotation direction, the strains in the top bars see an increase in tensile strain up to a beam chord rotation of approximately 0.125%, but remain nearly constant afterwards. In the negative
(i.e., counterclockwise) direction, the strains in the bottom bars increase in tension and the top bars go into compression due to the closing of the gap. Recall from Chapter 3 that the primary purpose of the longitudinal mild steel reinforcement in the beam specimens is the transfer of the tension angle forces into the concrete. In the absence of the angle-to-beam connections in Test 4A, the longitudinal steel strains in tension remain negligible; and thus, it can be concluded that the longitudinal reinforcement did not play an essential role in the behavior of the beam in Test 4A. Gap opening at the beam-to-wall interfaces and the lack of the angle-to-beam connections in Test 4A prevented the longitudinal steel strains from increasing as the beam was subjected to large nonlinear displacements.
Figure 7.165: Test 4A beam looping reinforcement top longitudinal leg strains –
(a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$; (h) $\varepsilon_{6MT-W}$. 
Figure 7.165 continued.

Figure 7.166: Test 4A beam looping reinforcement bottom longitudinal leg strains –
(a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$;
(f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MB-E}$; (h) $\varepsilon_{6MB-W}$.

720
Figure 7.166 continued.

Figure 7.167: Test 4A beam looping reinforcement top longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)T-E}-\theta_b$; (b) $\varepsilon_{6(1)T-W}-\theta_b$; (c) $\varepsilon_{6(2)T-E}-\theta_b$; (d) $\varepsilon_{6(2)T-W}-\theta_b$; (e) $\varepsilon_{6(3)T-E}-\theta_b$; (f) $\varepsilon_{6(3)T-W}-\theta_b$; (g) $\varepsilon_{6MT-E}-\theta_b$; (h) $\varepsilon_{6MT-W}-\theta_b$. 
Figure 7.167 continued.
Figure 7.168: Test 4A beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)B-E} - \theta_b$; (b) $\varepsilon_{6(1)B-W} - \theta_b$; (c) $\varepsilon_{6(2)B-E} - \theta_b$; (d) $\varepsilon_{6(2)B-W} - \theta_b$; (e) $\varepsilon_{6(3)B-E} - \theta_b$; (f) $\varepsilon_{6(3)B-W} - \theta_b$; (g) $\varepsilon_{6MB-E} - \theta_b$; (h) $\varepsilon_{6MB-W} - \theta_b$. 

723
7.3.15 Beam Transverse Reinforcement Strains

Figure 7.168 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4A. The final strains from Test 4 are used as the “initial” strains; however, since no angle-to-beam connections (applying transverse compression at the beam ends) were used in Test 4A, the initial strain values in the transverse reinforcement at the beam ends are not correct. Therefore, it is important to note the changes in the strain readings rather than the actual strain values during the test. To give more insight into the measurements, Figure 7.169 plots the strain data against the beam chord rotation. It can be seen that the largest strain change in the transverse leg of the looping reinforcement is less than 0.00015 throughout the test. Assuming all of this strain change to be tensile, it is still well below the yield strain of the reinforcing steel ($\varepsilon_{yy} = 0.00283$, see Chapter 4). Note also
that the variation of the beam transverse reinforcement strain with beam chord rotation in Test 4A is different than that in Test 4, which is possibly because of the lack of angle-to-beam connections.

Similarly, Figure 7.170 shows the strain measurements from gauges MH-E and MH-W placed on the vertical legs of the No. 3 transverse hoop at the beam midspan. The locations of these gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4A and the “initial” strains were assumed to be equal to the final strains from Test 4. Note that due to the distance away from the angle-to-beam connections, this assumption can be made. To give more insight into the measurements, Figure 7.171 plots the strain data against the beam chord rotation. It can be seen that the midspan hoop strains remain small throughout the test; and thus, the use of nominal transverse reinforcement within the span of the beam is adequate. Note that these strains are smaller than the strains from previous tests due to the removal of the top and seat angles.
strain gauge 6SE(E)-E removed from Beam #4

strain gauge 6SE(E)-W removed from Beam #4

(a) (b)

test duration

strain, ε

0.00005

no data collected from strain gauge
6SE(I)-W

(c) (d)

Figure 7.169: Test 4A beam looping reinforcement vertical leg strains –
(a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$. 
strain gauge 6SE(E)-E removed from Beam #4

strain gauge 6SE(E)-W removed from Beam #4

(a) beam chord rotation, $\theta_b$(%) 

(b) no data collected from strain gauge 6SE(I)-W

(c) strain, $\varepsilon_{6SE(I)-E}$

(d) strain, $\varepsilon_{6SE(I)-W}$

Figure 7.170: Test 4A beam looping reinforcement vertical leg strains versus beam chord rotation – (a) $\varepsilon_{6SE(E)-E}$-$\theta_b$; (b) $\varepsilon_{6SE(E)-W}$-$\theta_b$; (c) $\varepsilon_{6SE(I)-E}$-$\theta_b$; (d) $\varepsilon_{6SE(I)-W}$-$\theta_b$.

strain gauge MHE removed from Beam #4

(a) test duration

(b) strain, $\varepsilon_{MHE}$

Figure 7.171: Test 4A beam midspan transverse hoop reinforcement strains – (a) $\varepsilon_{MH-E}$; (b) $\varepsilon_{MH-W}$.
7.3.16 Beam Confined Concrete Strains

Figures 7.172 and 7.173 show the measurements from the strain gauges placed on the No. 3 support bars inside the hoop confined concrete at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4A and the “initial” strains were assumed to be equal to the final strains from Test 4 (since the beam post-tensioning tendon in Test 4A was the same as that in Test 3). Note that the initial strains are close to zero. Note also that these initial strain values do not include any reduction in strain due to relaxation losses (between the end of Test 4 and the beginning of Test 4A) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.3.4). Their effects on the strain measurements are expected to be negligible. For further insight into the strain gauge readings, Figures 7.174 and 7.175 plot the strain data against the beam chord rotation. As the beam is rotated in the positive (i.e., clockwise) direction, the compression strains in the bottom bars increase due to the transfer of the contact stresses.
to the bottom corner of the beam. In the opposite (i.e., counterclockwise) direction, the strains in the bottom bars remain relatively constant and negligibly small (since most of the tensile deformations of the beam occur through gap opening). It can be seen that the strain gauge measurements remain below the yield strain $\varepsilon_{hy} = 0.00240$ of the No. 3 support bars in tension and below the expected crushing strain $\varepsilon_{cu} = 0.004$ of the unconfined concrete in compression.

Figure 7.173: Test 4A No. 3 top hoop support bar strains – (a) $\varepsilon_{3THT-(1)}$; (b) $\varepsilon_{3THB-(1)}$; (c) $\varepsilon_{3THT-(2)}$; (d) $\varepsilon_{3THB-(2)}$. 
Figure 7.174: Test 4A No. 3 bottom hoop support bar strains –
(a) $\varepsilon_{3BHB-(1)}$; (b) $\varepsilon_{3BHT-(1)}$; (c) $\varepsilon_{3BHB-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. 

strains gauge 3BHT-(1) removed from Beam #4

strains gauge 3BHT-(2) removed from Beam #4
Figure 7.175: Test 4A No. 3 top hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3THT-(1)} - \theta_b$; (b) $\varepsilon_{3THB-(1)} - \theta_b$; (c) $\varepsilon_{3THT-(2)} - \theta_b$; (d) $\varepsilon_{3THB-(2)} - \theta_b$. 
Figure 7.176: Test 4A No. 3 bottom hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3BHB-(1)}-\theta_b$; (b) $\varepsilon_{3BHT-(1)}-\theta_b$; (c) $\varepsilon_{3BHB-(2)}-\theta_b$; (d) $\varepsilon_{3BHT-(2)}-\theta_b$.

7.3.17 Beam End Confinement Hoop Strains

Figures 7.176 and 7.177 show the measurements from the strain gauges placed on the vertical legs of the bottom layer No. 3 confinement hoops at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4A. The strain gauges were not re-zeroed at the beginning of Test 4A. The final strains from Test 4 are used as the “initial” strains; however, since no angle-to-beam connections (applying transverse compression at the
beam ends) were used in Test 4A, the initial strain values in the transverse reinforcement at the beam ends are not correct. Therefore, it is important to note the changes in the strain readings rather than the actual strain values during the test. For further insight into the measurements, Figures 7.178 and 7.179 plot the strain data against the beam chord rotation. Throughout the test, the changes in the confinement hoop strains remain small.

![Figure 7.177: Test 4A beam end confinement hoop east leg strains – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$.](image1)

![Figure 7.177: Test 4A beam end confinement hoop east leg strains – (a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$.)](image2)
Figure 7.178: Test 4 beam end confinement hoop west leg strains –
(a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$. 
Figure 7.179: Test 4A beam end hoop confinement hoop east leg strains versus beam chord rotation – (a) $\varepsilon_{1HB-E}-\theta_b$; (b) $\varepsilon_{2HB-E}-\theta_b$; (c) $\varepsilon_{3HB-E}-\theta_b$; (d) $\varepsilon_{4HB-E}-\theta_b$. 

strains gauge 2HB-E removed from Beam #4

strains gauge 4HB-E removed from Beam #4
7.3.18 Wall Test Region Confined Concrete Strains

As described previously, the strain gauge wires coming out of the reaction block used in Tests 2 through 4B were all severed during the removal of the steel casting mold. Thus, no measurements were recorded for the wall test wall region confined concrete strains in Test 4A.
7.3.19 Wall Test Region Confinement Hoops Strains

Similar to above, no measurements were recorded for the wall test region confinement hoop strains in Test 4A since the strain gauge wires were severed.

7.3.20 Crack Patterns

Cracks were not marked for Test 4A due to the damage that occurred previously in Test 4.
7.4 Test 4B

The beam used in Test 4B (i.e., Beam 4) has the following properties: (1) beam depth, \( h_b = 18 \text{ in. (457 mm)} \); (2) beam width, \( b_b = 7.5 \text{ in. (191 mm)} \); (3) mild steel reinforcement of two No. 6 bars looping around the beam vertical perimeter along its length; (4) No. 3 full-depth rectangular hoops [6.125 in. by 16.675 in. (156 mm by 424 mm)] placed at a nominal 7.0 in. (178 mm) spacing to provide transverse reinforcement in the beam midspan region; (5) No. 3 partial-depth rectangular hoops [6.125 in. by 4.375 in. (156 mm by 111 mm)] placed at a 1.5 in. (38 mm) spacing to provide concrete confinement at the beam ends; (6) a beam post-tensioning tendon comprised of four 0.6 in. (15.24 mm) nominal diameter high-strength strands with a total area of \( A_{bp} = 0.868 \text{ in.}^2 \) \( (560 \text{ mm}^2) \); (7) average initial beam post-tensioning strand stress of \( f_{bpi} = 0.41 f_{bpu} \), where \( f_{bpu} = 270 \text{ ksi (1862 MPa)} \) is the design maximum strength of the post-tensioning steel; (8) total initial beam post-tensioning force of \( P_{bi} = 96.1 \text{ kips (427 kN)} \); (9) initial beam concrete nominal axial stress (based on actual cross-sectional area with beam post-tensioning duct removed) of \( f_{bc_i} = 0.73 \text{ ksi (5.0 MPa)} \); and (10) two top and two seat angles (L8x8x1/2) with length, \( l_a = b_b = 7.5 \text{ in. (191 mm)} \).

The primary parameter differences of Test 4B from Test 4 are: (1) increased beam post-tensioning area; (2) increased initial beam concrete nominal axial stress; (3) increased top and seat angle strength; and (4) no angle-to-wall connection plates behind the vertical legs of the angles. The same displacement loading history from Test 4 was also used for Test 4B.
7.4.1 Test Photographs

Photographs of the original and displaced subassembly configurations from Test 4B are shown in Figures 7.181 and 7.182. Figures 7.181(a) through 7.181(f) show overall subassembly photographs as follows: (a) pre-test undisplaced position; (b) displaced to $\theta_b = 3.33\%$; (c) displaced to $\theta_b = -3.33\%$; (d) displaced to $\theta_b = 6.4\%$; (e) displaced to $\theta_b = -6.4\%$; and (f) final post-test undisplaced position. Similarly, Figures 7.182(a) through 7.182(f) show close-up photographs of the south end of the beam at the beam-to-reaction-block interface. The accumulation of damage at the south end of the beam is shown in more detail in Figure 7.183.

Up through a beam chord rotation of $\theta_b = 2.25\%$, the wall test region of the reaction block did not receive any additional damage (no cracking and/or spalling of the cover concrete). However, at larger beam chord rotations, cracking and spalling of the cover concrete occurred, especially in the region patched with fiber-reinforced grout after the Test 3 series. Due to the increased post-tensioning force and increased angle strength, this was not unexpected behavior. Minimal additional spalling of the cover concrete at the beam ends was seen up through a beam chord rotation of, approximately, $\theta_b = 3.33\%$. After this rotation, a significant amount of damage occurred at the beam ends, which influenced the behavior of the system as described later.

The angle-to-wall connections performed well with no yielding in the connection strands. A small amount of slip in the angle-to-beam connections was observed during the test, most likely due to the loss of force in the angle-to-beam connection bolts caused by the deterioration of the concrete at the beam ends. Slip between the coupling beam and the walls did not occur demonstrating that the friction resistance due to the post-
tensioning force provided adequate vertical support to the beam together with the resistance from the top and seat angles.

Gap opening formed on both sides of the fiber-reinforced grout column throughout the test as a result of the bond being broken between the grout and the beam ends in Tests 4 and 4A. Crushing of the grout at the beam-to-wall interfaces was observed in the larger displacement cycles, leading to portions of the grout column to separate and fall behind the seat angles. Note that the grout column was left approximately 0.25 in. (6.4 mm) short of the beam depth at the top and bottom, as was done in the previous tests (except Test 1). The poor performance of the grout toward the end of Test 4B most likely occurred due to the repeated loadings through Tests 4, 4A, and 4B combined with the increased stresses in Test 4B.
Figure 7.181: Test 4B overall photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 6.4\%$; (e) $\theta_b = -6.4\%$; (f) final post-test undisplaced position.
Figure 7.182: Test 4B beam south end photographs – (a) pre-test undisplaced position; (b) $\theta_b = 3.33\%$; (c) $\theta_b = -3.33\%$; (d) $\theta_b = 6.4\%$; (e) $\theta_b = -6.4\%$; (f) final post-test undisplaced position.
7.4.2 Beam Shear Force versus Chord Rotation Behavior

Figure 7.184(a) shows the hysteretic coupling beam shear force, $V_b$ versus chord rotation, $\theta_b$ behavior from Test 4B, where $V_b$ and $\theta_b$ are calculated from Equations 5.5 and 5.35, respectively. For comparison, Figure 7.184(b) plots the $V_b-\theta_{b,lb}$ behavior, where $\theta_{b,lb}$ is the beam chord rotation determined from the vertical ($y$-direction) displacement of the load block centroid using Equation 5.36. As shown in Figure 7.184, the structure was able to sustain three cycles at 5.0% rotation with a 9.3% loss in shear resistance. The
subassembly was able to undergo one cycle to a beam chord rotation of 6.4%. During the second cycle to 6.4% rotation, a large portion of the grout column at the north end of the beam fell behind the vertical leg of the seat angle (when the gap was open) leading to the failure of the system as shown in Figure 7.185.

Looking at the hysteresis loops, it can be seen that the specimen was able to dissipate a considerable amount of energy. Most of this energy dissipation occurred due to the yielding of the top and seat angles. The beam had a sufficient amount of restoring force to yield the tension angles back in compression and close the gaps at the beam ends upon unloading, resulting in a large self-centering capability. Starting in the beam chord rotation cycle of 3.33%, a slight decrease in the lateral resistance of the system is seen in each subsequent cycle to a given beam chord rotation. This decrease occurred due to the damage at the beam ends as well as in the wall test region of the reaction block. In the 5.0% and 6.4% beam chord rotation cycles, there are drops (or jumps) in the hysteresis curves, caused by the slipping of the top and seat angles as damage accumulated at the beam ends reducing the angle-to-beam connection force. A considerable reduction in the self-centering capability of the structure can also be seen in the 6.4% cycles. The reduction in the self-centering capability occurred as a result of pieces of grout falling behind the seat angles and preventing the gaps from being fully closed at the beam ends. The test was stopped following this undesirable behavior after the second cycle to 6.4% rotation.
Figure 7.184: Test 4B coupling beam shear force versus chord rotation behavior –  
(a) using beam displacements; (b) using load block displacements.
7.4.3 Beam End Moment Force versus Chord Rotation Behavior

Figure 7.186 shows the hysteretic coupling beam end moment, $M_b$, versus chord rotation, $\theta_b$, behavior from Test 4B, where $M_b$ and is calculated from Equation 5.6 as described in Chapter 5. Since the beam end moment is calculated from the beam shear force, the results shown in Figure 7.186 are directly related to the results in Figure 7.184, and thus, no further discussion is provided herein.
7.4.4 Beam Post-Tensioning Forces

The coupling beam post-tensioning strand forces from the test are measured using load cells LC15 – LC18 mounted at the dead ends of the four strands (see Chapter 5). As described previously, a fourth post-tensioning strand was used in Test 4B in addition to the three strains in Tests 4 and 4A. Load cells LC15 – LC17 measured the forces in the original three strands and LC18 measured the force in the added strand. The forces from the four load cells, $F_{LC15}$, $F_{LC16}$, $F_{LC17}$, and $F_{LC18}$ are shown in Figure 7.187, and are plotted against the beam chord rotation, $\theta_b$ in Figure 7.188. Figure 7.189 shows the total beam post-tensioning tendon force, $P_{bp}$ (sum of the forces in the four strands) normalized.
with the total design ultimate strength of the tendon, $\Sigma a_{tip},f_{tpu}$. The total initial beam post-tensioning tendon force is equal to 96.1 kips (427 kN), resulting in an initial beam concrete nominal axial stress of $f_{bci} = 0.73$ ksi (5.0 MPa). Note that the increase in the beam post-tensioning tendon area allowed for a higher beam post-tensioning force, resulting in a higher concrete axial stress in Test 4B than in Tests 4 and 4A. The fourth post-tensioning strand was jacked while the original three strands were in place. It can be seen that the initial stresses in these three strands at the beginning of Test 4B are slightly lower than the final stresses in Test 4A. This reduction in prestress may have occurred due to some relaxation in the strands after Test 4A as well as due to additional shortening of the subassembly as the total post-tensioning force was increased.

Figures 7.188 and 7.189 show that as the structure is displaced and gap opening occurs at the beam ends, the post-tensioning strands elongate and the post-tensioning forces increase. Since the strands are unbonded over the entire length of the subassembly, the nonlinear straining of the post-tensioning steel is significantly delayed. Accumulation of damage at the beam ends, the grout, and the wall test region at large rotations of the beam led to non-symmetric behavior and “jumps” in the post-tensioning forces. The steps taken to help prevent premature wire fracture of the post-tensioning strands (i.e., the use of reduced initial post-tensioning stresses and the use of extra anchor barrels to help reduce strand “kinking” inside the anchor wedges) were successful to achieve satisfactory performance of the strand/anchor system during the test.
Post-Tensioning Strand Force 1

Post-Tensioning Strand Force 2

Post-Tensioning Strand Force 3

Post-Tensioning Strand Force 4

Figure 7.187: Test 4B beam post-tensioning strand forces – (a) strand 1; (b) strand 2; (c) strand 3; (d) strand 4.
Figure 7.188: Test 4B $F_{LC-\theta_b}$ behavior –
(a) strand 1; (b) strand 2; (c) strand 3; (d) strand 4.
Figure 7.189: Test 4B beam post-tensioning force versus chord rotation behavior – (a) using beam displacements; (b) using load block displacements.
7.4.5 Angle-to-Wall Connection Post-Tensioning Forces

The beam south end (i.e., reaction block end) angle-to-wall connection post-tensioning strand forces, $F_{LC3} - F_{LC6}$, measured using load cells LC3 – LC6, respectively, are shown in Figures 7.190 through 7.194. The target initial force for each connection strand is 20 kips (89 kN); whereas, the measured initial forces in the four strands are $F_{i,LC3} = 27.1$ kips (121 kN), $F_{i,LC4} = \text{not working}$, $F_{i,LC5} = 30.4$ kips (135 kN), and $F_{i,LC6} = 33.4$ kips (149 kN). A significant variation is observed in the initial connection strand forces since even a slight difference in the amount of anchor wedge seating has a large effect on the initial force (due to the short length of the strands).

Figures 7.194(a) and 7.194(b) show the total forces in the south top and south seat angle connection strands, respectively, plotted against the beam chord rotation, $\theta_b$. The connection forces are normalized with the total design ultimate strength of the strands, $P_{abu} = \sum a_{ap} f_{apu}$, where $f_{apu} = 270$ ksi (1862 MPa). The expected behavior of the strands is that as the structure is displaced and the angles are pulled in tension, the connection forces increase, and upon unloading, the connection forces return more or less back to the initial forces with possibly some losses occurring due to additional seating of the anchor wedges and any permanent deformations in the concrete (note that the nonlinear straining of the post-tensioning steel is prevented since the strands are left unbonded). These trends are not seen in Test 4B, possibly due to the damage occurring at the beam ends and in the wall test region, and/or due to the malfunctioning of the load cells under the non-uniform loads applied on the load cells during the prying deformations of the angles.
Figure 7.190: Test 4B south end top angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.191: Test 4B south end angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LC3} - \theta_b$; (b) $F_{LC4} - \theta_b$. 

753
Figure 7.192: Test 4B south end seat angle-to-wall connection strand forces – (a) east strand; (b) west strand.

Figure 7.193: Test 4B south end angle-to-wall connection strand forces versus beam chord rotation – (a) $F_{LCS}-\theta_b$; (b) $F_{LCS}-\theta_b$. 
7.4.6 Vertical Forces on Wall Test Region

Load cells LC7 – LC14 are used to measure the forces in the eight vertical bars applying axial compression forces to the wall test region of the reaction block and anchoring the block to the strong floor. The total vertical force, $F_{wt}$ can be determined as described in Chapter 5, with the target initial total force ranging between 150 – 160 kips (667 – 712 kN). Figure 7.195(a) shows $F_{wt}$ for the duration of the test and Figure 7.195(b) plots $F_{wt}$ against the beam chord rotation, $\theta_b$. The initial total force, $F_{wt,i}$ is 165 kips (734 kN), slightly above the target force range. Note that the vertical force was increased following Test 4A to accommodate the expected higher forces on the reaction block. The effect of the increased vertical force on the other subassembly measurements (e.g., strain gauges) is assumed to be negligible. As the beam is displaced in the positive (i.e., clockwise) direction, $F_{wt}$ decreases since the beam applies a downward force on the reaction block. Similarly, as the beam is displaced in the negative (i.e., counterclockwise)
direction, $F_{wt}$ increases since the beam applies an upward force on the reaction block. Note that, as described in Chapter 5, the amount of variation in $F_{wt}$ during the cyclic displacements of the beam is relatively small as compared with the expected variation of axial forces in the wall pier coupling regions of a multi-story coupled wall system. Upon unloading, $F_{wt}$ returns more or less to its initial value.

![Graphs showing vertical force on wall test region](image)

Figure 7.195: Test 4B vertical force on the wall test region, $F_{wt} -$
(a) $F_{wt}$-test duration; (b) $F_{wt}$-$\theta_B$.

### 7.4.7 Beam Vertical Displacements

The vertical displacements $\Delta_{DT9}$ and $\Delta_{DT10}$ at the south and north ends of the beam are measured using string pots DT9 and DT10, respectively. These displacements are used to calculate the beam chord rotation, $\theta_B$. As described in Chapter 5, as the subassembly is displaced, the transducer string undergoes a change of angle, which can be “adjusted” to give the vertical displacements in the $y$-direction. Figures 7.196 and 7.197 show the measured displacements at $\Delta_{DT9}$ and $\Delta_{DT10}$, respectively, the
corresponding adjusted $y$-displacements $\Delta_{DT9,y}$ and $\Delta_{DT10,y}$, respectively, and the difference between the measured and adjusted displacements for the duration of the test. Note that the displacement measurement $\Delta_{DT9}$ displays a downward shift from the origin in Figure 7.196 throughout the test, which occurred due to the shifting of the ferrule insert as damage accumulated at the south end of the beam.

It can be seen from Figures 7.196 and 7.197 that $\Delta_{DT9}$ and $\Delta_{DT10}$ are close to $\Delta_{DT9,y}$ and $\Delta_{DT10,y}$, respectively, with the difference being less than 0.06 in. (1.5 mm). Figure 7.198 plots the percent difference between the measured and adjusted displacements versus the beam chord rotation, $\theta_b$. The results indicate that the largest percent differences for $\Delta_{DT10}$ occur when the beam chord rotation is close to zero; however, these differences are not significant since the corresponding measurements are very small and are mostly outside of the sensitivity of the transducers. The percent differences for $\Delta_{DT9}$ remain less than 8.0% for the duration of the test. Similar to Test 3B, the measurements from DT9 and DT10 require larger adjustments than seen in the virgin beam tests (Tests 1 – 4) and post-virgin beam Tests 3A and 4A, possibly due to the accumulation of damage at the beam ends and/or the pieces of grout falling behind the vertical legs of the seat angles. It is also observed that for negative rotations, DT9 displays a larger error than under positive rotations because the measured displacements under negative rotations are smaller (possibly due to the drift in the data) than the measured displacements under positive rotations. Therefore, similar differences between the measured and adjusted displacements under the negative and positive directions result in larger percent errors in the negative direction. Since the adjustments described in Chapter 5 require certain assumptions and approximations and since the amplitude differences (which are more
important than percent differences for the calculation of the beam chord rotation) between the measured and adjusted displacements remain small, these differences are ignored and the measurements from DT9 and DT10 are used as the vertical $y$-displacements of the beam throughout this dissertation. Figure 7.199 plots the measured data from DT9 and DT10 against the beam chord rotation, $\theta_b$.

Figure 7.196: Test 4B south end beam vertical displacement – (a) measured, $\Delta_{DT9}$; (b) adjusted, $\Delta_{DT9y}$; (c) difference, $\Delta_{DT9y} - \Delta_{DT9}$.
Figure 7.197: Test 4B north end beam vertical displacement—
(a) measured, $\Delta DT10$; (b) adjusted, $\Delta DT10_y$; (c) difference, $\Delta DT10_y - \Delta DT10$.

Figure 7.198: Test 4B percent difference between measured and adjusted displacements—
(a) south end, DT9; (b) north end, DT10.
7.4.8 Beam Chord Rotation

The beam chord rotation is defined as the relative vertical displacement of the beam ends divided by the beam length. The beam chord rotation $\theta_b$ determined based on the $\Delta DT9$ and $\Delta DT10$ measurements in Test 4B is shown in Figure 7.200(a). For comparison, Figure 7.200(b) shows the load block beam chord rotation, $\theta_{b,lb}$ calculated using $\Delta_{LB,y}$, and Figure 7.201 shows the percent difference between $\theta_b$ and $\theta_{b,lb}$ plotted against $\theta_b$. It can be seen that there is a large percent difference for small beam chord rotations; with the difference dropping down to less than 20% at larger beam rotations. Figure 7.202 plots the beam chord rotation, $\theta_b$ and the load block beam chord rotation, $\theta_{b,lb}$ against the beam chord rotation, $\theta_b$. The results show that as damage occurs at the beam ends and the ferrule insert anchors loosen, the beam chord rotation drifts slightly away from the origin. Due to the pieces of grout falling behind the vertical legs of the
seat angles, the load block beam chord rotation shifts as the load block is pushed horizontally and rotated away from the beam.

Figure 7.200: Test 4B beam chord rotation – (a) $\theta_b$ from $\Delta_{DT9}$ and $\Delta_{DT10}$; (b) $\theta_{b,lb}$ from $\Delta_{LB,y}$. 

761
7.4.9 Local Beam Rotations

Local beam rotations were measured using two rotation transducers (inclinometers); one near the south end of the beam (RT1) and the other near the midspan (RT2). Figure 7.203 shows the time history results, $\theta_{RT1}$ and $\theta_{RT2}$ from these transducers.
and Figures 7.204(a) and 7.204(b) compare $\theta_{RT1}$ and $\theta_{RT2}$, respectively, with the beam chord rotation, $\theta_b$. Note that RT1 is affected by the loosening of the ferrule insert anchor near the beam end and the measurements from RT2 show some shift in the data, especially towards that later cycles. This shift may have occurred due to the pieces of grout falling behind the vertical legs of the seat angles. The rotation measurements are positive when the load block is displaced in the downward direction (i.e., clockwise beam rotation). As a result of the bending deformations over the length of the beam, it may be expected that the midspan rotation, $\theta_{RT2}$ is larger than the chord rotation, $\theta_b$, and that the chord rotation is larger than the end rotation, $\theta_{RT1}$ [see Figure 7.204(c)]. However, since the nonlinear lateral displacements of the beam are primarily governed by the gap opening at the ends, the differences in the measured end, midspan, and chord rotations for the test beams are in general too small to make conclusive comparisons, and the different instruments utilized for the chord rotation measurements (using displacement transducers) and for the beam end and midspan rotation measurements (using rotation transducers) further make these comparisons difficult.
Figure 7.203: Test 4B beam inclinometer rotations –  
(a) near beam south end, $\theta_{RT1}$; (b) near beam midspan, $\theta_{RT2}$. 
7.4.10 Load Block Displacements and Rotations

String pots DT3 – DT5 are used to measure the vertical $y$-displacements and the horizontal $x$-displacement of the load block. Similar to the vertical beam displacements, as the load block is displaced, the strings of the load block displacement transducers undergo a change in angle; and thus, their measurements may need to be adjusted to give the $x$- and $y$-displacements of the load block as described in Chapter 5.

Figures 7.205 through 7.207 show the measured displacements $\Delta_{DT3}$, $\Delta_{DT4}$, and $\Delta_{DT5}$, respectively, the corresponding adjusted displacements $\Delta_{DT3,x}$, $\Delta_{DT4,y}$, and $\Delta_{DT5,y}$, respectively, and the percent differences between the measured and adjusted
displacements. Note that, as described in Chapter 5, the negative $\Delta_{DT3}$ and $\Delta_{DT3,x}$ measurements indicate the movement of the load block in the north direction, away from the reaction block. It can be seen that the difference between $\Delta_{DT3}$ and $\Delta_{DT3,x}$ is well over 10% for much of the duration of the test; and thus, adjustments need to be applied to the measurements from DT3. In comparison, the adjustments needed for the vertical displacement measurements from DT4 and DT5 remain small throughout the test with the largest difference being less than 4.0%. Figure 7.208 shows the percent difference between the measured and adjusted displacements for DT4 and DT5 plotted against the beam chord rotation, $\theta_b$. It can be seen that away from the origin, the maximum differences between the unadjusted and adjusted measurements from DT4 and DT5 remain less than 0.5%.

The measurements from DT3 require larger adjustments than those from DT4 and DT5 since the changes in the string angle for DT3, which occur due to the applied vertical displacements of the structure, are much larger than the changes in the string angles for DT4 and DT5, which occur due to the gap opening displacements at the beam ends. In evaluating the results from Test 4B, adjusted measurements are used for $\Delta_{DT3}$; however, the measurements for $\Delta_{DT4}$ and $\Delta_{DT5}$ are not adjusted. Figure 7.209 plots $\Delta_{DT4}$, $\Delta_{DT5}$, and $\Delta_{DT3,x}$ against the beam chord rotation, $\theta_b$, respectively. It can be seen in Figures 7.209(a) and 7.209(b) that the vertical displacements of the load block at the north and south ends are nearly the same.

Combining these displacements, the $x$-displacement, $y$-displacement, and rotation of the load block centroid can be determined as described in Chapter 5 and shown in Figures 7.210 and 7.211. Figure 7.210(a) plots the $y$-displacement versus the $x$-
displacement showing the path of the load block centroid during the test. As the subassembly is displaced under positive (i.e., clockwise) and negative (i.e., counterclockwise) rotations, the load block is pushed north in the $x$-direction (away from the reaction block) due to the gap opening at the beam ends. After each cycle, the load block returns to its initial position with minimal residual displacements (with the exception of the last few cycles after the falling of grout pieces behind the seat angles, resulting in a loss of self-centering capability). Figures 7.210(a) and 7.211(a) show that the $x$-direction displacements of the load block centroid are smaller during the negative rotations of the subassembly as compared to the displacements during the positive rotations. The increased horizontal displacements of the load block under positive rotations, as well as the residual horizontal displacement of the load block centroid seen in Figures 7.210(a) and 7.210(c), is possibly due to the pieces of grout falling behind the vertical legs of the seat angles. In the $y$-direction, the load block displaces nearly symmetric (there is a slightly larger displacement under positive rotation) during the positive and negative rotations as shown in Figures 7.209(a), 7.209(b), 7.210(d), and 7.211(b). Finally, the rotation of the load block is shown to remain small throughout the duration of the test as shown in Figures 7.210(b) and 7.211(c). The load block rotation remains below 0.003 radians indicating that the two hydraulic actuators moved near simultaneously.
Figure 7.205: Test 4B load block horizontal displacements – (a) measured, $\Delta DT_3$; (b) adjusted, $\Delta DT_{3,x}$; (c) percent difference.
Figure 7.206: Test 4B load block north end vertical displacements—
(a) measured, $\Delta DT_4$; (b) adjusted, $\Delta DT_{4,y}$; (c) percent difference.
Figure 7.207: Test 4B load block south end vertical displacements – (a) measured, \( \Delta DT_5 \); (b) adjusted, \( \Delta DT_{5,y} \); (c) percent difference.

Figure 7.208: Test 4B percent difference between measured and adjusted displacements versus beam chord rotation – (a) DT4; (b) DT5.
Figure 7.209: Test 4B load block displacements versus beam chord rotation – (a) $\Delta_{DT4} \theta_b$; (b) $\Delta_{DT5} \theta_b$; (c) $\Delta_{DT3x} \theta_b$. 
Figure 7.210: Test 4B load block centroid displacements –
(a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
Figure 7.211: Test 4B load block centroid displacements versus beam chord rotation – (a) x-displacement-θ_b; (b) y-displacement-θ_b; (c) rotation-θ_b.

### 7.4.11 Reaction Block Displacements and Rotations

String pots DT6 – DT8 are used to measure the vertical y-displacements and the horizontal x-displacement of the reaction block. Figure 7.212 shows the measurements from DT6 – DT8 for the duration of the test. Since the reaction block is tied to the strong floor, the measured displacements remain very small throughout the test. Due to these small displacements and the use of lead cables for each string pot, the change in angle that the string undergoes during testing is very small. Thus, it can be assumed that no
adjustments are needed for the displacements measured from the reaction block
displacement transducers. Figure 7.213 plots the measurements from DT6 – DT8 against
the beam chord rotation.

The \( x \)-displacement, \( y \)-displacement, and rotation of the reaction block centroid
can be determined (see Chapter 5) as shown in Figure 7.214 and plotted against the beam
chord rotation in Figure 7.215. It is concluded that the vertical displacements of the
reaction block do not have a significant effect on the displacements of the test structure
(e.g., the beam chord rotation), and the test results are evaluated with the reaction block
displacements taken as zero (i.e., the measured displacements of the reaction block are
ignored in investigating the response of the subassembly). Note that the horizontal
displacements of the reaction block are significant when determining the total elongation
of the post-tensioning tendon; and thus, are included in those calculations.
Figure 7.212: Test 4B reaction block displacements –
(a) $\Delta_{D76}$; (b) $\Delta_{D77}$; (c) $\Delta_{D78}$. 
Figure 7.213: Test 4B reaction block displacements versus beam chord rotation –  
(a) $\Delta_{DT7} - \theta_b$; (b) $\Delta_{DT8} - \theta_b$; (c) $\Delta_{DT9} - \theta_b$. 
Figure 7.214: Test 4B reaction block centroid displacements – (a) $x$-$y$ displacements; (b) rotation; (c) $x$-displacements; (d) $y$-displacements.
7.4.12 Contact Depth and Gap Opening at Beam-to-Wall Interfaces

The beam contact depth and gap opening displacements are measured at the beam-to-reaction-block interface using displacement transducers DT11–DT13. Note that since the beam post-tensioning tendon in Test 4B was the same as that in Test 4A with the addition of a fourth strand, the contact depth and gap opening transducers were not re-zeroed at the beginning of Test 4B. The transducers were initialized and zeroed prior to the application of the post-tensioning force at the beginning of Test 4. Note that
deformation (i.e., shortening) due to the increased post-tensioning tendon force (i.e., the addition of the fourth post-tensioning strand) is captured by the transducers. As described in Chapter 5, these LVDTs rotate with the beam, and thus, their measurements may need to be adjusted to determine the gap opening displacements in the horizontal $x$-direction.

Figures 7.216 through 7.218 plot the measured displacements $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$, respectively, the corresponding adjusted $x$-displacements $\Delta_{DT11,x}$, $\Delta_{DT12,x}$, and $\Delta_{DT13,x}$, respectively, and the percent differences between the measured and adjusted displacements. The results indicate that the adjusted measurements are less than 3.0% different from the original measurements, and thus, $\Delta_{DT11}$, $\Delta_{DT12}$, and $\Delta_{DT13}$ can be taken as the displacements in the $x$-direction. Figure 7.219 plots the measured data from DT11, DT12, and DT13 against the beam chord rotation.

The maximum average concrete compressive strain in the beam-to-wall contact regions can be calculated by dividing the measured displacements from DT11 and DT13 with the gauge length (i.e., the distance from the LVDT ferrule insert in the beam to the reaction plate ferrule insert in the wall test region; see Chapter 5). For Test 4B, the maximum average compressive strain is 0.0046. Note that this measurement includes the compressive strain occurring in the fiber-reinforced grout at the beam-to-wall interface as well as the patched concrete deformations in wall test region of the reaction block.
Figure 7.216: Test 4B beam-to-reaction-block interface top LVDT displacements – (a) measured, $\Delta DT_{11}$; (b) adjusted, $\Delta DT_{11,x}$; (c) percent difference.
Figure 7.217: Test 4B beam-to-reaction-block interface middle LVDT displacements – (a) measured, $\Delta_{DT1}$; (b) adjusted, $\Delta_{DT1,x}$; (c) percent difference.
Figure 7.218: Test 4B beam-to-reaction-block interface bottom LVDT displacements – (a) measured, $\Delta_{DT13}$; (b) adjusted, $\Delta_{DT13,x}$; (c) percent difference.
Using the measured data, the contact depth and the largest (i.e., at the beam top and bottom) gap opening displacements at the beam-to-reaction-block interface can be determined following the procedures in Chapter 5. Figures 7.220(a) and 7.221(a) show the results based on the measured data from DT11 – DT13 (method 1); Figures 7.220(b) and 7.221(b) show the results based on the measured data from RT1, DT11, and DT13 (method 2); Figures 7.220 (c) and 7.221(c) show the results based on the measured data from RT1 and DT12 (method 3); Figures 7.220(d) and 7.221(d) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT12 (method 4); and Figures
7.220(e) and 7.221(e) show the results based on the beam chord rotation, $\theta_b$ and the measurements from DT11 and DT13 (method 5). Each $\circ$ marker indicates the contact depth or gap opening displacement at the peak of a loading cycle up to a beam chord rotation of 6.4%. Note that, as described in Chapter 5, the contact depth and gap opening results from methods 1, 3, and 4 are valid only when $\Delta_{DT12}$ is positive (i.e., the gap extends beyond the level of DT12 and the contact depth is less than $h_b/2$). Figures 7.220 and 7.221 show the results within the validity range of these methods.

Looking at Figure 7.220, it can be stated that the contact depth results obtained using the five methods are somewhat different (possibly because of differences in the measurements used in the different methods and different amounts of loosening in the sensor inserts as damage occurred at the beam ends, especially since the contact depth calculations are sensitive to these measurement differences) but show similar trends. There is a rapid reduction in the contact depth up to a beam chord rotation of about 2.0%. After this rotation, the contact depth remains relatively stable due to nonlinear behavior of the concrete in compression. In comparison, the gap opening results obtained using the five methods in Figure 7.221 are reasonably similar and the increase in gap opening with the rotation of the beam is very close to linear.

Figure 7.222 shows a continuous plot of the largest gap opening displacements determined from method 4 (using the beam chord rotation and DT12) against the beam chord rotation. Similarly, Figure 7.223(a) plots the beam contact depth from method 4 against the beam chord rotation as continuous data. Furthermore, Figures 7.223(b) and 7.223(c) show continuous plots of the contact depth during the 2.25% and 5.0% beam chord rotation cycles, respectively. Note that method 3 (using the measured data from
RT1 and DT12) can also be used to obtain the continuous plots above; however, the measurements from RT1 were found to be not always reliable (especially at small rotations); and thus, method 4 is used instead. The gap opening and contact depth plots in Figures 7.222 and 7.223 could have been affected by the use of $\theta_b$ (i.e., chord rotation) instead of $\theta_{RT1}$ (i.e., local rotation) to determine the behavior of the south end of the beam. The use of the beam mid-height transducer DT12 instead of the extreme beam top and bottom transducer (DT11 or DT13) may also have affected the results, especially the contact depth plots in Figure 7.223, which are very sensitive to the measurements. The estimated contact depths at small beam rotations ($\theta_b < 0.25\%$) should be used with caution.

Unlike Test 4 in Chapter 6, no ruler measurements of the gap opening displacements were taken during Test 4B (Table 7.4).
Figure 7.220: Test 4B contact depth at beam-to-reaction-block interface – (a) method 1 using DT11, DT12, and DT13; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using DT12 and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.221: Test 4B gap opening at beam-to-reaction-block interface –
(a) method 1 using $\Delta DT11$, $\Delta DT12$, and $\Delta DT13$; (b) method 2 using RT2, DT11, and DT13; (c) method 3 using RT2 and DT12; (d) method 4 using $\Delta DT12$ and $\theta_b$; (e) method 5 using $\theta_b$, DT11, and DT13.
Figure 7.222: Test 4B gap opening at beam-to-reaction-block interface using method 4.

Figure 7.223: Test 4B contact depth at beam-to-reaction-block interface –
(a) method 4 using $\Delta DT12$ and $\theta_{b,b}$; (b) 2.25% beam chord rotation cycle; (c) 5.0% beam chord rotation cycle.
TABLE 7.4

RULER MEASUREMENTS OF GAP OPENING AT SOUTH BEAM END

<table>
<thead>
<tr>
<th>Nominal Rotation (%)</th>
<th>Gap Opening, $\Delta g$ [in. (mm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no measurements taken</td>
<td></td>
</tr>
</tbody>
</table>

7.4.13 Wall Test Region Local Concrete Deformations

The reaction block confined concrete deformations near the beam-to-wall interface of the wall test region are measured using displacement transducers DT14 and DT15. Figure 7.224 plots the time history results from the top (DT14) and bottom (DT15) transducers and Figure 7.225 plots the measured data from DT14 and DT15 against the beam chord rotation. As expected, the concrete deformations are mostly compressive (negative), due to the compression stresses that are transferred through the contact region from post-tensioning and gap opening. Note that DT14 has a sudden jump that is most likely due to the loosening of the ferrule insert anchors in the wall test region.

From Figure 7.225, the maximum average concrete compressive strain in the wall test region can be calculated by dividing the measured deformations with the gauge length (i.e., the distance from the LVDT ferrule insert in the wall test region to the reaction plate; see Chapter 5). For Test 4B, the maximum average concrete compressive strain is 0.0217, which is greater than the expected unconfined (cover) concrete crushing strain of 0.004 but less than the confined concrete crushing strain estimate of 0.037. This is in
accordance with the observed behavior of the reaction block during the test. Note that most of the compressive strains in the wall test region occurred in the patched concrete.

![Graph](attachment:image.png)

Figure 7.224: Test 4B wall test region concrete deformations – (a) DT14; (b) DT15.

![Graph](attachment:image.png)

Figure 7.225: Test 4B wall test region concrete deformations versus beam chord rotation – (a) $\Delta_{DT14}-\theta_b$; (b) $\Delta_{DT15}-\theta_b$. 
7.4.14 Beam Looping Reinforcement Longitudinal Leg Strains

Figures 7.226 and 7.227 show the strain gauge measurements for the top and bottom horizontal legs of the east and west No. 6 mild steel looping reinforcing bars in the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed prior to applying force to the addition (i.e., fourth) post-tensioning strand in Test 4B. The “initial” strains were assumed to be the equal to the final strains from Test 4A (since the beam post-tensioning strands in Test 4A were used in Test 4B); and thus, the gauge measurements captured any additional compressive strain due to the force applied to the fourth post-tensioning strand. Note that these “initial” values do not include any reduction in strain due to relaxation losses (between the end of Test 4A and the beginning of Test 4B) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.4.4) and their effects on the strain measurements are expected to be negligible. Upon lateral loading of the subassembly, the largest tensile strains occur, as expected, in the gauges closest to the angle-to-beam connection bolts [i.e., gauges 6(1)T-E, 6(1)T-W, 6(1)B-E, and 6(1)B-W]. The measurements in the gauges away from the angle-to-beam connection decrease with distance from this critical location.

To provide a better understanding of the strain measurements in the horizontal legs of the beam looping reinforcement, the △ and □ markers in Figures 7.226a) and 7.226(b) for gauges 6(1)T-E and 6(1)T-W correspond to positive and negative chord rotation peaks for the beam, respectively, and the ○ markers indicate zero rotation positions. To provide further insight into the results, Figures 7.228 and 7.229 show the strains plotted against the beam chord rotation. In the positive (i.e., clockwise) rotation
direction, the strains in the top bars increase in tension as the gap opens at the top south corner of the beam and the top angle is pulled in tension. In the negative (i.e., counterclockwise) direction, the strains in the bottom bars increase in tension and the top bars go into compression due to the closing of the gap.

The horizontal lines in Figures 7.226 through 7.229 show the yield strain of the longitudinal steel ($\varepsilon_{ly} = 0.00283$) from the material tests in Chapter 4. The maximum strains in the four gauges closest the critical section (angle-to-beam connection) remain below the yield strain of the longitudinal steel until the 6.4% beam chord rotation cycle; and thus, it is concluded that the amount of mild steel reinforcement used to transfer the angle forces into the beam is adequate.

![Graph](image)

Figure 7.226: Test 4B beam looping reinforcement top longitudinal leg strains – (a) $\varepsilon_{6(1)T-E}$; (b) $\varepsilon_{6(1)T-W}$; (c) $\varepsilon_{6(2)T-E}$; (d) $\varepsilon_{6(2)T-W}$; (e) $\varepsilon_{6(3)T-E}$; (f) $\varepsilon_{6(3)T-W}$; (g) $\varepsilon_{6MT-E}$; (h) $\varepsilon_{6MT-W}$.
Figure 7.226 continued.
Figure 7.227: Test 4B beam looping reinforcement bottom longitudinal leg strains –
(a) \( \varepsilon_{b(1)B-E} \); (b) \( \varepsilon_{b(1)B-W} \); (c) \( \varepsilon_{b(2)B-E} \); (d) \( \varepsilon_{b(2)B-W} \); (e) \( \varepsilon_{b(3)B-E} \); (f) \( \varepsilon_{b(3)B-W} \);
(g) \( \varepsilon_{bMB-E} \); (h) \( \varepsilon_{bMB-W} \).
Figure 7.227 continued.

Figure 7.228: Test 4B beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)B-E}$; (b) $\varepsilon_{6(1)B-W}$; (c) $\varepsilon_{6(2)B-E}$; (d) $\varepsilon_{6(2)B-W}$; (e) $\varepsilon_{6(3)B-E}$; (f) $\varepsilon_{6(3)B-W}$; (g) $\varepsilon_{6MB-E}$; (h) $\varepsilon_{6MB-W}$. 

\[ \varepsilon_{ly} = 0.00283 \]
Figure 7.228 continued.

Figure 7.229: Test 4B beam looping reinforcement bottom longitudinal leg strains versus beam chord rotation – (a) $\varepsilon_{6(1)B-E-\theta_b}$; (b) $\varepsilon_{6(1)B-W-\theta_b}$; (c) $\varepsilon_{6(2)B-E-\theta_b}$; (d) $\varepsilon_{6(2)B-W-\theta_b}$; (e) $\varepsilon_{6(3)B-E-\theta_b}$; (f) $\varepsilon_{6(3)B-W-\theta_b}$; (g) $\varepsilon_{6MB-E-\theta_b}$; (h) $\varepsilon_{6MB-W-\theta_b}$. 

$\varepsilon_{6b} = 0.00283$
Figure 7.229 continued.
7.4.15 Beam Transverse Reinforcement Strains

Figure 7.230 shows the strain measurements from gauges 6SE(I)-E, 6SE(E)-E, 6SE(I)-W, and 6SE(E)-W placed on the transverse (i.e., vertical) legs of the east and west No. 6 looping reinforcing bars at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4B. The “initial” strains, prior to connecting the top and seat angles, were assumed to be equal to the final strains from Test 4A; and thus, the gauge measurements capture any additional compressive strain due to the angle-to-beam connections (applying transverse compression at the beam ends). However, the assumption for the “initial” strain might not be accurate since no angle-to-beam connections were used in Test 4A; therefore, it is important to note the changes in the strain reading rather than the actual strain values during the test. To give more insight into the measurements, Figure 7.231 plots the strain data against the beam chord rotation. It can be seen that the largest strain change in the transverse leg of the looping reinforcement in Test 4B is approximately 0.002. Assuming all of this strain change to be tensile, it is still below the yield strain of the reinforcing steel (\(\varepsilon_{yw} = 0.00283\), see Chapter 4), demonstrating that the design of the transverse reinforcement at the beam end is adequate. Note that the angle-to-beam connection bolts may have acted as transverse reinforcement in the beam; however, this could not be confirmed from the test results since the connection bolts were not instrumented.

Similarly, Figure 7.232 shows the strain measurements from gauges MH-E and MH-W placed on the vertical legs of the No. 3 transverse hoop at the beam midspan. The locations of these gauges can be found in Chapter 5. The strain gauges were not re-zeroed
at the beginning of Test 4B and the “initial” strains were assumed to be equal to the final strains from Test 4A. Note that due to the distance away from the angle-to-beam connections, this assumption can be made. To give more insight into the measurements, Figure 7.233 plots the strain data against the beam chord rotation. It can be seen that the midspan hoop strains remain small throughout the test; and thus, the use of nominal transverse reinforcement within the span of the beam is adequate.

Figure 7.230: Test 4B beam looping reinforcement vertical leg strains –
(a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$. 

*Figure 7.230: Test 4B beam looping reinforcement vertical leg strains – (a) $\varepsilon_{6SE(E)-E}$; (b) $\varepsilon_{6SE(E)-W}$; (c) $\varepsilon_{6SE(I)-E}$; (d) $\varepsilon_{6SE(I)-W}$.***
strain gauge 6SE(E)-E removed from Beam #4

strain gauge 6SE(E)-W removed from Beam #4

(a) beam chord rotation, $\theta_b$ (%)

(b) no data collected from strain gauge 6SE(I)-W

(c) $\varepsilon_{6SE(E)-E} - \theta_b$

(d) $\varepsilon_{6SE(I)-W} - \theta_b$

Figure 7.231: Test 4B beam looping reinforcement vertical leg strains versus beam chord rotation behavior – (a) $\varepsilon_{6SE(E)-E} - \theta_b$; (b) $\varepsilon_{6SE(E)-W} - \theta_b$; (c) $\varepsilon_{6SE(I)-E} - \theta_b$; (d) $\varepsilon_{6SE(I)-W} - \theta_b$. 
7.4.16 Beam Confined Concrete Strains

Figures 7.234 and 7.235 show the measurements from the strain gauges placed on the No. 3 support bars inside the hoop confined concrete at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed prior to applying force to the addition (i.e., fourth) post-tensioning strand in Test 4B. The “initial” strains were assumed to be the equal to the final strains from Test
4A (since the beam post-tensioning strands in Test 4A were used in Test 4B); and thus, the gauge measurements captured any additional compressive strain due to the force applied to the fourth post-tensioning strand. Note that these “initial” values do not include any reduction in strain due to relaxation losses (between the end of Test 4A and the beginning of Test 4B) in the beam post-tensioning tendon force; however, these losses are small (see Section 7.4.4) and their effects on the strain measurements are expected to be negligible. For further insight into the strain gauge readings, Figures 7.236 and 7.237 plot the strain data against the beam chord rotation. The results show that there is a small compressive strain at the beginning of the test due to the initial post-tensioning force. As the beam is rotated in the positive (i.e., clockwise) direction, the compression strains in the bottom bars increase due to the transfer of the contact stresses to the bottom corner of the beam. In the opposite (i.e., counter clockwise) direction, the strains in the top and bottom bars reverse due to the reversal of the load. It can be seen that the strain gauge measurements from the support bars remain below the yield strain $\varepsilon_{hy} = 0.00240$ of the No. 3 support bars in tension and below the expected crushing strain $\varepsilon_{cu} = 0.004$ of the unconfined concrete in compression.
Figure 7.234: Test 4B No. 3 top hoop support bar strains —
(a) $\varepsilon_{3THT-(1)}$; (b) $\varepsilon_{3THB-(1)}$; (c) $\varepsilon_{3THT-(2)}$; (d) $\varepsilon_{3THB-(2)}$. 
Figure 7.235: Test 4B No. 3 bottom hoop support bar strains –
(a) $\varepsilon_{3BHB-(1)}$; (b) $\varepsilon_{3BHT-(1)}$; (c) $\varepsilon_{3BHB-(2)}$; (d) $\varepsilon_{3BHT-(2)}$. 

strain gauge 3BHT-(1) removed from Beam #4

strain gauge 3BHT-(2) removed from Beam #4
strain gauge 3THT-(1) removed from Beam #4

strain gauge 3THB-(1) removed from Beam #4

strain gauge 3THT-(2) removed from Beam #4

strain gauge 3THB-(2) removed from Beam #4

Figure 7.236: Test 4B No. 3 top hoop support bar strains versus beam chord rotation –
(a) $\varepsilon_{3THT-(1)}-\theta_b$; (b) $\varepsilon_{3THB-(1)}-\theta_b$; (c) $\varepsilon_{3THT-(2)}-\theta_b$; (d) $\varepsilon_{3THB-(2)}-\theta_b$.  

805
Figure 7.237: Test 4B No. 3 bottom hoop support bar strains versus beam chord rotation – (a) $\varepsilon_{3BHB-(1)} - \theta_b$; (b) $\varepsilon_{3BHT-(1)} - \theta_b$; (c) $\varepsilon_{3BHB-(2)} - \theta_b$; (d) $\varepsilon_{3BHT-(2)} - \theta_b$.

7.4.17 Beam End Confinement Hoop Strains

Figures 7.238 and 7.239 show the measurements from the strain gauges placed on the vertical legs of the bottom layer No. 3 confinement hoops at the south end of the beam. The locations of these strain gauges can be found in Chapter 5. The strain gauges were not re-zeroed at the beginning of Test 4B. The “initial” strains, prior to connecting the top and seat angles, were assumed to be equal to the final strains from Test 4A; and thus, the gauge measurements capture any additional compressive strain due to the angle-
to-beam connections (applying transverse compression at the beam ends). However, the assumption for the “initial” strain might not be accurate since no angle-to-beam connections were used in Test 4A; therefore, it is important to note the changes in the strain reading rather than the actual strain values during the test. For further insight into the measurements, Figures 7.4240 and 7.241 plot the strain data against the beam chord rotation. It can be seen that for most of the test, the strain measurements remain relatively small; however, at large beam chord rotations ($\theta_b = 5.0\%$ and above), the strain measurements from 1HB-E and 2HB-W have significant increases in compressive strain. It is not clear if this is actual data or the malfunctioning of the strain gauge.
Figure 7.238: Test 4B beam end hoop confinement strains (east legs) –
(a) $\varepsilon_{1HB-E}$; (b) $\varepsilon_{2HB-E}$; (c) $\varepsilon_{3HB-E}$; (d) $\varepsilon_{4HB-E}$. 
Figure 7.239: Test 4B beam end hoop confinement strains (west legs) – (a) $\varepsilon_{1HB-W}$; (b) $\varepsilon_{2HB-W}$; (c) $\varepsilon_{3HB-W}$; (d) $\varepsilon_{4HB-W}$. 
Figure 7.240: Test 4B beam end hoop confinement strains (east legs) versus beam chord rotation – (a) $\varepsilon_{1HB-E} - \theta_b$; (b) $\varepsilon_{2HB-E} - \theta_b$; (c) $\varepsilon_{3HB-E} - \theta_b$; (d) $\varepsilon_{4HB-E} - \theta_b$. 

Strain gauge 2HB-E removed from Beam #4

Strain gauge 4HB-E removed from Beam #4
7.4.18 Wall Test Region Confined Concrete Strains

As described previously, the strain gauge wires coming out of the reaction block used in Tests 2 through 4B were all severed during the removal of the steel casting mold. Thus, no measurements were recorded for the wall test wall region confined concrete strains in Test 4B.
7.4.19 Wall Test Region Confinement Hoops Strains

Similar to above, no measurements were recorded for the wall test region confinement hoop strains in Test 4B since the strain gauge wires were severed.

7.4.20 Crack Patterns

The hand-drawn crack patterns recorded for Test 4B can be found in Appendix F.