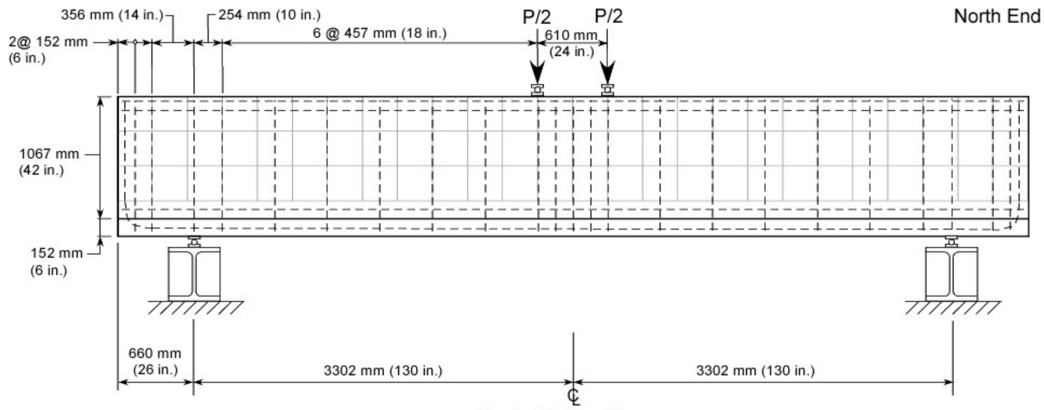
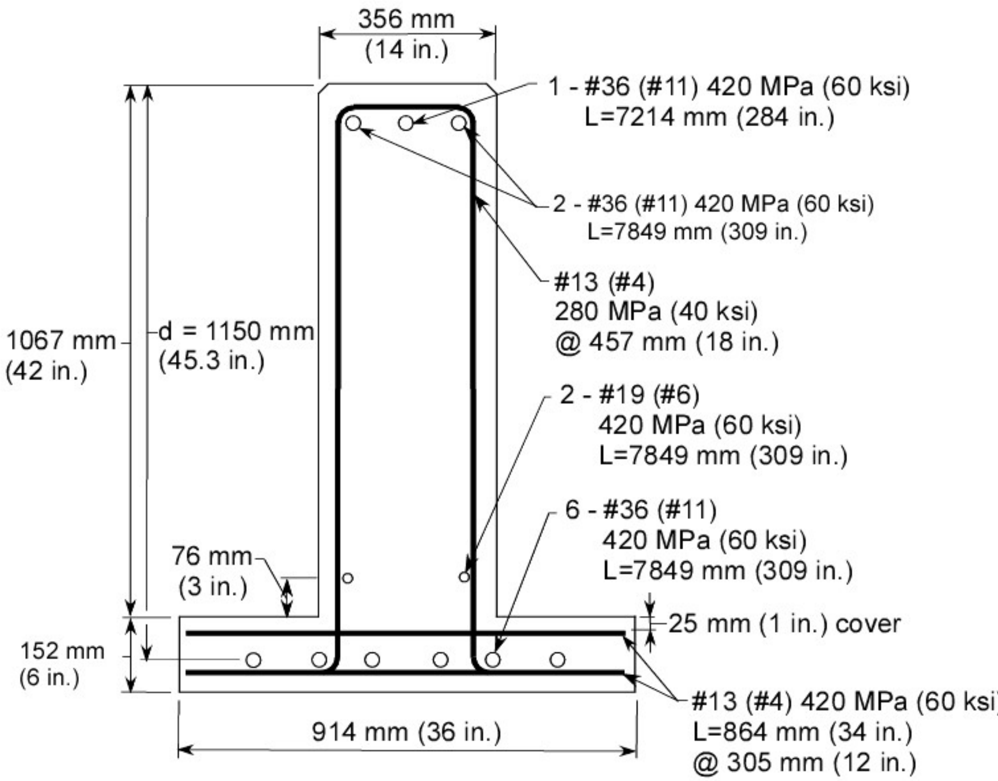
APPENDICES

APPENDIX A-1: SPECIMEN B.IT.NC.ES

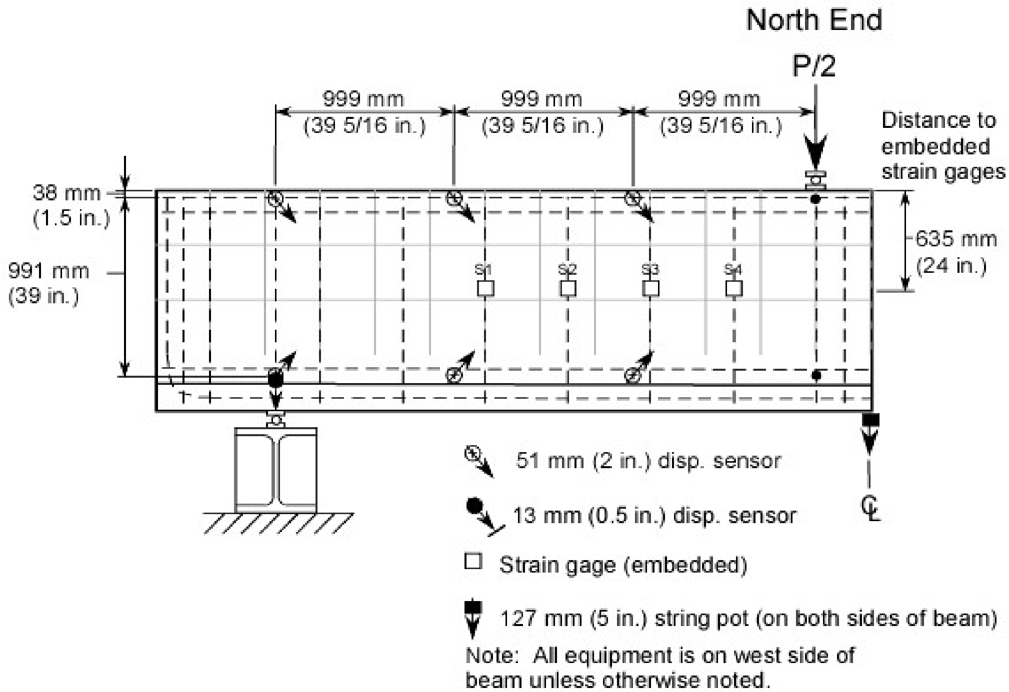


Typical IT Specimen

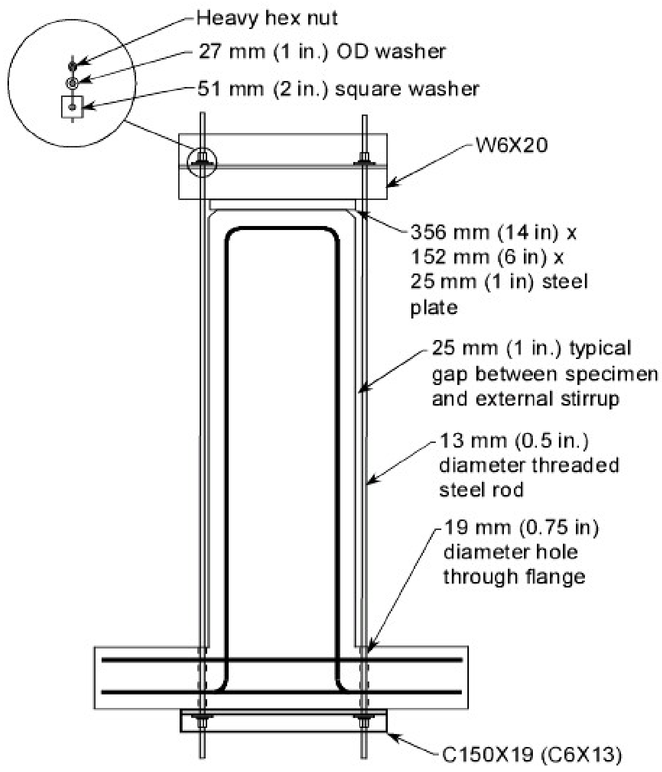


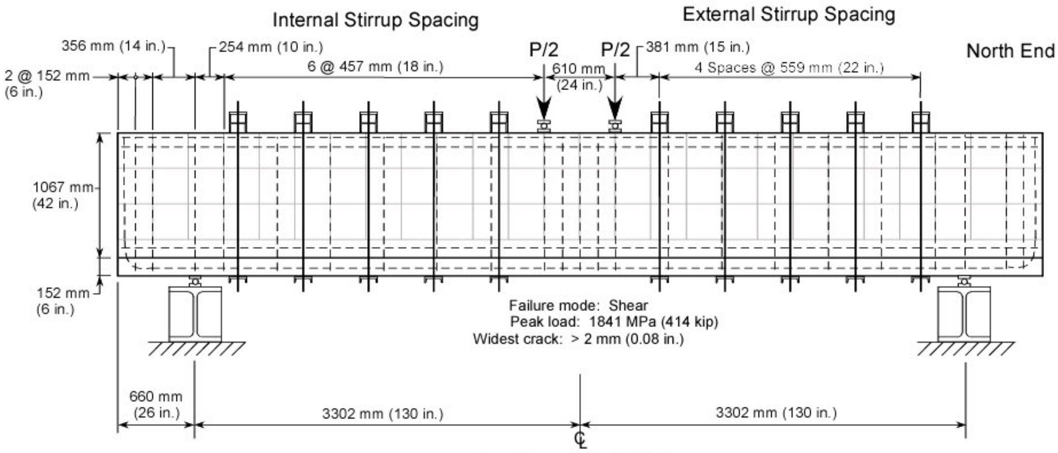
Note: 38 mm (1.5 in.) Cover Unless Noted

IT Beam Typical Section



IT Specimen Instrumentation



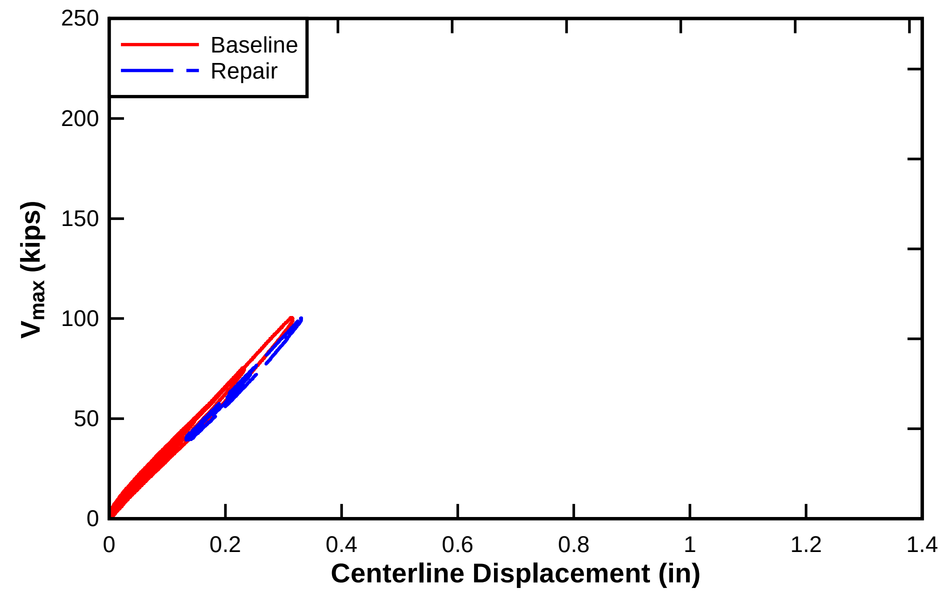


Specimen B.IT.NC.ES

B.IT.NC.ES North End

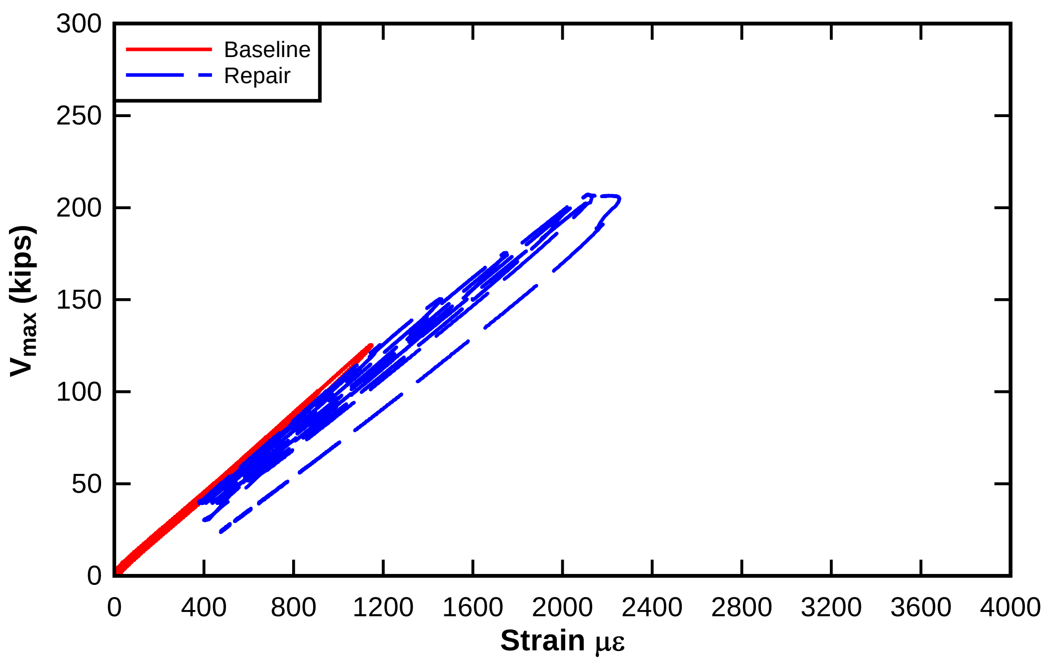
B.IT.NC.ES South End

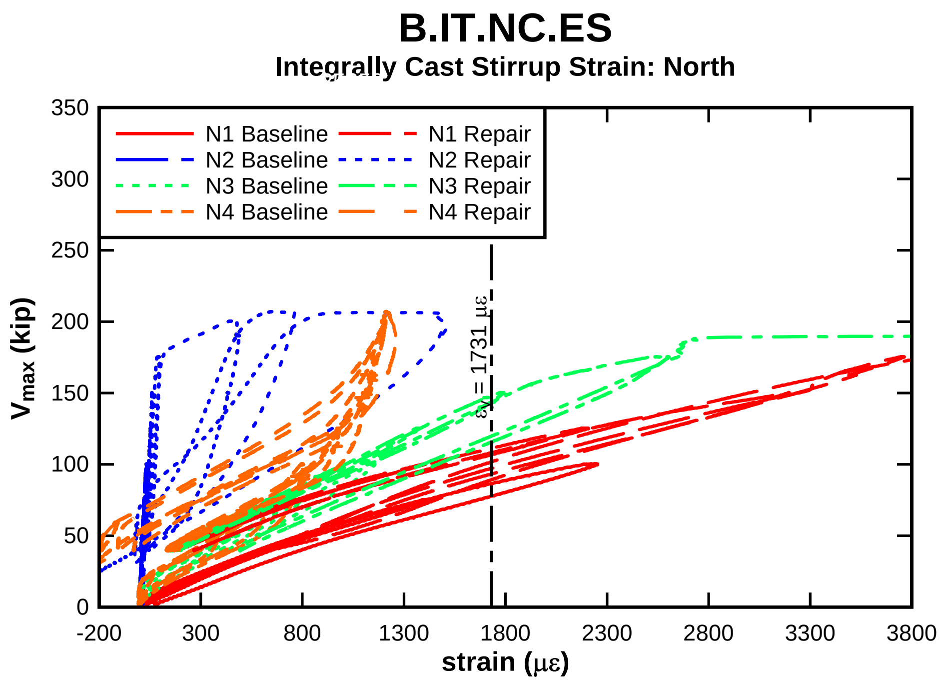
B.IT.NC.ES

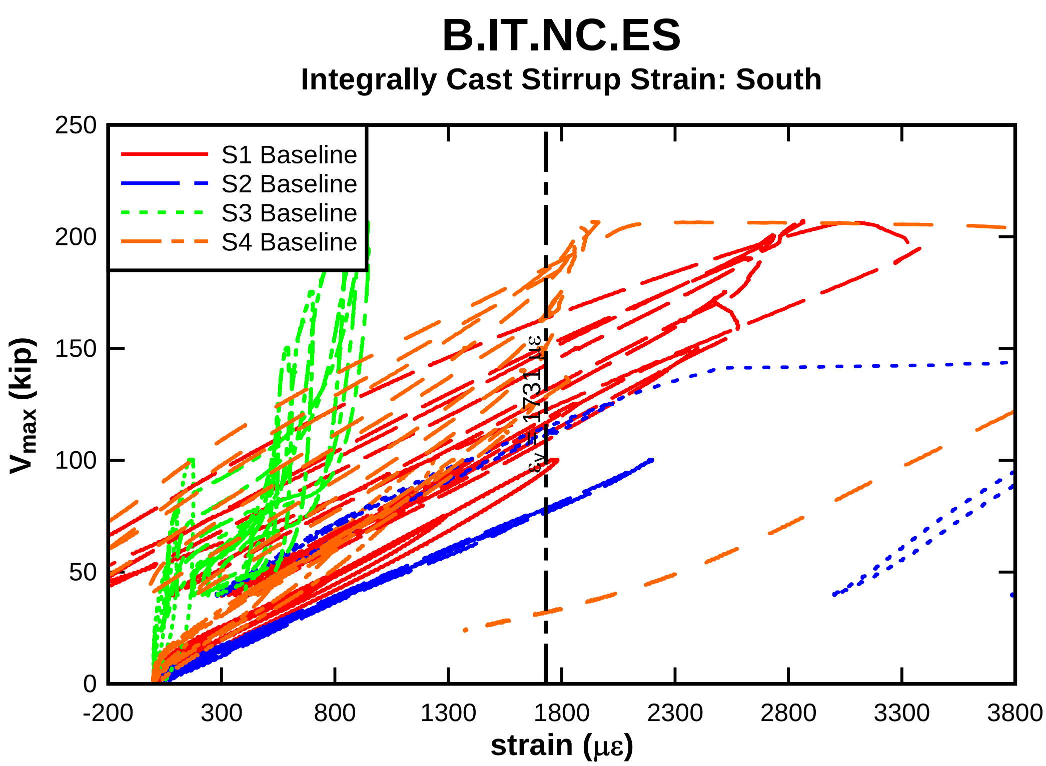


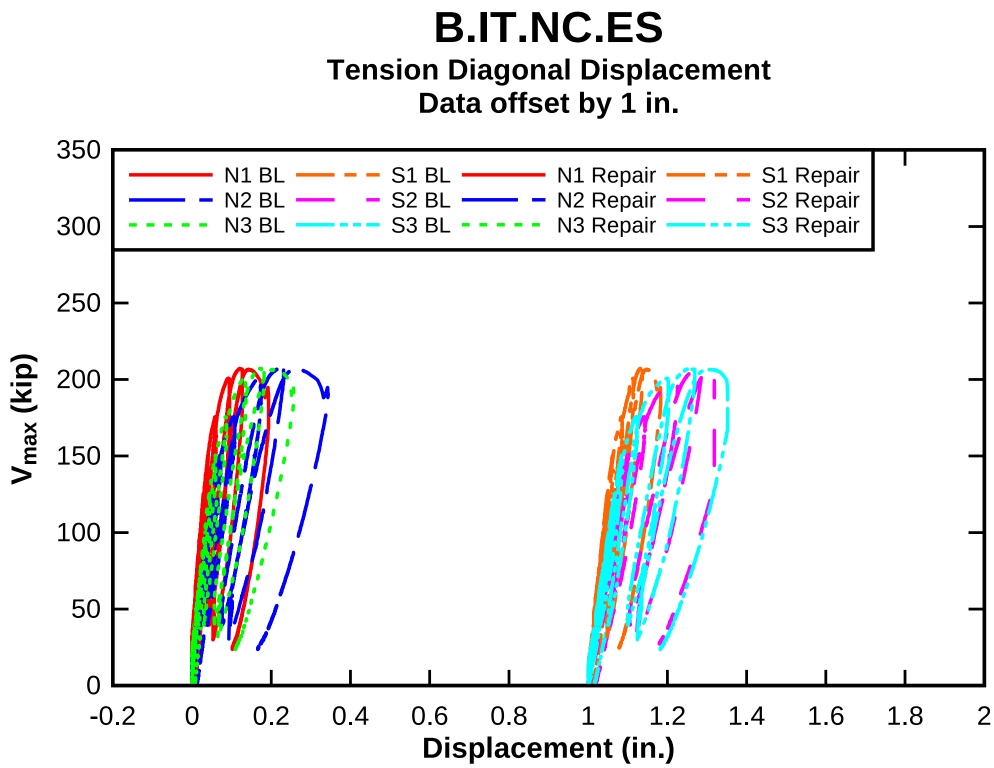
B.IT.NC.ES

Flexural Strain

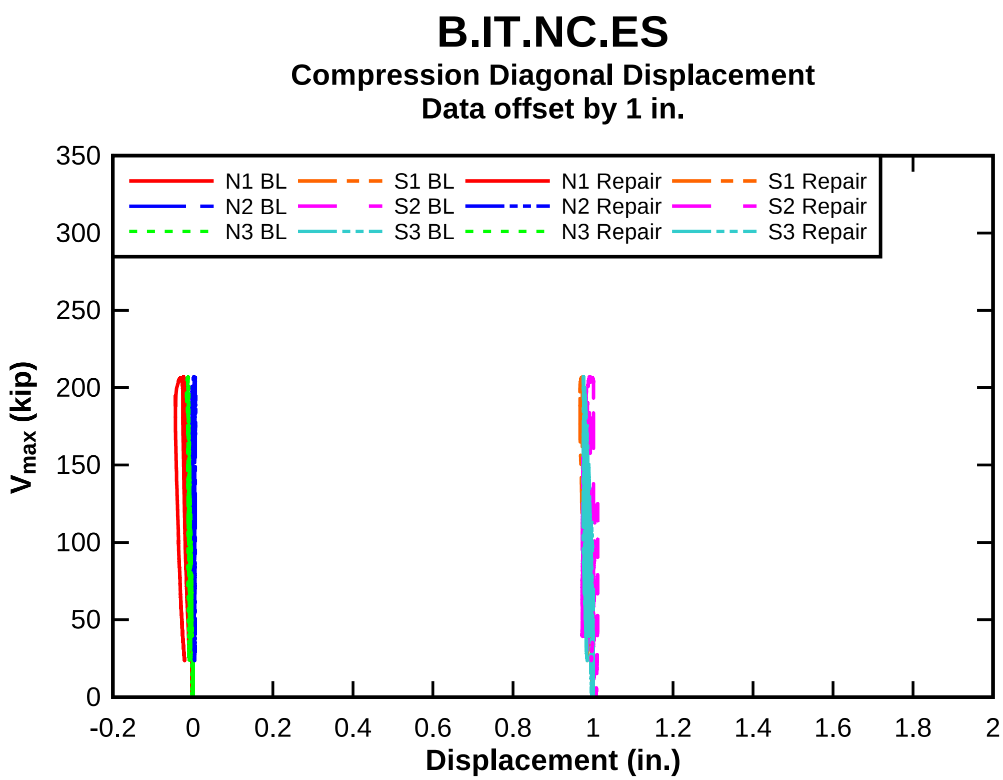



B.IT.NC.ES
Integrally Cast Stirrup Strain: North
N1 Baseline
N1 Repair
N2 Baseline
N2 Repair
N3 Baseline
N3 Repair
N4 Baseline
N4 Repair
εy = 1731 με
Vmax (kip)
strain (με)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800

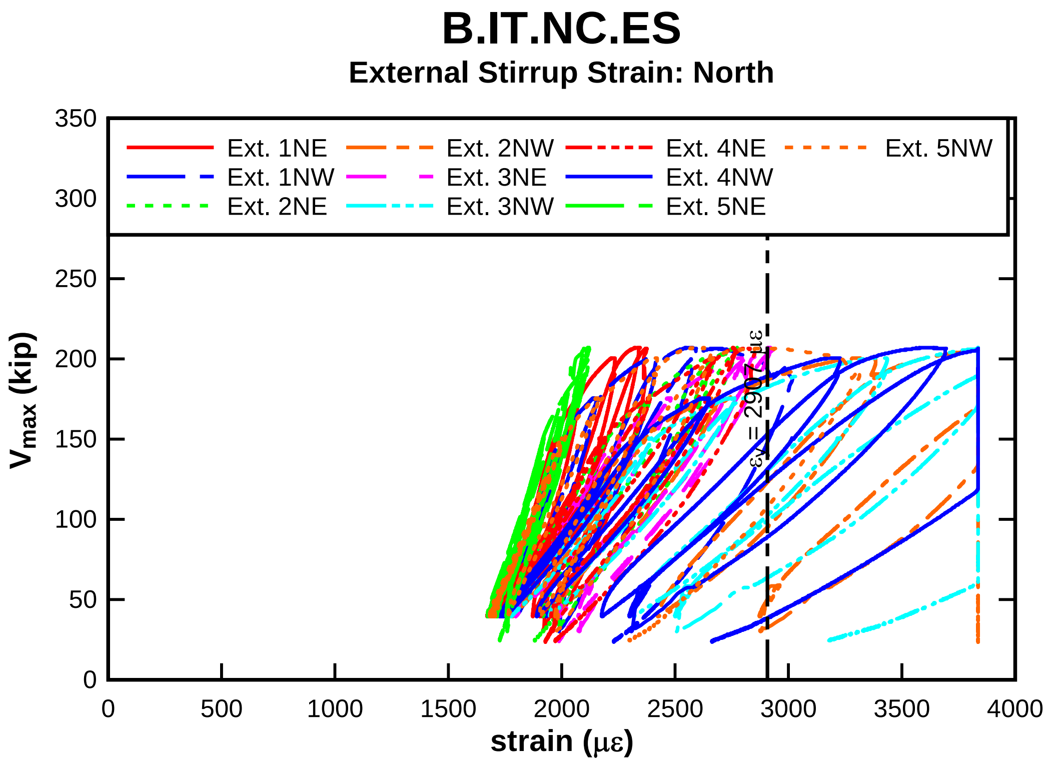

B.IT.NC.ES
Integrally Cast Stirrup Strain: South
S1 Baseline
S2 Baseline
S3 Baseline
S4 Baseline
εy = 1731 με
Vmax (kip)
strain (με)
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800

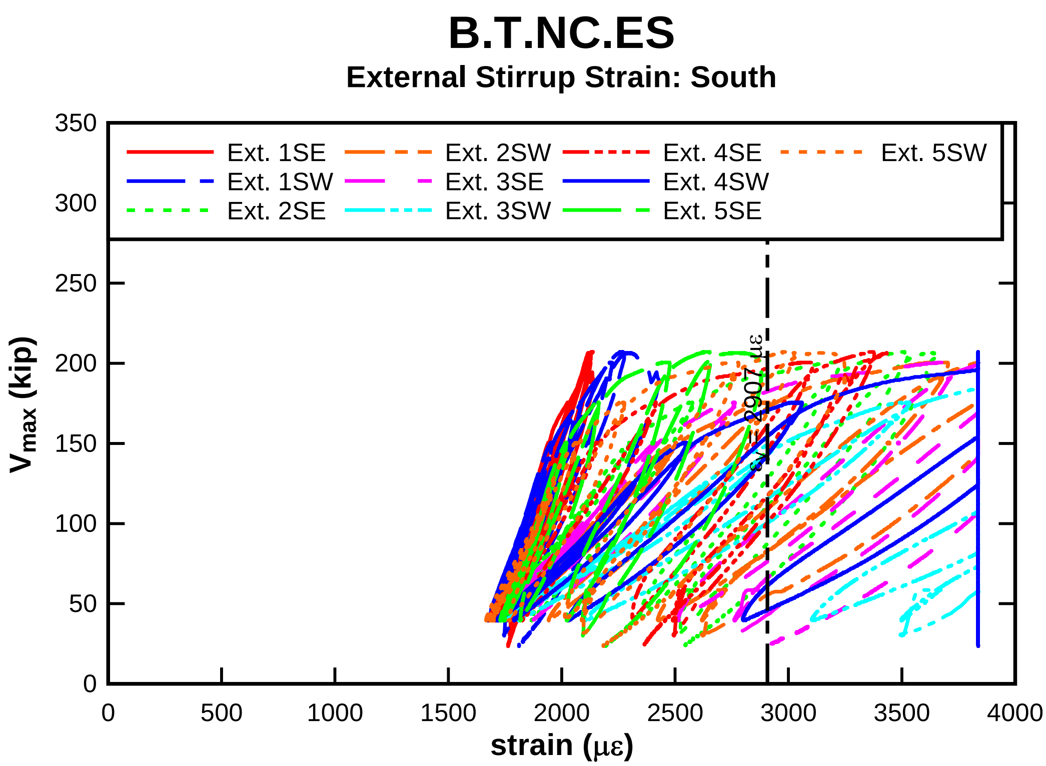


B.IT.NC.ES
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N2 BL
N3 BL
S1 BL
S2 BL
S3 BL
N1 Repair
N2 Repair
N3 Repair
S1 Repair
S2 Repair
S3 Repair
V_max (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

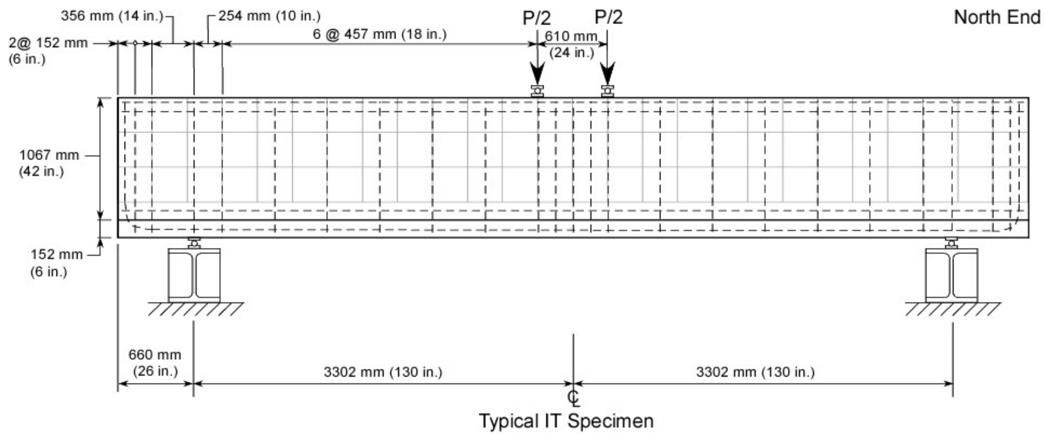


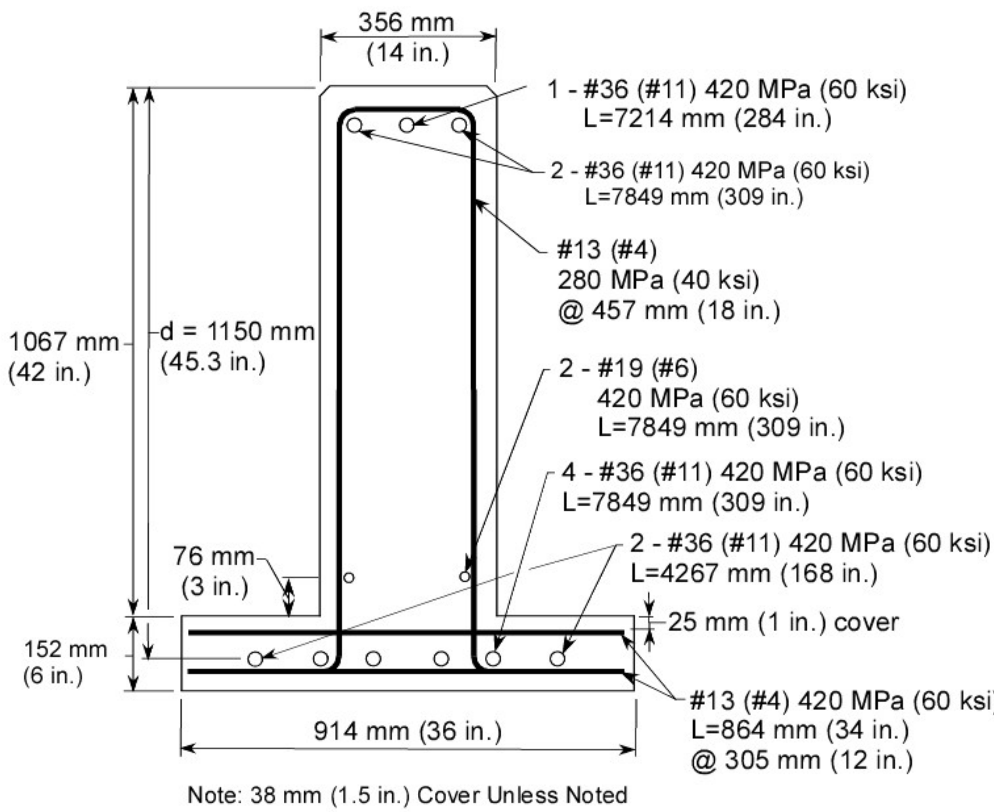
B.IT.NC.ES
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N2 BL
N3 BL
S1 BL
S2 BL
S3 BL
N1 Repair
N2 Repair
N3 Repair
S1 Repair
S2 Repair
S3 Repair
V_max (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


B.IT.NC.ES
External Stirrup Strain: North
Ext. 1NE
Ext. 1NW
Ext. 2NE
Ext. 2NW
Ext. 3NE
Ext. 3NW
Ext. 4NE
Ext. 4NW
Ext. 5NE
Ext. 5NW
εy = 2907 με
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
0
500
1000
1500
2000
2500
3000
3500
4000

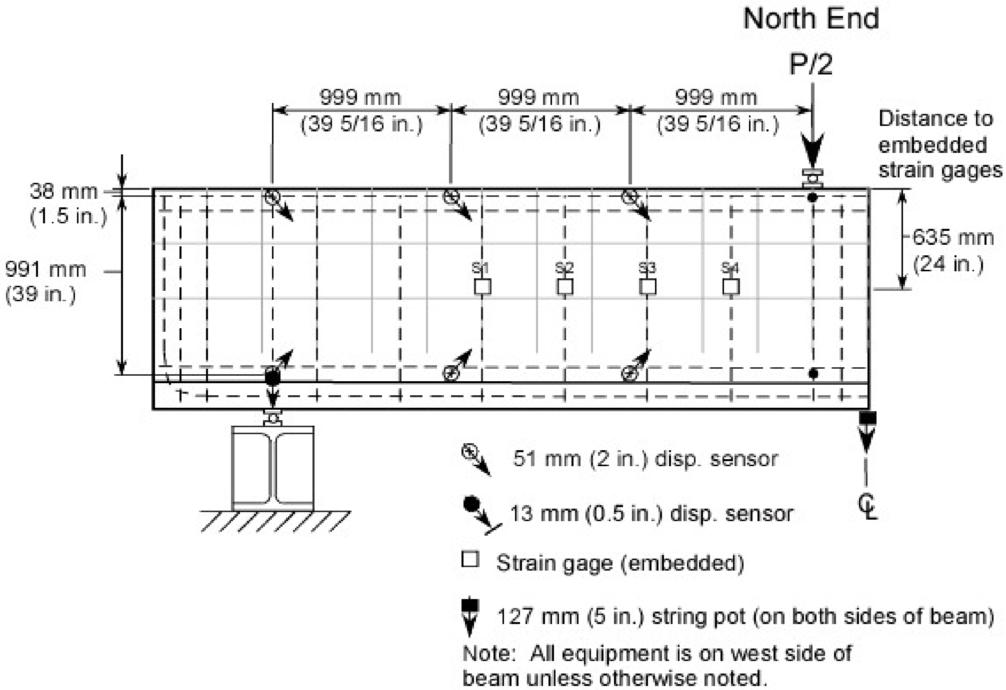

B.T.NC.ES
External Stirrup Strain: South
Ext. 1SE
Ext. 1SW
Ext. 2SE
Ext. 2SW
Ext. 3SE
Ext. 3SW
Ext. 4SE
Ext. 4SW
Ext. 5SE
Ext. 5SW
εy = 2907 με
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
0
500
1000
1500
2000
2500
3000
3500
4000

APPENDIX A-2: SPECIMEN B.IT.C.ES

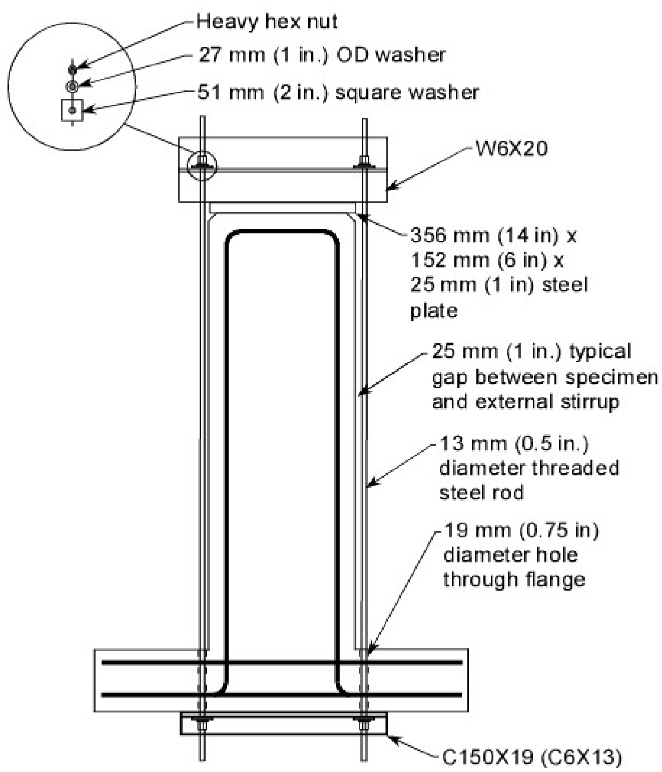


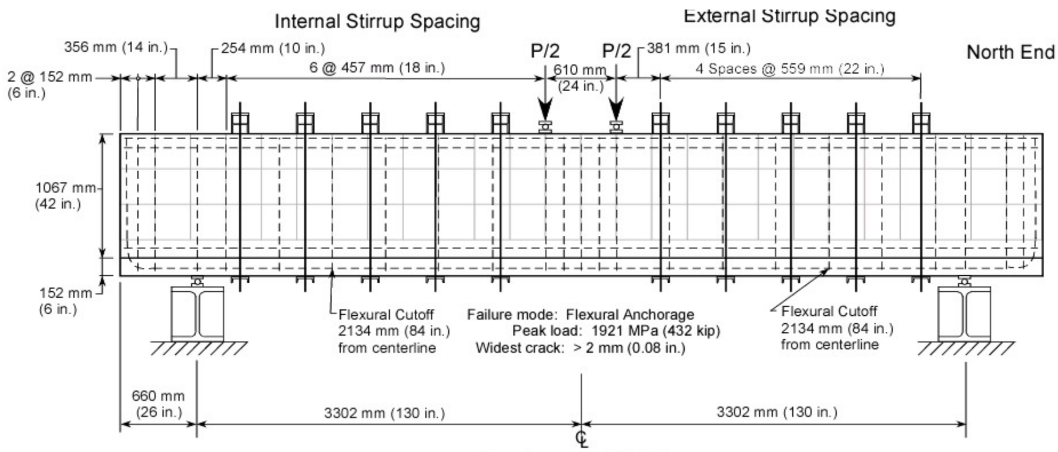


IT Beam with Cutoff Typical Section

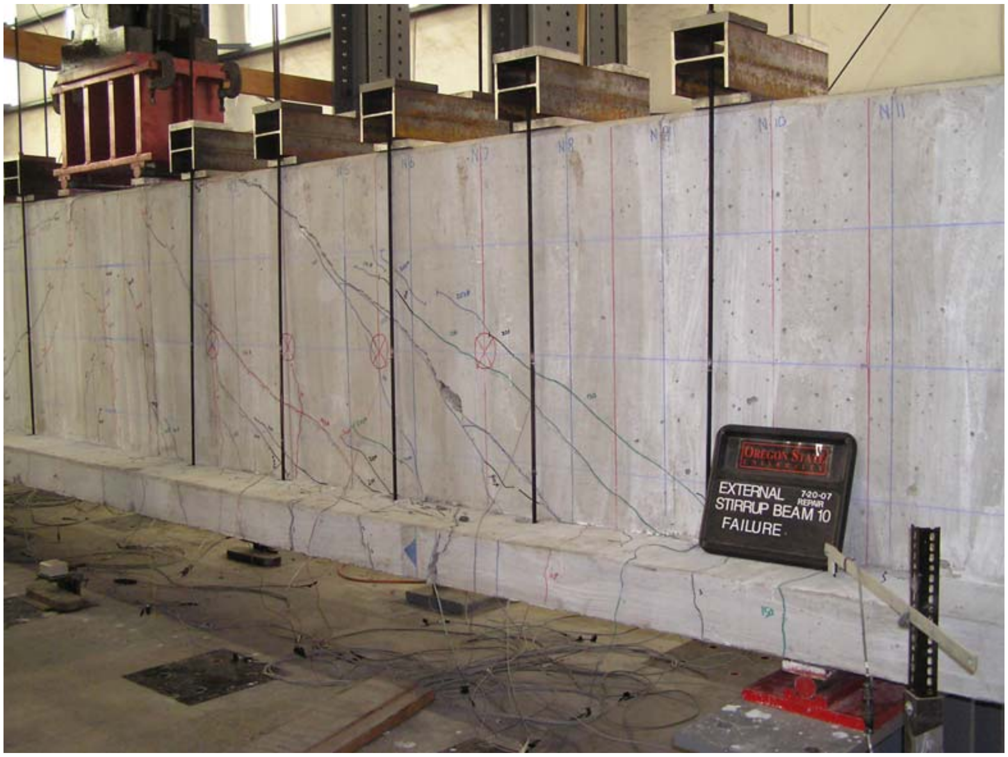


IT Specimen Instrumentation



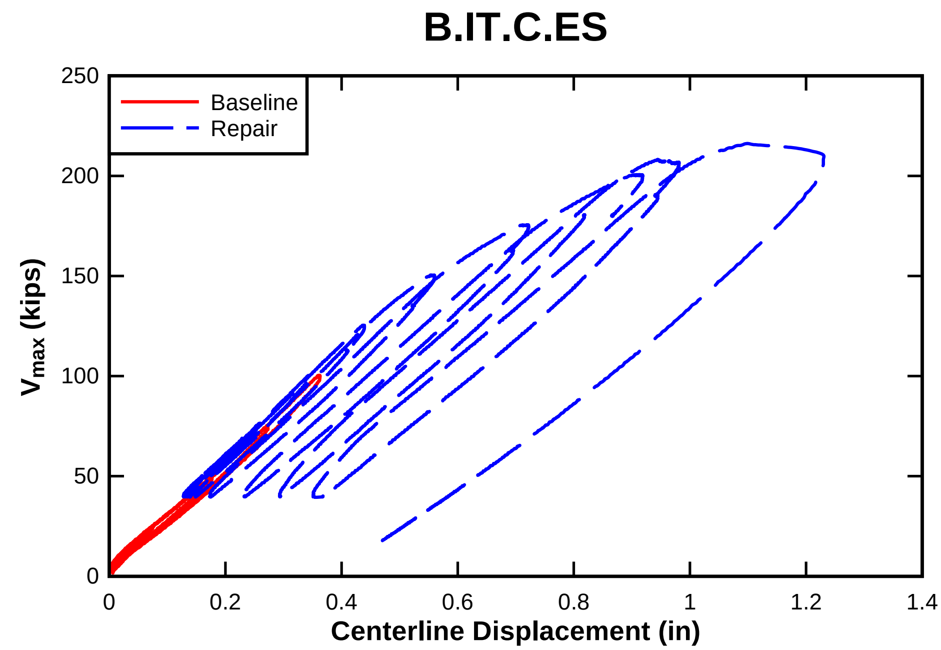


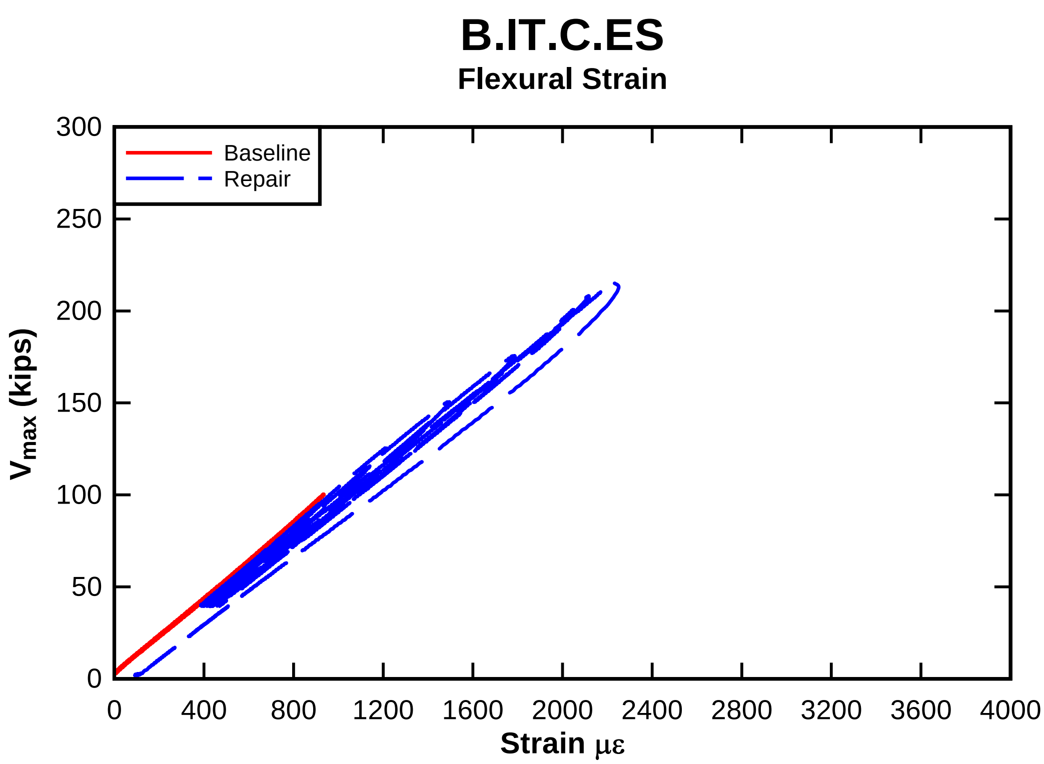
Specimen B.IT.NC.ES

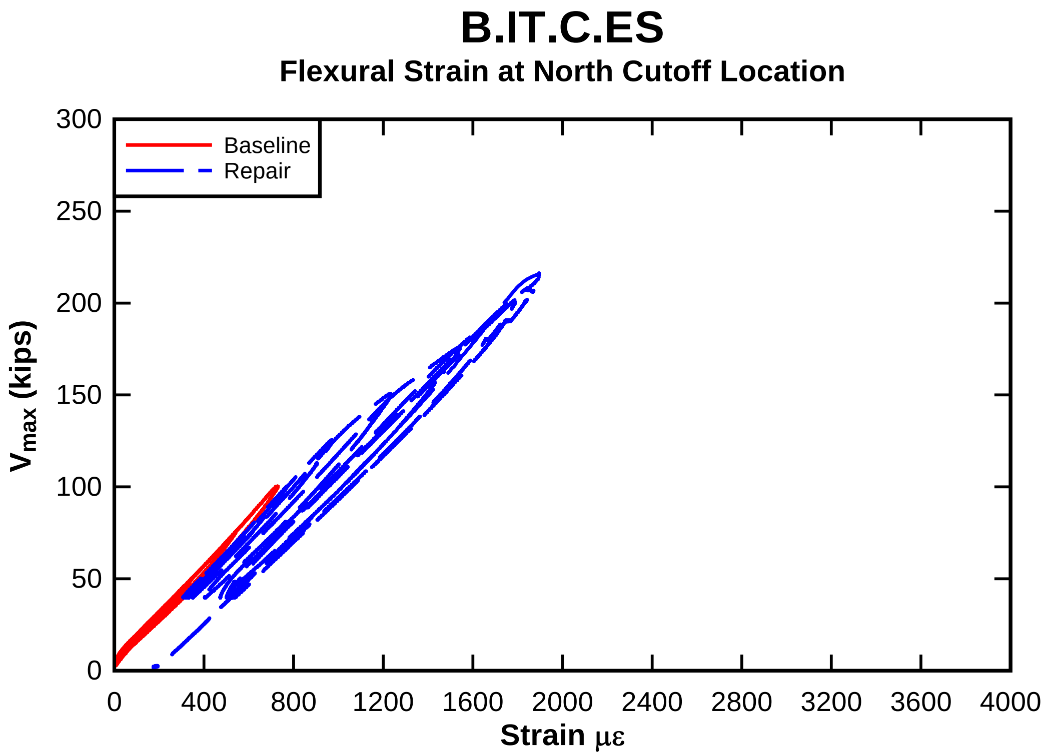


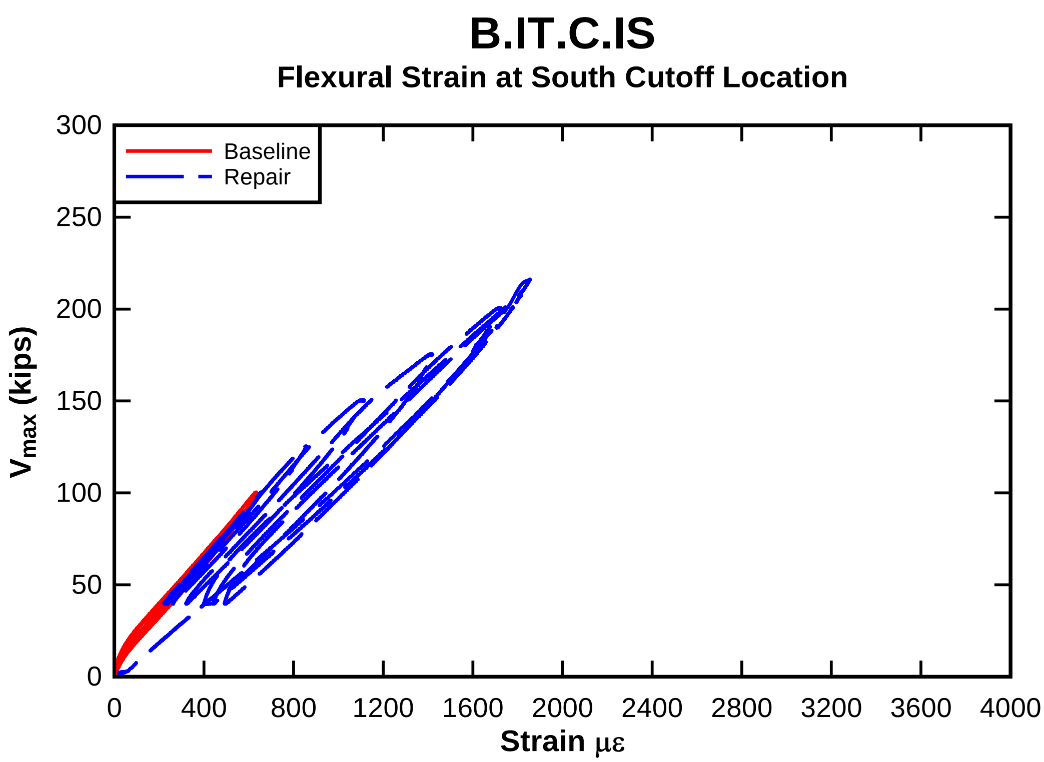
B.IT.C.ES North End

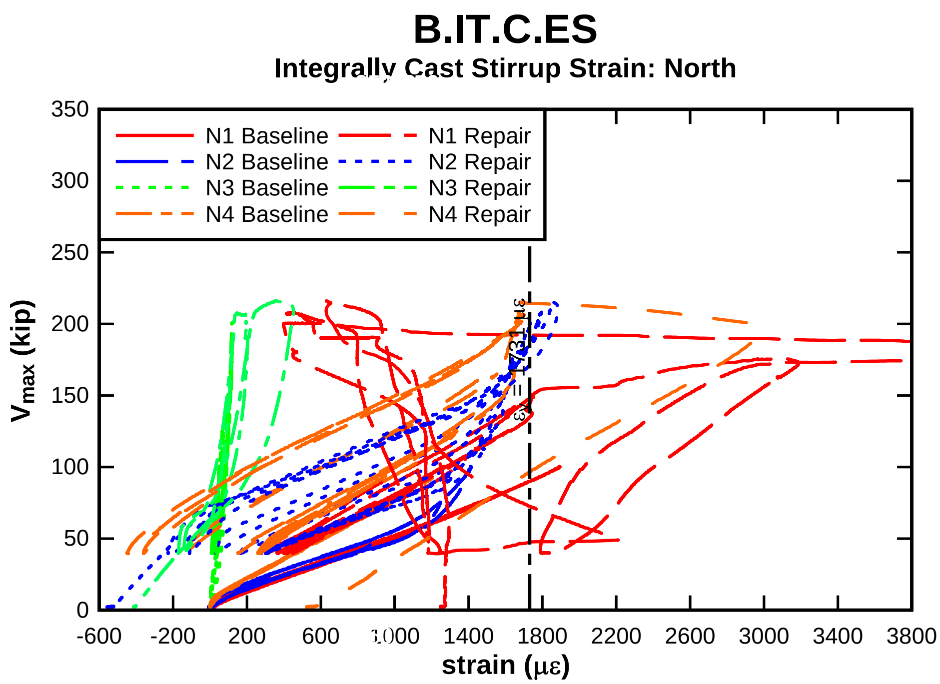
B.IT.C.ES South End

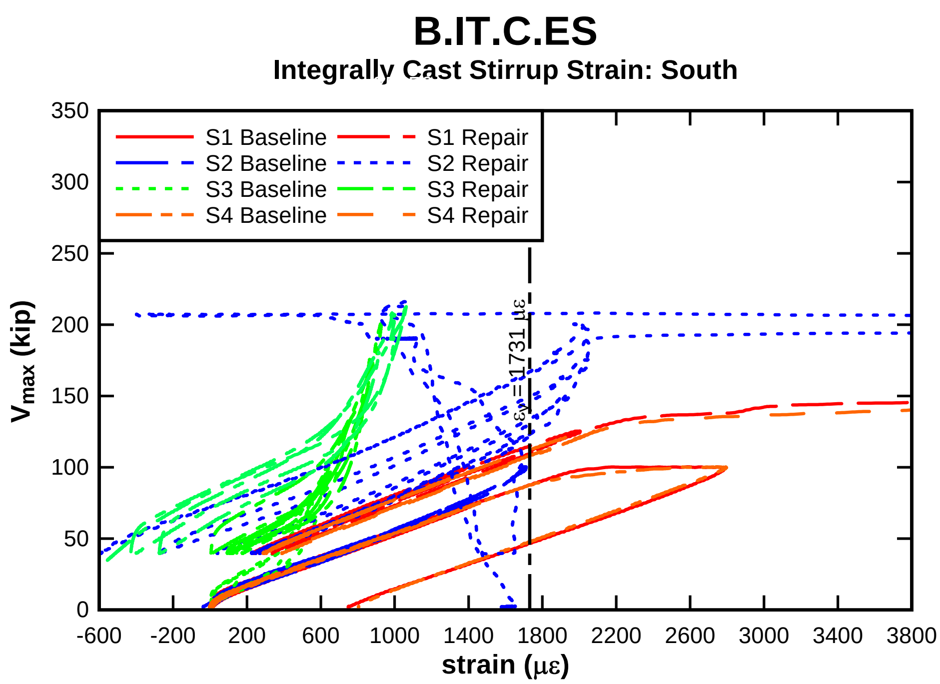

B.IT.C.ES
Baseline
Repair
V_{max} (kips)
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Centerline Displacement (in)

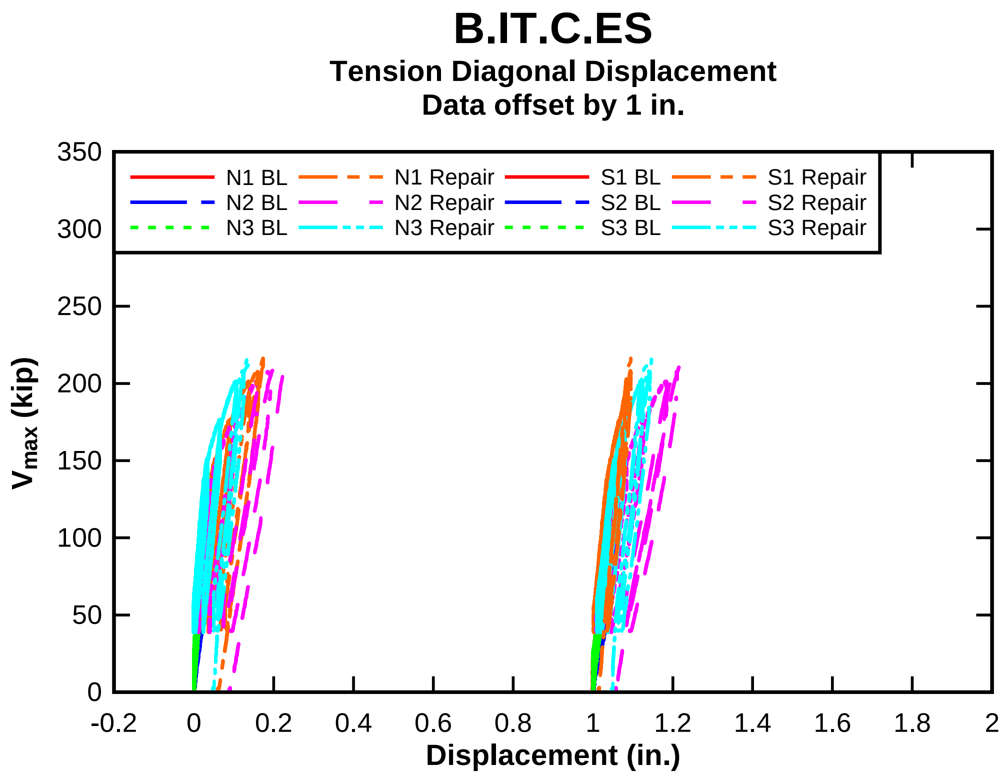

B.IT.C.ES
Flexural Strain
Baseline
Repair
V_{max} (kips)
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Strain με

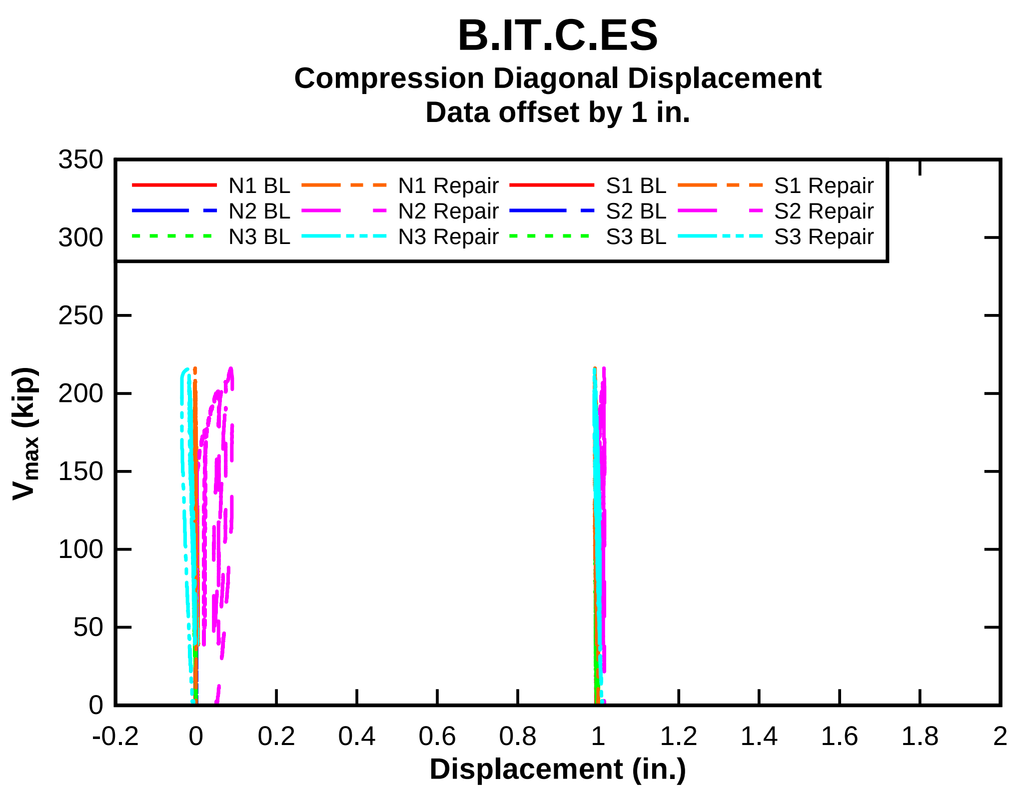

B.IT.C.ES
Flexural Strain at North Cutoff Location
Baseline
Repair
V_{max} (kips)
Strain με
0
50
100
150
200
250
300
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000


B.IT.C.IS
Flexural Strain at South Cutoff Location
Baseline
Repair
V_{max} (kips)
Strain με
0
50
100
150
200
250
300
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000


B.IT.C.ES
Integrally Cast Stirrup Strain: North
N1 Baseline
N1 Repair
N2 Baseline
N2 Repair
N3 Baseline
N3 Repair
N4 Baseline
N4 Repair
V_{max} (kip)
strain (με)
ε_y=1731 με
350
300
250
200
150
100
50
0
-600
-200
200
600
1000
1400
1800
2200
2600
3000
3400
3800

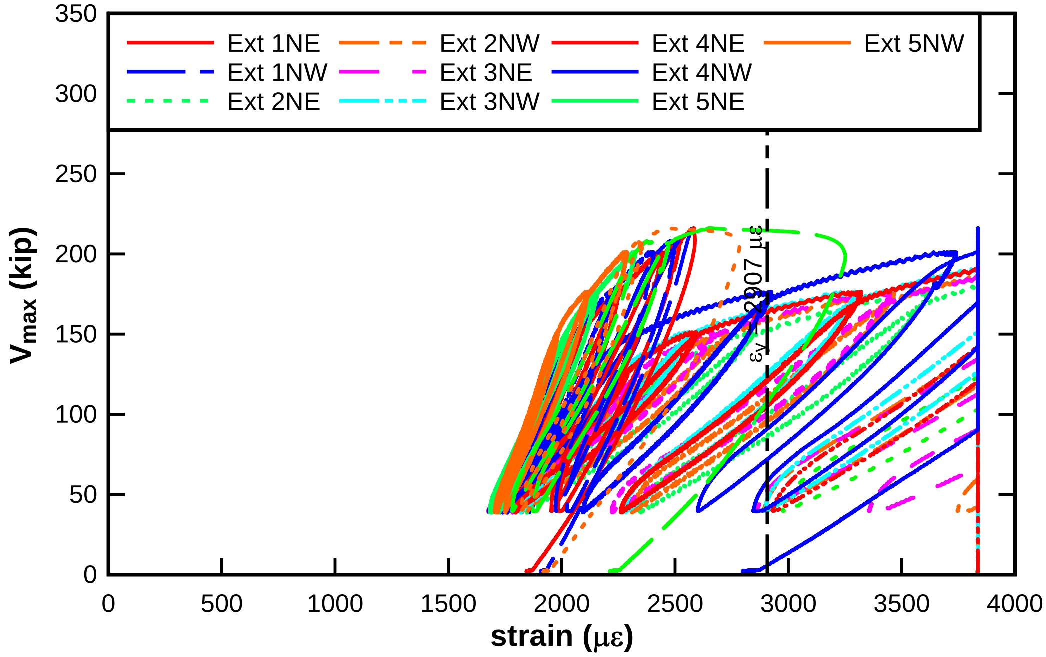

B.IT.C.ES
Integrally Cast Stirrup Strain: South
S1 Baseline
S1 Repair
S2 Baseline
S2 Repair
S3 Baseline
S3 Repair
S4 Baseline
S4 Repair
V_{max} (kip)
strain (με)
ε_y=1731 με
350
300
250
200
150
100
50
0
-600
-200
200
600
1000
1400
1800
2200
2600
3000
3400
3800


B.IT.C.ES
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Displacement (in.)


B.IT.C.ES
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Displacement (in.)

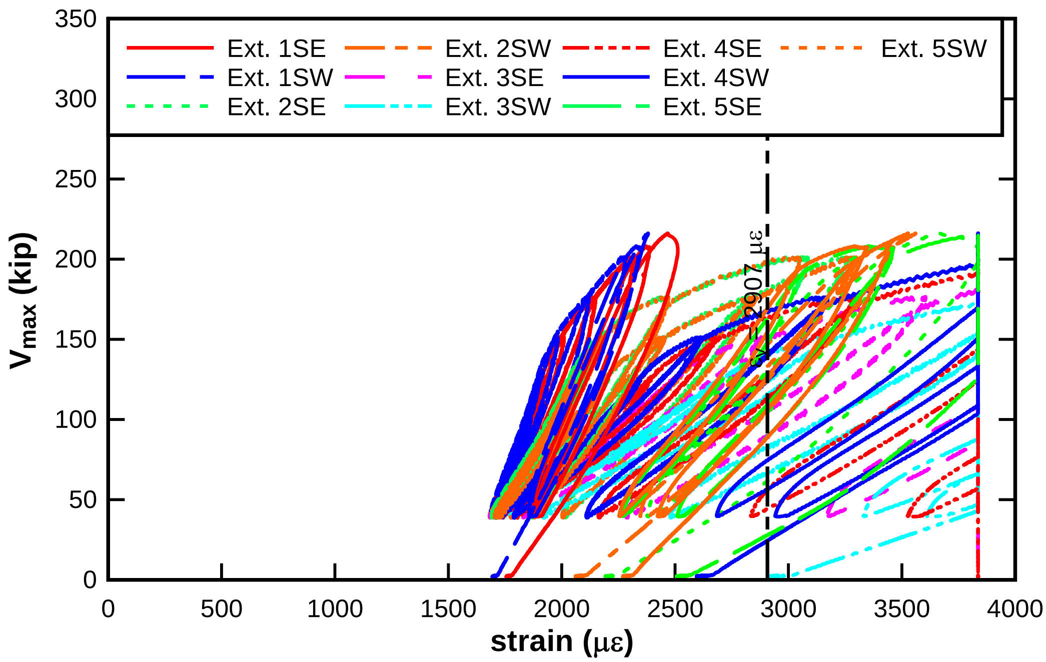
B.IT.C.ES

External Stirrup Strain: North

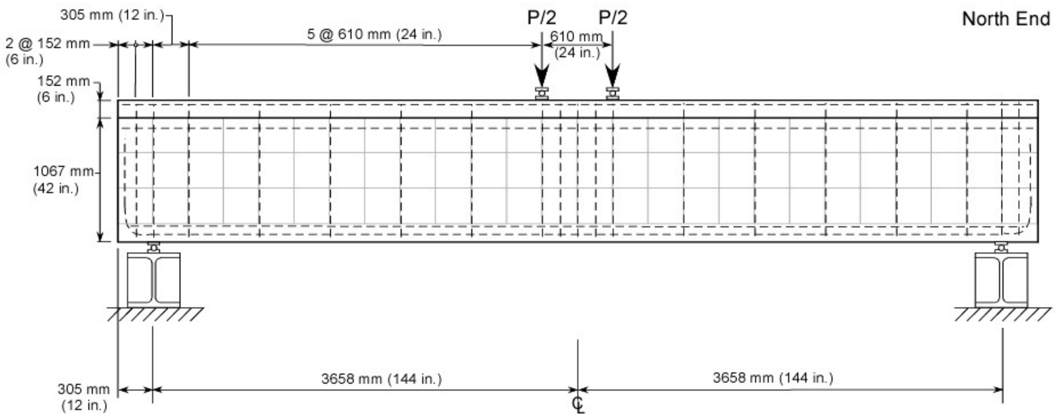


B.IT.C.ES

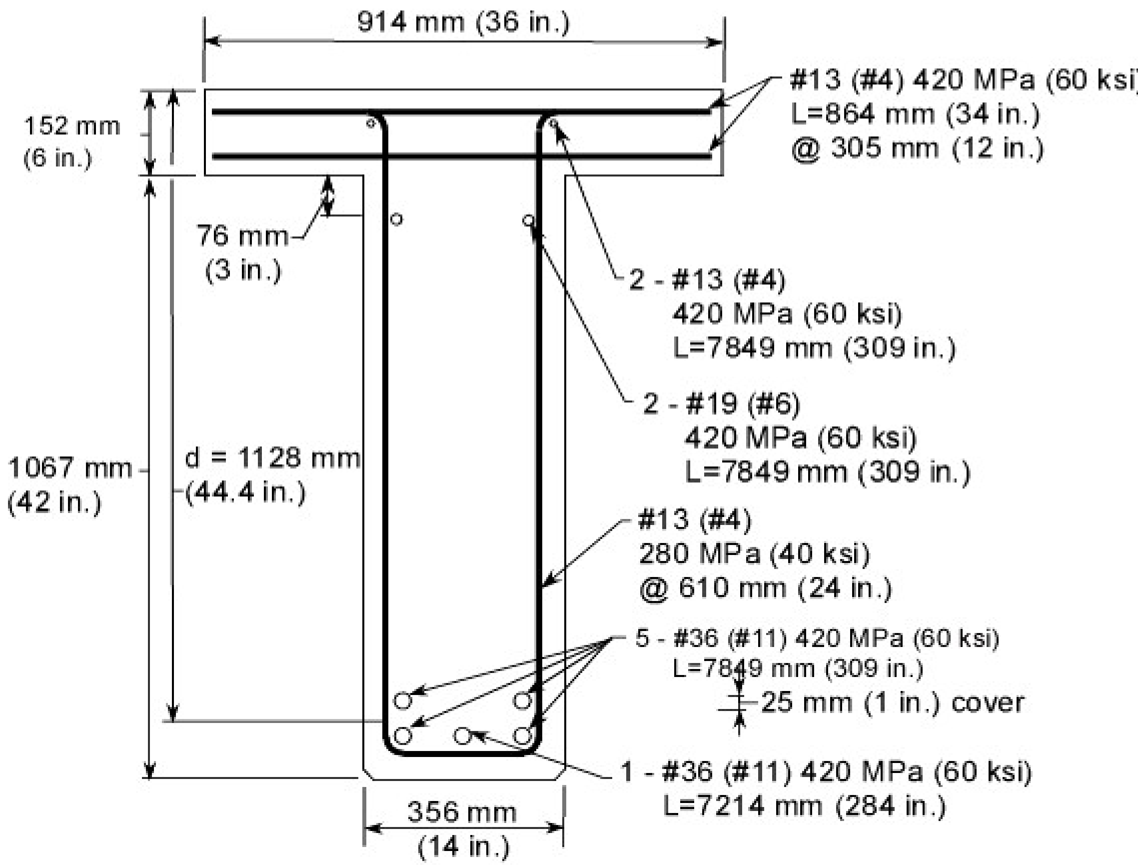
External Stirrup Strain: South



APPENDIX A-3: SPECIMEN B.T.NC.ES

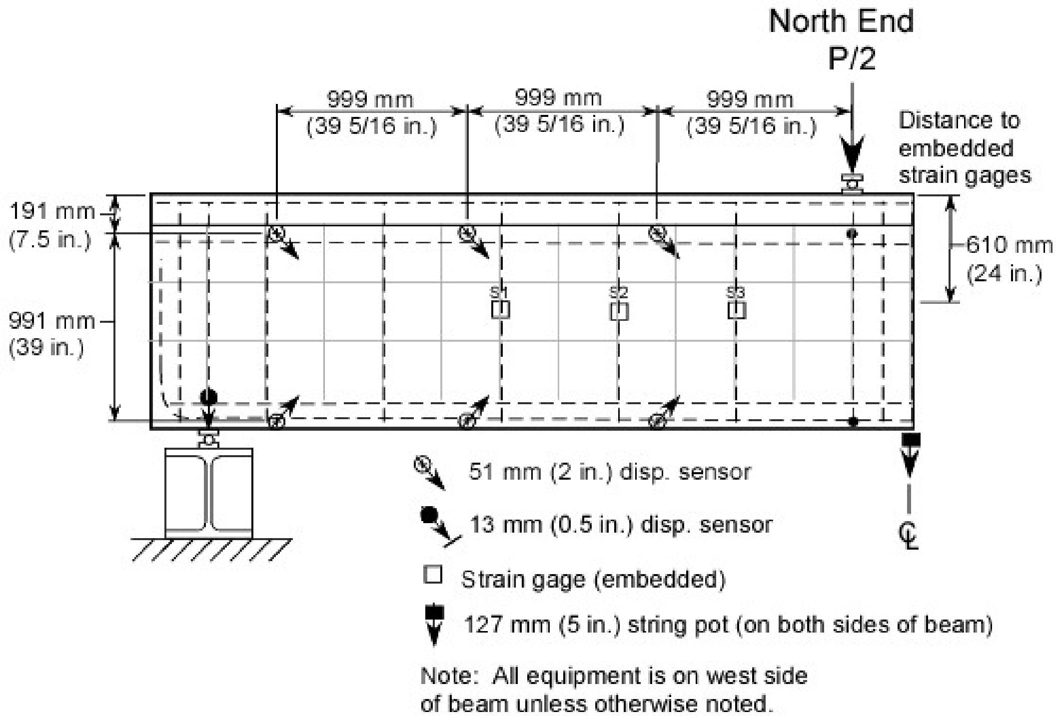


Typical T Beam

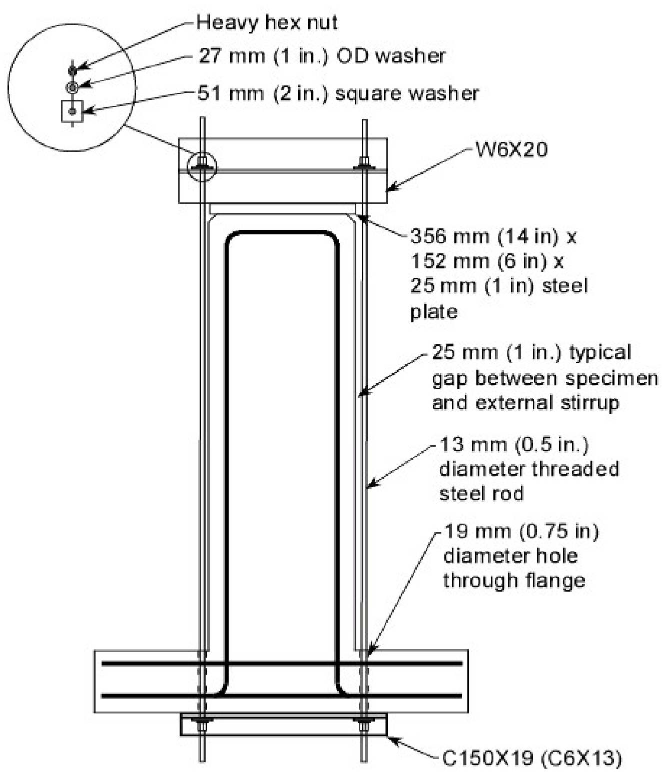


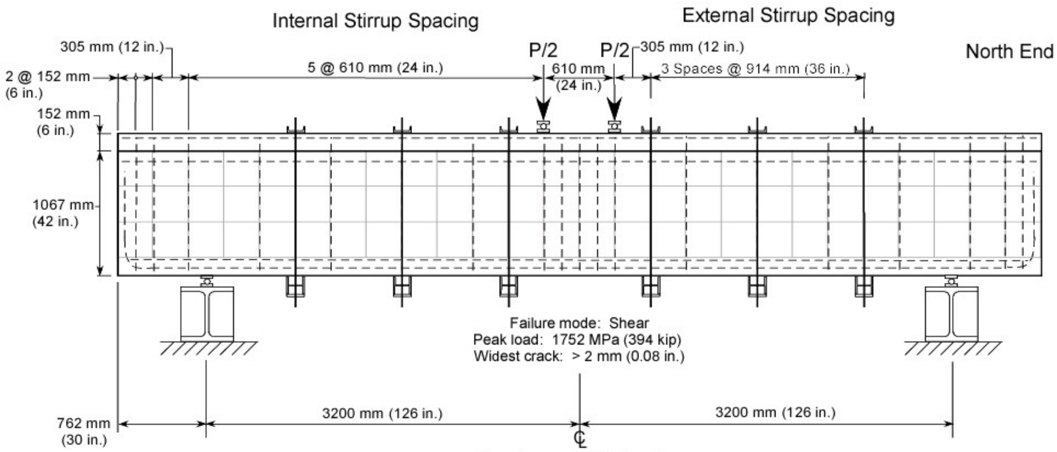
Note: 38 mm (1.5 in.) Cover Unless Noted

T Beam Typical Section



T Beam Instrumentation

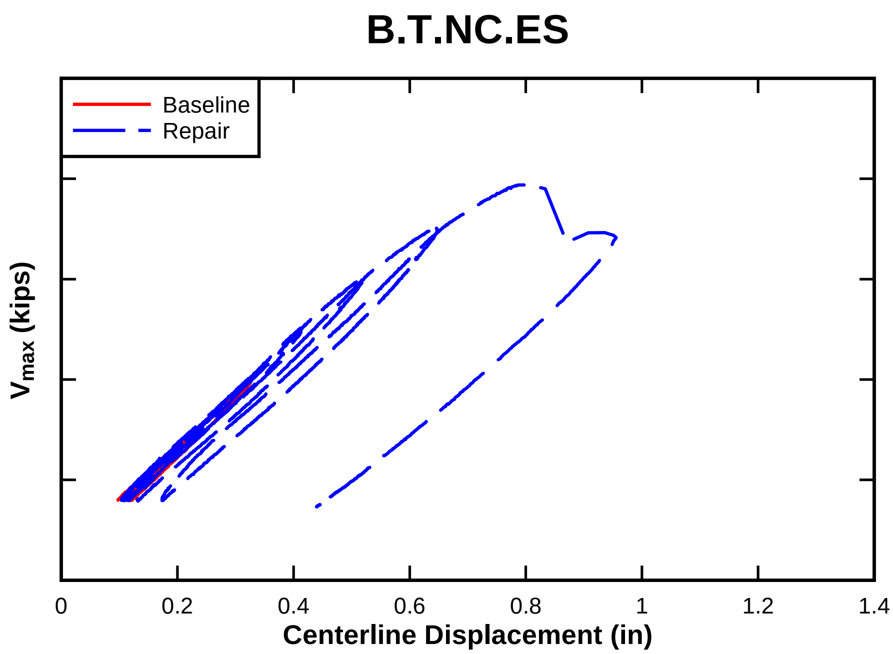




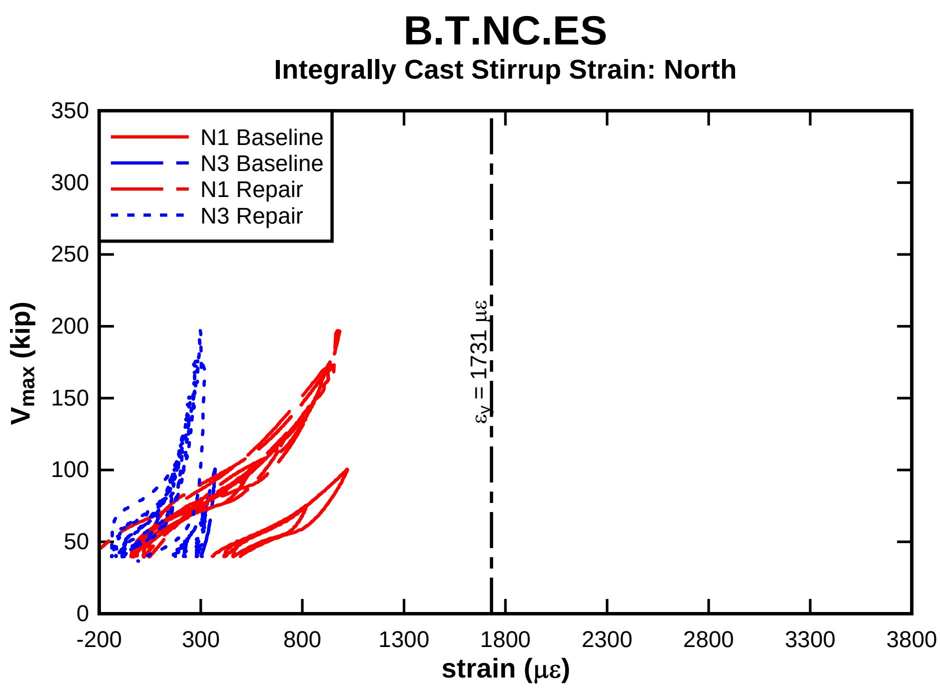
Specimen B.T.NC.ES

B.T.NC.ES North End

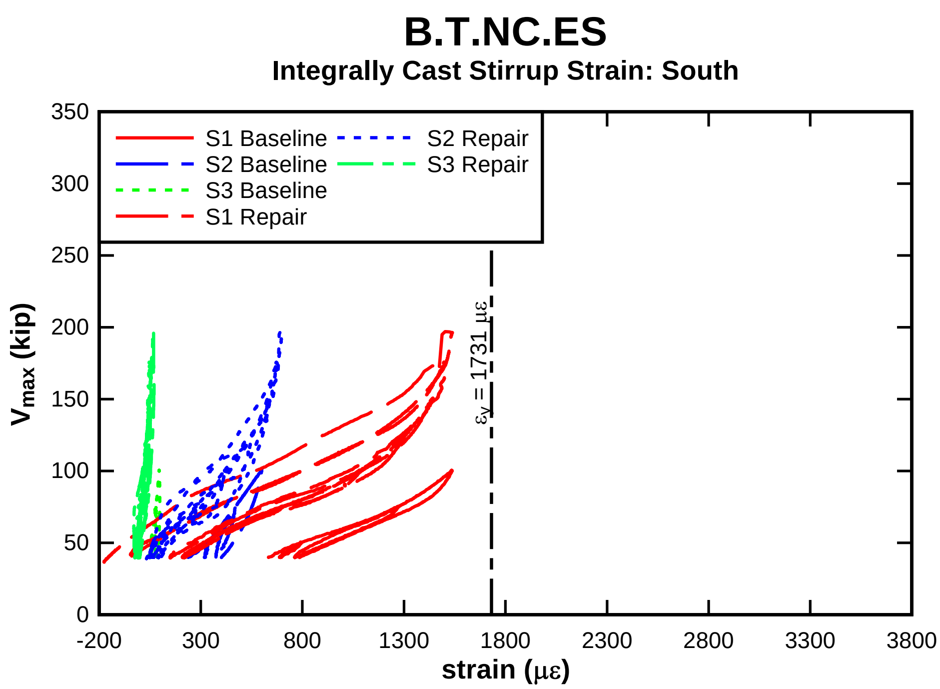
B.T.NC.ES South End



Note: Flexural strain data not available for this specimen, as all strain gages failed during initial test A failure.

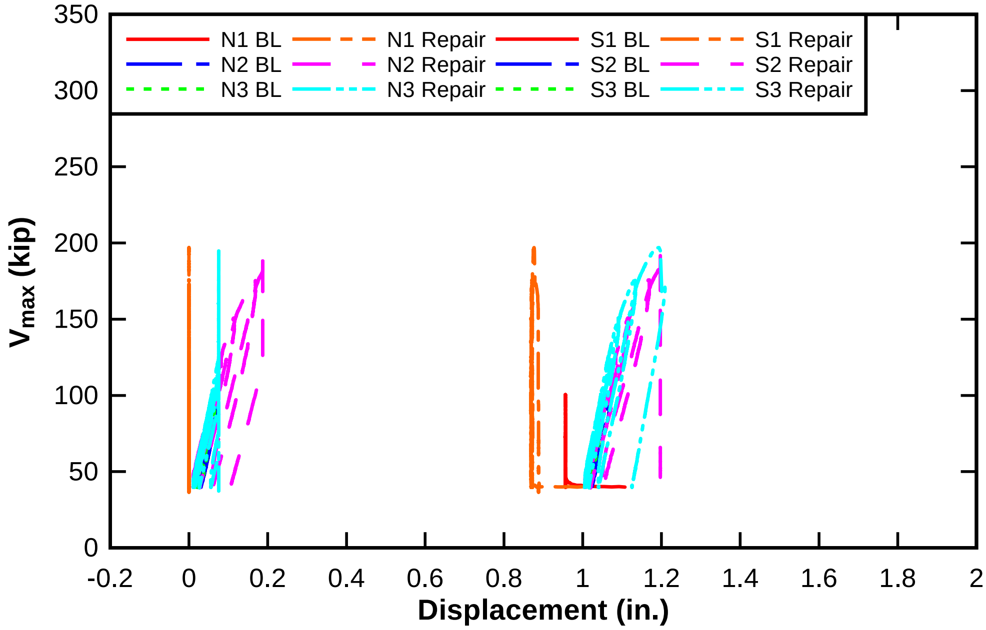


B.T.NC.ES
Integrally Cast Stirrup Strain: North
N1 Baseline
N3 Baseline
N1 Repair
N3 Repair
ε_y = 1731 $\mu\varepsilon$
V_{max} (kip)
strain ($\mu\varepsilon$)
0
50
100
150
200
250
300
350
-200
300
800
1300
1800
2300
2800
3300
3800

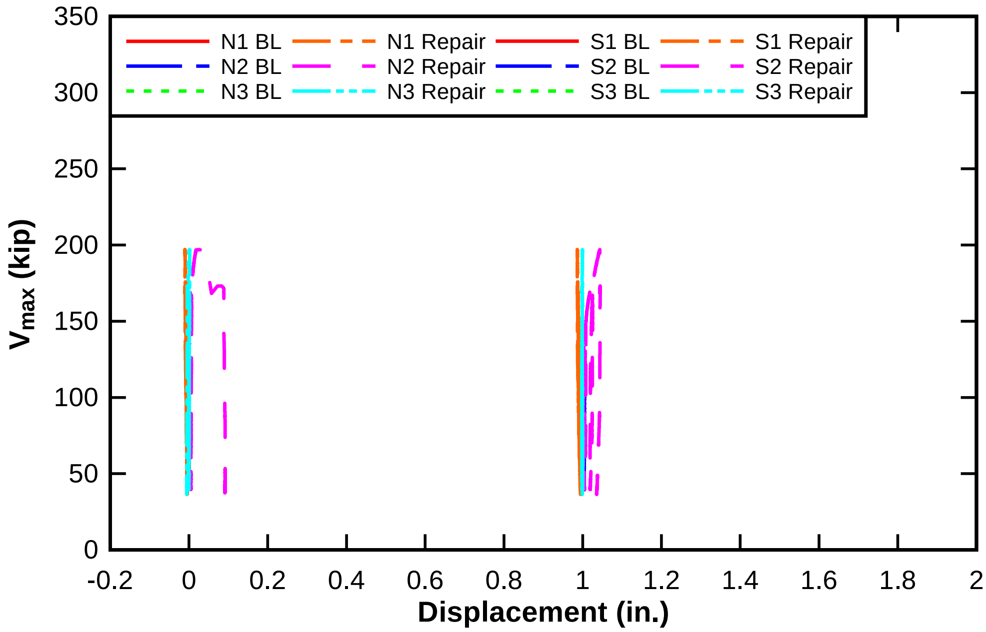


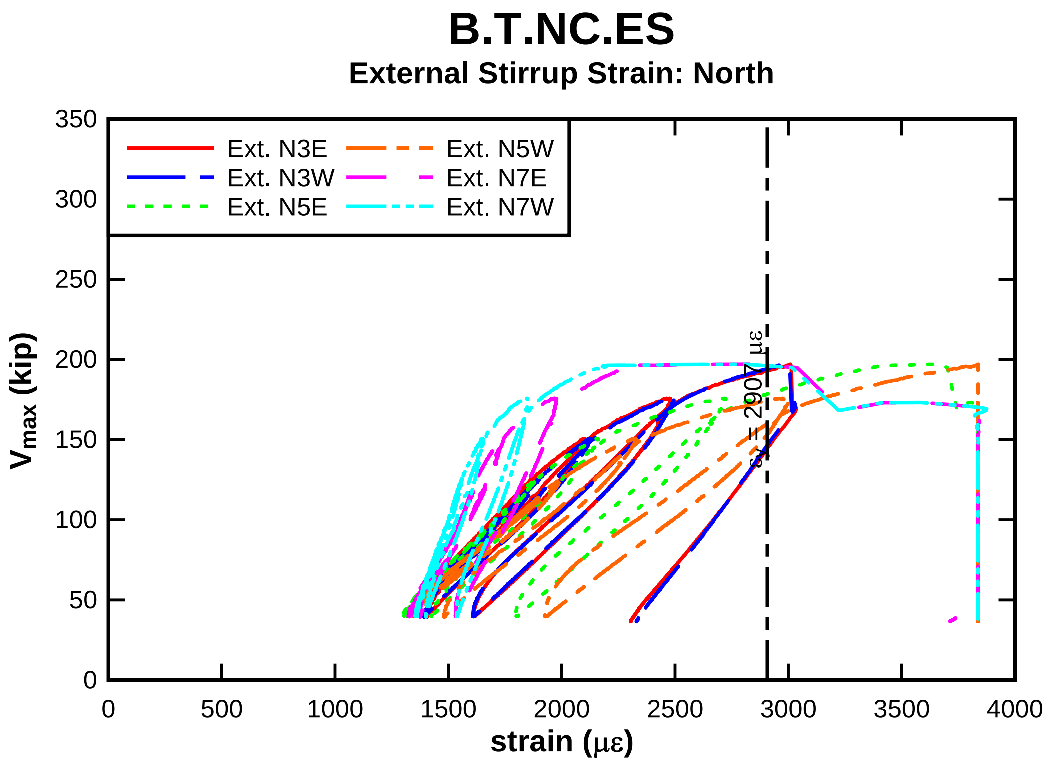
B.T.NC.ES
Integrally Cast Stirrup Strain: South
S1 Baseline
S2 Baseline
S3 Baseline
S1 Repair
S2 Repair
S3 Repair
ε_y = 1731 $\mu\varepsilon$
V_{max} (kip)
strain ($\mu\varepsilon$)
0
50
100
150
200
250
300
350
-200
300
800
1300
1800
2300
2800
3300
3800

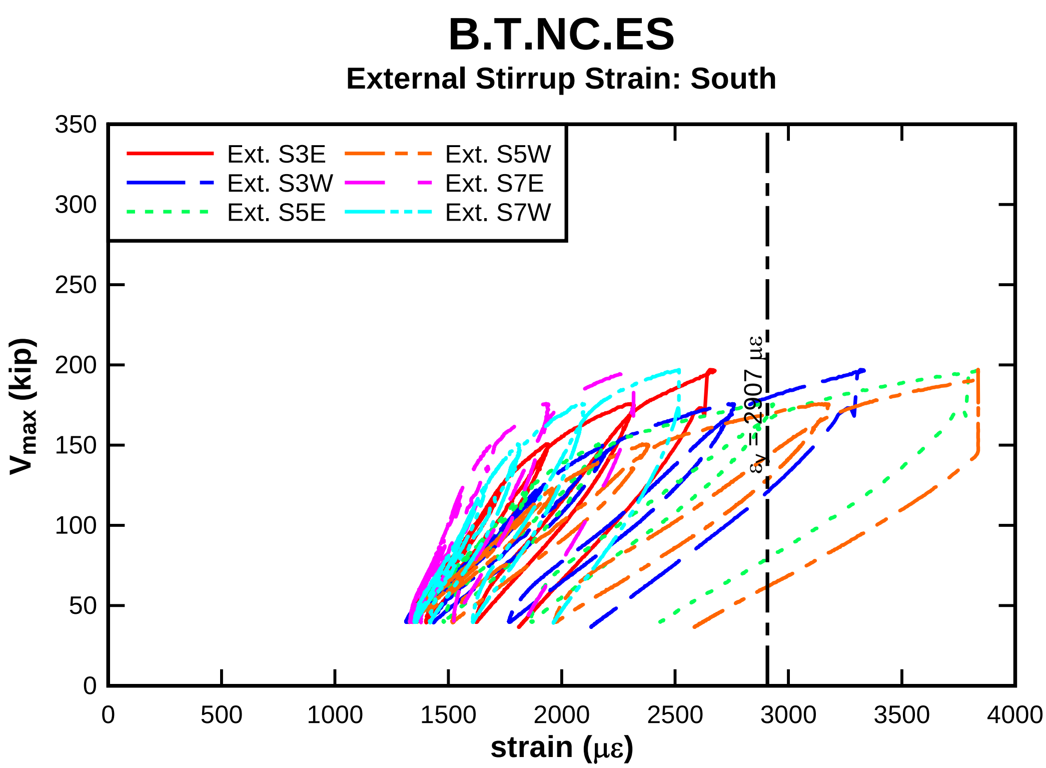
B.T.NC.ES
Tension Diagonal Displacement
Data offset by 1 in.



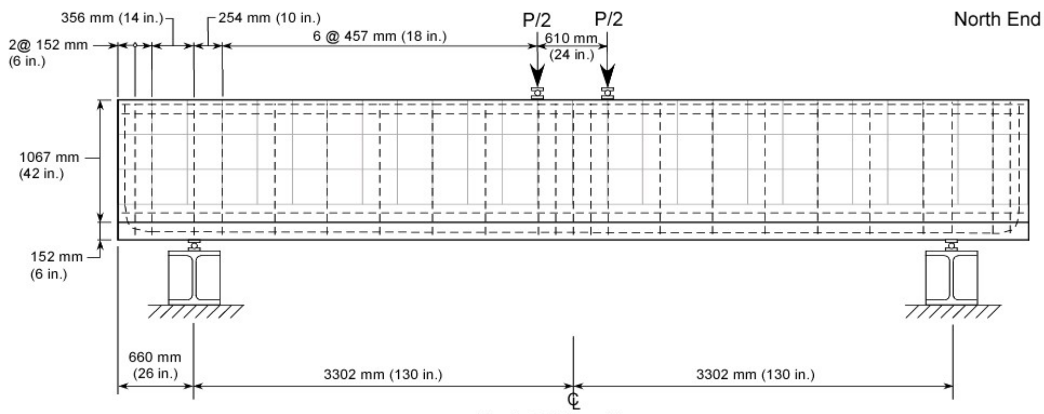
B.T.NC.ES
Compression Diagonal Displacement
Data offset by 1 in.



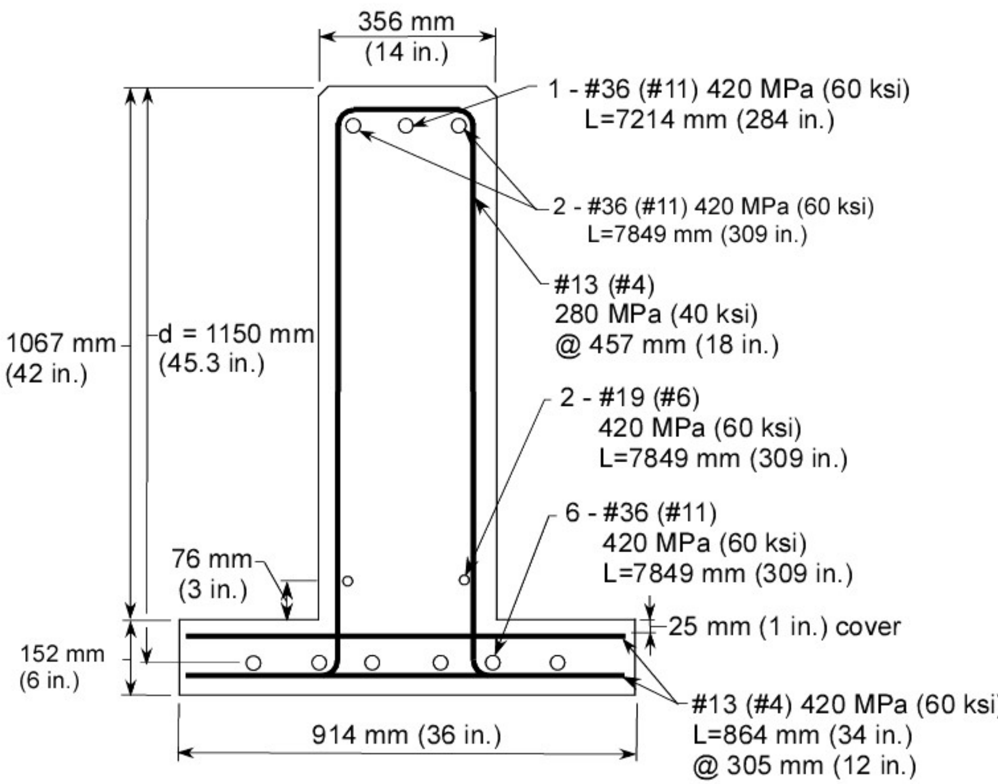

B.T.NC.ES
External Stirrup Strain: North
Ext. N3E
Ext. N3W
Ext. N5E
Ext. N5W
Ext. N7E
Ext. N7W
ε_y = 2907 με
V_{max} (kip)
strain (με)
0
50
100
150
200
250
300
350
0
500
1000
1500
2000
2500
3000
3500
4000


B.T.NC.ES
External Stirrup Strain: South
Ext. S3E
Ext. S3W
Ext. S5E
Ext. S5W
Ext. S7E
Ext. S7W
ε_y = 2907 με
V_{max} (kip)
strain (με)
0
50
100
150
200
250
300
350
0
500
1000
1500
2000
2500
3000
3500
4000

APPENDIX A-4: SPECIMEN B.IT.NC.IS

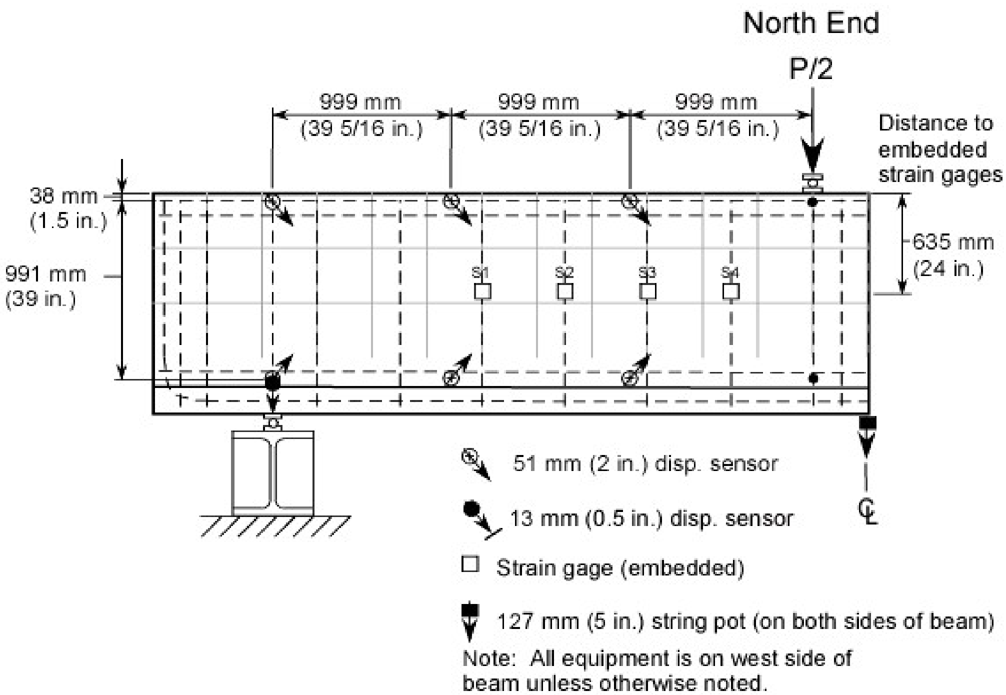


Typical IT Specimen

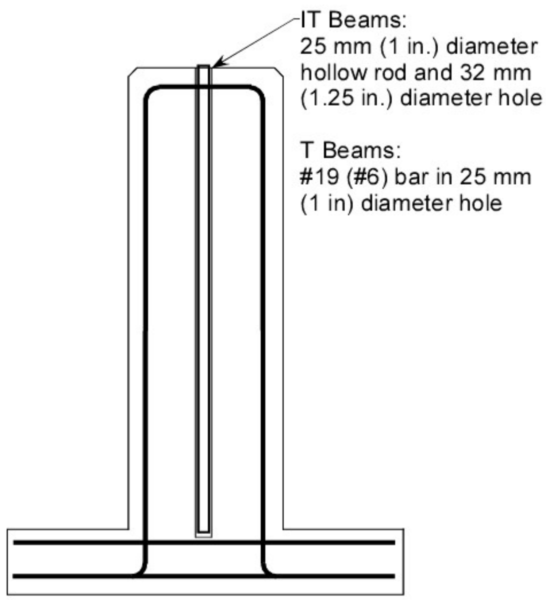


Note: 38 mm (1.5 in.) Cover Unless Noted

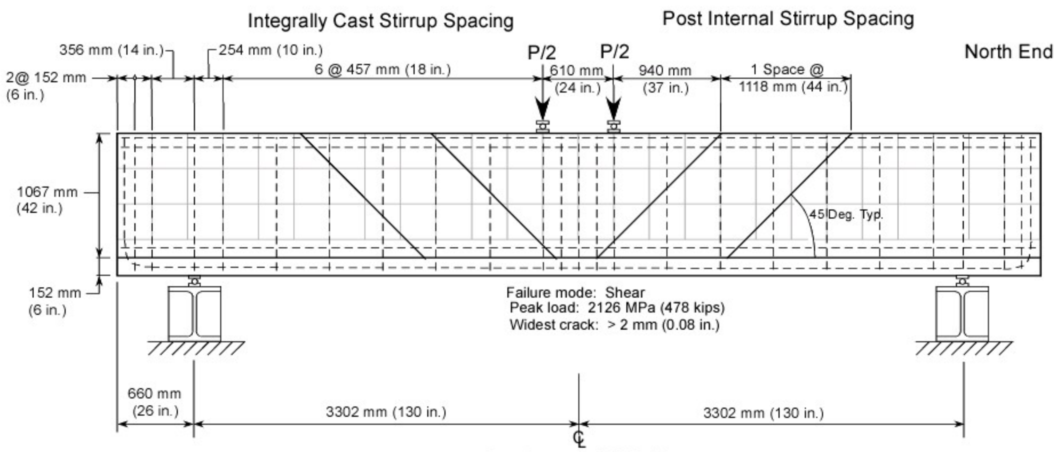
IT Beam Typical Section



IT Specimen Instrumentation

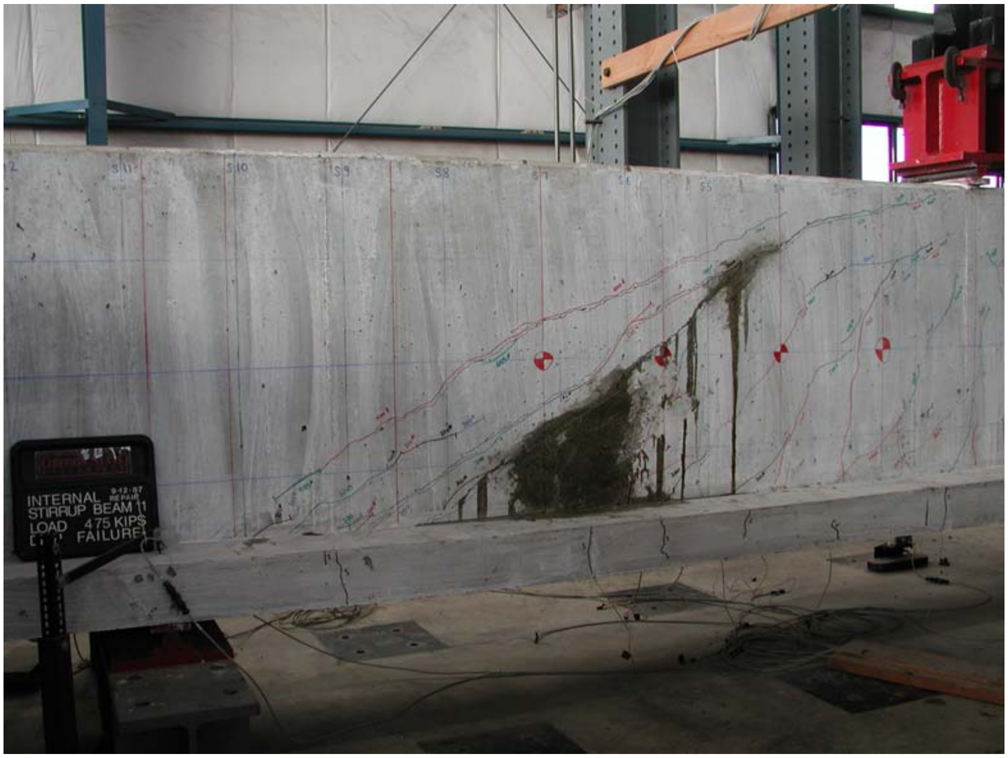


Internal Stirrup
Repair: Typical Section



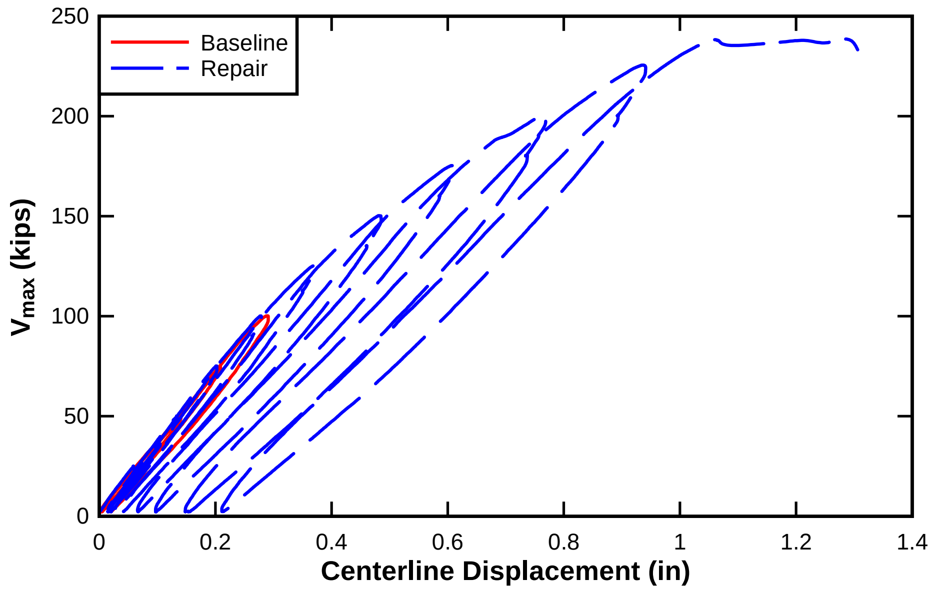
Specimen B.IT.NC.IS

B.IT.NC.IS North End



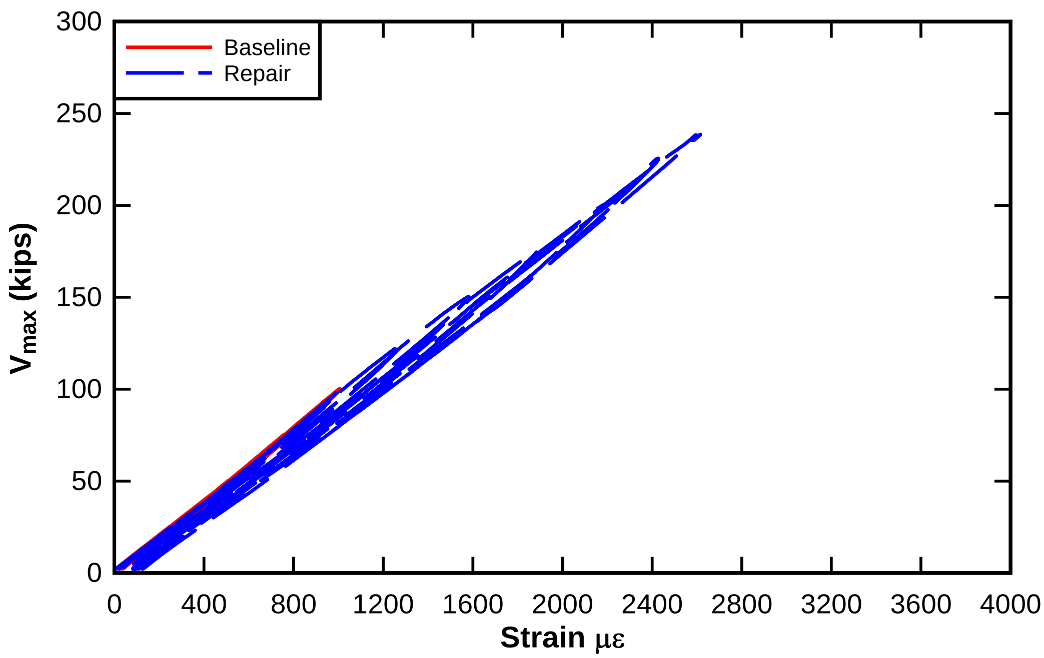
B.IT.NC.IS South End

B.IT.NC.IS



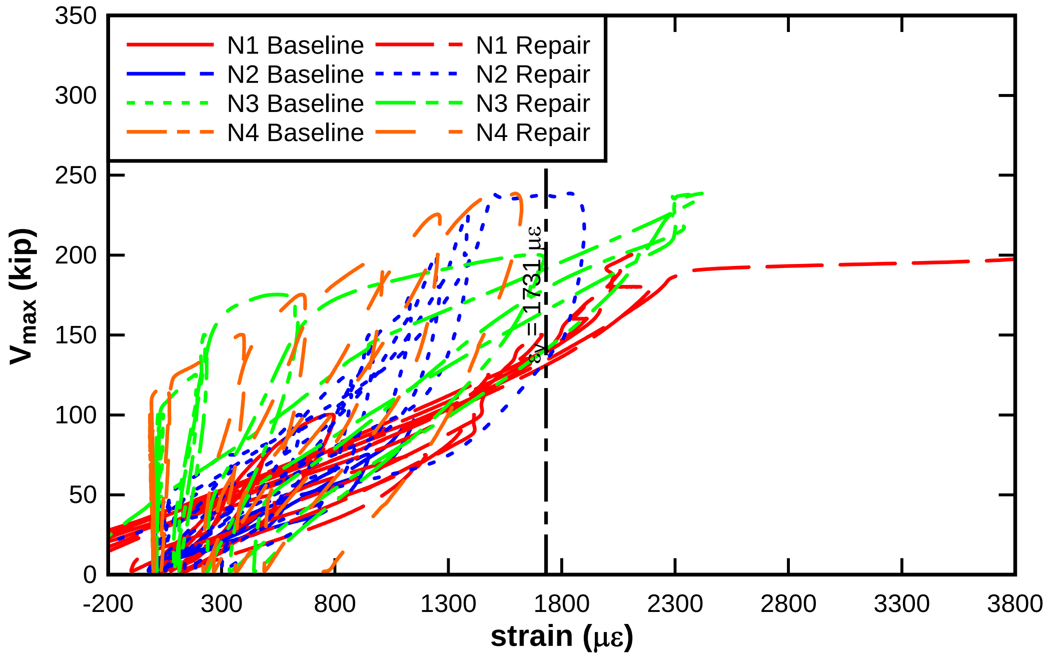
B.IT.NC.IS

Flexural Strain



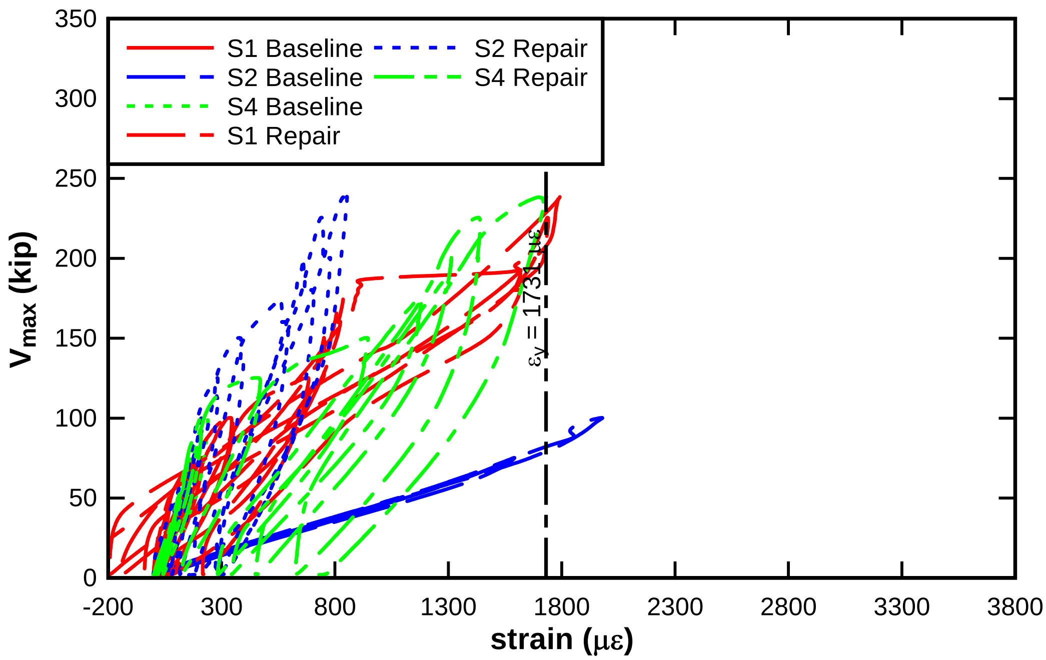
B.IT.NC.IS

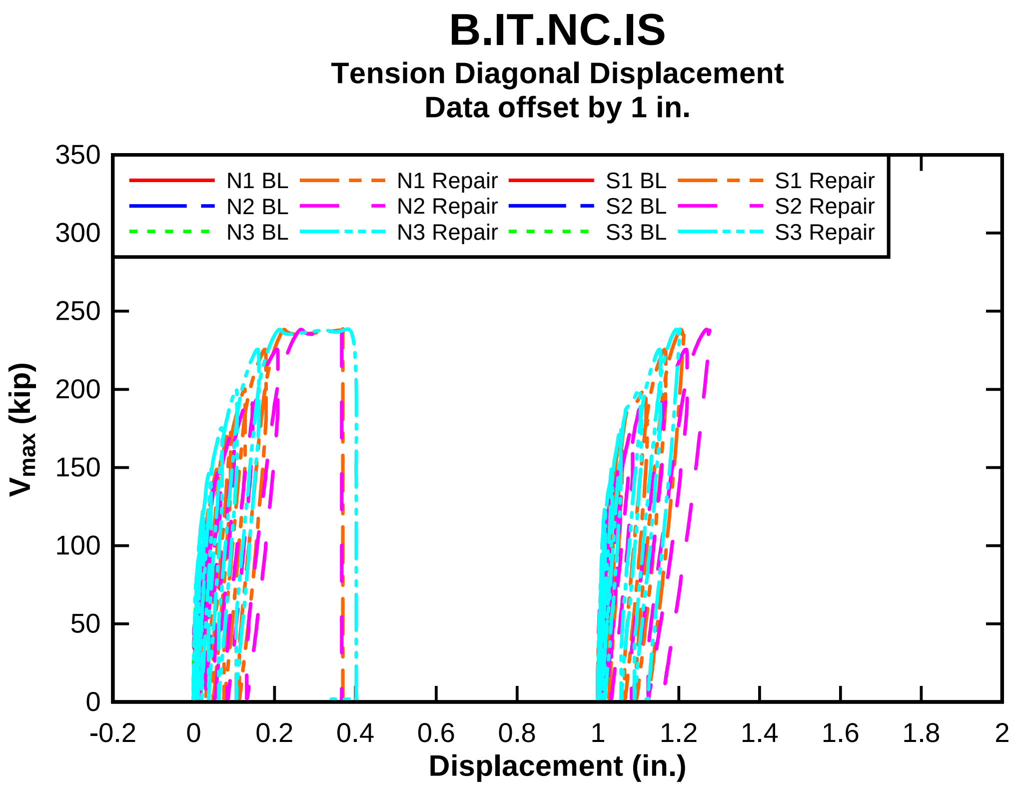
Integrally Cast Stirrup Strain: North

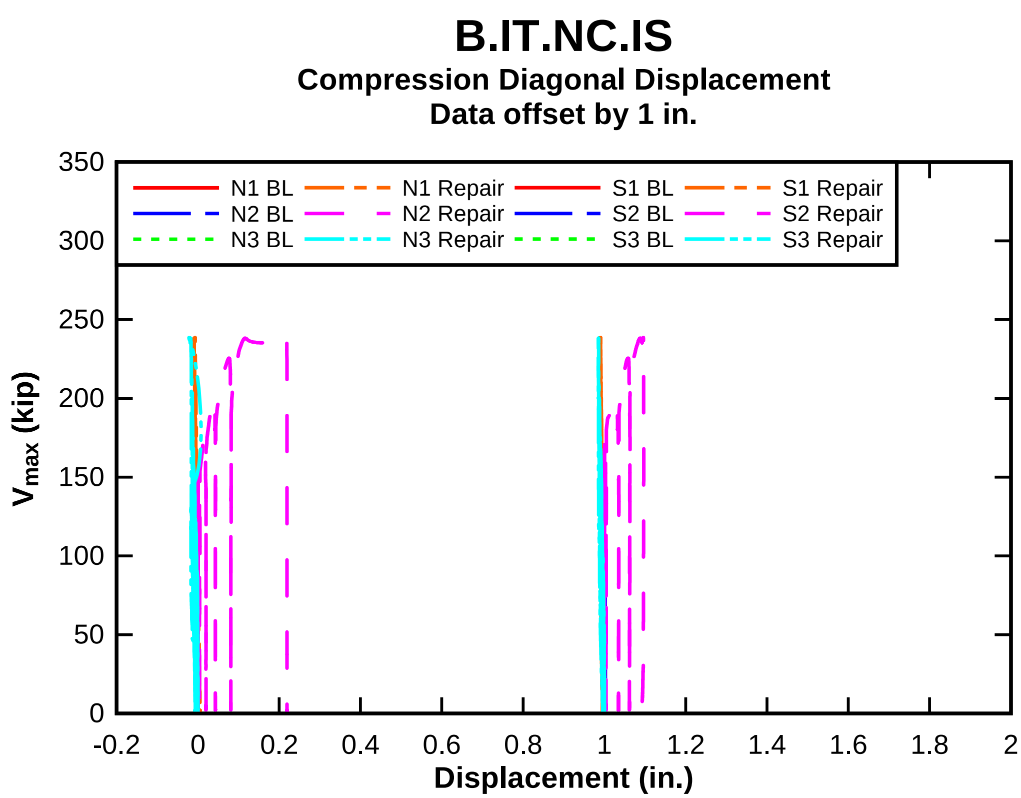


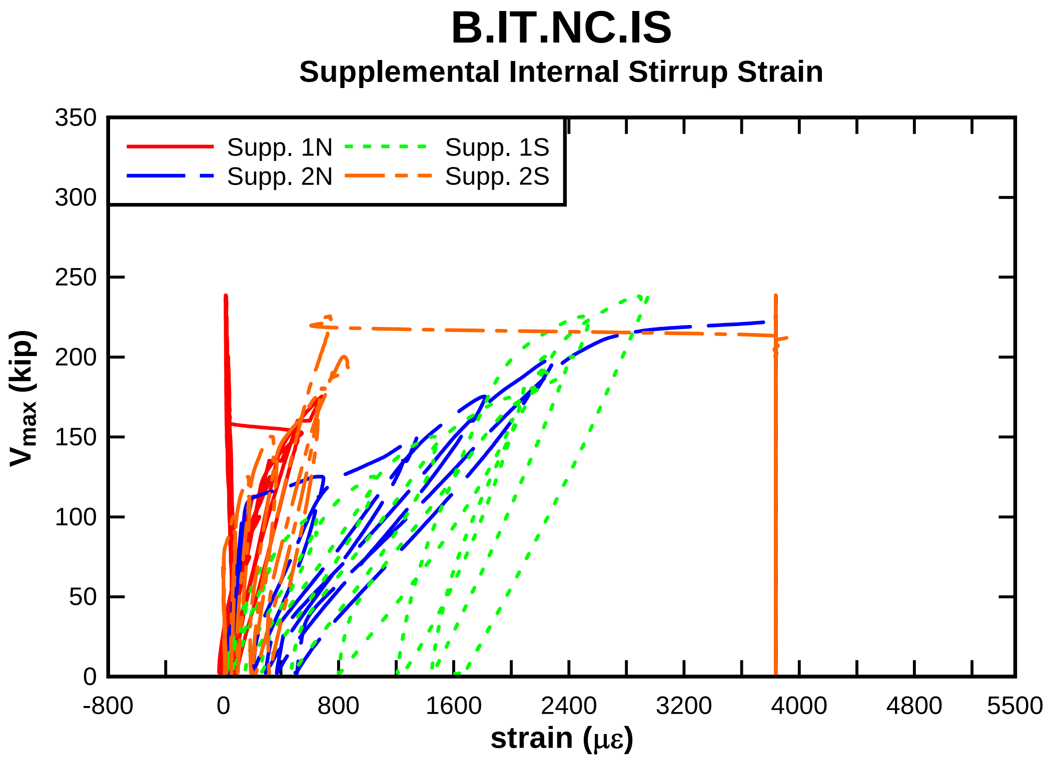
B.IT.NC.IS

Integrally Cast Stirrup Strain: South



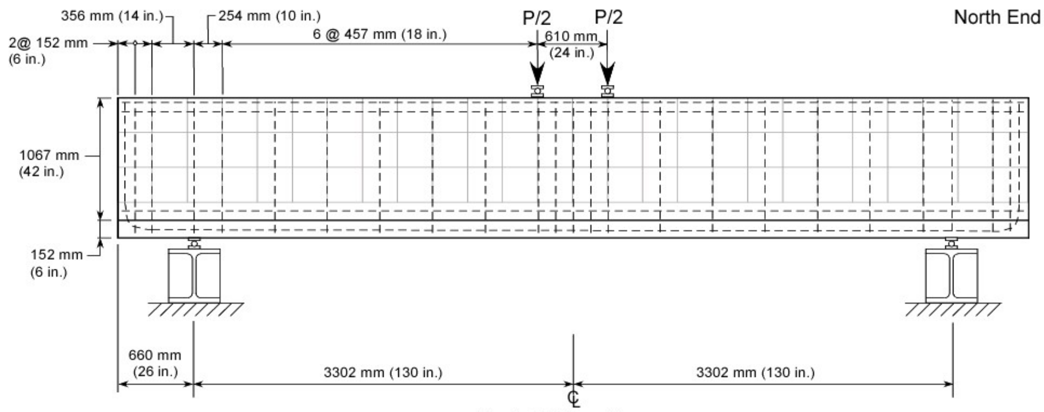

B.IT.NC.IS
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N2 BL
N3 BL
N1 Repair
N2 Repair
N3 Repair
S1 BL
S2 BL
S3 BL
S1 Repair
S2 Repair
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


B.IT.NC.IS
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N2 BL
N3 BL
N1 Repair
N2 Repair
N3 Repair
S1 BL
S2 BL
S3 BL
S1 Repair
S2 Repair
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

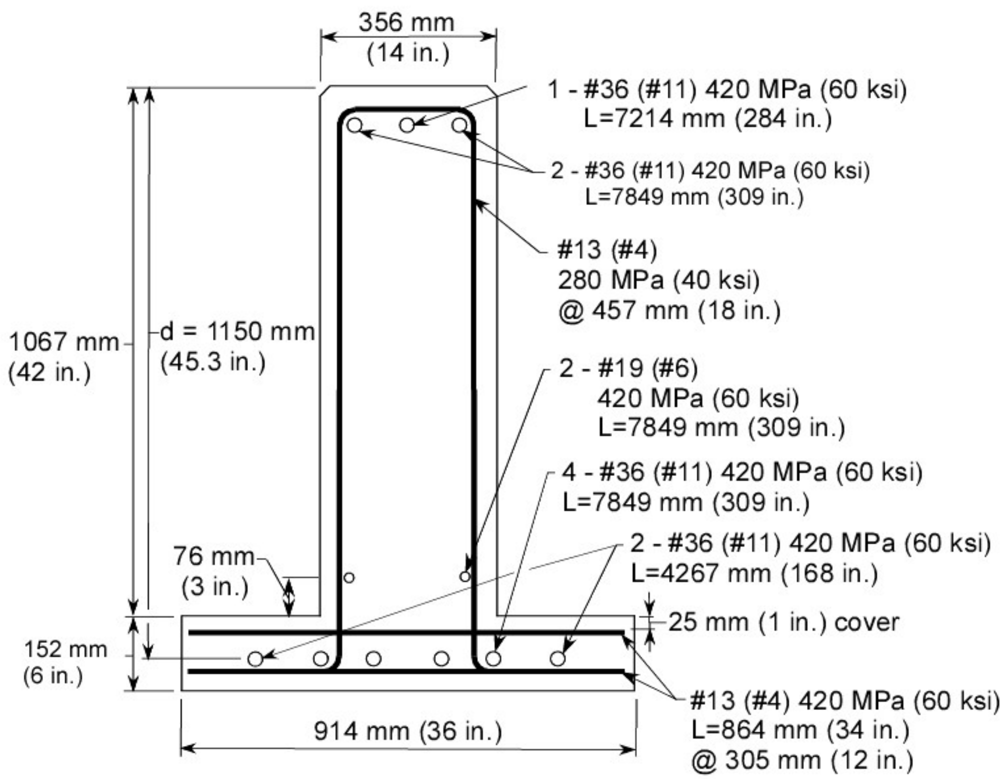


B.IT.NC.IS
Supplemental Internal Stirrup Strain
Supp. 1N
Supp. 1S
Supp. 2N
Supp. 2S
350
300
250
200
150
100
50
0
-800
0
800
1600
2400
3200
4000
4800
5500
strain (με)
Vmax (kip)

APPENDIX A-5: SPECIMEN B.IT.C.IS

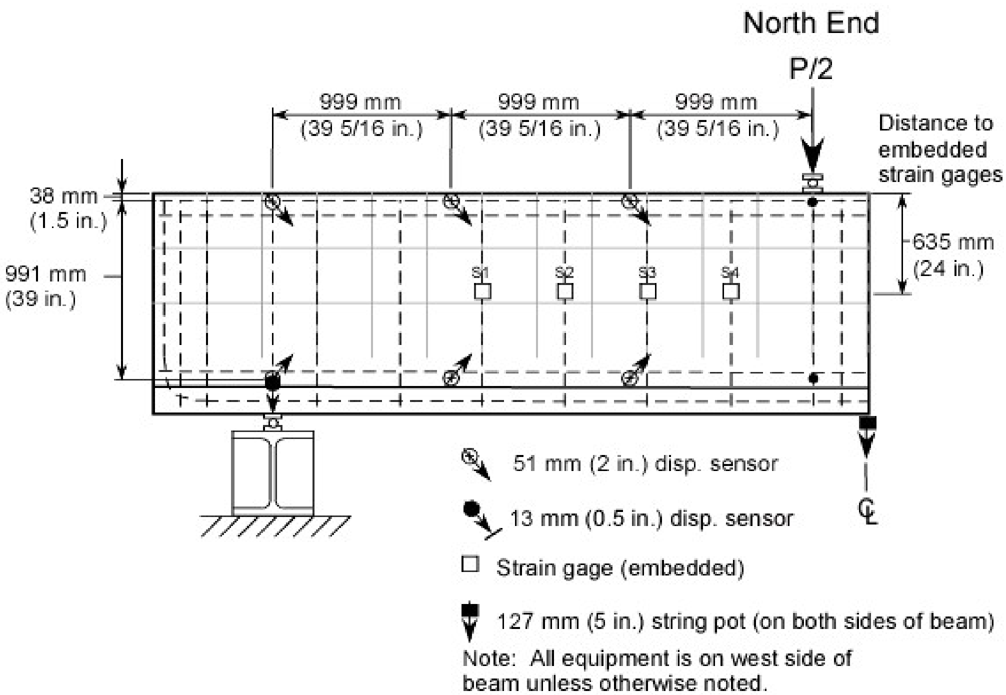


Typical IT Specimen

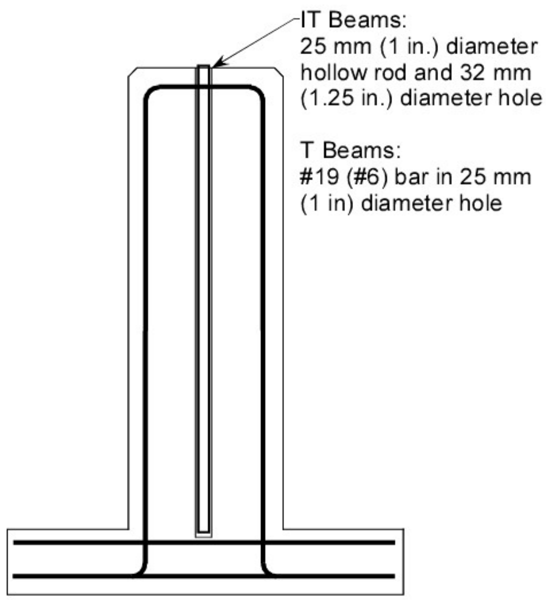


Note: 38 mm (1.5 in.) Cover Unless Noted

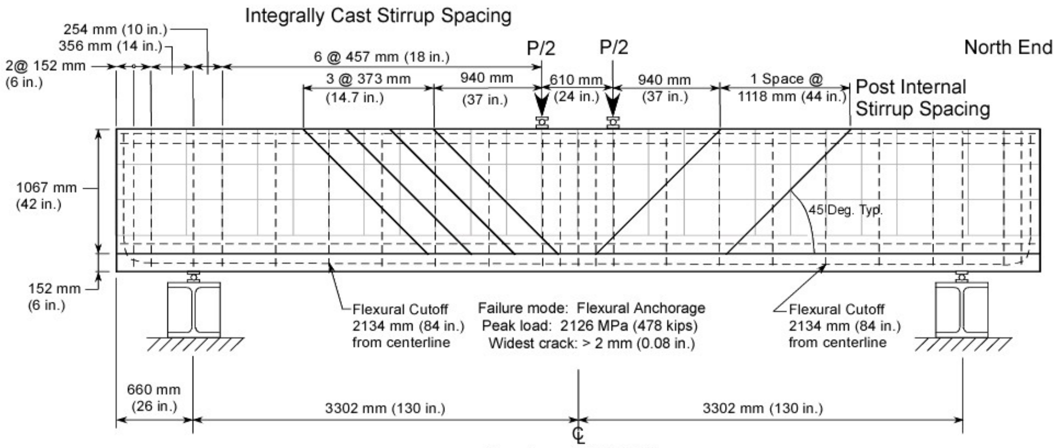
IT Beam with Cutoff Typical Section



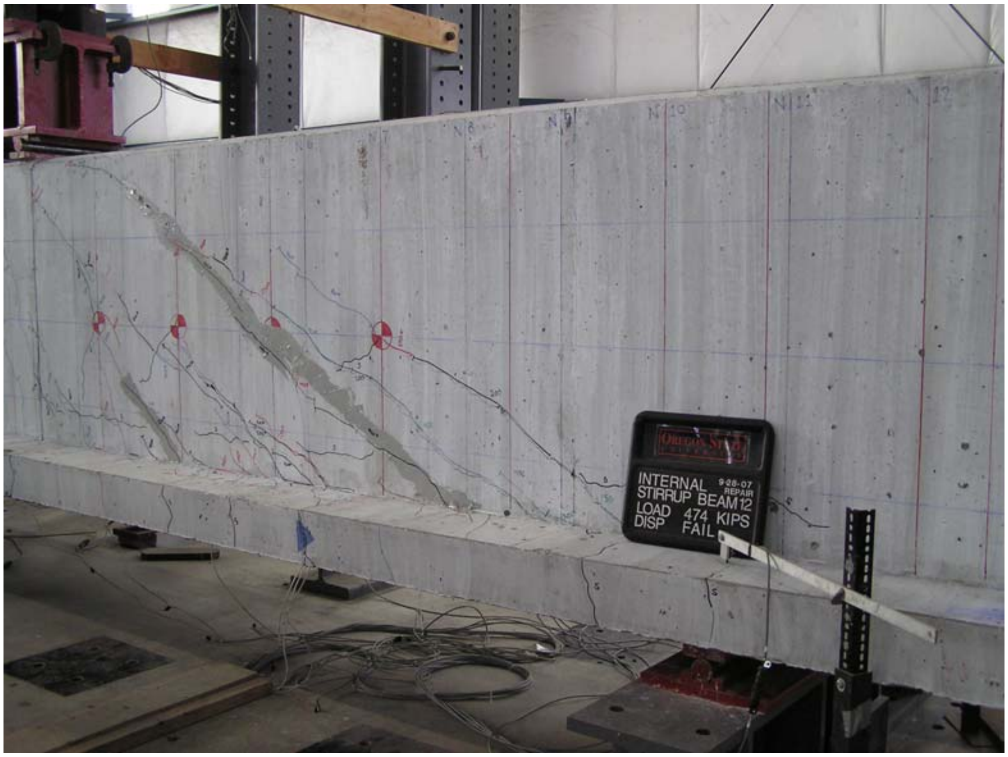
IT Specimen Instrumentation



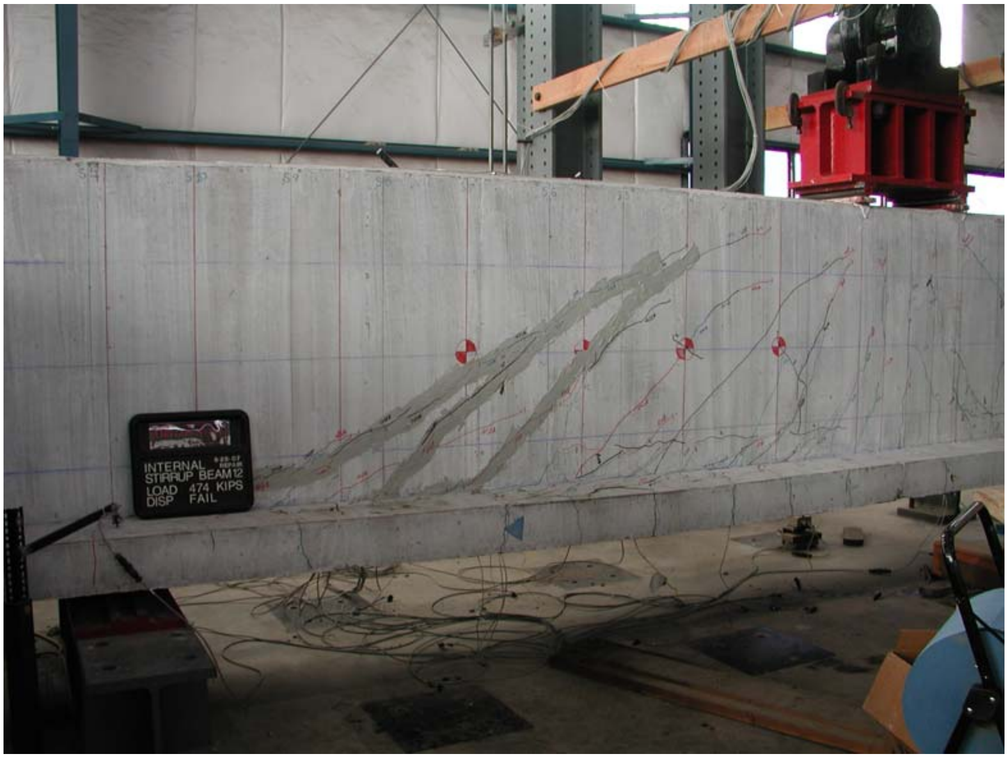
Internal Stirrup Repair: Typical Section



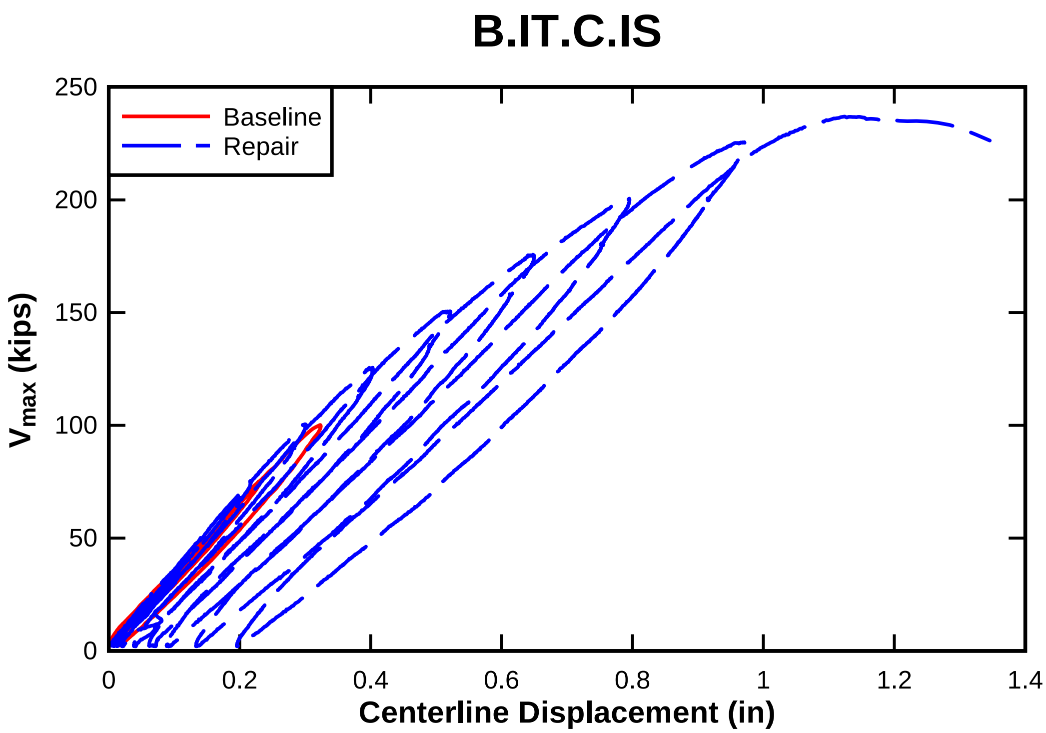
Specimen B.IT.C.IS

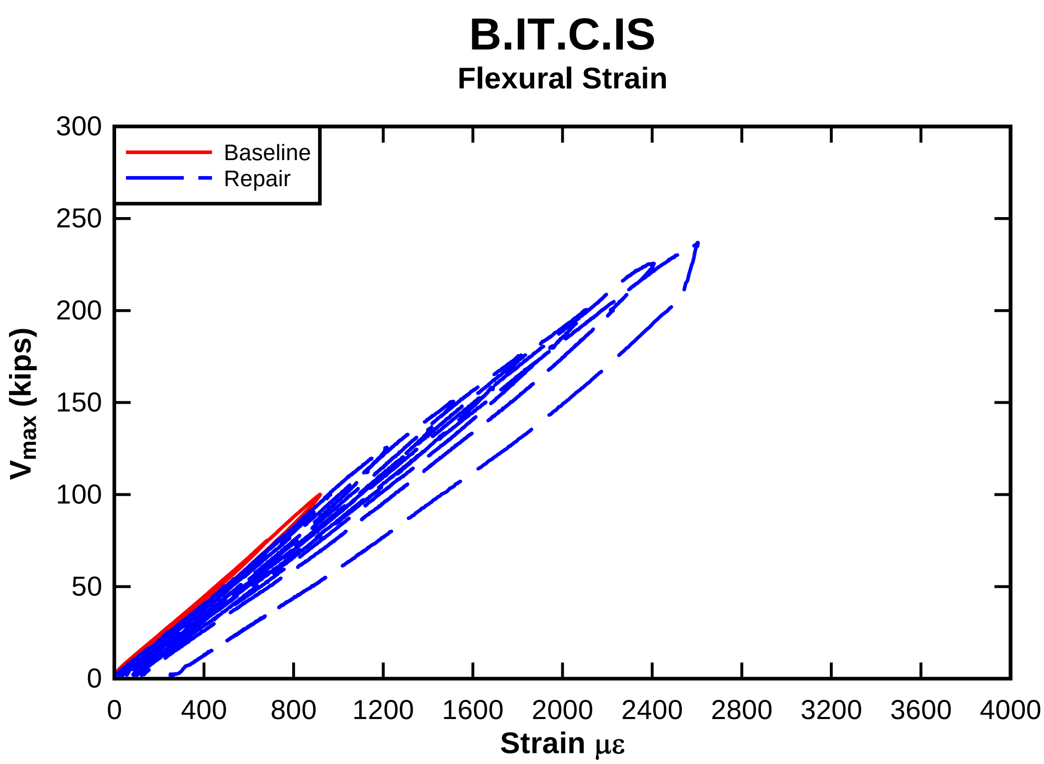


B.IT.C.IS North End



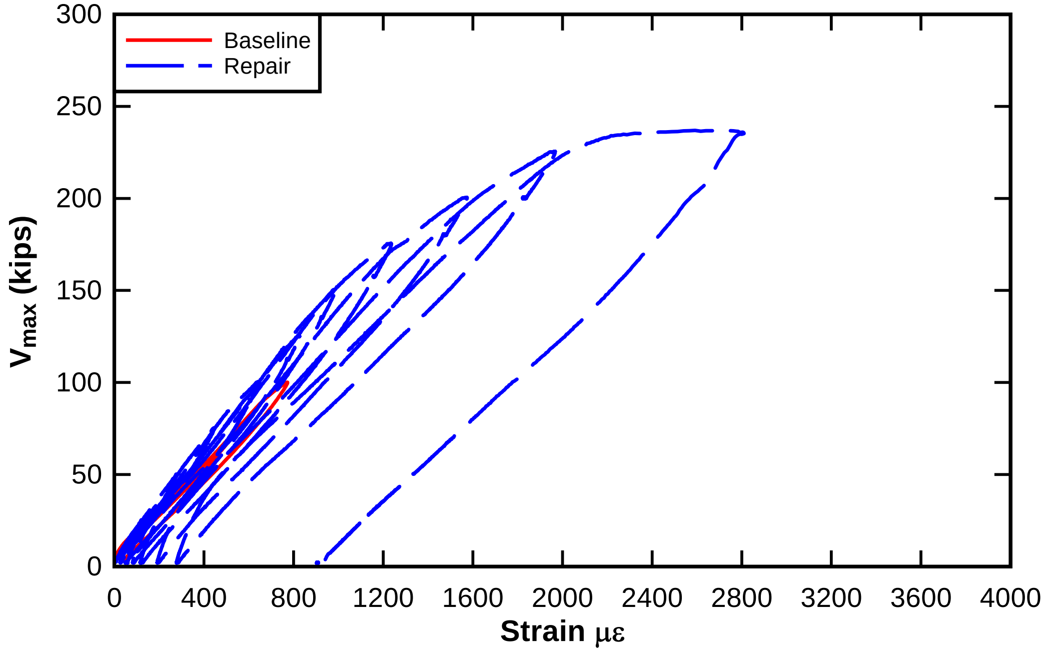
B.IT.C.IS South End


B.IT.C.IS
Baseline
Repair
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Centerline Displacement (in)
V_{max} (kips)


B.IT.C.IS
Flexural Strain
Baseline
Repair
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Strain με
V_{max} (kips)

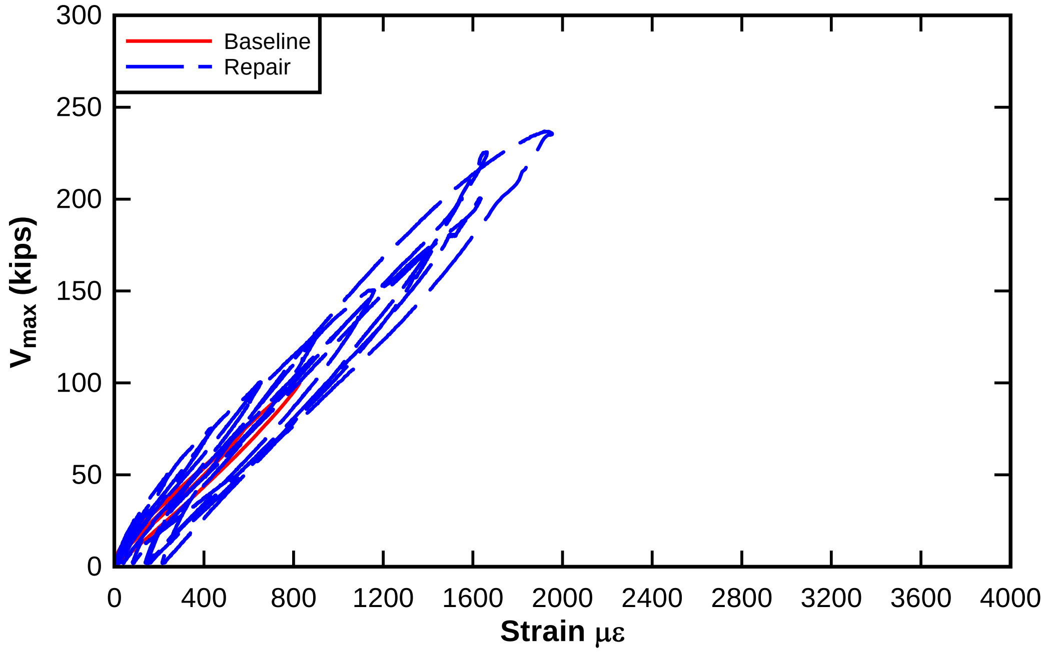
B.IT.C.IS

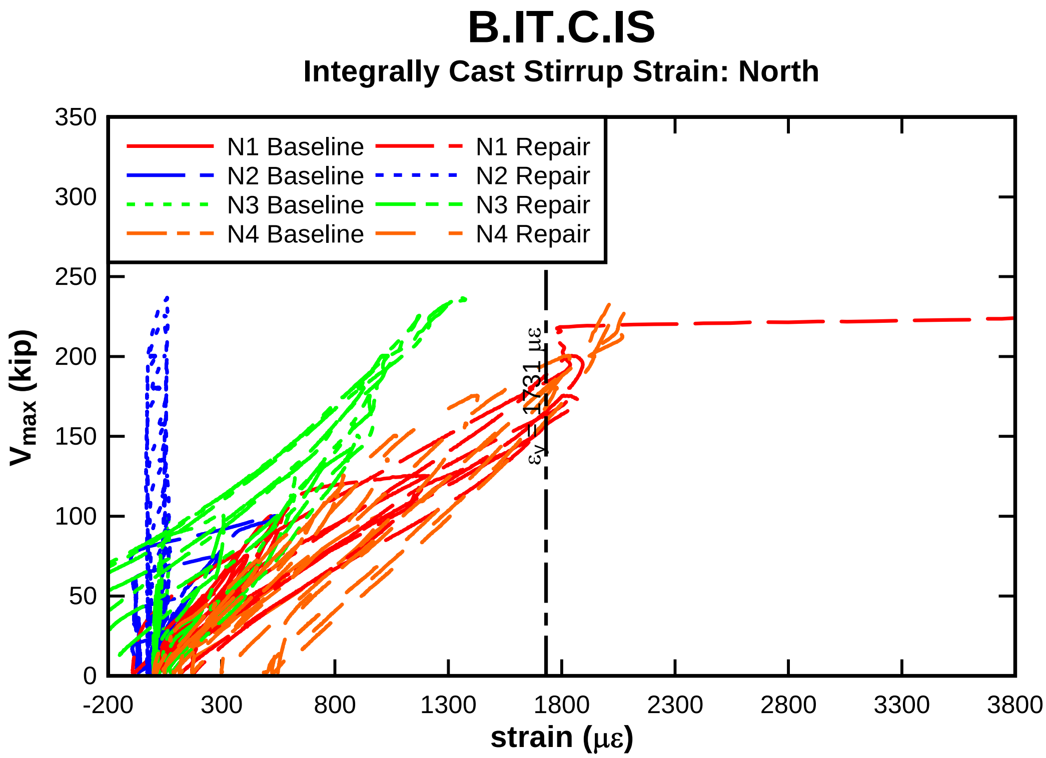
Flexural Strain at North Cutoff Location



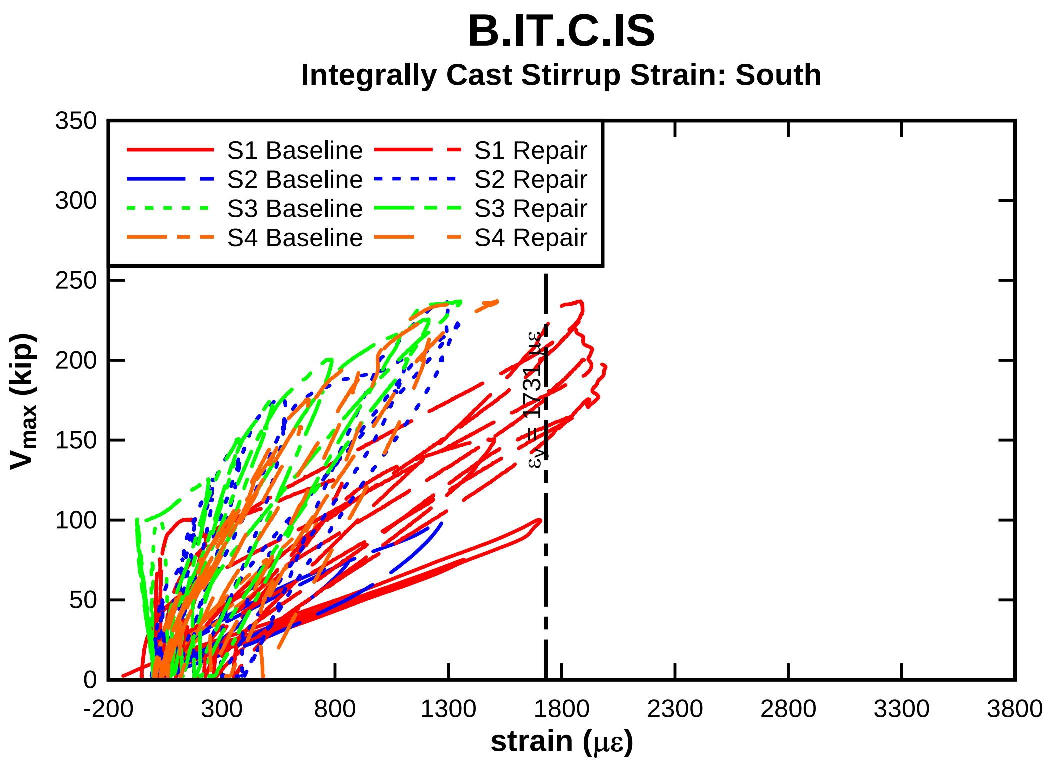
B.IT.C.IS

Flexural Strain at South Cutoff Location





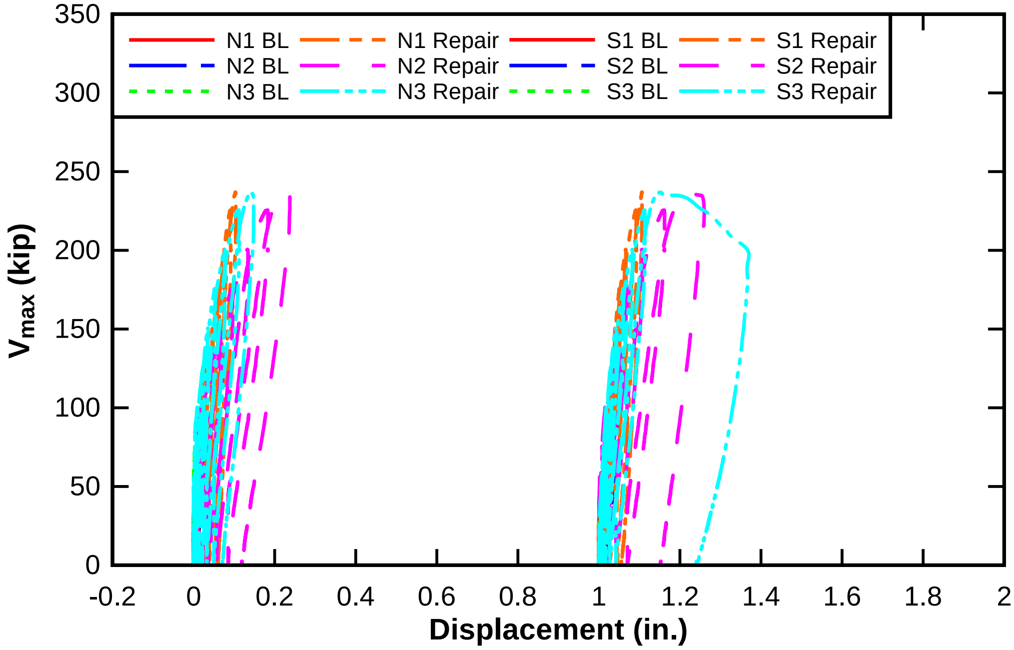
B.IT.C.IS
Integrally Cast Stirrup Strain: North
N1 Baseline
N1 Repair
N2 Baseline
N2 Repair
N3 Baseline
N3 Repair
N4 Baseline
N4 Repair
ε_y = 1731 με
V_{max} (kip)
strain (με)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800



B.IT.C.IS
Integrally Cast Stirrup Strain: South
S1 Baseline
S1 Repair
S2 Baseline
S2 Repair
S3 Baseline
S3 Repair
S4 Baseline
S4 Repair
ε_y = 1731 με
V_{max} (kip)
strain (με)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800

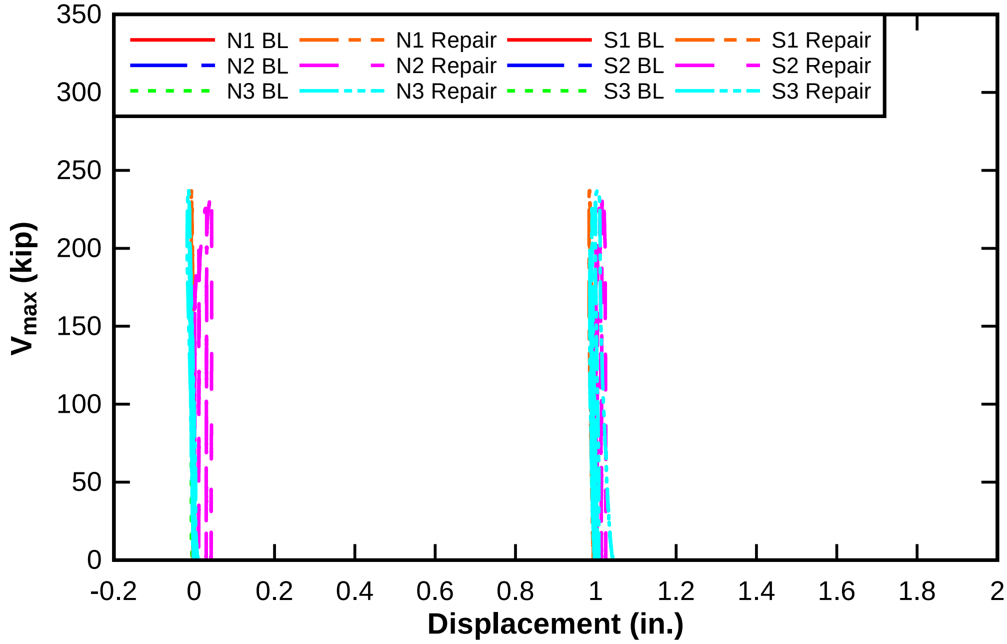
B.IT.C.IS

Tension Diagonal Displacement
Data offset by 1 in.



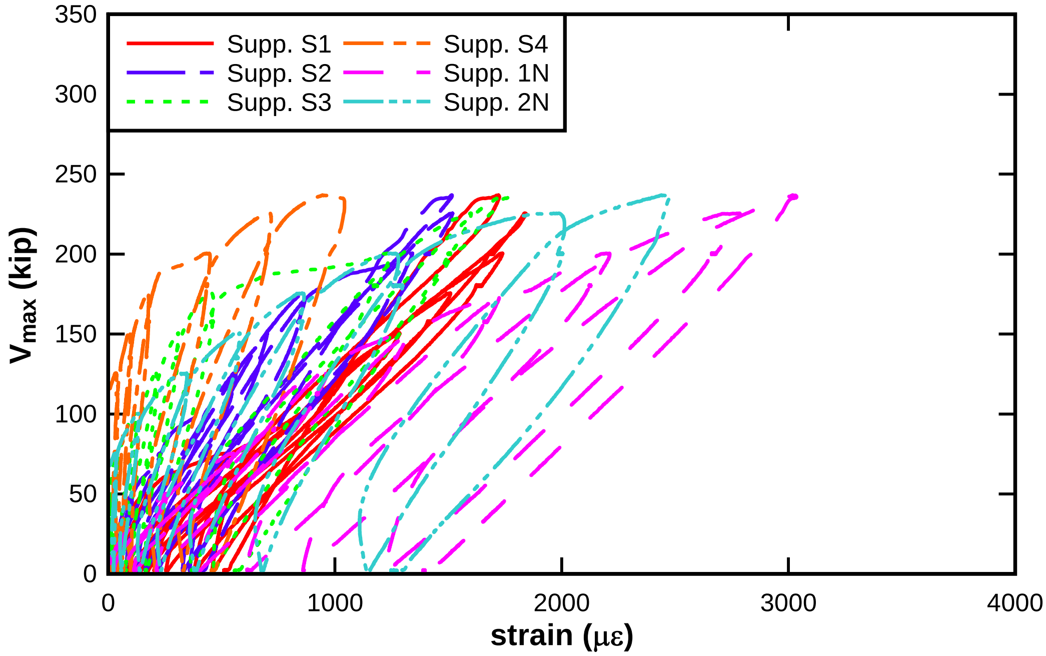
B.IT.C.IS

Compression Diagonal Displacement
Data offset by 1 in.

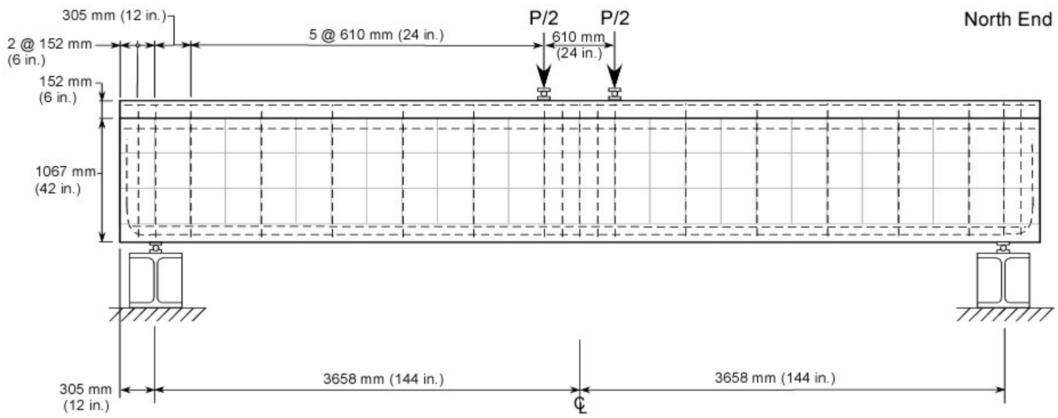


B.IT.C.IS

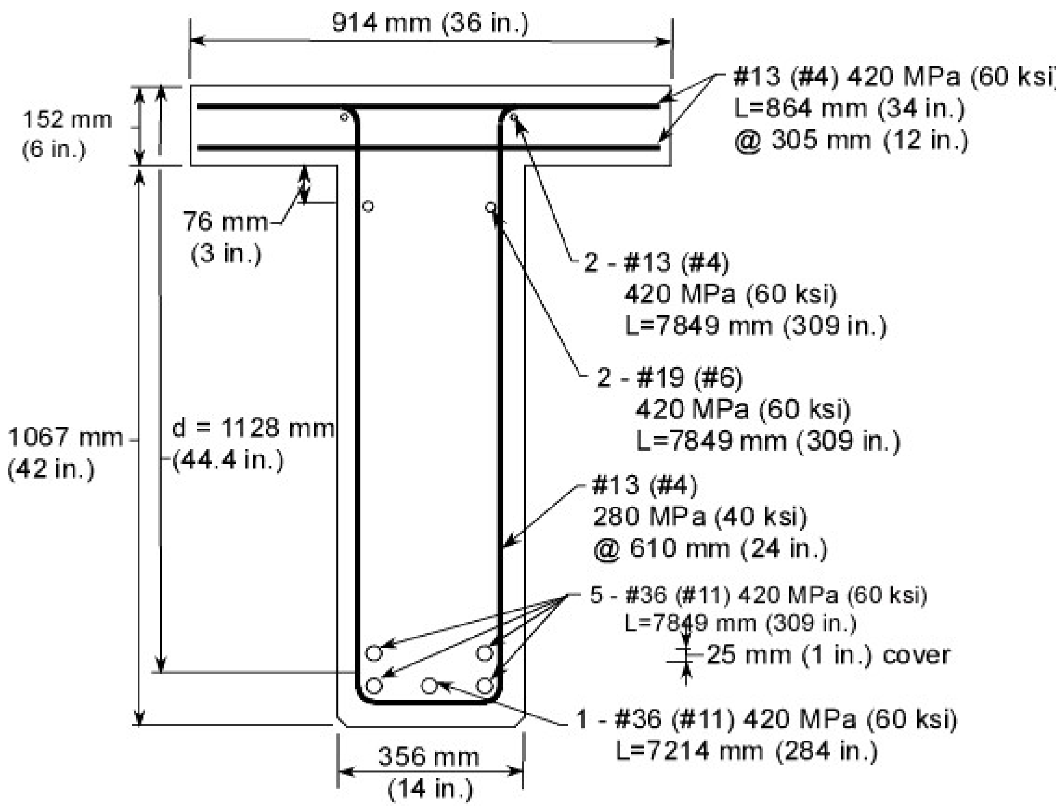
Supplemental Stirrup Strain



APPENDIX A-6: SPECIMEN B.T.NC.IS

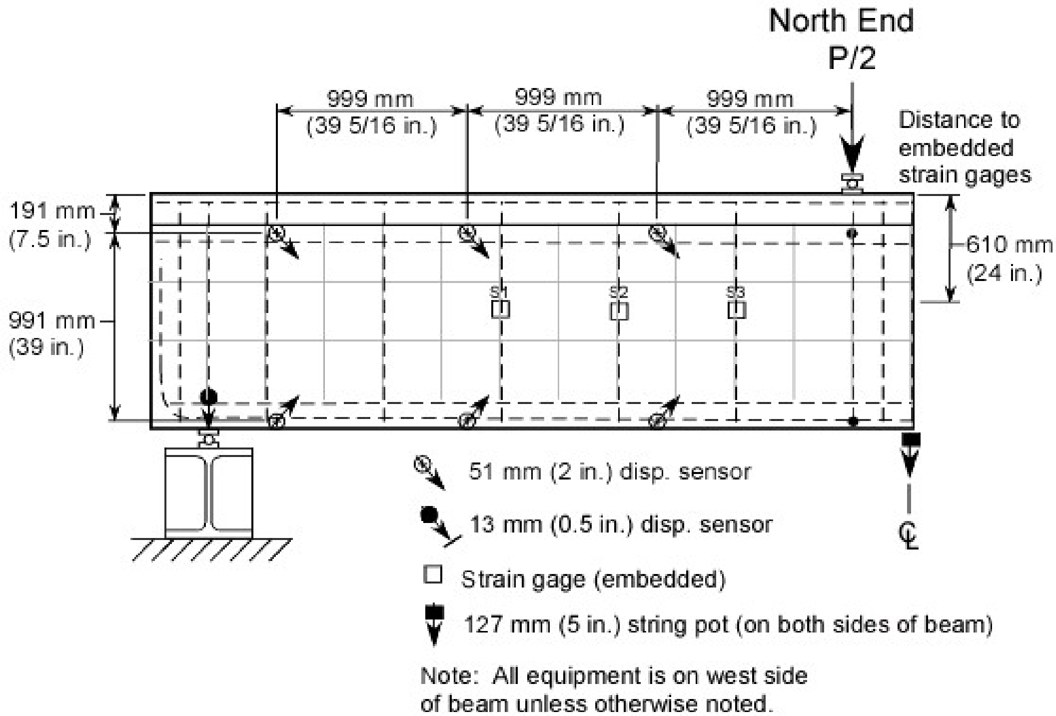


Typical T Beam

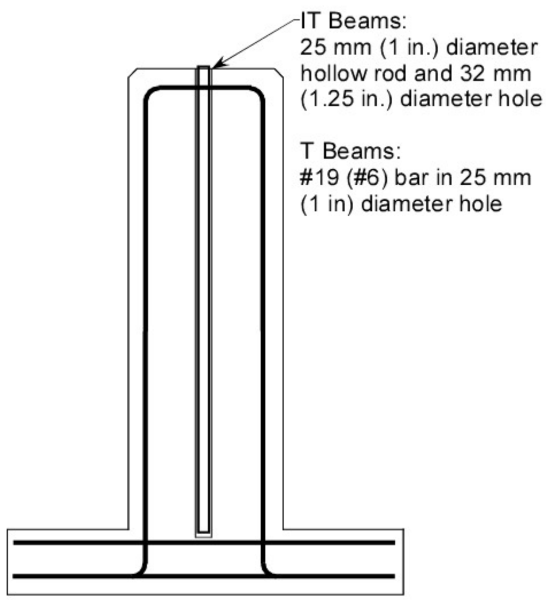


Note: 38 mm (1.5 in.) Cover Unless Noted

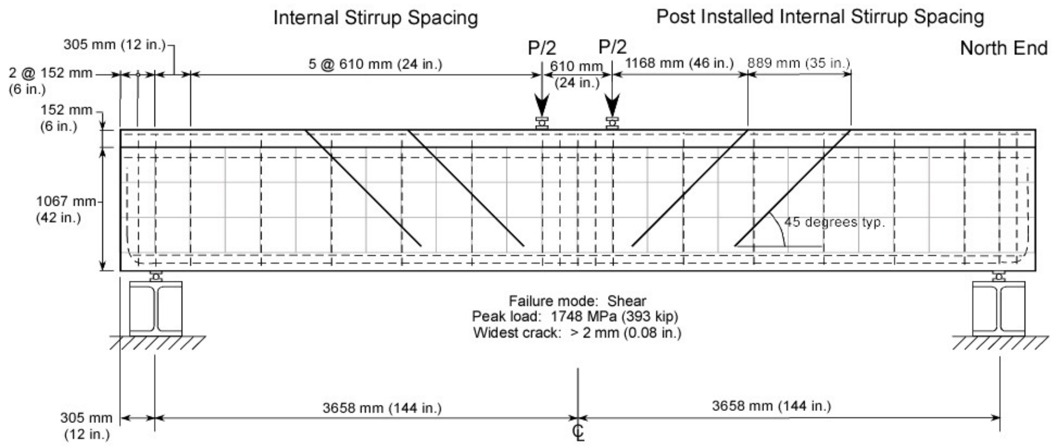
T Beam Typical Section



T Beam Instrumentation



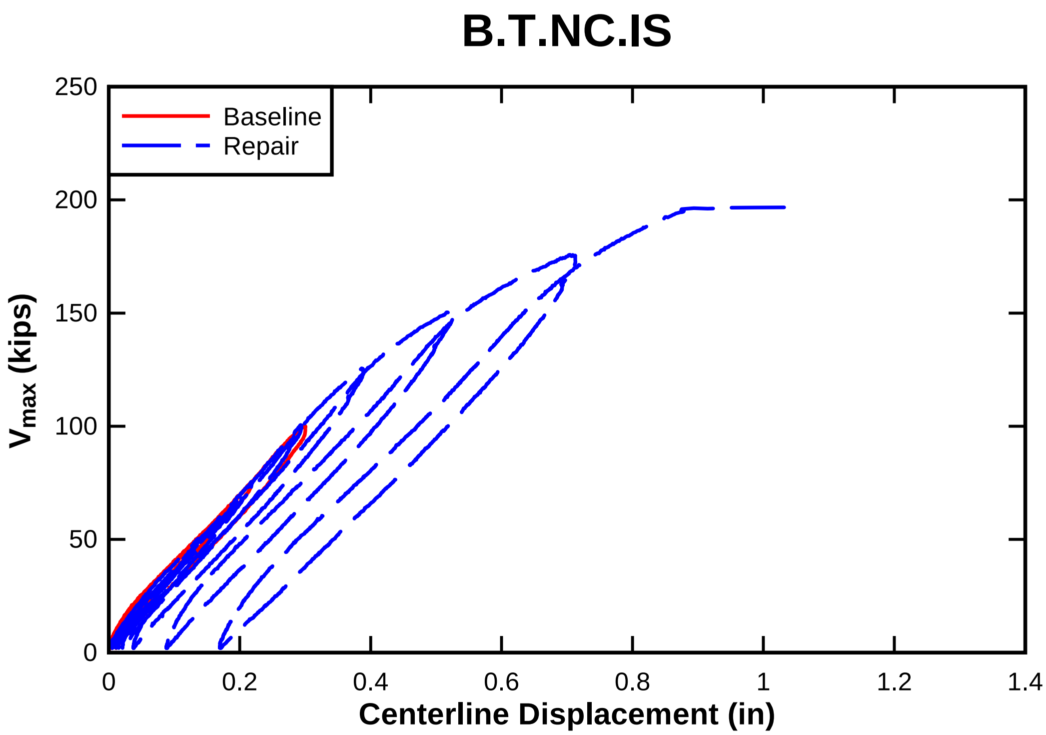
Internal Stirrup
Repair: Typical Section

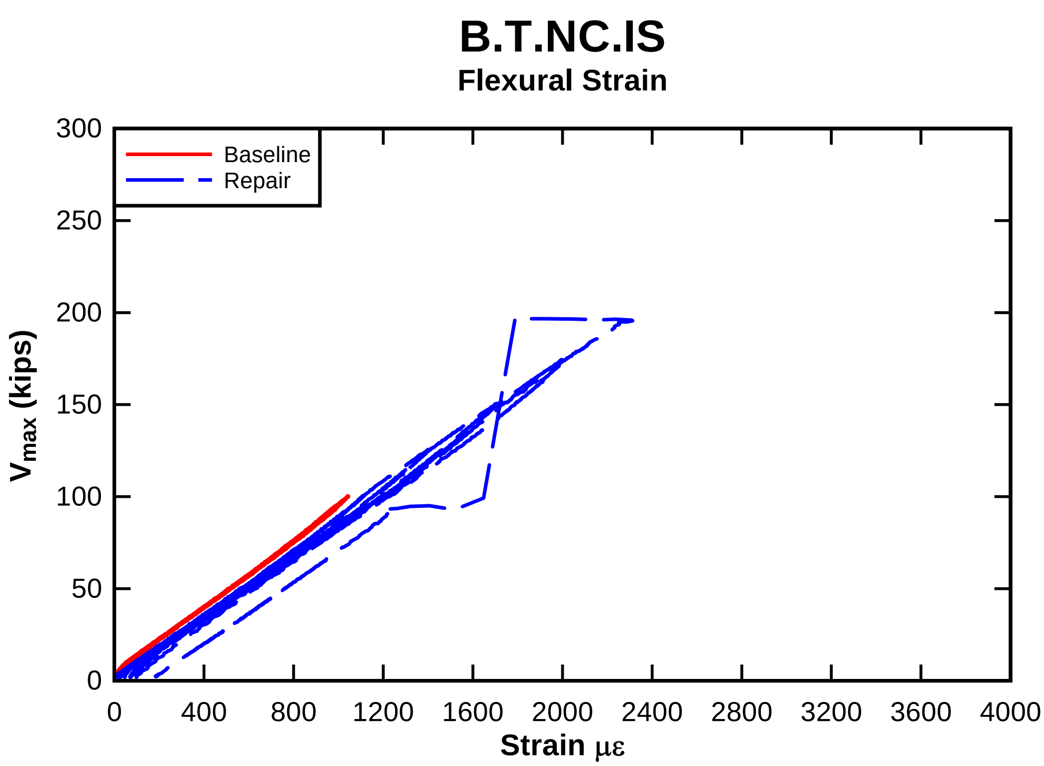


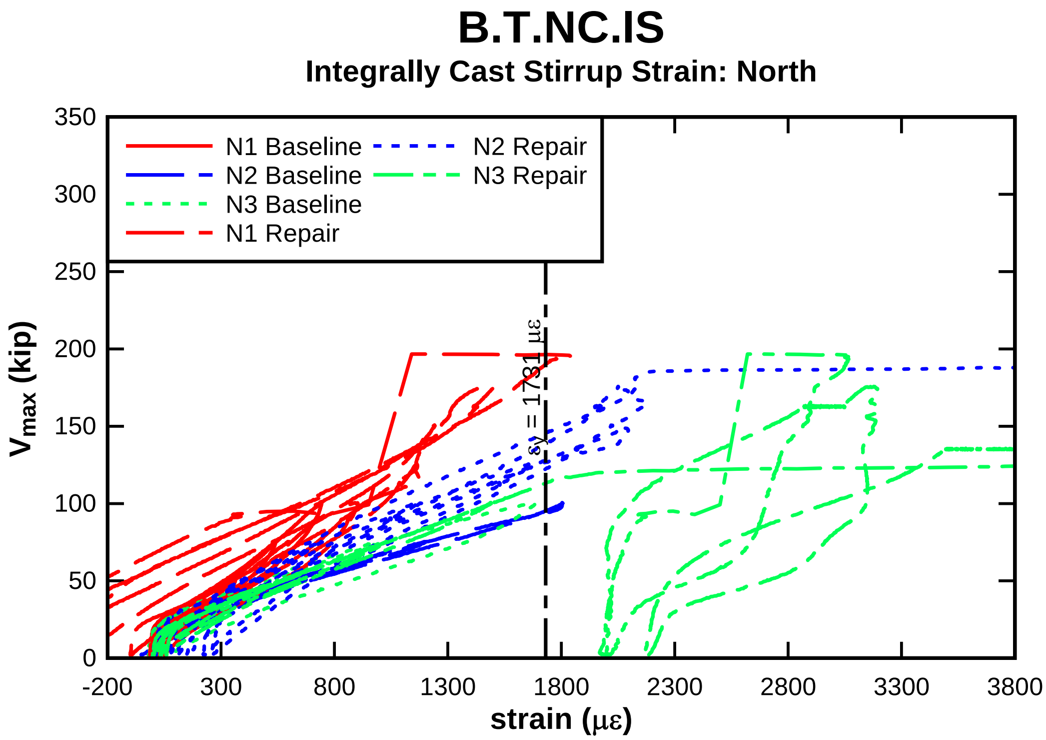
Specimen B.T.NC.IS

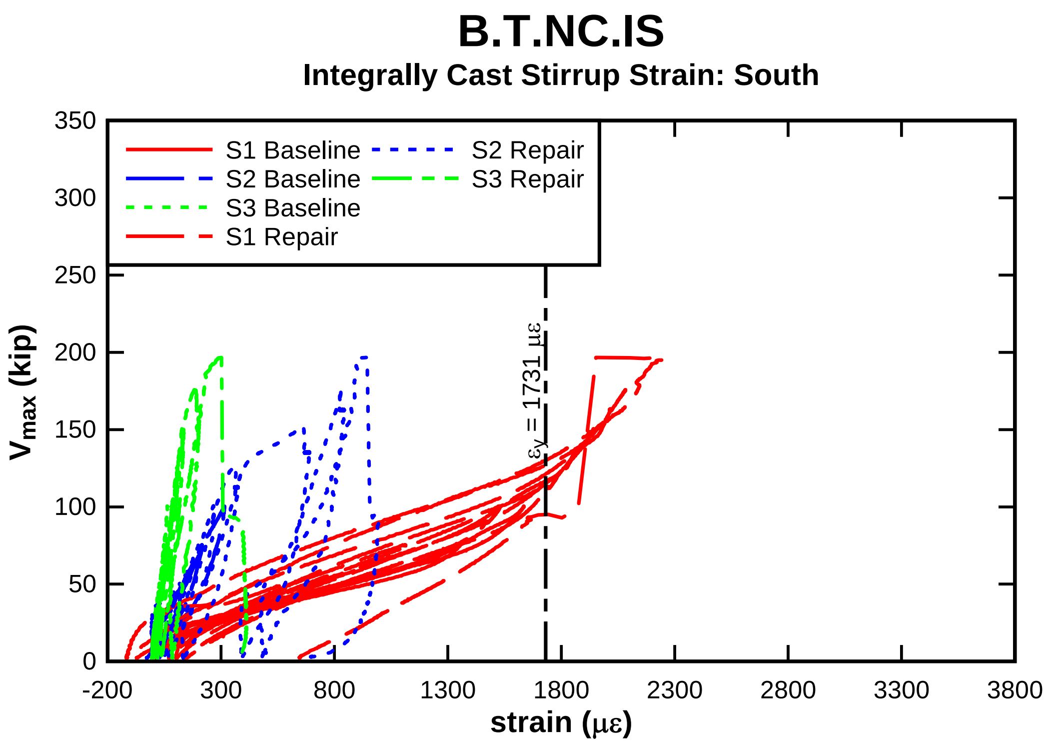
B.T.NC.IS North End

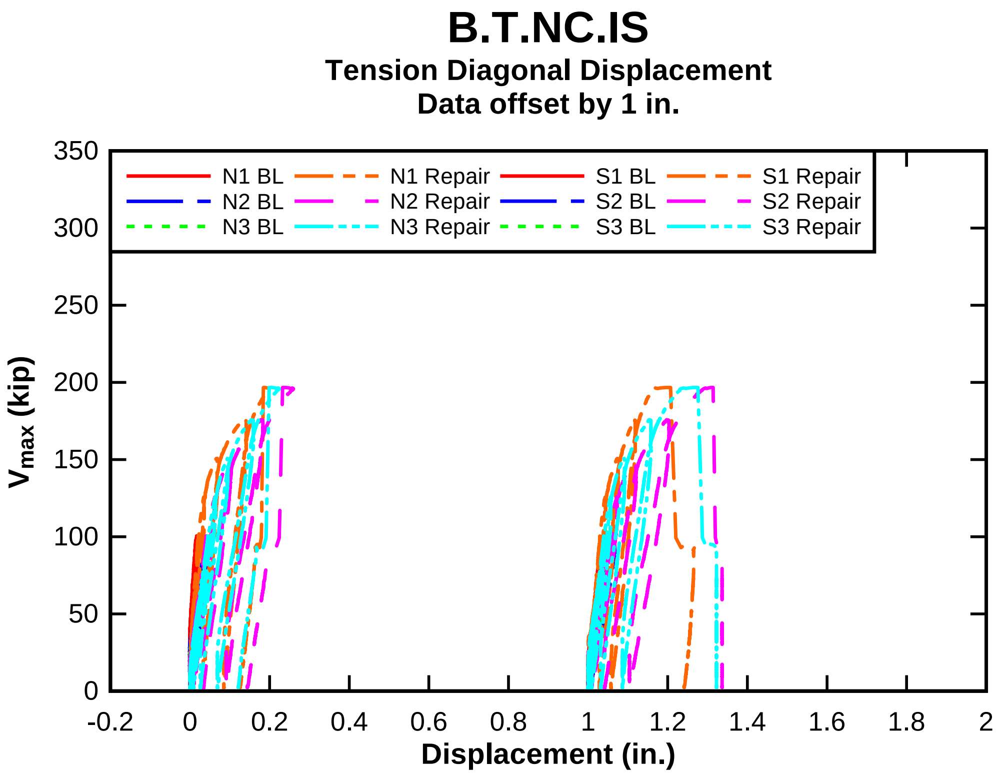
B.T.NC.IS South End

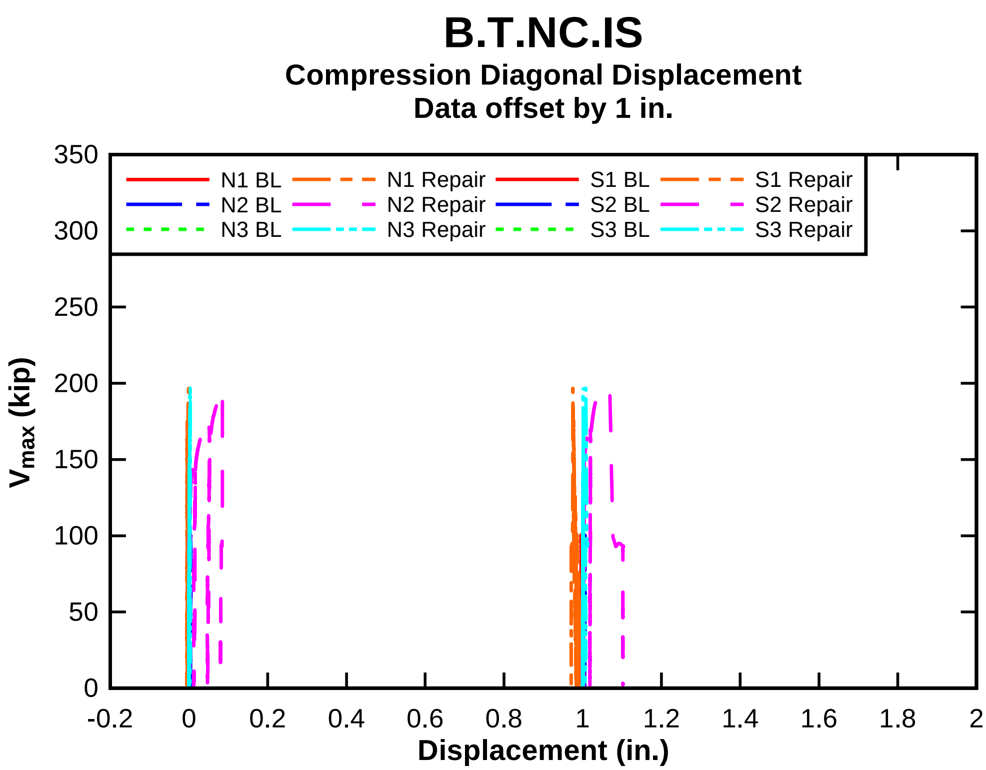

B.T.NC.IS
Baseline
Repair
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Centerline Displacement (in)
V_{max} (kips)


B.T.NC.IS
Flexural Strain
Baseline
Repair
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Strain με
V_{max} (kips)


B.T.NC.IS
Integrally Cast Stirrup Strain: North
N1 Baseline
N2 Baseline
N3 Baseline
N1 Repair
N2 Repair
N3 Repair
ε_y = 1731 $\mu\varepsilon$
V_{max} (kip)
strain ($\mu\varepsilon$)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800

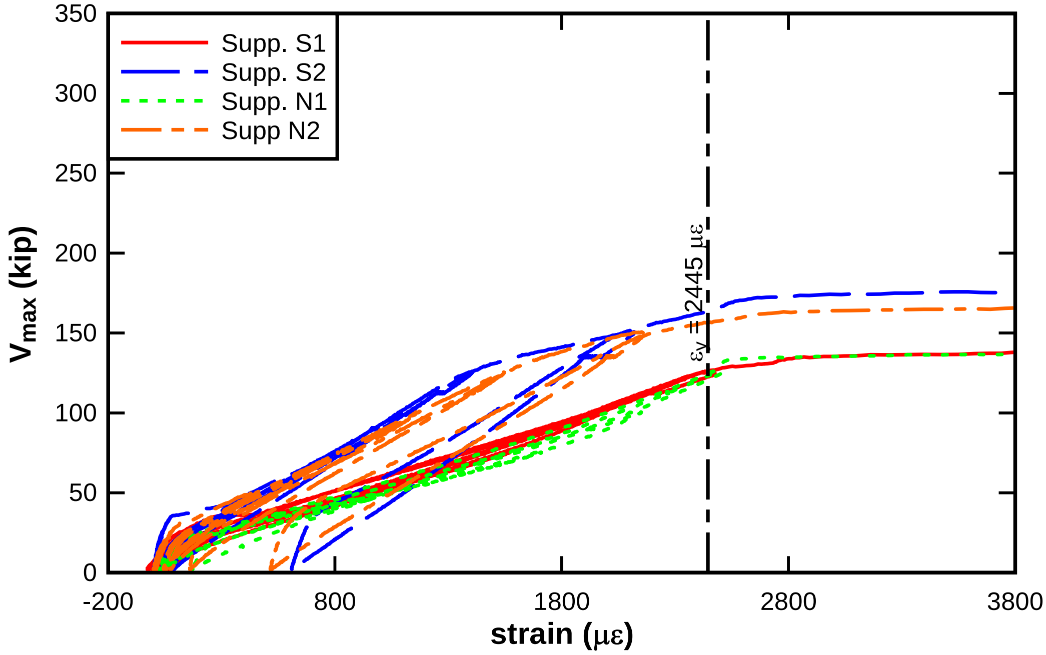

B.T.NC.IS
Integrally Cast Stirrup Strain: South
S1 Baseline
S2 Baseline
S3 Baseline
S1 Repair
S2 Repair
S3 Repair
ε_y = 1731 $\mu\varepsilon$
V_{max} (kip)
strain ($\mu\varepsilon$)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800


B.T.NC.IS
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

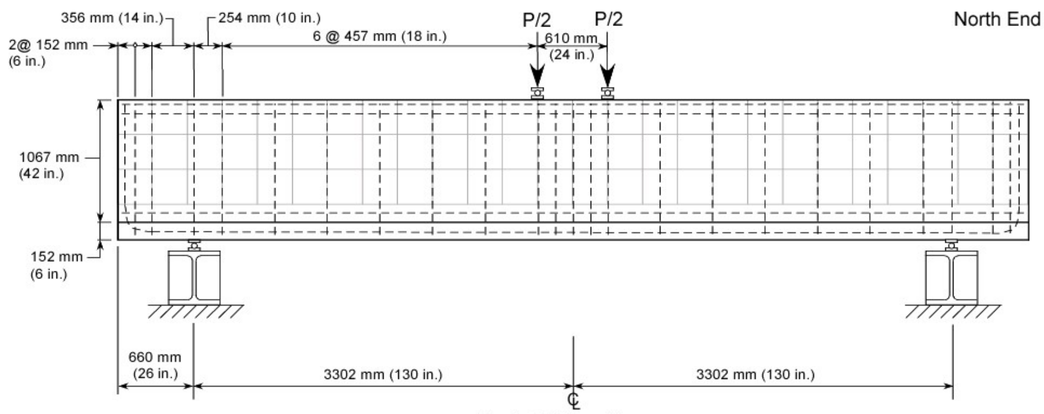

B.T.NC.IS
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

B.T.NC.IS

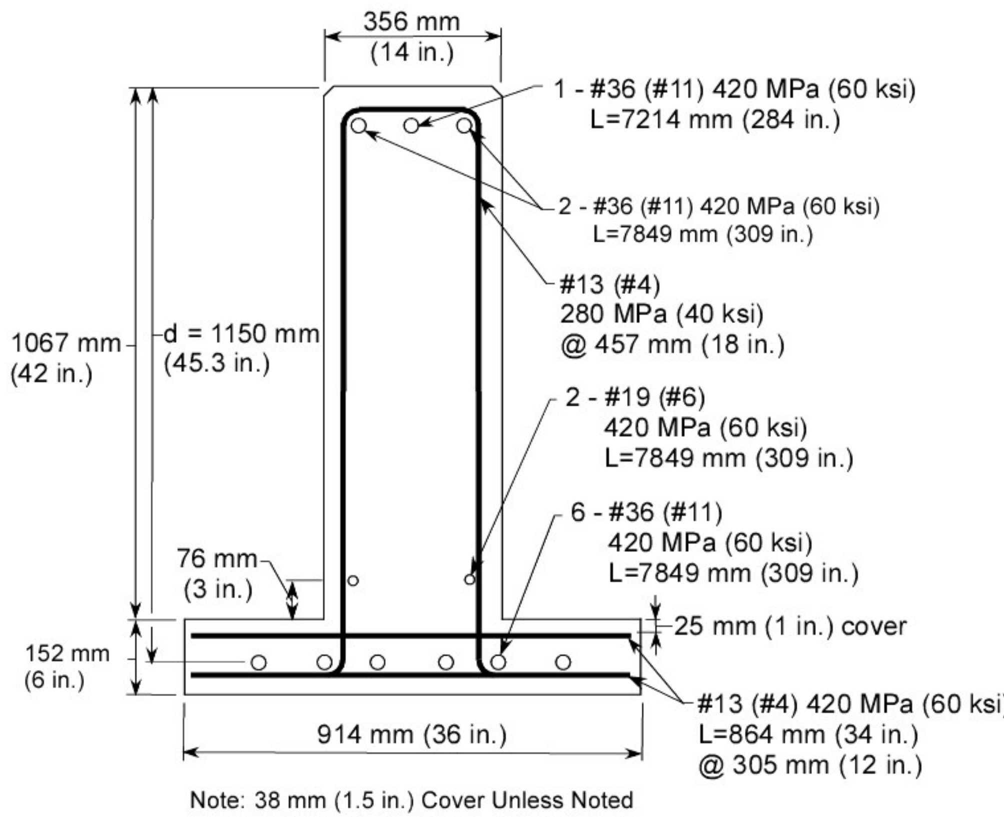
Supplemental Stirrup Strain



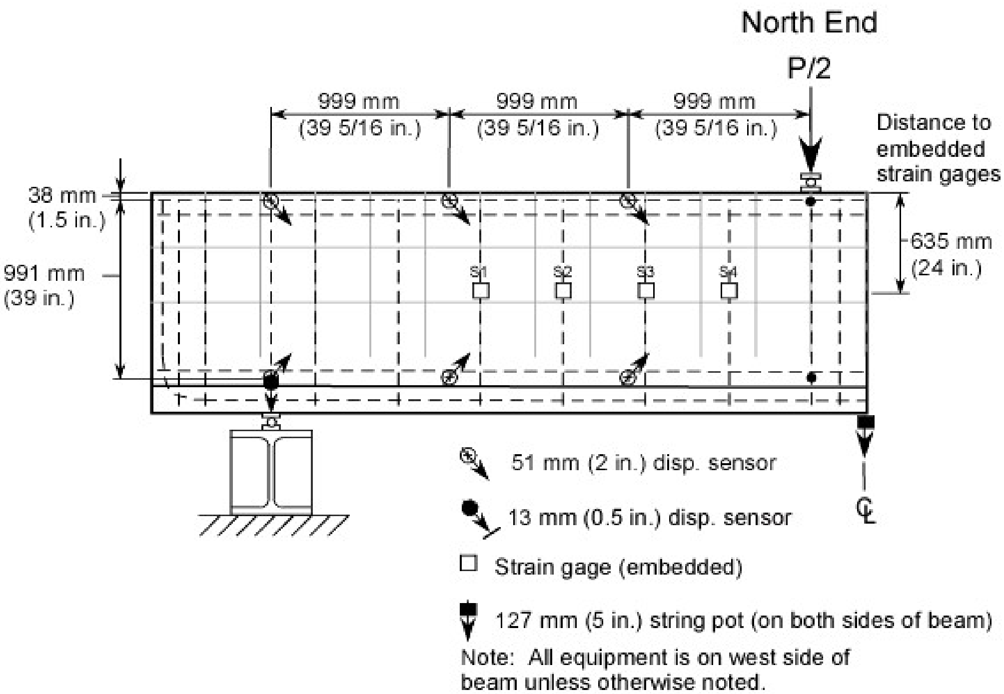
APPENDIX A-7: SPECIMEN B.IT.NC.CF



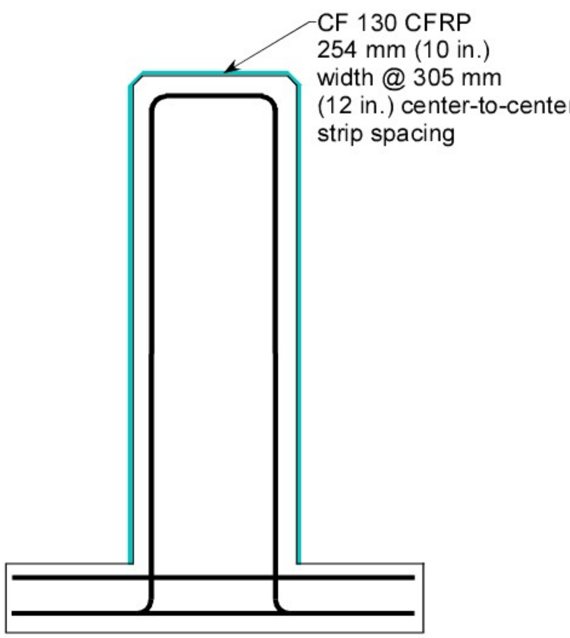
Typical IT Specimen



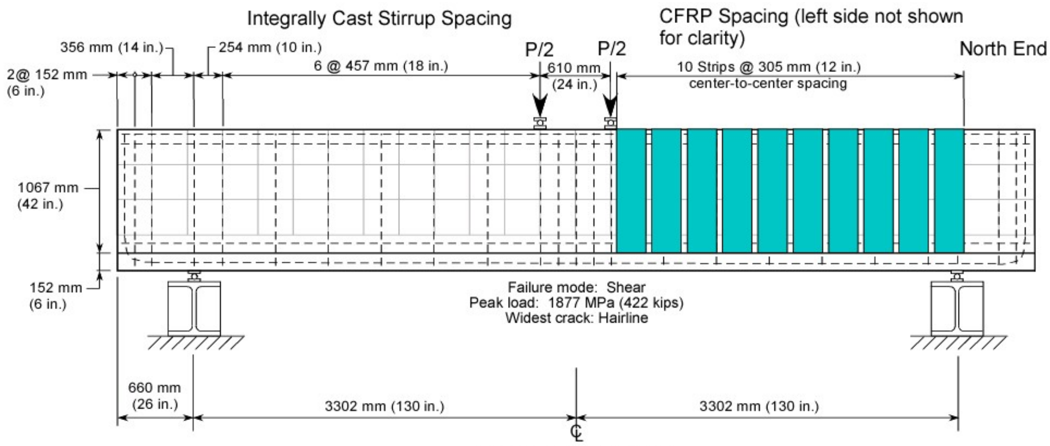
IT Beam Typical Section



IT Specimen Instrumentation

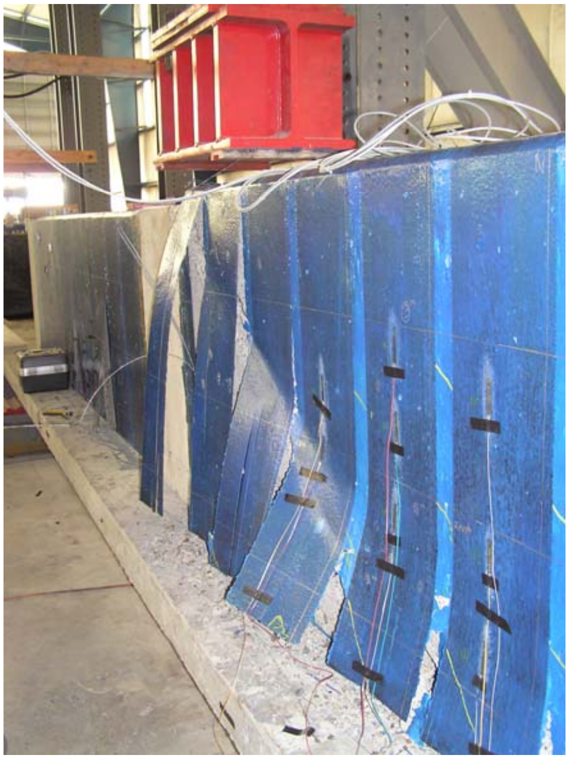


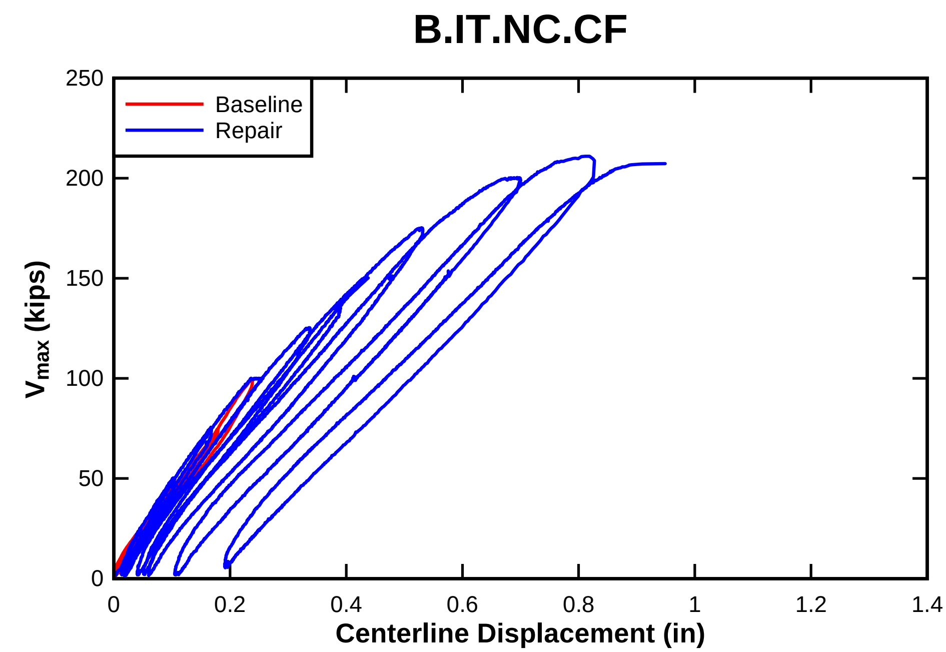
CFRP Strip Repair:
Typical Section



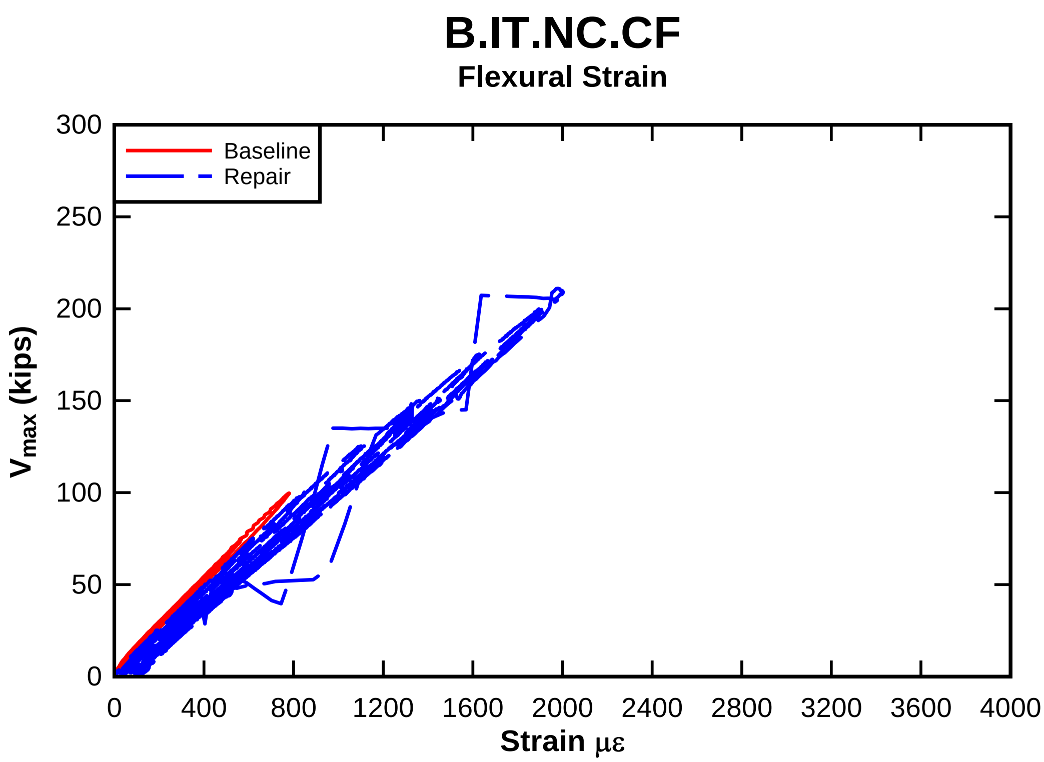
Specimen B.IT.NC.CF


B.IT.NC.CF North End

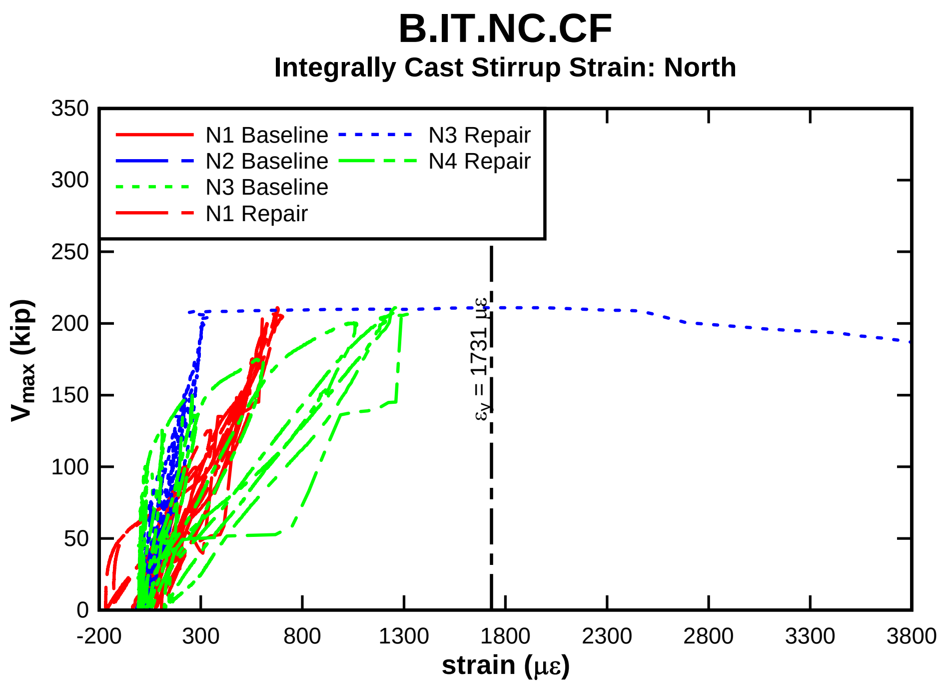

B.IT.NC.CF South End

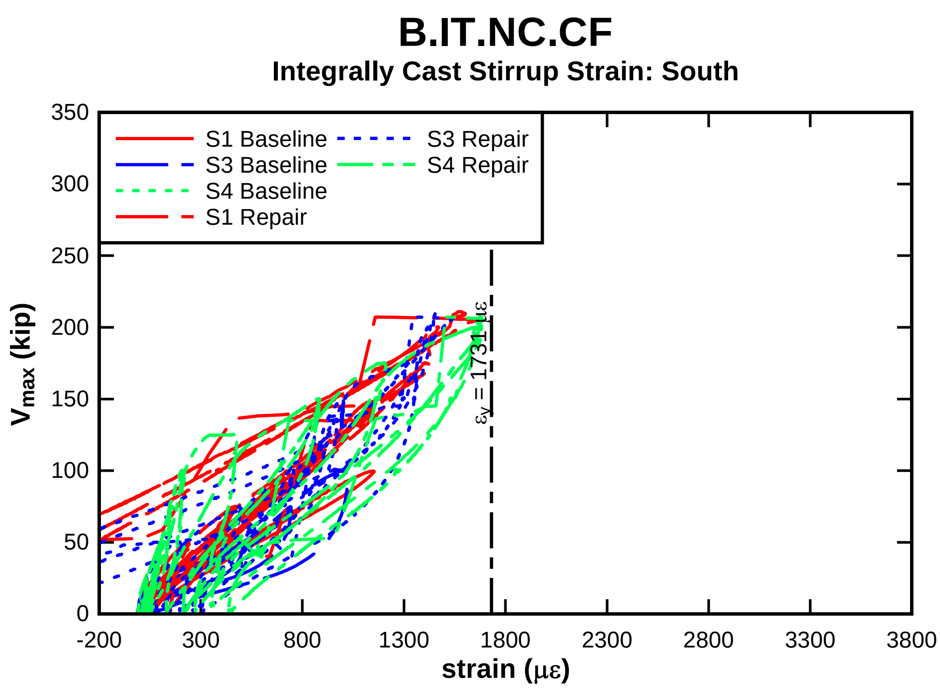


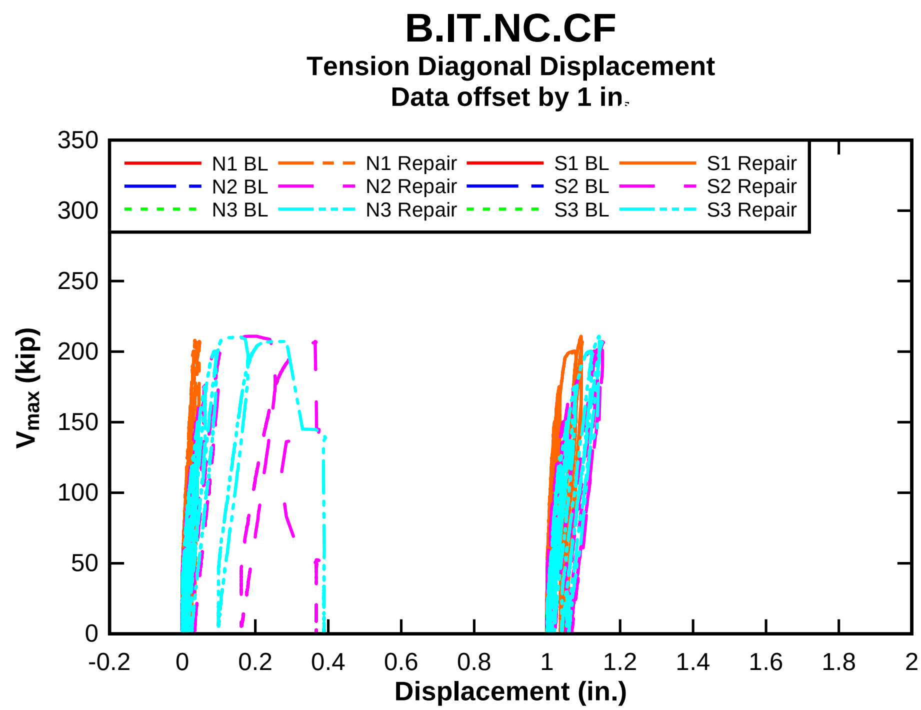
B.IT.NC.CF
Baseline
Repair
V_{max} (kips)
Centerline Displacement (in)
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4



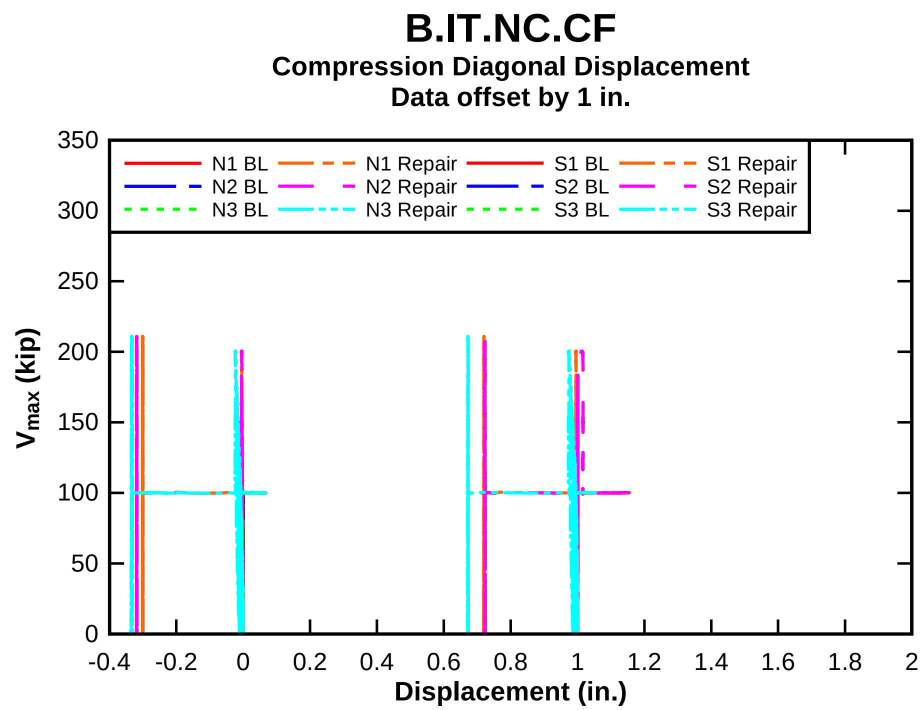
B.IT.NC.CF
Flexural Strain
Baseline
Repair
V_{max} (kips)
Strain με
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000


B.IT.NC.CF
Integrally Cast Stirrup Strain: North
N1 Baseline
N2 Baseline
N3 Baseline
N1 Repair
N3 Repair
N4 Repair
ε_y = 1731 με
V_{max} (kip)
strain (με)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800

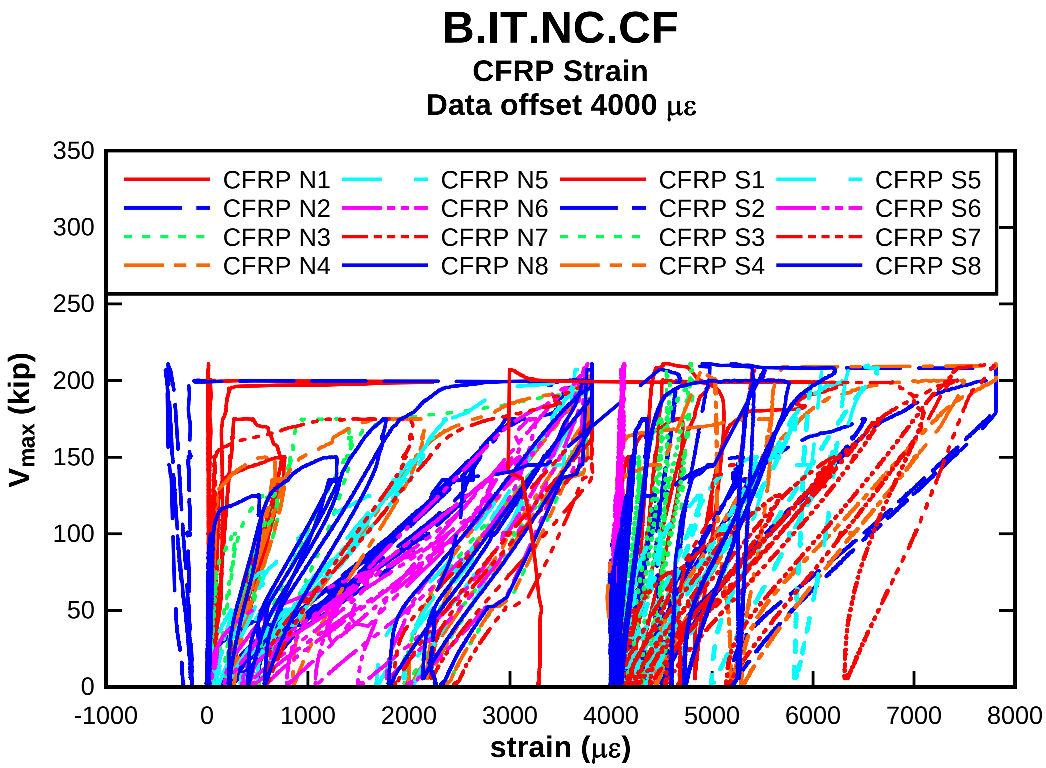

B.IT.NC.CF
Integrally Cast Stirrup Strain: South
S1 Baseline
S3 Baseline
S4 Baseline
S1 Repair
S3 Repair
S4 Repair
ε_y = 1731 με
V_{max} (kip)
strain (με)
350
300
250
200
150
100
50
0
-200
300
800
1300
1800
2300
2800
3300
3800



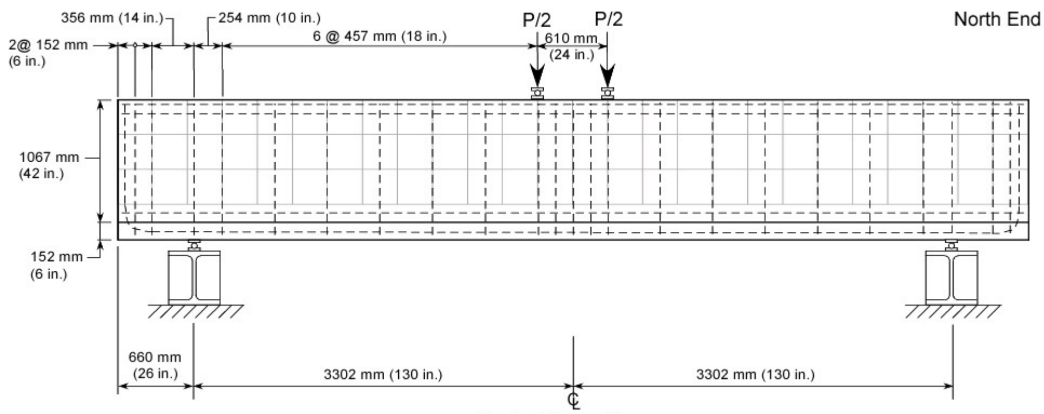
B.IT.NC.CF
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)



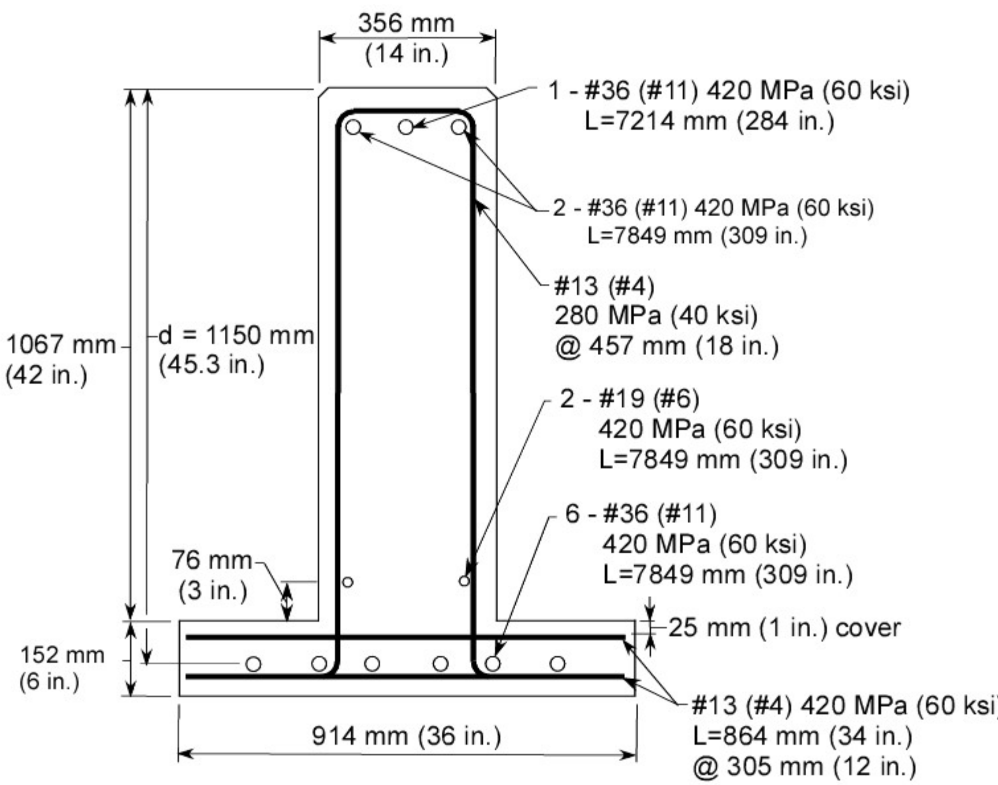
B.IT.NC.CF
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)


B.IT.NC.CF
CFRP Strain
Data offset 4000 με
CFRP N1
CFRP N2
CFRP N3
CFRP N4
CFRP N5
CFRP N6
CFRP N7
CFRP N8
CFRP S1
CFRP S2
CFRP S3
CFRP S4
CFRP S5
CFRP S6
CFRP S7
CFRP S8
Vmax (kip)
strain (με)
350
300
250
200
150
100
50
0
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000

APPENDIX A-8: SPECIMEN B.IT.NC.NS

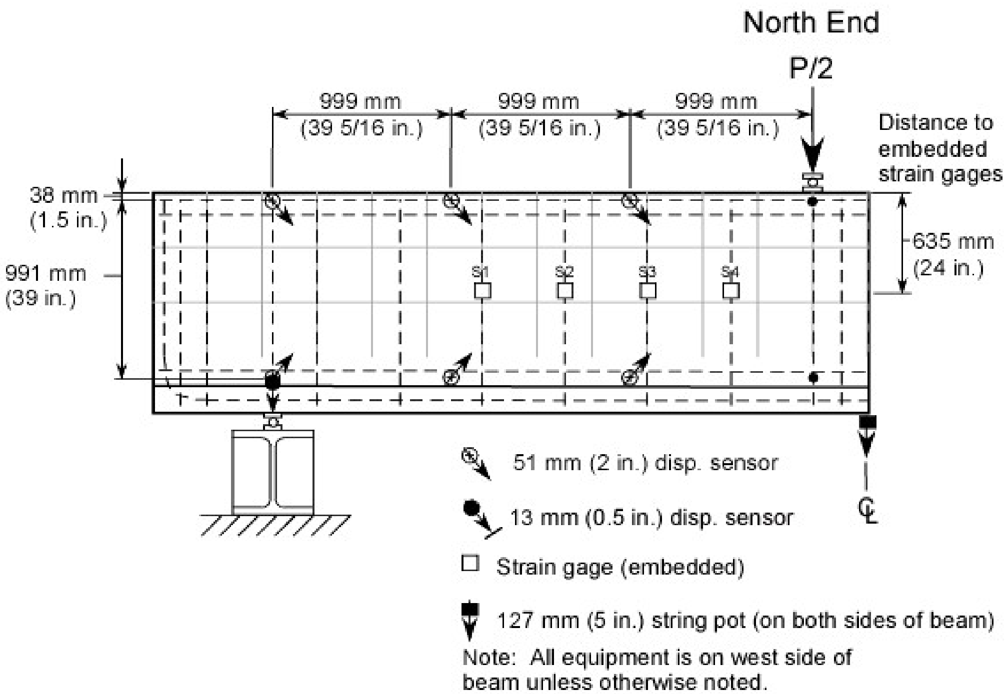


Typical IT Specimen

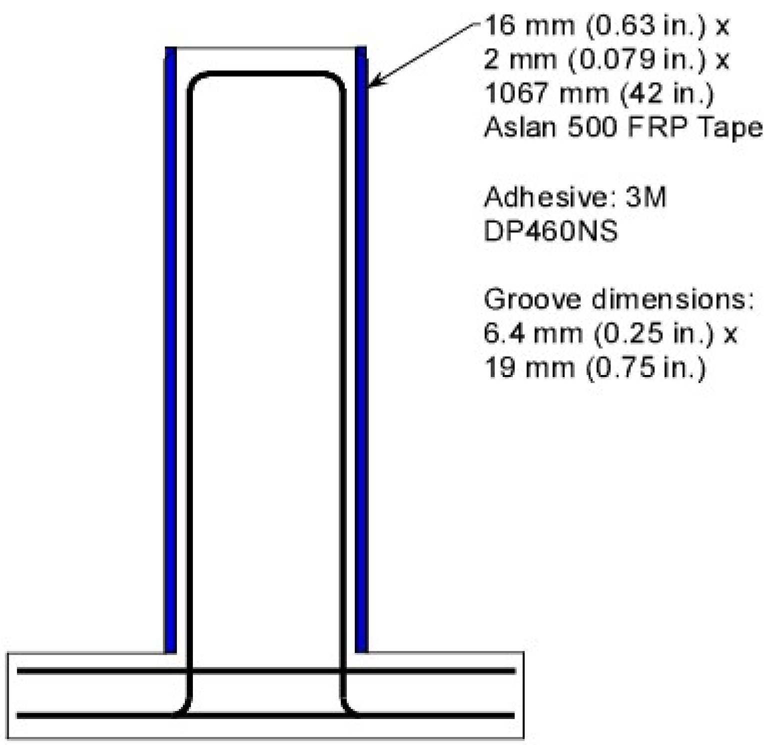


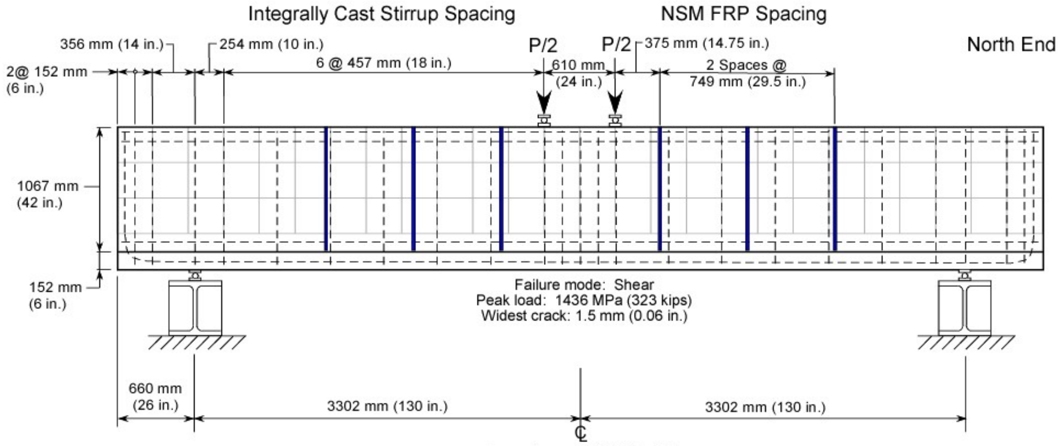
Note: 38 mm (1.5 in.) Cover Unless Noted

IT Beam Typical Section



IT Specimen Instrumentation

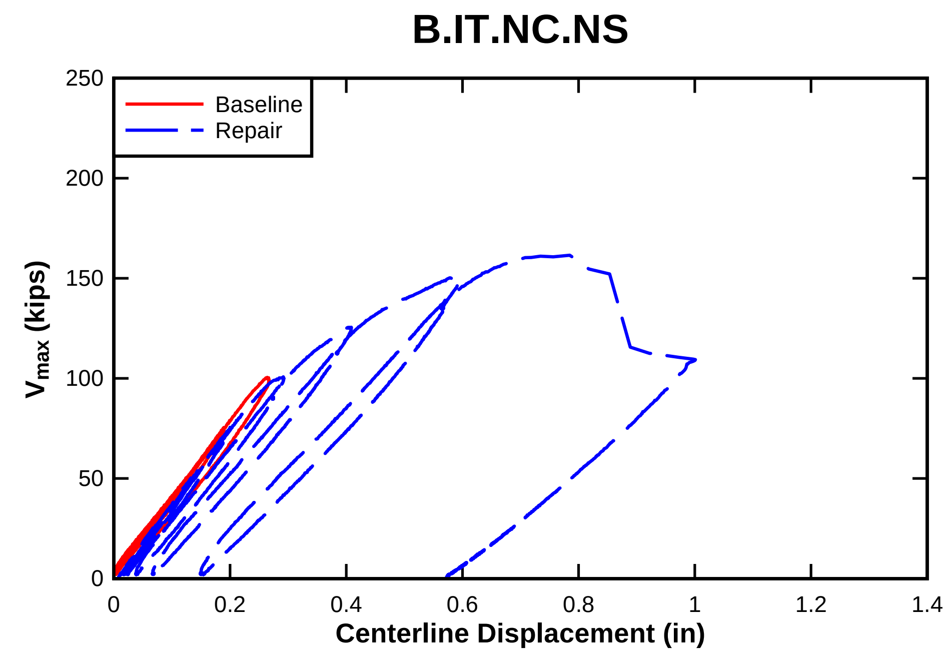




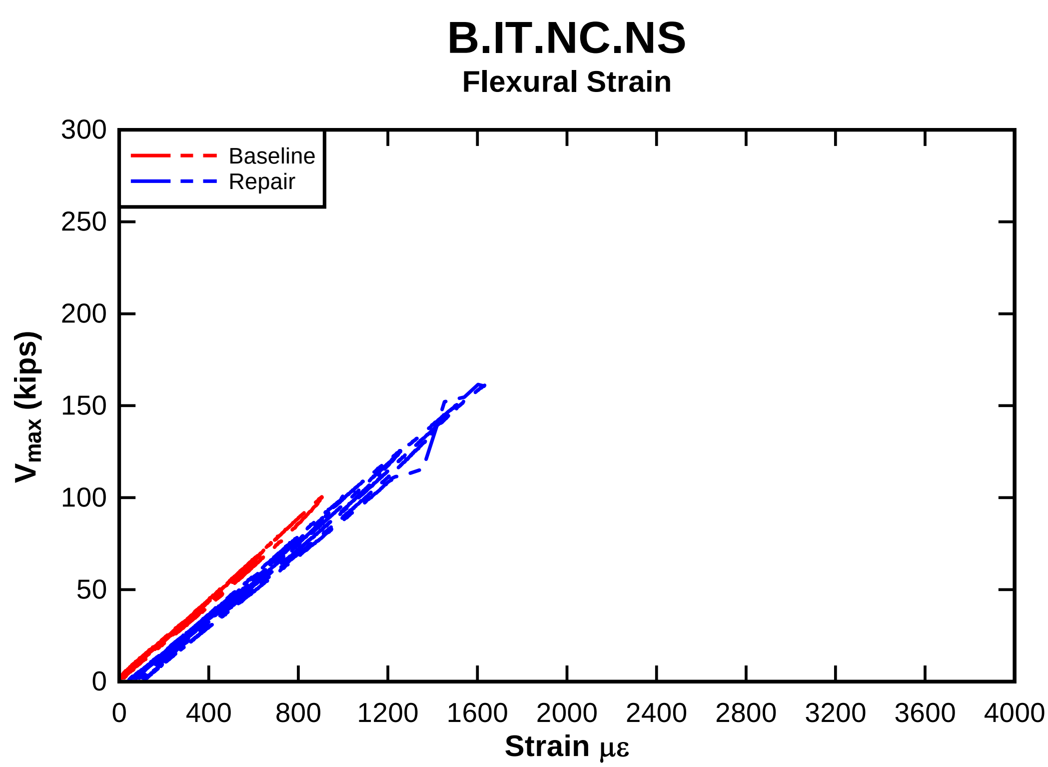
Specimen B.IT.NC.NS

B.IT.NC.NS North End

B.IT.NC.NS South End



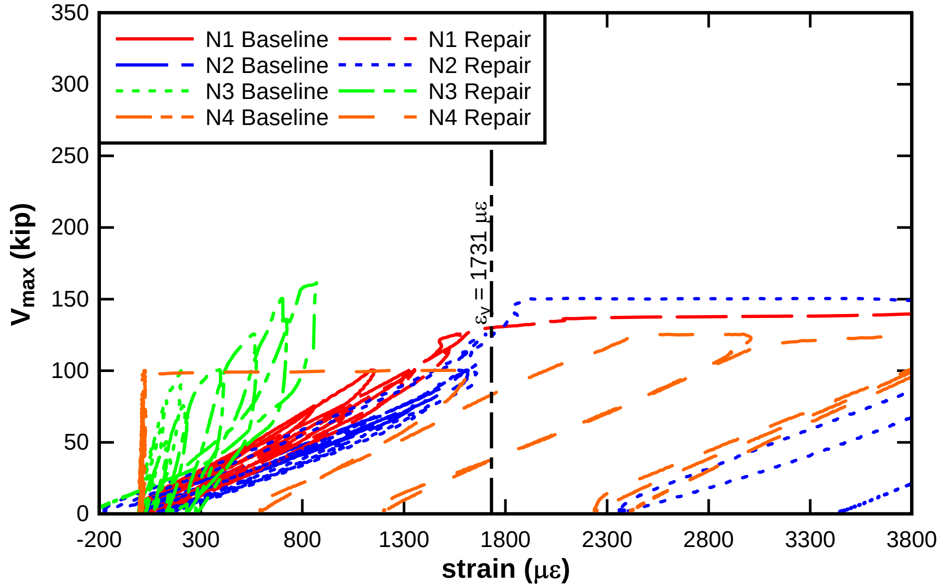
B.IT.NC.NS
Baseline
Repair
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Centerline Displacement (in)
V$_{max}$ (kips)



B.IT.NC.NS
Flexural Strain
Baseline
Repair
300
250
200
150
100
50
0
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000
Strain με
V$_{max}$ (kips)

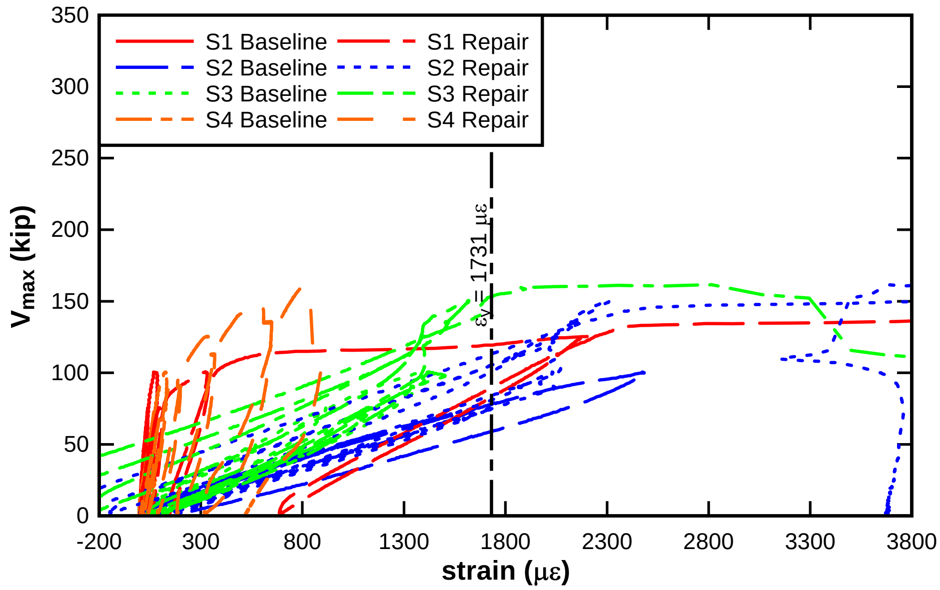
B.IT.NC.NS

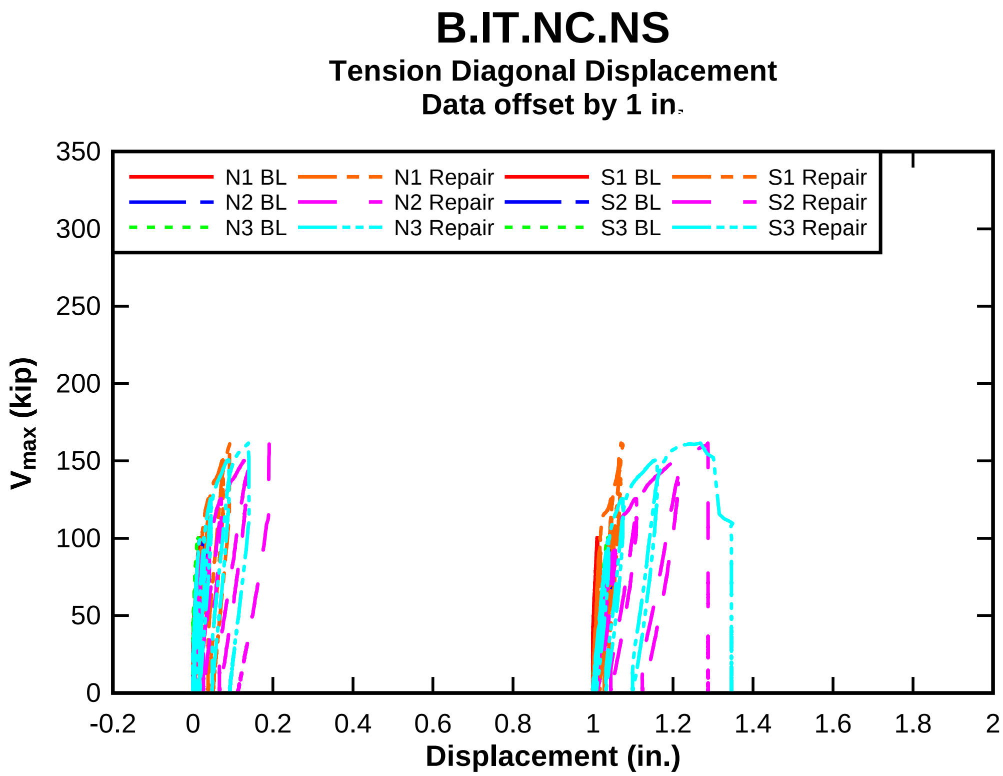
Integrally Cast Stirrup Strain: North



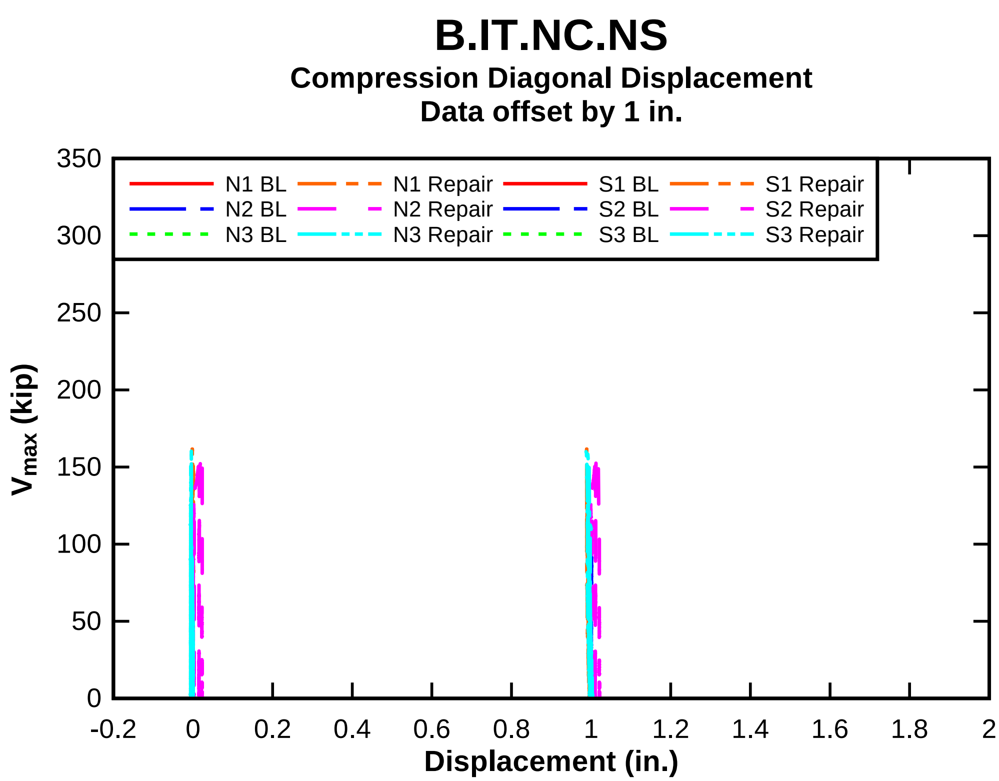
B.IT.NC.NS

Integrally Cast Stirrup Strain: South

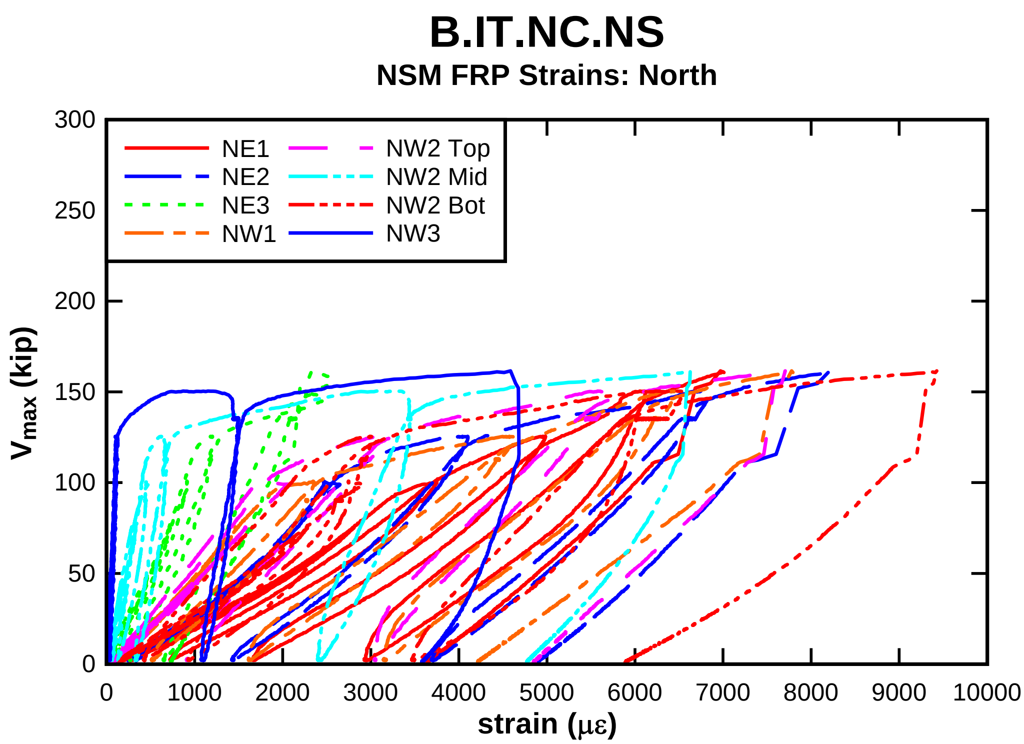




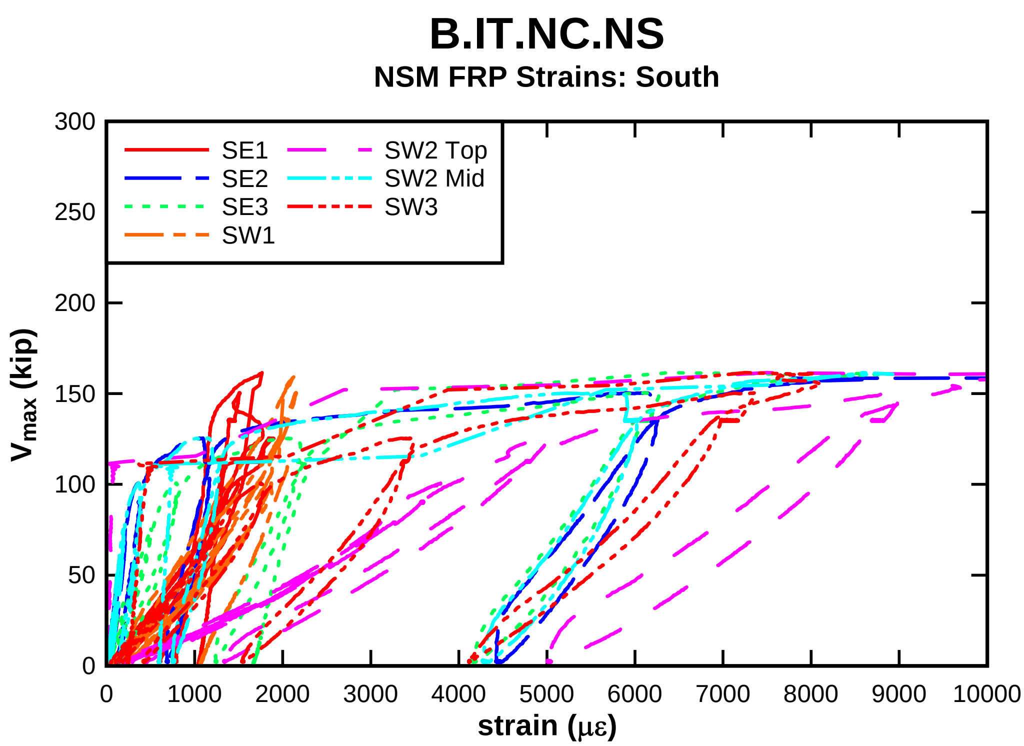
B.IT.NC.NS
Tension Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



B.IT.NC.NS
Compression Diagonal Displacement
Data offset by 1 in.
N1 BL
N1 Repair
S1 BL
S1 Repair
N2 BL
N2 Repair
S2 BL
S2 Repair
N3 BL
N3 Repair
S3 BL
S3 Repair
V_{max} (kip)
Displacement (in.)
0
50
100
150
200
250
300
350
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

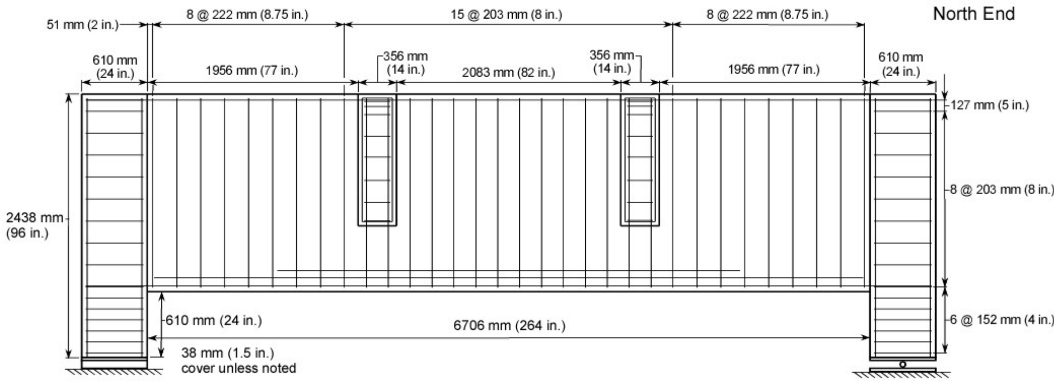


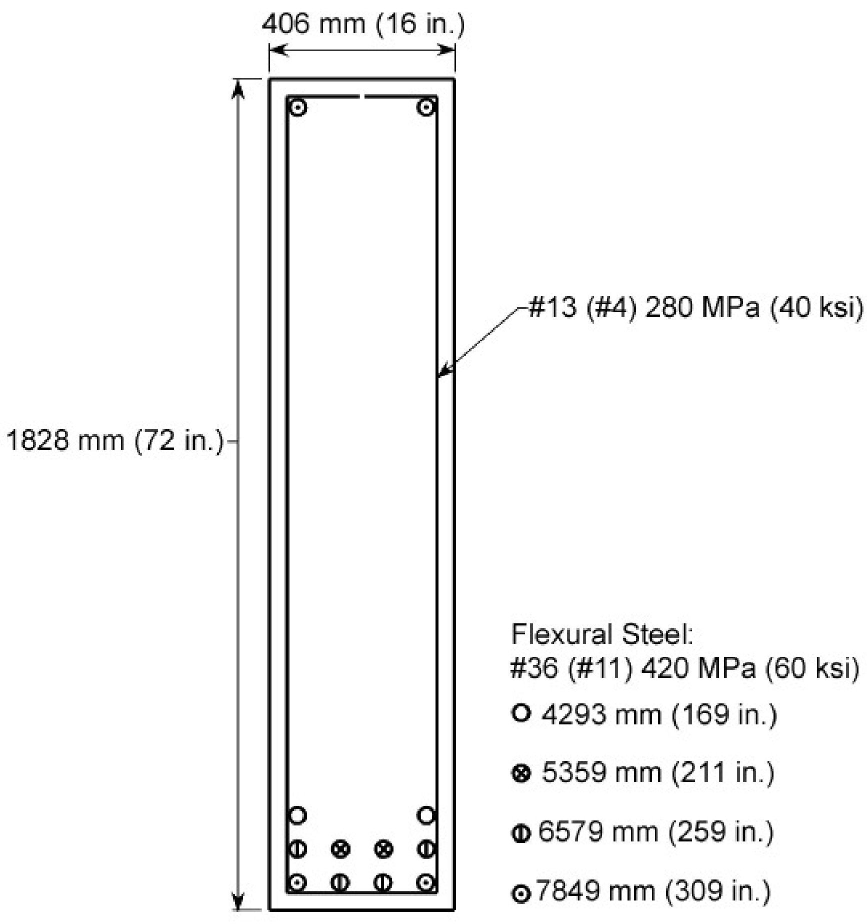
B.IT.NC.NS
NSM FRP Strains: North
NE1
NE2
NE3
NW1
NW2 Top
NW2 Mid
NW2 Bot
NW3
V_{max} (kip)
strain (με)
0
50
100
150
200
250
300
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000



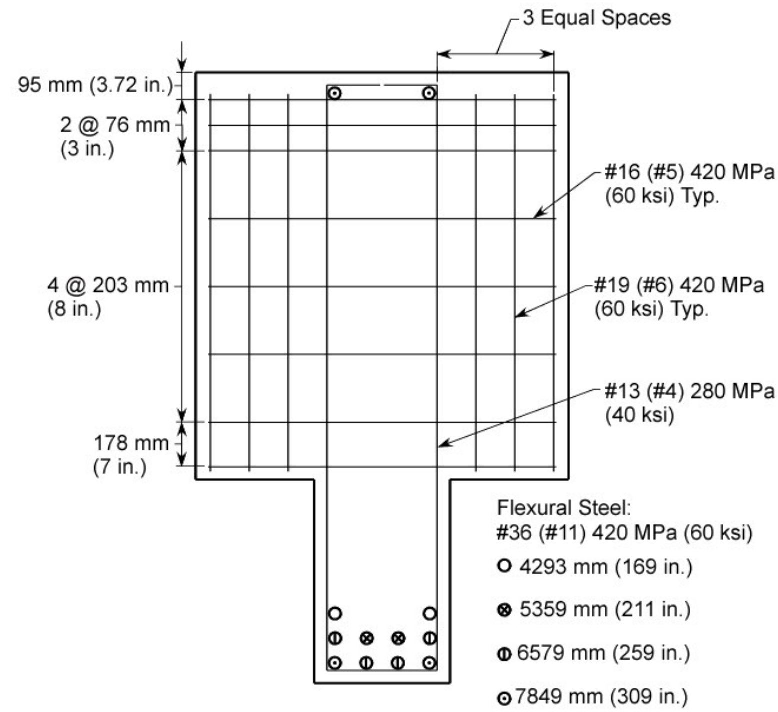
B.IT.NC.NS
NSM FRP Strains: South
SE1
SE2
SE3
SW1
SW2 Top
SW2 Mid
SW3
V_{max} (kip)
strain (με)
0
50
100
150
200
250
300
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

APPENDIX A-9: SPECIMEN D.T.C.PT

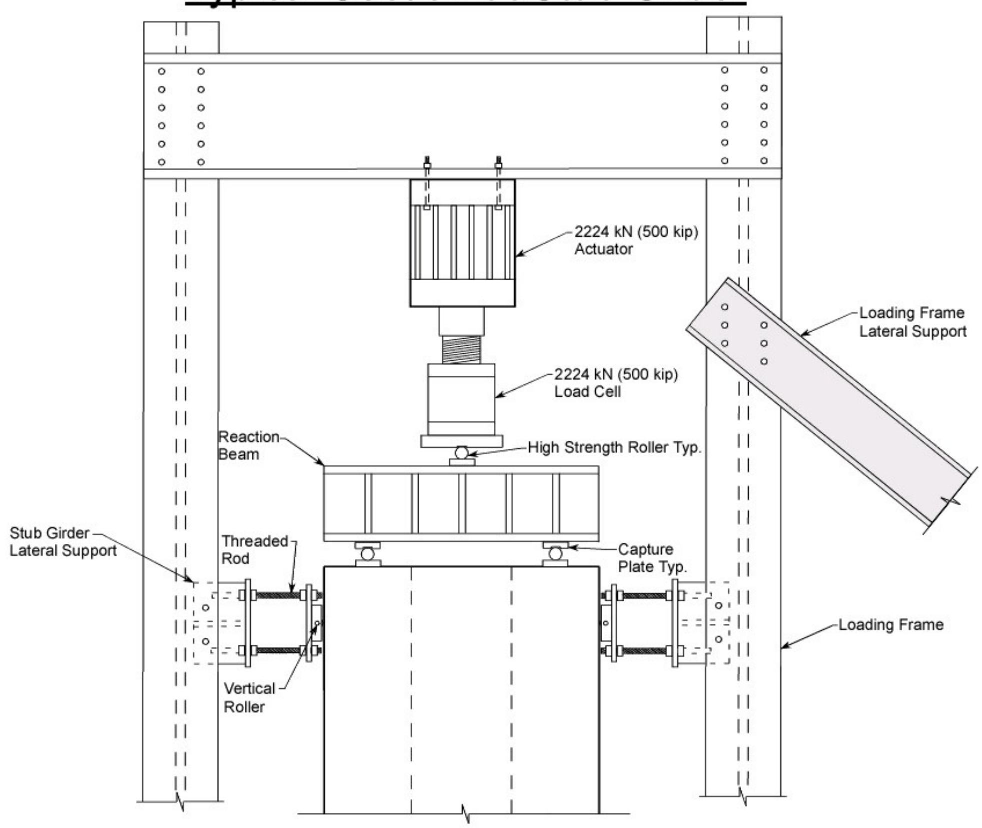


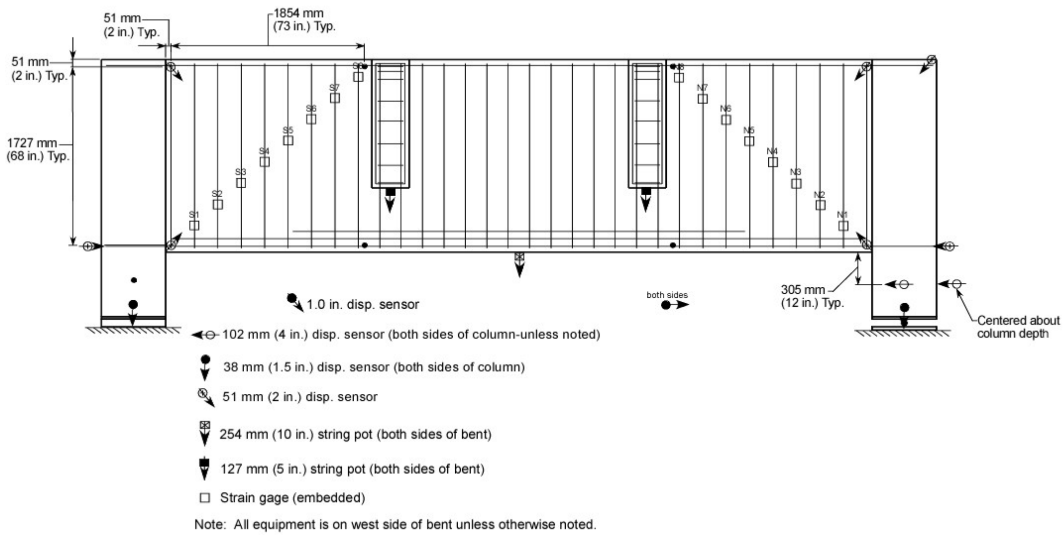


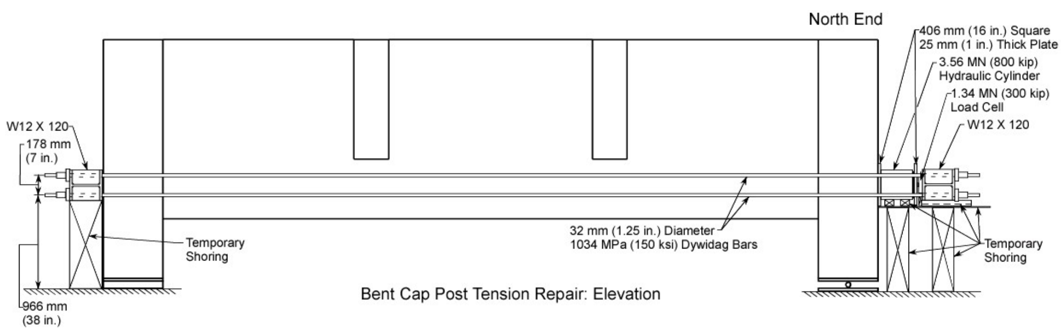
<u>Typical Section at Mid Span</u>



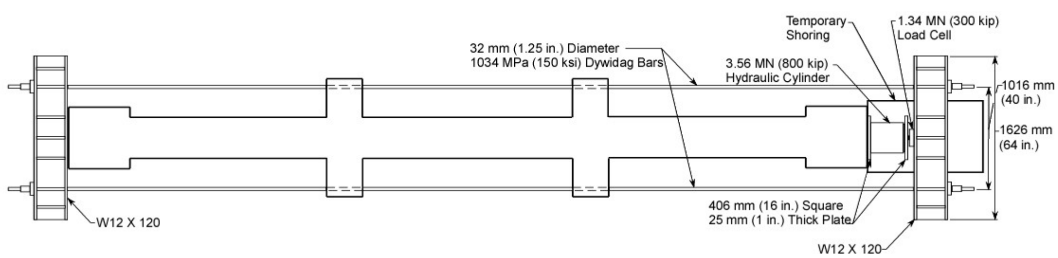
Typical Section at Stub Girder



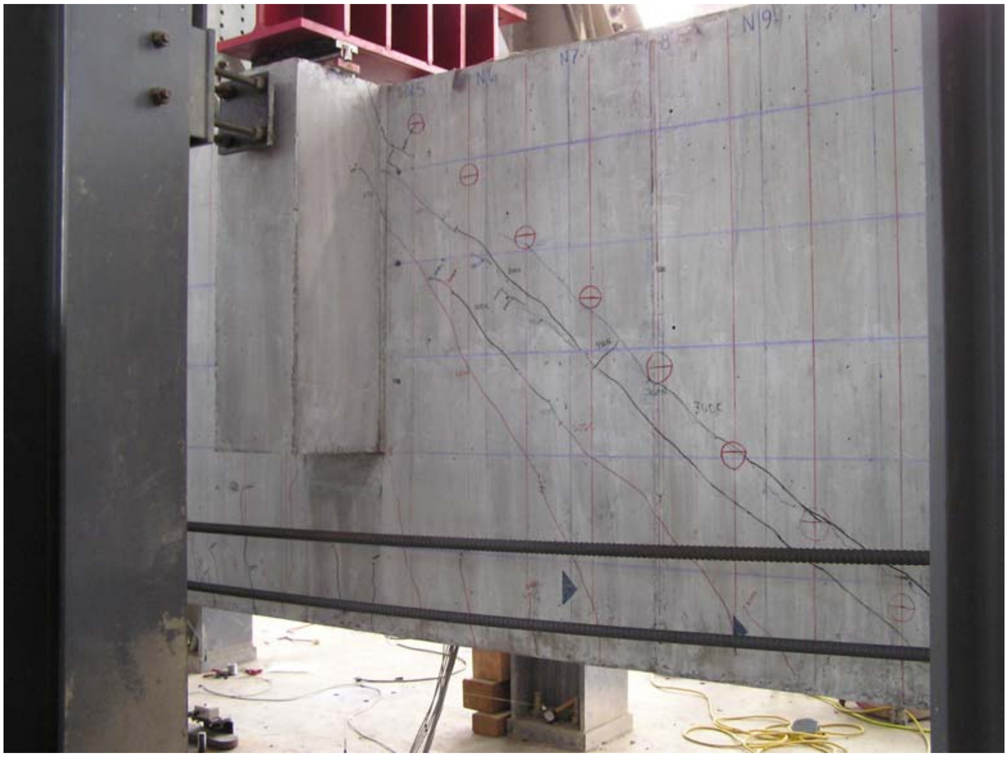




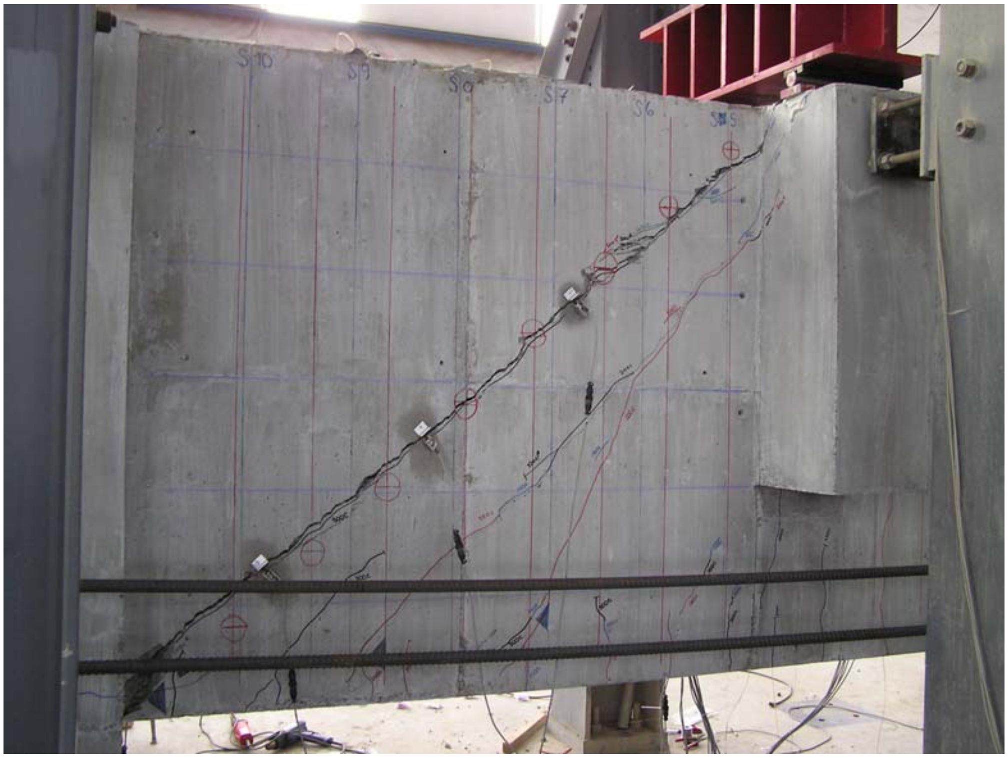
Bent Cap Post Tension Repair: Elevation



Bent Cap Post Tension Repair: Top View

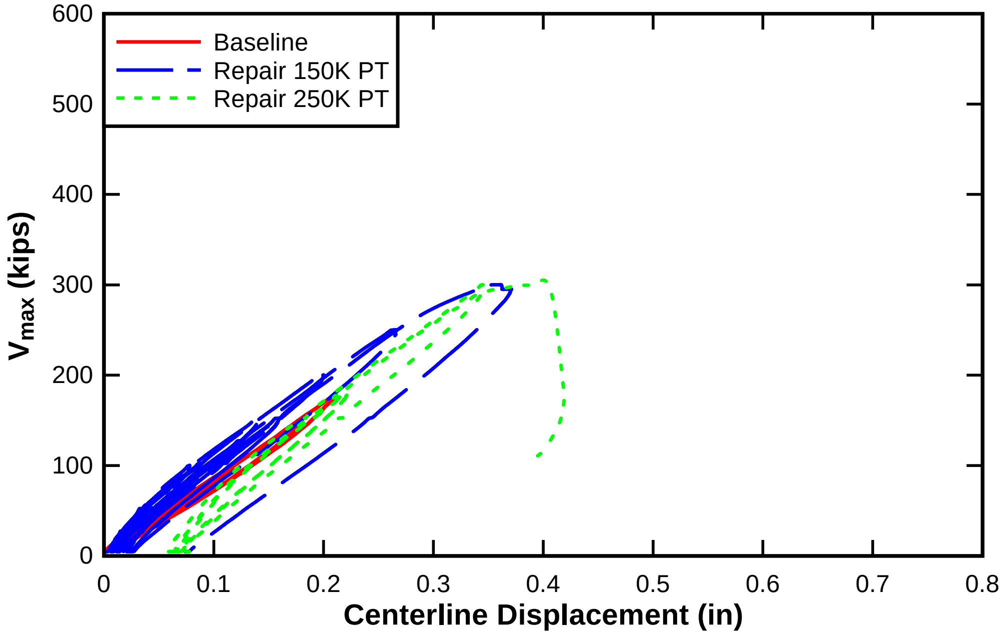


D.T.C.PT North End



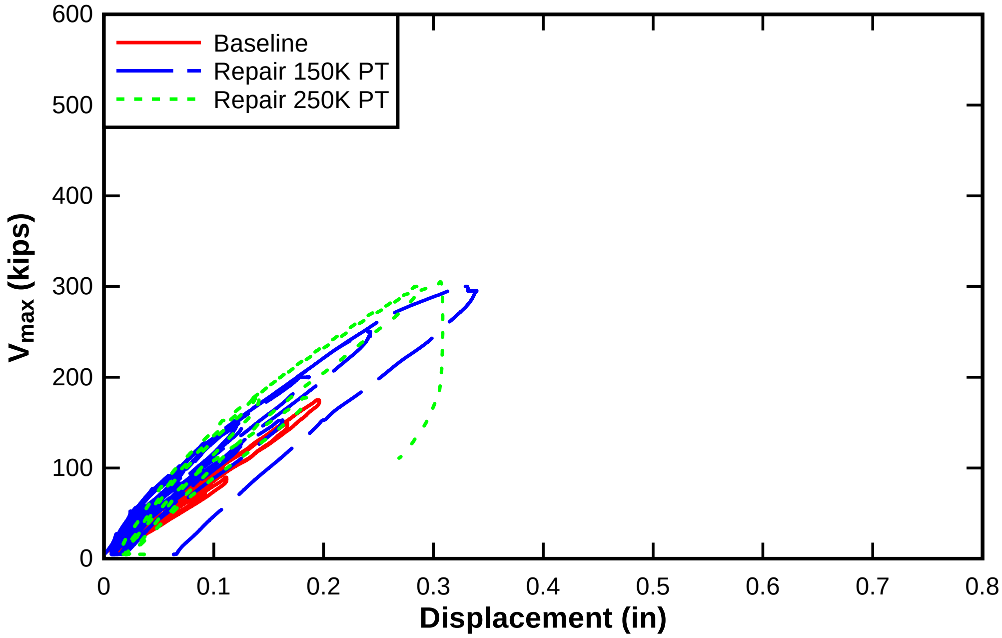
D.T.C.PT South End

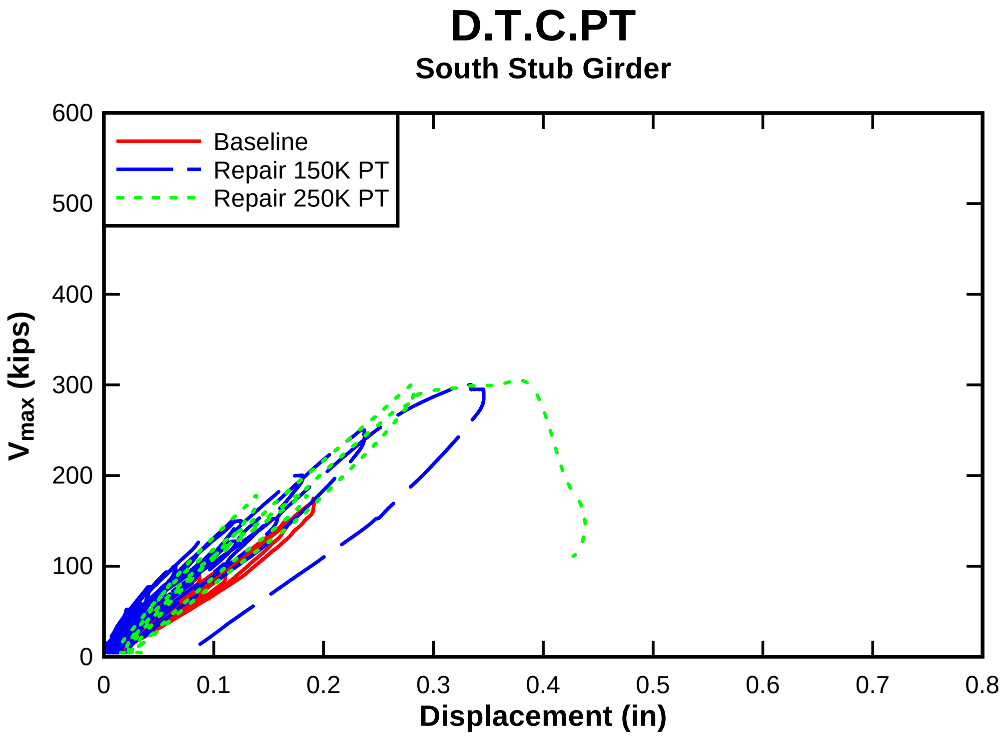
D.T.C.PT



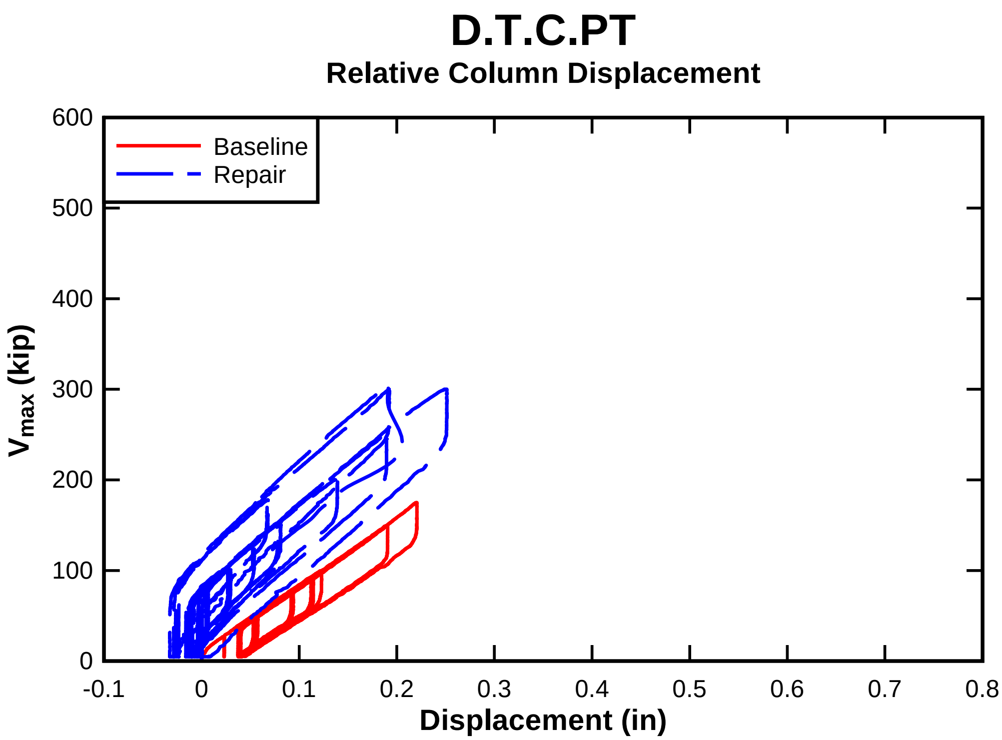
D.T.C.PT

North Stub Girder

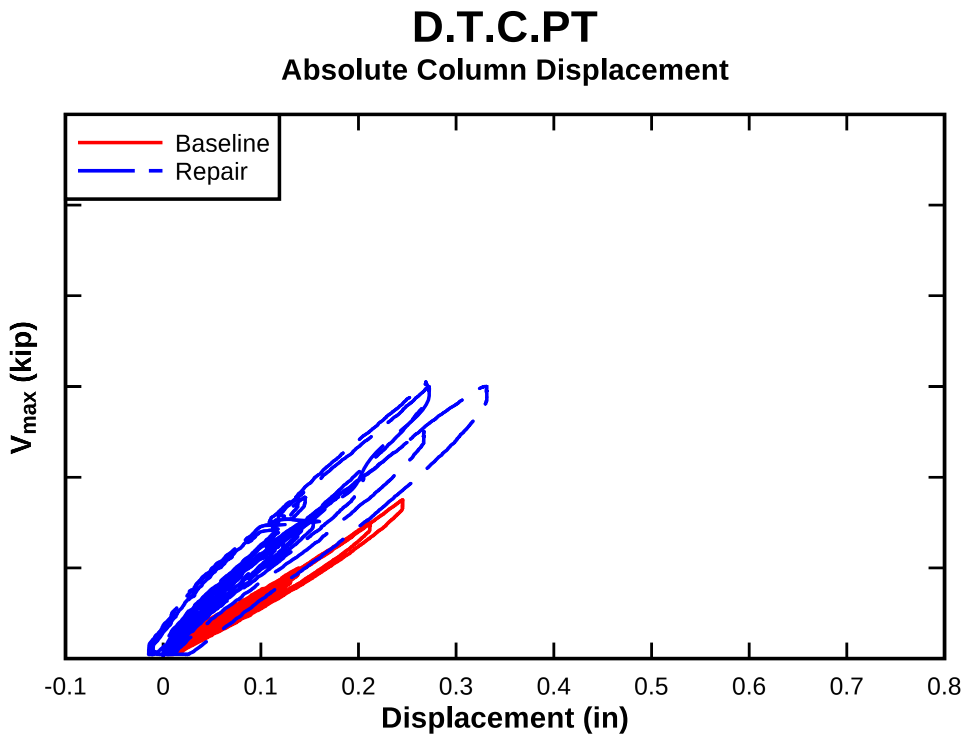


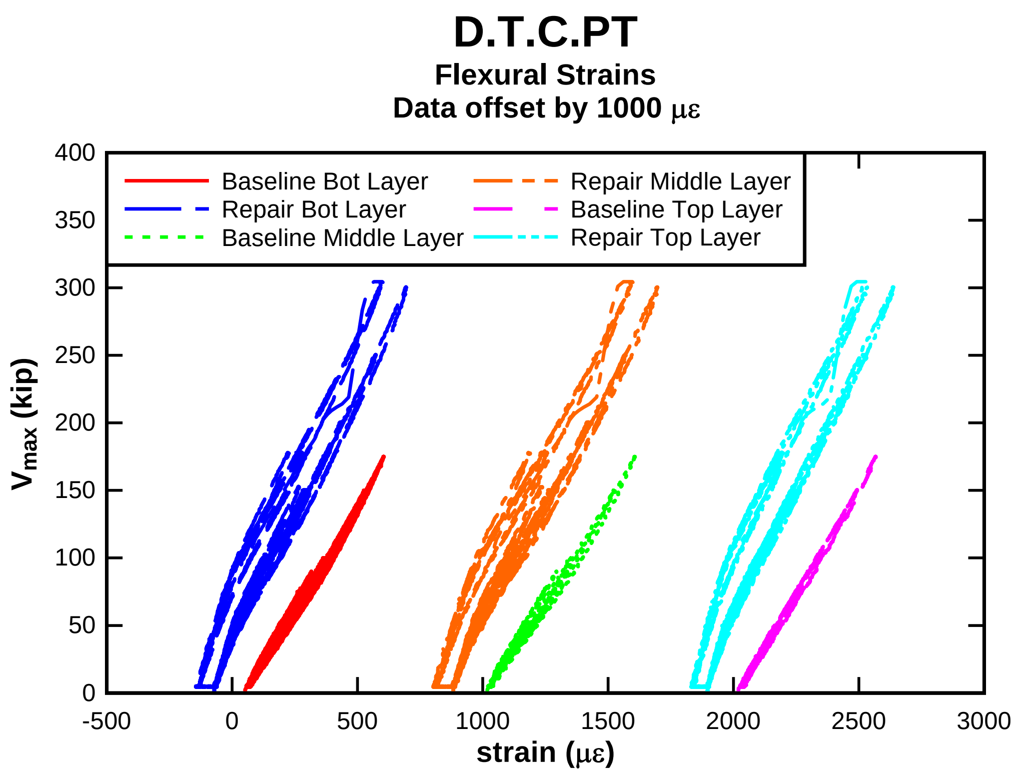


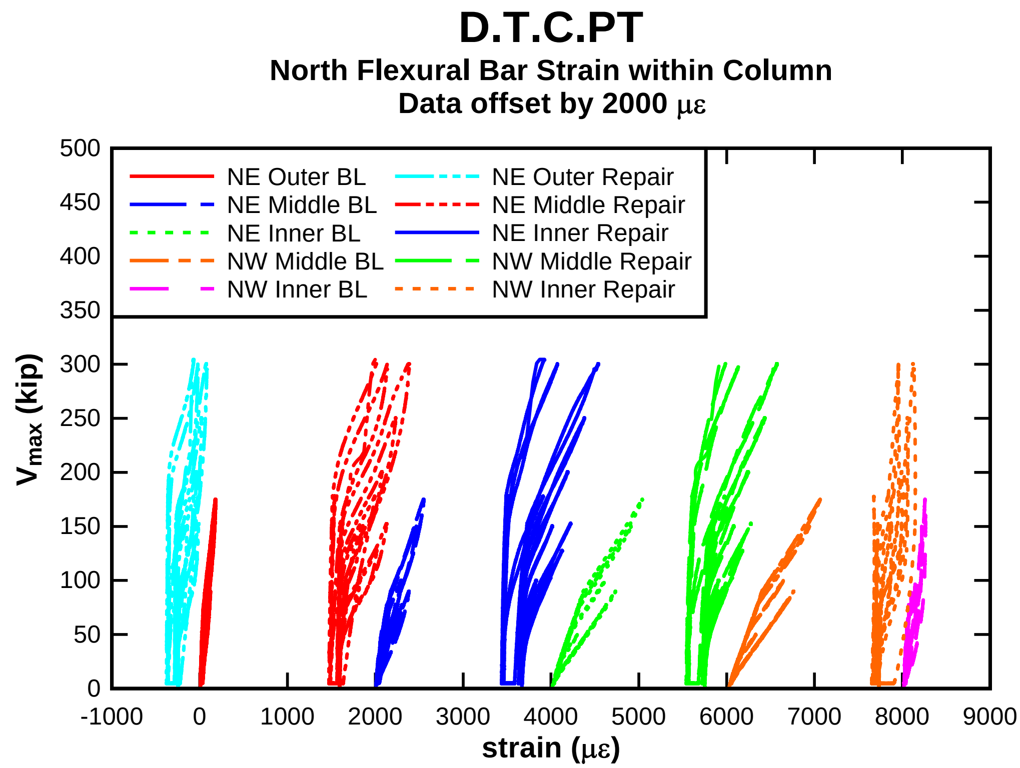
D.T.C.PT
South Stub Girder
Baseline
Repair 150K PT
Repair 250K PT
V_{max} (kips)
Displacement (in)
0
100
200
300
400
500
600
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

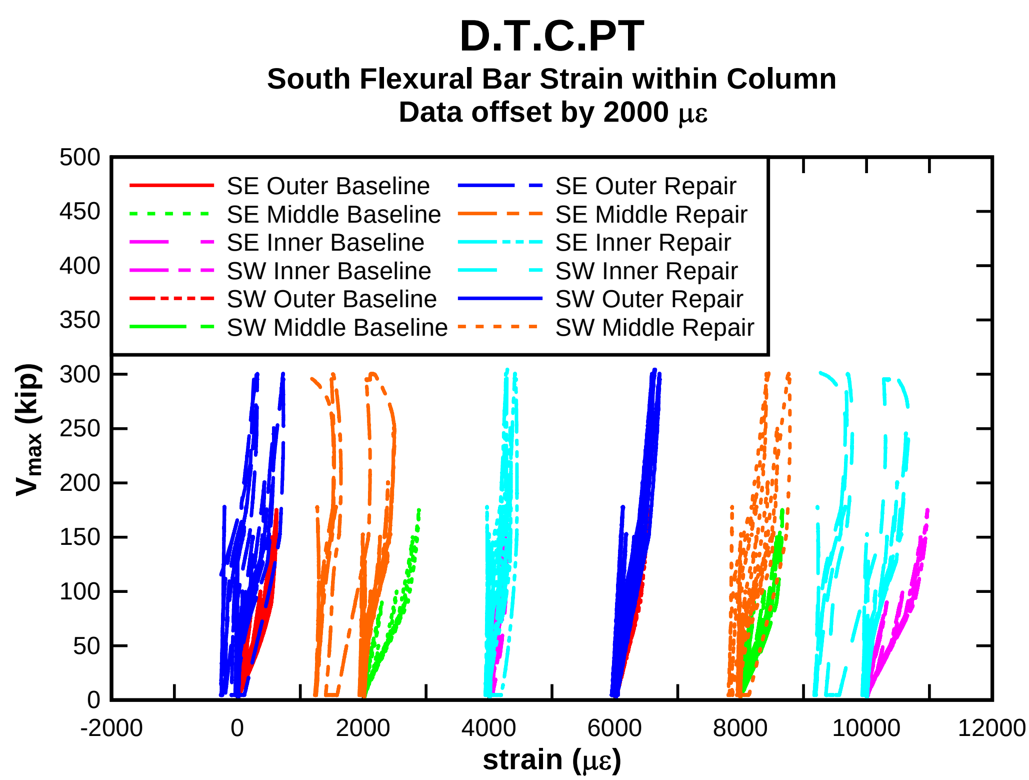


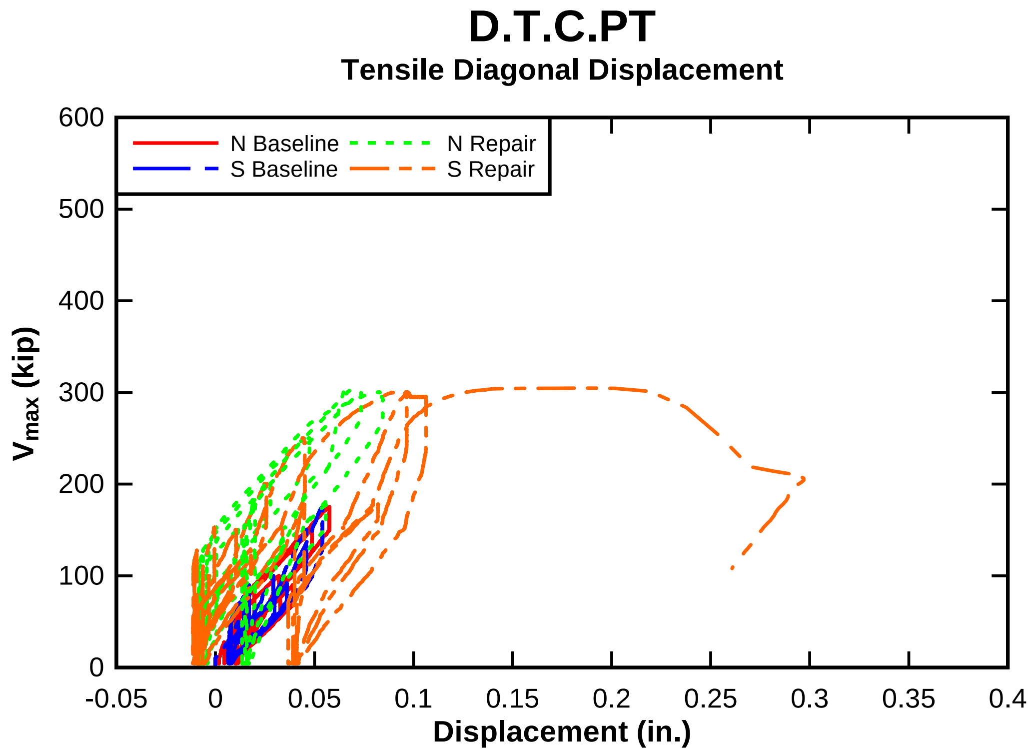
D.T.C.PT
Relative Column Displacement
Baseline
Repair
V_{max} (kip)
Displacement (in)
0
100
200
300
400
500
600
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

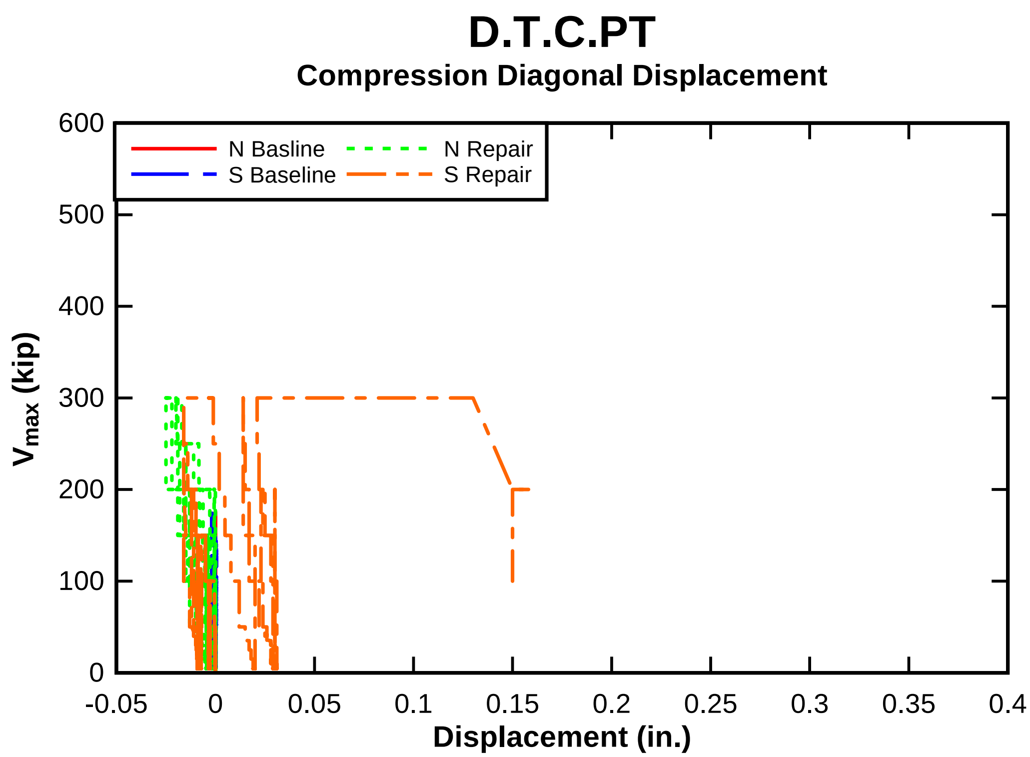

D.T.C.PT
Absolute Column Displacement
Baseline
Repair
Vmax (kip)
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Displacement (in)

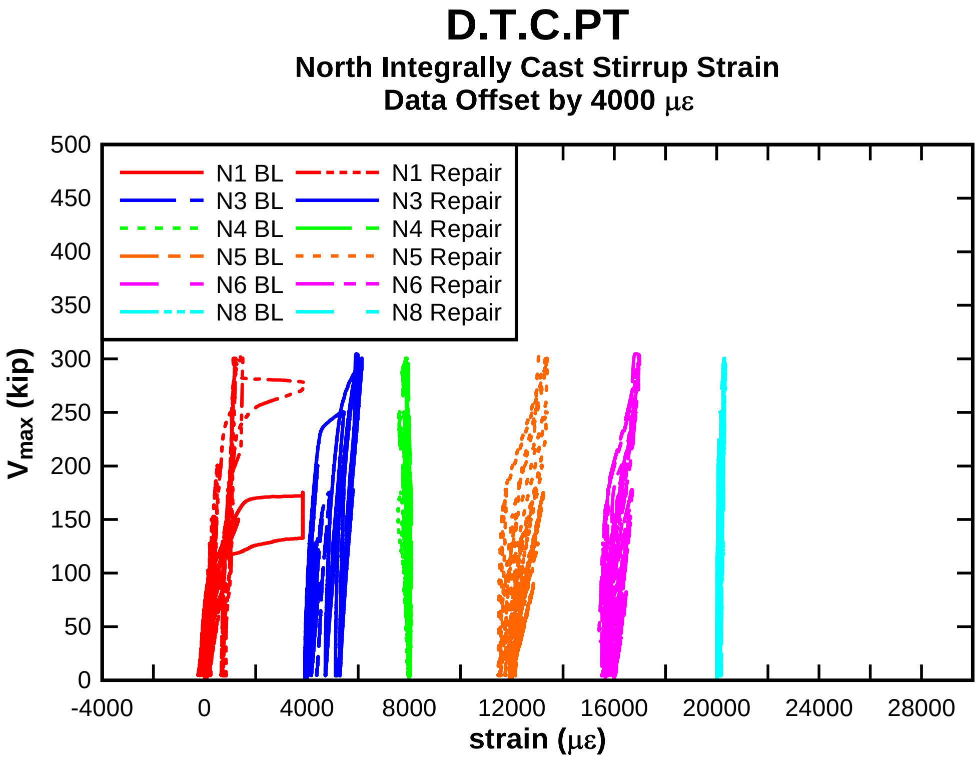

D.T.C.PT
Flexural Strains
Data offset by 1000 με
Baseline Bot Layer
Repair Bot Layer
Baseline Middle Layer
Repair Middle Layer
Baseline Top Layer
Repair Top Layer
Vmax (kip)
400
350
300
250
200
150
100
50
0
-500
0
500
1000
1500
2000
2500
3000
strain (με)

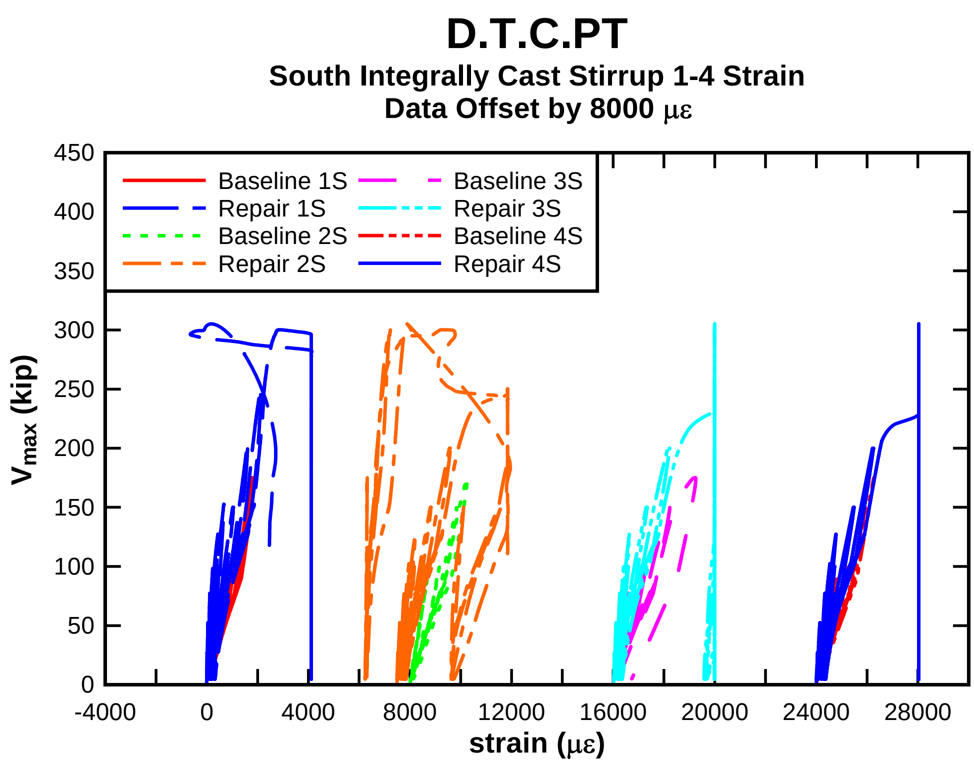

D.T.C.PT
North Flexural Bar Strain within Column
Data offset by 2000 με
NE Outer BL
NE Middle BL
NE Inner BL
NW Middle BL
NW Inner BL
NE Outer Repair
NE Middle Repair
NE Inner Repair
NW Middle Repair
NW Inner Repair
V_{max} (kip)
strain (με)
500
450
400
350
300
250
200
150
100
50
0
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

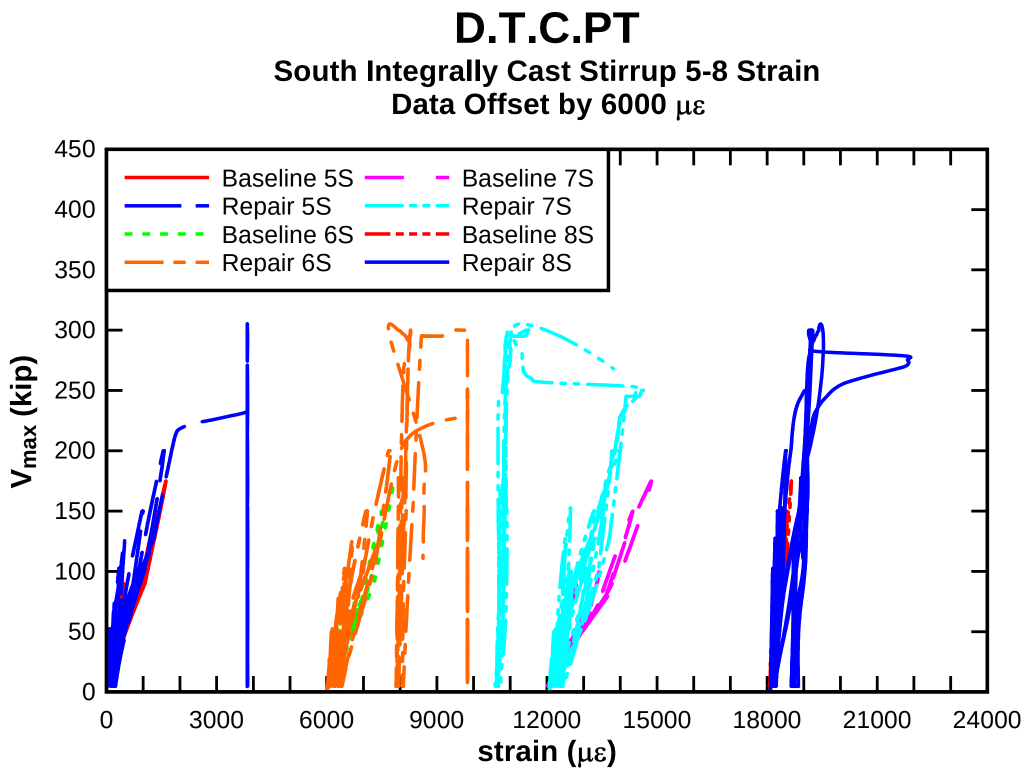

D.T.C.PT
South Flexural Bar Strain within Column
Data offset by 2000 με
SE Outer Baseline
SE Middle Baseline
SE Inner Baseline
SW Inner Baseline
SW Outer Baseline
SW Middle Baseline
SE Outer Repair
SE Middle Repair
SE Inner Repair
SW Inner Repair
SW Outer Repair
SW Middle Repair
V_{max} (kip)
strain (με)
500
450
400
350
300
250
200
150
100
50
0
-2000
0
2000
4000
6000
8000
10000
12000


D.T.C.PT
Tensile Diagonal Displacement
N Baseline
N Repair
S Baseline
S Repair
Vmax (kip)
Displacement (in.)
600
500
400
300
200
100
0
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

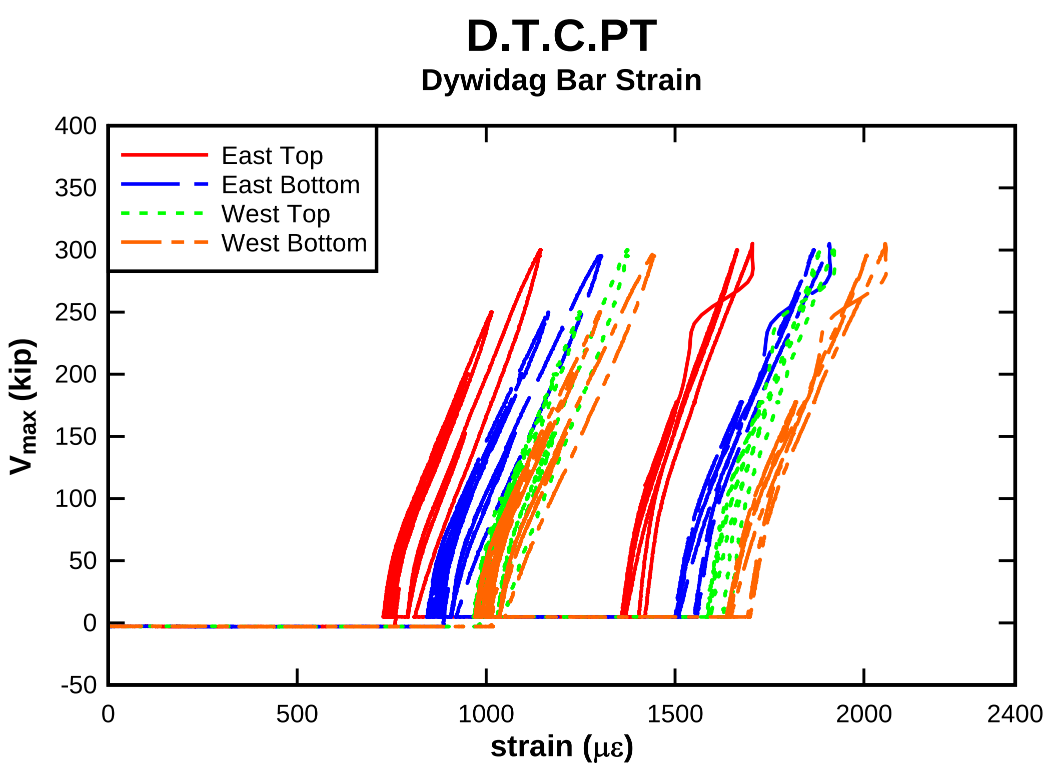

D.T.C.PT
Compression Diagonal Displacement
N Basline
N Repair
S Baseline
S Repair
Vmax (kip)
Displacement (in.)
600
500
400
300
200
100
0
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4


D.T.C.PT
North Integrally Cast Stirrup Strain
Data Offset by 4000 με
N1 BL
N1 Repair
N3 BL
N3 Repair
N4 BL
N4 Repair
N5 BL
N5 Repair
N6 BL
N6 Repair
N8 BL
N8 Repair
Vmax (kip)
strain (με)
500
450
400
350
300
250
200
150
100
50
0
-4000
0
4000
8000
12000
16000
20000
24000
28000


D.T.C.PT
South Integrally Cast Stirrup 1-4 Strain
Data Offset by 8000 με
Baseline 1S
Repair 1S
Baseline 2S
Repair 2S
Baseline 3S
Repair 3S
Baseline 4S
Repair 4S
Vmax (kip)
strain (με)
450
400
350
300
250
200
150
100
50
0
-4000
0
4000
8000
12000
16000
20000
24000
28000

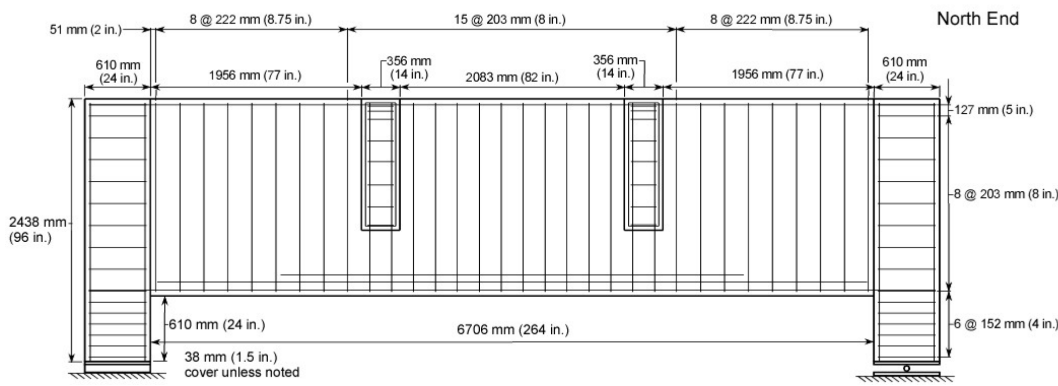


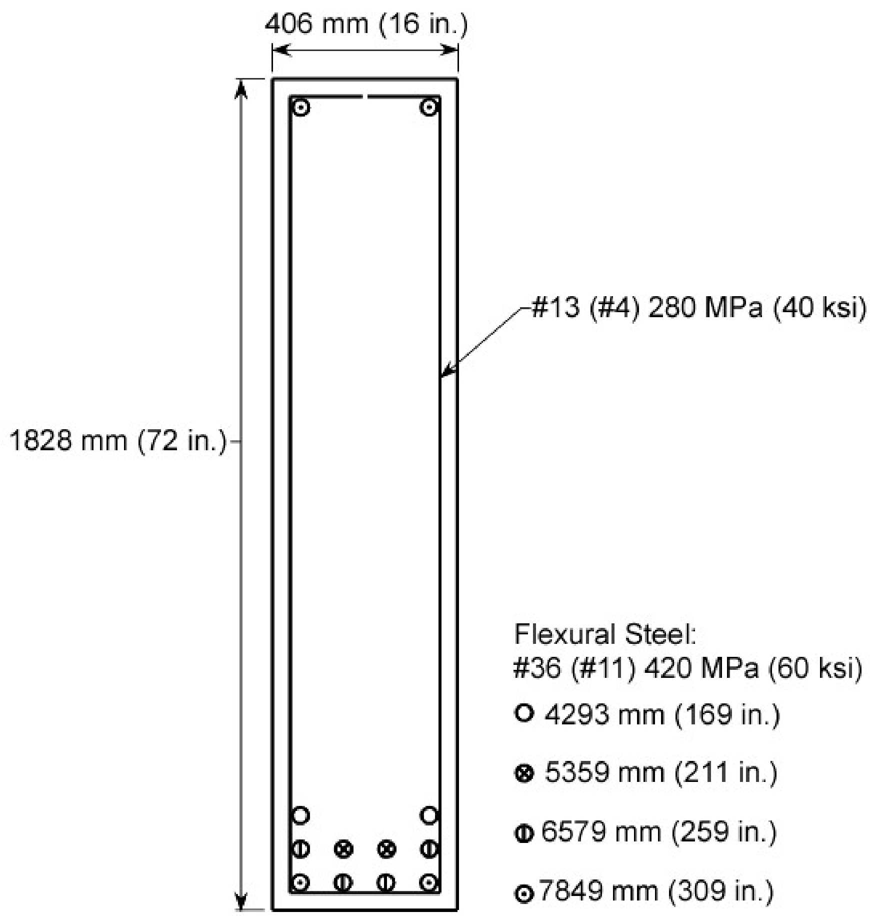
D.T.C.PT
South Integrally Cast Stirrup 5-8 Strain
Data Offset by 6000 με
Baseline 5S
Repair 5S
Baseline 6S
Repair 6S
Baseline 7S
Repair 7S
Baseline 8S
Repair 8S
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
400
450
0
3000
6000
9000
12000
15000
18000
21000
24000



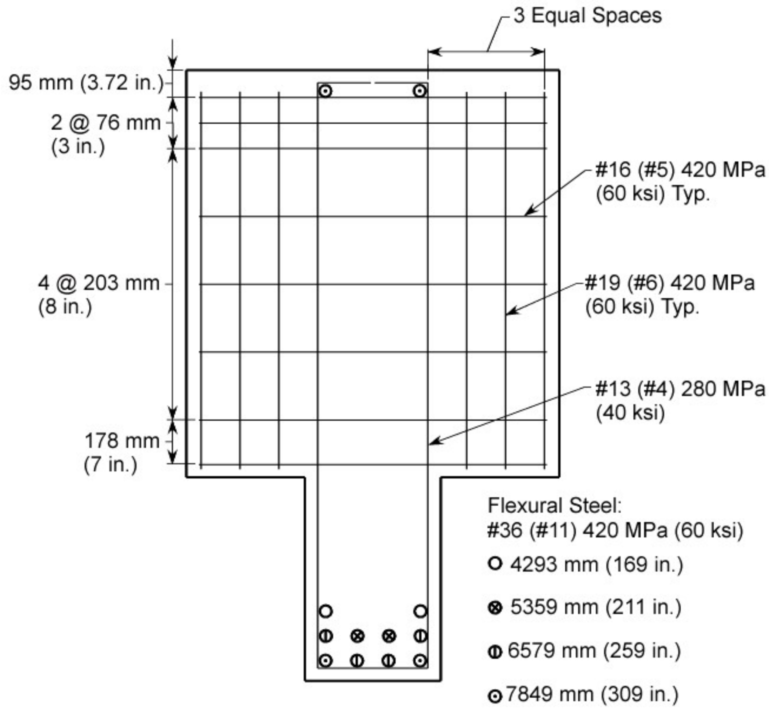
D.T.C.PT
Dywidag Bar Strain
East Top
East Bottom
West Top
West Bottom
Vmax (kip)
strain (με)
-50
0
50
100
150
200
250
300
350
400
0
500
1000
1500
2000
2400

APPENDIX A-10: SPECIMEN D.T.C.CF

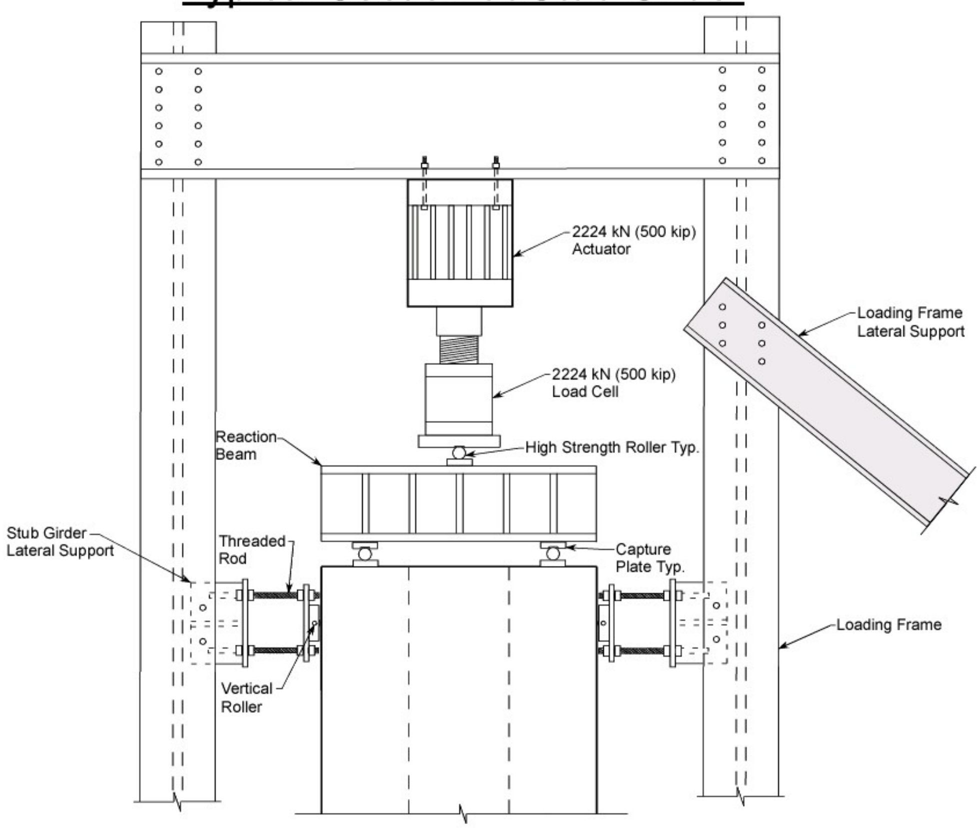


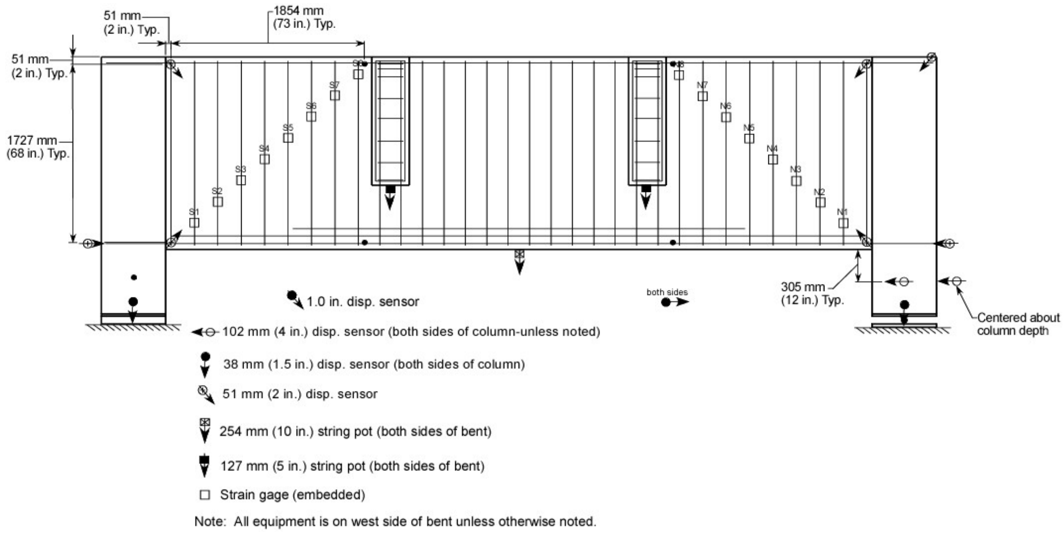


<u>Typical Section at Mid Span</u>

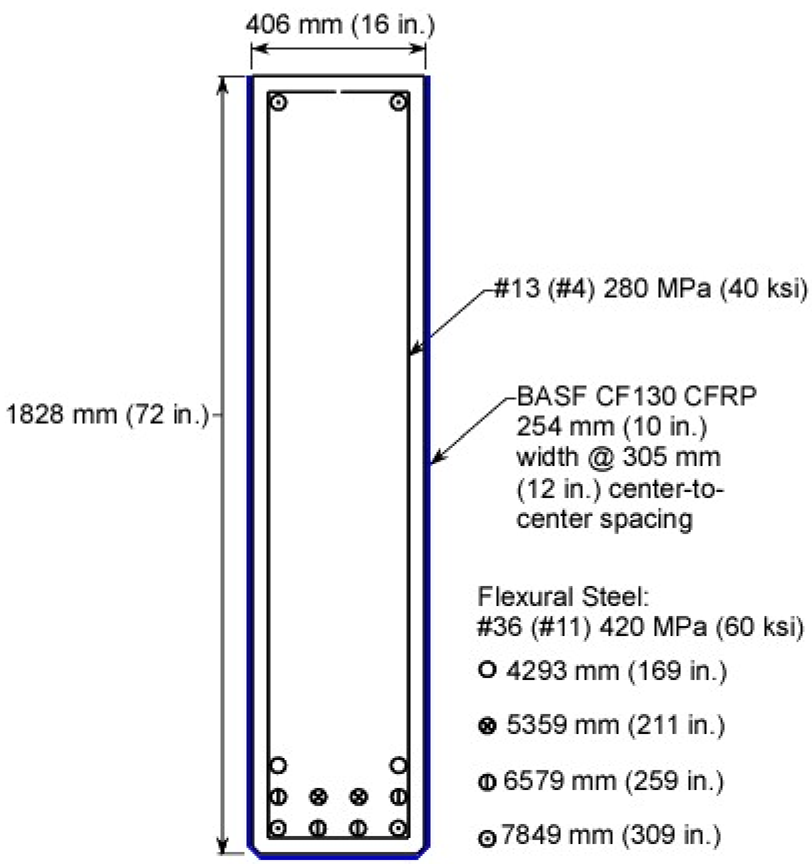


Typical Section at Stub Girder

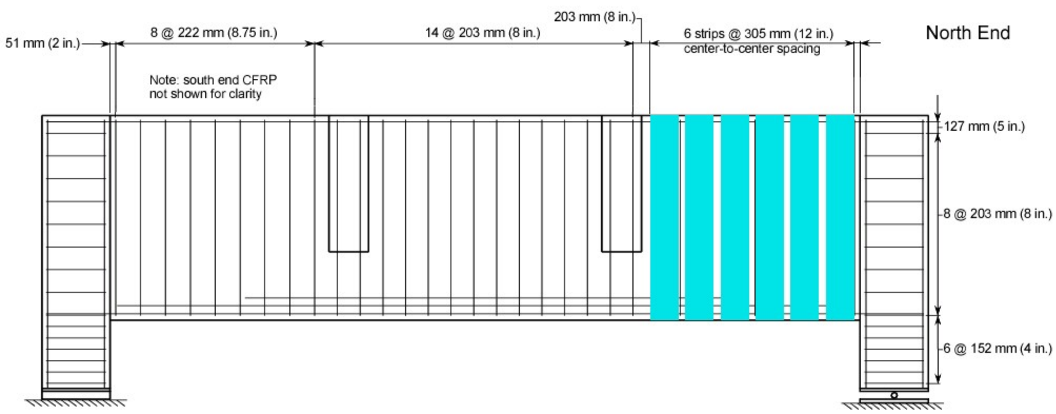




51 mm (2 in.) Typ.
1854 mm (73 in.) Typ.
51 mm (2 in.) Typ.
1727 mm (68 in.) Typ.
S1
S2
S3
S4
S5
S6
S7
S8
N1
N2
N3
N4
N5
N6
N7
N8
305 mm (12 in.) Typ.
Centered about column depth
both sides
1.0 in. disp. sensor
102 mm (4 in.) disp. sensor (both sides of column-unless noted)
38 mm (1.5 in.) disp. sensor (both sides of column)
51 mm (2 in.) disp. sensor
254 mm (10 in.) string pot (both sides of bent)
127 mm (5 in.) string pot (both sides of bent)
Strain gage (embedded)
Note: All equipment is on west side of bent unless otherwise noted.



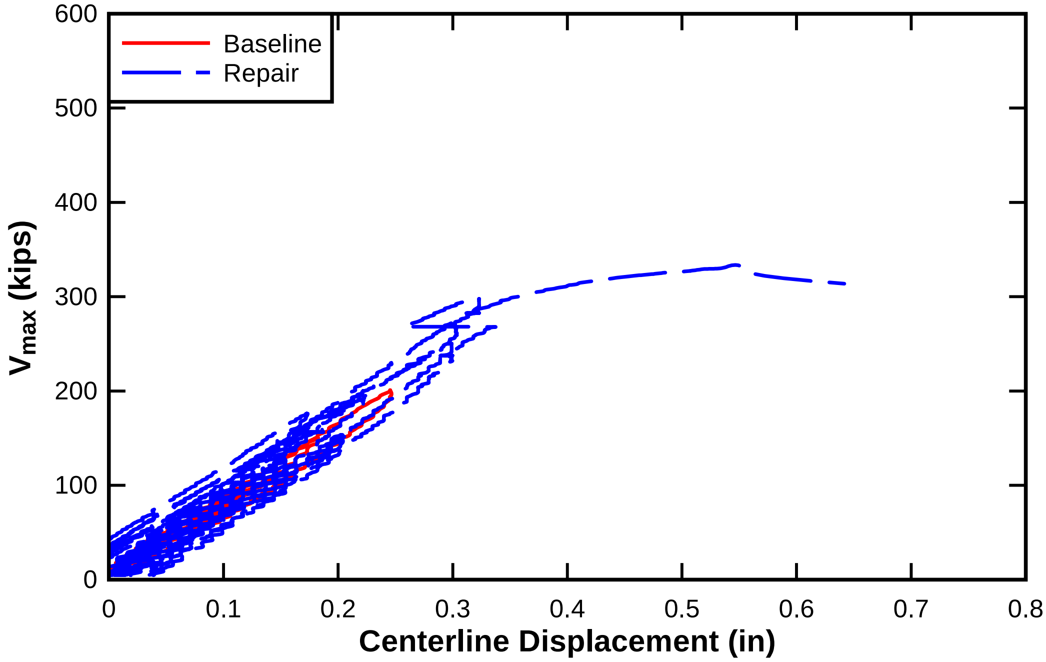
406 mm (16 in.)
1828 mm (72 in.)
#13 (#4) 280 MPa (40 ksi)
BASF CF130 CFRP
254 mm (10 in.)
width @ 305 mm
(12 in.) center-to-
center spacing
Flexural Steel:
#36 (#11) 420 MPa (60 ksi)
4293 mm (169 in.)
5359 mm (211 in.)
6579 mm (259 in.)
7849 mm (309 in.)


203 mm (8 in.)
51 mm (2 in.)
8 @ 222 mm (8.75 in.)
14 @ 203 mm (8 in.)
6 strips @ 305 mm (12 in.)
center-to-center spacing
North End
Note: south end CFRP
not shown for clarity
127 mm (5 in.)
8 @ 203 mm (8 in.)
6 @ 152 mm (4 in.)

D.T.C.CF North End

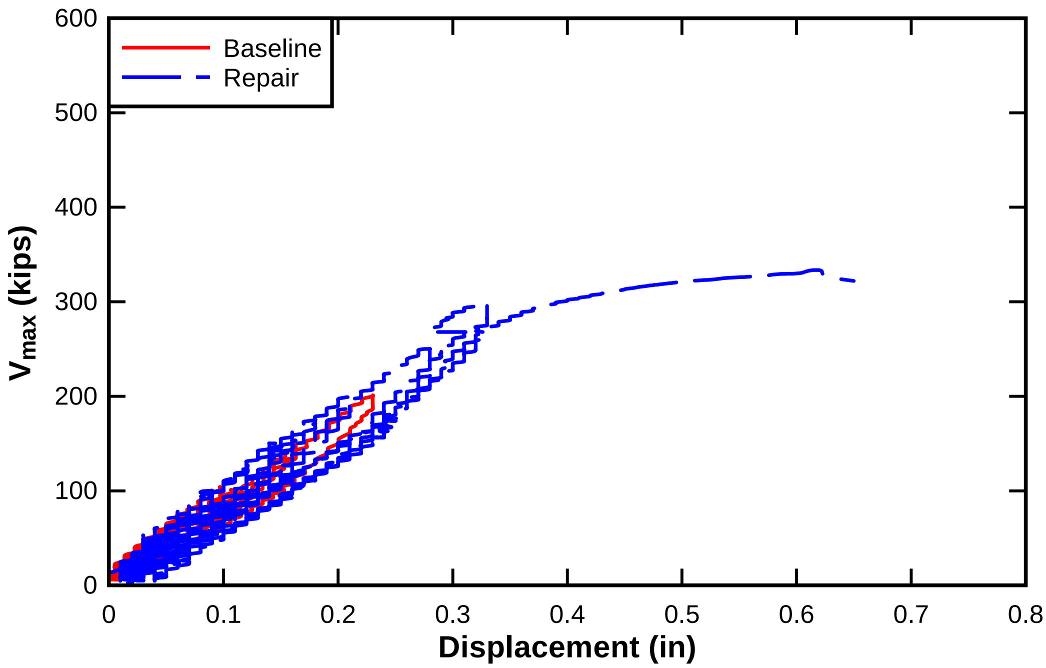
D.T.C.CF South End

D.T.C.CF



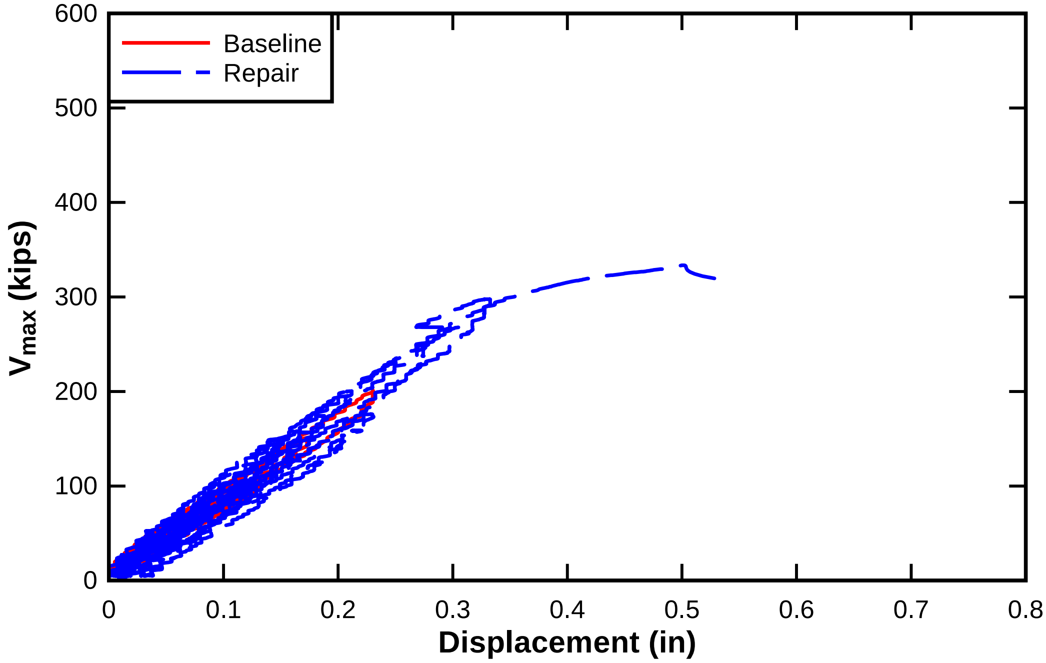
D.T.C.CF

North Stub Girder



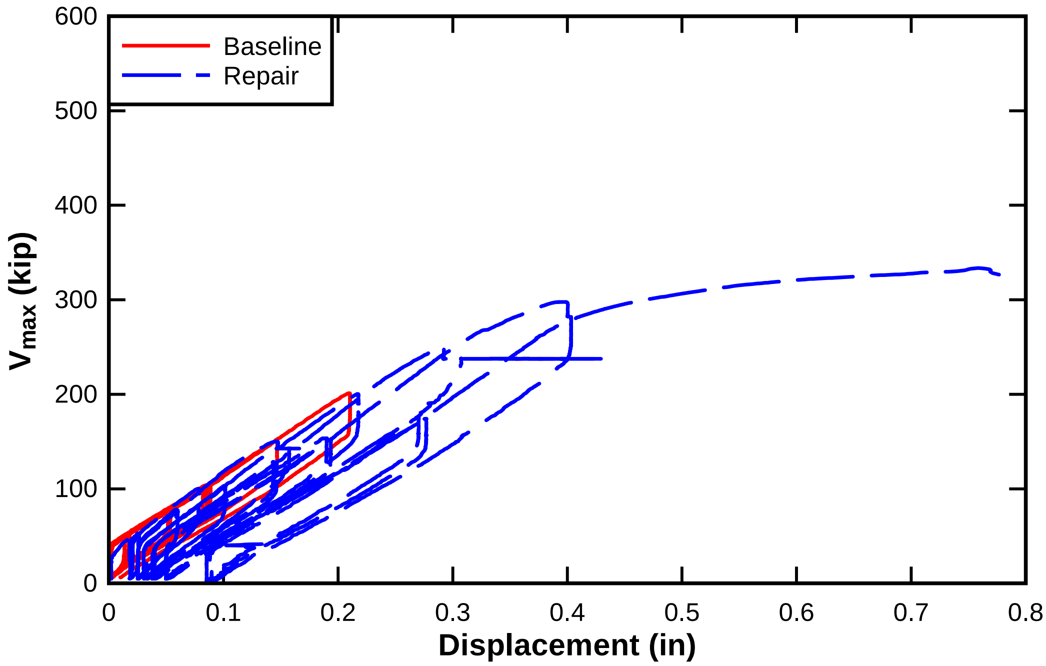
D.T.C.CF

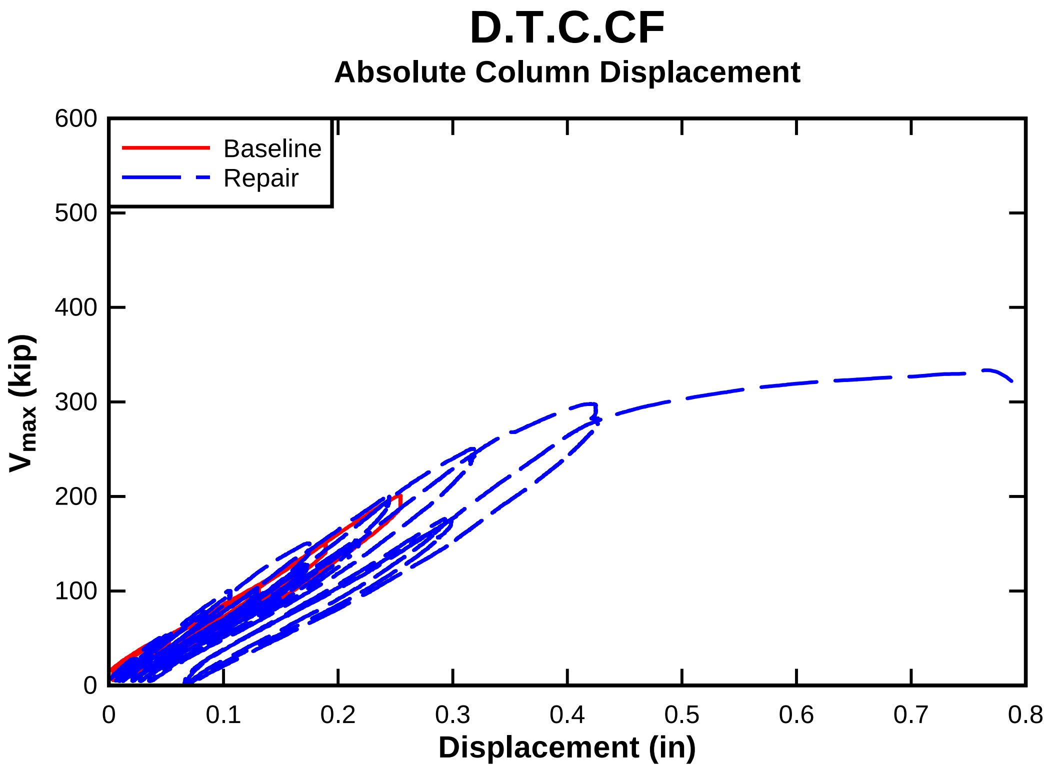
South Stub Girder



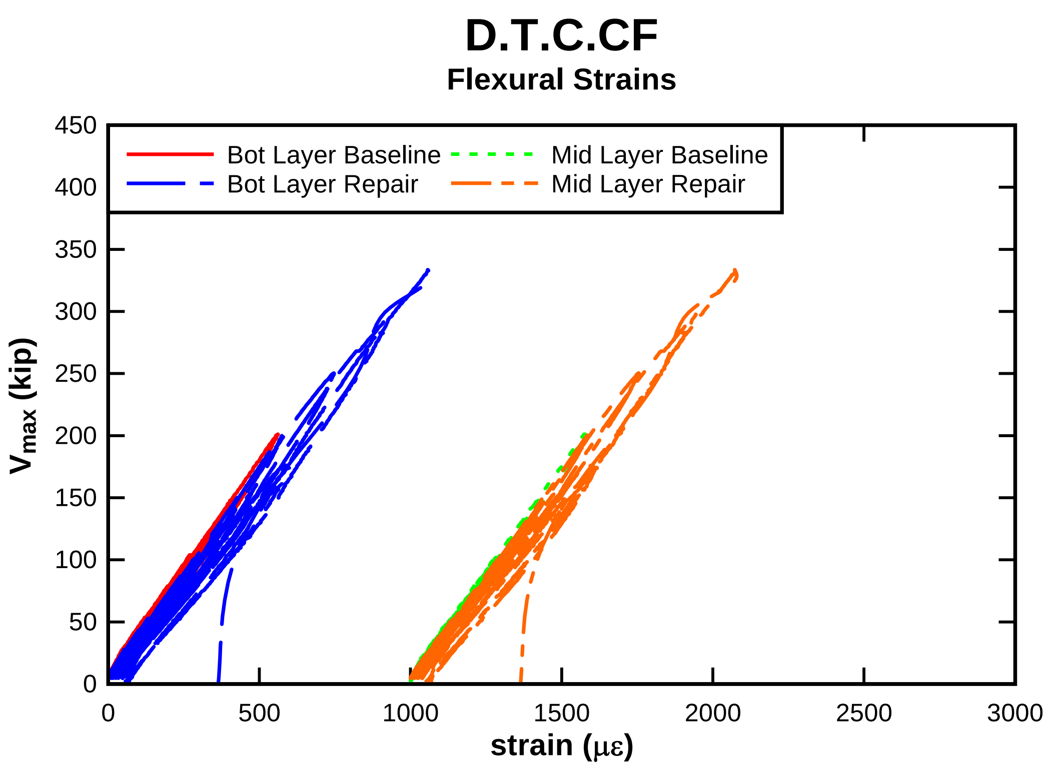
D.T.C.CF

Relative Column Displacement

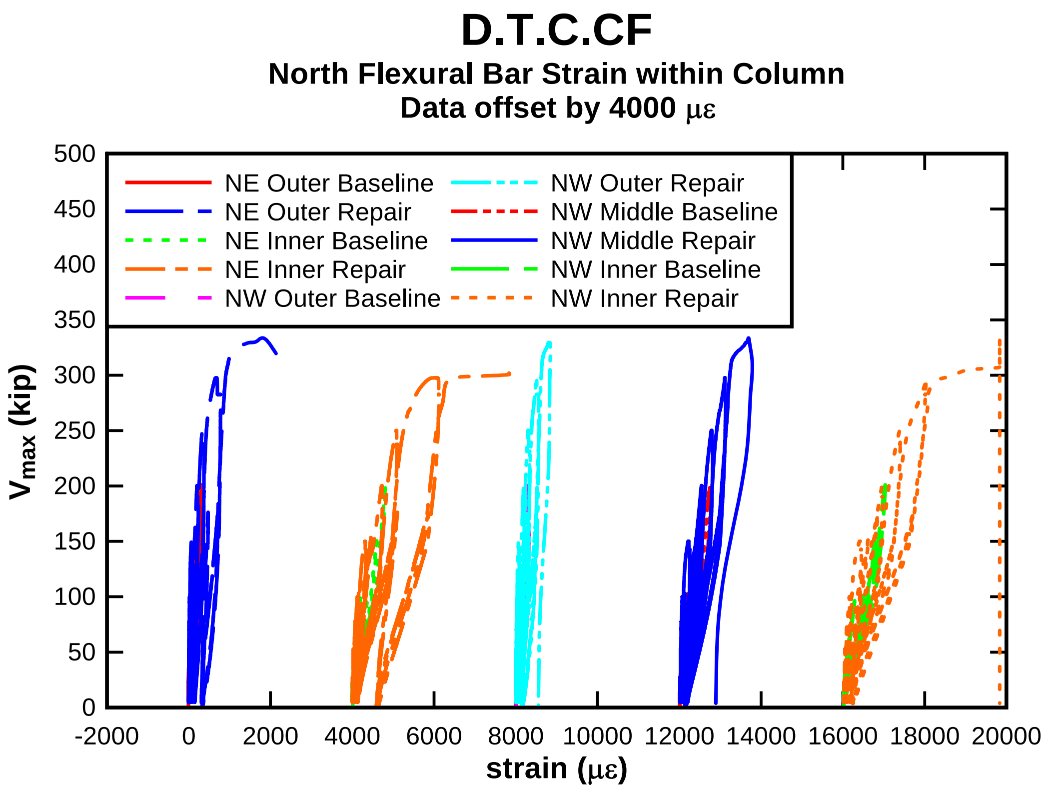


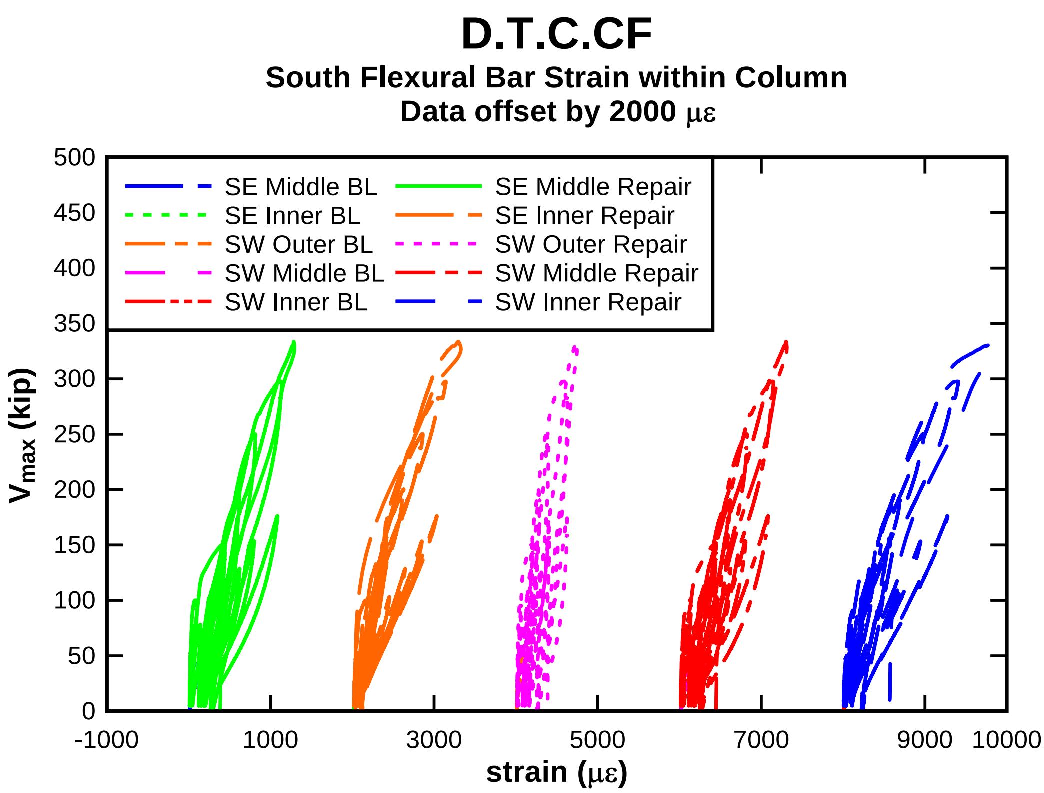


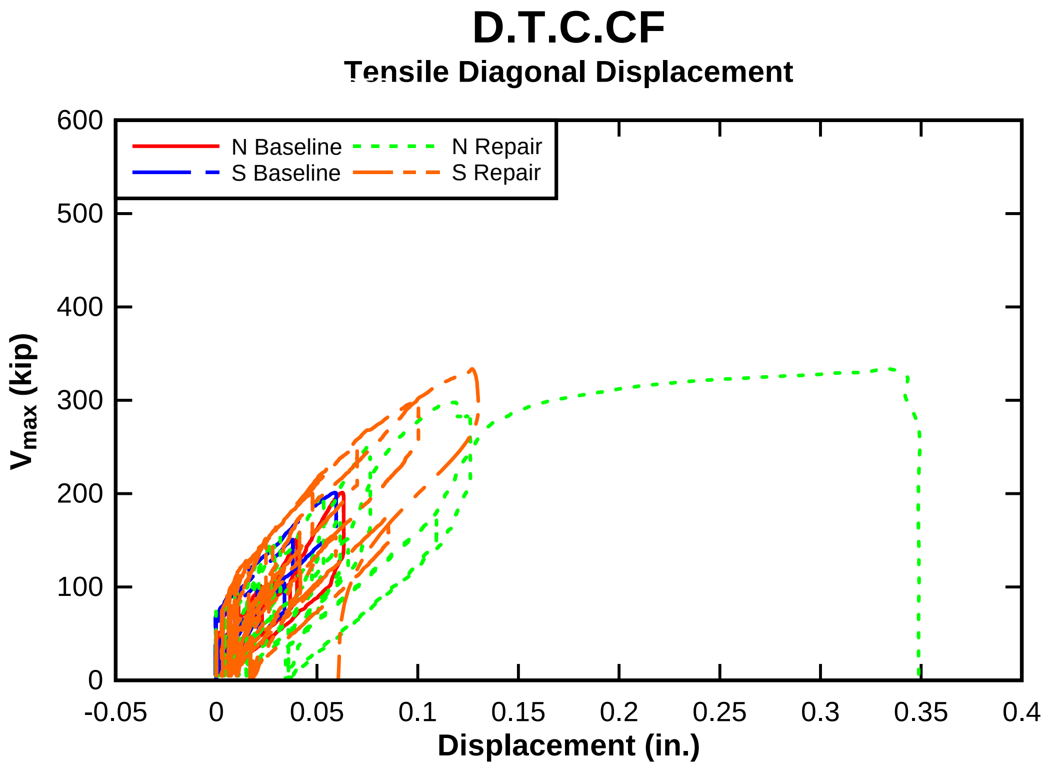
D.T.C.CF
Absolute Column Displacement
Baseline
Repair
Vmax (kip)
Displacement (in)
0
100
200
300
400
500
600
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

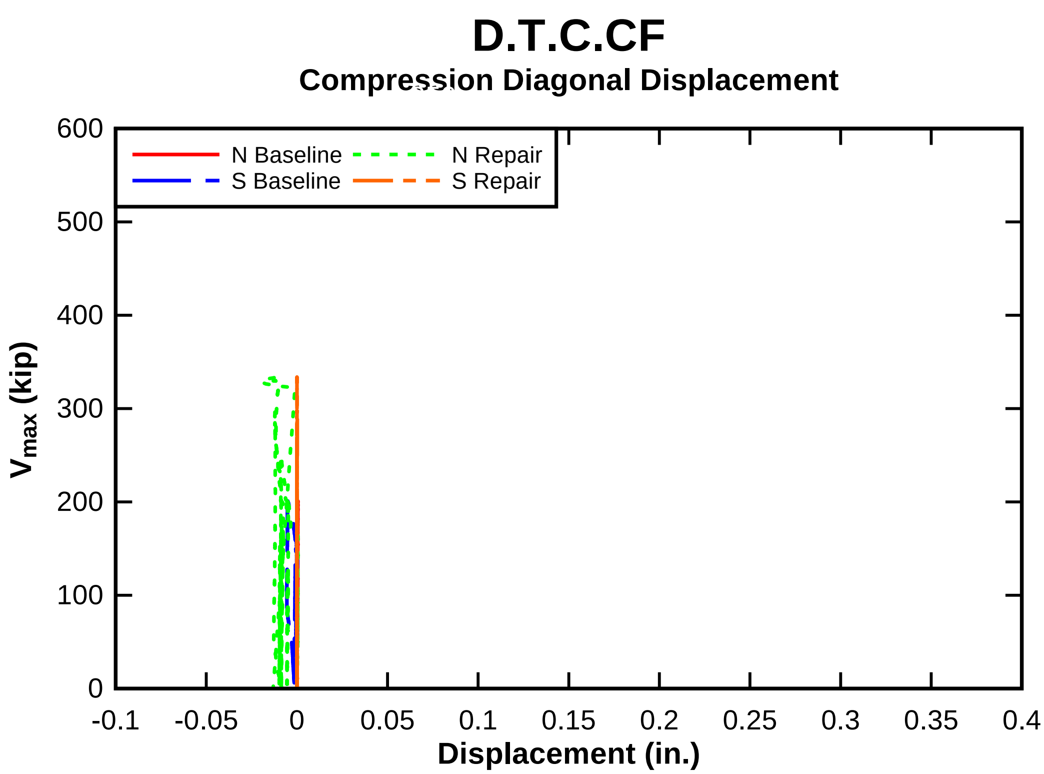


D.T.C.CF
Flexural Strains
Bot Layer Baseline
Bot Layer Repair
Mid Layer Baseline
Mid Layer Repair
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
400
450
0
500
1000
1500
2000
2500
3000


D.T.C.CF
North Flexural Bar Strain within Column
Data offset by 4000 με
NE Outer Baseline
NE Outer Repair
NE Inner Baseline
NE Inner Repair
NW Outer Baseline
NW Outer Repair
NW Middle Baseline
NW Middle Repair
NW Inner Baseline
NW Inner Repair
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
400
450
500
-2000
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000

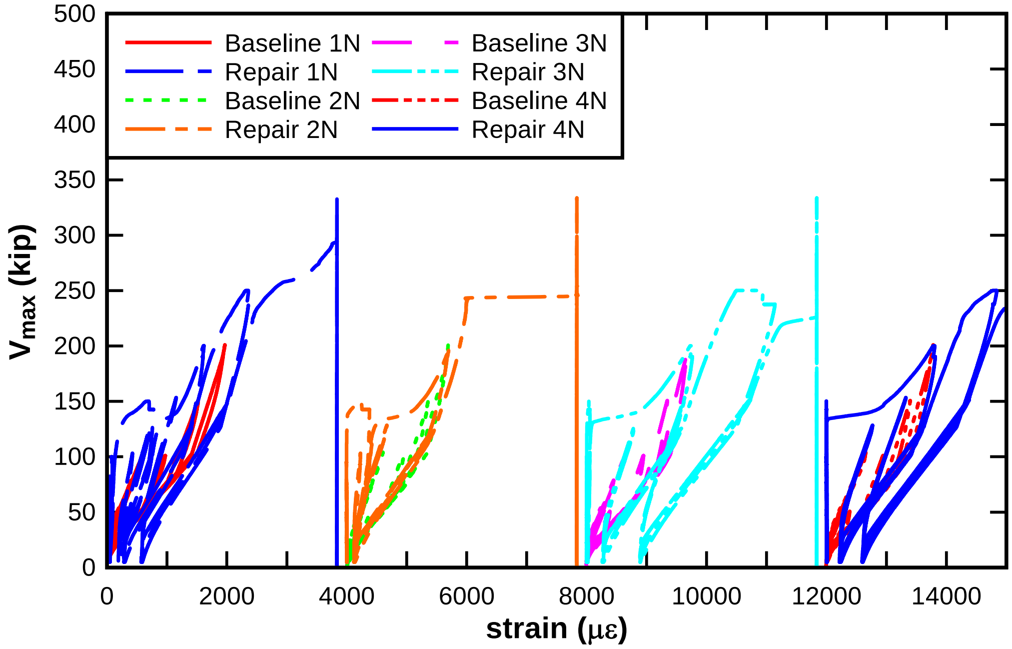

D.T.C.CF
South Flexural Bar Strain within Column
Data offset by 2000 με
SE Middle BL
SE Inner BL
SW Outer BL
SW Middle BL
SW Inner BL
SE Middle Repair
SE Inner Repair
SW Outer Repair
SW Middle Repair
SW Inner Repair
Vmax (kip)
strain (με)
0
50
100
150
200
250
300
350
400
450
500
-1000
1000
3000
5000
7000
9000
10000


D.T.C.CF
Tensile Diagonal Displacement
N Baseline
S Baseline
N Repair
S Repair
600
500
400
300
200
100
0
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in.)
V_{max} (kip)


D.T.C.CF
Compression Diagonal Displacement
N Baseline
S Baseline
N Repair
S Repair
600
500
400
300
200
100
0
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (in.)
V_{max} (kip)

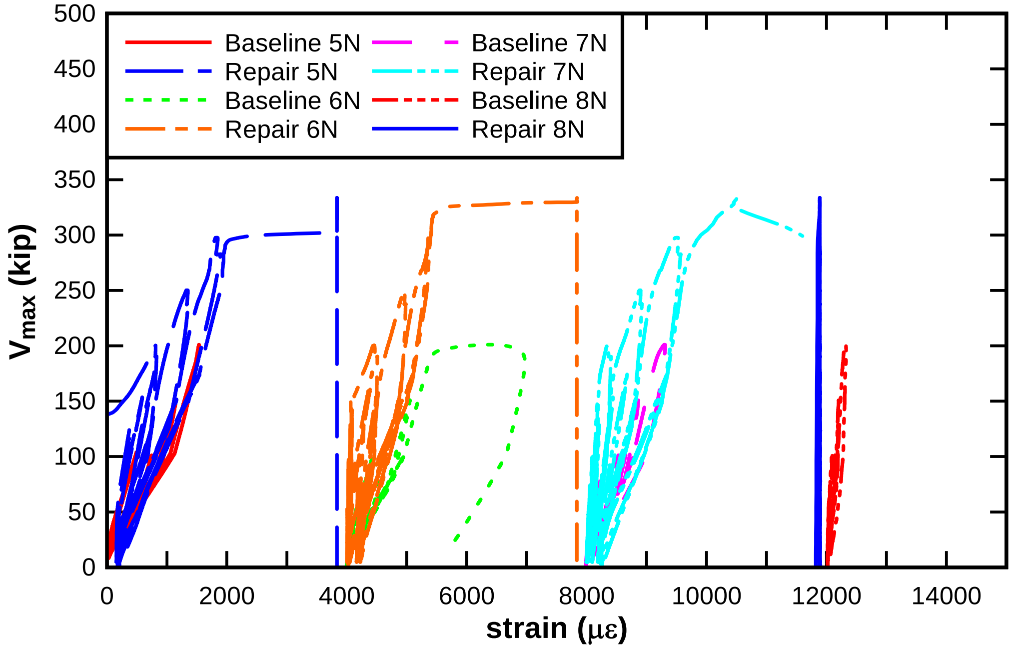
D.T.C.CF

North Integrally Cast Stirrup 1-4 Strain
Data offset by 4000 με



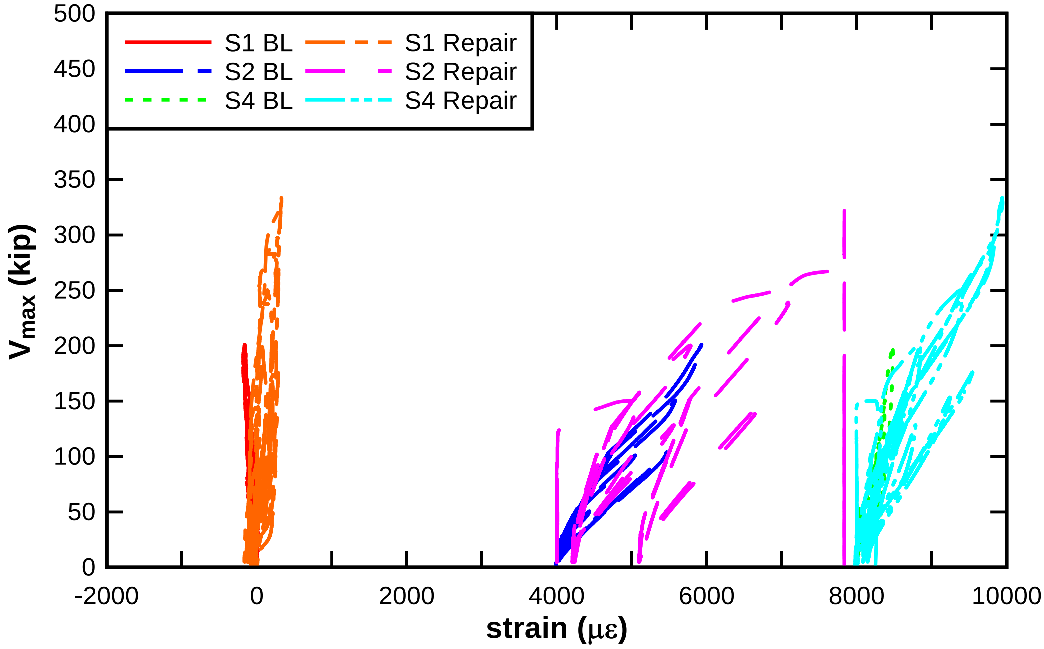
D.T.C.PT

North Integrally Cast Stirrup 5-8 Strain
Data offset by 4000 με



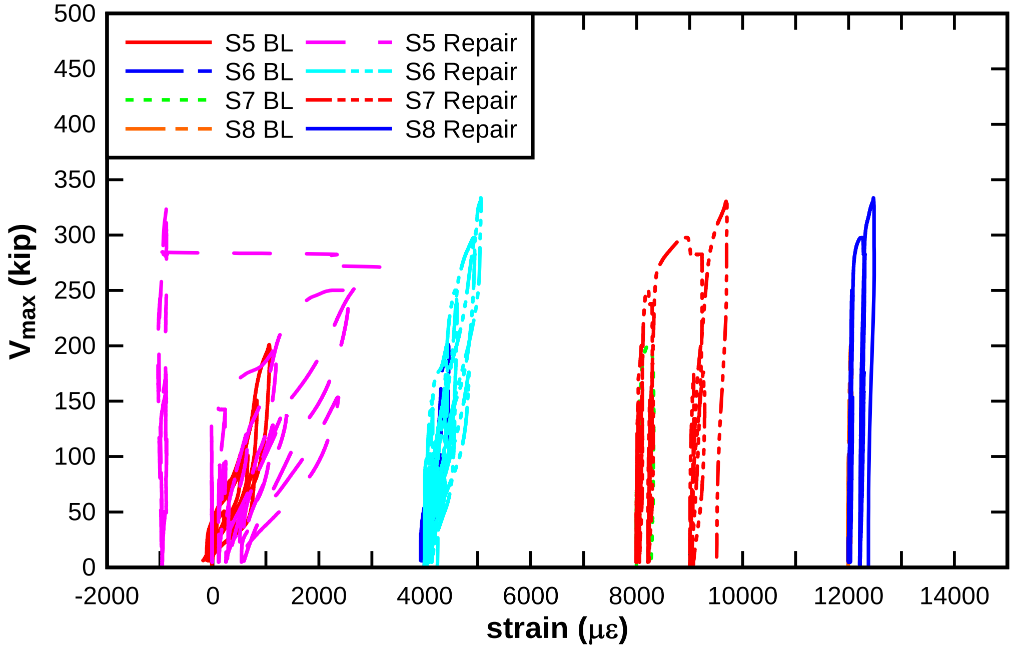
D.T.C.CF

South Integrally Cast Stirrup 1-4 Strain
Data offset by 4000 με



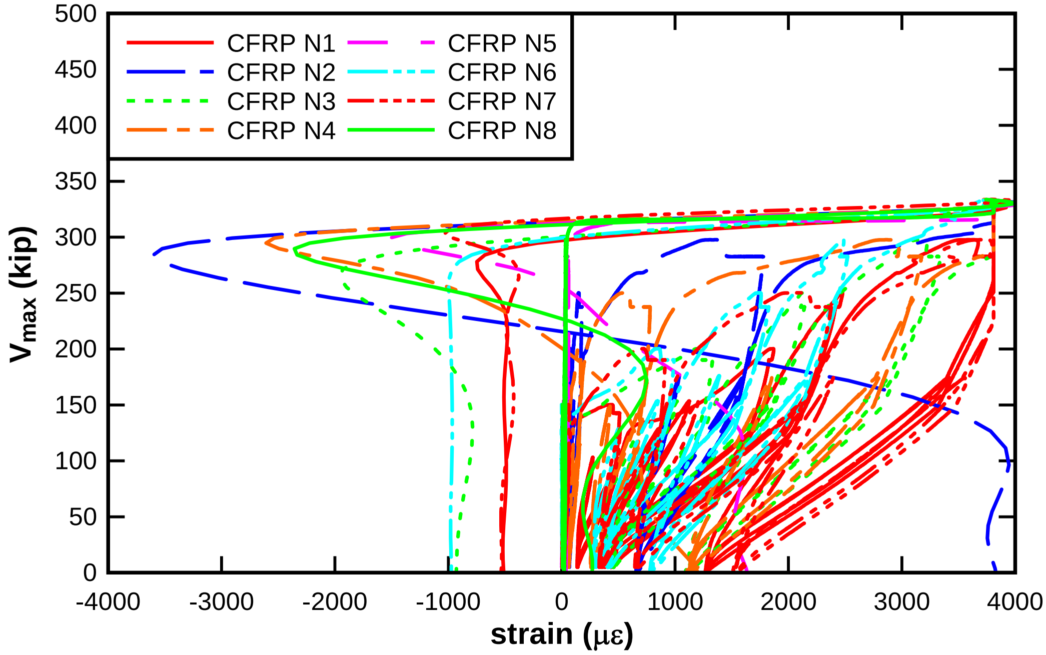
D.T.C.PT

South Integrally Cast Stirrup 5-8 Strain
Data offset by 4000 με



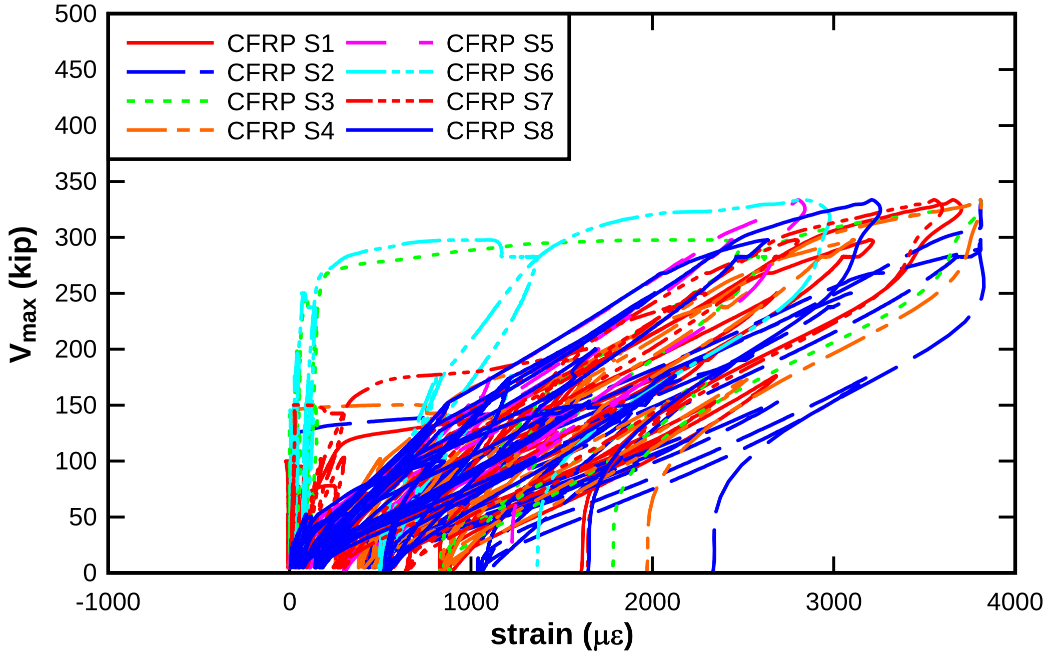
D.T.C.CF

North CFRP Strain



D.T.C.CF

South CFRP Strain



APPENDIX B: DESIGN WITH ALTERNATIVE SHEAR STRENGTHENING METHODS

APPENDIX B Design with Alternative Shear Strengthening Methods

The basic steps for shear strengthening include:

1) Perform structural analysis of rating and permit trucks to find demands at locations on the bridge. The factored shear and moments should be taken as those that are coincident and the separate peaks should not be combined.

2) Determine current capacity of the section according to AASHTO-MCFT.

3) Identify critical moment-shear interactions that need to be addressed (where demands exceed capacity).

4) Develop shear stress-stirrup quantity interaction plots for these critical M/V ratios.

5) Identify the amount of shear pressure required to meet design objective at the critical M/V ratios.

6) Proportion the supplemental reinforcing according to the method chosen.

7) Detail the repair.

8) Check strengthening design with the demands from 1) to ensure design is adequate.

9) Check flexural steel for additional demands to ensure adequate anchorage.

The first step is to conduct an analysis of the bridge under the desired legal/permit/inventory/ operating rating level. Structural analysis under the load cases should consider coincident moment and shear effects rather than lumping the maximums that do not occur simultaneously.

Consider a three-span continuous RCDG bridge with 50 ft spans. Structural analysis shows the inventory load rating is controlled by a coincident factored shear of 99 kips and factored moment of 900 kip-ft at the negative moment region (the corresponding M/V ratio is 9.09 ft).

The available strength of the section should be computed and compared with the load demands. The capacity of the section can be estimated using the sectional analysis procedure in AASHTO-LRFD which takes into account shear-moment interaction. The cross section to be evaluated is shown in Figure B1. The effective depth for shear (d_v) is 40.2 in. The design concrete strength is 3300 psi. There are 5#11 bars of Intermediate Grade (Grade 40) fully developed at the section. The stirrups are #4 bars of Intermediate Grade (Grade 40). It is desired to upgrade the bridge to an inventory rating level of 1.0 (beta =3.5 for HL93). The AASHTO-MCFT interaction strength curve and factored moment and shear are shown in Figure B2. As seen in this figure, the section requires additional shear strength to achieve the desired rating.

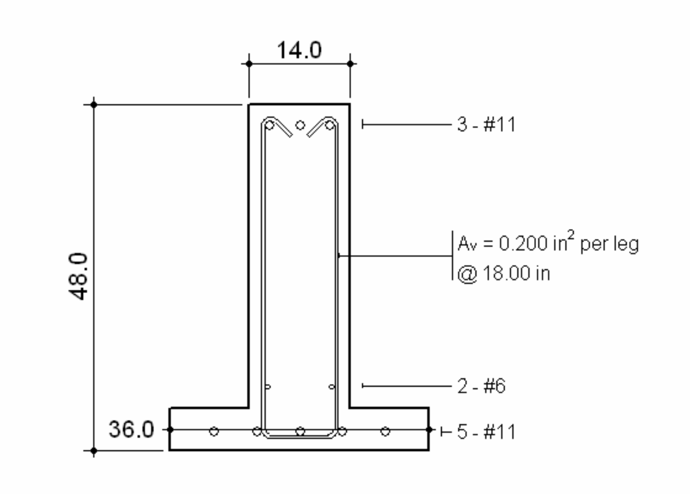


Figure B1: Existing cross section (shown inverted)

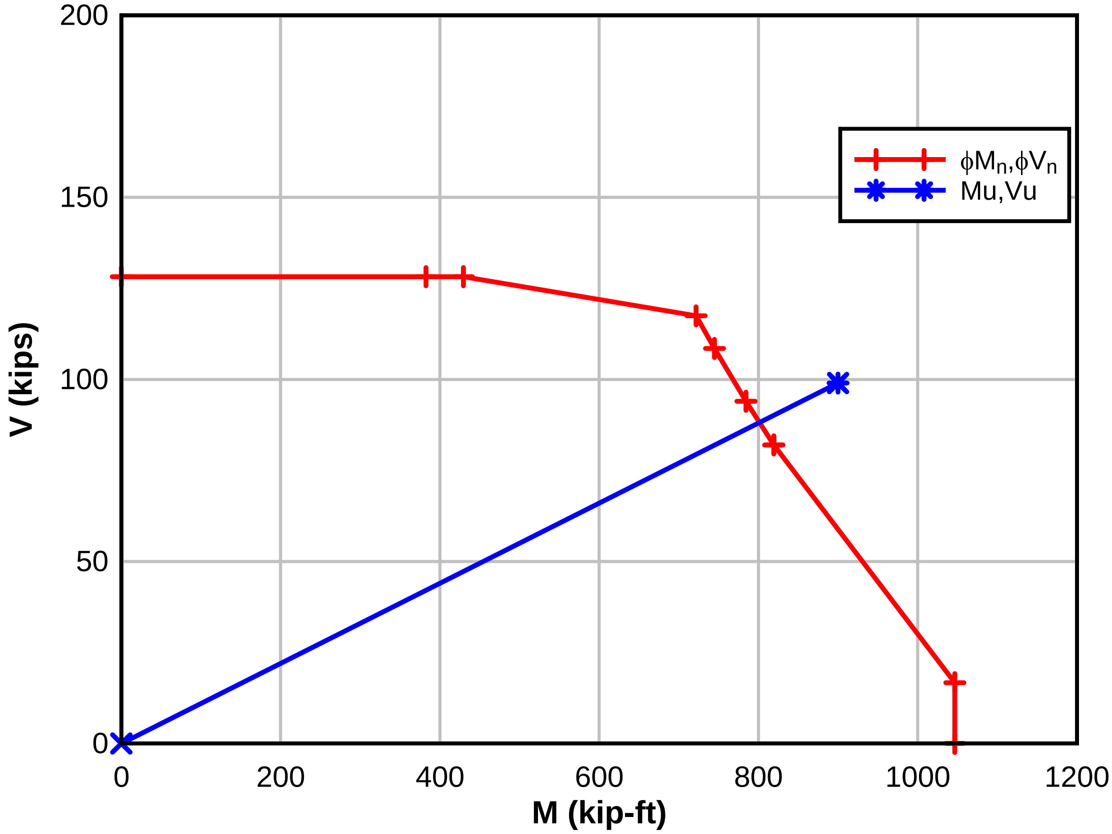


Figure B2: Current M,V resistance and demands that produce inventory rating below 1.0

The ability to increase the shear capacity of a section can best be visualized by considering the average shear strength vs stirrup quantity for the given M/V ratio that controls the rating (9.09 ft for the current case). For the given section and M/V ratio the shear stress (V/ bd_v) vs stirrup quantity (A_vf_y/ bs) is shown in Figure B3. To achieve the required 99 kips of factored shear the nominal average shear stress required is $V_u/\phi bd_v$=99/(0.9(14/40.2)= 195 psi. This is shown as the reference line in Figure B3. The current V_n, M_n for the 18 in. stirrup spacing is shown as a vertical line at 63.5 psi on the abscissa. The ACI 318 approach of superposition with additional transverse stele is shown in the figure as the dashed line. If this approach were considered, it would falsely require very little additional transverse steel to achieve the required strength (approximately 81-63=18 psi of transverse reinforcing stress). However, as revealed by the MCFT interaction curve due to nonlinear response of the flexural steel, a much larger amount of transverse reinforcing pressure is required to achieve the strengthening goal (228-63=165 psi). If significantly more shear strength were required, it would be very difficult to increase the strength of the section further without also increasing the flexural strength.

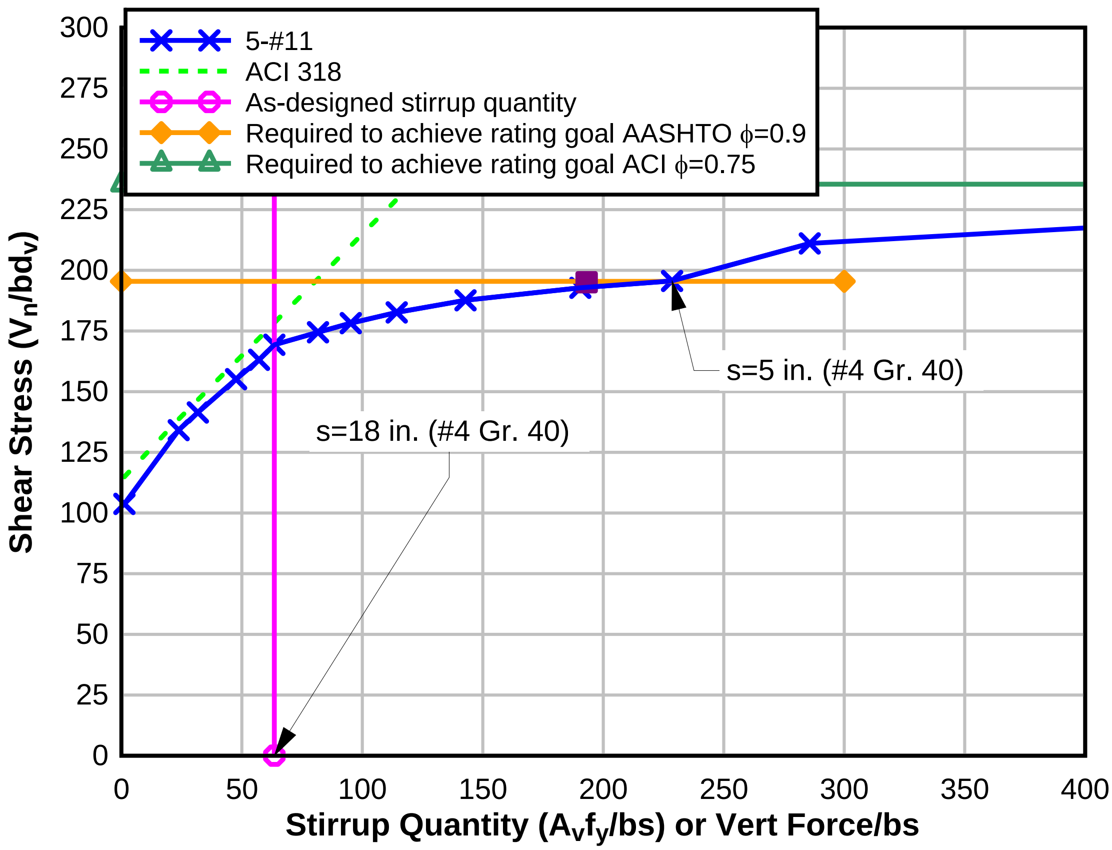


Figure B3: Average shear stress and stirrup quantity for M/V=9.09 ft (the critical load effect demand from Figure B2) on the current cross section. In situ condition to be strengthened is for internal cast-in-place stirrup spacing of s=18 in.

To achieve the goal of 165 psi of additional transverse reinforcing pressure, several options are possible. Using the present research results, these include internal stirrups, external stirrups, or surface bonded CFRP which follows a separate approach. Each of these approaches is described subsequently.

External stirrups

Consider an option that uses ½ in. diameter threaded bars with nominal yield of 70 ksi. The bar area is taken as 0.2 in^2. The unbonded length of the bars will be 48 in. The stiffness of the stirrup will be AE/L =0.2(29000)/48=120.8 kip/in. Stirrups should be as close to the web as possible to minimize the moment arm on the supporting steel section. Nominally the bars could be placed within 1 in. from the face of the web, but due to tolerances required to avoid drilling through flexural bars, the permissible offset can be this amount plus the diameter of the flexural bars in the deck (#11 bars in the present example). For the present case the total maximum offset is 1+11/8 = 2 3/8 in. To provide a section such that only 2/100 of the deformation occurs in the steel support sections, an idealized four-point bending setup is considered with the bars loading the section and reactions occurring on the face of the edge of the chamfer on the stem. Computing the deflection at the rod location, the required moment of inertia for a steel section to provide the requisite stiffness is 13 in^4 . (use W6x20, I=13.3 in^4 and the efficiency is 98%). This enables the threaded rod to be 98% efficient. To achieve higher levels of efficiency requires much stiffer sections (for example 99% requires I=30 in^4). For the given service dead load shear (considered here as 30 kips), then the estimated dead load stirrup stress is taken as $(V_{DL}/V_n)f_y$ =(30/110)40=10.9 ksi (taking V_n as V_u/ϕ). To ensure that the external stirrups yield at approximately the same time as the external stirrups (assuming internal stirrups have already yielded at cracked locations and thus will behave almost elastically until ultimate taken as 60 ksi) as well as ensure strain compatibility, the external stirrups will be post-tensioned to 20 ksi. To determine the spacing of stirrups required, the required stirrup quantity is rearranged as:

$$s_{\sup} = \frac{\lambda A_{v\sup} f_{yv\sup}}{SQb} \text{=(0.98*2*0.2*70000)/(165*14)=11.8 in. use 11 in.spacing} \quad \text{[B.1]}$$

In this equation, λ is the efficiency of the stirrups considering the flexibility of the supporting steel sections. The effective spacing used in computing the repaired section is taken as:

$$s_{eff} = \frac{A_{vCIP} f_{yvCIP} d_v}{\dfrac{A_{vCIP} f_{yvCIP} d_v}{s_{CIP}} + \dfrac{\lambda A_{v\sup} f_{yv\sup} d_v}{s_{\sup}}} \text{=4.73 in. spacing of \#4 Grade 60 stirrups} \quad \text{[B.2]}$$

The trial design is checked with AASHTO-MCFT and the M,V interaction curve is shown in Figure B4 indicating adequate shear strength.

Finally, due to the increased capacity of the section, the flexural demands must also be checked to ensure anchorage demands will not be exceeded per AASHTO-LRFD section 5.8.3.5.

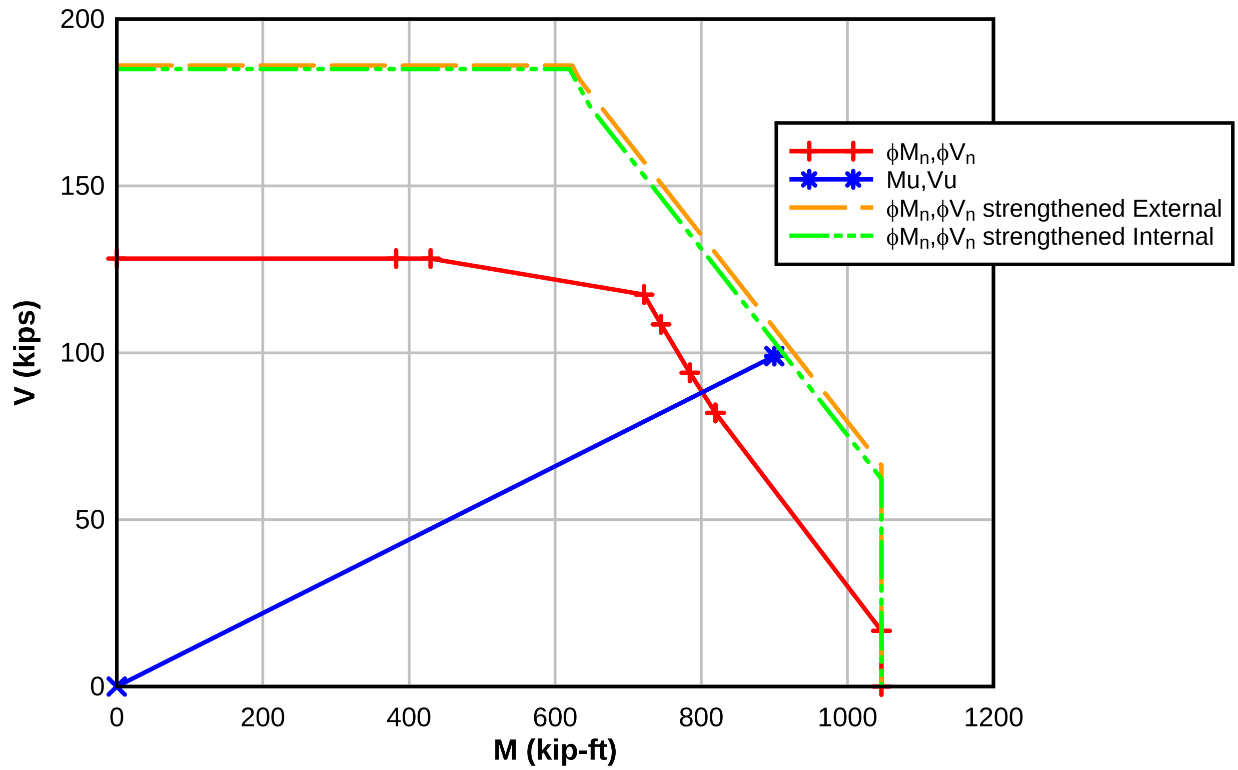


Figure B4: M,V resistance provided by supplemental external stirrups that will achieve inventory rating for section (internal stirrup option and external stirrup options shown)

Internal stirrups

Consider #6 Grade 60 reinforcing steel as the supplemental internal transverse reinforcing. One could use higher strength bars, but the bar stress should be limited to a design maximum of 80 ksi. The bars will be placed at a 45 degree angle. Thus, the supplemental bars contribution to shear strength can be computed as:

$$V_{S\sup} = \frac{A_{v\sup} f_{yv\sup} d_v (\sin\alpha + \cos\alpha \tan\theta)}{s_{\sup}} \qquad \text{[B.3]}$$

For the initial design the crack angle θ is also assumed to be 45 degrees. Given the required additional stirrup pressure to achieve the desired rating (SQ=165 psi), the above equation can be recast as:

$$s_{\sup} = \frac{A_{v\sup} f_{yv\sup} (\sin\alpha + \cos\alpha)}{SQb} \text{=(0.44(60000)(cos45+sin45))/(165*14))=16.2 in. say 16 in.} \qquad \text{[B.4]}$$

The effective spacing used in computing the repaired section for equivalent #4 Grade 60 stirrups is taken from Eqn 2. as 4.96 in. The trial design is checked with AASHTO-MCFT and the M,V interaction curve is shown in Figure B4 indicating adequate shear strength

Finally, due to the increased capacity of the section, the flexural demands must also be checked to ensure anchorage demands will not be exceeded per AASHTO-LRFD section 5.8.3.5.

Surface Bonded CFRP

CFRP strengthening should follow ACI 440 procedures and be combined with ACI 318 base strengths. This approach is described subsequently. In the present approach, the d term is replaced with d_v which results in slightly smaller strength predictions. The ACI average shear strength vs stirrup quantity is shown in Figure B3. As seen in this figure the section requires a nominal transverse reinforcing quantity of $(99/\phi)/bd_v$= (99/0.75)/(14*40.2)=234.5 psi. To achieve this average shear stress, the supplemental transverse reinforcing must be able to provide 121 psi of transverse pressure. The current cross section provides 63.5 psi, thus an additional 57.5 psi is need from supplemental transverse reinforcing. Using a single layer of CF130 material with 10 in. wide strips and following ACI 440 guidelines, the spacing of strips can be determined. To do so, the reduced effective CFRP stress for vertical strips is calculated as:

$$\psi V_f\left(lb\right) = \frac{\psi A_{fv} f_{fe} d_{fv}}{s_f} \qquad \text{[B.5]}$$

where d_{fv} (in) = height of the web above the flexural steel, s_f (in) = CFRP strip spacing, and ψ is a reduction coefficient for the wrap configuration (0.85 for the 3 sided U wrap) and A_{fv} is the area of the CFRP strips as:

$$A_{fv} = 2nt_f w_f = 2(1)0.0065*10=0.13 \text{ in}^2 \qquad \text{(10-4) [B.6]}$$

and f_{fe} is the effective CFRP strain for debonding failure as:

$$f_{fe} = \varepsilon_{fe} E_f \qquad \text{(10-5) [B.7]}$$

ACI 440.2R-02 limits the ultimate strain of the FRP, ε_{fu}, to an effective strain, ε_{fe}, using a bond-reduction coefficient, κ_v, which is based on the development length, L_e, and other FRP properties:

$$L_e = \frac{2500}{(n\, t_f E_f)^{0.58}} \text{=2500/((1*0.0065*33,000,000)^0.58)=2.0 in} \qquad \text{(10-7) [B.8]}$$

$$k_1 = \left(\frac{f_c'}{4000}\right)^{2/3} \text{=(3.3/4)^(2/3)=0.88} \qquad \text{(10-8) [9]}$$

$$k_2 = \left(\frac{d_f - L_e}{d_f}\right) \text{= (33.5-2.0)/33.5=0.94} \qquad \text{(10-9) [B.10]}$$

$$\kappa_v = \frac{k_1 k_2 L_e}{468\varepsilon_{fu}} \le 0.75 \text{=0.88*0.94*2.0/(468*0.017)=0.208<0.75} \qquad \text{(10-10) [B.11]}$$

$$\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \le 0.004 \text{ = 0.208*0.017=0.0035} \qquad \text{(10-6b) [B.12]}$$

where n = number of FRP layers, t_f = FRP thickness, E_f = FRP elastic modulus, f_c' = concrete compression strength and d_f = depth of FRP reinforcement. Note that the environmental exposure factor (0.85 for bridges) is applied to the effective CFRP strain at the very end based on previous research (Higgins et al. 2009).

$$C_E \varepsilon_{fe} = 0.85*0.0035=0.0030<0.004 \qquad \text{(10-6b) [B.13]}$$

The effective stress, f_{fe}, is finally calculated from Eqn. 7 as 33,000*0.003=99 ksi.

For the negative moment region, d_{fv} is not well defined and was taken as the clear web distance (36 in for the present case) minus the distance to the compression steel (approximately 2.5 in.) =33.5 in. For the selected trial material, the effective stress was computed as 99 ksi. Rearranging the equation in terms of the stirrup quantity required of the CFRP the required, the strip spacing is computed as:

$$s_f = \frac{\psi A_{fv} f_{fe}}{SQb} = \text{(0.85*0.13*99000)/(57.5*14)=13.5 in. use 13 in.spacing} \qquad \text{[B.14]}$$

The required strip spacing was computed as 13 in. A check of the bond demand for the large expected demand on the CFRP due to flexural steel yielding (consider Figure B3). The shear stress expected on the CFRP is likely to be significantly larger than that predicted by ACI 440 given the nonlinear response of the section as the flexural steel begins to yield. In fact, for the present section, MCFT results indicate that the section cannot achieve the ACI 440 capacity as seen in Figure B6. This repair method may not be the most suitable for this section.

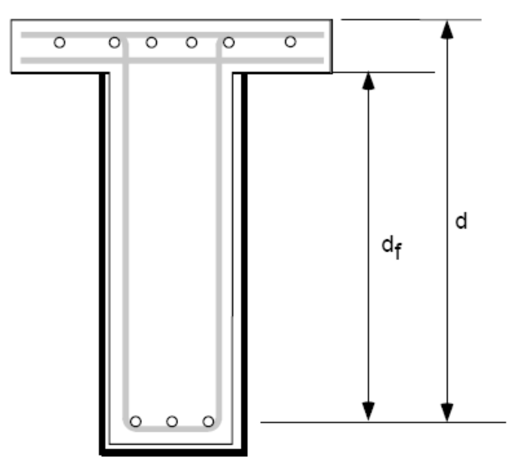


Figure B5: Graphical definition of d_f from ACI-440

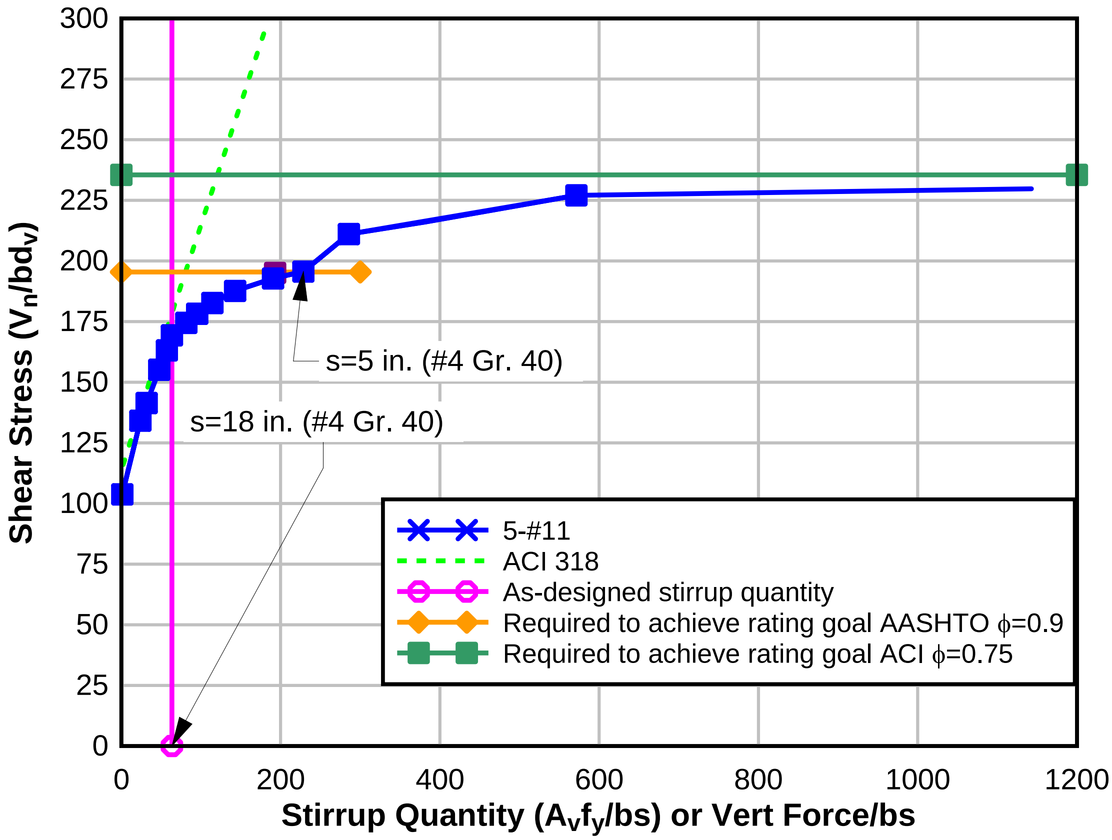


Figure B6: Repair design approach with ACI-440

ACI-440 limits the FRP strip spacing to the limits set forth in ACI-318 for the internal shear steel reinforcing. However, because of the typical debonding failures, additional detailing should be considered. A spacing that is based on CFRP strip width, the crack angle, and the web height is recommended that will ensure ***at least*** one strip crosses the diagonal crack with an anchorage length of ***at least*** one-half the height of the web. The maximum gap spacing between strips to ensure this condition is:

$$g = \frac{1}{2}\left(\frac{h_w}{\tan\theta} - 3w_f\right) = 0.5((42/\tan 45) - 3*10) = 6 \text{ in.} \qquad [B.15]$$

As the crack angle becomes smaller, the wider the gap is permitted to be between strips. For a 45° crack angle, the FRP strip spacing becomes:

$$s = \frac{1}{2}\left(h_w - w_f\right) = 0.5(42-10) = 16 \text{ in.} \qquad [B.16]$$

where g (in) = gap spacing between FRP strips, h_w (in) = height of the web, θ = crack angle, and w_f (in) = FRP strip width. The 13 in. spacing will provide a gap of 3 in., thus the above details are satisfied.

Finally, due to the increased capacity of the section, the flexural demands must also be checked to ensure anchorage demands will not be exceeded per AASHTO-LRFD section 5.8.3.5.