REPAIR AND STRENGTHENING OF BRIDGES IN INDIANA USING FIBER REINFORCED POLYMER SYSTEMS

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Lyles School of Civil Engineering

INTRODUCTION

CHRIS WILLIAMS, Ph.D.
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RESEARCH TEAM

Purdue Team

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Bobby Jacobs (HNTB)
Jon Pevey (Walter P Moore)

Study Advisory Committee

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INDOT

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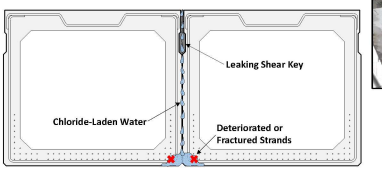
BACKGROUND AND MOTIVATION



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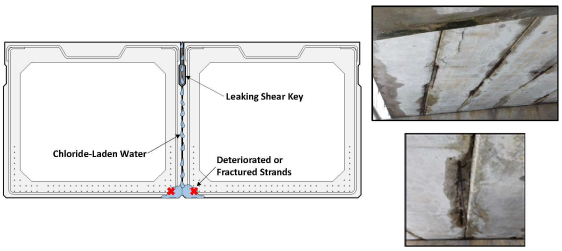
BACKGROUND AND MOTIVATION



Other Repair/Strengthening Applications

- Repair after vehicle impact
- Column confinement
- Other strength deficiencies (Shear/Flexure)
- Increase member stiffness

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OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Flexural Strengthening Experimental Program

End Region Repair Experimental Program

Key Considerations for Design & Implementation

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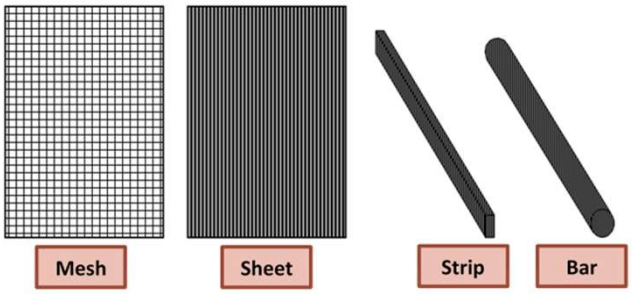
CONSTITUENT MATERIALS & PROPERTIES



Resins and Adhesives

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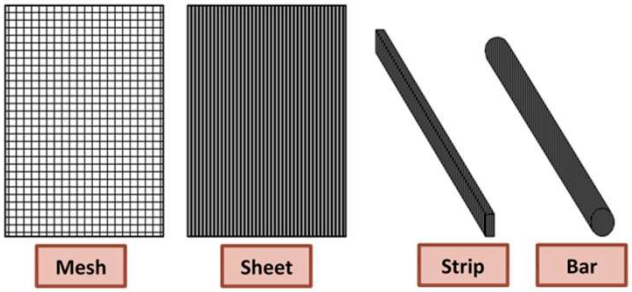
CONSTITUENT MATERIALS & PROPERTIES



FRP System (w/ epoxy)	Young's Modulus (ksi)	Ultimate Strength (ksi)	Rupture Strain
Carbon (high-strength)	15,000 - 21,000	150 - 350	0.010 - 0.015
Glass (E-glass)	3000 - 6000	75 - 200	0.015 - 0.030
Aramid (high-performance)	7000 - 10,000	100 - 250	0.020 - 0.030
Fiber volume fraction of the laminates shown is about 40-60%			

Adapted from ACI 440.2R-17, as presented in Kim et al. (2012)

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TYPES OF FRP REPAIR/STRENGTHENING SYSTEMS

Externally Bonded

Sheets

Near-Surface-Mounted (NSM)

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EXTERNALLY BONDED FRP INSTALLATION

1. Surface Preparation

2. Round Edges

3a. Seal Surface

3b. Saturate FRP

3c. Place FRP

3d. Roll FRP

3e. Squeegee FRP

3f. Insert FRP Anchor

3g. Fan FRP Anchors

3h. Apply FRP Patches

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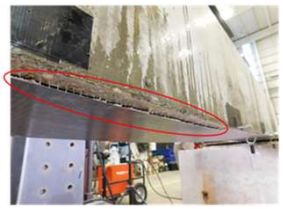
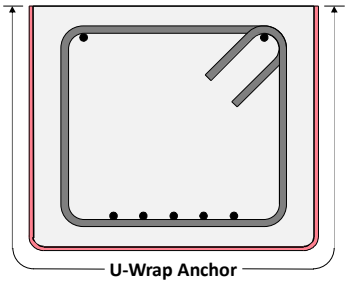
FRP ANCHORAGE

- Externally Bonded Sheets
  - Contact Critical
  - Bond Critical
- Common Anchorage Techniques Using FRP
  - U-Wrap Anchors





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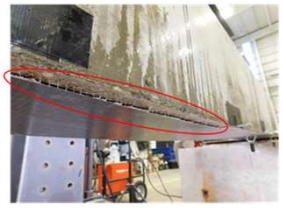
FRP ANCHORAGE

- Externally Bonded Sheets
  - Contact Critical
  - Bond Critical
- Common Anchorage Techniques Using FRP
  - U-Wrap Anchors
  - Spike Anchors
- Metallic Anchors



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TYPES OF FRP REPAIR/STRENGTHENING SYSTEMS

Externally Bonded →

Near-Surface-Mounted (NSM)

Bars or Strips →

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NEAR-SURFACE-MOUNTED (NSM) FRP INSTALLATION

1. Cut Grooves

2. Partially Fill Groove

3. Insert Strip

4. Fill Groove and Level

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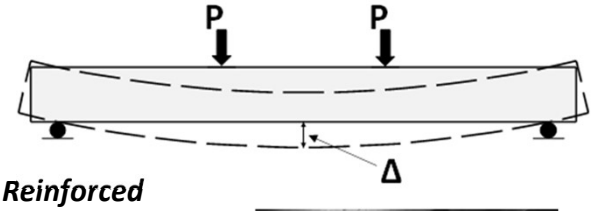
OUTLINE

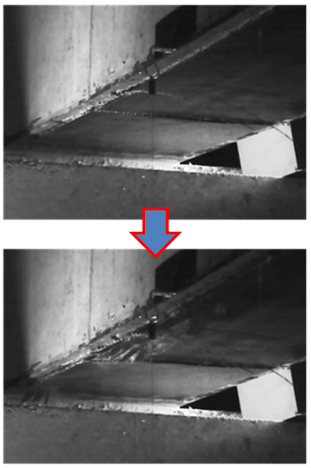


Introduction to Fiber Reinforced Polymer (FRP) Systems

Flexural Strengthening Experimental Program

End Region Repair Experimental Program

Key Considerations for Design & Implementation



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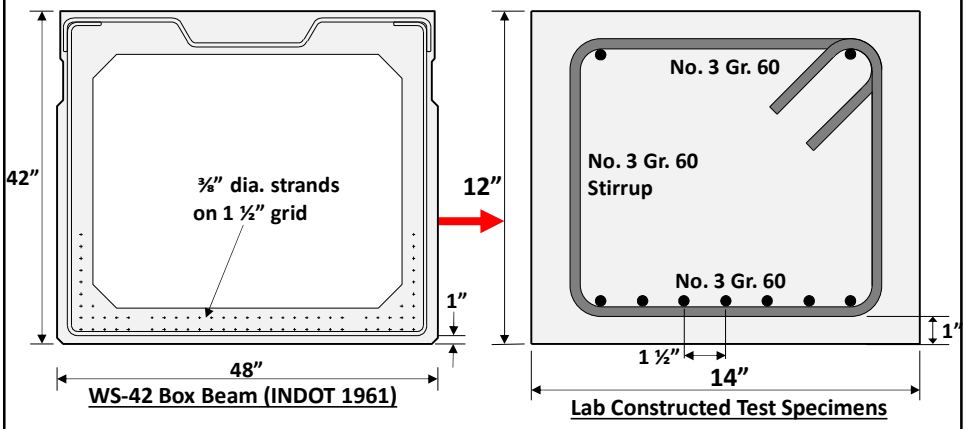
SPECIMEN DESIGN



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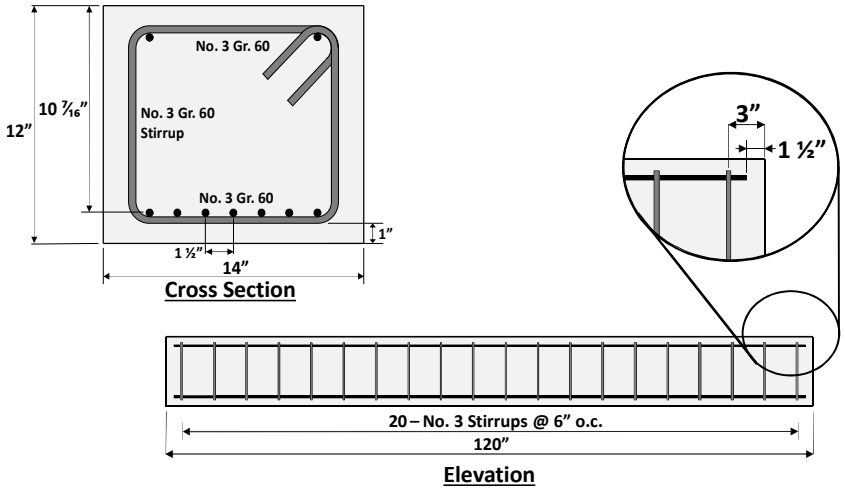
SPECIMEN DESIGN



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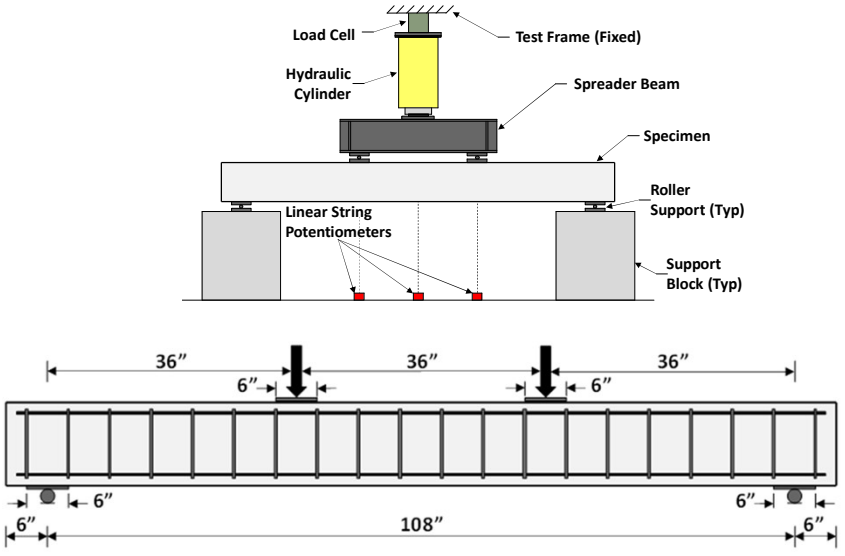
TEST SETUP



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TEST MATRIX

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	No FRP
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			
2	2-C	■										■
	2-D			■								
	2-EB.1			■		■						
	2-EB.2			■			■					
	2-NSM.1			■					■			
3	3-C	■										■
	3-D				■							
	3-EB.1				■	■						
	3-EB.2				■		■					
	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

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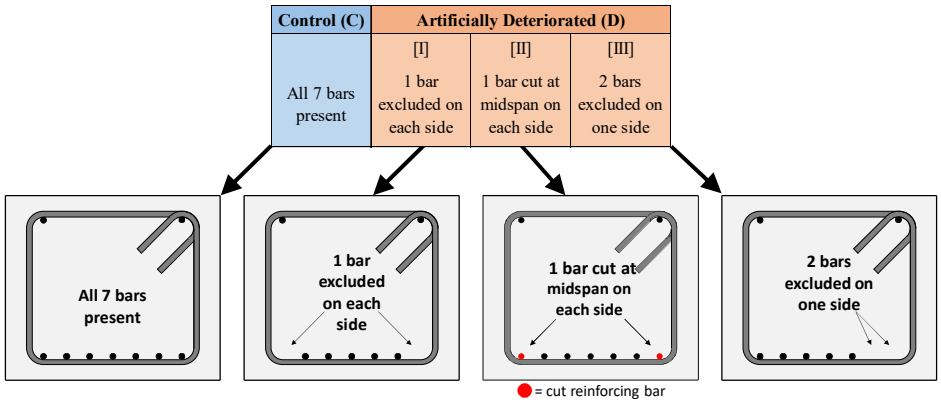
SIMULATED FIELD CONDITIONS



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TEST MATRIX

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			
2	2-C	■										■
	2-D			■								
	2-EB.1			■		■						
	2-EB.2			■			■					
	2-NSM.1			■					■			
3	3-C	■										■
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	3-EB.1				■	■						
	3-EB.2				■		■					
	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

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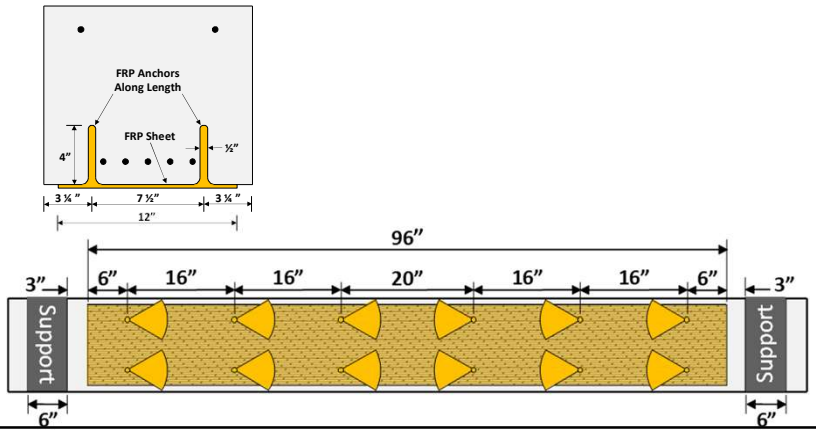
EXTERNALLY BONDED (EB) FRP SHEETS

Externally Bonded Sheet (EB)		
[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends



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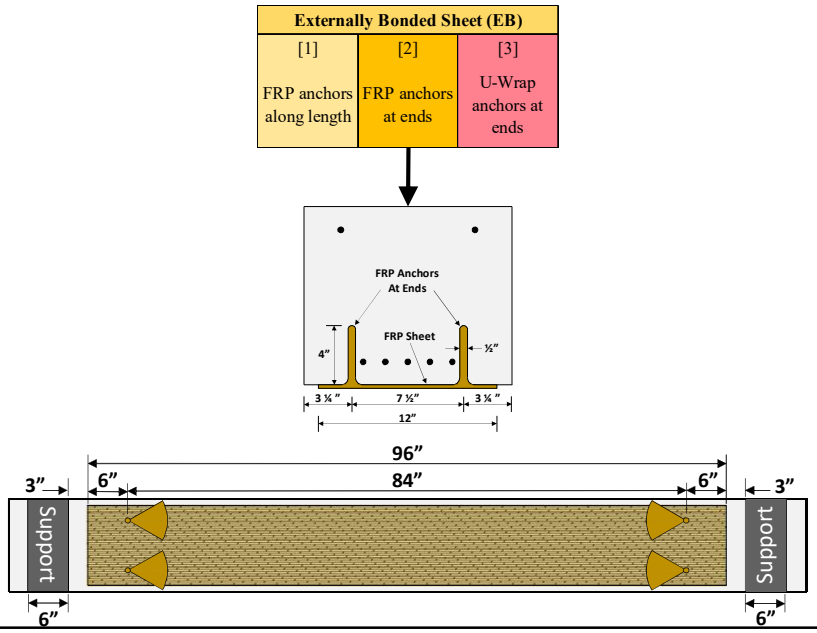
EXTERNALLY BONDED (EB) FRP SHEETS



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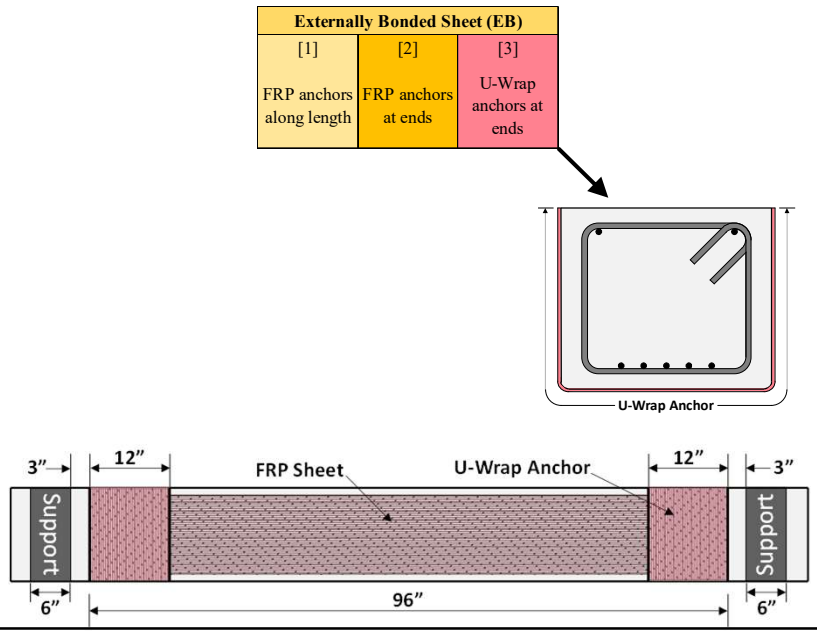
EXTERNALLY BONDED (EB) FRP SHEETS



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TEST MATRIX

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	No FRP
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			
2	2-C	■										■
	2-D			■								
	2-EB.1			■		■						
	2-EB.2			■			■					
	2-NSM.1			■					■			
3	3-C	■										■
	3-D				■							
	3-EB.1				■	■						
	3-EB.2				■		■					
	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

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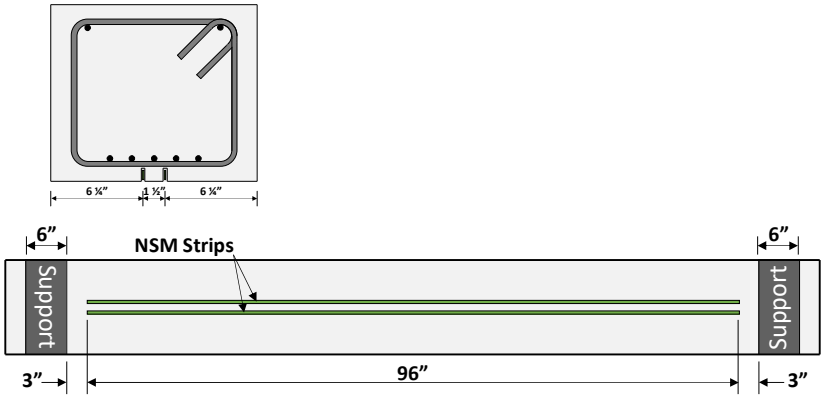
NEAR-SURFACE-MOUNTED (NSM) FRP

Near-Surface-Mounted Strips (NSM)		
[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars



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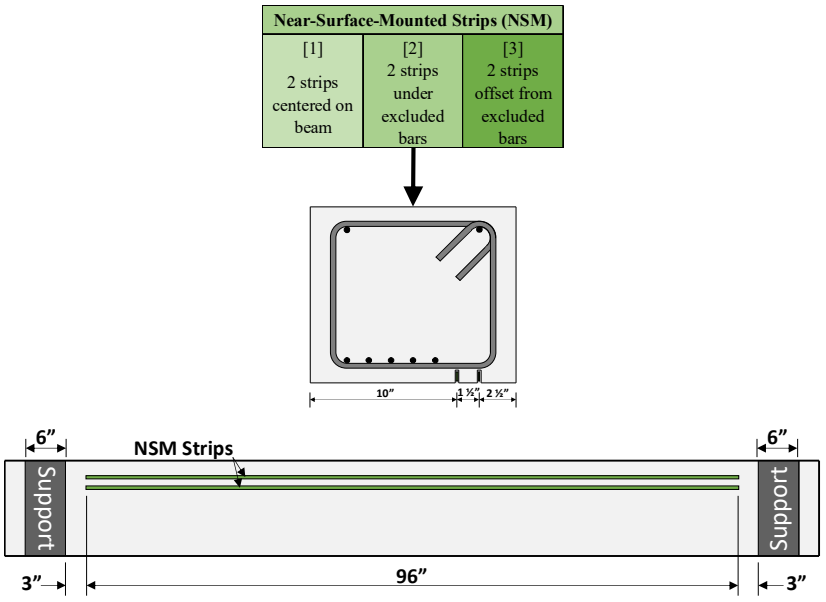
NEAR-SURFACE-MOUNTED (NSM) FRP



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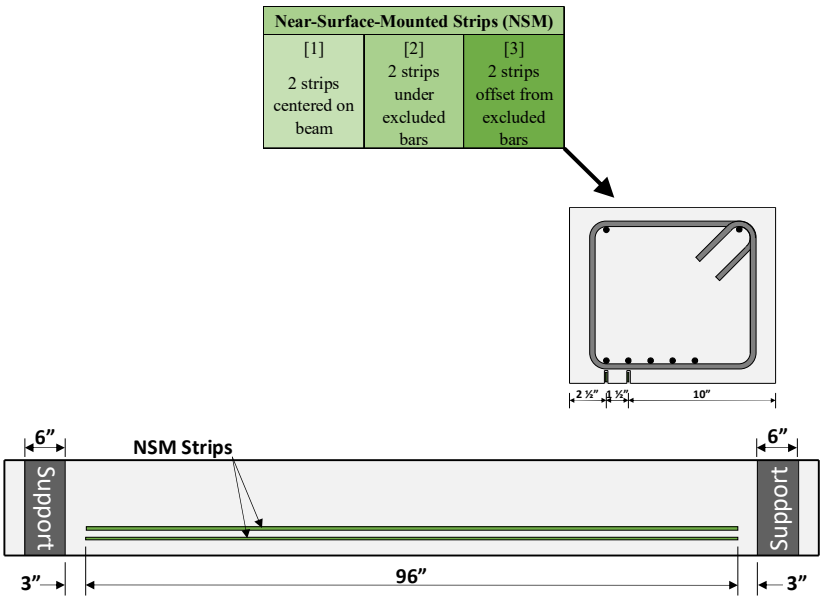
NEAR-SURFACE-MOUNTED (NSM) FRP



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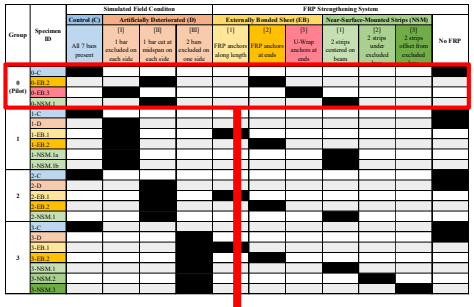
TEST RESULTS – PILOT GROUP

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			
2	2-C	■										■
	2-D			■								
	2-EB.1			■		■						
	2-EB.2			■			■					
	2-NSM.1			■					■			
3	3-C	■										■
	3-D				■							
	3-EB.1				■	■						
	3-EB.2				■		■					
	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

TEST RESULTS – PILOT GROUP



Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
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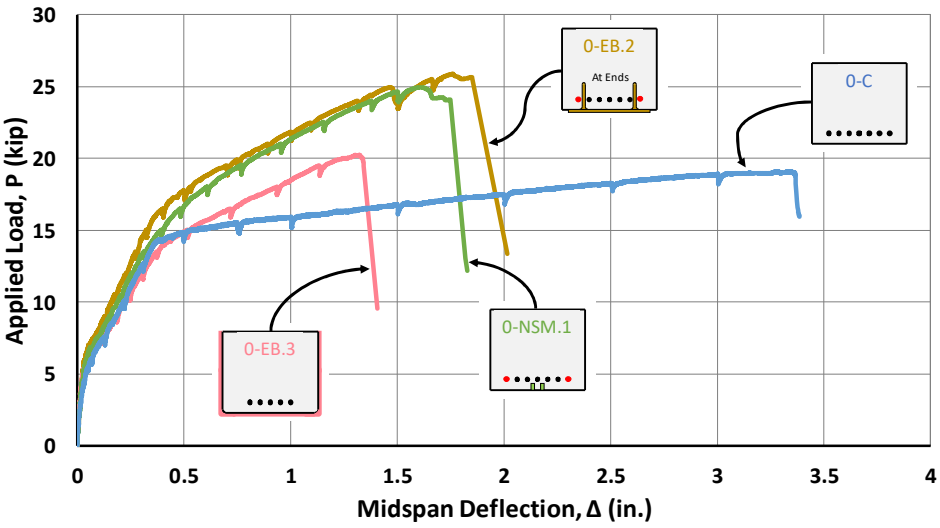
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			

TEST RESULTS – PILOT GROUP



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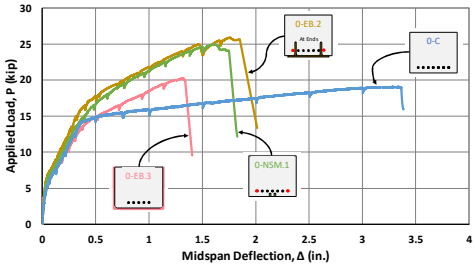
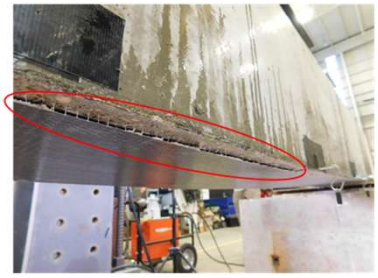
TEST RESULTS – PILOT GROUP





Key Results

- U-wrap anchorage system replaced with spike anchors installed along the length of sheet
  - Based on performance/behavior and limitations for adjacent box beams
  - Local debonding along the edge of the FRP sheet

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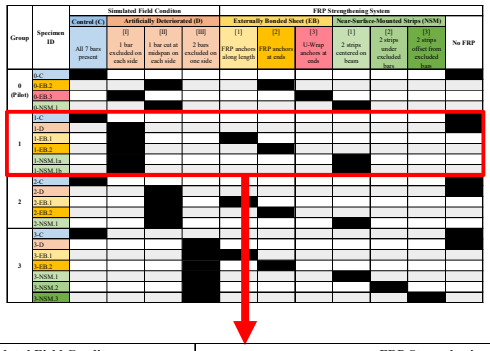
TEST RESULTS – GROUP 1

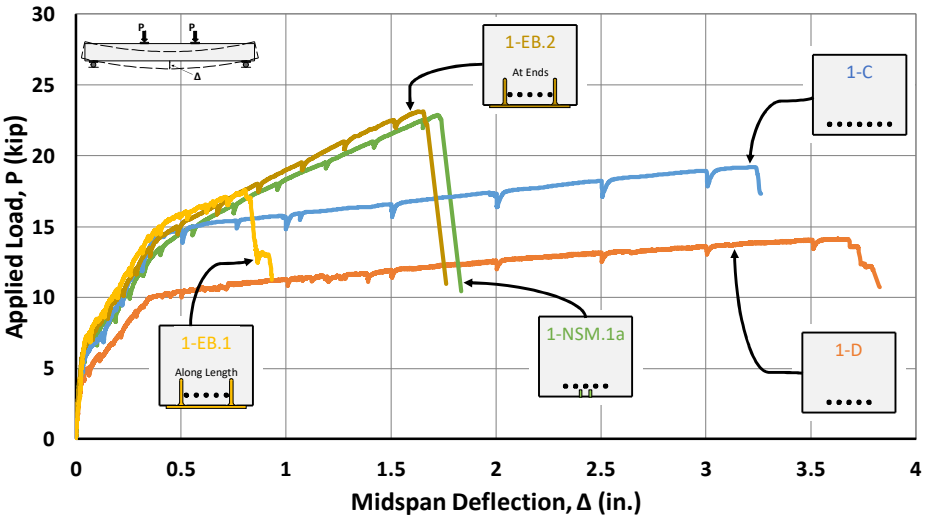
Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	No FRP
0 (Pilot)	0-C	■										■
	0-EB.2			■			■					
	0-EB.3		■					■				
	0-NSM.1			■					■			
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			
2	2-C	■										■
	2-D			■								
	2-EB.1			■		■						
	2-EB.2			■			■					
	2-NSM.1			■					■			
3	3-C	■										■
	3-D				■							
	3-EB.1				■	■						
	3-EB.2				■		■					
	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

TEST RESULTS – GROUP 1



Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	No FRP
1	1-C	■										■
	1-D		■									
	1-EB.1		■			■						
	1-EB.2		■				■					
	1-NSM.1a		■						■			
	1-NSM.1b		■						■			

TEST RESULTS – GROUP 1



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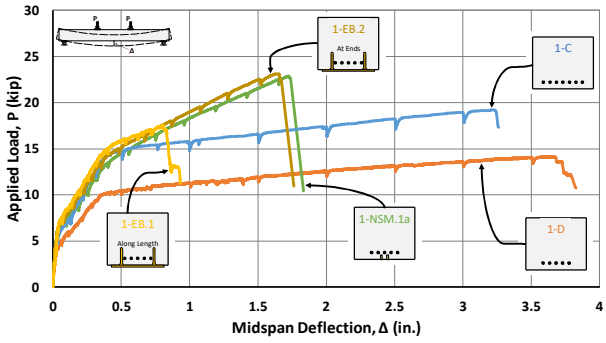
TEST RESULTS – GROUP 1



Key Results

- Strengths of Spec. 1-EB.2 & 1-NSM.1a exceed control
- Stiffness restored (before yielding of steel)
- Decreased ductility; increased post-yielding stiffness
- Experimental strengths exceed calculated strengths

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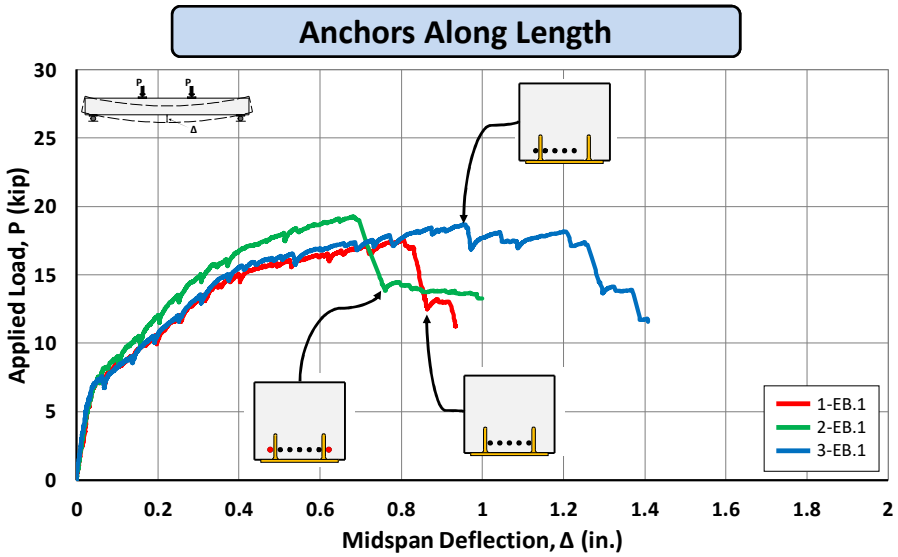
TEST RESULTS – EXTERNALLY BONDED (EB) SPECIMENS

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	
1	1-EB.1		■			■						
2	2-EB.1			■		■						
3	3-EB.1				■	■						

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors at ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	
0	0-EB.2			■			■					
1	1-EB.2		■				■					
2	2-EB.2			■			■					
3	3-EB.2				■		■					

37

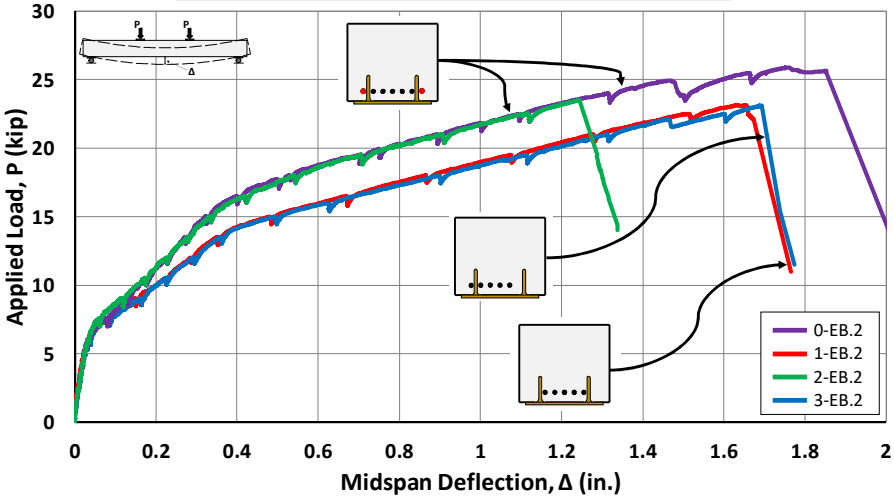
TEST RESULTS – EXTERNALLY BONDED (EB) SPECIMENS



38

TEST RESULTS – EXTERNALLY BONDED (EB) SPECIMENS

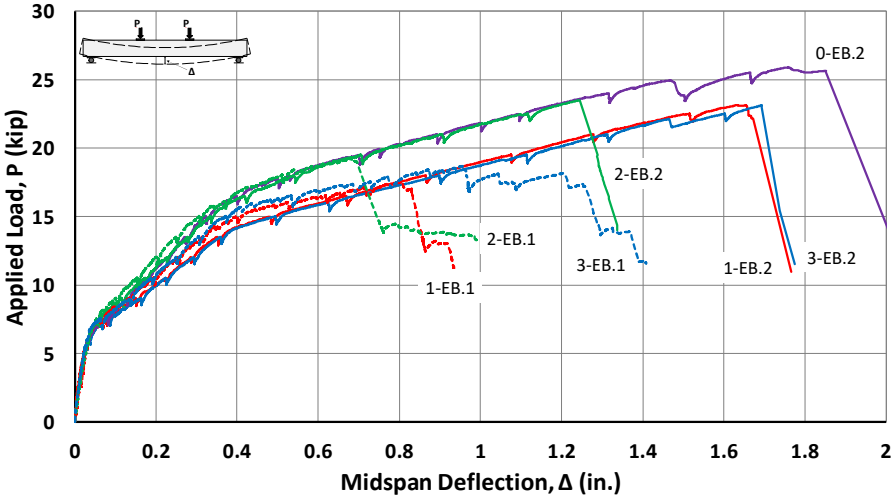
Anchors Along Length



39

TEST RESULTS – EXTERNALLY BONDED (EB) SPECIMENS

All Externally Bonded Specimens



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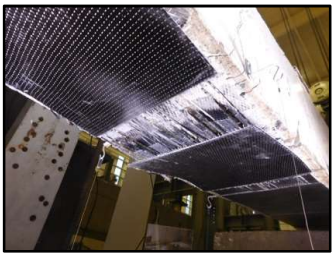
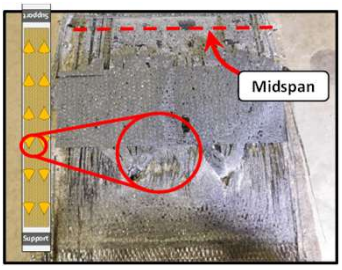
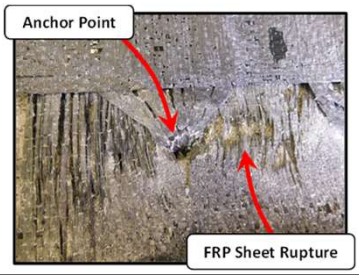
TEST RESULTS – EXTERNALLY BONDED (EB) SPECIMENS

Premature Rupture Near Anchor







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TEST RESULTS – NEAR-SURFACE-MOUNTED (NSM) SPECIMENS

Group	Specimen ID	Simulated Field Conditon				FRP Strengthening System						
		Control (C)	Artificially Deteriorated (D)			Externally Bonded Sheet (EB)			Near-Surface-Mounted Strips (NSM)			No FRP
		All 7 bars present	[I] 1 bar excluded on each side	[II] 1 bar cut at midspan on each side	[III] 2 bars excluded on one side	[1] FRP anchors along length	[2] FRP anchors at ends	[3] U-Wrap anchors a ends	[1] 2 strips centered on beam	[2] 2 strips under excluded bars	[3] 2 strips offset from excluded bars	
0	0-NSM.1			■					■			
1	1-NSM.1a		■						■			
	1-NSM.1b								■			
2	2-NSM.1			■					■			
3	3-NSM.1				■				■			
	3-NSM.2				■					■		
	3-NSM.3				■						■	

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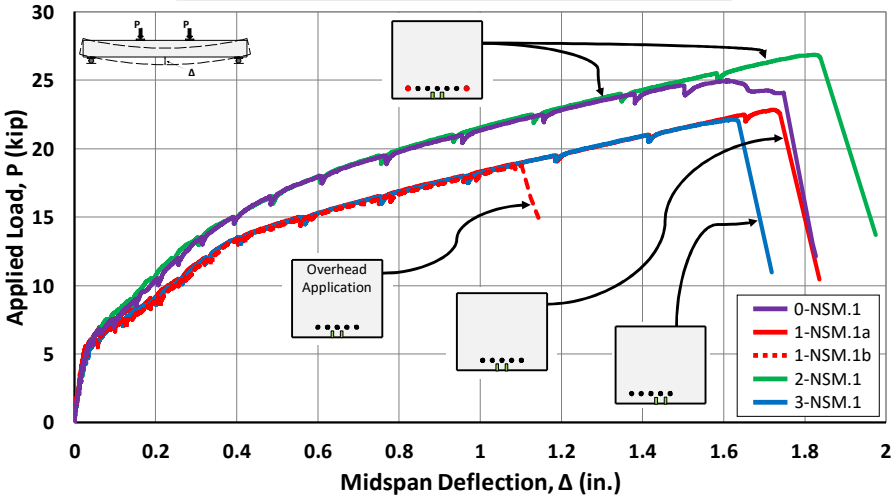
TEST RESULTS – NEAR-SURFACE-MOUNTED (NSM) SPECIMENS

Centered NSM Strips



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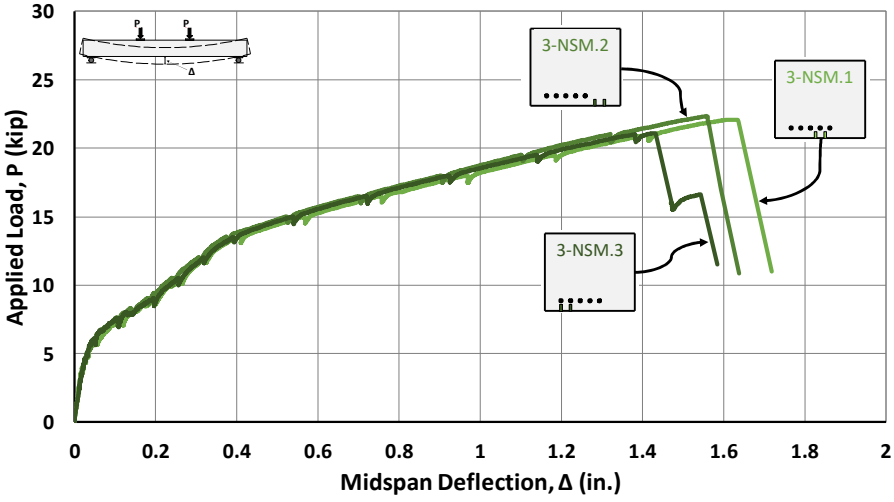
TEST RESULTS – NEAR-SURFACE-MOUNTED (NSM) SPECIMENS

Effect of Eccentricity



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TEST RESULTS – NEAR-SURFACE-MOUNTED (NSM) SPECIMENS

Overhead Application

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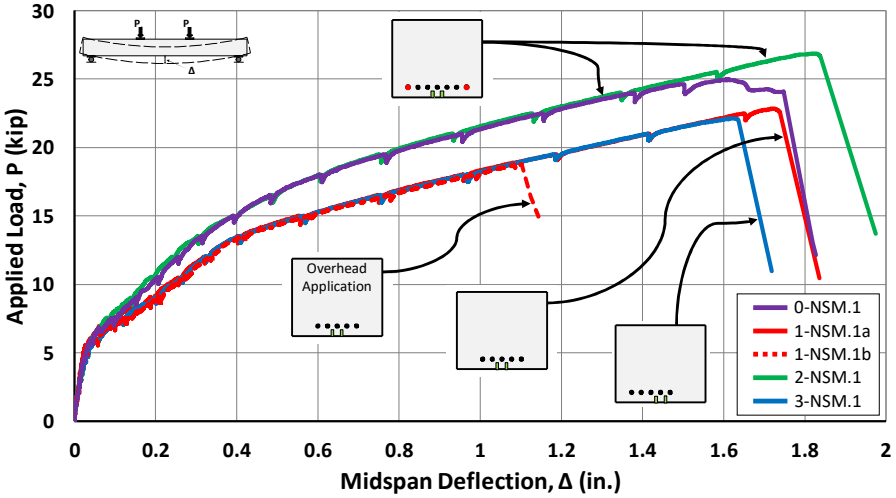
TEST RESULTS – NEAR-SURFACE-MOUNTED (NSM) SPECIMENS

Overhead Application



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EXPERIMENTAL PROGRAM CONCLUSIONS

Externally Bonded and NSM systems are suitable for flexural strengthening. Reduced ductility and importance of bond should be noted.

FRP spike anchors should not be placed along the length of the FRP sheet; place at the ends of the FRP sheet and avoid regions of high moment demand.

Eccentricity of the longitudinal steel and relative placement of NSM strips did not play a significant role in the effectiveness of the system.

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OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Flexural Strengthening Experimental Program

End Region Repair Experimental Program

Key Considerations for Design & Implementation

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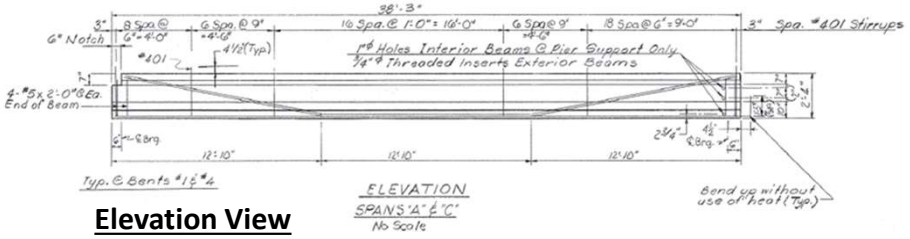
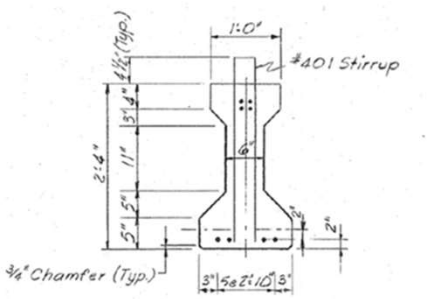
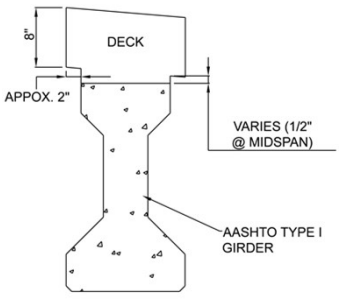
SPECIMEN BACKGROUND



Elevation View



Cross Section at Original Supports



Cross Section of Test Specimens

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GIRDER CONDITION (AS RECEIVED)

Girder	End Region Condition	Repair Technique
3-C	Good	Control
20-C	Deteriorated	Tested in Deteriorated Condition
19-A	Deteriorated	Externally Bonded FRP
17-C	Deteriorated	NSM FRP

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GIRDER CONDITION

3-C

20-C

19-A

17-C

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REPAIR PROCEDURE

1. Remove Unsound Concrete

2. Sandblast

3. Condition After Sandblasting

4. Restore Cross Section

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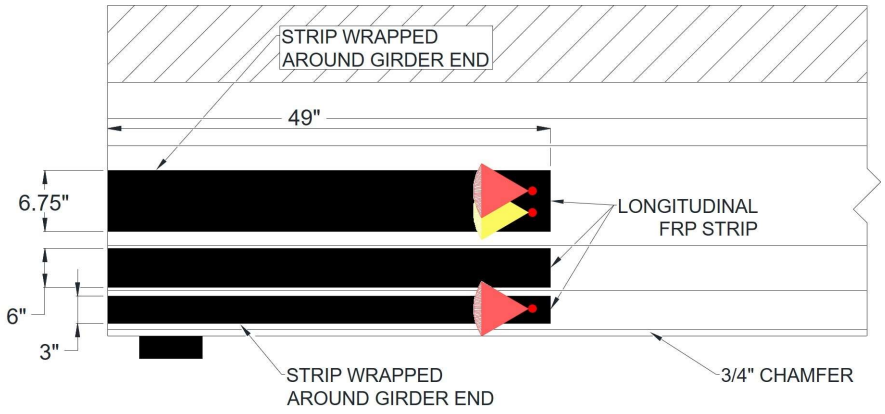
EXTERNALLY BONDED (EB) FRP SHEETS

Elevation View: Layer 1



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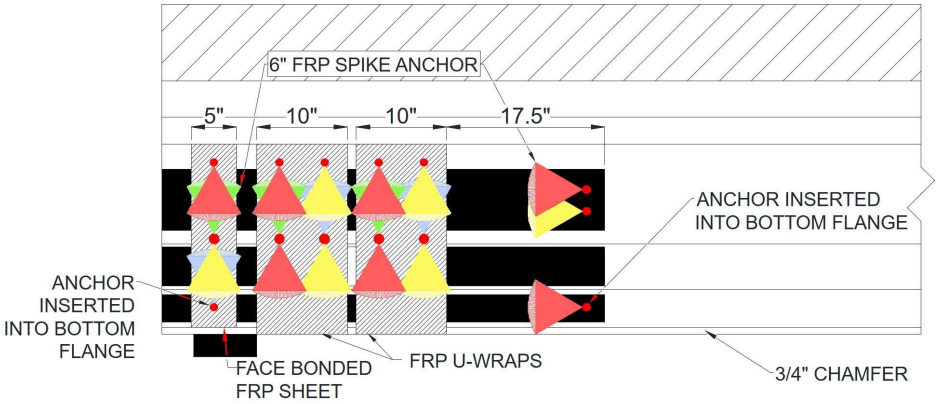
EXTERNALLY BONDED (EB) FRP SHEETS

Elevation View: Layer 2



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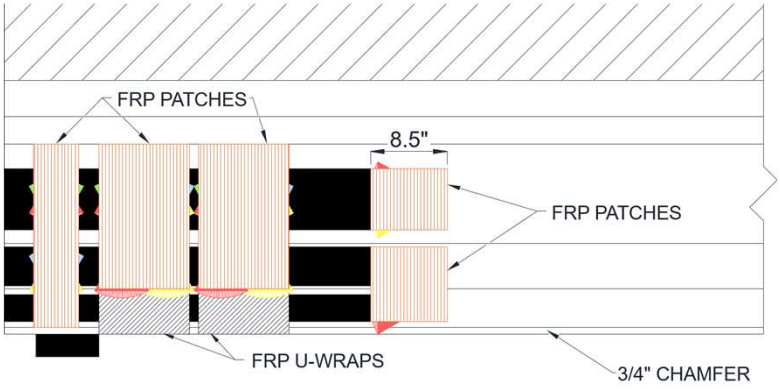
EXTERNALLY BONDED (EB) FRP SHEETS

Elevation View: Layer 3



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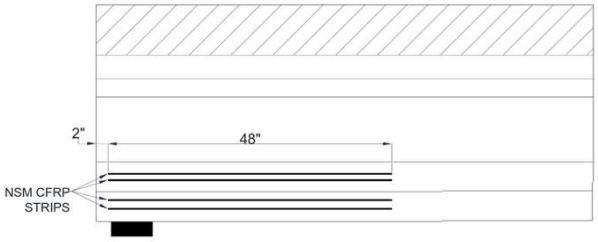
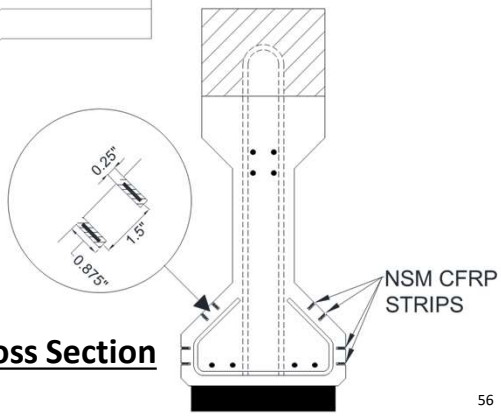
NEAR-SURFACE-MOUNTED (NSM) FRP STRIPS



Elevation View



Cross Section

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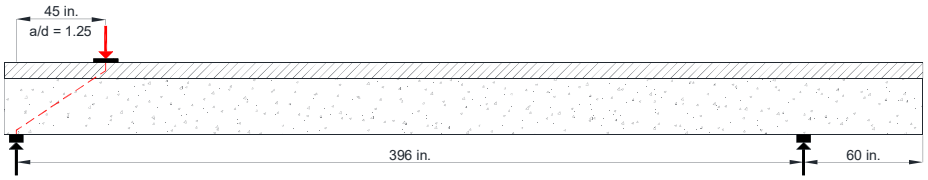
TEST SETUP



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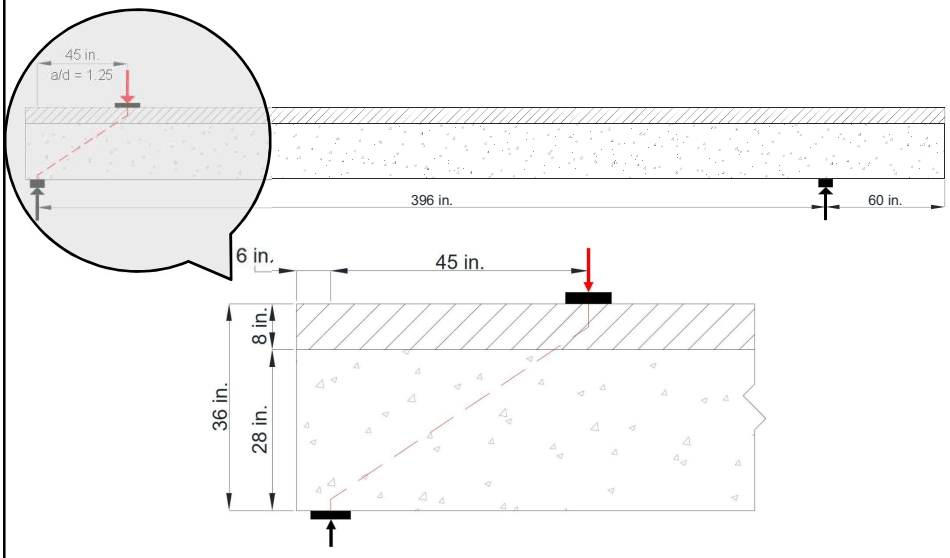
TEST SETUP



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TEST MATRIX

Girder	End Region Condition	Repair Technique
3-C	Good	Control
20-C	Deteriorated	Tested in Deteriorated Condition
19-A	Deteriorated	Externally Bonded FRP
17-C	Deteriorated	NSM FRP

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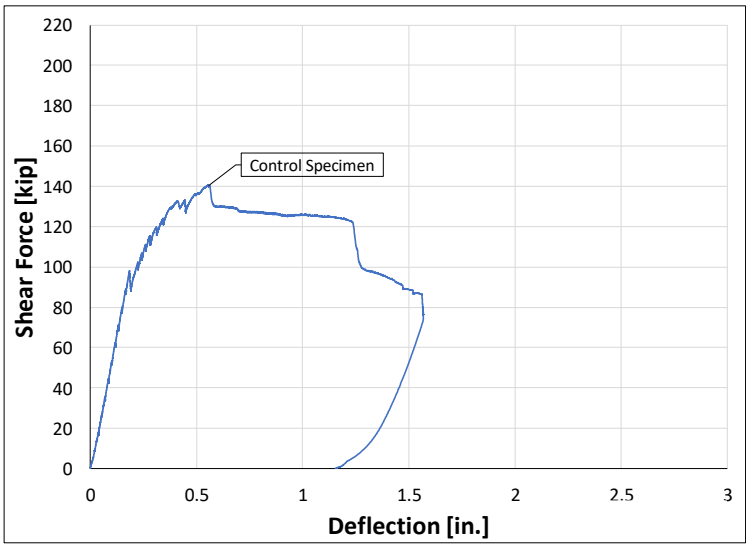
TEST RESULTS – CONTROL



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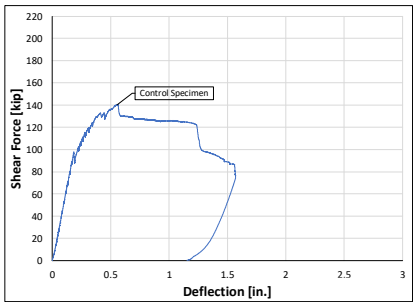
TEST RESULTS – CONTROL



Observations

- Peak Shear = 141 kips
- Failure controlled by the formation of a diagonal strut.
- No abrupt drop in load.
- Slip of prestressing strands in the bottom flange.

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TEST MATRIX

Girder	End Region Condition	Repair Technique
3-C	Good	Control
20-C	Deteriorated	Tested in Deteriorated Condition
19-A	Deteriorated	Externally Bonded FRP
17-C	Deteriorated	NSM FRP

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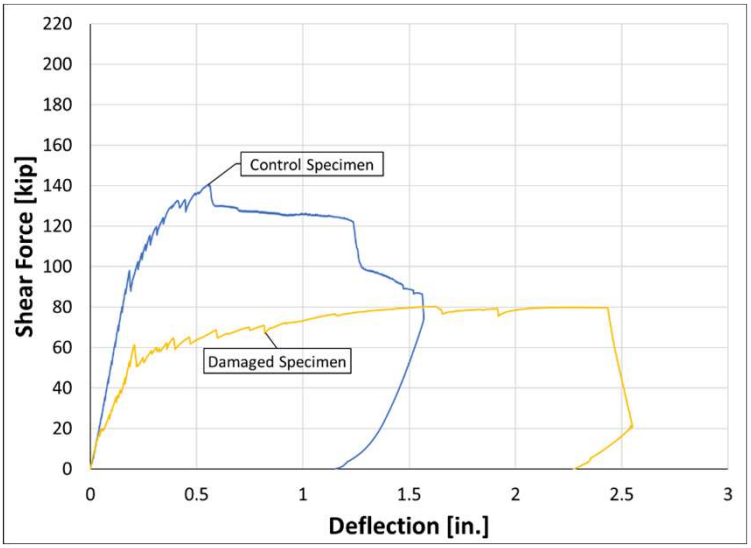
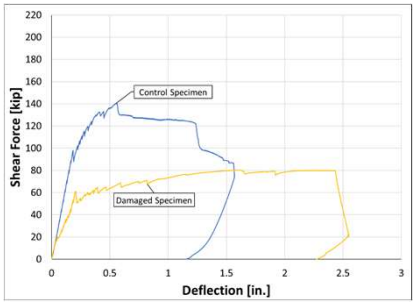
TEST RESULTS – TESTED IN DAMAGED STATE



63

TEST RESULTS – TESTED IN DAMAGED STATE

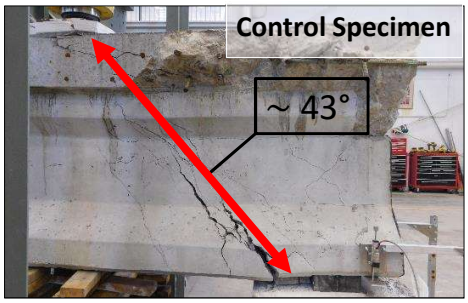


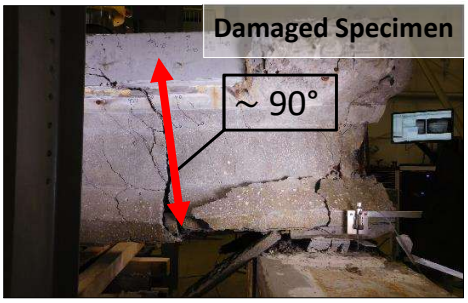
Observations

- $V_{test}/V_{control} = 0.57$

64

TEST RESULTS – TESTED IN DAMAGED STATE





Observations

- $V_{test}/V_{control}$ = 0.57
- Different failure mechanism.
- The crack angle increased to nearly 90°.

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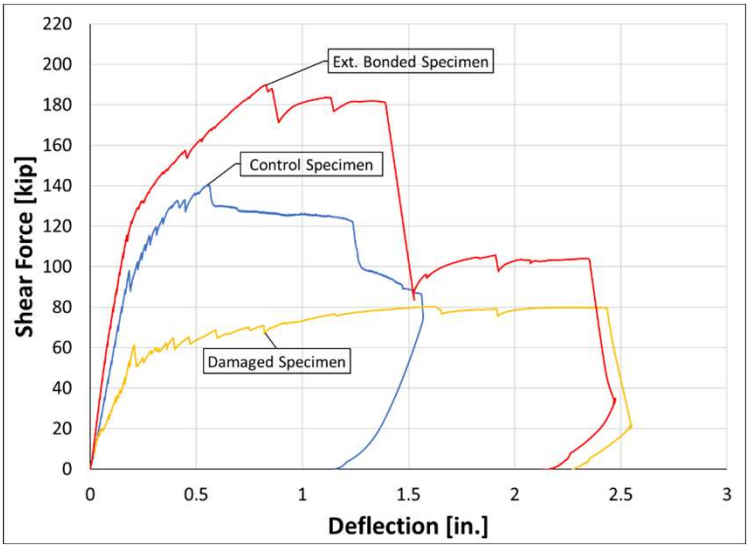
TEST MATRIX

Girder	End Region Condition	Repair Technique
3-C	Good	Control
20-C	Deteriorated	Tested in Deteriorated Condition
19-A	Deteriorated	Externally Bonded FRP
17-C	Deteriorated	NSM FRP

66

TEST RESULTS – EXTERNALLY BONDED



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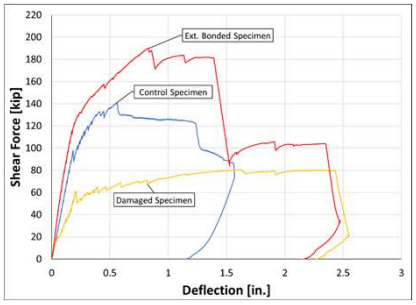
TEST RESULTS – EXTERNALLY BONDED



Observations

- $V_{test}/V_{control}$ = 1.34
- Increased stiffness.
- Flexural failure at the end of the repair → strand fracture.

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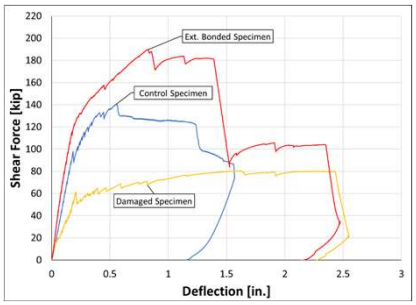
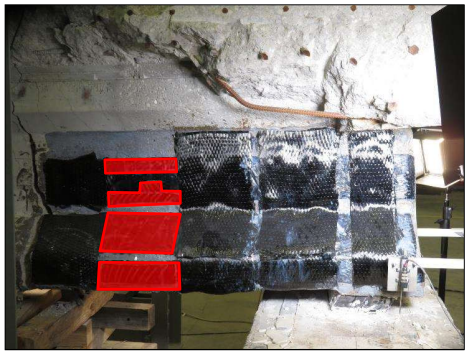
TEST RESULTS – EXTERNALLY BONDED





Observations

- $V_{test}/V_{control}$ = 1.34
- Increased stiffness.
- Flexural failure at the end of the repair → strand fracture.
- Minimal delamination of the FRP was observed.

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TEST MATRIX

Girder	End Region Condition	Repair Technique
3-C	Good	Control
20-C	Deteriorated	Tested in Deteriorated Condition
19-A	Deteriorated	Externally Bonded FRP
17-C	Deteriorated	NSM FRP

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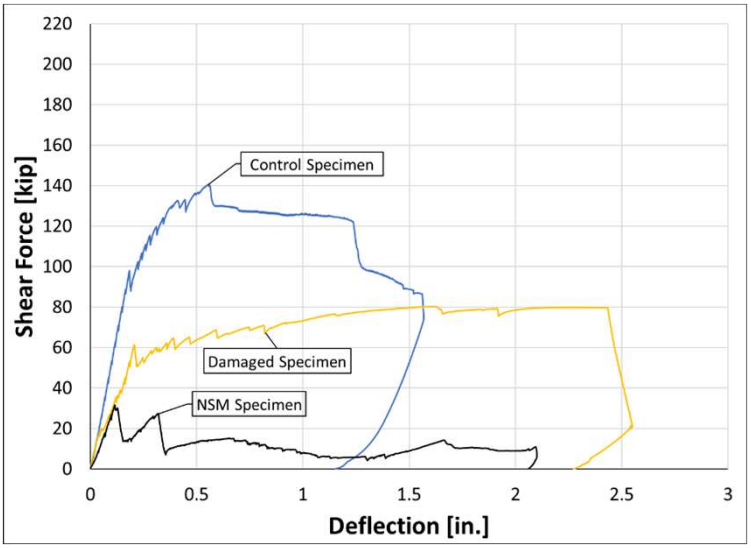
TEST RESULTS – NSM



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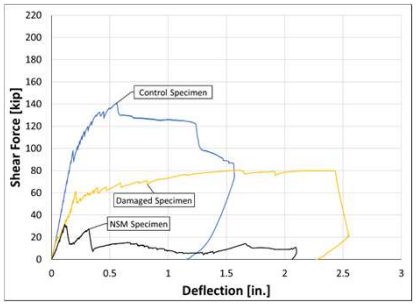
TEST RESULTS – NSM



Observations

- $V_{test}/V_{control}$ = 0.22
- Similar initial stiffness to damaged specimen.

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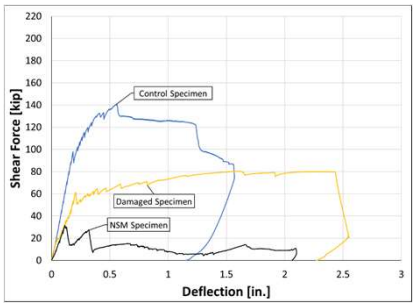
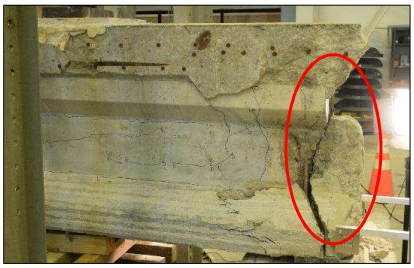
TEST RESULTS – NSM





Observations

- $V_{test}/V_{control}$ = 0.22
- Similar initial stiffness to damaged specimen.
- Cracking/splitting at the notch above the bearing location.

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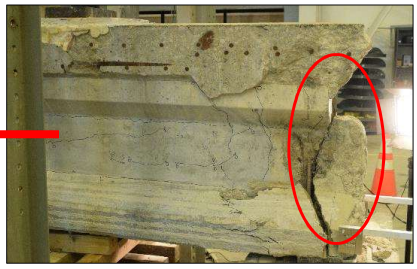
TEST RESULTS – NSM



Observations

- $V_{test}/V_{control}$ = 0.22
- Similar initial stiffness to damaged specimen.
- Cracking/splitting at the notch above the bearing location.
- Bottom flange separated from the web.

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EXPERIMENTAL PROGRAM CONCLUSIONS

Restoring the tensile capacity lost due to deteriorated prestressing strands is critical.

Ensuring adequate confinement of the repair region is critical.

The externally bonded system is a viable repair option.

The NSM system did not perform adequately. A hybrid system using both NSM and externally bonded elements may be a viable repair solution.

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OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Flexural Strengthening Experimental Program

End Region Repair Experimental Program

Key Considerations for Design & Implementation

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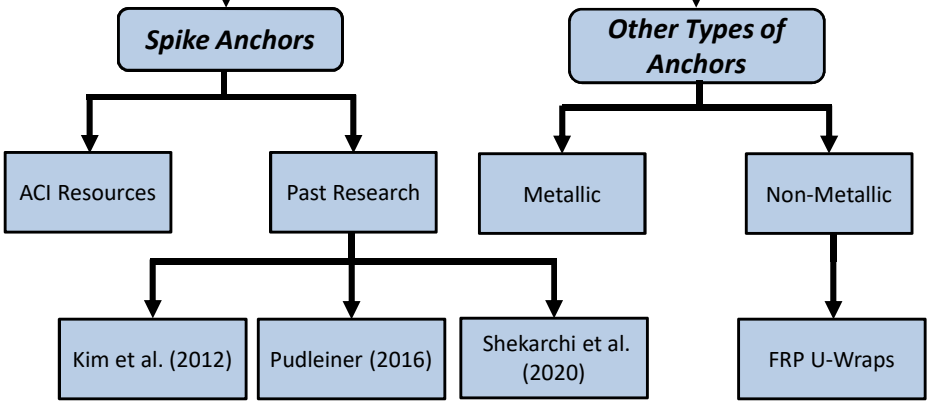
KEY DESIGN CONSIDERATIONS

Proper Anchorage of Externally Bonded FRP is Critical



KEY DESIGN CONSIDERATIONS

Only Restoring A Member's Cross Section with a Repair Material is Insufficient

A Mock-Up is Recommended for Complicated Cases

Comprehensive Guides are Available:

- AASHTO: *Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements*

- ACI: 440R-07 & 440.2R-17

- ICRI: 310R-2008, 310.2R, & 330.2

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Thank You!

Questions?

PURDUE UNIVERSITY
Lyles School of Civil Engineering

JTRP

INDIANA DEPARTMENT OF TRANSPORTATION
INDOT

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Shekarchi, W. A, Pudleiner, D. K., Alotaibi, N. K., Ghannoum, W. M., & Jirsa, J. O. (2020) *Carbon Fiber-Reinforced Polymer Spike Anchor Design Recommendations.* ACI Structural Journal, Nov. 117(6), 171-182. doi: 10.14359/51728065