FIBER WRAP FOR BEAM END REPAIR

CHRIS WILLIAMS, Ph.D.
Assistant Professor of Civil Engineering
Purdue University

February 22, 2022

PURDUE UNIVERSITY
Lyles School of Civil Engineering

1

RESEARCH TEAM

Purdue Team
Chris Williams, Ph.D.
Robert Frosch, Ph.D.
William Rich
Bobby Jacobs
Jon Pevey

Study Advisory Committee
Jeremy Hunter, INDOT
Prince Baah, INDOT
Jennifer Hart, INDOT
Greg Klevitsky, INDOT
Jose Ortiz, FHWA
Stephanie Wagner, INDOT
Peter White, INDOT

Special Thanks to Will Rich for Slide Contents

PURDUE UNIVERSITY
Lyles School of Civil Engineering

2

2

OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Background to Problem of End Region Deterioration

End Region Repair Experimental Program

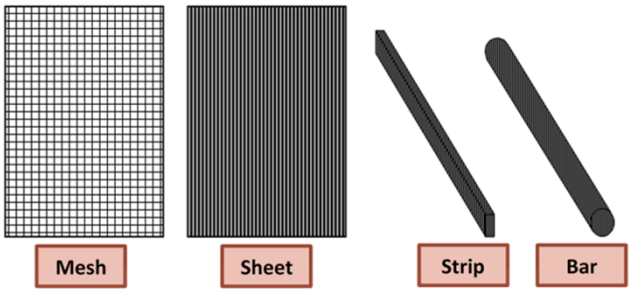
FRP Application AND Key Considerations for Design & Implementation

Other Resources

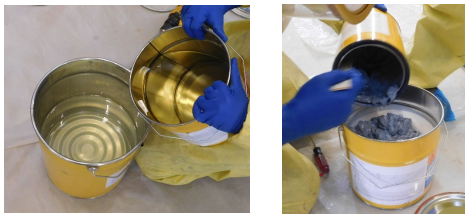
3

3

CONSTITUENT MATERIALS & PROPERTIES



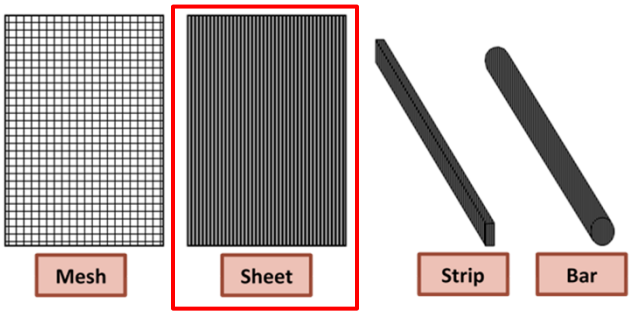
Resins and Adhesives



4

4

CONSTITUENT MATERIALS & PROPERTIES



Common Fiber Materials

Carbon
Glass
Aramid

See ACI 440.2R-17 for typical material properties.

5

5

TYPES OF COMMON FRP REPAIR/STRENGTHENING SYSTEMS

Externally Bonded

Sheets (Typical)

Near-Surface-Mounted (NSM)

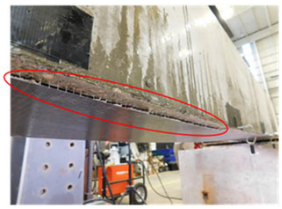
Bars or Strips

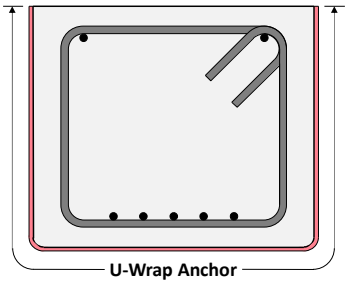
6

6

ANCHORAGE FOR EXTERNALLY BONDED FRP

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



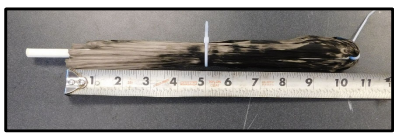


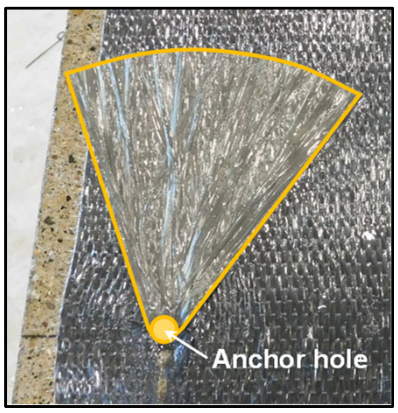
7

7

EXTERNALLY BONDED FRP DETAILS

FRP Spike Anchors

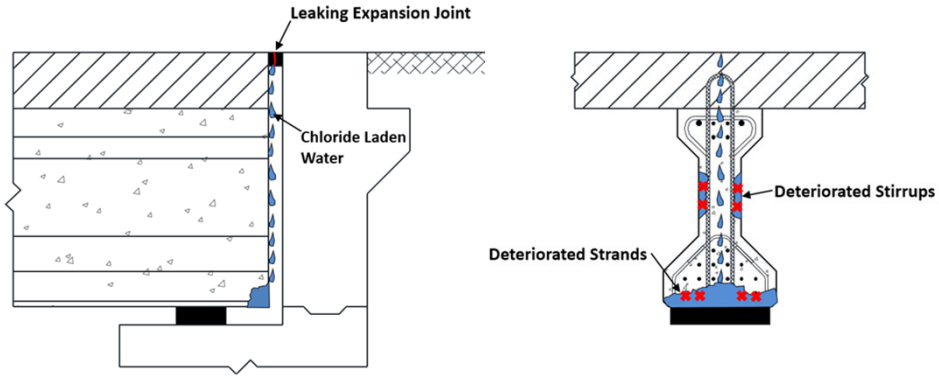




8

8

BACKGROUND AND MOTIVATION



9

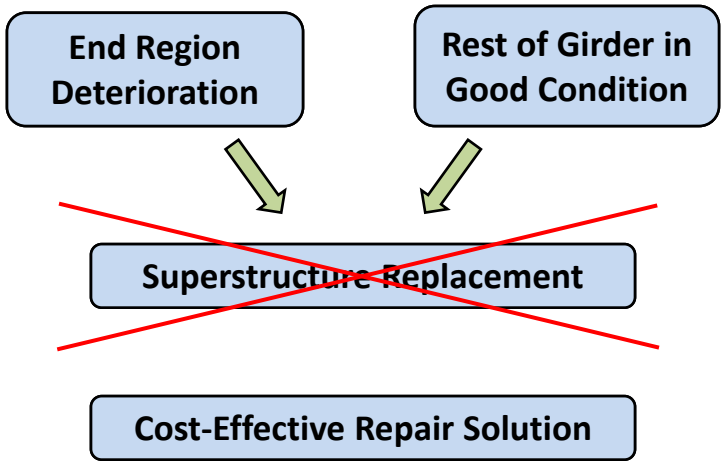
9

BACKGROUND AND MOTIVATION

10

10

BACKGROUND AND MOTIVATION



11

11

OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Background to Problem of End Region Deterioration

End Region Repair Experimental Program

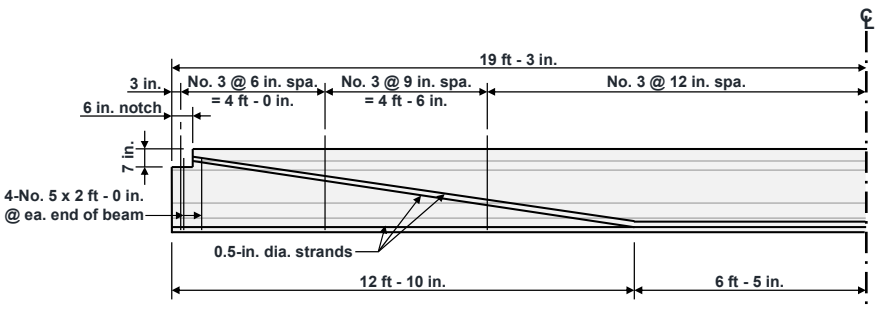
FRP Application AND Key Considerations for Design & Implementation

Other Resources

12

12

SPECIMEN BACKGROUND



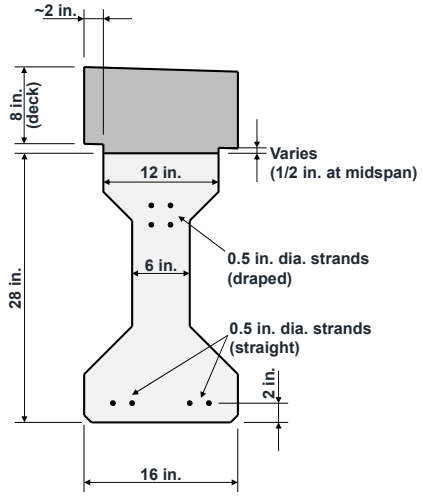
Elevation

Based on Bridge Drawings
(Indiana Department of Highways 1987)

13

13

SPECIMEN BACKGROUND



Cross Section

Based on Bridge Drawings
(Indiana Department of Highways 1987)

14

14

SPECIMEN DETAILS

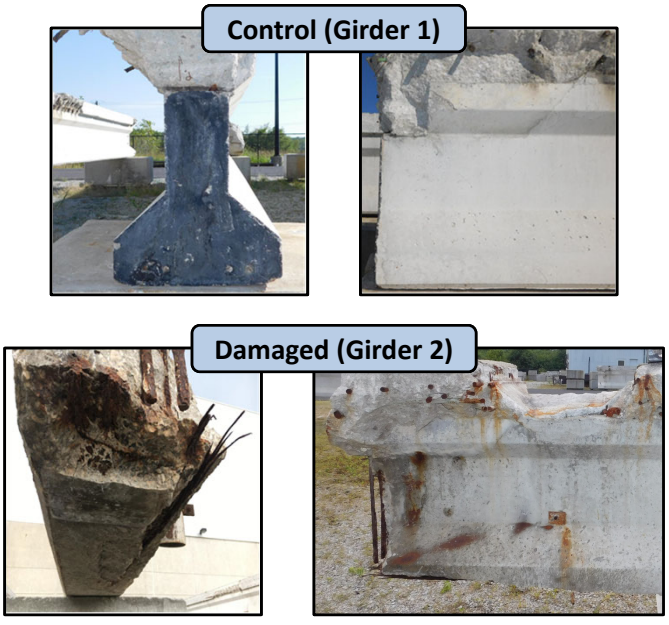
Girder	End Region Condition	Repair Technique
1	Good	Control
2	Deteriorated	Tested in Deteriorated Condition
3	Deteriorated	Externally Bonded FRP*
4	Deteriorated	NSM FRP*
5	Deteriorated	End Block

*Cross sections restored using fast-setting mortar mix

15

15

GIRDER CONDITION



16

16

GIRDER CONDITION

Externally Bonded FRP (Girder 3)

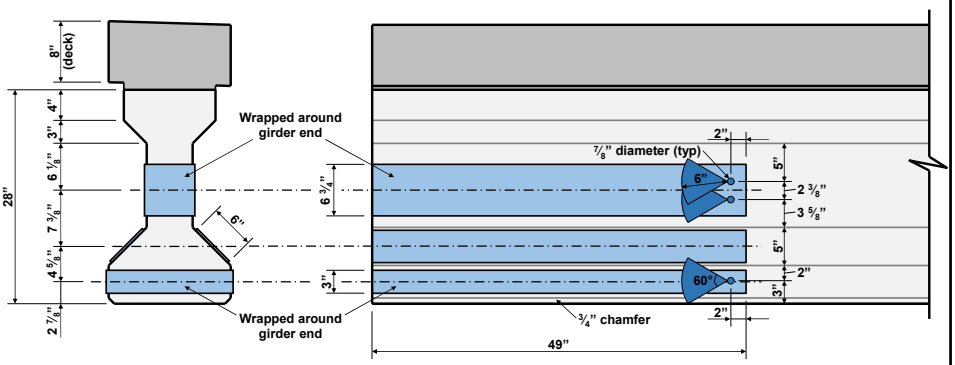
NSM FRP (Girder 4)

End Block (Girder 5)

17

17

EXTERNALLY BONDED FRP DETAILS

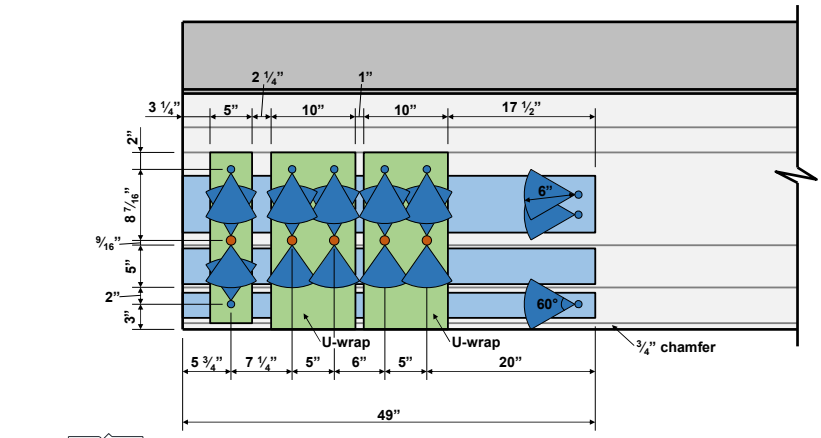


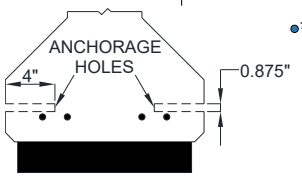
First Layer

18

18

EXTERNALLY BONDED FRP DETAILS



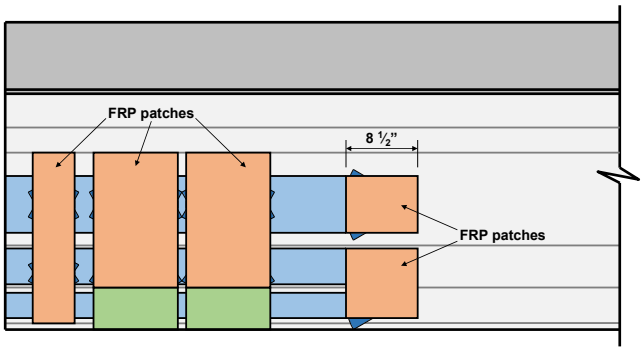


Second Layer

19

19

EXTERNALLY BONDED FRP DETAILS

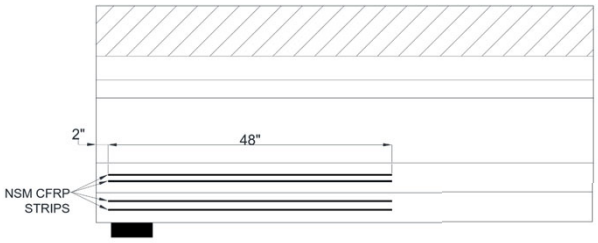


Third Layer

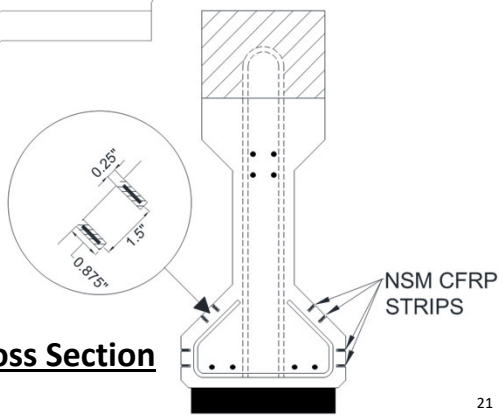
20

20

NEAR-SURFACE-MOUNTED (NSM) FRP DETAILS



Elevation View

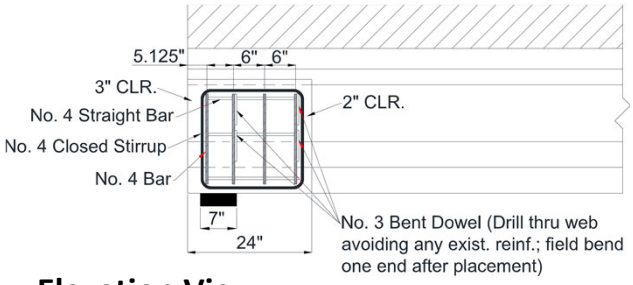


Cross Section

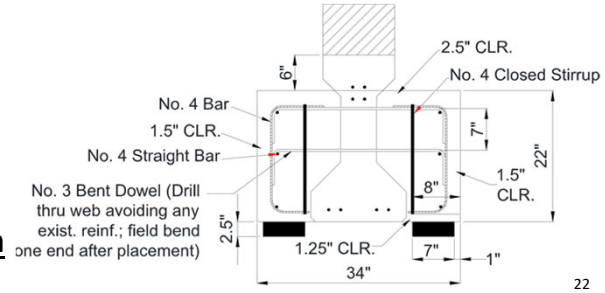
21

21

END BLOCK DETAILS



Elevation View



Cross Section

22

22

RESTORING CROSS SECTION

Externally Bonded and NSM FRP Specimens

1. Remove Unsound Concrete

2. Sandblast

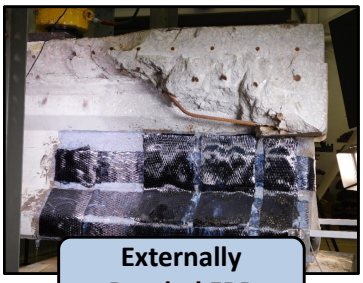
4. Restore Cross Section

3. Condition After Sandblasting

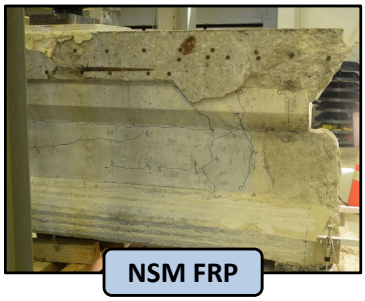
23

23

REPAIRED GIRDERS



Externally Bonded FRP



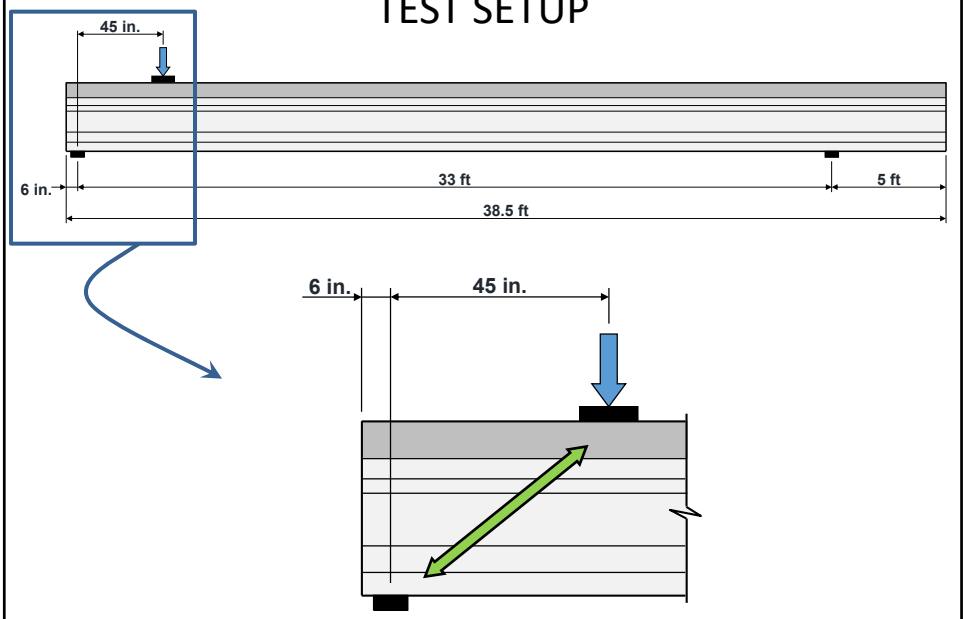
NSM FRP

End Block

24

24

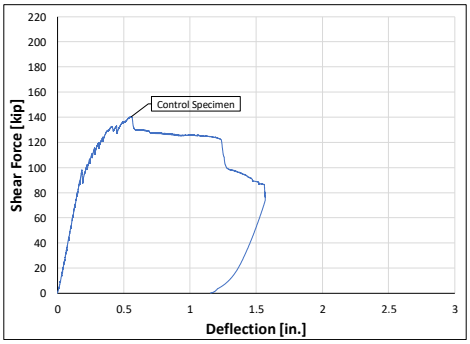
TEST SETUP

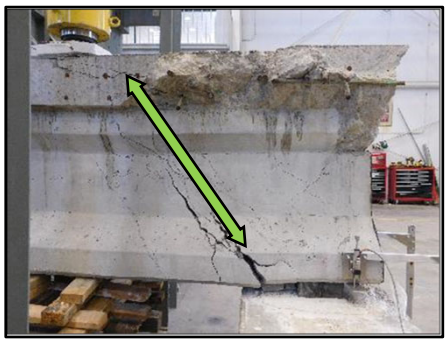


25

25

TEST RESULTS – CONTROL





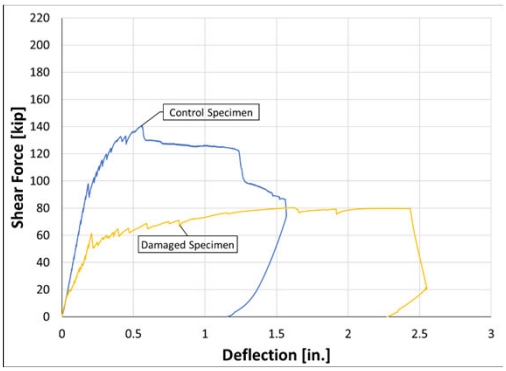
Observations

- Formation of a diagonal strut.
- Slip of prestressing strands in the bottom flange.

26

26

TEST RESULTS – TESTED IN DAMAGED STATE



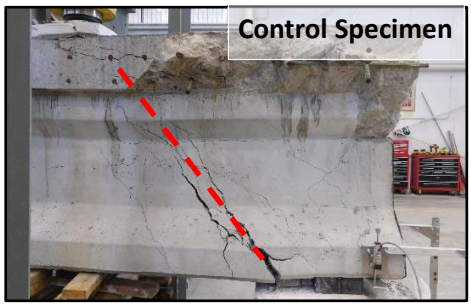
Observations

- $V_{test}/V_{control}$ = 0.57
- Different failure mechanism.

27

27

TEST RESULTS – TESTED IN DAMAGED STATE



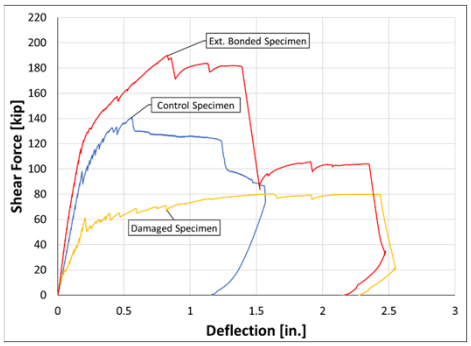
Observations

- $V_{test}/V_{control}$ = 0.57
- Different failure mechanism.

28

28

TEST RESULTS – EXTERNALLY BONDED FRP



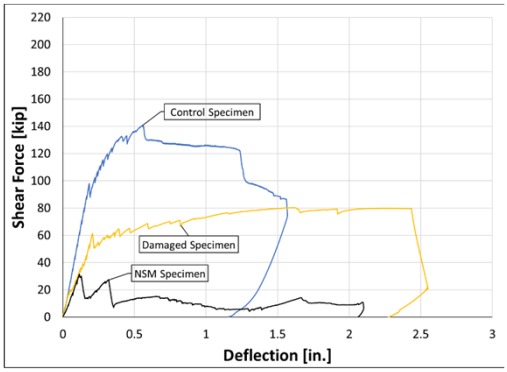
Observations

- Exceeded strength of control specimen.
- Restored stiffness.
- Flexural failure at the end of the repair → strand fracture.
- Some debonding of the FRP was observed.

29

29

TEST RESULTS – NSM FRP



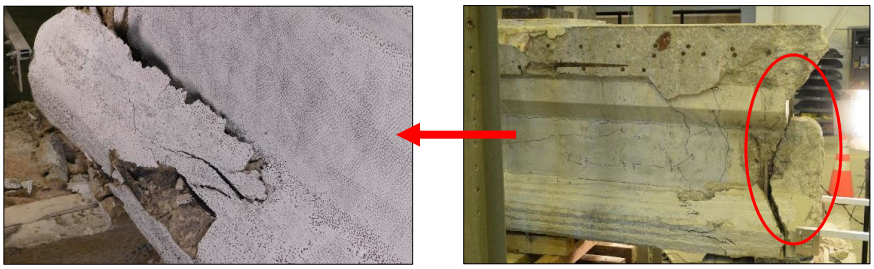
Observations

- Premature failure.
- Cracking/splitting at the notch above the bearing location.
- Bottom flange separated from the web.

30

30

TEST RESULTS – NSM FRP



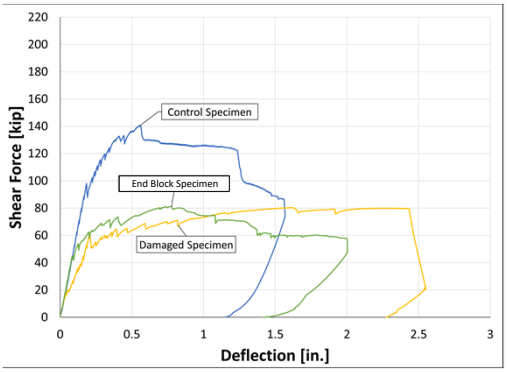
Observations

- Premature failure.
- Cracking/splitting at the notch above the bearing location.
- Bottom flange separated from the web.

31

31

TEST RESULTS – END BLOCK



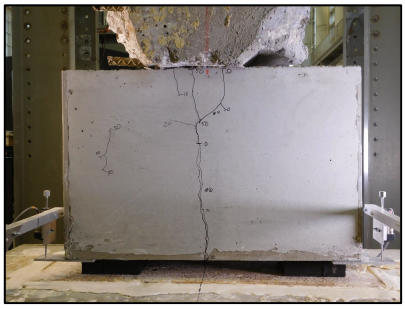
Observations

- Similar initial stiffness to control specimen.
- Cracking/splitting of the diaphragm.
- Interface failure → diaphragm rotation.

32

32

TEST RESULTS – END BLOCK



Observations

- Similar initial stiffness to control specimen.
- Cracking/splitting of the diaphragm.
- Interface failure → diaphragm rotation.

33

33

TEST RESULTS – END BLOCK

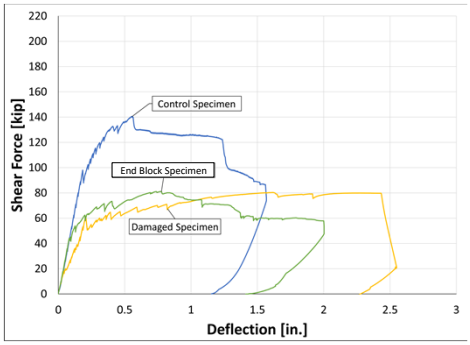
Observations

- Similar initial stiffness to control specimen.
- Cracking/splitting of the diaphragm.
- Interface failure → diaphragm rotation.

34

34

TEST RESULTS – END BLOCK



Observations

- Similar initial stiffness to control specimen.
- Cracking/splitting of the diaphragm.
- Interface failure → diaphragm rotation.

35

35

EXPERIMENTAL PROGRAM CONCLUSIONS

End region deterioration can significantly reduce the strength of prestressed concrete bridge girders.

Only restoring the girder cross section with mortar is insufficient based on test observations.

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

36

36

EXPERIMENTAL PROGRAM CONCLUSIONS

Ensuring adequate confinement of the repair region is critical.

The externally bonded FRP system is a viable repair option based on test results.

37

37

OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Background to Problem of End Region Deterioration

End Region Repair Experimental Program

FRP Application AND Key Considerations for Design & Implementation

Other Resources

38

38

EXTERNALLY BONDED FRP REPAIR PROCEDURE

39

39

EXTERNALLY BONDED FRP REPAIR PROCEDURE

40

40

EXTERNALLY BONDED FRP REPAIR PROCEDURE

Rolling to Eliminate Air Pockets

Removing Excess Epoxy

Installed Strips/Sheets

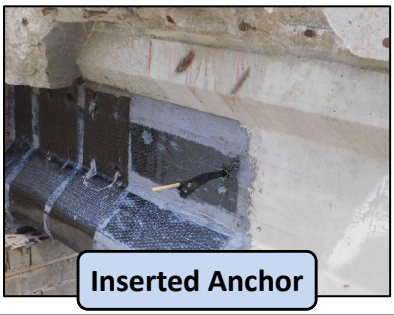
41

41

EXTERNALLY BONDED FRP REPAIR PROCEDURE

FRP Spike Anchor

Injecting Epoxy



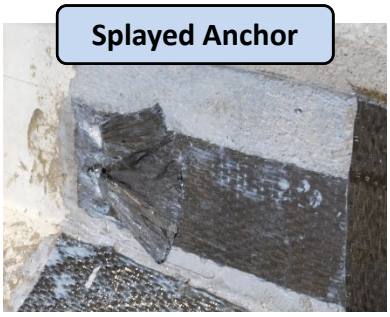
Inserted Anchor

42

42

EXTERNALLY BONDED FRP REPAIR PROCEDURE


Removing Dowel


Splayed Anchor


Applying Epoxy


Injecting Epoxy

43

43

EXTERNALLY BONDED FRP REPAIR PROCEDURE


Saturating Patch Sheets


Installing Patch Sheets


Completed Externally Bonded Repair

44

44

FIRST-HAND OBSERVATIONS

- **A mock-up is recommended for complex repairs.**
- **A satisfactory trial batch of the repair material should be created prior to application.**
- **Internal steel should be located prior to drilling into the girder.**
- **Holes through the entire web should be drilled from both sides of the girders.**
- **For overhead applications, supporting the mortar is recommended.**

45

45

KEY DESIGN CONSIDERATIONS

Proper Anchorage of Externally Bonded FRP is Critical

- ***FRP Spike Anchors***
  - Past Research
- ***Other Types of Anchors***
  - Metallic
  - Non-Metallic
    - FRP U-Wraps

46

OUTLINE

Introduction to Fiber Reinforced Polymer (FRP) Systems

Background to Problem of End Region Deterioration

End Region Repair Experimental Program

FRP Application AND Key Considerations for Design & Implementation

Other Resources

47

47

RESOURCES
(Not an Exhaustive List)

Design/Construction of FRP Systems

- AASHTO Guide Specification for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements (2012)
- ACI PRC-440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
- ICRI 330.2-2016: Guide Specifications for Externally Bonded FRP Fabric Systems for Strengthening Concrete Structures
- *fib* Bulletin No. 14: Externally Bonded FRP Reinforcement for RC Structures (2001)

FRP - General

- ACI PRC-440R-07: Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

Concrete Repair (ACI)

- ACI CODE-562-21: Assessment, Repair, and Rehabilitation of Existing Concrete Structures – Code and Commentary
- ACI PRC-546R-14: Guide to Concrete Repair
- ACI PRC-546.3R-14: Guide to Materials Selection for Concrete Repair
- ACI PRC-224.1R-07: Causes, Evaluation, and Repair of Cracks in Concrete Structures

48

48

RESOURCES
(Not an Exhaustive List)

Concrete Repair (ICRI)

- ICRI 310.1R-2008: Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion
- ICRI 310.2R-2013: Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair
- ICRI 330.1-2006: Guide for the Selection of Strengthening Systems for Concrete Structures
- ICRI 320.2R-2018: Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces

Spike Anchor Design and Detailing

- Shekarchi et al. (2020) – Carbon Fiber-Reinforced Polymer Spike Anchor Design Recommendations (also see sources referenced in this paper)

49

49

RESOURCES
(Not an Exhaustive List)

Past End Region Repair Studies

- ***FRP Repairs***
  - Andrawes et al. (2018) – University of Illinois study
  - Petty et al. (2011) – Utah State University study
  - Ramseyer and Kang (2012) – University of Oklahoma study
- ***End Block Repairs***
  - Needham (1999, 2000) – Michigan DOT study/implementation
  - Shield and Bergson (2018) – University of Minnesota study/implementation
  - Floyd et al. (2020) – University of Oklahoma study/implementation (UHPC, FR-SCC, MALP)
- ***Patching Using Specialized Concrete***
  - Shafei et al. (2020) – Iowa State University study (UHPC, HESC)

INDOT/JTRP Study

- Pevey et al. (2021)
- Rich et al. (2021)

50

50

Thank You!

Questions?

The contents of this presentation reflect the views of the researchers, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

PURDUE UNIVERSITY
Lyles School of Civil Engineering

JOINT TRANSPORTATION RESEARCH PROGRAM
Discovery with Delivery
Since 1937
JTRP

INDIANA DEPARTMENT OF TRANSPORTATION
INDOT

51

51

REFERENCES

AASHTO. (2012). *Guide Specifications for Design of Externally Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements.* 1st edition. Washington, DC: American Association of State Highway and Transportation Officials.

ACI Committee 224. (2007). *ACI PRC-224.1R-07: Causes, Evaluation, and Repair of Cracks in Concrete Structures*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 440. (2007). *ACI PRC-440R-07: Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 440. (2017). *ACI PRC-440.2R-17: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 546. (2014). *ACI PRC-546R-14: Guide to Concrete Repair*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 546. (2014). *ACI PRC-546.3R-14: Guide to Materials Selection for Concrete Repair*. Farmington Hills, MI: American Concrete Institute.

ACI Committee 562. (2021). *ACI CODE-562-21: Assessment, Repair, and Rehabilitation of Existing Concrete Structures – Code and Commentary*. Farmington Hills, MI: American Concrete Institute.

52

52

REFERENCES

Andrawes, B., Shaw, I. D., and Zhao, H. (2018). *Repair and Strengthening of Distressed/Damaged Ends of Prestressed Beams with FRP Composites*. Report No. FHWA-ICT-18-001. Illinois Center for Transportation. University of Illinois at Urbana-Champaign. https://doi.org/10.36501/0197-9191/18-001

fib Task Group 9.3. (2001). *fib Bulletin No. 14: Externally Bonded FRP Reinforcement for RC Structures*. Lausanne, Switzerland: Fédération internationale de béton.

Floyd, R. W., Volz, J. S., Looney, T., Mesigh, M., Ahmadi, M., Roswurm, S., Huynh, P., and Manwarren, M. (2020). *Evaluation of Ultra-High Performance Concrete, Fiber Reinforced Self-Consolidating Concrete, and MALP Concrete for Prestressed Girder Repair*. Report No. FHWA-OK-21-03. Oklahoma Department of Transportation. https://shareok.org/handle/11244/330981

ICRI. (2006). *ICRI Guideline No. 330.1-2006: Guide for the Selection of Strengthening Systems for Concrete Structures*. Saint Paul, MN: International Concrete Repair Institute.

ICRI. (2008). *ICRI Guideline No. 310.1R-2008: Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion*. Saint Paul, MN: International Concrete Repair Institute.

ICRI. (2013). *ICRI Guideline No. 310.2R-2013: Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair*. Saint Paul, MN: International Concrete Repair Institute.

53

REFERENCES

ICRI. (2016). *ICRI Guide No. 330.2-2016: Guide Specifications for Externally Bonded FRP Fabric Systems for Strengthening Concrete Structures*. Saint Paul, MN: International Concrete Repair Institute.

ICRI. (2018). *ICRI Guideline 320.2R-2018: Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces*. Saint Paul, MN: International Concrete Repair Institute.

Indiana Department of Highways. 1987. Bridge Plans for Spans over 20 Feet on State Road No. 24 (Project No. MAF-170-1). Indiana Department of Highways.

Kim, Y., Quinn, K., Satrom, N., Garcia, J., Sun, W., Ghannoum, W. M., and Jirsa, J. O. (2012). Shear Strengthening of Reinforced and Prestressed Concrete Beams Using Carbon Fiber Reinforced Polymer (CFRP) Sheets and Anchors. Report No. FHWA/TX-12/0-6306-1. Center for Transportation Research. The University of Texas at Austin. https://ctr.utexas.edu/wp-content/uploads/pubs/0_6306_1.pdf

Needham, D. E. (1999). *Prestressed Concrete Beam End Repair (Interim Report)*. Report No. R-1373. Michigan Department of Transportation. https://www.michigan.gov/documents/mdot_c&t_r-1373_67458_7.pdf

Needham, D. E. (2000). *Prestressed Concrete Beam End Repair (Final Report)*. Report No. R-1380. Michigan Department of Transportation. https://www.michigan.gov/documents/mdot_c&t_r-1380_67568_7.pdf

54

REFERENCES

Petty, D. A., Barr, P. J., Osborn, P. G., Halling, M. W., and Brackus, T. R. (2011). "Carbon Fiber Shear Retrofit of Forty-Two-Year-Old AASHTO I-Shaped Girders." *Journal of Composites for Construction* 15 (5). pp. 773–781. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000208

Pevey, J. M., Rich, W. B., Williams, C. S., and Frosch, R. J. (2020). *Repair and Strengthening of Bridges in Indiana Using Fiber Reinforced Polymer Systems: Volume 1–Review of Current FRP Repair Systems and Application Methodologies*. Report No. FHWA/IN/JTRP-2021/09. Joint Transportation Research Program. Purdue University. https://docs.lib.purdue.edu/jtrp/1750

Pudleiner, D. K. (2016). *Design Considerations Based on Size Effects of Anchored Carbon Fiber Reinforced Polymer (CFRP) System*. MS thesis. The University of Texas at Austin. http://hdl.handle.net/2152/39031

Ramseyer, C., and Kang, T. H.-K. (2012). "Post-Damage Repair of Prestressed Concrete Girders." *International Journal of Concrete Structures and Materials* 6 (3). pp. 199-207. https://doi.org/10.1007/s40069-012-0019-7

Rich, W. B., Jacobs, R. R., Williams, C. S., and Frosch, R. J. (2020). *Repair and Strengthening of Bridges in Indiana Using Fiber Reinforced Polymer Systems: Volume 2–FRP Flexural Strengthening and End Region Repair Experimental Programs*. Report No. FHWA/IN/JTRP-2021/10. Joint Transportation Research Program. Purdue University. https://docs.lib.purdue.edu/jtrp/1755

55

55

REFERENCES

Shafei, B., Phares, B., and Weizhuo, S. (2020). *Beam End Repair for Prestressed Concrete Beams*. Report No. IHRB Project TR-715. Bridge Engineering Center. Iowa State University. http://publications.iowa.gov/33803/1/TR-715_Final%20Report_Beam%20End%20Repair%20for%20Prestressed%20Concrete%20Beams.pdf

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

Shield, C., and Bergson, P. (2018). *BR27568 – Experimental Shear Capacity Comparison Between Repaired and Unrepaired Girder Ends*. Report No. MN/RC 2018-07. Michigan Department of Transportation. http://www.dot.state.mn.us/research/reports/2018/201807.pdf

56

56