Behavior of Concrete Beams with Corroded Reinforcement Retrofitted with CFRP

By:

Needa Lingga, MSCE, ACI Member

Franz N. Rad, PhD, PE, SE, FASCE, FACI

Portland State University

Overview

- Introduction and Research Objectives
- Review of Steel Corrosion in Reinforced Concrete Structures
- Review of Carbon Fiber Reinforced Polymer (CFRP)
- Experimental Study
- Experimental Study Results
- Conclusion

Introduction

- Corrosion of steel is a common problem in reinforced concrete structures.
- Different techniques developed and used to repair structural deficiencies.
- Example of conventional methods :
  - ✧ Concrete jacketing : increase the size of existing sections
  - ✧ Steel plates bonding: enhance strength or improve stiffness
- Conventional techniques are not cost effective, and some common problems such as corrosion will also be present after the repair.

Introduction

- Innovative method
  - ✧ CFRP composite are now used increasingly in the construction industry.
- Published studies provided valuable information regarding use of CFRP in strengthening the flexural strength and stiffness of concrete members.
- Corrosion is accelerated in the systems.
- Corrosion rate is varied between 5% (mild) & 20% (severe).
- However, little research has been devoted to study the feasibility of using CFRP to improve the strength of fully corroded beams.

In This Study

- A worst case scenario of corrosion was considered.
- Definition :
  - 100% corrosion
  - A complete loss in the bond between concrete and reinforcement
  - A complete loss in rebar cross sectional area and strength
  - Steel reinforcement is considered non-active
  - Steel reinforcement is eliminated in the experiment

Research Objective

- Provide an insight into the effect of bonding CFRP on the :
  1. Load carrying capacity of concrete members with fully corroded reinforcement (worst case scenario)
  2. Stiffness and deflection
  3. Energy absorption
- Compare the flexural capacity of retrofitted beam to the original beam before corrosion
- Compare results of ACI 440.2R design guidelines to the experimental results

Steel Corrosion in Reinforced Concrete Structures

- Concrete normally provide protection against corrosion of the embedded reinforcement
    - ➢ pH level between 12.5 and 13 →form a passive film of iron oxides
    - ➢ Physical barrier that prevents the steel from coming in contact with the external environment.
- Corrosion will take place in structures where there is:
    - Poor maintenance
    - Poor initial design or construction
    - Harsh environmental conditions

Cause of Reinforcement Corrosion

External Factors (Environmental Factors)

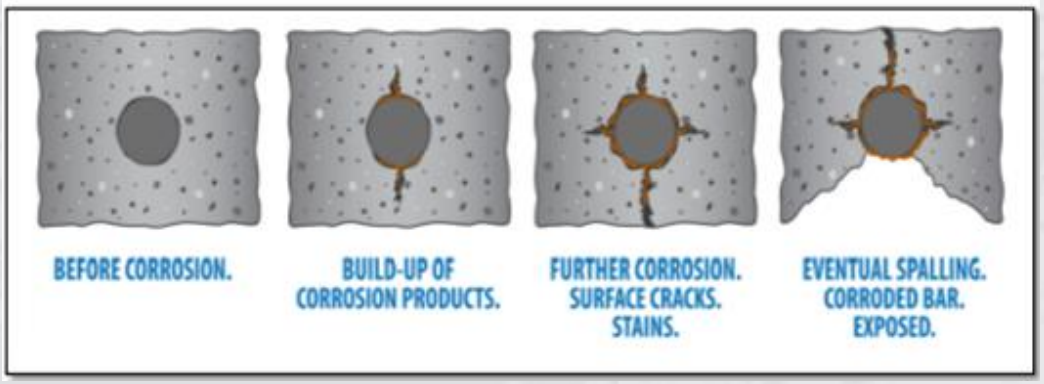
- Presences of chloride ions [costal areas]
- Penetration of carbon dioxide [lower pH of concrete]

Internal Factors (Concrete Quality Parameters)

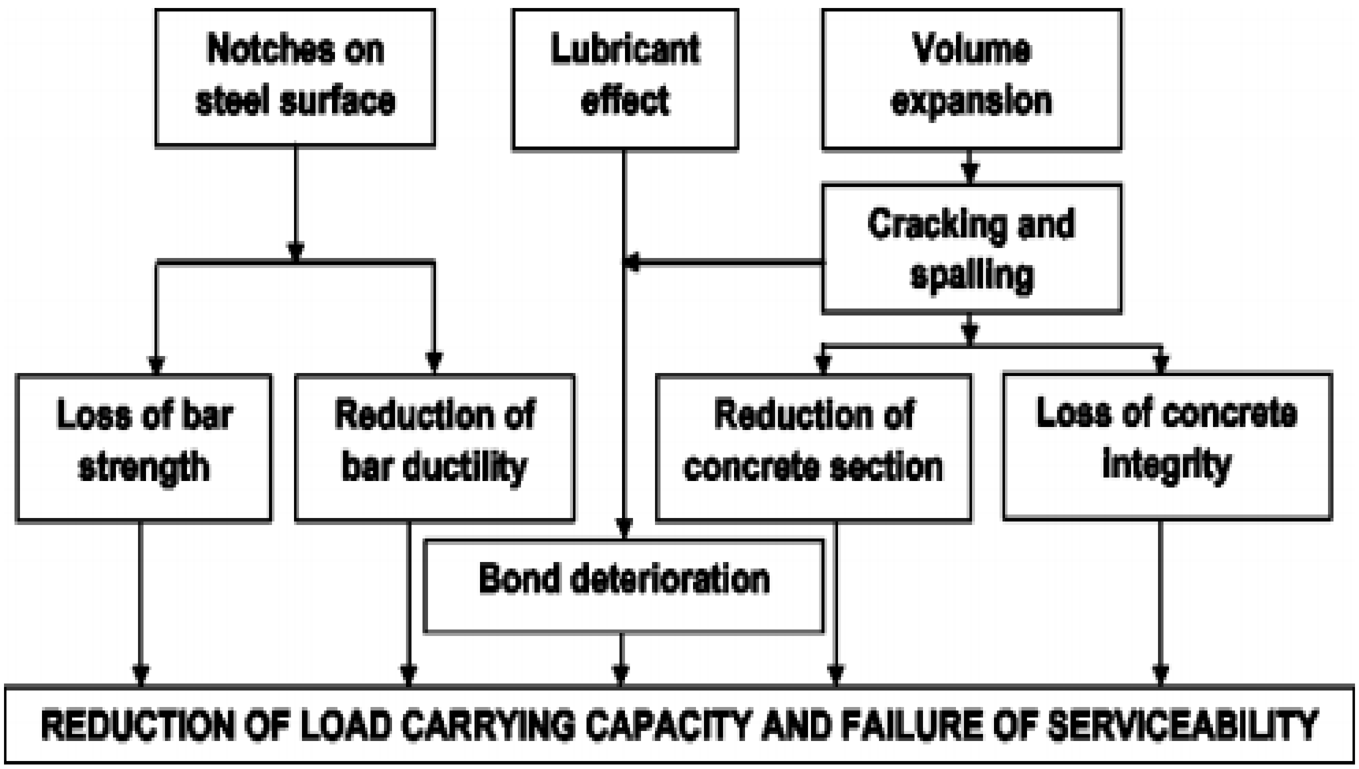
- Concrete properties
  - Concrete mix
  - Water/cement ratio,
  - Type of cement used,
  - Workability
  - Curing
  - Quality control at construction site .

Steel Reinforcement Cross Section

- Formation of rust → corrosion → reduce the cross sectional area of steel → reduce the flexural and shear strength capacity of RC → loss the bond between concrete and reinforcement



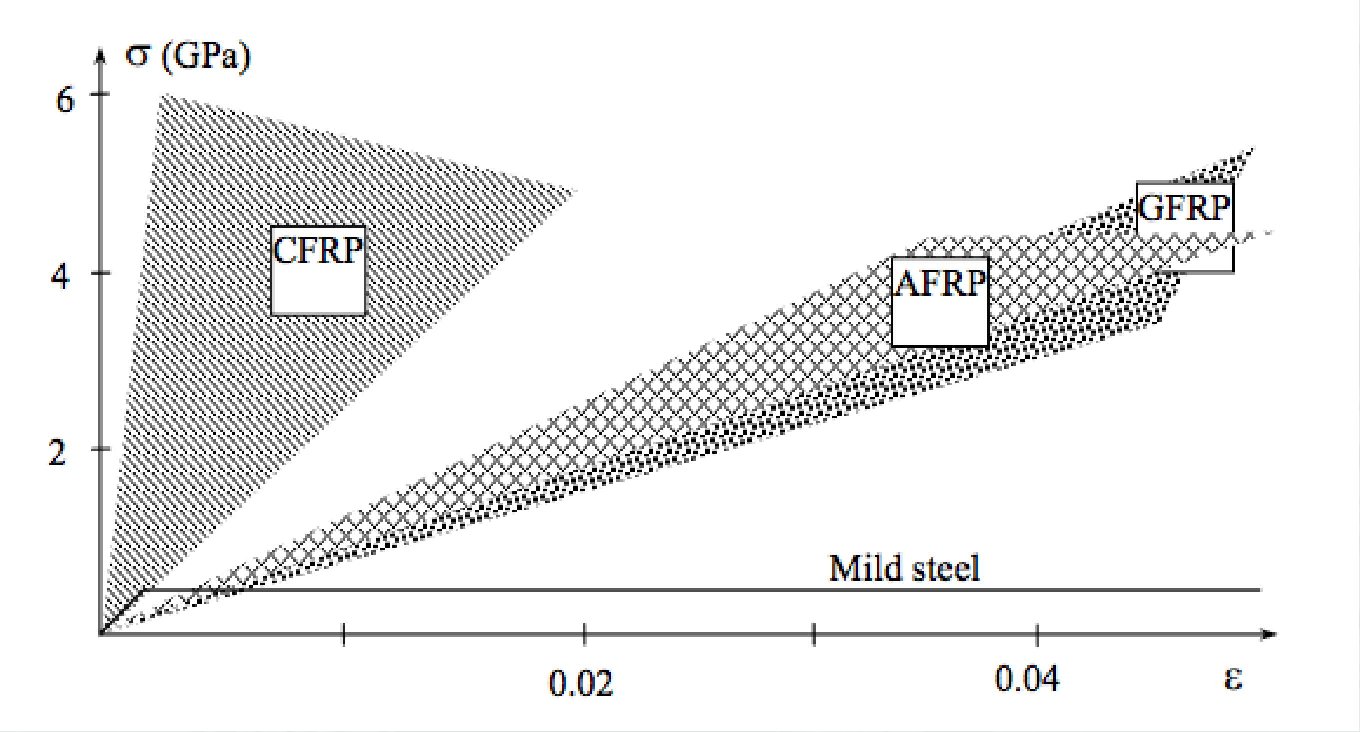
Effect of Corrosion on RC Structures



Carbon Fiber Reinforced Polymer (CFRP)

A group of advanced composite materials composed of synthetic or organic fibers embedded in a resin

Stress-Strain diagrams for different FRPs and Steel



CFRP = Carbon FRP
AFRP = Aramid FRP
GFRP = Glass FRP

Advantages of Carbon Fiber Reinforced Polymer (CFRP)

Advantages of CFRP
Excellent corrosion resistance
Good flexibility
High ultimate strength (2-3 times greater than steel)
Requires little maintenance
Strength to weight ratio is higher than for steel
Lower density than steel
Handling and installation is significantly easier than for steel
Excellent durability

Experimental Study

- Five beams were designed and analyzed in according to:
  - American Concrete Institute ACI 318-14
  - ACI 440.2R-08

- All five beams :
- Same cross section [4 in. x 6 in x 6 ft.]
- Tested under third-point loading

Description of Beam Specimens

Beam No.	Description
Beam #1	Deteriorated beam
Beam #2	Plain concrete beam
Beam #3	Control beam (Original beam)
Beam #4	Deteriorated beam + One layer of CFRP
Beam #5	Deteriorated beam + Two layers of CFRP

Beam formwork construction

Plain Concrete

Original Beam

Deteriorated Beam

Concrete Mix

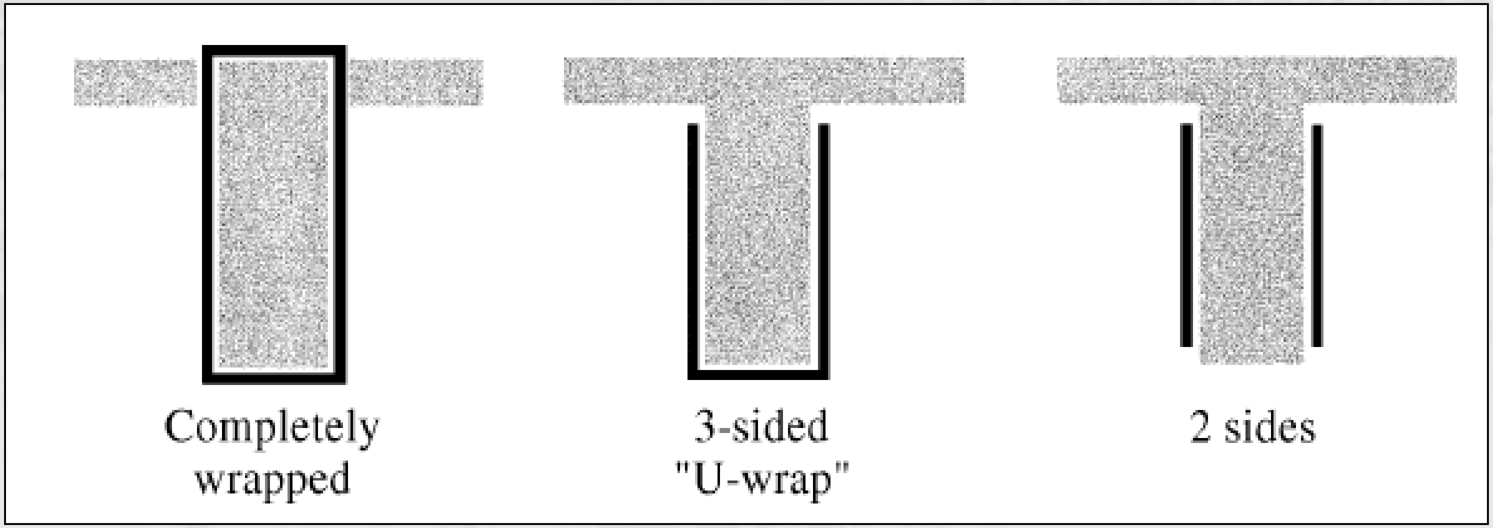
Target compressive strength = 3000 psi

Deteriorated RC Beam (Fully corroded steel)



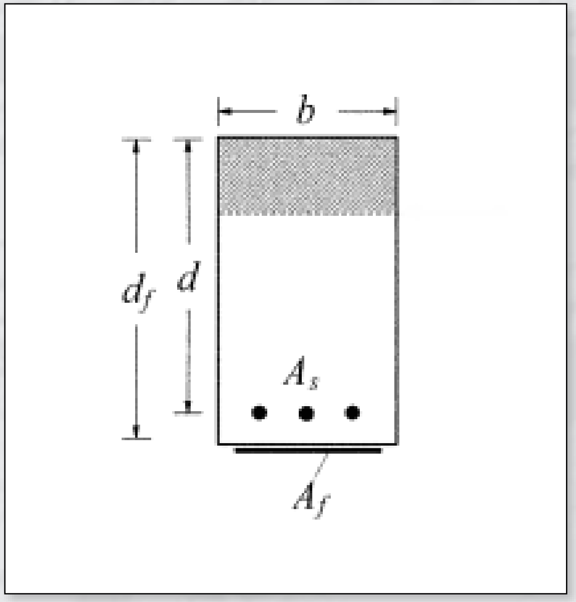
Application of Carbon Fiber Reinforced Polymer (CFRP)

- ACI 440.2R-08 recommended these schemes for shear strengthening



Application of Carbon Fiber Reinforced Polymer (CFRP)

- ACI 440.2R-08 recommended these scheme for flexural strengthening



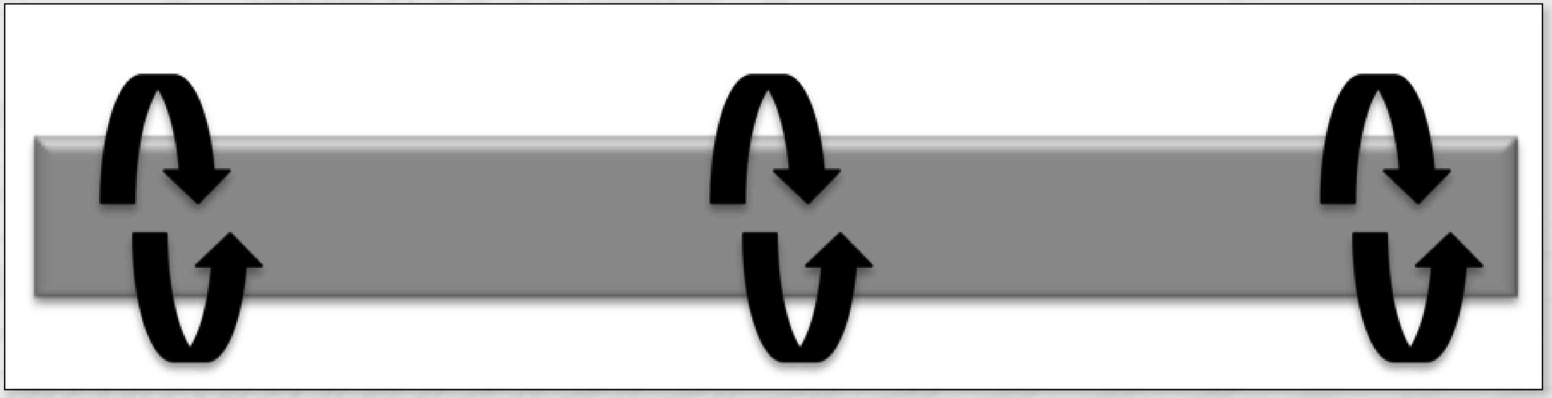
Application of Carbon Fiber Reinforced Polymer (CFRP)

- ✓ Surfaces was grinded
- ✓ Edges were rounded
- ✓ Big cavities were grouted using cement mortar

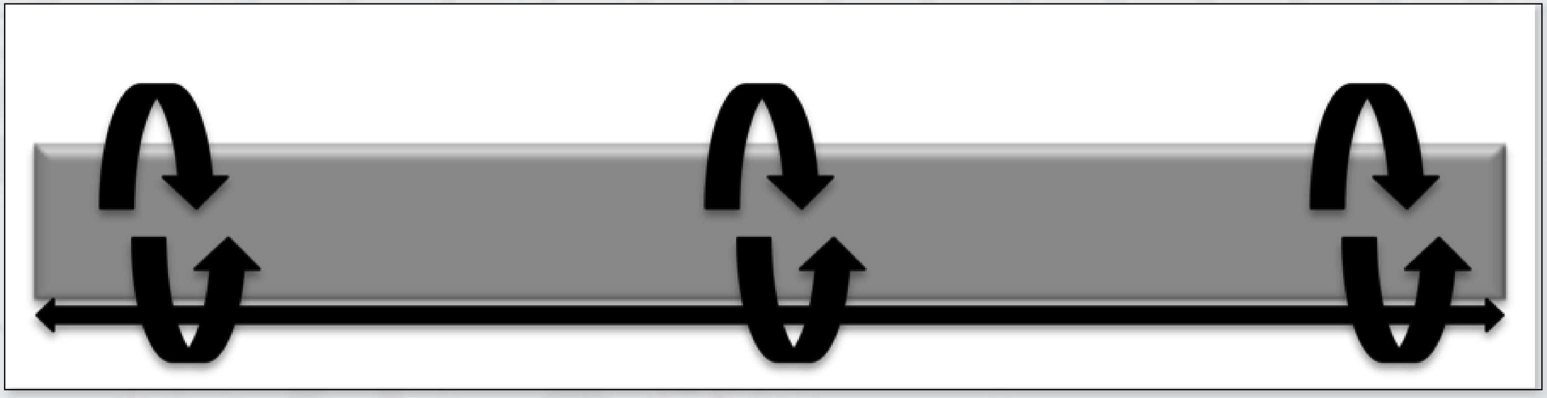
Application of Carbon Fiber Reinforced Polymer (CFRP)

- ✓ Each epoxy sets for 24 hours.
- ✓ Minimum one week for curing

Orientation of CFRP Circumferential



Orientation of CFRP Longitudinal

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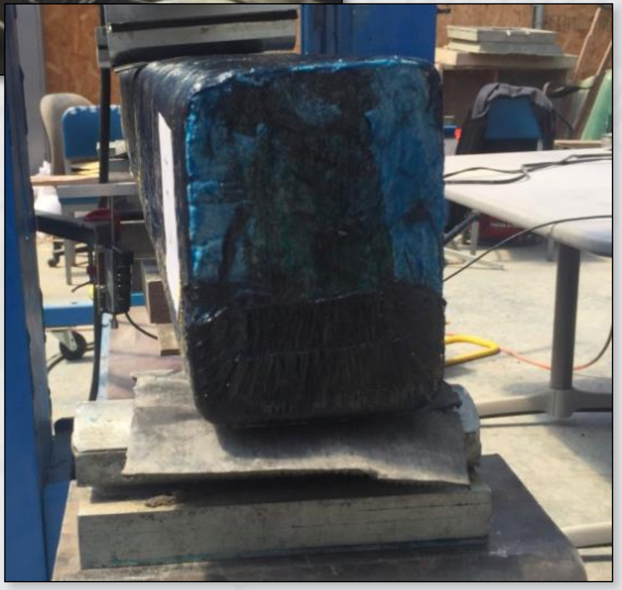


Testing Setup and Data Collection

- All beams were tested to failure under third-point loading.
- Two channels of data were collected during the tests
  - Applied load
  - Middle deflection

Test Result Beam #1

Deteriorated Beam

Classic brittle failure

Test Result Beam #2

Plain Concrete Beam

Classic brittle failure

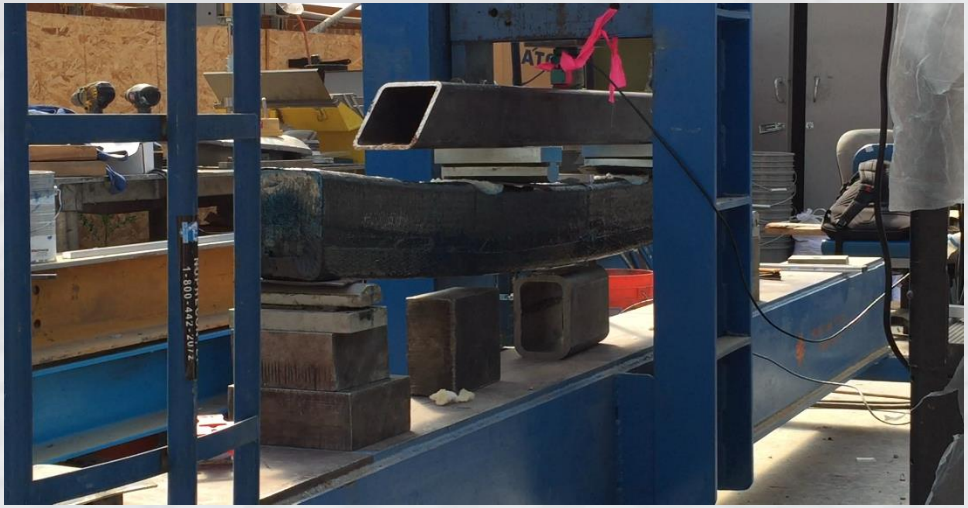
Test Result Beam #3

Reinforced Concrete Beam

Classic ductile failure, gradual and controlled

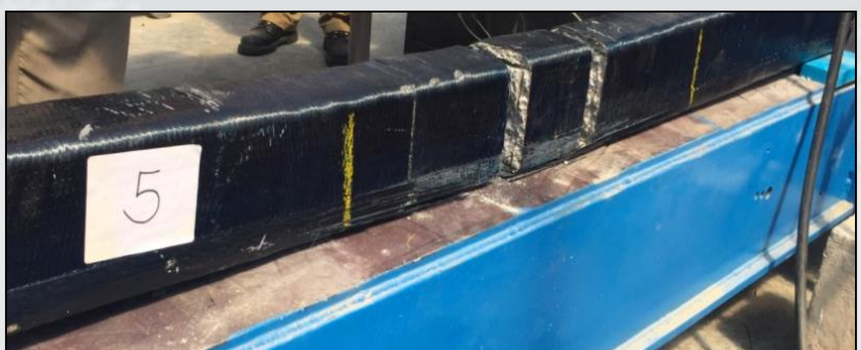
Test Result Beam #4

Deteriorated beam with one layer of CFRP



Test Result Beam #5

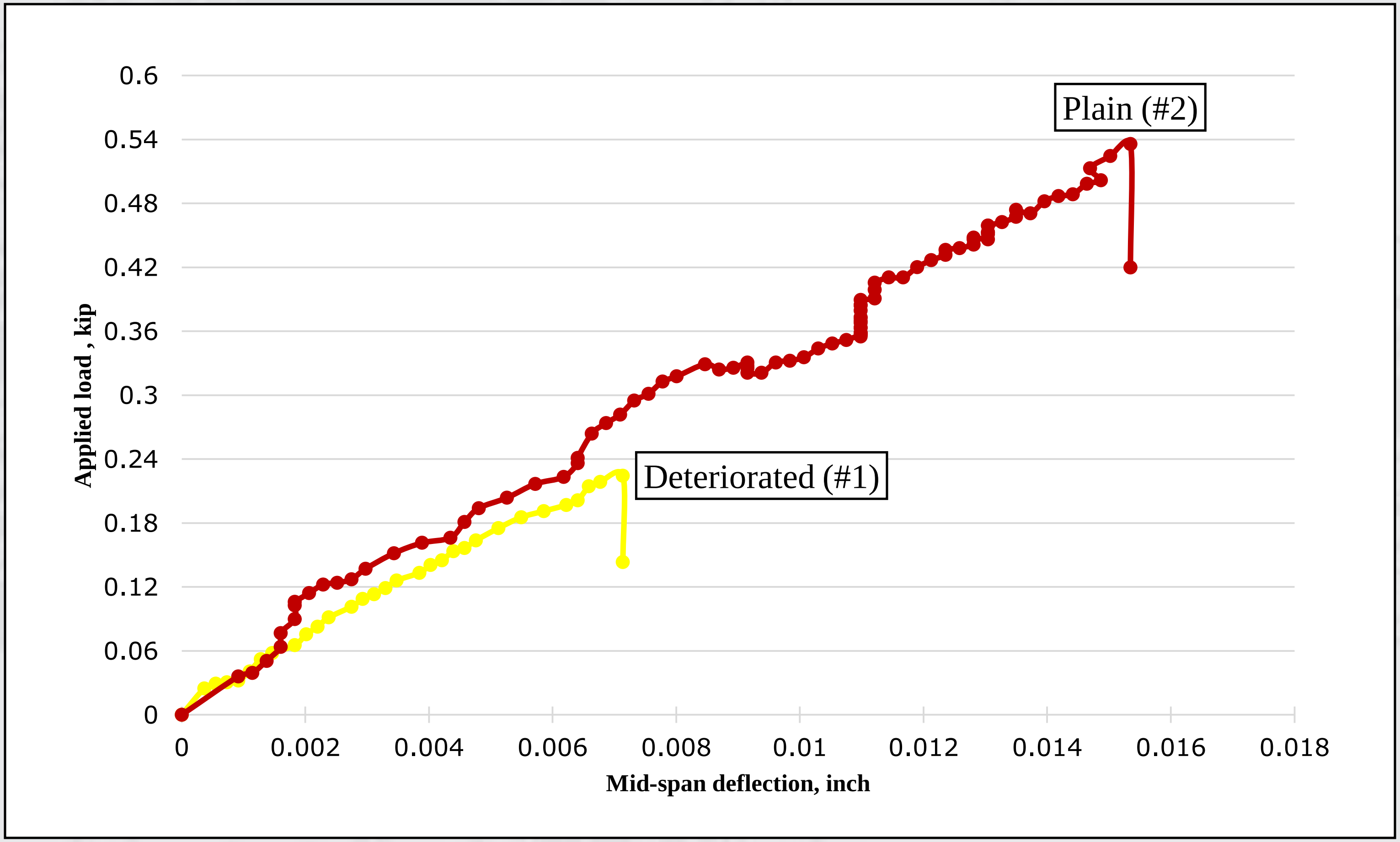
Deteriorated beam with two layers of CFRP



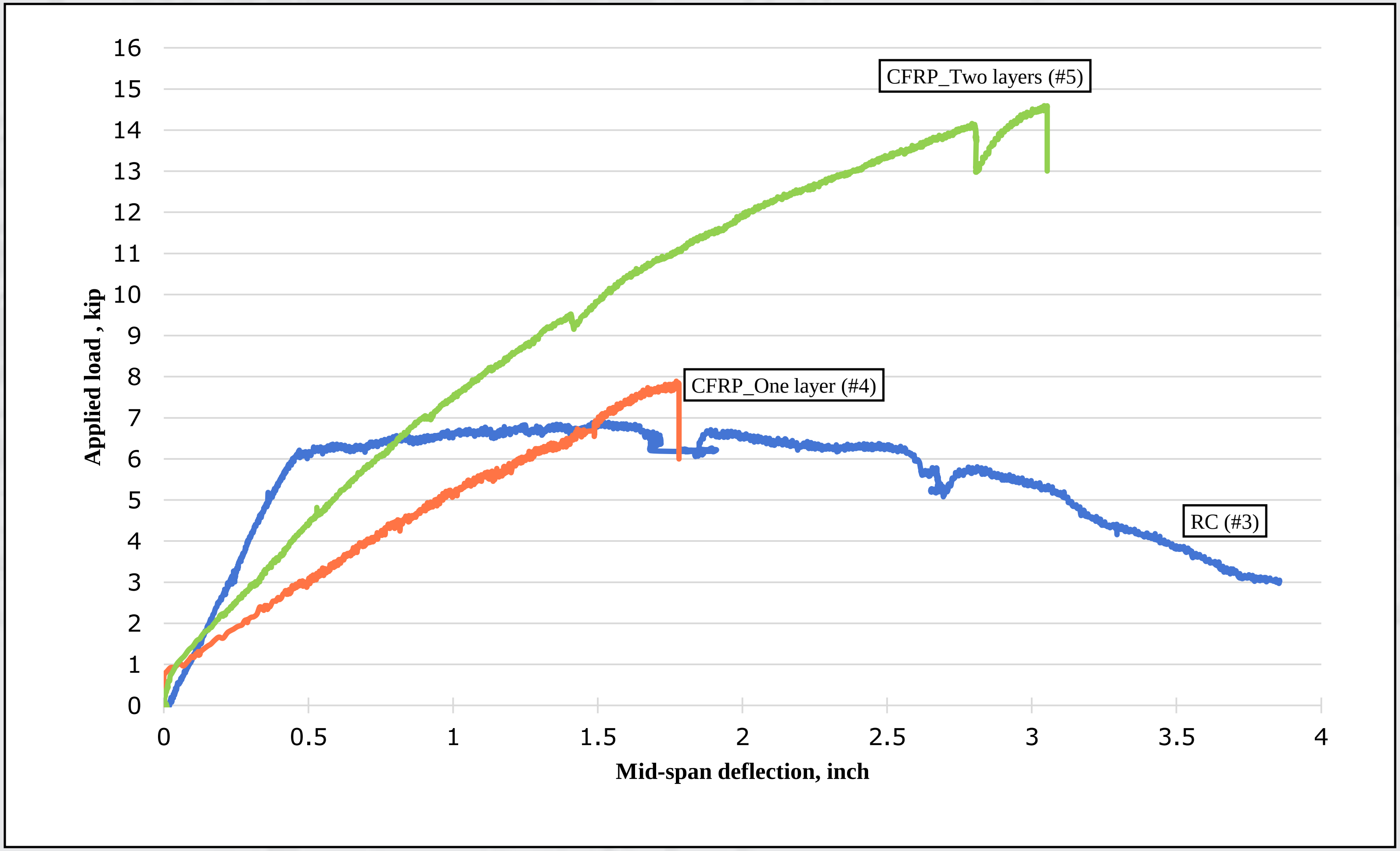
Failure Loads

Beam No.	Beam	Experimental Failure Load (kips)	Ratio $P_{exp.} / P_{RC}$
1	Deteriorated	0.274	0.040
2	Plain	0.538	0.078
3	RC (Control)	6.89	1.00
4	CFRP (One layer)	7.89	1.15
5	CFRP (Two layers)	14.58	2.12

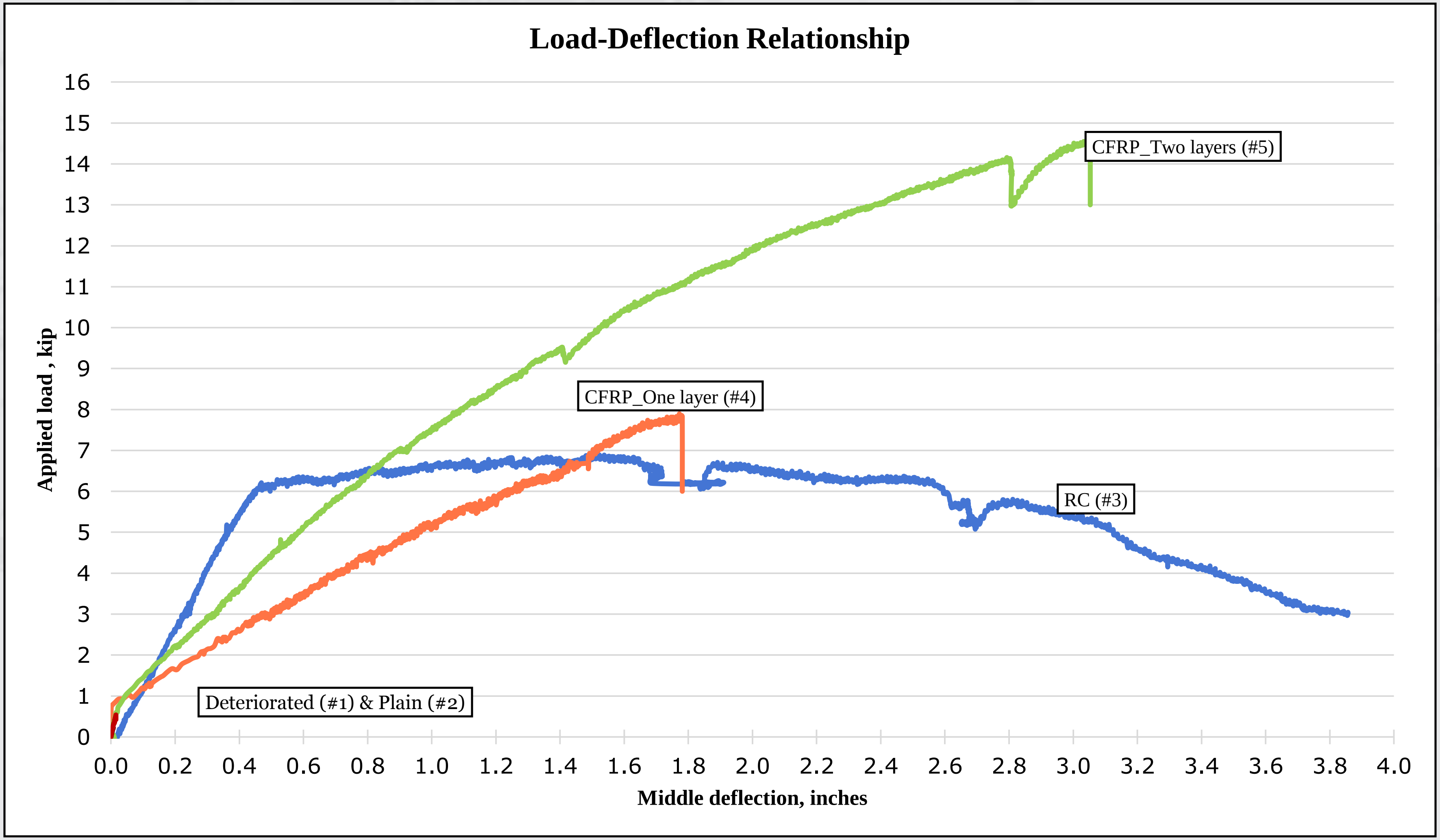
Load-Deflection Response (Beams #1 & #2)



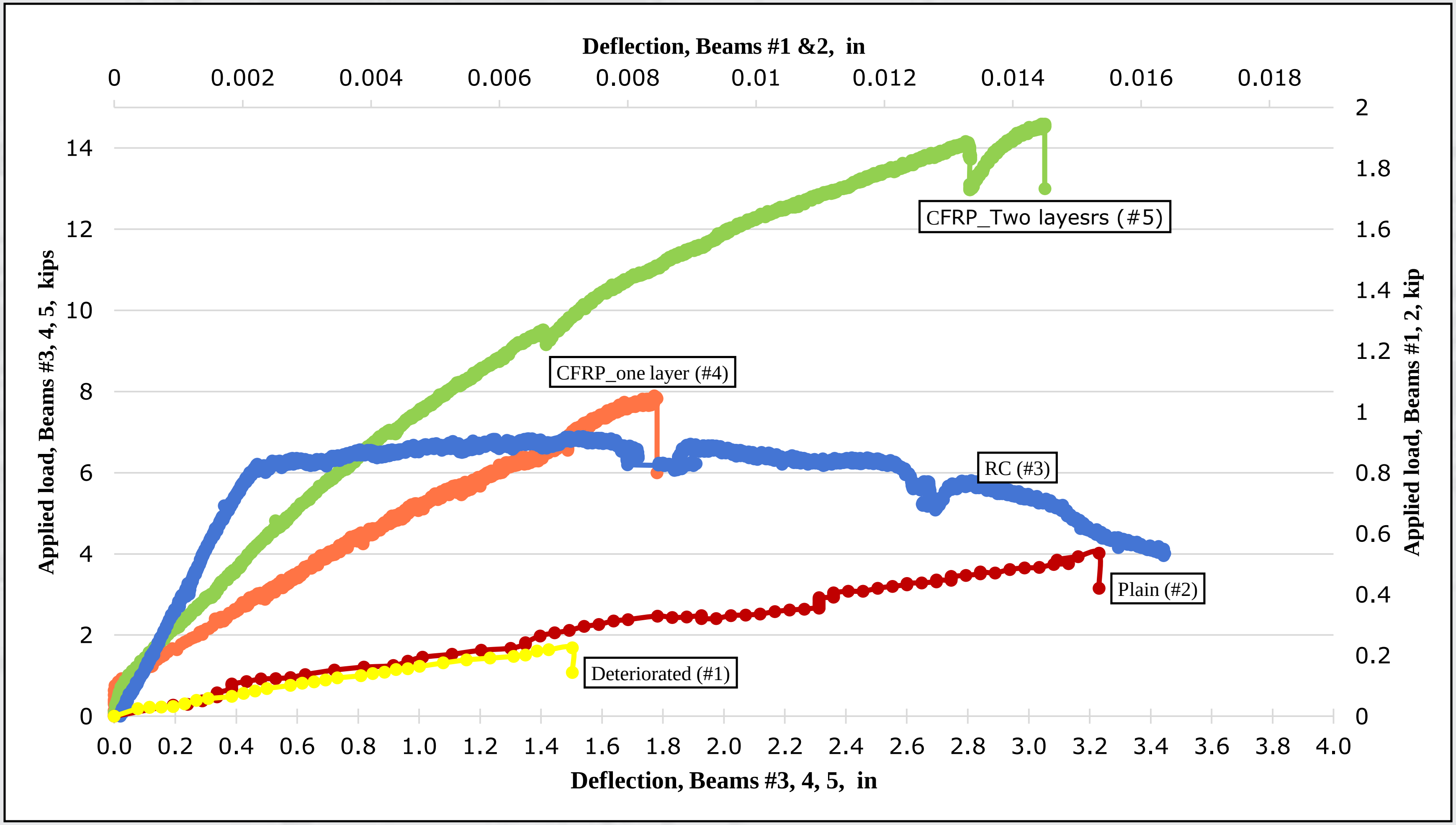
Load-Deflection Response (Beams #3, 4, 5)



Load-Deflection, All Beams



Load-Deflection, All Beams



Mid-span Deflection

- CFRP reinforced beams experienced significantly larger deflections.
- Increasing the number of layers, increased the stiffness of the beam

Beam No.	Beam	Experimental Max Deflection (in.)
1	Deteriorated	0.0071
2	Plain	0.0153
3	Control	1.55
4	CFRP (One layer)	1.78
5	CFRP (Two layers)	3.05

Absorbed Energy

- Area under the P-Δ curve

Beam No.	Beam	Absorbed Energy @ max load
1	Deteriorated	0.000877
2	Plain	0.0043
3	Control	8.53
4	CFRP (One layer)	8.13
5	CFRP (Two layers)	28.08

Theoretical Correlation

- The guidelines suggested by ACI 440.2R on calculations for shear and flexural strengthening effect using FRP to a reinforced concrete beams were used to predict the contribution of CFRP

Flexure:

$$M_n = A_s f_s \left(d \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe} (h \frac{\beta_1 c}{2})$$

Shear :

$$\mathrm{V_n} = \mathrm{V_c} + \mathrm{V_s} + \psi_f \mathrm{V_f}$$

$$V_f = \frac{A_{fv} f_{fe} (\sin\alpha + \cos\alpha) d_{fv}}{s_f}$$

Theoretical Correlation

Beam No.	Beam	Experimental max load (kip)	Theoretical max load (kip)	Ratio P_{exp}/P_{theo}
1	Deteriorated	0.274	0.266	1.03
2	Plain	0.538	0.531	1.01
3	RC	6.89	6.64	1.04
4	CFRP (One layer)	7.89	7.60	1.04
5	CFRP (Two layers)	14.58	14.40	1.01

Results

- Carbon fiber reinforced polymer significantly improved the behavior of concrete beams with fully corroded reinforcement.
- The capacity of the deteriorated beam with one layer was restored to the capacity of the original beam.
- Two layers of fiber improved the capacity by a factor of about 2 compared to one layer.
- Estimates of flexural and shear capacity of retrofitted beams based on ACI 440.2 R guidelines were close to the experimental results.

Further Study

- Provide experimental studies for the use of the more practical U- jacket configuration.
- Investigate the use of different orientations of CFRP sheets.
- Use finite element analysis (FEA) to verify the experimental results of beams retrofitted with CFRP.

Special Thanks to:

- Maseeh College of Engineering and Computer Science
- And CEE Department, Portland State University
- Our Grad students who helped with testing
- Lab Technician who helped with setting up the tests
- Contech and BM Group for supporting the dissemination of results

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