Seismic Repairing of a Seismically Damaged Bridge Column with Low-Grade GFRP Material

Mosharef Hossain, MASc,

Structural Engineer-in-Training, Stantec, Victoria, BC

M. Shahria Alam, PhD, PEng

The University of British Columbia, Okanagan

aci Spring 2018 | Salt Lake City
The Concrete Convention and Exposition

Background

Interstates 5 and 14
San Fernando earthquake, 1971

Cypress viaduct
Loma Prieta Earthquake, 1989

Shizunai Bridge
Urakawa-oki Earthquake, 1982

Fukae Viaduct
Kobe Earthquake, 1995

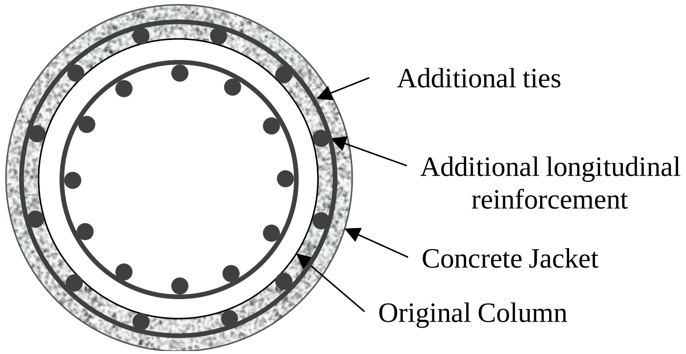
Lack of lateral reinforcement

BRIDGE COLUMN RETROFITTING TECHNIQUES

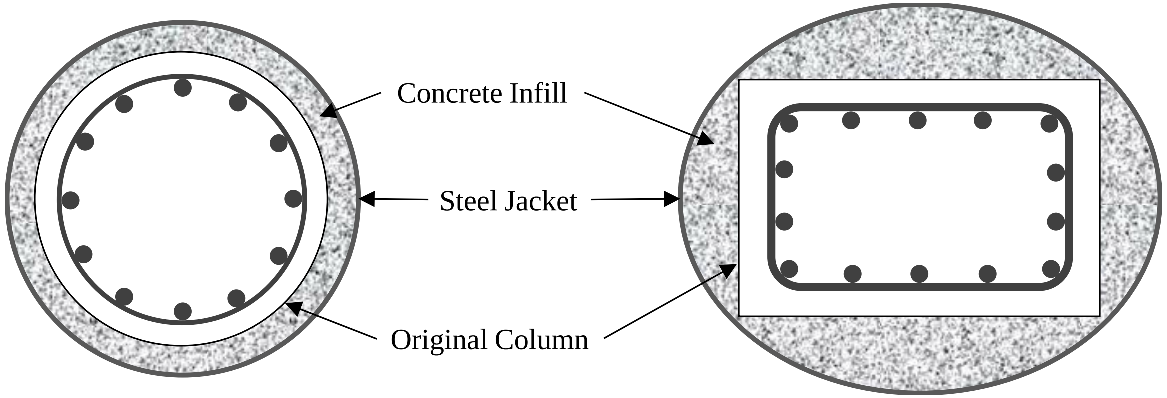
- **Confinement Techniques**
  - **Active**
    - **External Pre-stressing**
      - ✓ Flexural and shear Stiffness
      - ○ Only for circular column
    - **SMA Spirals**
      - ✓ Strength, stiffness and ductility
      - ○ Costly
      - ○ temperature sensitive
      - ○ Only for circular column
  - **Passive**
    - **Concrete Jacketing**
      - ✓ Flexural and shear Strength
      - ✓ Low cost
      - ✓ Underwater work
      - ○ Biaxial stress state causes reduced compressive strength
    - **Steel Jacketing**
      - ✓ Low cost
      - ✓ Readily available
      - ✓ Good aesthetic
      - ○ Corrosion
      - ○ Heavy weight
      - ○ Difficulty in cutting and welding
    - **ECC Jacketing**
      - ✓ Ductile
      - ✓ High energy dissipation
      - ✓ Strain hardening
      - ○ High cost
      - ○ Limited design guidelines
    - **Ferro Cement Jacketing**
      - ✓ Low cost
      - ✓ Easy application
      - ✓ Both circular and rectangular column
      - ○ Low durability
      - ○ Poor aesthetics
    - **FRP Composite Jacketing**
      - ✓ High strength
      - ✓ Lightweight and easy application
      - ✓ Flexural and shear enhancement
      - ○ Costly

Available Retrofitting Techniques

External Pre-stressing



Concrete Jacketing



Steel Jacketing

FRP Jacketing

Effect of GFRP Confinement on the Compressive Strength of Concrete

FRP COMPOSITES

- Carbon Fiber Reinforced Polymer (CFRP)
- Glass Fiber Reinforced Polymer (GFRP)
- Aramid Fiber Reinforced Polymer (AFRP)
- Basalt Fiber Reinforced Polymer (BFRP)

→ Cheaper
→ Tensile Strength, Corrosion resistant
→ Available and reliably serve the purpose

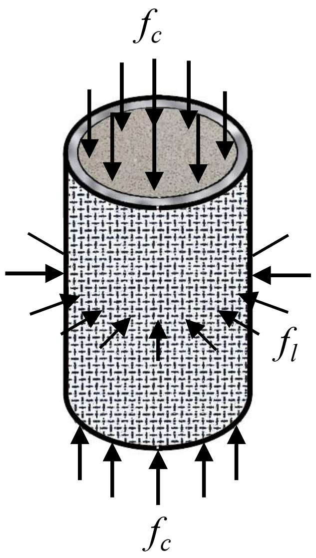
Type of FRP	Tensile Strength (MPa)	Elastic Modulus (GPa)	Strain at Break (%)
CFRP	1720-3690	120-580	0.5-1.9
GFRP	480-1600	35-51	1.2-3.1
AFRP	1720-2540	41-125	1.9-4.4
BFRP	1035-1650	45-59	1.6-3.0

+ Polyester Resin (epoxy)

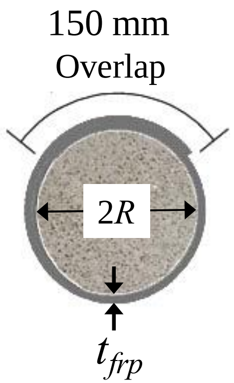
+ Methyl Ethyl Ketone Peroxide (catalyst)

Fig: Bi-directional Woven Roving Glass Fibers

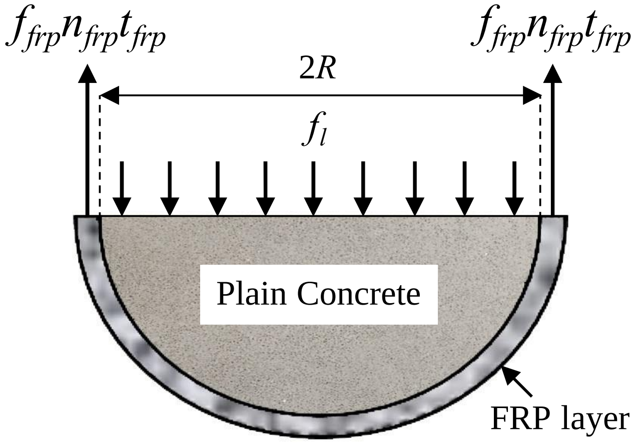
FRP CONFINEMENT MECHANISM



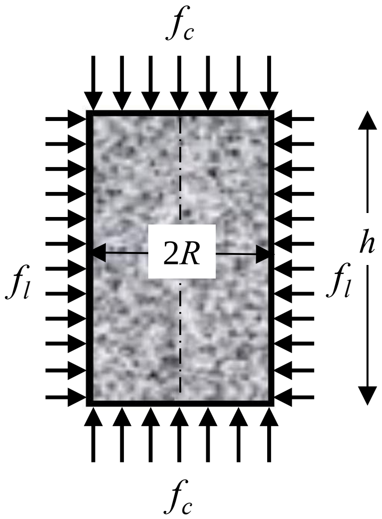
FRP wrapped cylinder



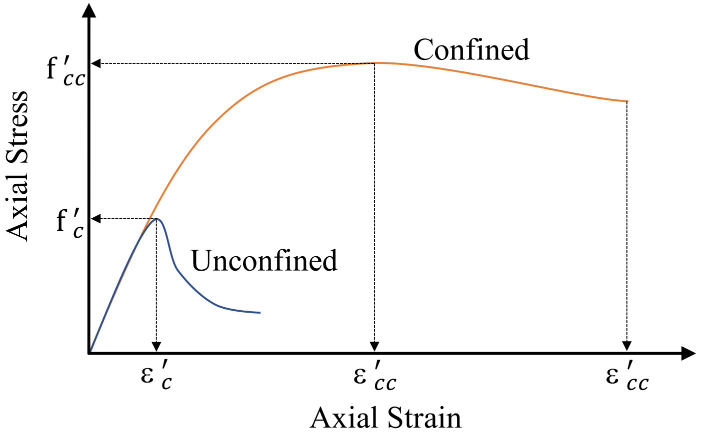
Overlapping on final layer



Free body diagram of FRP confined concrete

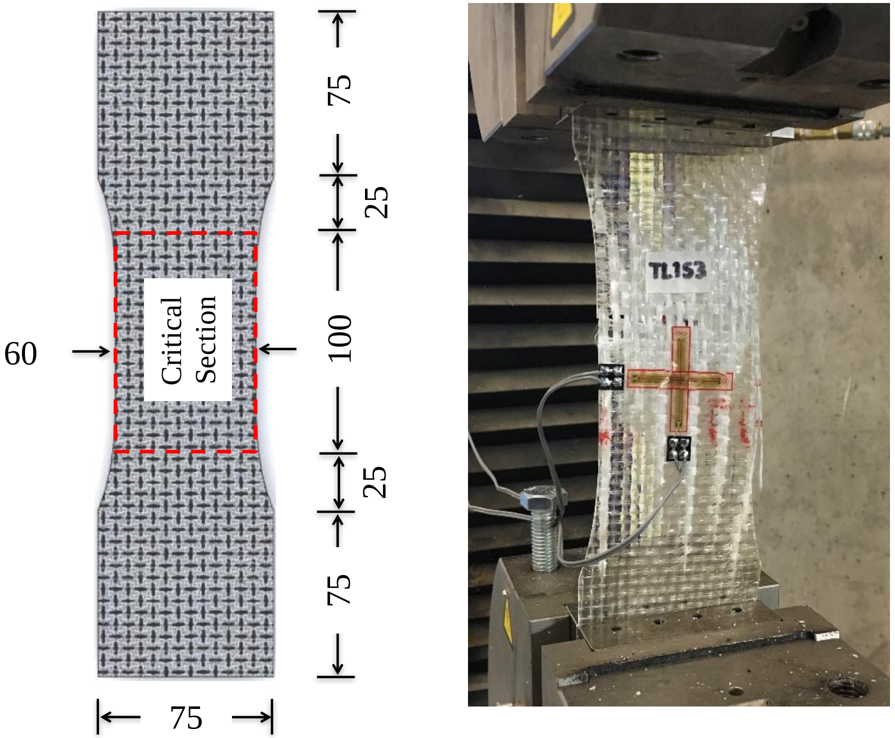


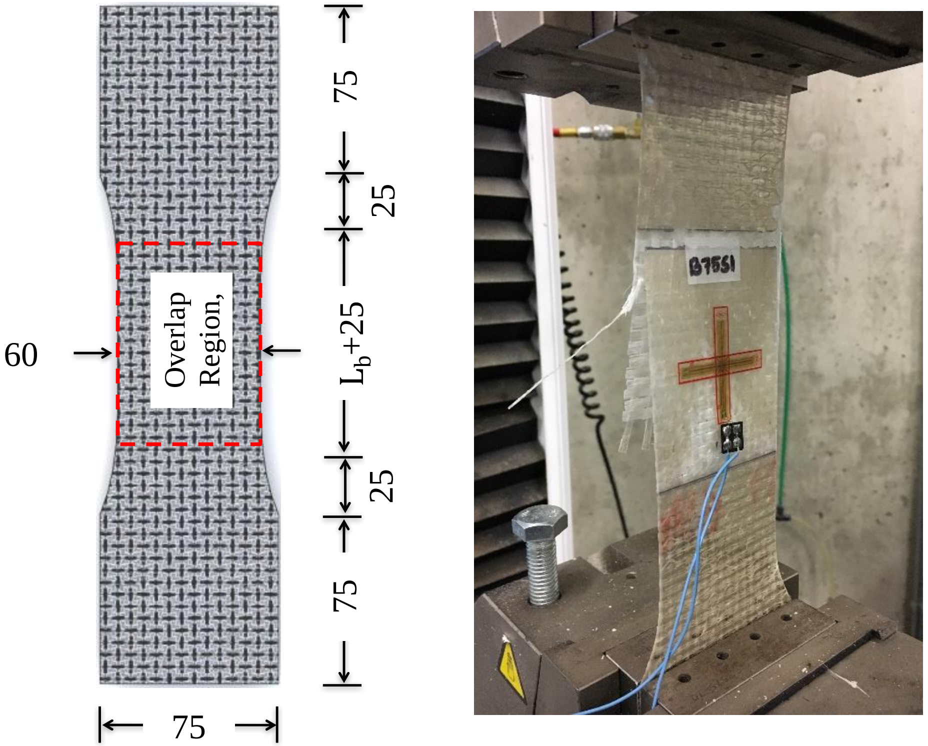
Tri-axial stress stage of concrete



Resulting strength (Mander et al. 1988)

Experimental Investigation on Materials



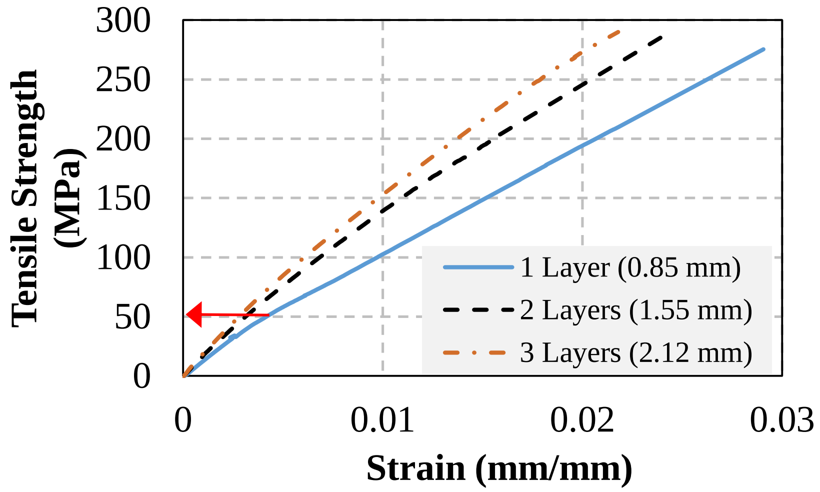


*all dimensions are in mm

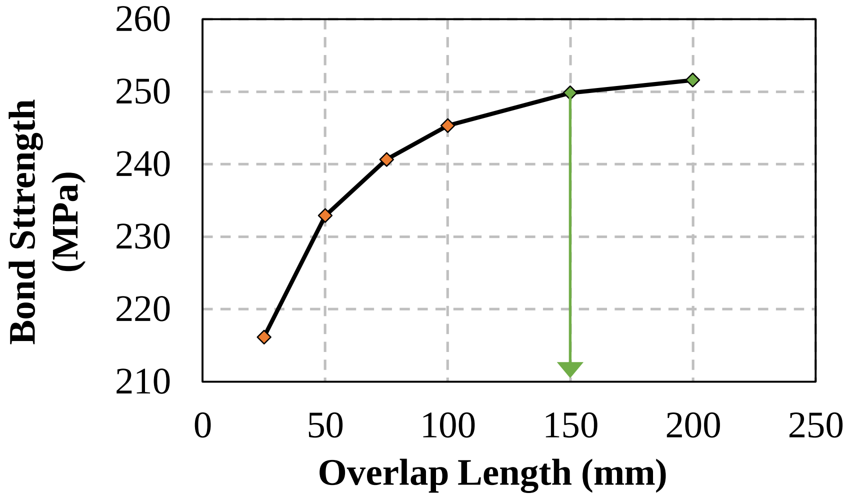
Coupon test for tensile strength

Coupon test for bond strength

PROPERTIES OF GFRP



Stress-strain relationship of GFRP



Bond between GFRP layers

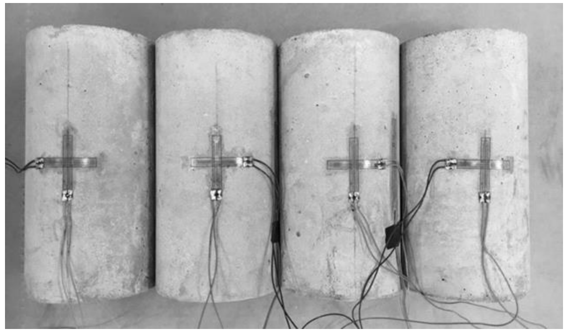
Table - Properties of GFRP obtained from tests

Properties	Value
Tensile strength (MPa)	275-290
Young's modulus of elasticity (GPa)	13.5-18
Fracture strain (%)	2.2-2.9
Strength of epoxy (MPa)	50
Optimum overlap length (mm)	150

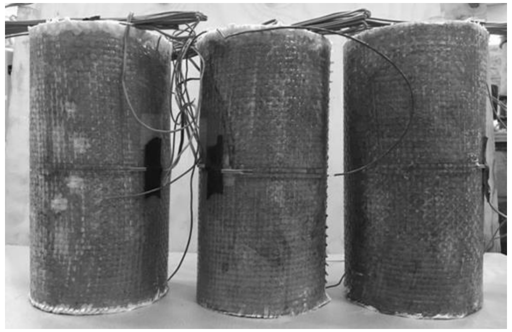
APPLICATION OF GFRP ON TEST SPECIMENS

Specimen

- **Type 22**
  22 MPa
  Old Infrastructure
- **Type 32**
  32 MPa
  Recent Construction



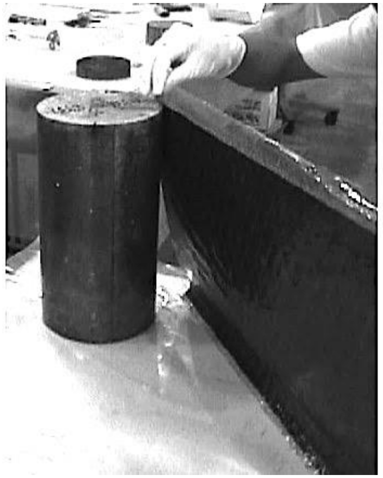
Control cylinders



GFRP confined cylinders

Priming

Epoxy on glass fiber

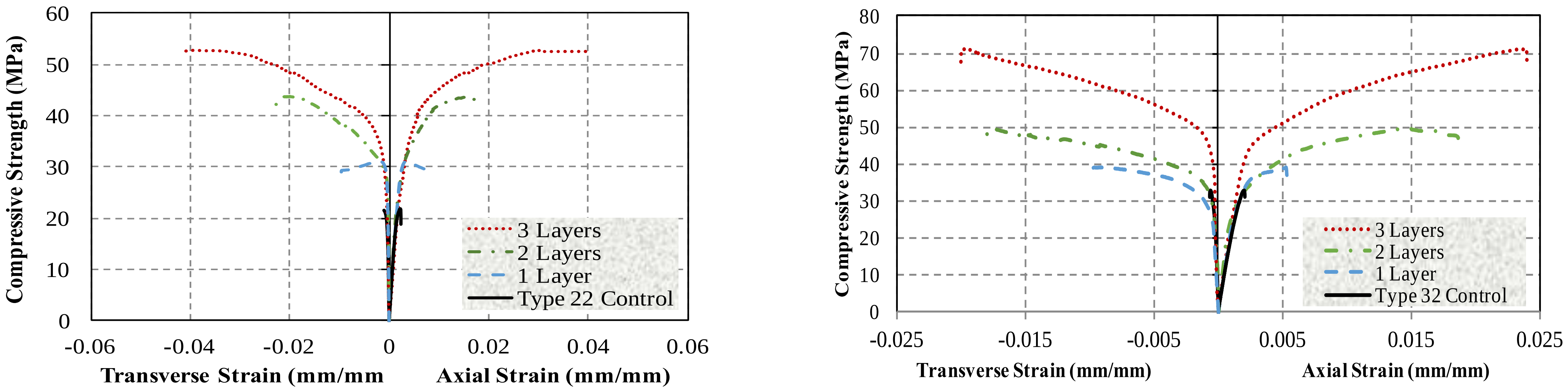


First layer

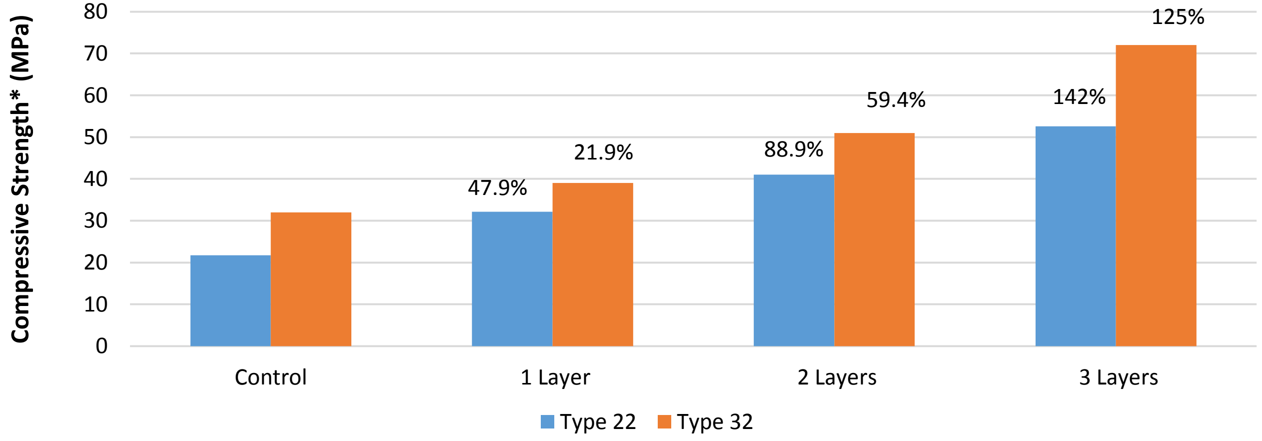
Pressing with grooved roller

Last layer

Effect of GFRP Confinement



Stress-strain curves for Type 22 and Type 32 cylinders



* Average of 3 specimens

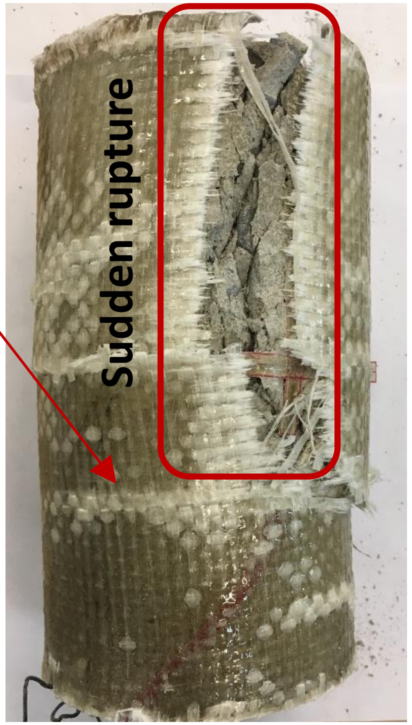
Failure Mode

Control Specimen

1 layer of GFRP confinement

Distortion under compression

2 layers of GFRP confinement



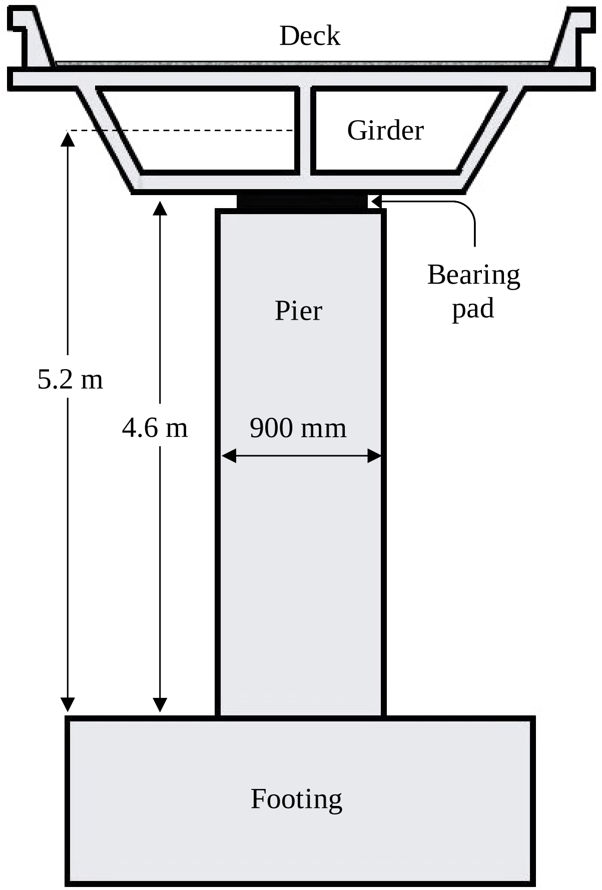
3 layers of GFRP confinement

SUMMARY

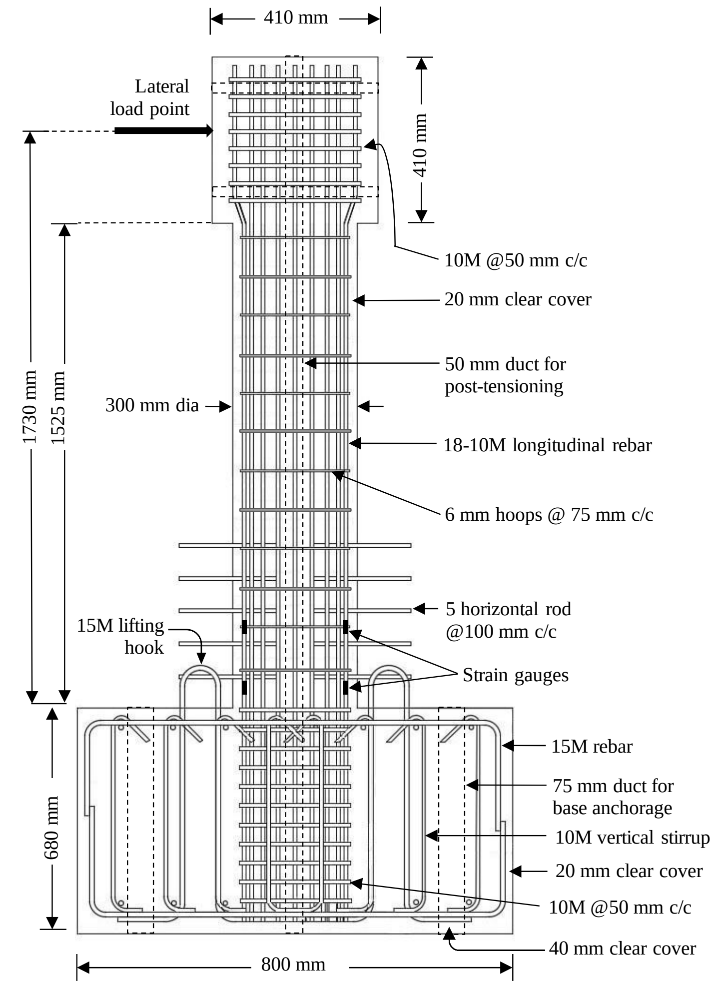
- GFRP confinement can significantly improve compressive strength and strain capacity of low strength concrete.
- Multi-layer of GFRP (thick) show better mechanical properties than a single layer.
- ⇧ Number of layer = ⇧ Compression carrying capacity + sudden blast type failure **X**
- Two layer of GFRP is considered to be the optimum confinement as it improves the compressive strength by 101% and shows gradual failure of fibers.

Cyclic Performance of RC Circular Bridge Piers Repaired and Retrofitted with GFRP

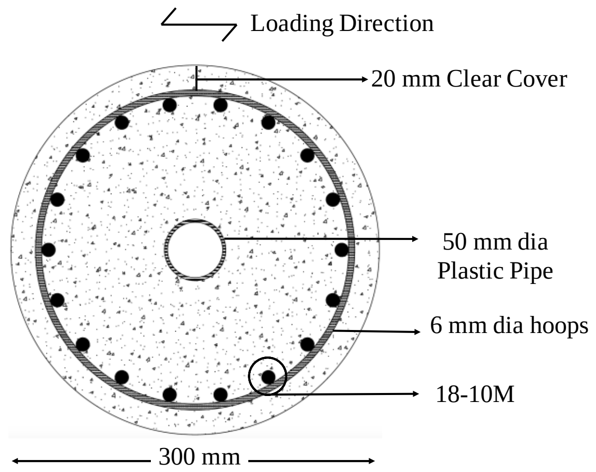
DESIGN AND GEOMETRY OF BRIDGE PIER



Prototype



Test specimen



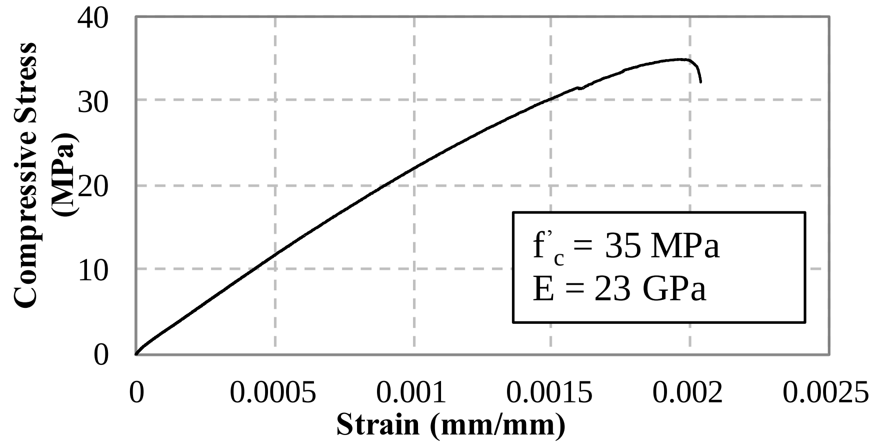
Cross-sectional detailing

DESIGN AND GEOMETRY OF BRIDGE PIER

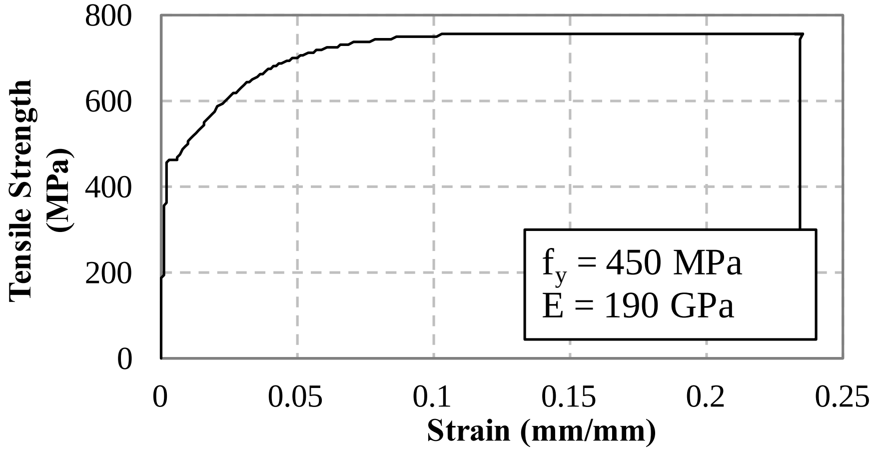
Table : Geometric comparison of prototype and test specimens

Description of properties	Prototype	Test Specimens
Diameter (mm)	900	300
Effective height (m)	5.2	1.73
Clear cover (mm)	60	20
Longitudinal reinforcement ratio (%)	2.52	2.55
Volumetric ratio of lateral reinforcement (%)	0.173	0.178
Tie spacing (mm)	15M @ 300	6mm @ 75
Axial Load, $P/f'_c A_g$ (%)	10	10
Yield Strength of Longitudinal reinforcement (MPa)	450	450
Yield Strength of transverse reinforcement (MPa)	400	400
Compressive strength of concrete (MPa)	35	35
Thickness of GFRP layer (mm)		1.55

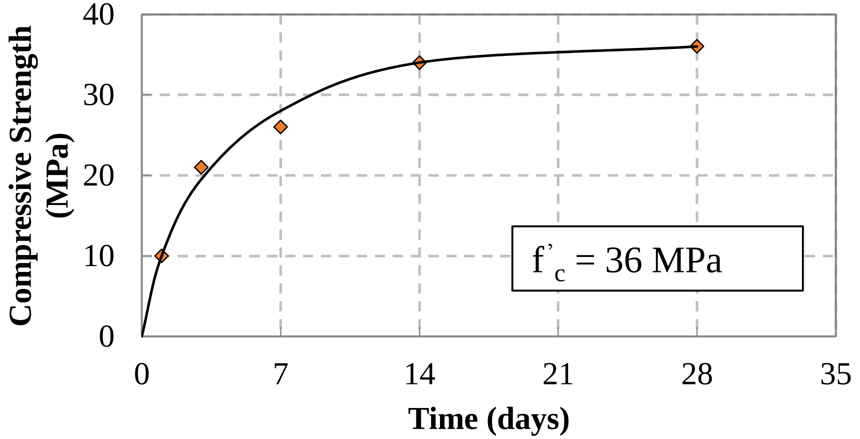
Material Properties



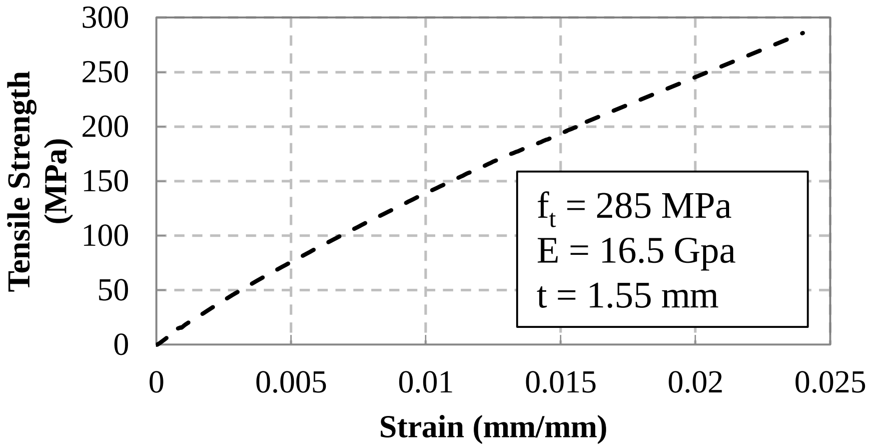
Ready-mix Concrete



Steel

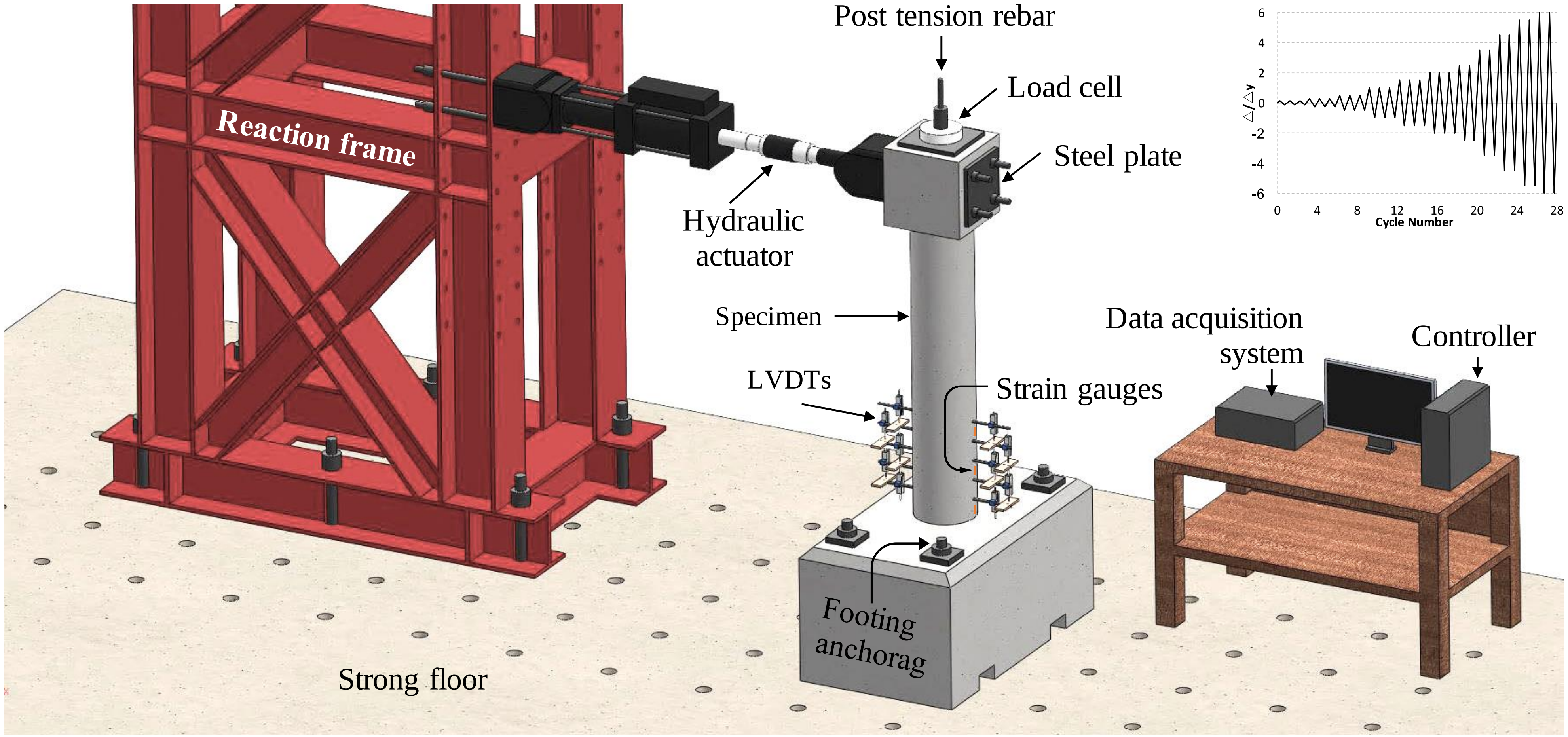


Repair Concrete



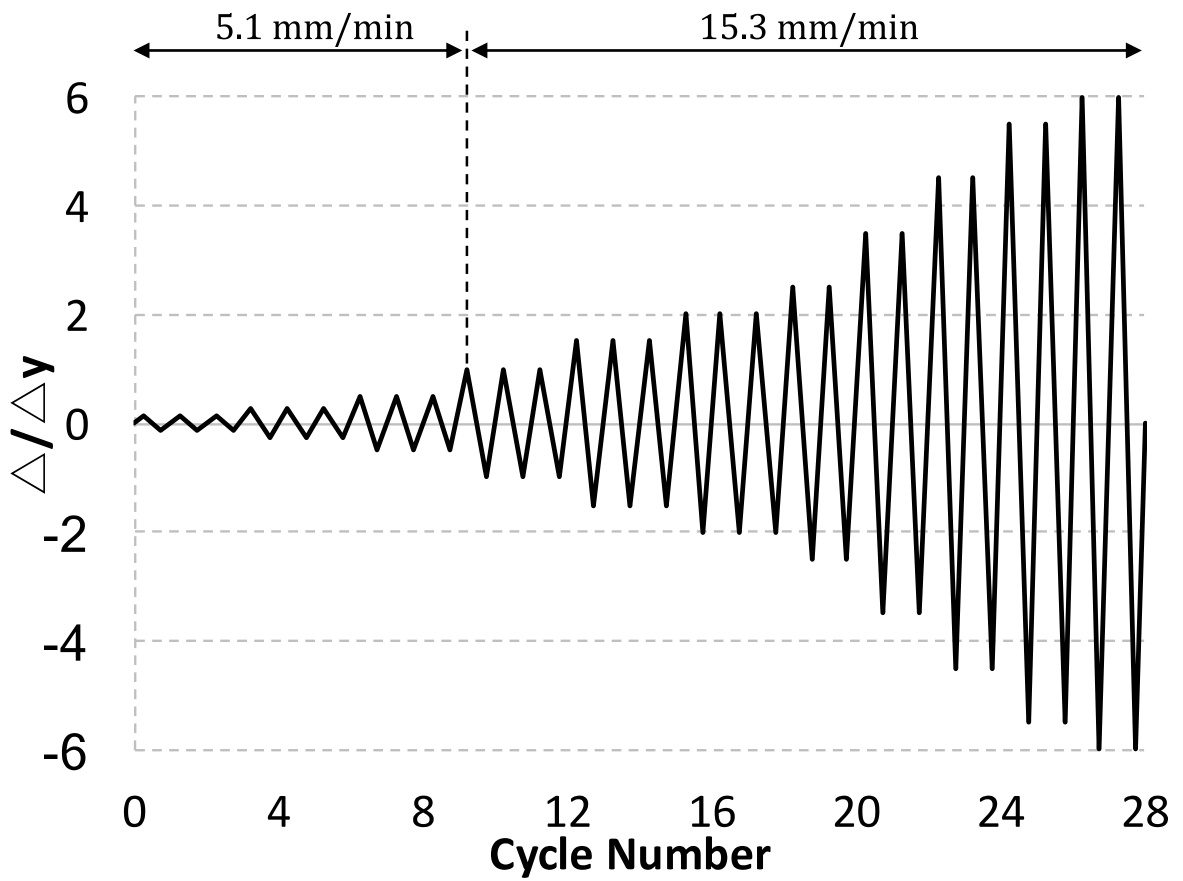
GFRP

Test Setup



Setup for bridge pier test under lateral cyclic load

TEST SETUP



Applied loading protocol on test specimen
(Chai et al. 1991, Ghannoum et al. 2012, Teng et al. 2013)

Pseudo-static loading Rate:
(Ghannoum et al. 2012)

Before Yielding: 5.1 mm/min

After Yielding: 15.3 mm/min

TEST SETUP

GFRP retrofitted pier under lateral cyclic test

Repairing and Retrofitting Method

Damaged Pier

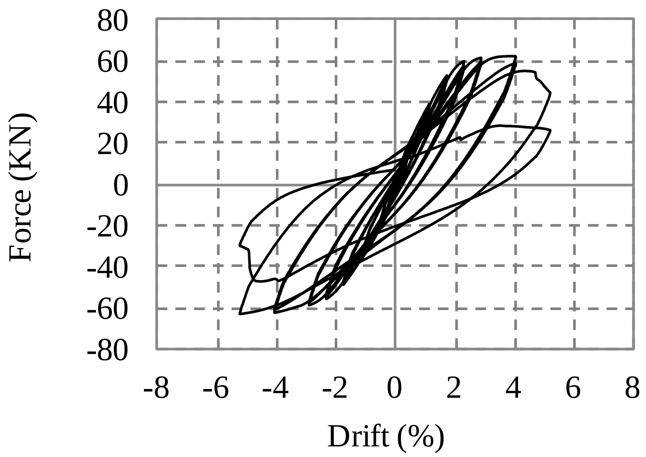
Vertical Support and Axial Load Removal

Formwork for pouring repair concrete

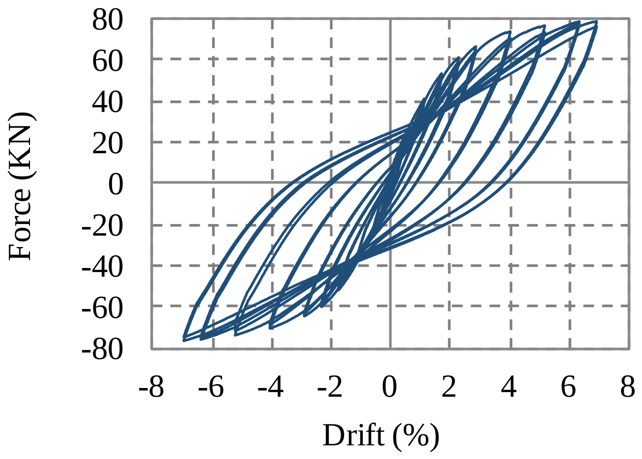
Repaired pier

Repaired pier with GFRP confinement

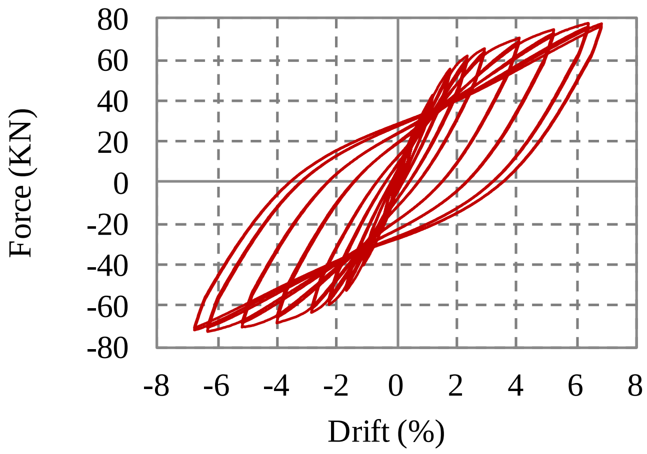
Cyclic Response



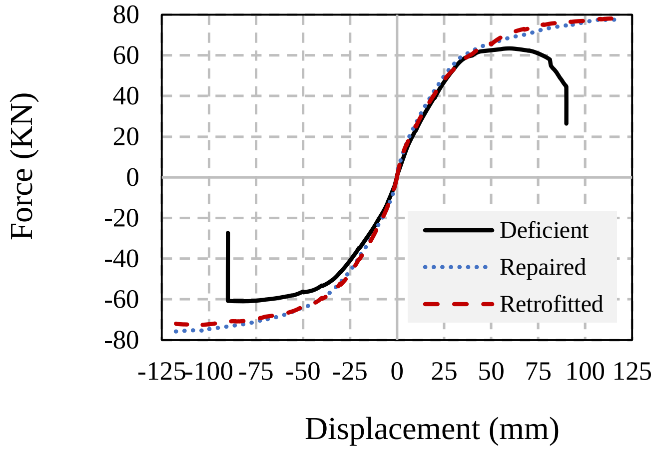
Deficient Pier



Repaired Pier



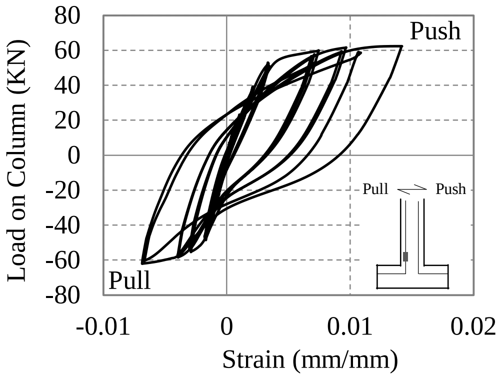
Retrofitted Pier



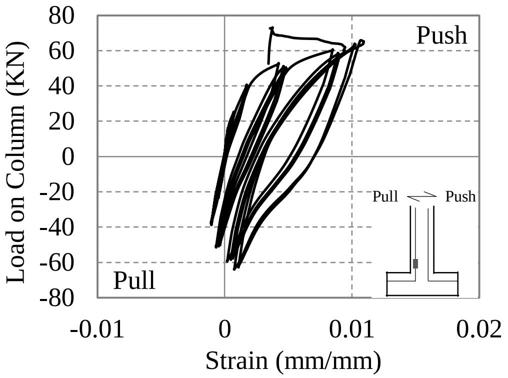
Skeleton Curve

	Maximum Force (kN)	Maximum Drift (%)
Deficient	62.3	4
Repaired	>78 ↑ 25%	>6.9 ↑ 73%
Retrofitted	>79 ↑ 27%	>6.9 ↑ 73%

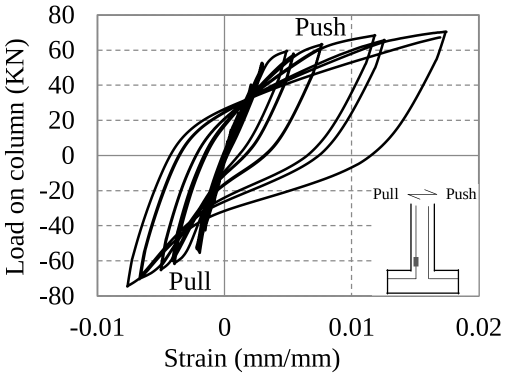
Strain Response



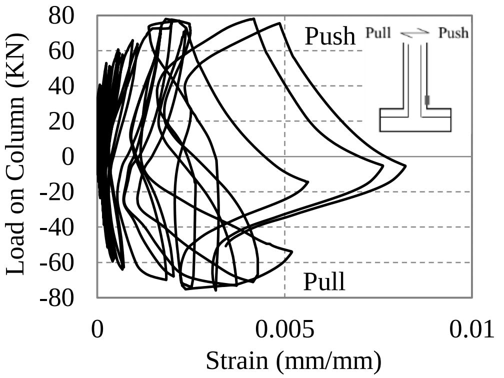
Steel (deficient)



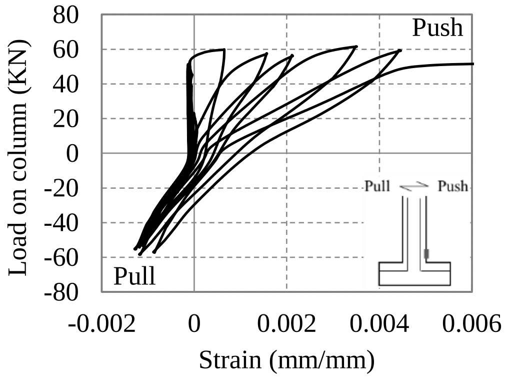
Steel (repaired)



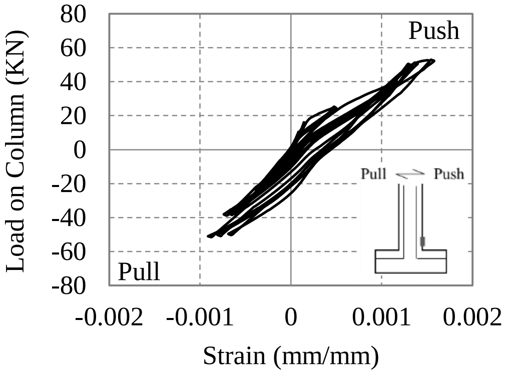
Steel (retrofitted)



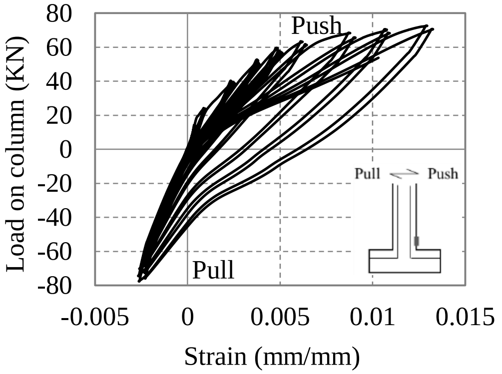
GFRP (repaired)



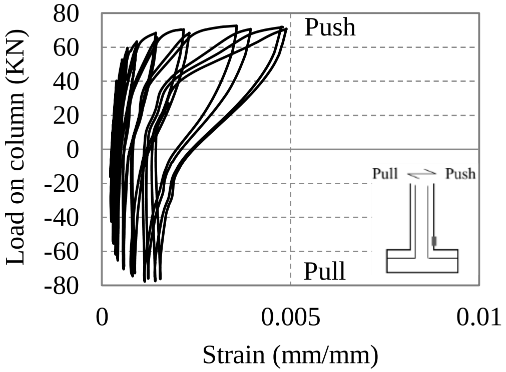
Concrete (deficient)



Concrete (repaired)

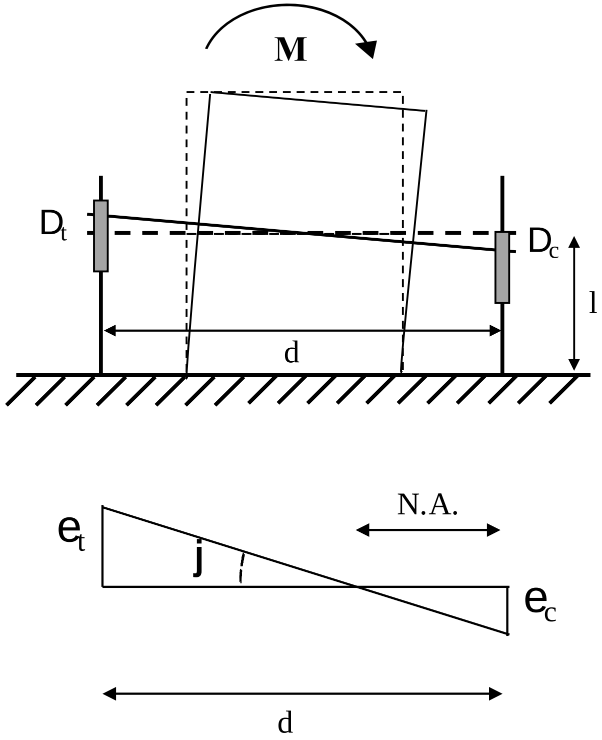


Concrete (retrofitted)



GFRP (retrofitted)

Moment-Curvature Response

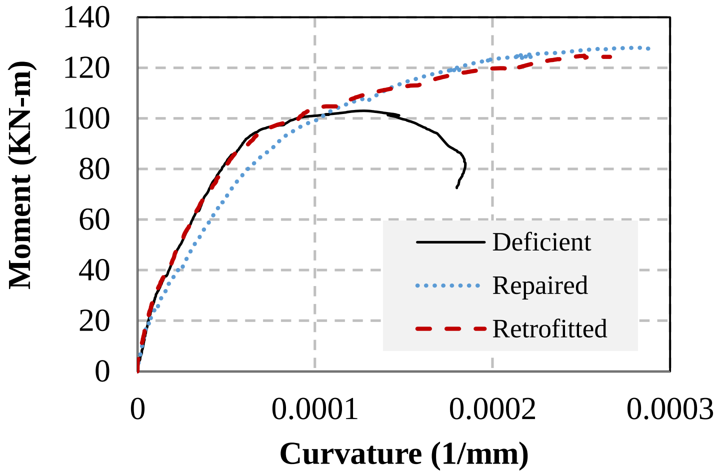


Measurement of curvature (φ)
(Ibrahim et al. 2016)

$$NA = \frac{d * \varepsilon_c}{\varepsilon_t + \varepsilon_c}$$

$$\varphi = \frac{\varepsilon_c}{NA} = \frac{\varepsilon_t}{d - NA} = \frac{|\varepsilon_t| + |\varepsilon_c|}{d}$$

$$M = F * L_e$$



Moment-curvature relationship obtained from test

Ductility Analysis

Yield / Ultimate Strain → **Strain Response**
- Force
- Moment

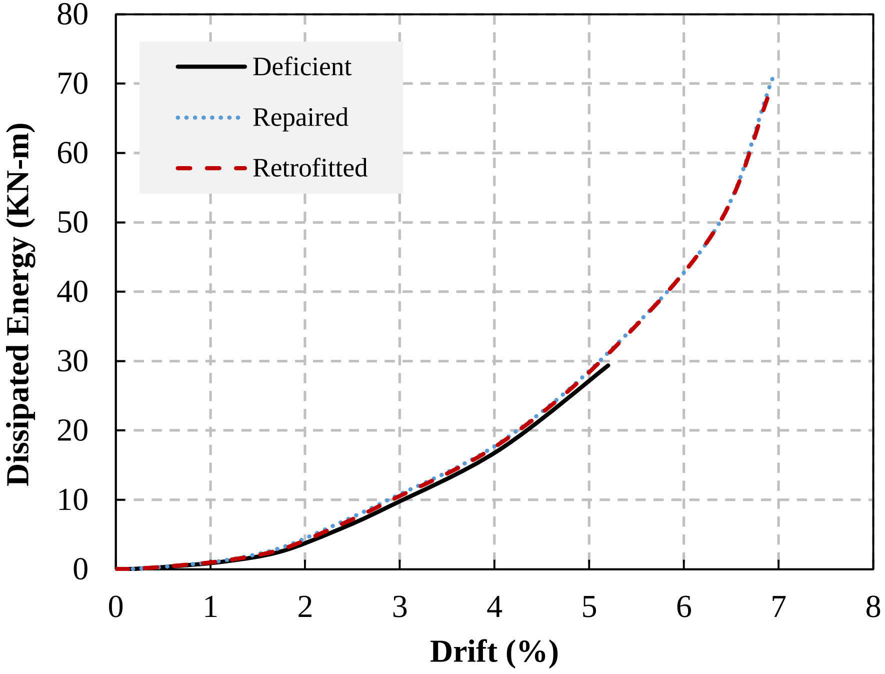
→ **Cyclic Response**
- Displacement

→ **Moment-Curvature Response**
- Curvature

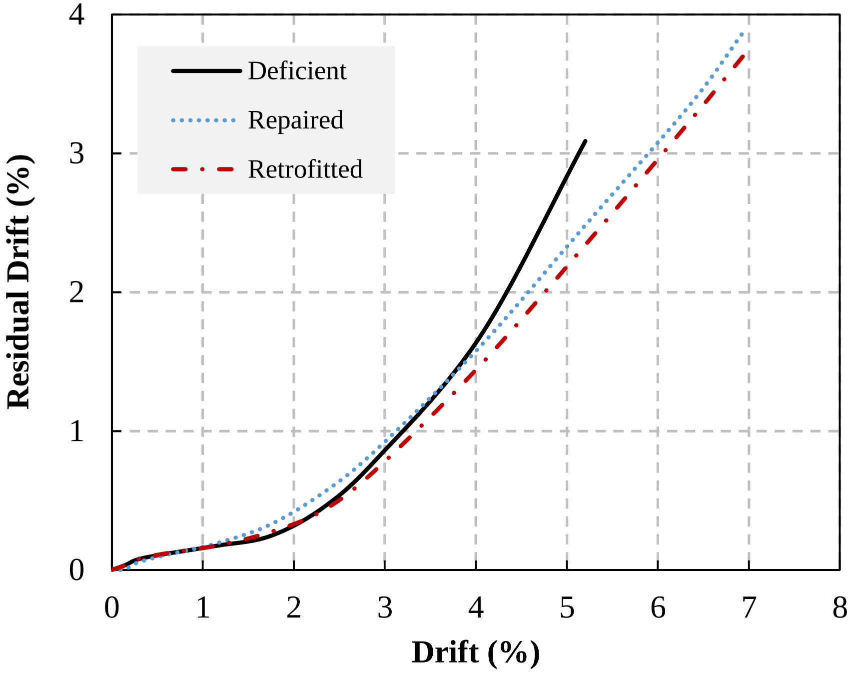
Table: Ductility of Piers obtained from test results

Specimen type	**Yielding**				**Ultimate**				**Displacement ductility**	**Curvature ductility**
	Force (kN)	Displacement (mm)	Moment (kN-m)	Curvature (1/mm)	Force (kN)	Displacement (mm)	Moment (kN-m)	Curvature (1/mm)		
Deficient	38.9	19.6	64.38	3.52×10^{-5}	62.3	69.3	103.11	9.64×10^{-5}	3.54	2.74
Repaired	43.13	25.2	71.38	5.25×10^{-5}	77.9	120	127.6	2.9×10^{-4}	>4.76	>5.52
Retrofitted	39.1	19.2	64.71	3.44×10^{-5}	79	120	130.75	2.66×10^{-4}	>6.25	>7.73

ENERGY DISSIPATION AND RESIDUAL DRIFT

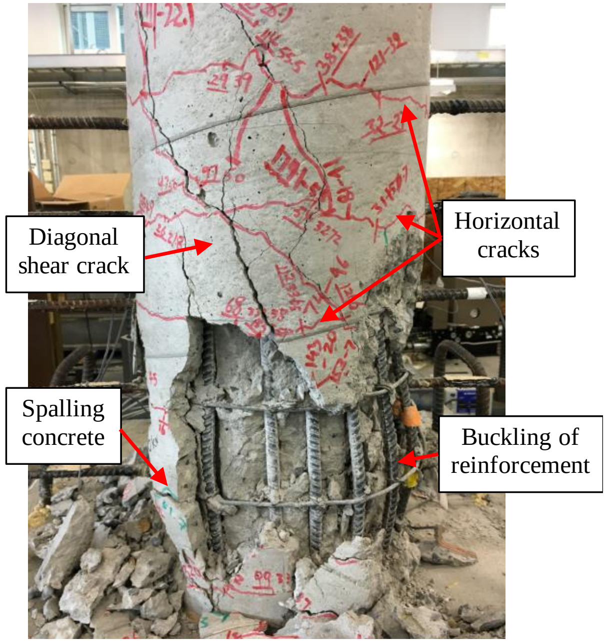


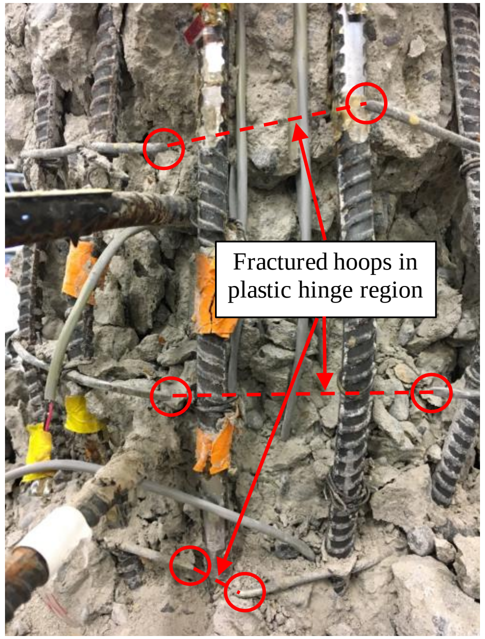
Cumulative energy dissipation

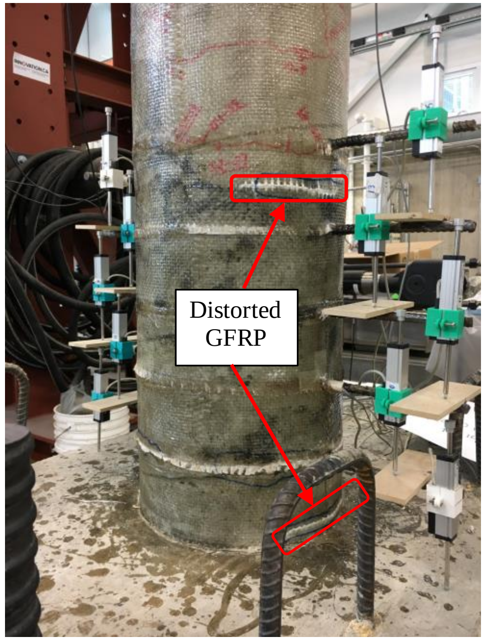


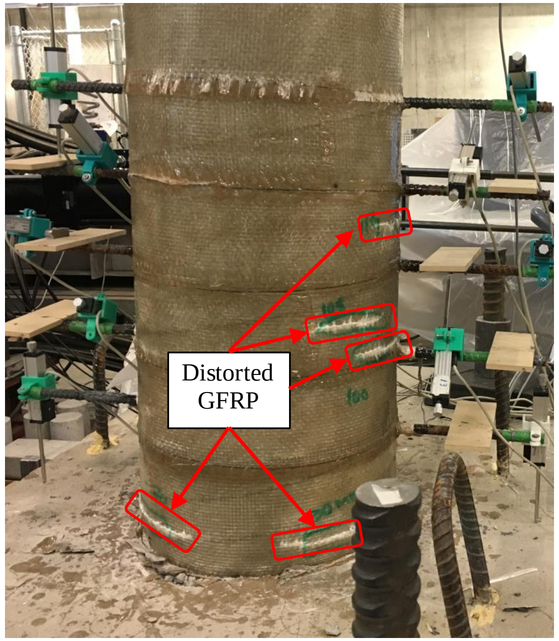
Residual Drift

FAILURE MODE









Deficient Pier

Repaired Pier

Retrofitted Pier

SUMMARY

- For the seismically damaged RC circular piers, repairing and retrofitting technique using passive confinement demonstrated the purpose of restoring strength and ductility of piers.
- The deficient pier once confined with GFRP jacketing showed increased lateral capacity (27%) and ductility (73%).
- From the experimental results it was found that, initial stiffness doesn't change for passive confinement techniques like GFRP jacketing.
- Except some horizontal distortions, GFRP repaired and retrofitted pier didn't show any significant damage up to the applied drift in the test.
- Damaged column repaired and strengthened with GFRP can perform similar to a retrofitted column under constant axial load and cyclic lateral load.

Thanks for your attention

Q

&

A

Acknowledgements

NSERC
CRSNG

UBC THE UNIVERSITY OF BRITISH COLUMBIA

ALAMS
Applied Laboratory for Advanced Materials & Structures