Convertible Bond Test Apparatus for EB FRP, NSM FRP, FRCM, and Allied Systems: Proof of Concept

Faisal Mukhtar

Associate Professor

Dep't of Civil and Env. Engineering, KFUPM

faisalmu@kfupm.edu.sa

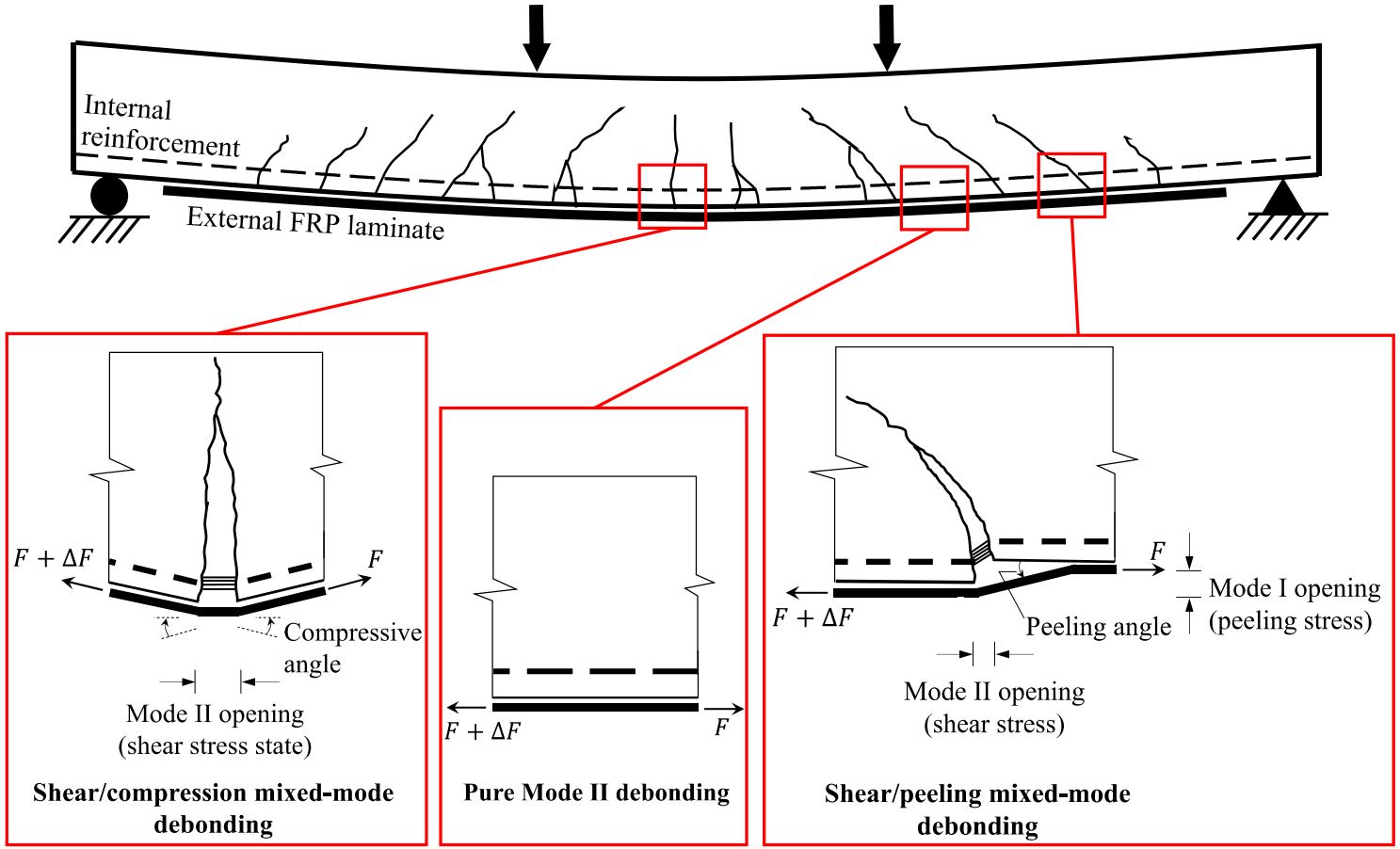
Outline

- Introduction
- Challenges and Goal
- Experimental Investigation
- Results
- Conclusions
- Future Work

Introduction

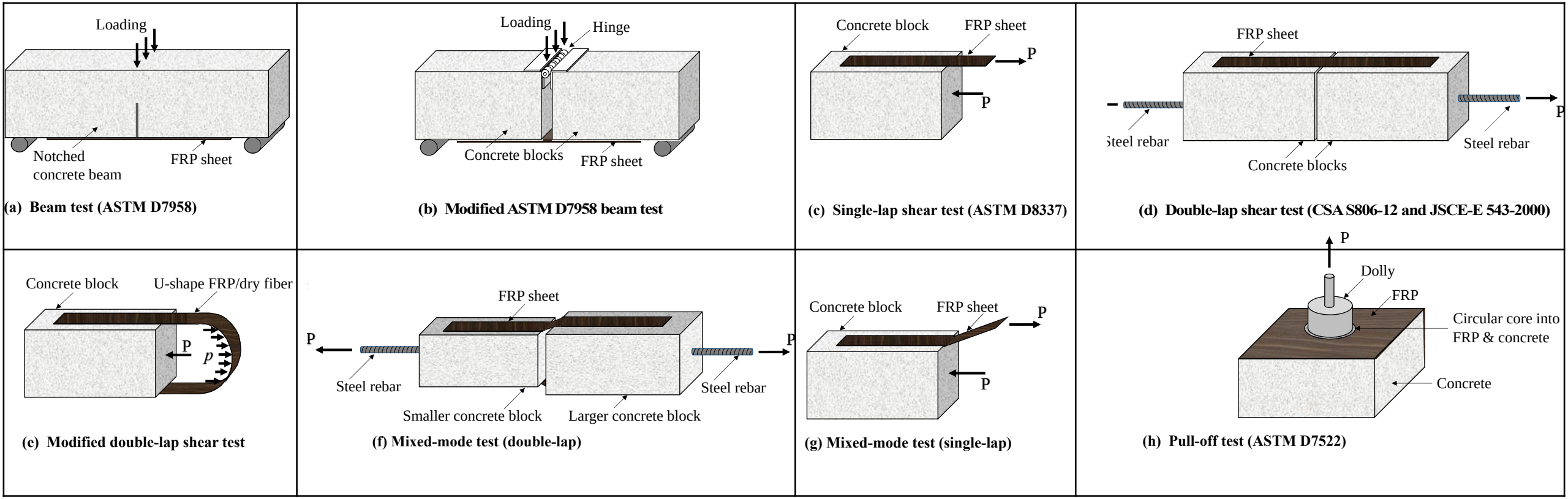
Why Bond Testing?

- Useful for the strengthening system design.
- Different tests mimics the different possible field scenario.



Introduction

Existing FRP-Concrete Bond Test Types:



Challenges and Goal

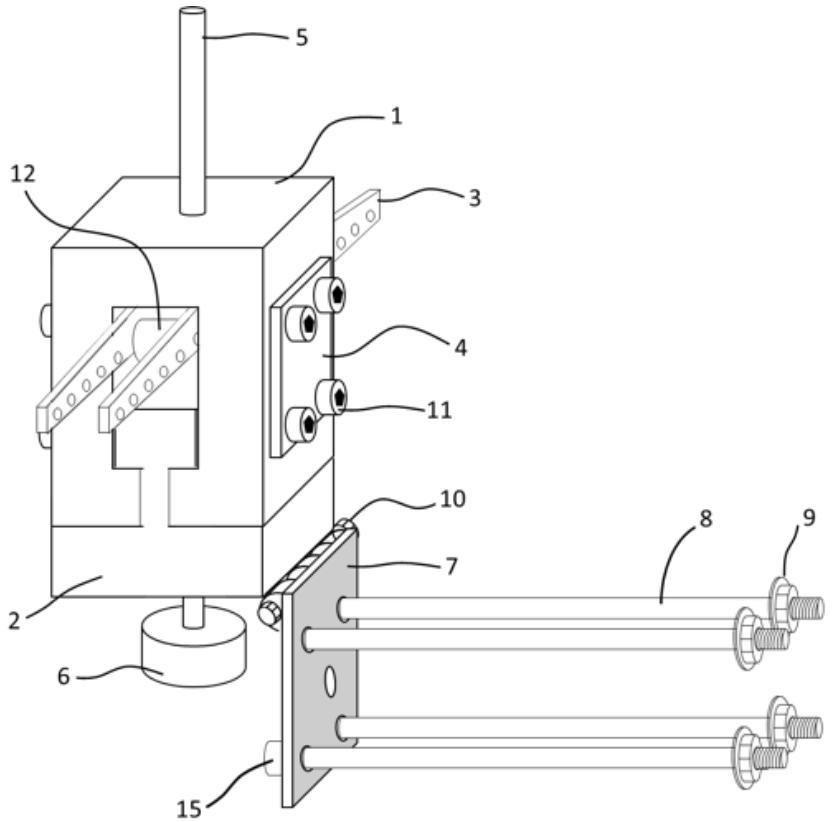
Existing FRP-Concrete Bond Test Types: Issues

- Individual test limitations
- Large dispersion of results
- Unavailability of standardized apparatus hampers FRP-concrete bond tests from capturing all scenarios illustrated earlier
- Each test requires its purpose-built system, and the adoption of a double-lap setup is common
- Non-convertibility of the double-lap setup to other test methods

Goal: Develop a robust test framework for comprehensive bond assessment of FRP-concrete bond and deploy the same for comparison of bond test methods.

Solution Phase 1: Test Device for EB Sheets

- Proposed solution for consistency: Universal Debonding Test Apparatus
- Patented device[1-3] convertible to all EB FRP-concrete test types
- Double-lap shear test limited to wet layup FRP



[1] F. Mukhtar (2023). U.S. Patent No. 11,169,082 B2. U.S. Patent and Trademark Office.
[2] F.M. Mukhtar (2023). U.S. Patent No. 11,719,620 B2 . U.S. Patent and Trademark Office.
[3] F.M. Mukhtar (2023). U.S. Patent No. 11,719,621 B2 . U.S. Patent and Trademark Office.

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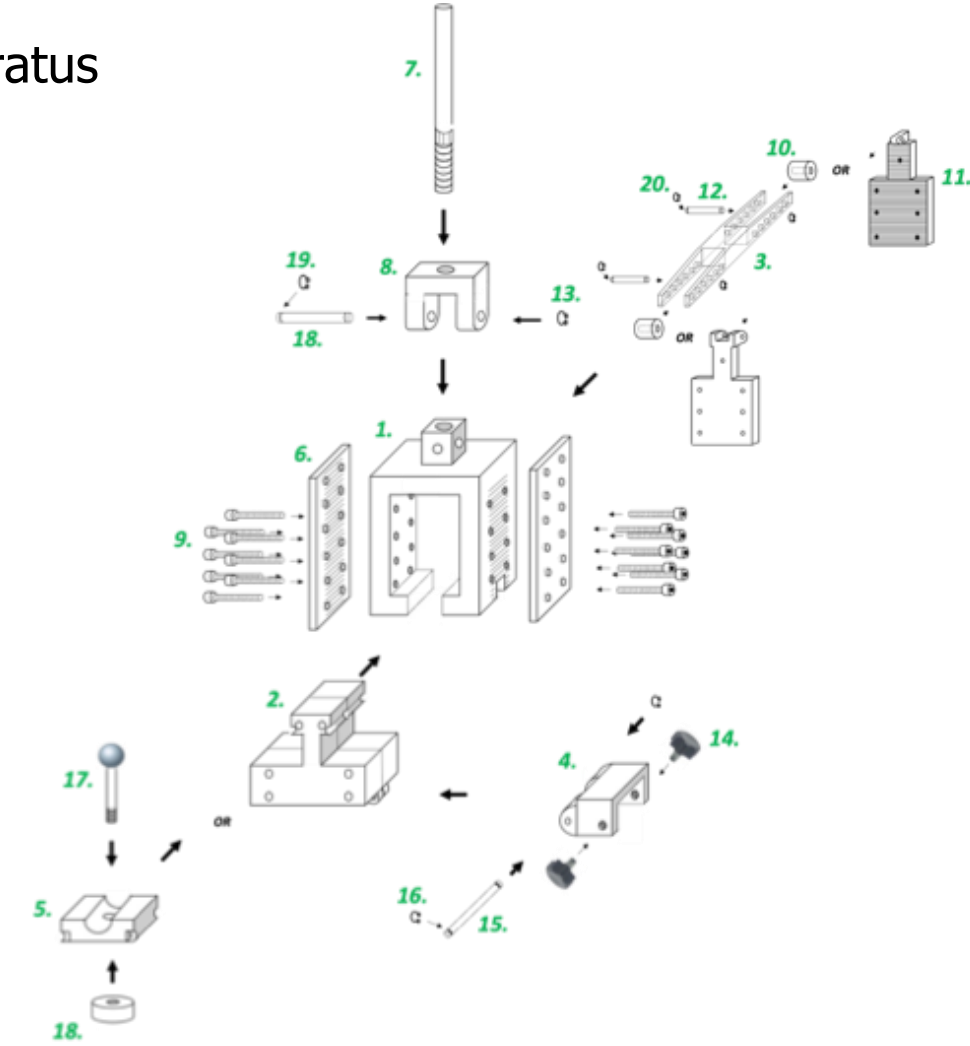
Composites for strengthening						
Typical literature field applications[1-3]						
	Wet layup FRP	Pultruded FRP laminate	FRCM	NSM FRP rods and strips	Heat activated NSM Fe-based shape memory alloy rods	Heat activated NSM Fe-based shape memory alloy plates

[1] rawlins (2024). https://www.rawlinspaints.com/carbon-fibre-fabric. Accessed March 11, 2024.
[2] Sika Group (2023). Sika CarboDur® for Structural Reinforcement. Zürich, Switzerland .
[3] re-fer (2023). re-plate 120 / 1.5 mm product data sheet. re-fer.eu Strengthening Solutions.

Solution Phase 2: Extension to Other Systems

- Proposed solution for consistency: Universal Debonding Test Apparatus
- Patented device[1-3] convertible to all EB FRP-concrete test types
- Double-lap shear test limited to wet layup FRP
- Current study redesigns the device and extends its applicability [4] to: (1) Pultruded EB-FRP
  (2) NSM FRP or SMA
  (3) FRCM
  (4) etc.



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[4] F. Mukhtar (2023). U.S. Patent Application No. 17687927 . U.S. Patent and Trademark Office.

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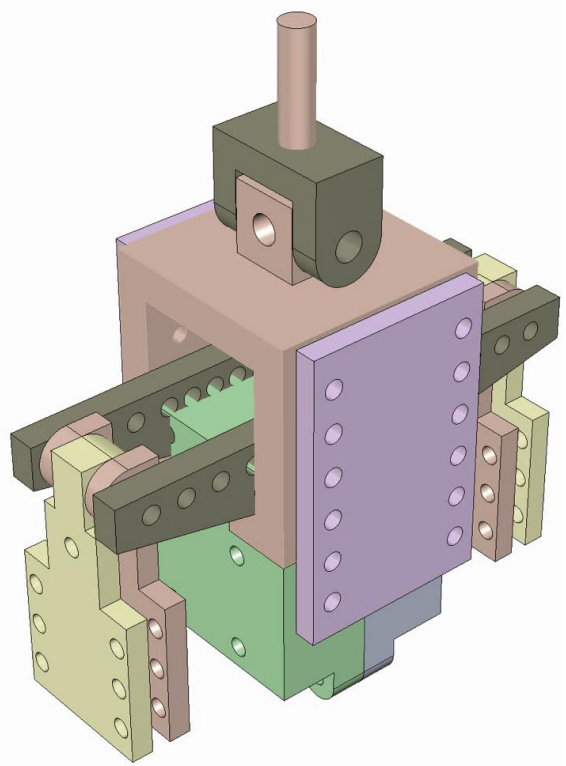

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[3] F.M. Mukhtar (2023). U.S. Patent No. 11,719,621 B2 . U.S. Patent and Trademark Office.
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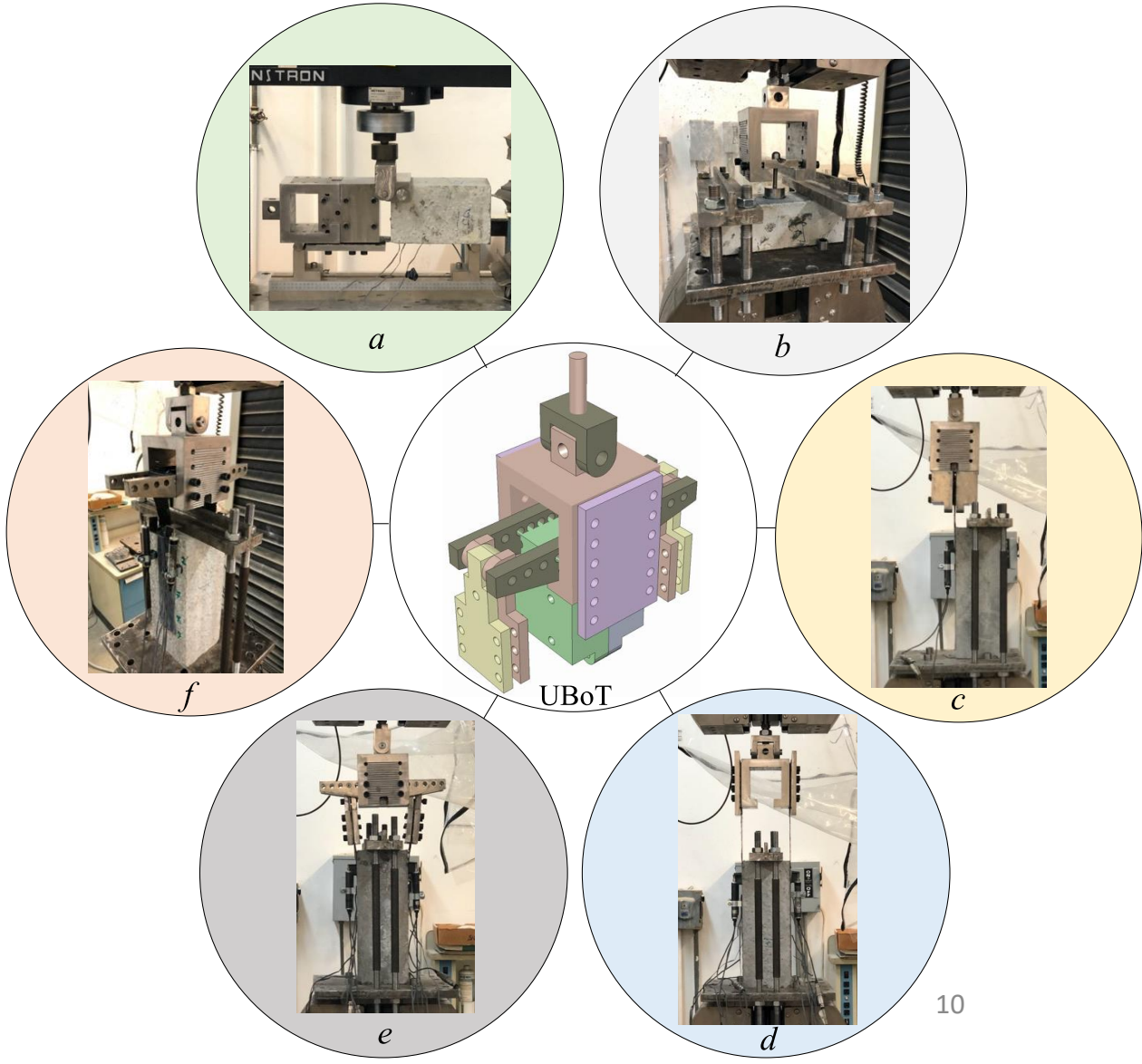
Solution Phase 2: Extension to Other Systems

- Application of the UBoT to:

(1) Wet layup and pultruded FRP systems

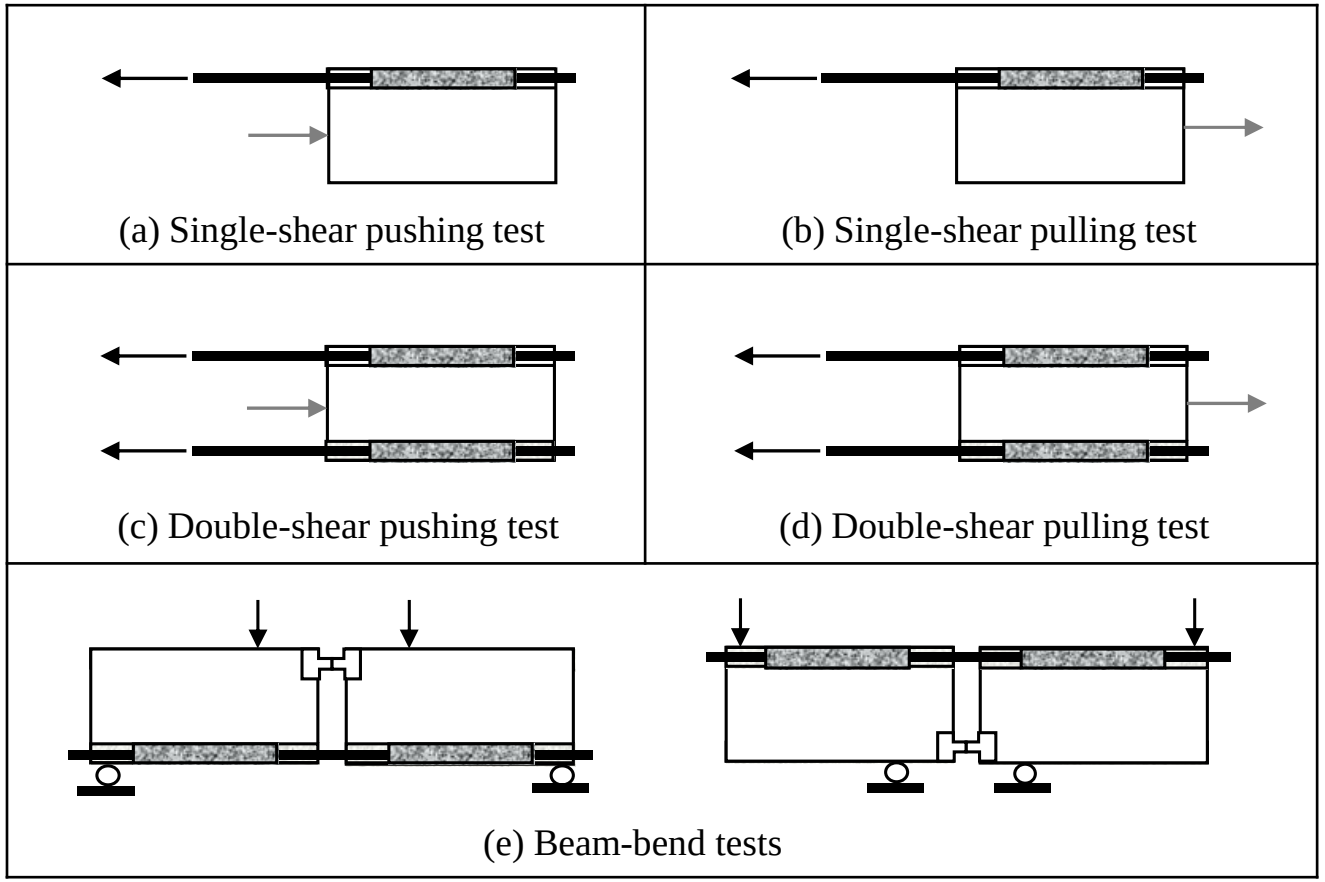
(2) FRCM

(3) Shape memory alloy (SMA) plates



Solution Phase 2: Extension to Other Systems

- Existing setups for evaluating the NSM FRP bond behavior [1]:



[1] Bilotta, A., Ceroni, F., Barros, J. A., Costa, I., Palmieri, A., Szabó, Z. K., ... & Pecce, M. (2016). Bond of NSM FRP-strengthened concrete: Round robin test initiative. Journal of Composites for Construction, 20(1), 04015026.

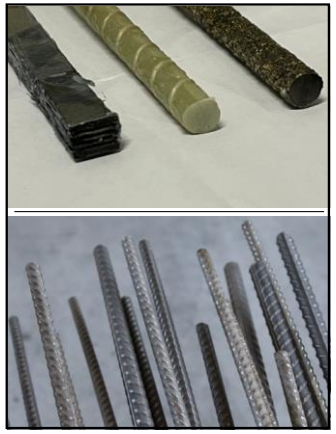
Solution Phase 2: Extension to Other Systems

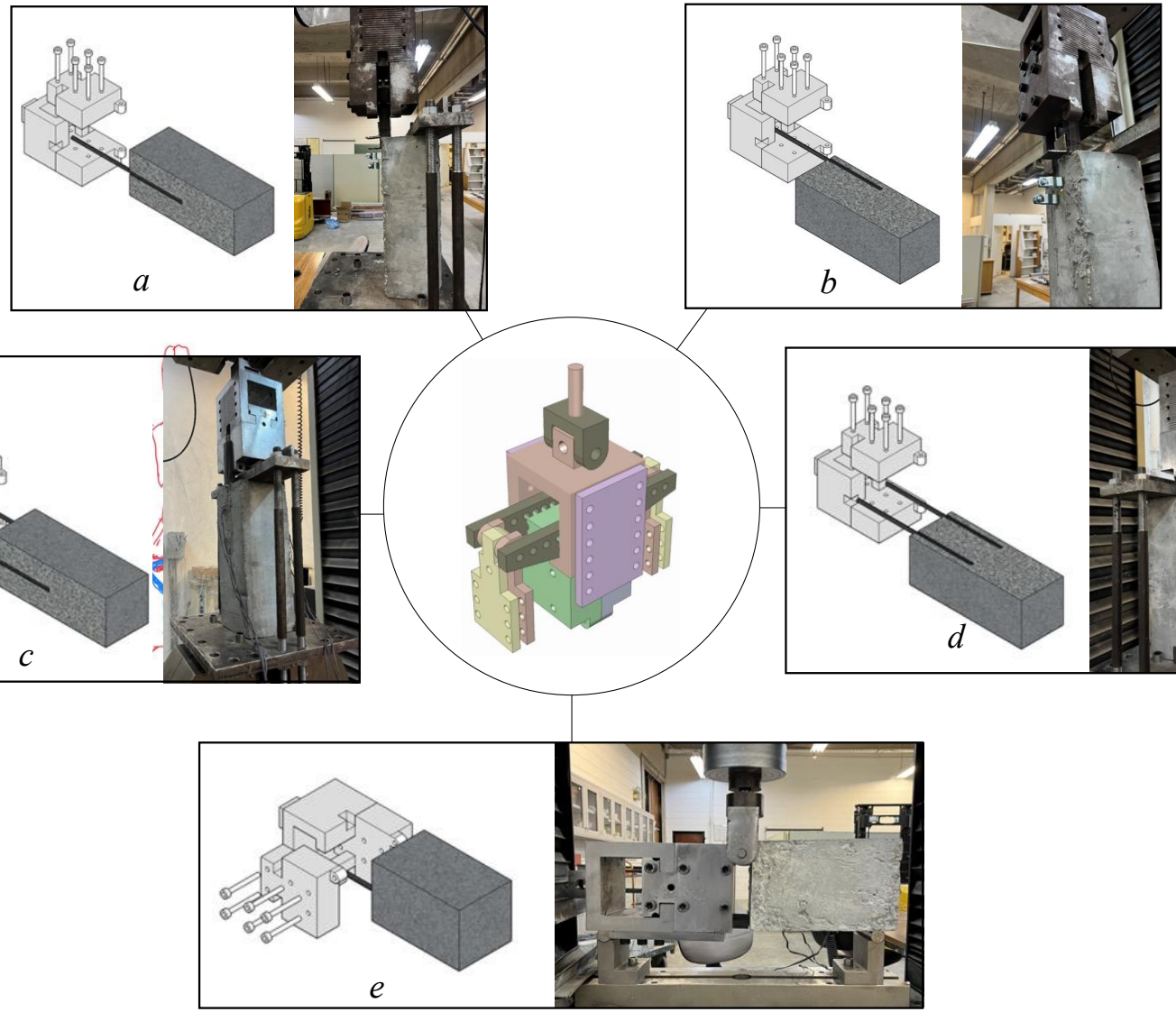
- Application of the UBoT to:

  NSM FRP and SMA systems

NSM FRP rods and strips

Heat activated NSM Fe-based shape memory alloy rods





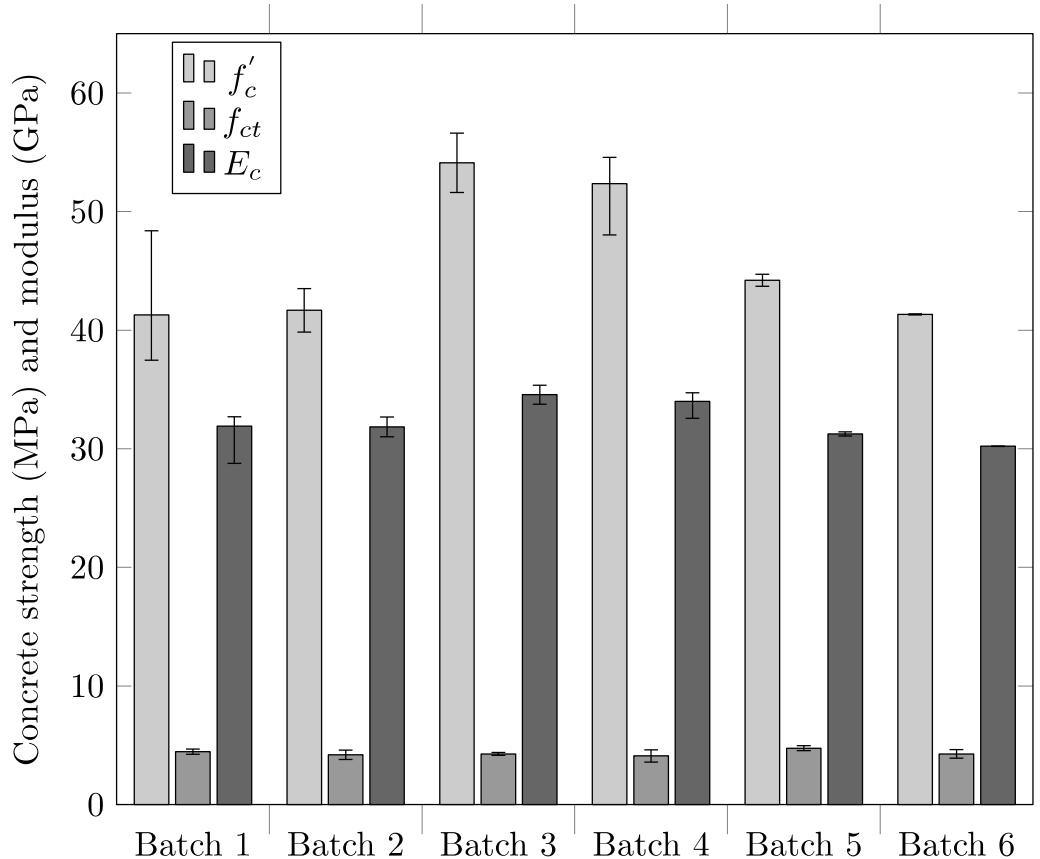
Experimental Investigation: EB-FRP

Materials: Concrete

- Mix design

Cement (kg/m³)	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air content (%)
418	180	1039	702	1.5

- Mechanical properties



Experimental Investigation: EB-FRP

Materials:

- FRP sheet and CFRP laminate

Width, b_f (mm) *	Thickness, t_f (mm)	Area, A_f (mm^2)	Dry fiber properties			
			ρ_f (g/cm^3)	f_f (MPa)	E_f (GPa)	ε_u (%)
60 (or 100)	0.29	17.4	1.82	4000	230	1.7
			CFRP Properties			
			–	3500	225	1.59

* 60 mm wide FRP was used for all bond tests except the pull-off test where 100 mm wide FRP was used.

- Epoxy

Mixing ratio by weight	Density (kg/m^3)	Glass transition temp. (°C)	Potlife (min)		Tensile strength (MPa)	Elastic modulus (MPa)		Ultimate strain (%)
			At 10°C	At 35°C		Flexural	Tensile	
4: 1	1310	58	90	30	30	3800	4500	0.9

Experimental Investigation: EB-FRP

Prepared concrete blocks

Dimensions (in mm) :

- Traditional ASTM D7958 = $500 \times 150 \times 15$
- Modified ASTM D7958 = $250 \times 150 \times 150$
- Modified ASTM D7958 with UBoT
  $= 250 \times 150 \times 150$
- ASTM D7522 = $350 \times 100 \times 150$
- All other tests = $400 \times 150 \times 150$

Experimental Investigation: EB-FRP

EB-FRP Specimens' Preparation

1. Wet layup system

2. Coring and mounting of dollies on the pull-off test specimens

3. Specimens ready for all test methods

Experimental Investigation: EB-FRP

EB-FRP (Wet Layup) Test Matrix

Approach/ Apparatus used [a]	Mix batch	Series ID	Number of Specimens for each Test Type/Standard				
			Beam test (ASTM D7958)	Single-lap shear test (ASTM D8337)	Double-lap shear test (CSA S806-12/JSCE-E 543-2000)	Mixed-mode test	Pull-off test (ASTM D7522)
Traditional ASTM D7958	B2	BM0-j	2				
Modified ASTM D7958	B3	BMI-j	2				
UBoT	B1	BMII-j	2				
UBoT	B1/B5	SS-j		2			
Traditional CSA S806-12/JSCE-E 543-2000	B5	DS0-j			2		
UBoT$^{U\text{-}FRP}$	B2	DSI-j			2		
UBoT$^{STR.\text{-}FRP}$	B1	DSII-j			2		
UBoT$^{STR.\text{-}FRP}$	B2/B3	DMM-STR-j				2	
UBoT	B4	PO^{top}-j [b]					2
	B4	PO$^{bot.}$-j [b]					2

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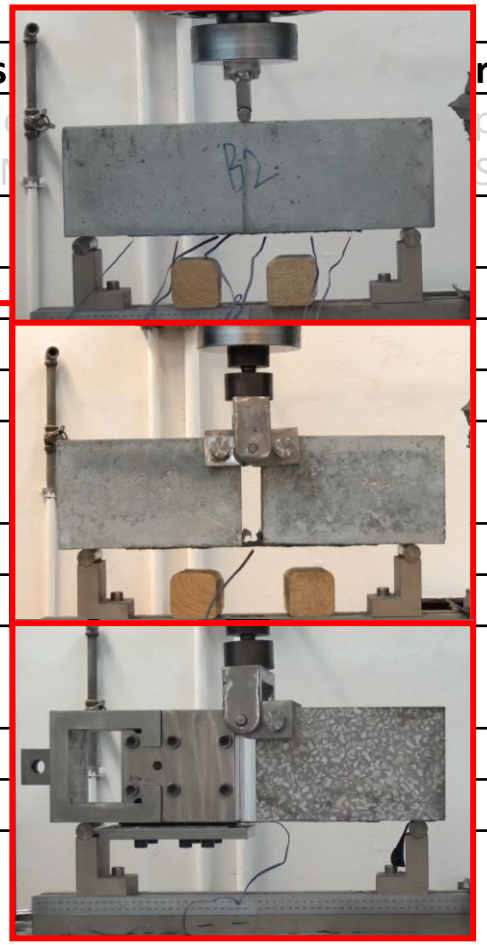

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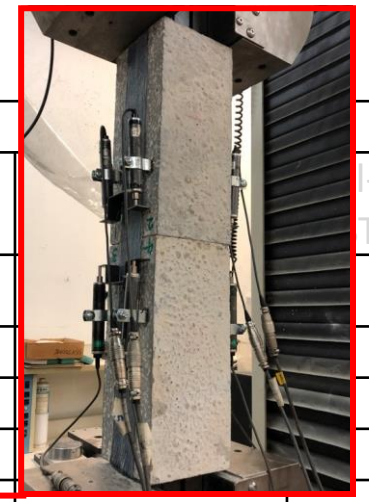

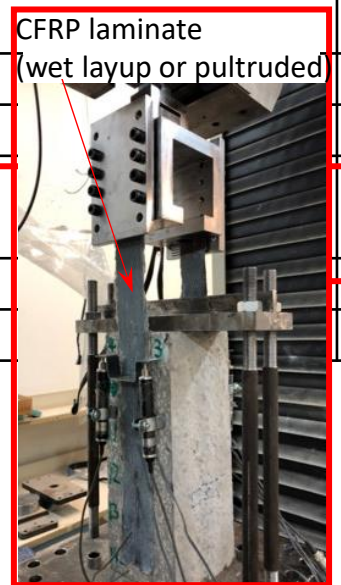

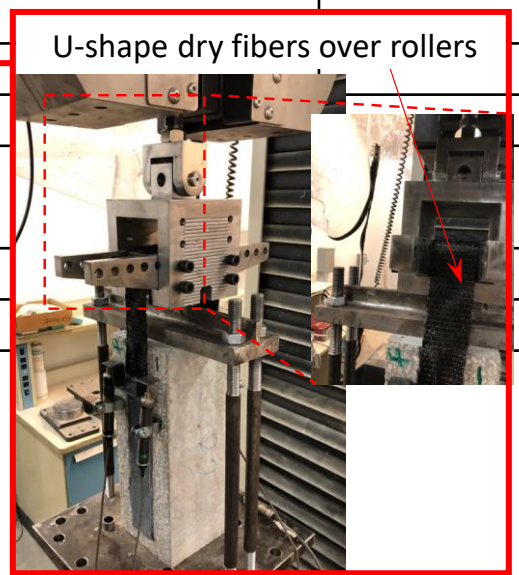

Experimental Investigation: EB-FRP

EB-FRP (Wet Layup) Test Matrix

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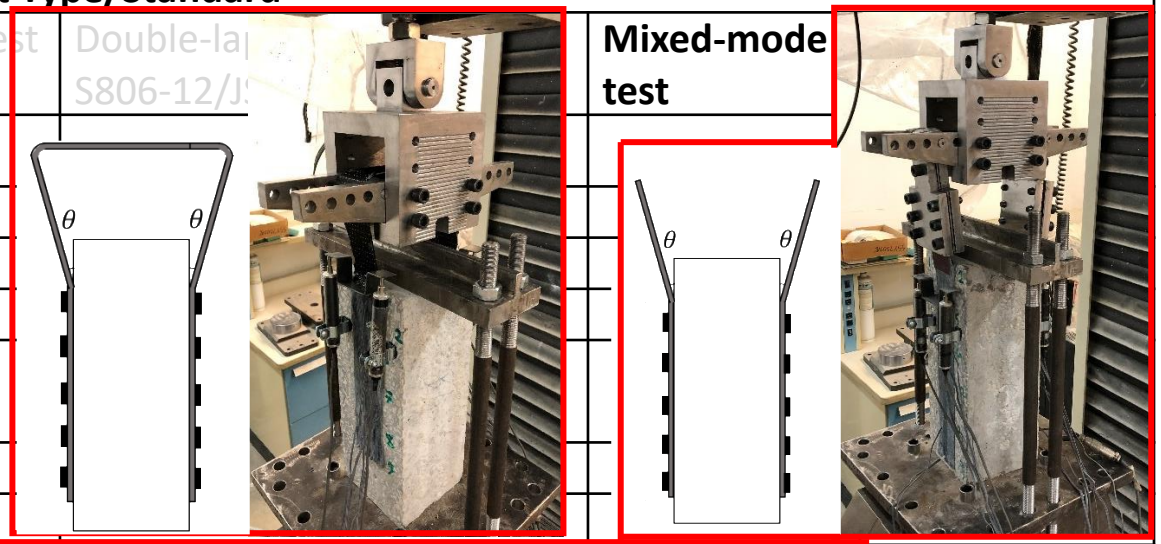

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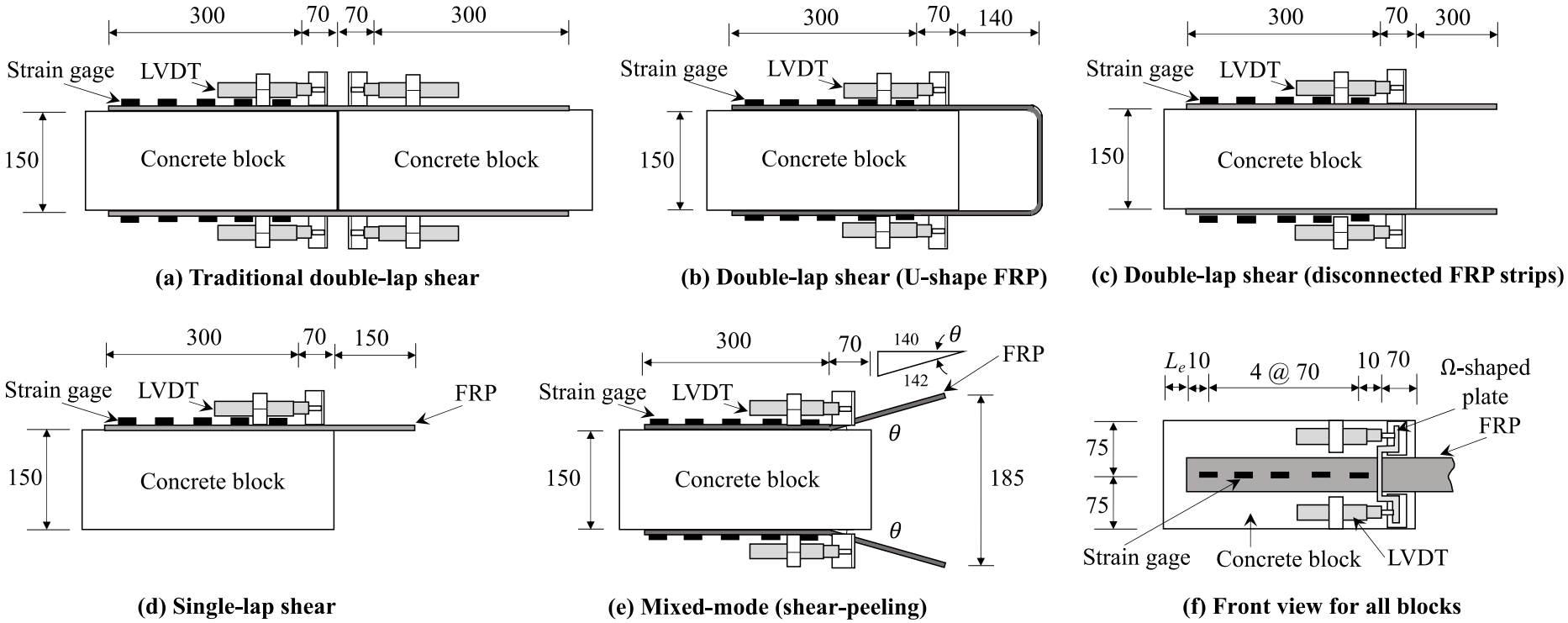
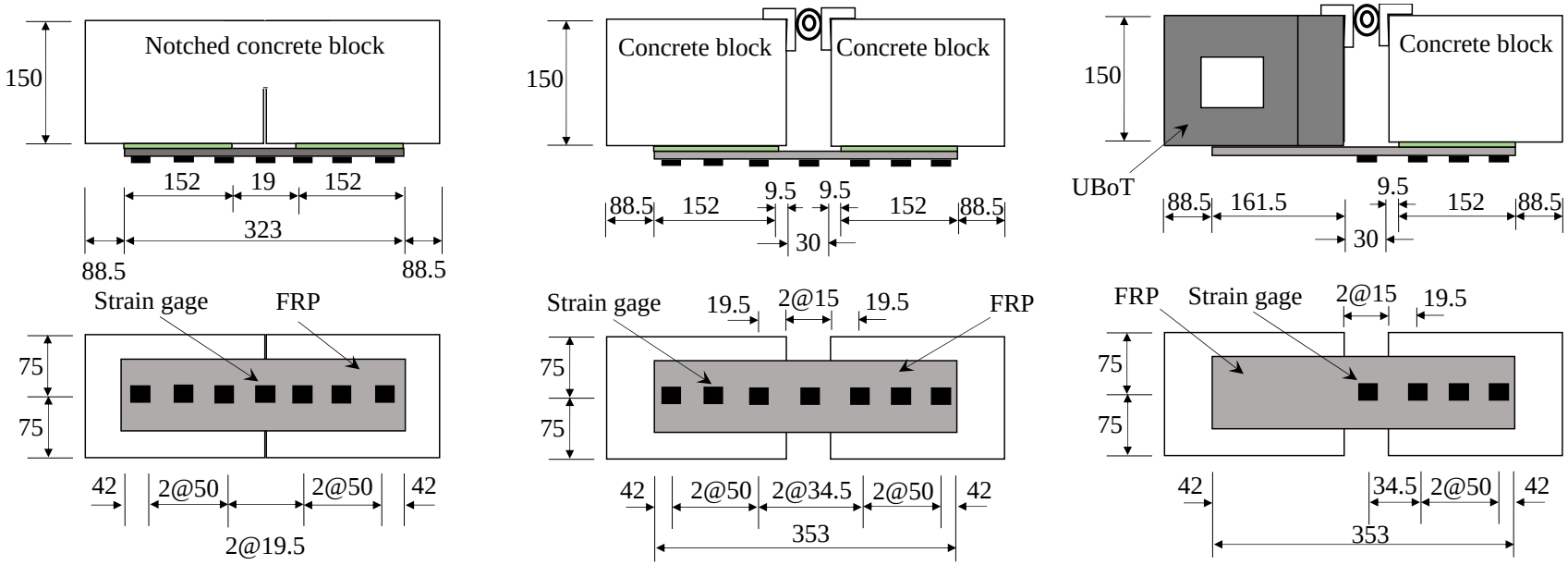
Experimental Investigation: EB-FRP

EB-FRP Specimen's Instrumentation: Double Shear, Single Shear, and Mixed-mode Tests



Experimental Investigation: EB-FRP

EB-FRP Specimen's Instrumentation: Beam tests



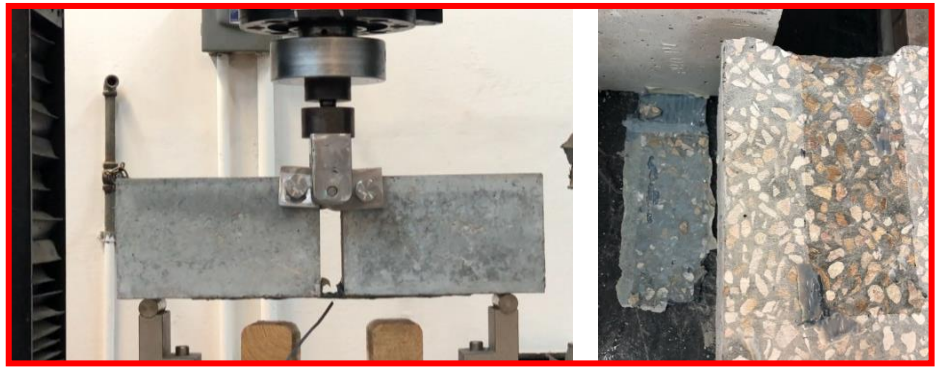
(a) Traditional ASTM D7958 (b) Modified ASTM D7958 (c) ASTM D7958 using UBoT

Results: Test Methods' Impact on Wet Layup FRP

Failure Modes

ASTM D7958

Modified ASTM D7958



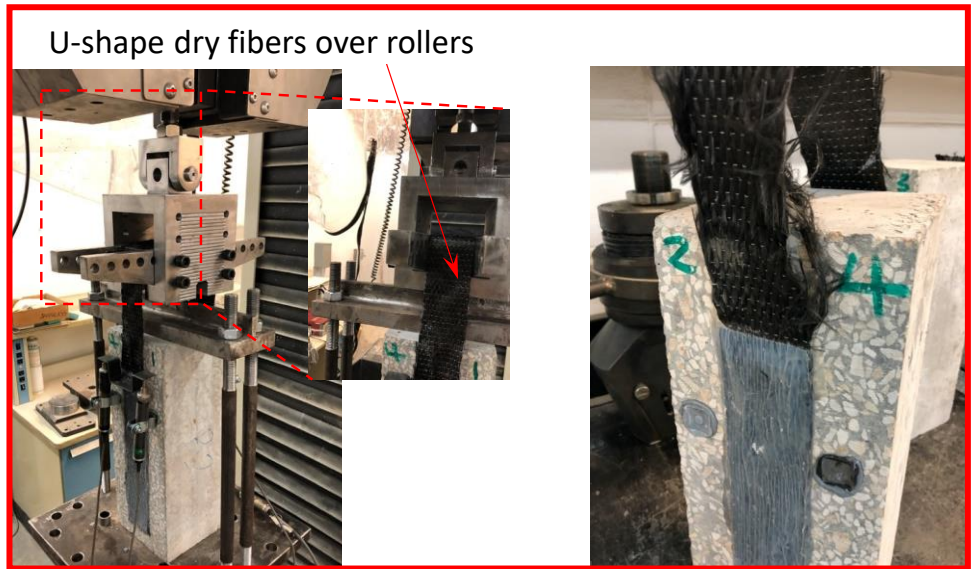
UBoT

Results: Test Methods' Impact on Wet Layup FRP

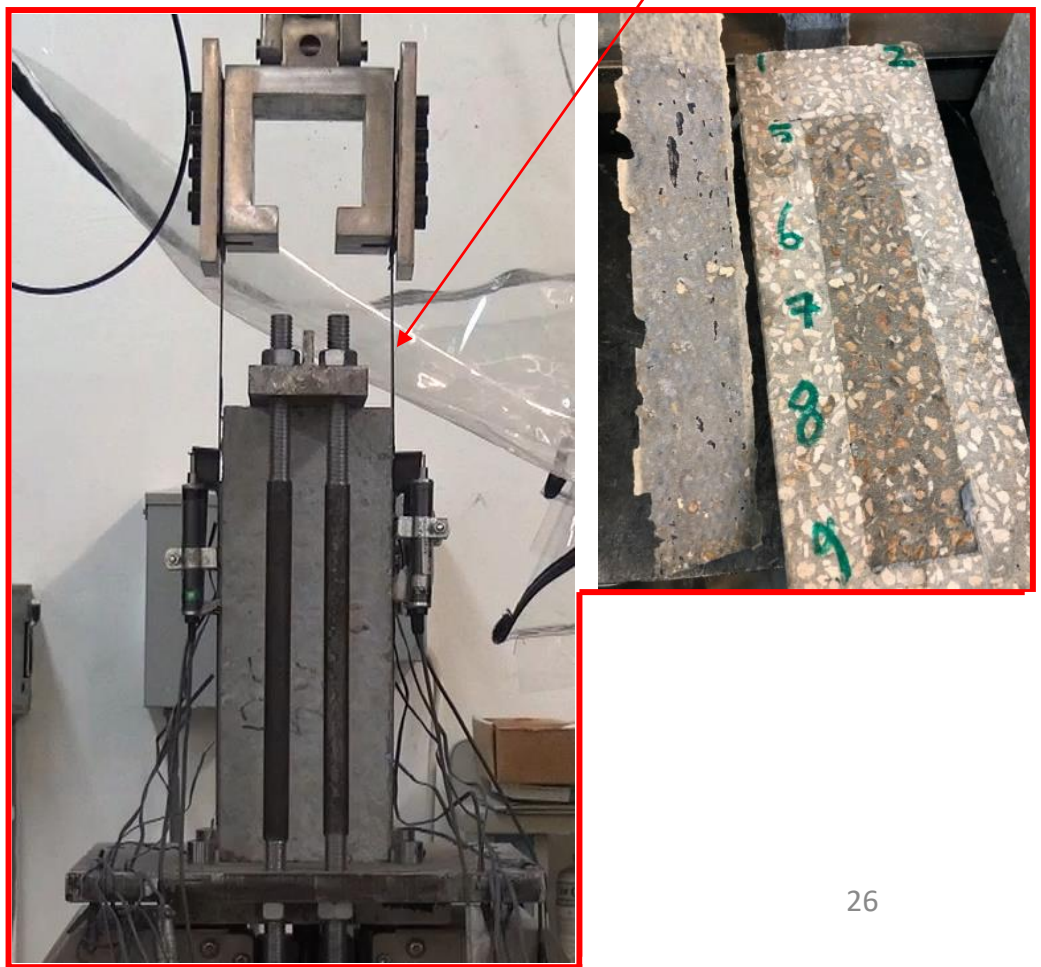
Failure Modes

CSA S806-12/JSCE-E 543-2000

CSA S806-12/JSCE-E 543-2000:
UBoT U-FRP



CSA S806-12/JSCE-E 543-2000:
UBoT STR-FRP

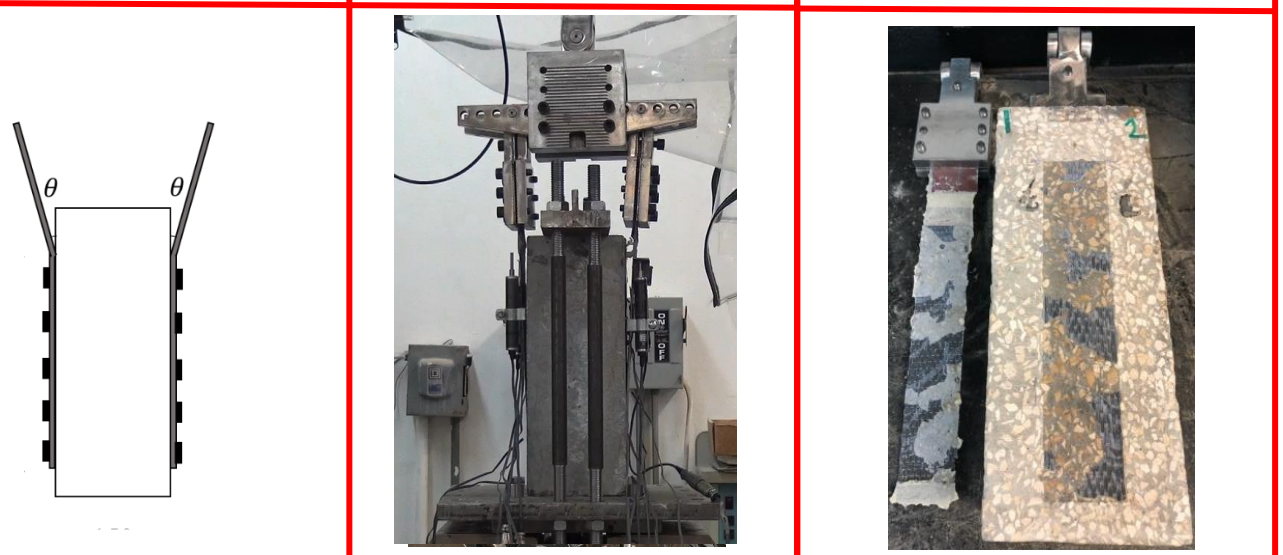


Results: Test Methods' Impact on Wet Layup FRP

Failure Modes

Mixed-mode test:
UBoT U-FRP

Mixed-mode test:
UBoT STR-FRP



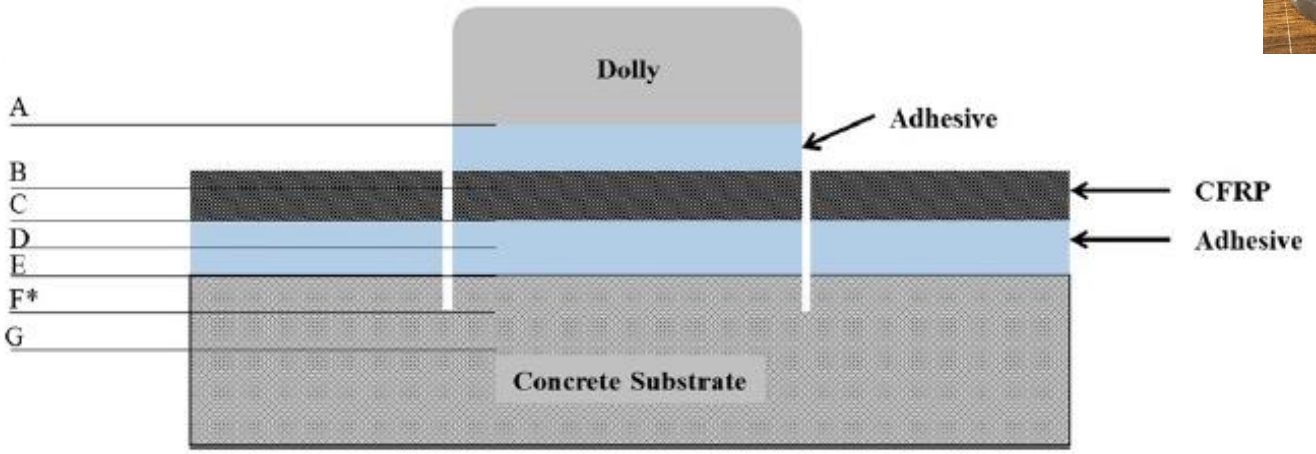
Results: Test Methods' Impact on Wet Layup FRP

Failure Modes

ASTM D7522

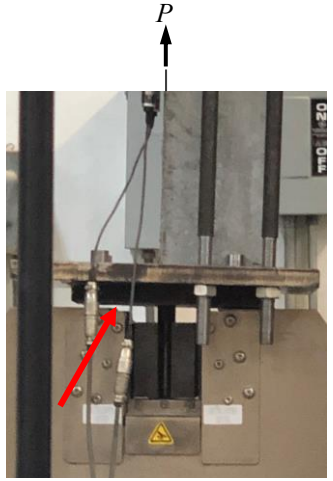
Cleaned dollies via application of only a slight lateral load misalignment

PO^top-1 PO^top-2 PO^bot-1 PO^bot-2

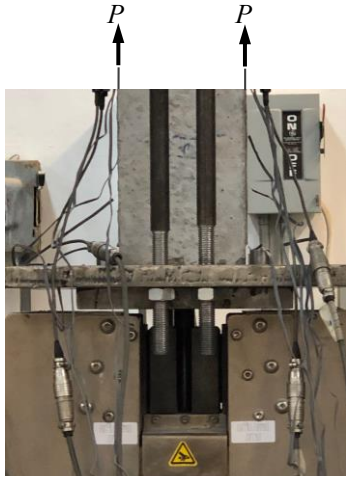


Results: Test Methods' Impact on Wet Layup FRP

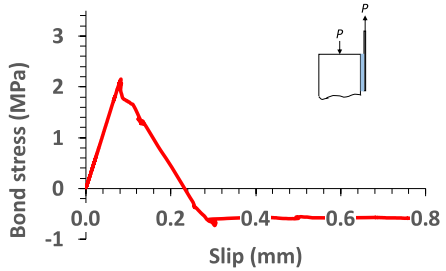
Bond-Slip Models: Trilinear



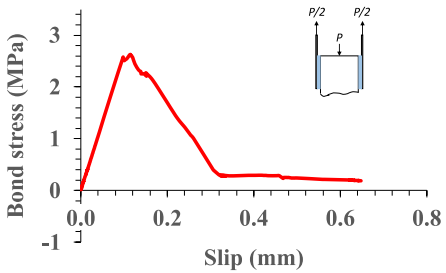
ASTM D8337



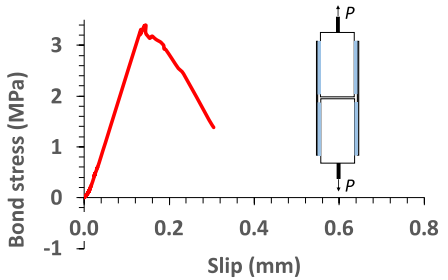
CSA S806-12/JSCE-E 543-2000



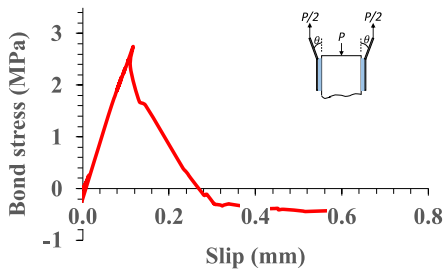
(a) ASTM D8337



(b) CSA S806-12/ JSCE-E 543-2000 (UBoT: straight FRP)

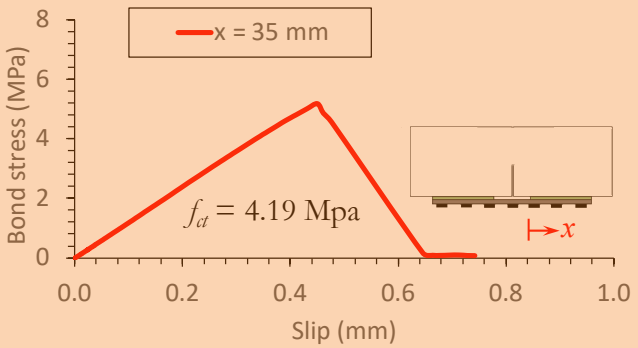


(c) CSA S806-12/ JSCE-E 543-2000 (traditional)

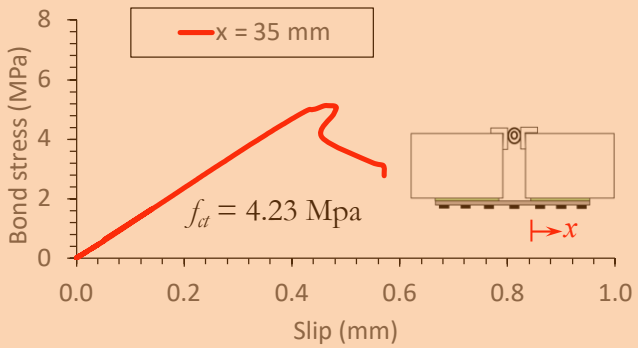


(d) Mixed-mode (UBoT: straight FRP)

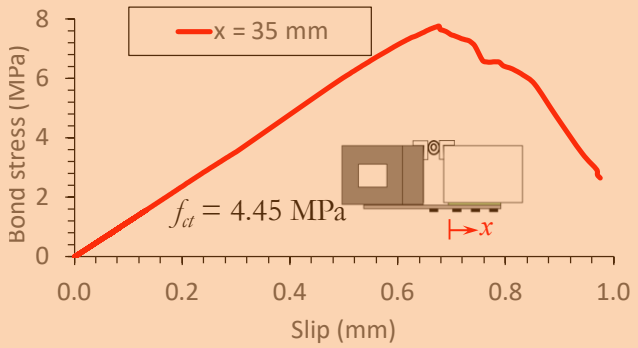
Not suitable for bond-slip analysis!



(a) Traditional ASTM D7958



(b) Modified ASTM D7958



(c) UBoT: ASTM D7958

Results: Test Methods' Impact on Wet Layup FRP

Shear-Dominant Tests versus ASTM D8337					
	Single-lap shear test (ASTM D8337): UboT*	**Double-lap shear test (CSA S806-12/JSCE-E 543-2000): UboT***	**Beam test (ASTM D7958): Traditional****	**Beam test (ASTM D7958): Modified****	**Beam test (ASTM D7958): UBoT****
Bond strength, τ_{max} or τ_{aver} (Mpa)	2.2	2.6	2.5	2.3	2.4
% diff. wrt single-lap shear test (ASTM D8337)	-	15.4	11.5	3.8	7.7

* τ_{max} from bond-slip curve

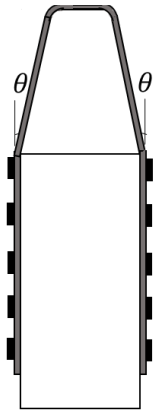
** τ_{aver} from $\frac{P_{FRP,max}}{\text{bonded area}}$

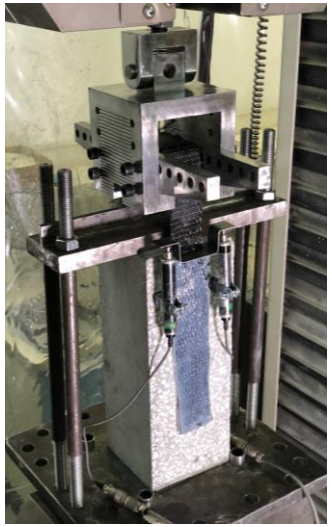
	Spec. ID	Mix batch	P_{max} (kN)	σ_u (MPa)	Mean σ_u (MPa)
Pull-off test (ASTM D7522)	PO^{top}-1	B1	6.8	3.46	3.57
	PO^{top}-2	B1	7.2	3.67	
	$PO^{bot.}$-1	B1	6.2	3.16	3.44
	$PO^{bot.}$-2	B1	7.3	3.72	

Miscellaneous EB-FRP Tests using the UBoT

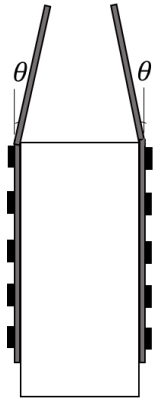
1. Negative mixed-mode test

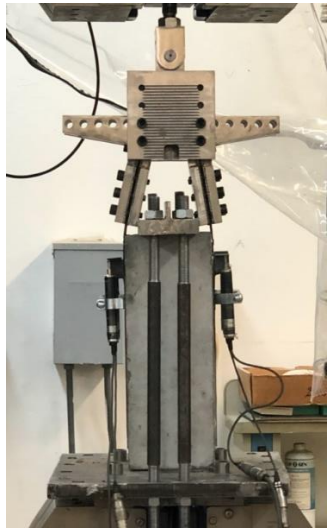
- U-shape dry fiber



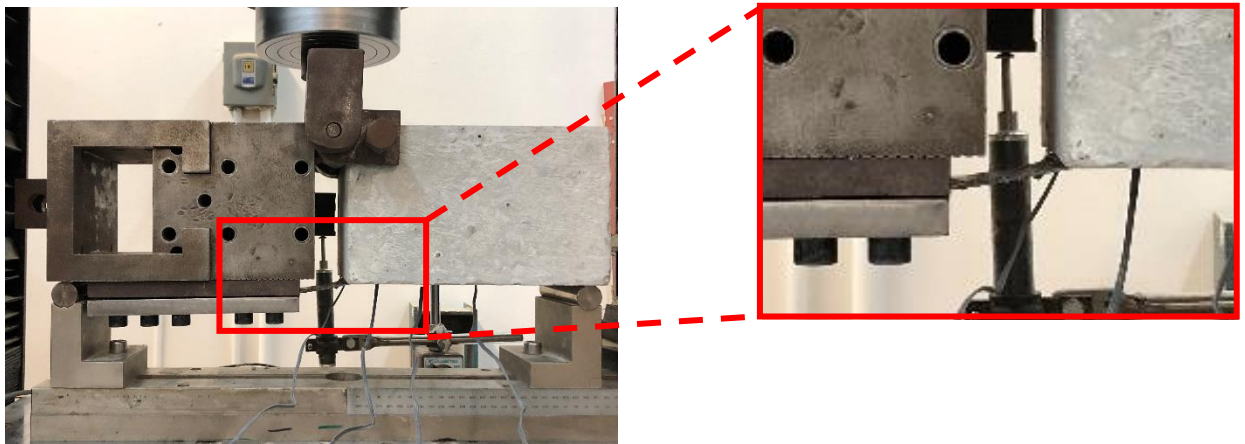


- Disconnected FRP



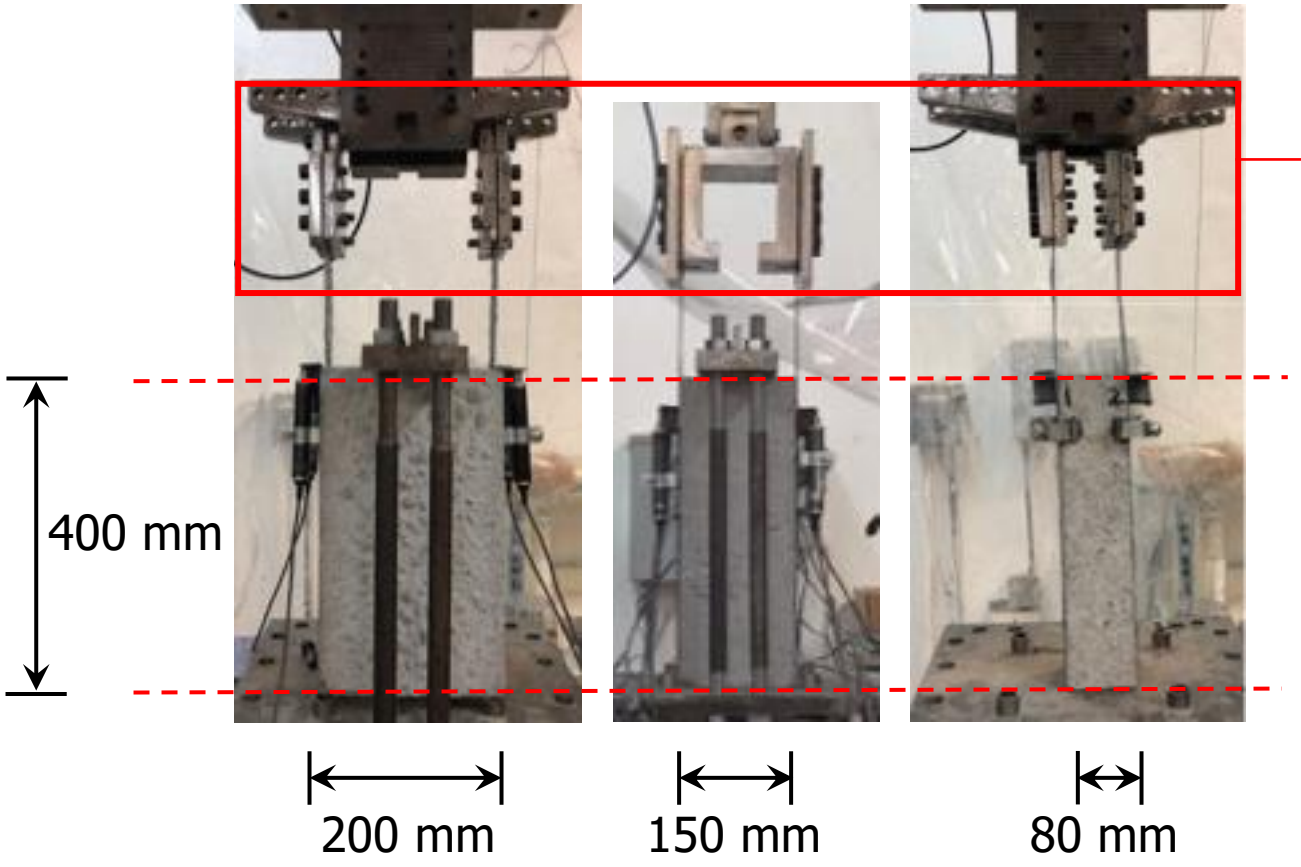


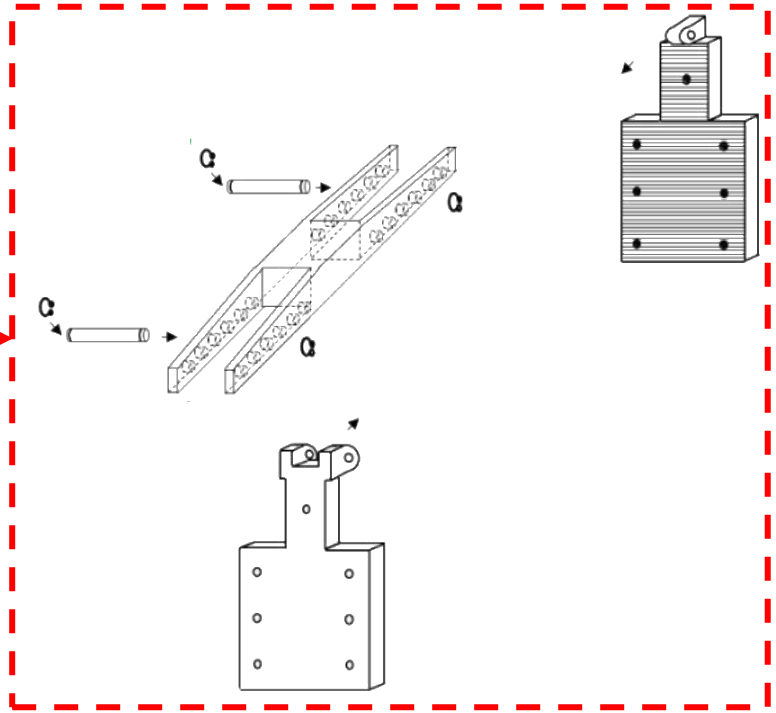
2. Bending-type mixed-mode test



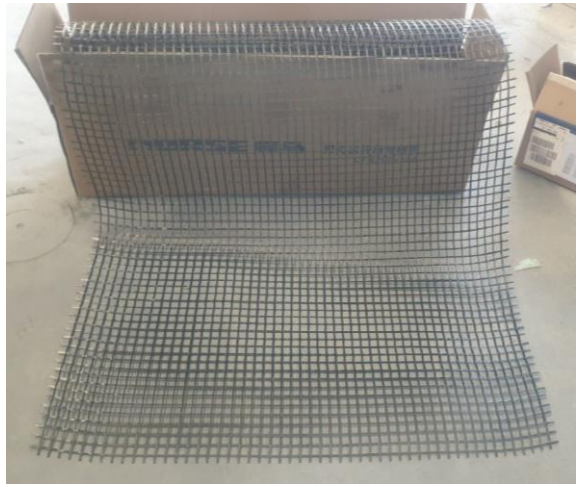
Miscellaneous EB-FRP Tests using the UBoT

3. Size effect analysis





Application of the UBoT to FRCM



CFRP Grid

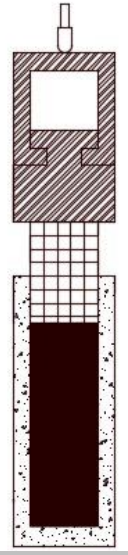
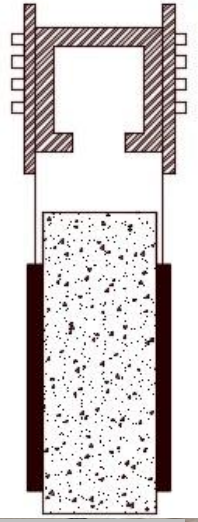
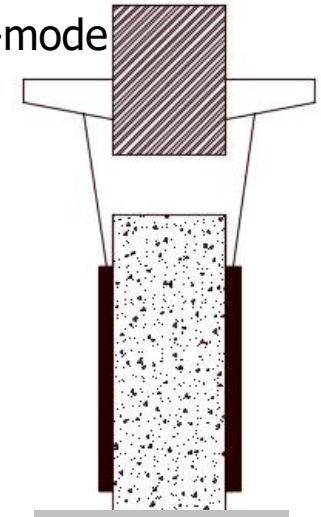
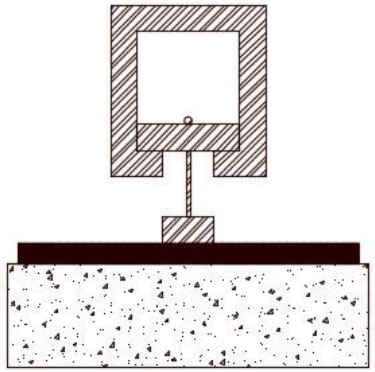
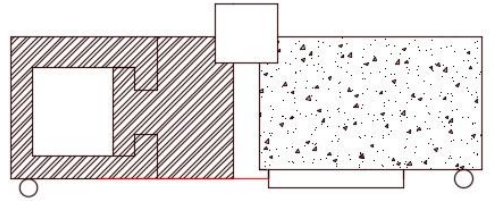
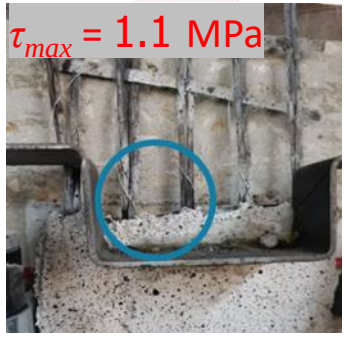
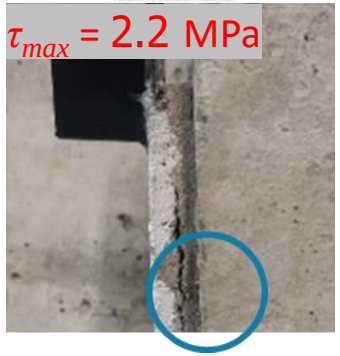
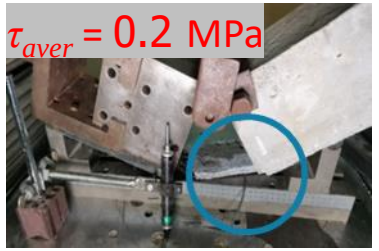
Tensile strength	4900 MPa
Tensile Elastic Modulus	234 GPa
Grid Size	20 mm x 20 mm
Thickness	0.047 mm

Concrete

Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	W/C ratio	f_c (MPa)
300	750	900	0.5	36.0

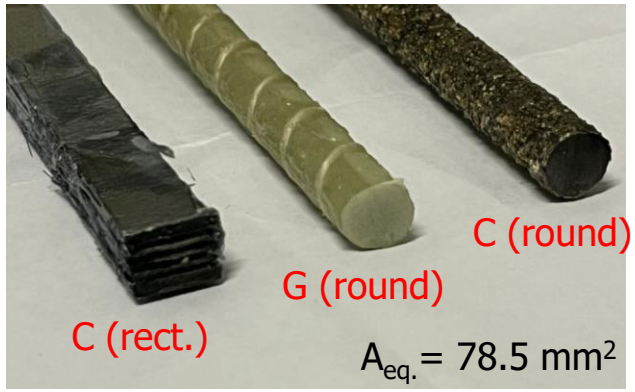
Application of the UBoT to FRCM

Comparison of Test Methods:

	Single-lap shear test	Double-lap shear test	Mixed-mode test	Pull-off test	Beam/bending test
					
	τ_{max} = 1.1 MPa	τ_{max} = 2.2 MPa	τ_{max} = 0.7 MPa	σ_{max} = 1.5 MPa	τ_{aver} = 0.2 MPa
					
Failure Mode:	Fiber slippage	Fiber slippage with matrix cracking	Fiber slippage with matrix cracking	Fabric/matrix interf.	Matrix/Concrete interf.

Application of the UBoT to NSM FRP [1]

Variables studied: (i) Bond test type (ii) FRP material [glass/carbon] (ii) FRP cross-section (round/rect.)



FRP

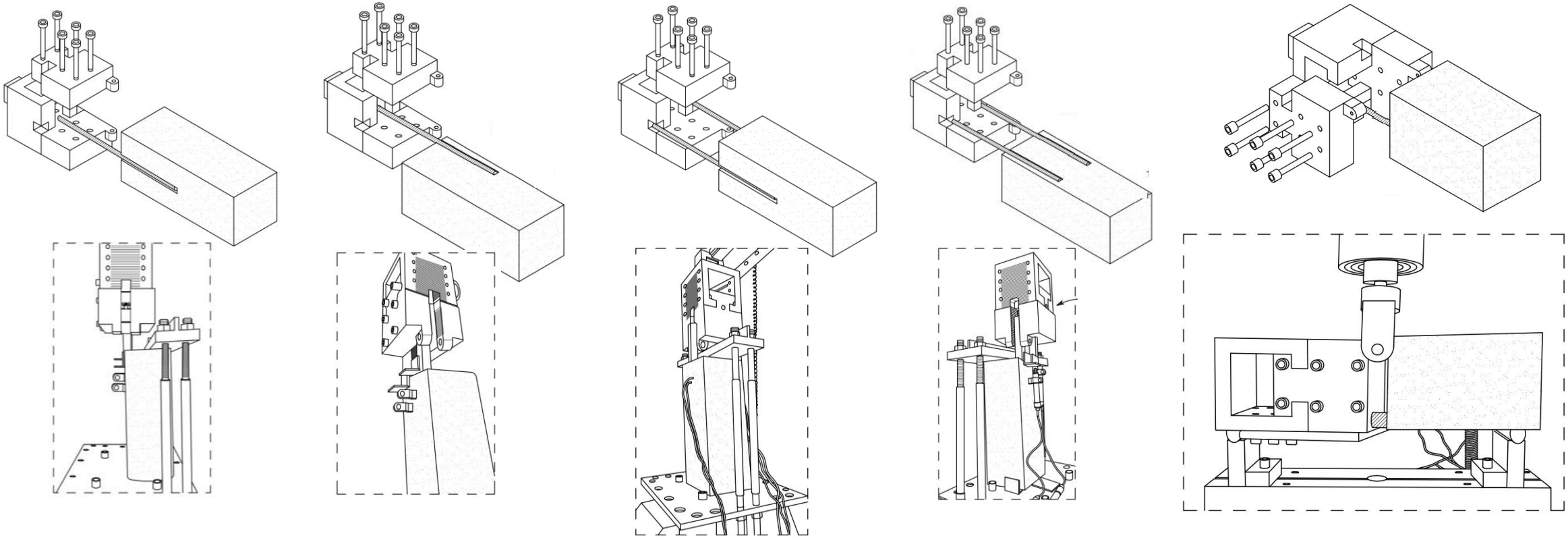
FRP	f_u (MPa)	E_f (GPa)	Rupture Strain
GFRP (round)	910	50	0.0182
CFRP (round)	2172	124	0.0175
CFRP (rect.)	3100	170	0.0180

Concrete

Cement (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	W/C ratio	f_c (MPa)	f_{ct} (MPa)
418	702	1,039	0.4	39.4	3.9

Application of the UBoT to NSM FRP [1]

Variables studied: (i) Bond test type (ii) FRP material [glass/carbon] (ii) FRP cross-section (round/rect.)



(a) Single shear

(b) Single-edge effect

(c) Double shear

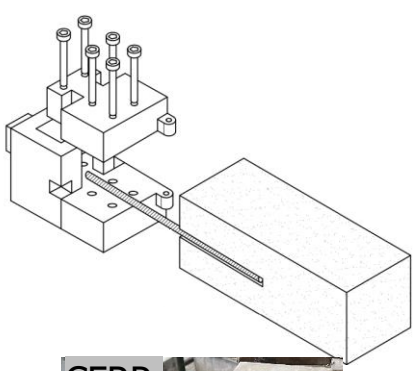
(d) Double-edge effect

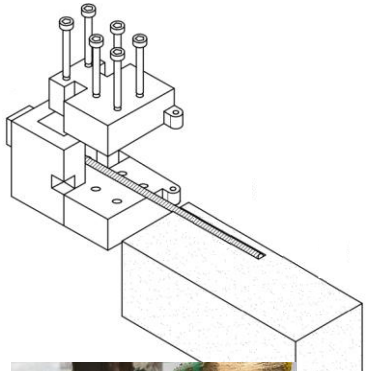
(e) Beam/bending

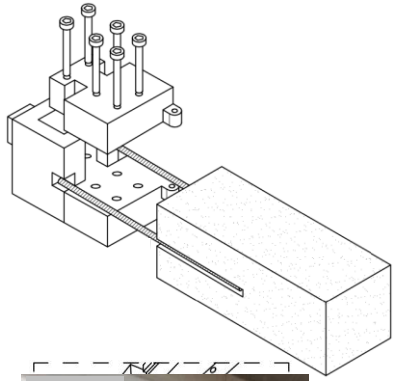
[1] F. Mukhtar (2023). U.S. Patent Application No. 17687927 . U.S. Patent and Trademark Office.

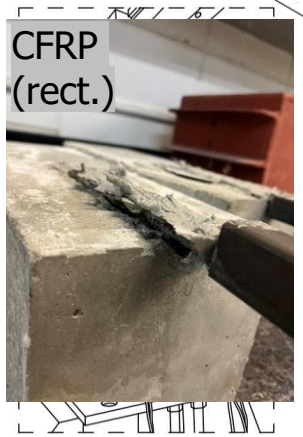
Application of the UBoT to NSM FRP

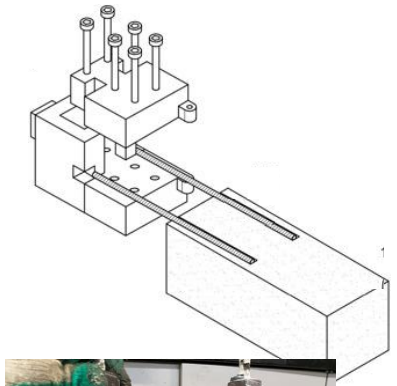
Variables studied: (i) Bond test type (ii) FRP material [glass/carbon] (ii) FRP cross-section (round/rect.)

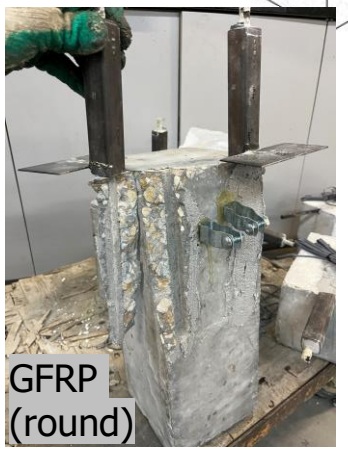


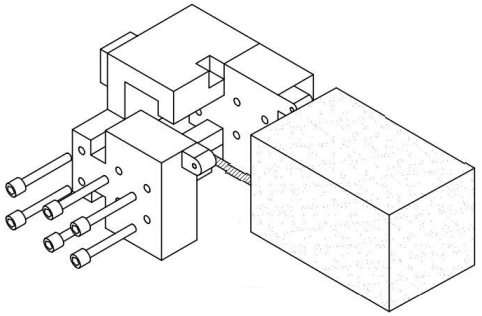


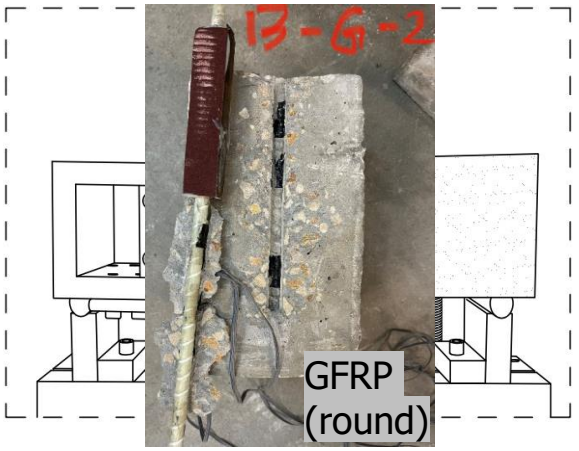












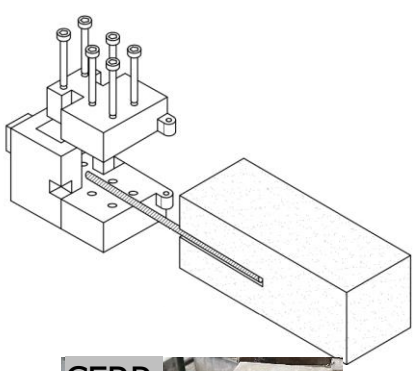
F: FRP
A: Adhesive
C: Concrete

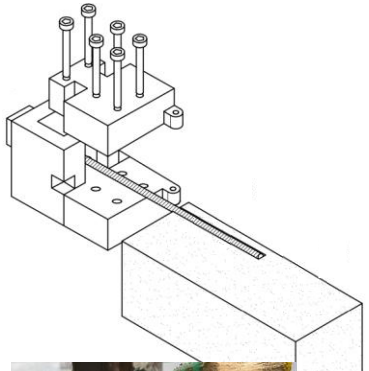
Failure mode:

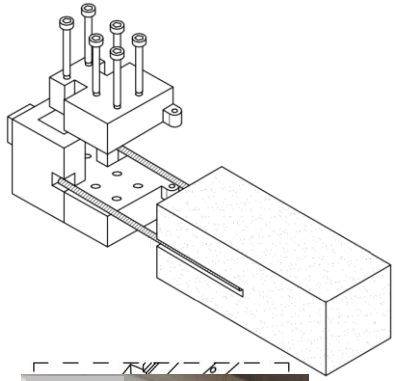
GFRP (round):	F/A interf.	C splitting, F/A interf.	F/A interf.	-	F/A interf.
CFRP (round):	F/A interf.	C splitting	F/A interf.	C splitting	F/A interf.
CFRP (rect.):	Wedge fail.	C splitting	C/A interf.	-	FRP rupture

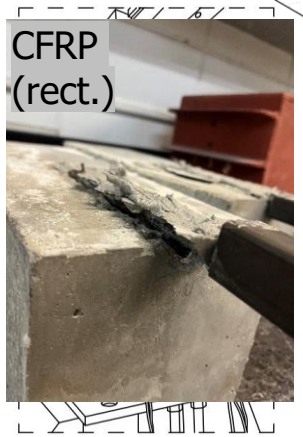
Application of the UBoT to NSM FRP

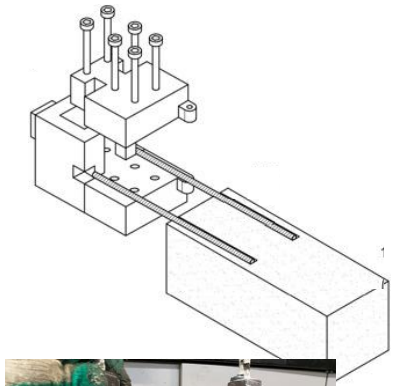
Variables studied: (i) Bond test type (ii) FRP material [glass/carbon] (ii) FRP cross-section (round/rect.)

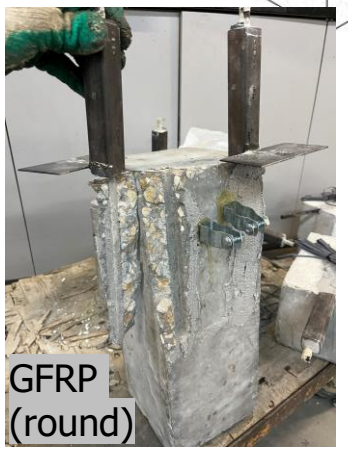


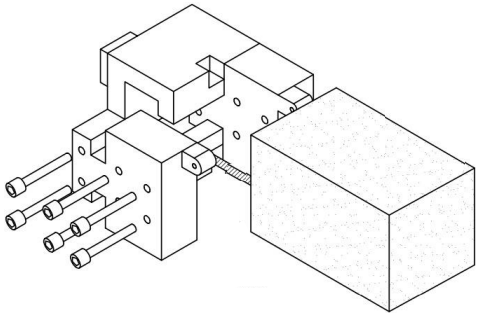


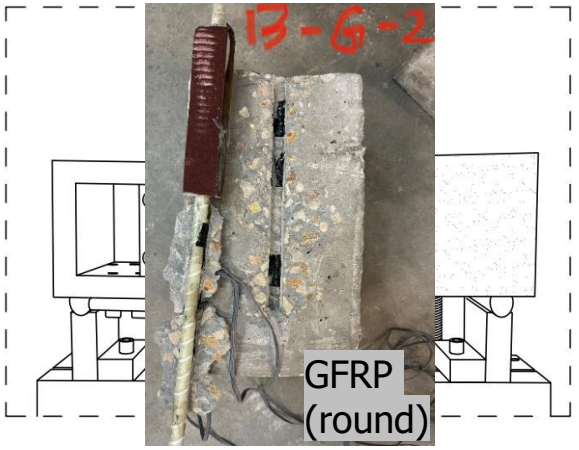












P_u (kN) [*% diff. wrt single shear*]

GFRP (round):	17.8 [-]	11.6 [-35%]	25.3 [+42%]	-	13.8 [-]
CFRP (round):	17.5 [-]	26.5 [+51.4%]	28.8 [+65%]	25.8 [+47%]	30.9 [-]
CFRP (rect.):	40.7 [-]	23.2 [-43%]	23.6 [-42%]	-	13.4 [-]

Conclusions

- Universal bond tester for wet layup EB FRP-concrete:
  - Robust and convertible to all test methods
  - Economically efficient framework for comparison of test methods
- Most consistent results: Pull-off test
- Single shear bond capacity = 85% of double shear bond capacity
- Beam test not suitable for bond-slip analysis
- The mixed-mode test (1) simulates the more realistic field behavior and (2) diagnoses the single shear test artifacts
- Successful extension to other strengthening systems: Pultruded EB-FRP, FRCM, NSM-FRP
- The tool can be useful for more detailed validations of numerical models

Ongoing Work: Heat-Activated Fe-based SMAs

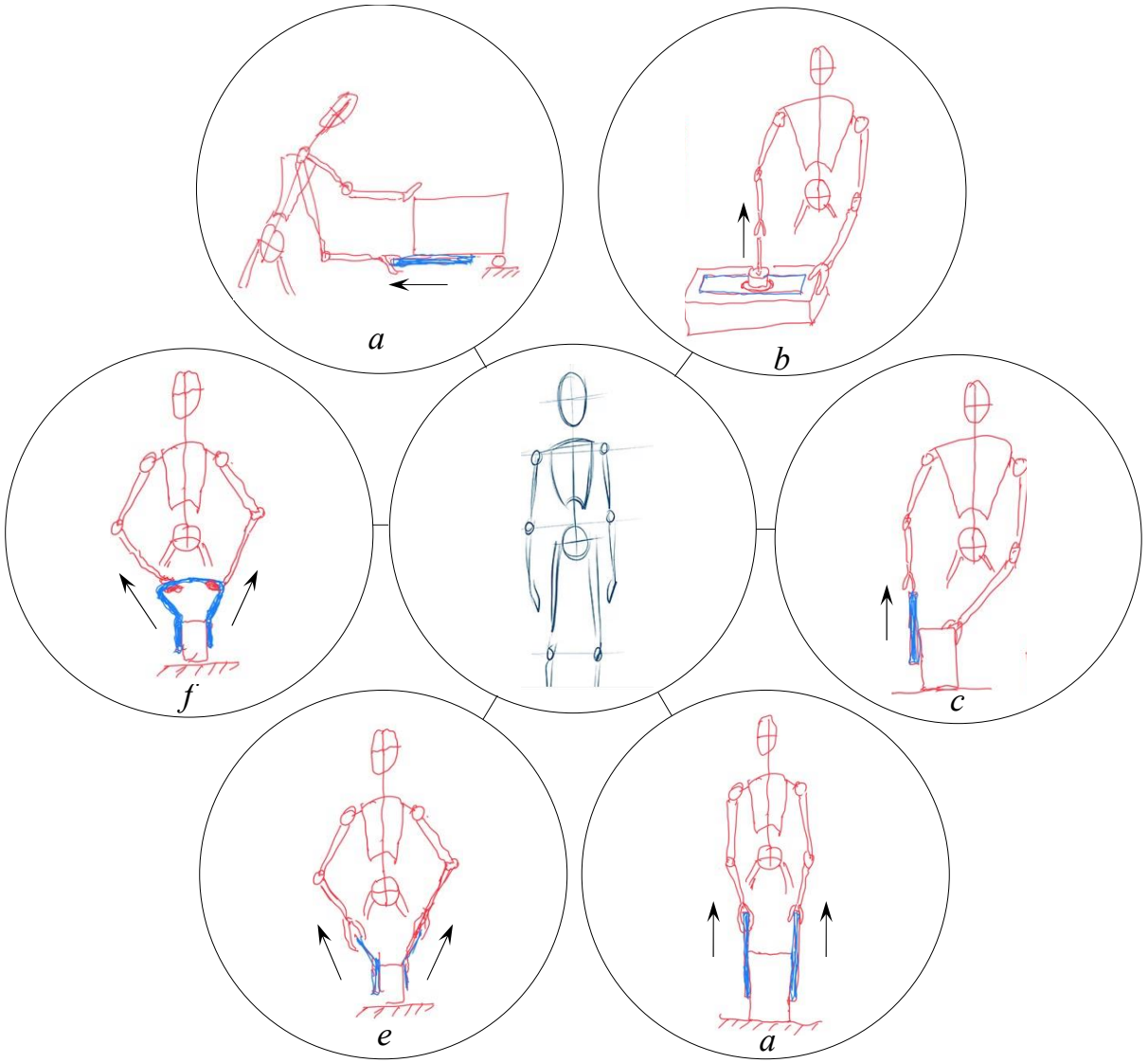
Bond integrity assessment using the UBoT and effect of activation temperature

Heat activated NSM Fe-based shape memory alloy rods [1-2]

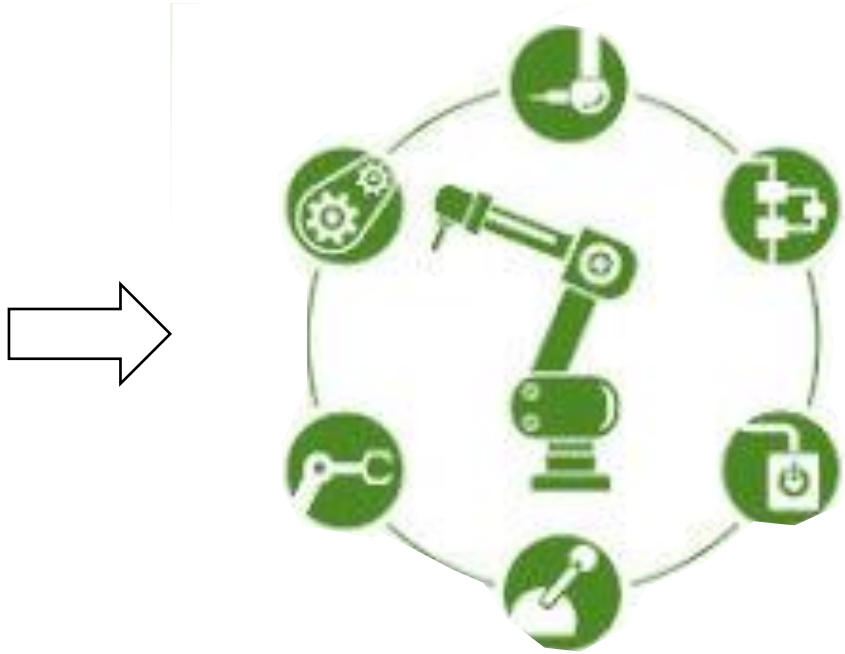
Heat activated Fe-based shape memory alloy plates [3]

[1] rawlins (2024). https://www.rawlinspaints.com/carbon-fibre-fabric. Accessed March 11, 2024.
[2] Sika Group (2023). Sika CarboDur® for Structural Reinforcement. Zürich, Switzerland .
[3] re-fer (2023). re-plate 120 / 1.5 mm product data sheet. re-fer.eu Strengthening Solutions.

Future Work: Automation (Solution Phase 3)



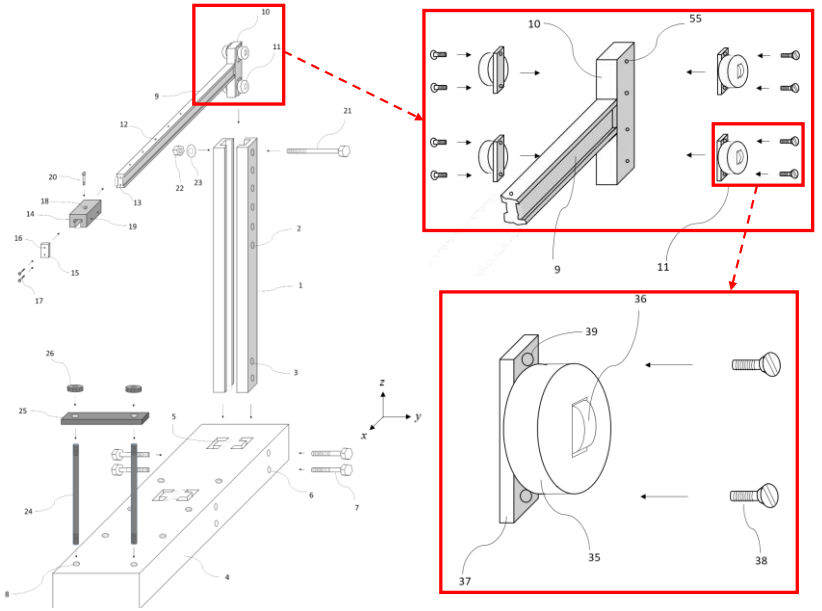
State-of-the-art



Target

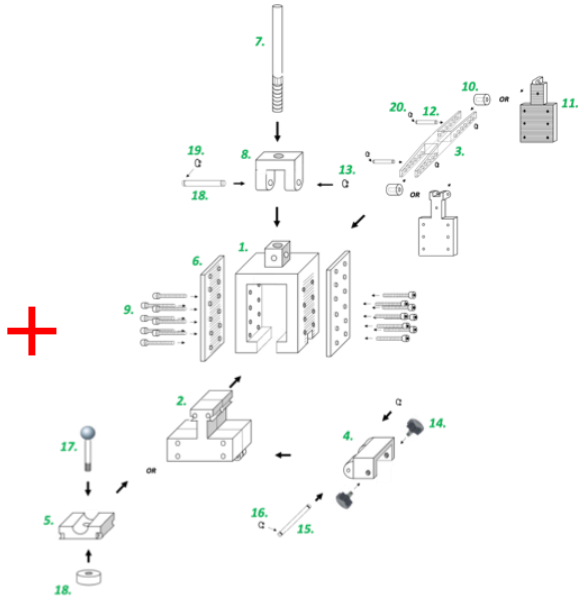
Future Work: Automation (Solution Phase 3)

Adaptable Loading Frame



Patent pending [1]

UBoT



Patent granted [2-4]

Machine Design

[1] F. Mukhtar (2023). U.S. Patent Application No. 18/520,754 . U.S. Patent and Trademark Office.
[2] F.M. Mukhtar (2023). U.S. Patent No. 11,169,082 B2. U.S. Patent and Trademark Office.
[3] F.M. Mukhtar (2023). U.S. Patent No. 11,719,620 B2 . U.S. Patent and Trademark Office.
[4] F.M. Mukhtar (2023). U.S. Patent No. 11,719,621 B2 . U.S. Patent and Trademark Office.
[5] F. Mukhtar (2023). U.S. Patent Application No. 17687927 . U.S. Patent and Trademark Office.

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- Engr. A. El-Tohfa, CEE Dep't., KFUPM

Questions, Comments?

faisalmu@kfupm.edu.sa