Strategic Use of Pseudo-ductile Cementitious Composites in Concrete Structures

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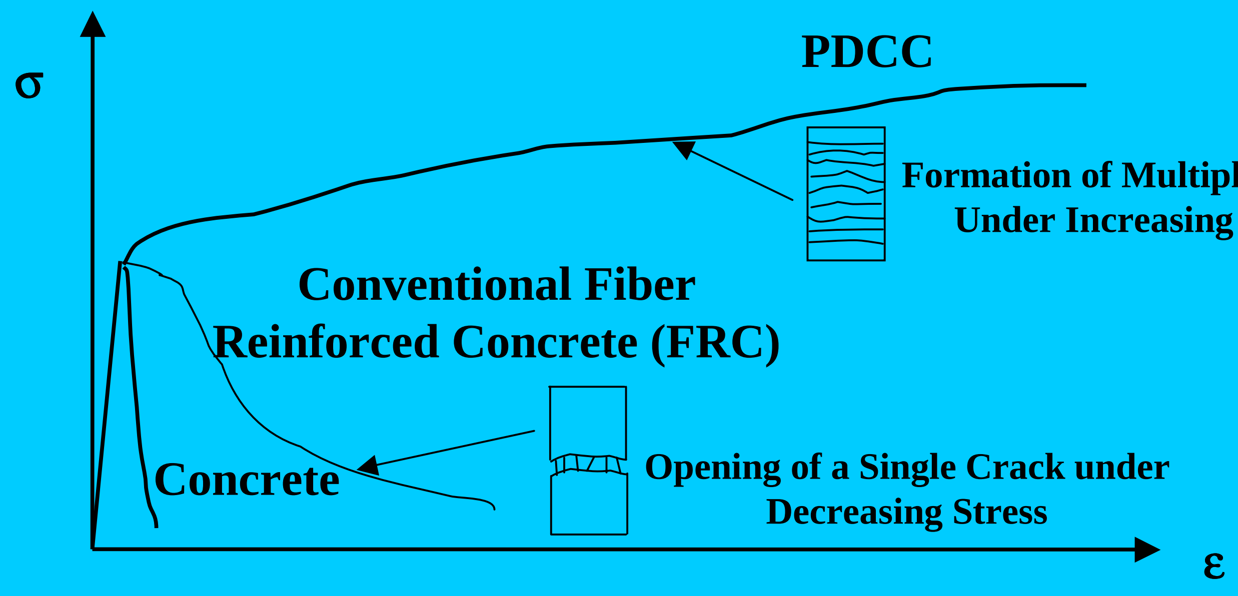
Outline

- Introduction to Pseudo-ductile Cementitious Composites (PDCC)
  - Design Principle
  - Large Scale Applications
  - Selective Applications
- Research on Strategic Use of PDCC at HKUST
  - Permanent Formwork for Structures
  - Anchorage Zone of Post-tensioned Members
- Conclusions and Outlook

Pseudo-Ductile Cementitious Composites (PDCC)

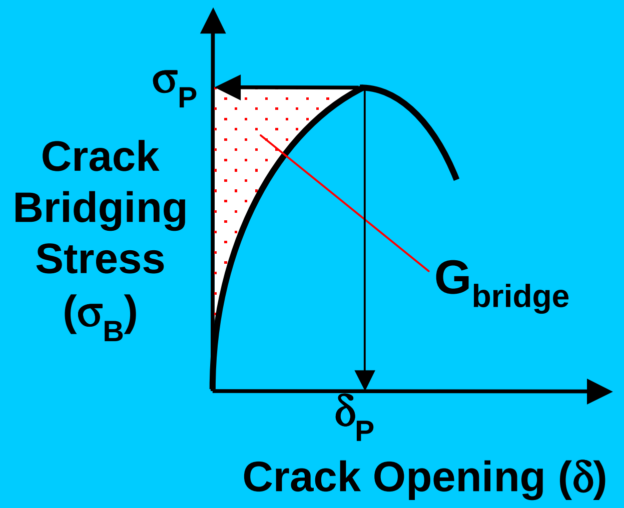
- Strength similar to Normal Concrete but exhibit Very High Ductility
  - Failure Strain up to several percents
  - Failure preceded by Formation of Well-Controlled Multiple Cracks



Tensile σ–ε Behavior of Cementitious Materials

Physical Principle

(Li and Leung, ASCE J Engineering Mechanics, 1992)



From Fracture Analysis

If $G_{bridge} > G_{tip}$

First Cracking occurs at a Stress Level below σ_p

Increase in Stress after first cracking

→ Formation of Multiple Cracks

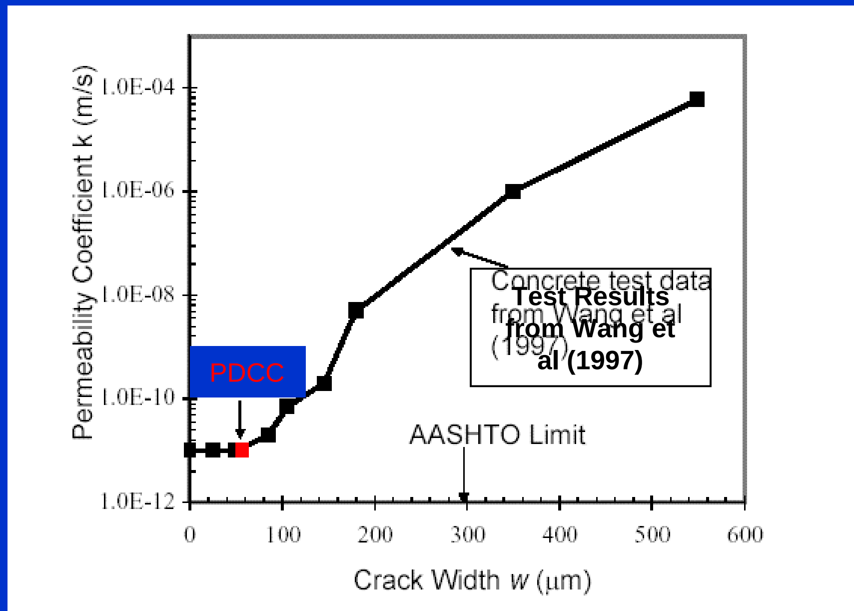
→ Strain Hardening

- **G_{tip} depends on matrix fracture toughness and composite modulus**
- **G_{bridge} depends on the properties of fiber, matrix and interface as well as fiber geometry and volume fraction**
- **Through the proper choice of composite micro-parameters to satisfy $G_{bridge} > G_{tip}$, Strain Hardening can be achieved**
- **Before ultimate failure, crack opening is kept below δ_p**

Engineering Properties of PDCC

- Very High Deformation Capability
- Closely Spaced Multiple Cracking before Ultimate Failure
- Very High Energy Absorption and Damping
- Excellent Control of Crack Opening
  - Improved Long-term Durability

PDCC under Bending



Transport Properties and Crack Control

PDCC Applications

- Hida Tunnel, Japan
  - Sprayed PDCC Lining
- Mihara Bridge, Hokkaido, Japan
  - Composite Steel/PDCC Deck

Sprayed PDCC Lining
for Hida Tunnel

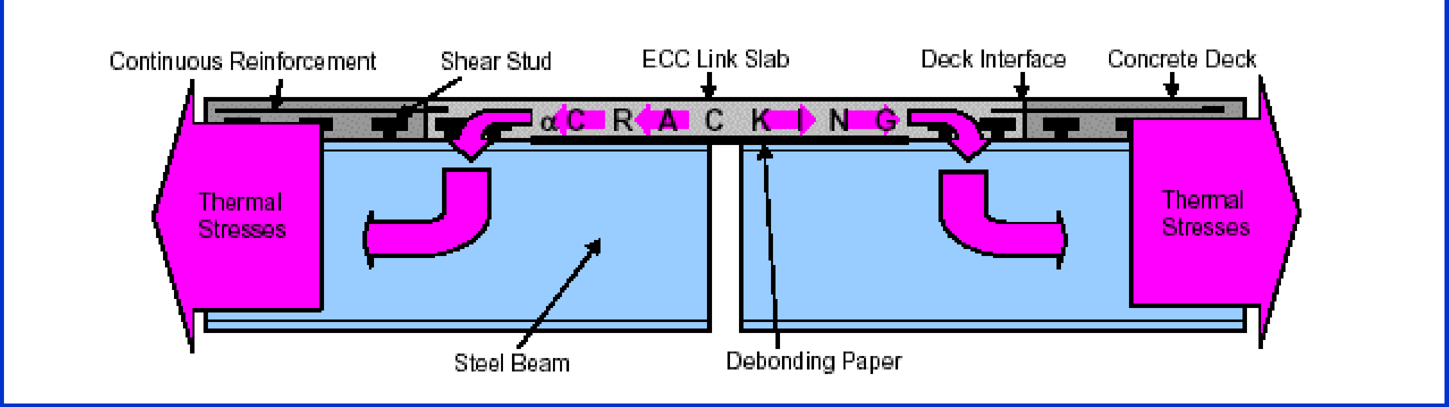
Self-Flow PDCC placed on top of
Steel Section for Mihara Bridge

Strategic Use of PDCC

- PDCC are far more expensive than Normal Concrete
  - PDCC/Concrete ~ 5-6 times in cost
- High cost limits application in large volumes
- Innovative use in Selected Parts of Structures can bring along higher performance/cost and wider acceptance of the material

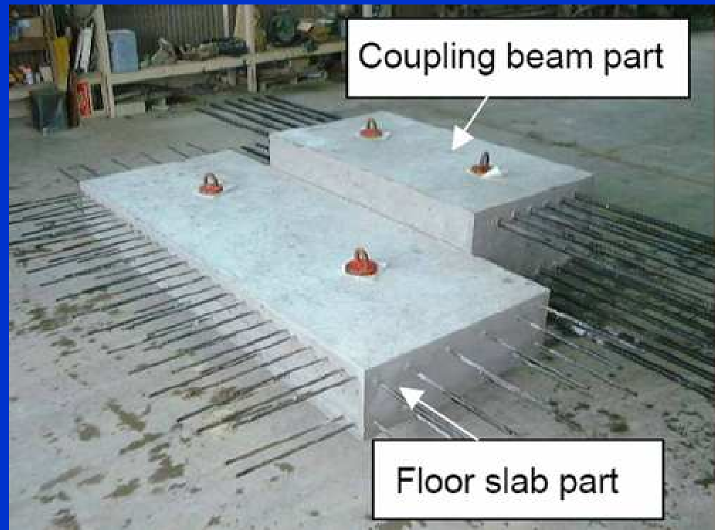
Strategic Use of PDCC - Example

- Link Slab for Highway Bridges
  - In the U.S., Steel Expansion Joints in Bridges often deteriorate and leak
  - Water (with Salt) may go through the joint, leading to corrosion of underlying steel girder
- <u>Solution</u>: Replacing Joint with Link Slab made of Pseudo-ductile Cementitious Composites
- Field Trial in Michigan show NO degradation after two years



Strategic Use of PDCC - Example

- Coupling Beam for Building

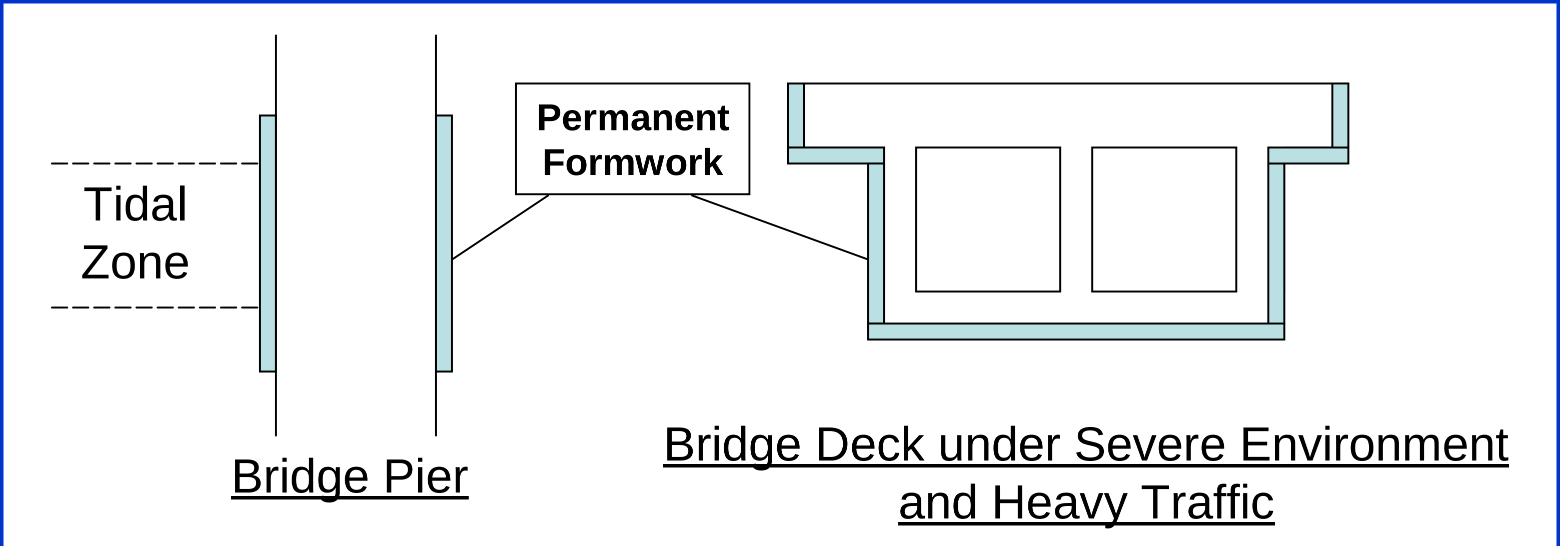


- Use of Steel Reinforced PDCC Coupling Beams can significantly increase damping of the Building
- Core and Columns sufficient to carry seismic action
- External Shear Walls can be removed to allow better views.

Strategic Use of PDCC –
Research Studies at HKUST

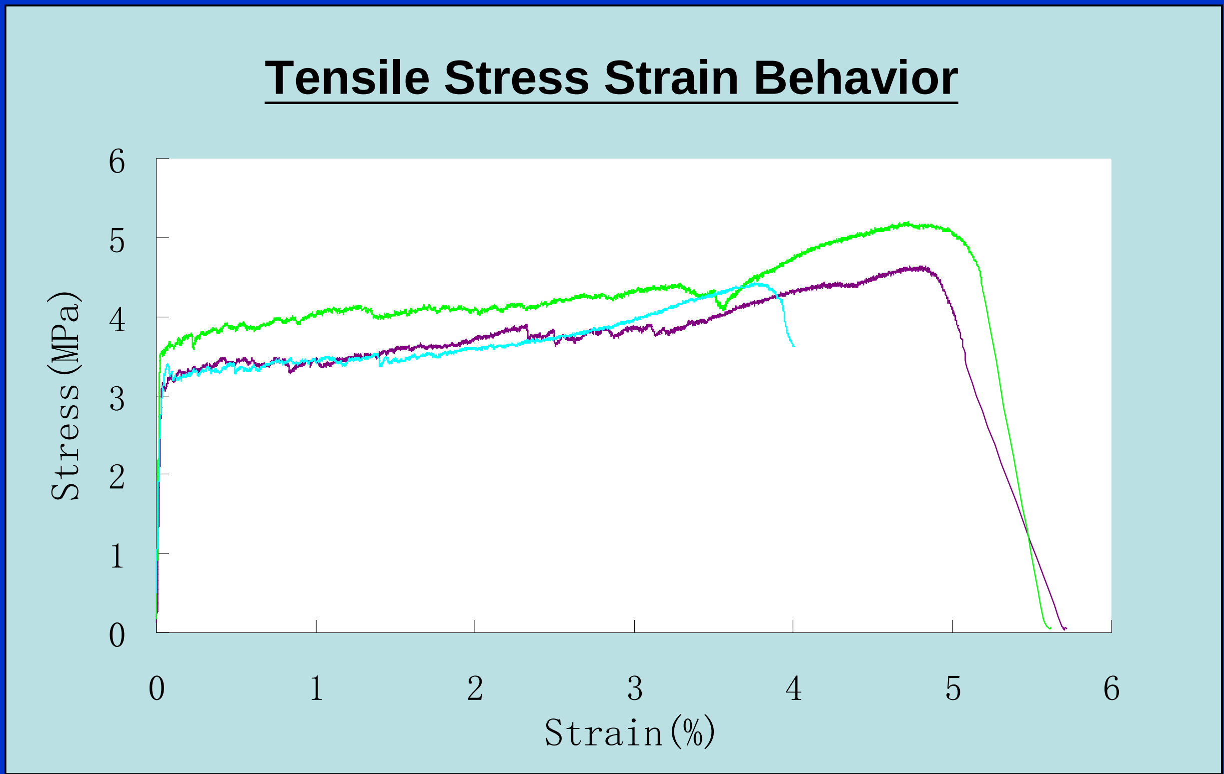
PDCC Permanent Formwork

- Durability of Concrete Structure governed by quality of cover concrete
- Un-cracked Concrete with low w/b ratio has excellent transport properties and hence good durability
  - Reinforced concrete members are designed to crack
  - Cracking will have significant effect on transport properties
- PDCC Permanent Formwork Controls Surface Crack Opening and Guarantees Long-term Durability
  - Can be used in Critical Parts of a Structure



PDCC Employed for Experimental Work

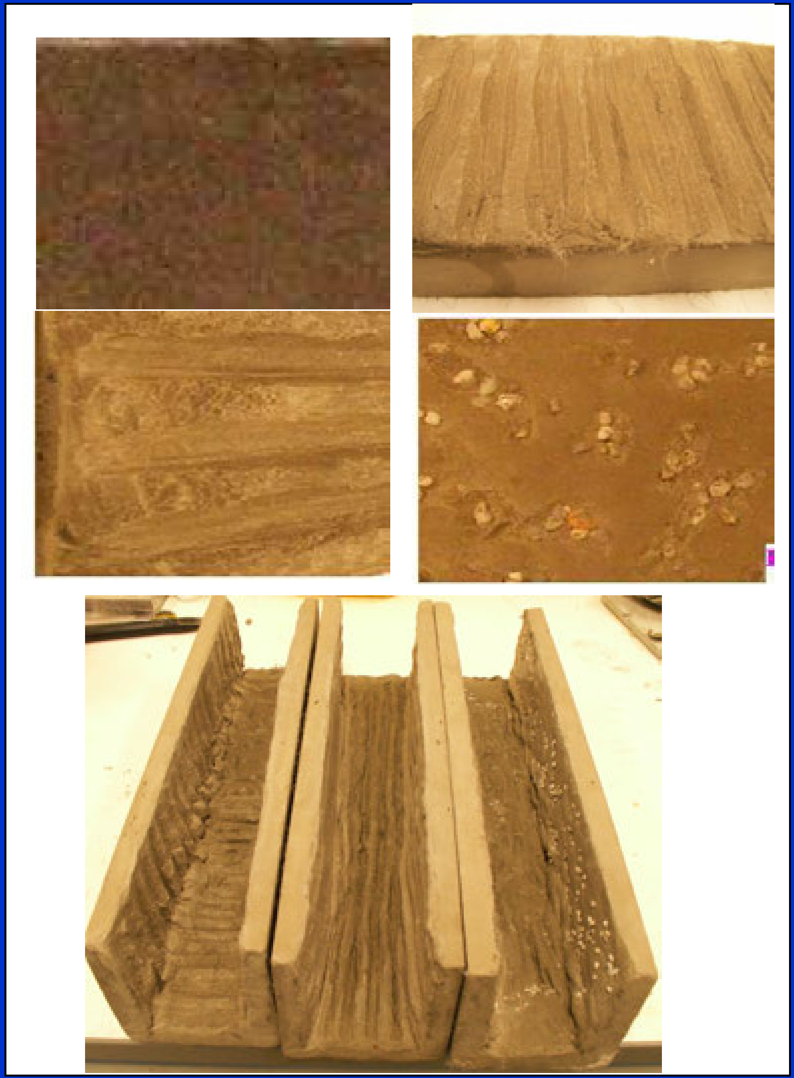
- Matrix of the following composition
  - Cement:fly ash:silica fume:sand=0.18:0.8:0.02:0.2
- 2 Vol% of PVA fiber added



Multiple Cracking of Specimen

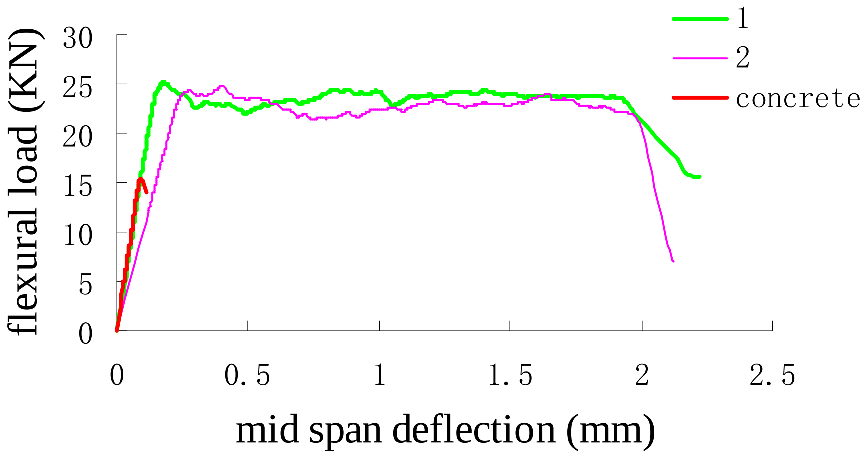
PDCC Formwork Fabrication

- 2 Types of Formwork Prepared
- Plate (400x100x25mm)
- U shape Formwork
- Surface Preparation
  - Smooth surface
  - Transverse grooves
  - Longitudinal grooves
  - Roughened with Chips
- Beams prepared by Casting of Plain Concrete

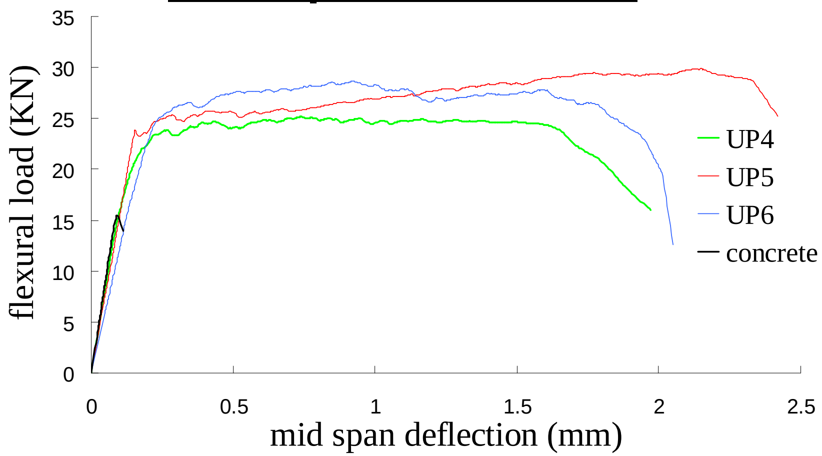


Three-Point Bending Test Results

Plate Formwork

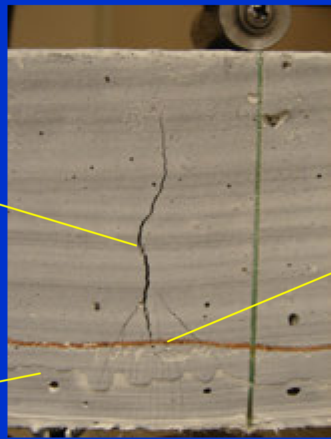


U-Shaped Formwork



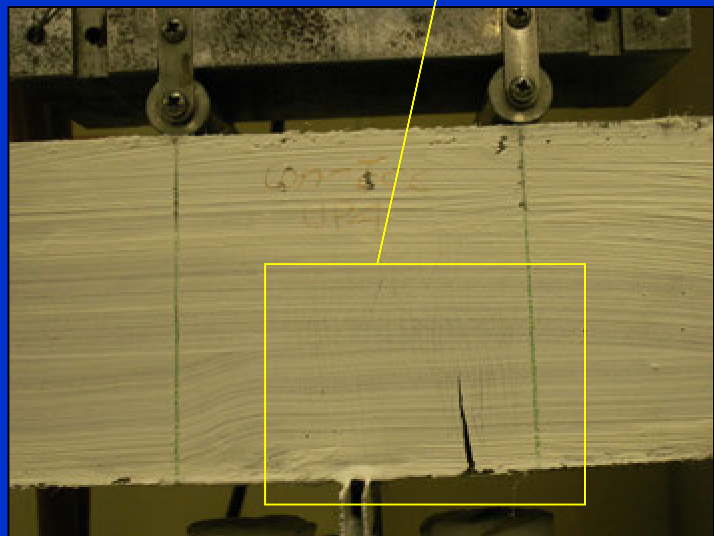
Concrete

PDCC



Discrete Crack Turns into Multiple Cracks (Similar Results For Different Surface Treatments)

Significant Multiple Crack before Final Failure

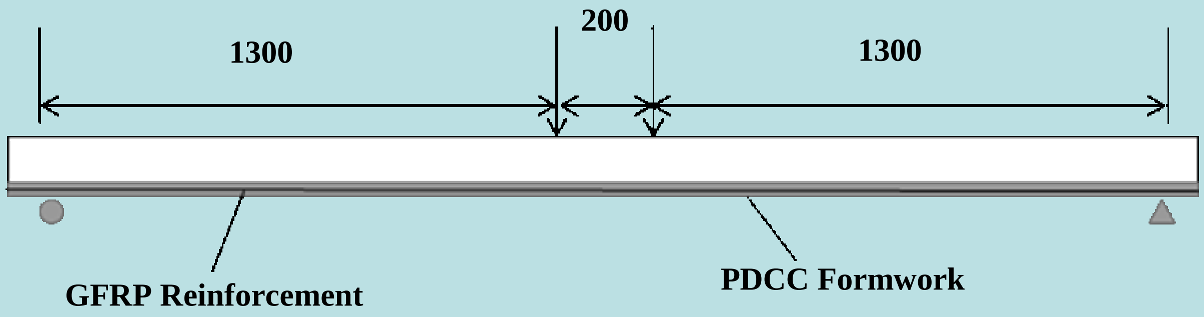


GFRP Reinforced PDCC Formwork

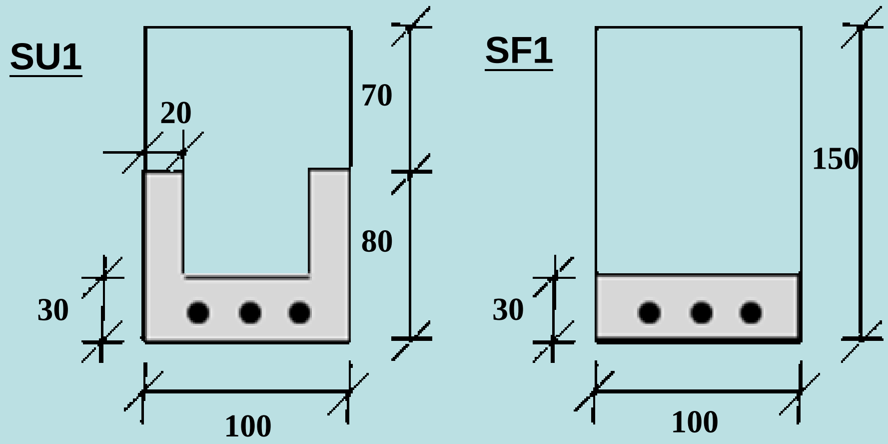
- Experimental Results show Ability of PDCC Formwork in Controlling Cracks
- GFRP can be added to provide Flexural Capacity
  - No Steel Needed for Some Cases
  - Simplify Construction for Members Requiring Multiple Layers of Steel
- GFRP does not corrode despite of Small Cover
- Excessive Crack Opening is a Concern when GFRP is used in Plain Concrete
  - Not a Problem With PDCC
- Optical Fiber Sensors can be Installed in GFRP to make Smart Formwork
  - Remove Difficulties associated with Site Installation

Beams made with GFRP Reinforced PDCC Formwork

Loading Configuration

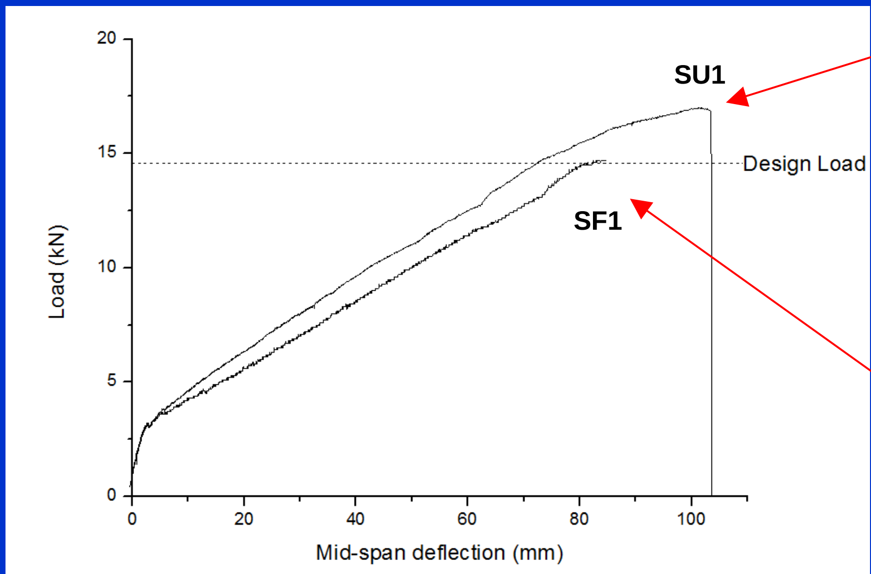


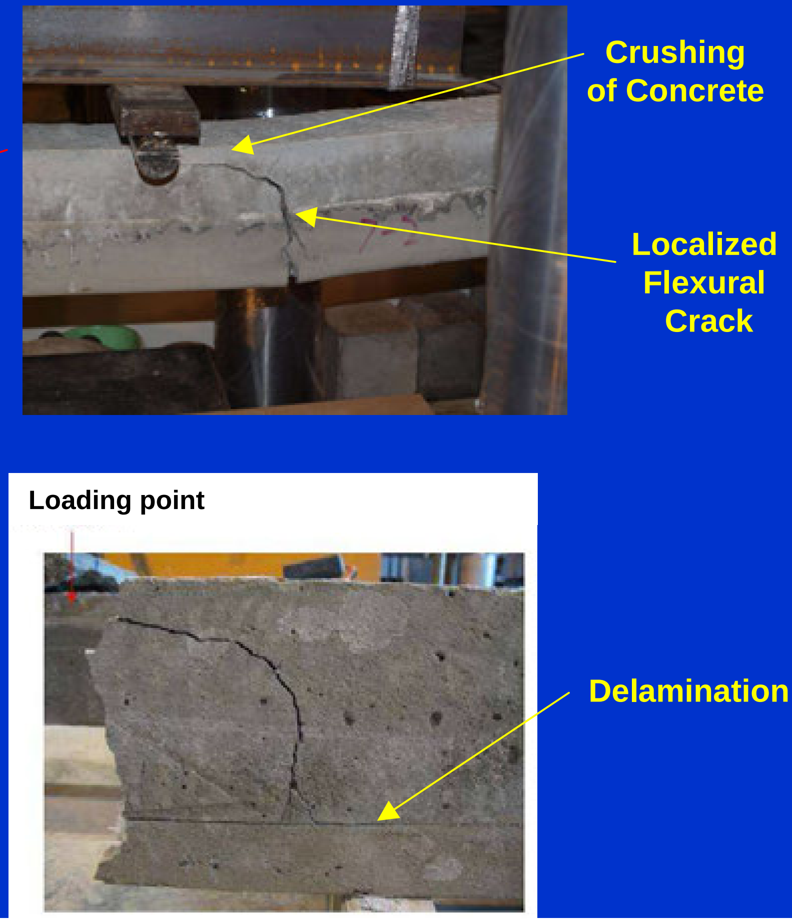
Sections for U-shaped and Flat Formwork



Test Results

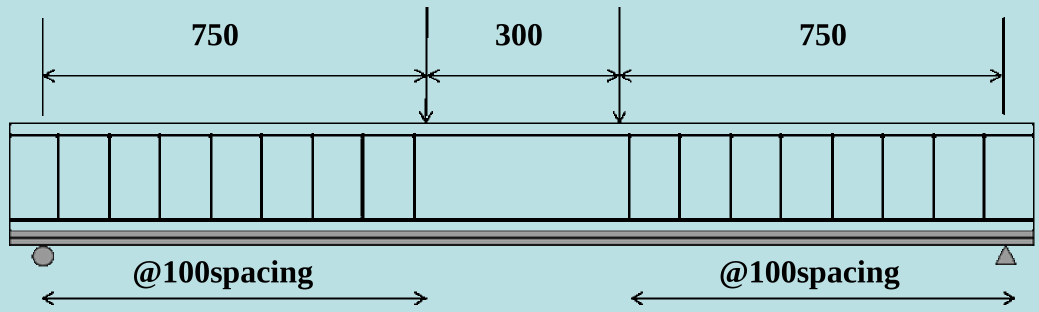
- Designed load of 14.6kN (from conventional RC analysis) approached or exceeded in both cases
- Beam with flat formwork shows delamination failure





Beams made with GFRP Reinforced PDCC Formwork

Loading Configuration



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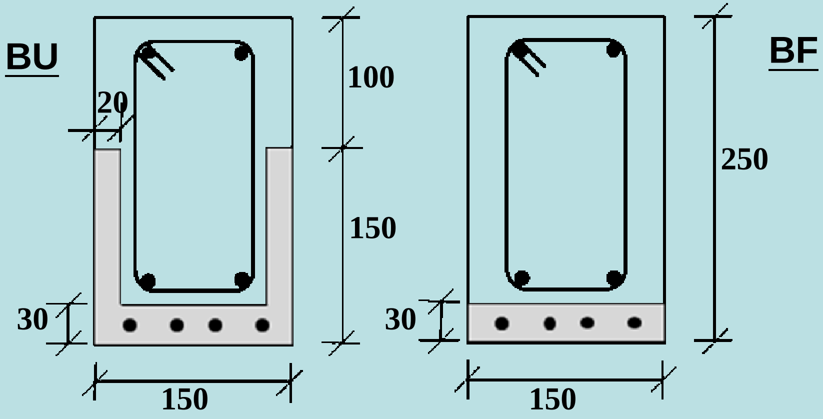
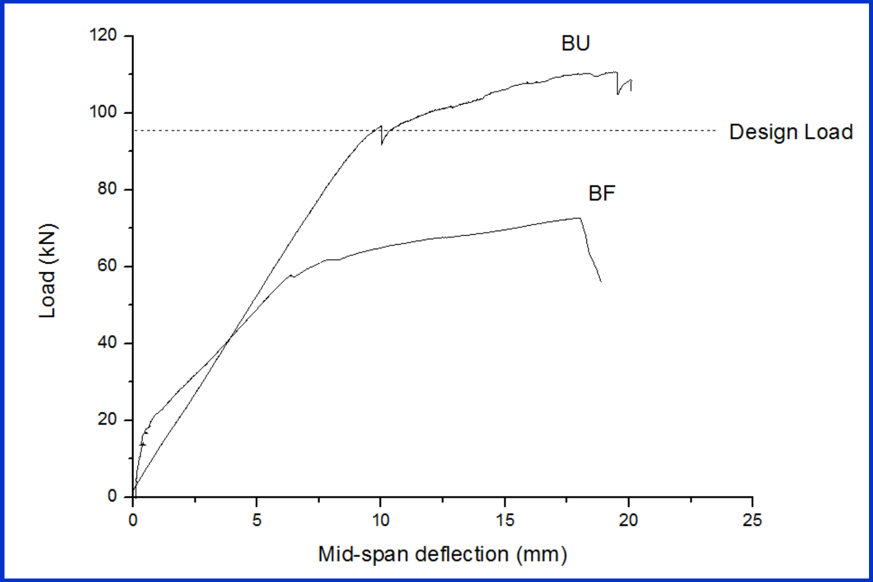


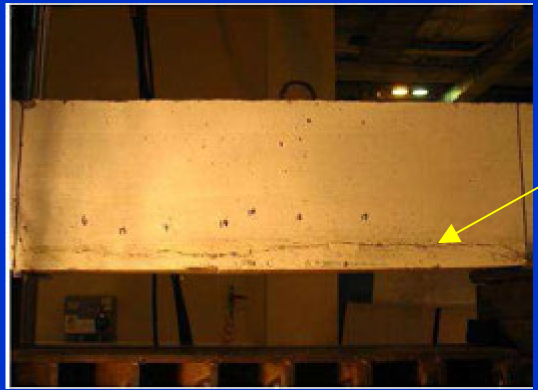
Test Results

- Designed load of 94.5kN
- Beam with flat formwork shows delamination failure at 73kN
- Beam with U-shaped formwork fails in rupture at 106kN



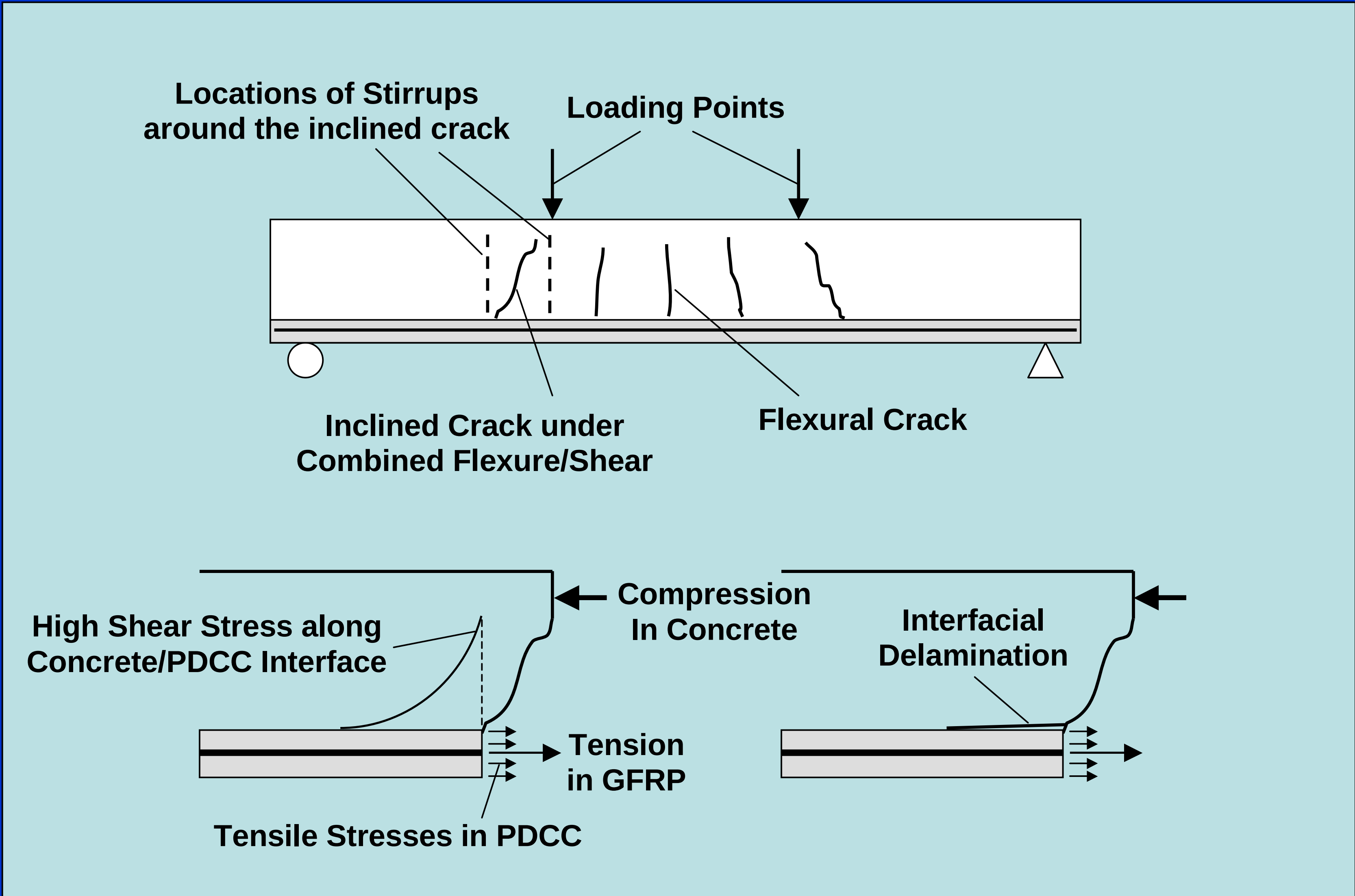
Crushing of Concrete

Localized Flexural Crack



Delamination

Mechanism of Delamination Failure

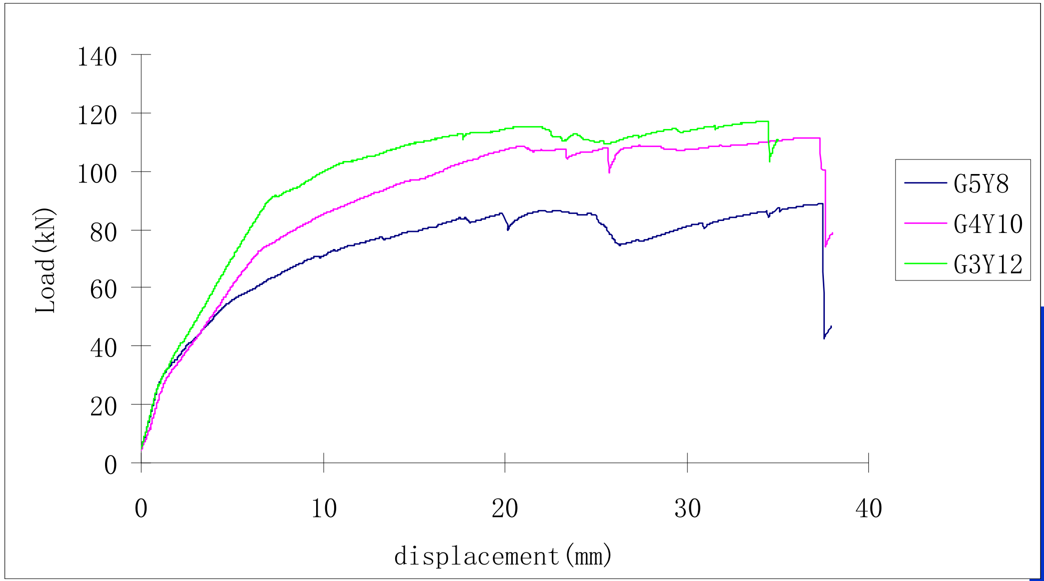


Additional Tests on Beams with U-shaped Formwork

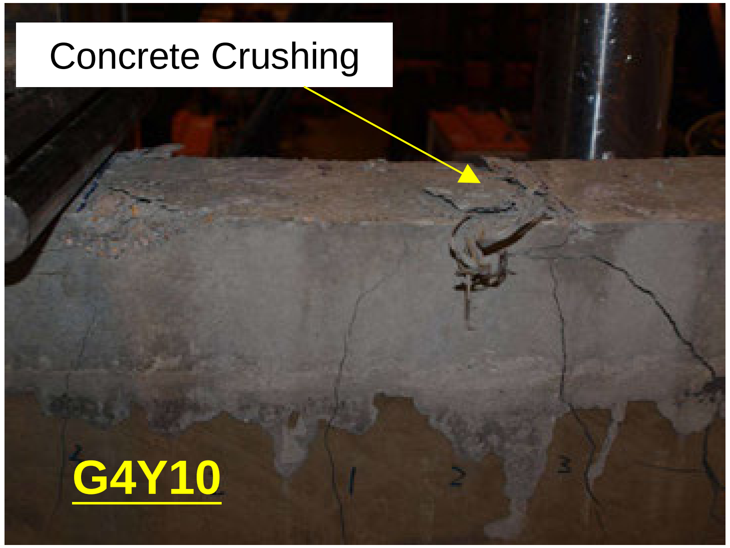
Series	Reinforcement Detail	Theoretical Moment (kN.m)	M/bd^2 (N/mm^2)	Test moment (kN.m)	Test Load kN	Failure Mode
G3Y12	GFRP 3Φ6 Steel 2T12	36.7	4.3	43.5	116	Flexure
G3Y12	GFRP 3Φ6 Steel 2T12	36.7	4.3	43.9	117	Flexure
G4Y10	GFRP 4Φ6 Steel 2T10	35.4	4.2	42	112	Flexure
G4Y10	GFRP 4Φ6 Steel 2T10	35.4	4.2	39.8	106	Flexure
G5Y8	GFRP 5Φ6 Steel 2T8	33.5	4	33.4	89	Delamination
G5Y8	GFRP 5Φ6 Steel 2T8	33.5	4	31.9	85	Delamination

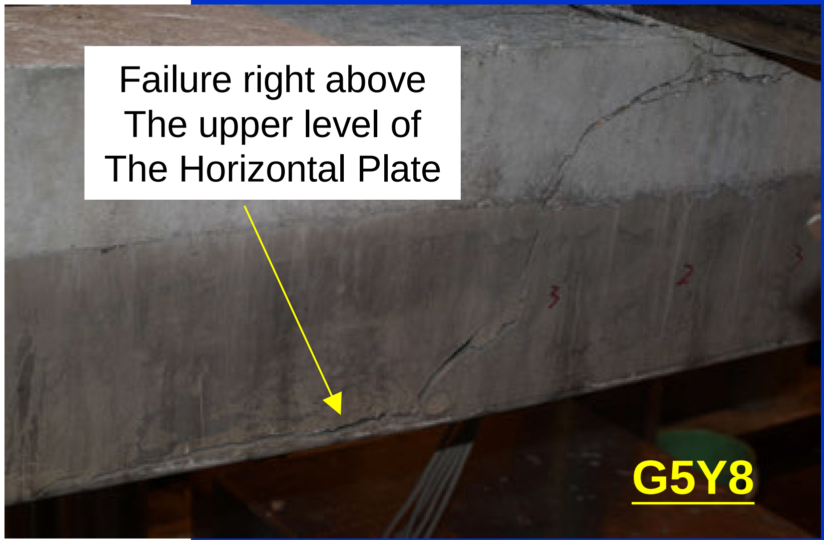
More GFRP in the Formwork leads to higher interfacial stress which favors Delamination Failure

Load vs Deflection Curves and Failure Modes



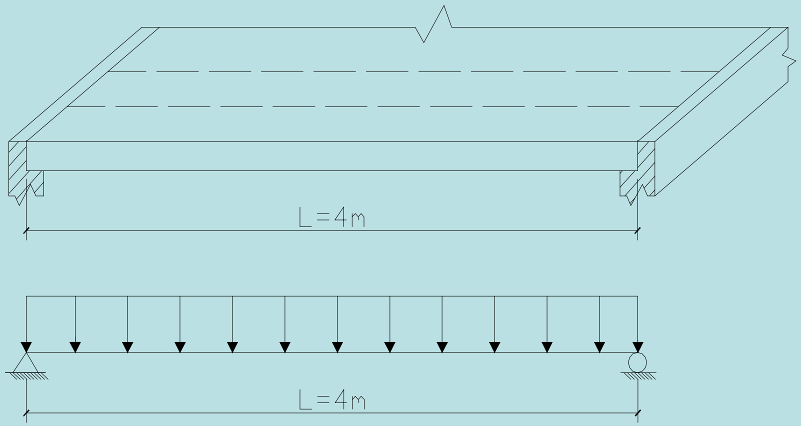
Similar Ductility Despite Different GFRP/Steel Ratios (may be due to Interfacial Delamination in cases with Higher GFRP Content)





A Design Example

4m Laterally Spanning Deck for a Footbridge



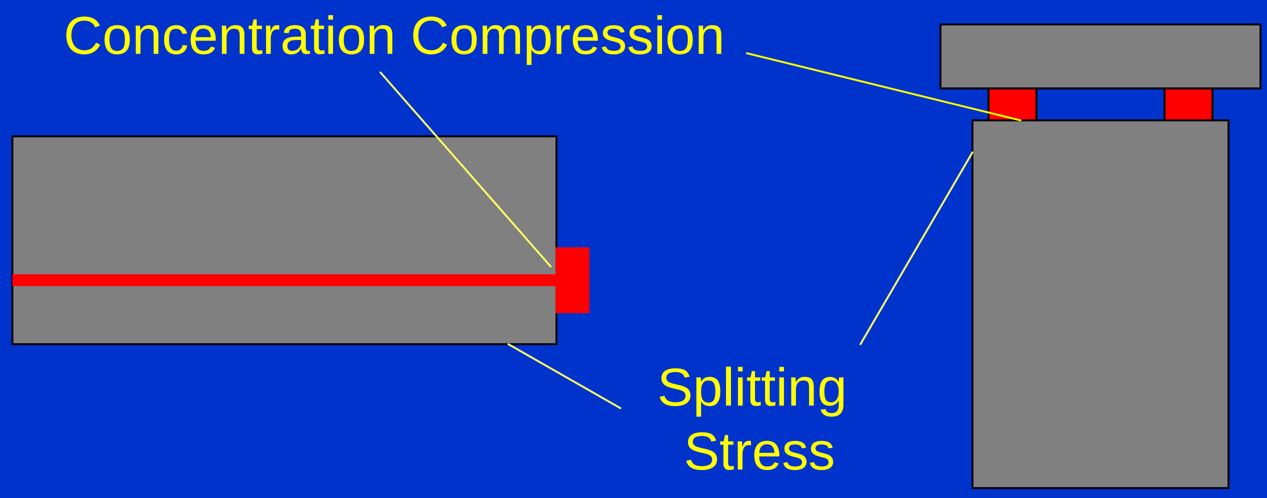
- With Loading from BS5400, Maximum Moment calculated to be 2.33 kNm
- Member made with Flat GFRP/PDCC Formwork + Plain Concrete exhibit Load Capacity of 9.6 kNm
- With U-shaped GFRP/PDCC Formwork, Load Capacity increases to 10.3 kNm
  - Permanent Formwork Suitable for Construction of the Deck
  - NO need to add Steel Reinforcements
  - Very High Durability under Aggressive Environment

PDCC for Resisting Local Splitting Stresses

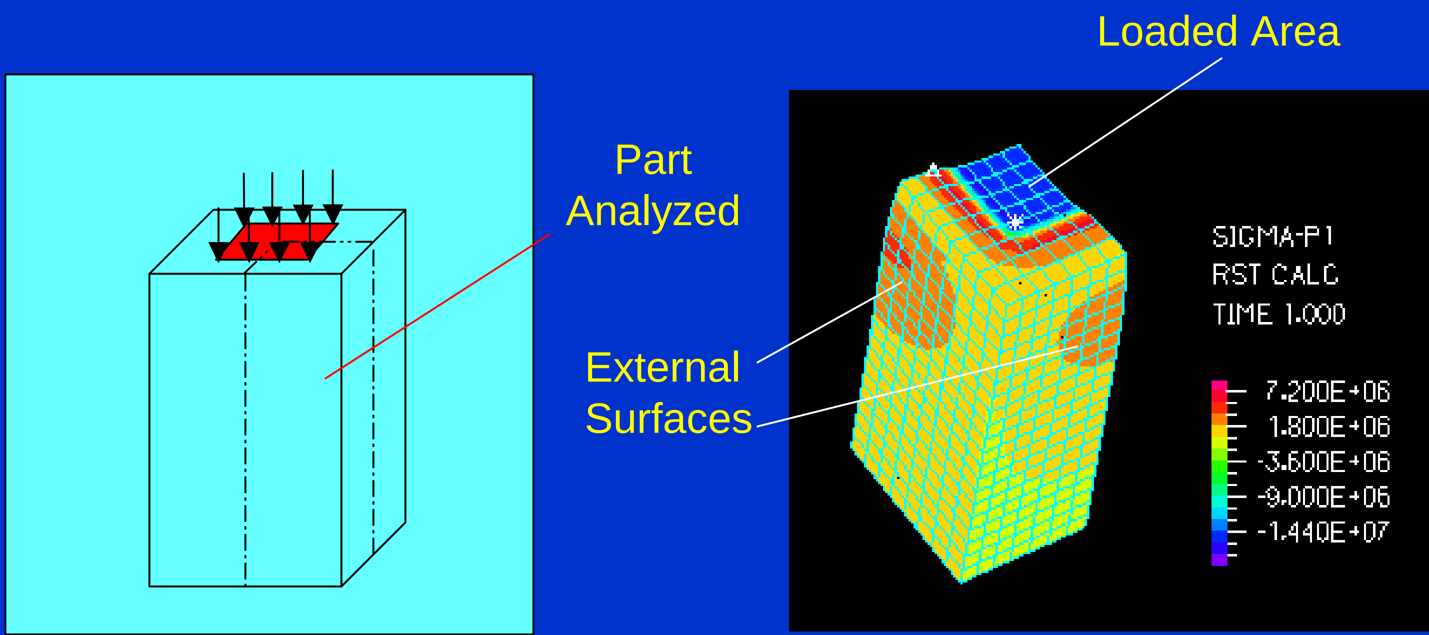
- Concentrated Compression can Lead to the Generation of Splitting Tensile Stresses
- Common Examples

Anchorage Zone of a Post-tensioned Member

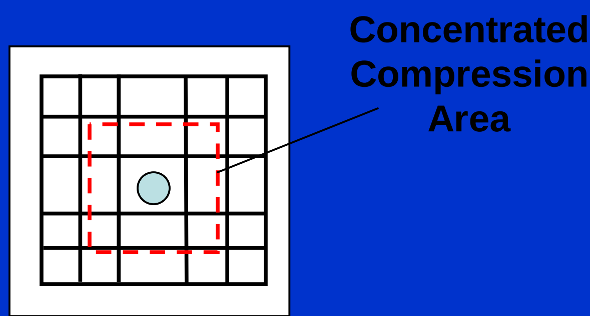
Bearing near the Edge of a Concrete Pier



Principal Stresses obtained from 3D Finite Element Analysis of a Rectangular Prism under Concentrated Compression

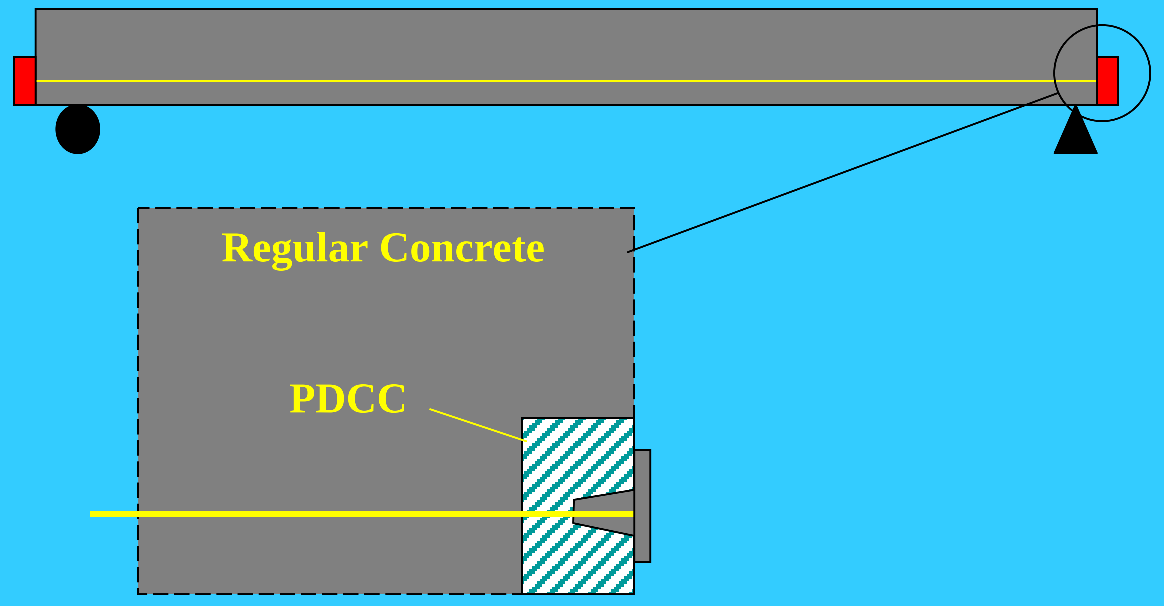


- High Splitting Tension is found on Exterior Surface of the Specimen
- Splitting prevented by closely-spaced steel hoops in Conventional Design
  - Labor Intensive Construction
  - Problem with Concrete Compaction



A New Design Concept

A Post-tensioned Concrete Beam

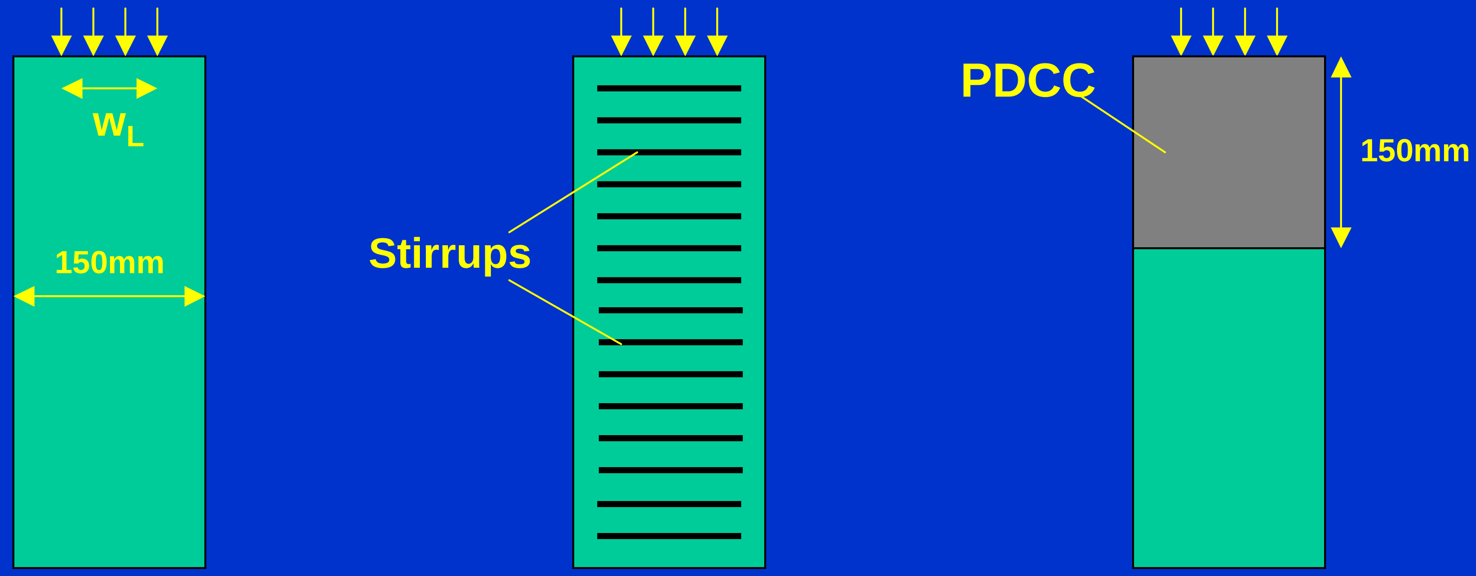


High Performance Pseudo-Ductile Material Employed in the Region around the Anchor to replace Steel Reinforcements

Experimental Verification of the New Concept

Three Types of Specimens Tested

Plain Concrete | **Concrete + Stirrup** | **Concrete +PDCC**



Concrete: σ_c = 39 MPa or 57.3 MPa

PDCC: **σ_c = 52.7 MPa, first cracking strength = 2.8 MPa**

(2% PVA) **Ultimate strength = 3.3 MPa, Failure Strain = 1%**

Results

Concrete Strength	A_L/A	Specimen Type	Ultimate Load (kN)
39 MPa	0.36	Plain Concrete	314
		Concrete + PDCC	587
		Concrete + Steel (1%)	445
57.3 MPa	0.16	Plain Concrete	247
		Concrete + PDCC	378
		Concrete + Steel (2.8%)	445
57.3 MPa	0.64	Plain Concrete	465
		Concrete + PDCC	686
		Concrete + Steel (1%)	590

Note: For Steel, '%' represents the Area Fraction of Confining Reinforcement

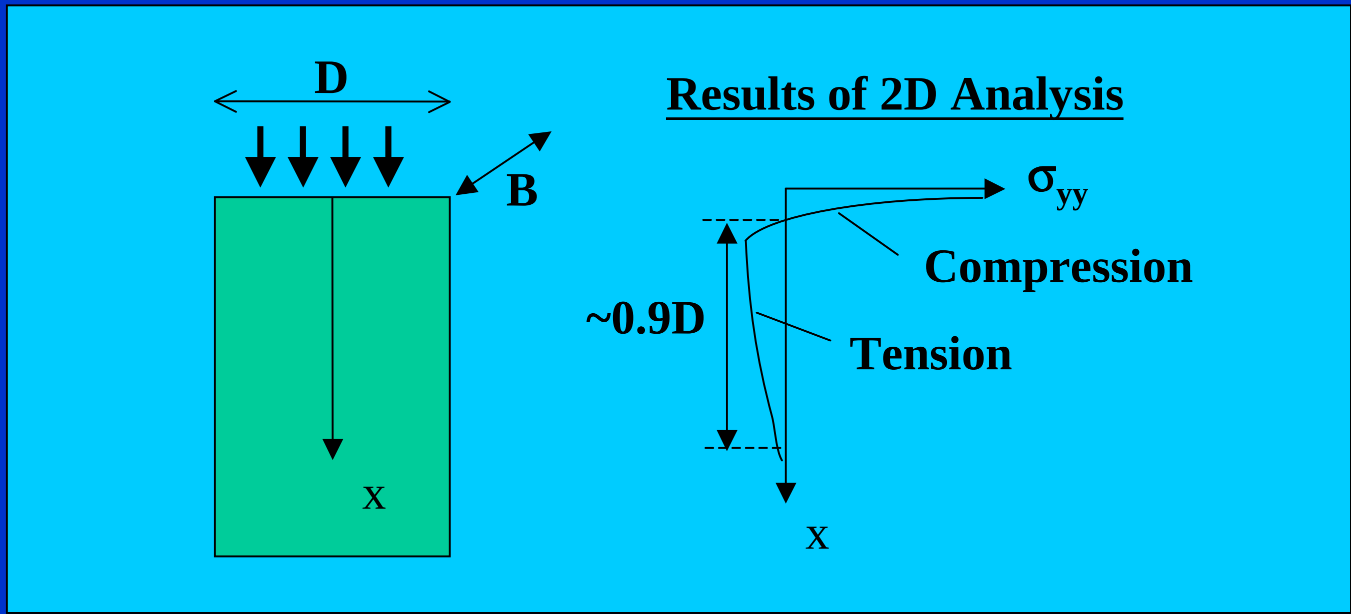
- PDCC can replace All the Confining Steel for Common Situation (Steel area fraction about 1%)
- PDCC can provide 80% of the Load Capacity for Congested Situations
  - Can replace most of the reinforcements for such a case

Effect of Material Properties

Concrete Cube Strength (MPa)	PDCC				Loading ratio A_L/A	Ultimate Load (kN)
	Cube Strength (MPa)	First Cracking Strength (MPa)	Ultimate Strength (MPa)	Ultimate Strain (%)		
70.0	Not used in these specimens				0.36	556
70.0	58.7	3.16	3.47	0.80	0.36	655
70.0	42.6	3.77	4.32	1.71	0.36	534
70.0	83.5	4.25	4.66	0.75	0.36	807
83.8	Not used in these specimens				0.36	622

- Tensile Ductility Improvement is much more beneficial than Pure increase in Compressive Strength
- Load Capacity Improves even with the use of PDCC with Lower Compressive Strength
- If PDCC Strength is too Low, Failure Occurs by Compressive Crushing
  - NO improvement over Plain Concrete

A Simple Design Approach



- Calculate Total Splitting Tensile Force in Anchorage Zone (0.9D in extent) from an Elastic Analysis

- Equate this to the total Resistance, given by $(\sigma_{fc})(B)(0.9D)$, where σ_{fc} is the first cracking strength of the PDCC

Results

(A_L/A)	a/D	First Cracking Strength of PDCC (MPa)	Ultimate Load		
			Expt (kN)	Predicted (kN)	$\frac{\text{Predicted-Expt}}{\text{Expt}}$
0.36	0.6	2.8	581	567	-2.4 %
0.16	0.4	2.8	378	378	0 %
0.64	0.8	2.8	686	709	3.3 %
0.36	0.6	3.16	655	640	-2.3 %
0.36	0.6	4.25	807	861	6.7 %

- Predicted Values from Simple Analysis Agree well with Test Data
- More Data is needed for Full Verification but the Simple Method Shows Promise for Design

Conclusions and Future Outlook

- Strategic Use of PDCC in Structures can
  - improve structural durability
  - facilitate the construction process
  - simplify complex designs
- This approach has good potential for practical applications
- Future Developments
  - Cost should be further reduced through better Material Design
  - Focus on Durability (Crack Control) and Performance-Based Design (with degree of damage being a performance criterion)