Field Implementation of Ultra-High-Performance Concrete in Bridge Rehabilitation Projects in Maricopa County

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UHPC

5/30/2009

- Compressive Strength:
  - - General concrete: 25-50 MPa, 3-4 ksi
  - - High performance concrete: 50-70, 10-13 Ksi MPa
  - - UHPC compressive strength: ~150 MPa, 22 Ksi
- Higher tensile and flexural strength (~10 MPa, 1300 Psi) for UHPC
- High dosage rate (of the order of 1%-3% by volume of steel fibers) increases the ductility
- Use of a low w/b, coupled with optimal particle packing, increases the durability properties of UHPC
- Obtaining a very high compressive strength is not the only important criteria
- Compressive strength alone does not correlate to crack resistance, ductility, and durability
- UHPC mixtures need to be designed for overall performance, including high flexural, tensile, and shear capacity as well as long service life, in addition to a higher compressive strength.

UHPC: Advantage

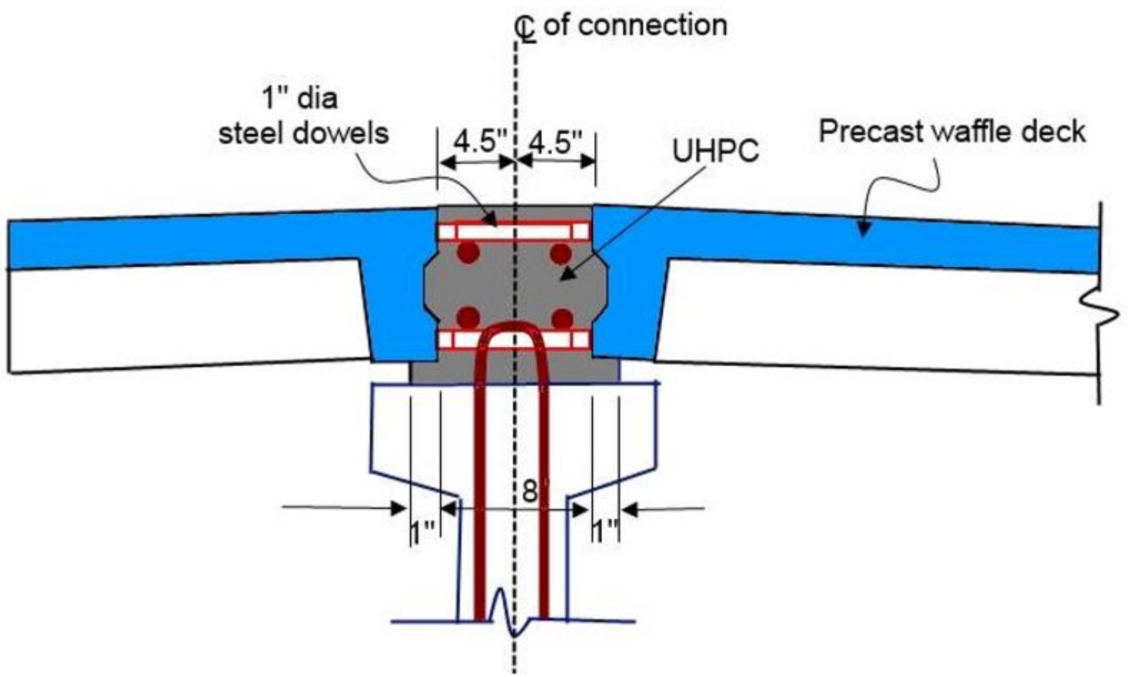
- Adequate control of shear cracking in conventional concrete requires tightly formed rebar cages and stirrup arrangements; increases the cost of the structural member
- With the enhanced tensile strength of UHPC, the shear strength is improved, and the tensile cracking reduced
- The discrete steel fiber reinforcement included in UHPC allows the concrete to maintain tensile capacity beyond the cracking strain of the cementitious matrix
- The increased ductility and crack resistance of UHPC reduces the need for excessive shear reinforcement, and some of the complexities of reinforcement placement can be avoided
- UHPCs can significantly shorten the development length of embedded discrete steel reinforcement

Field connections

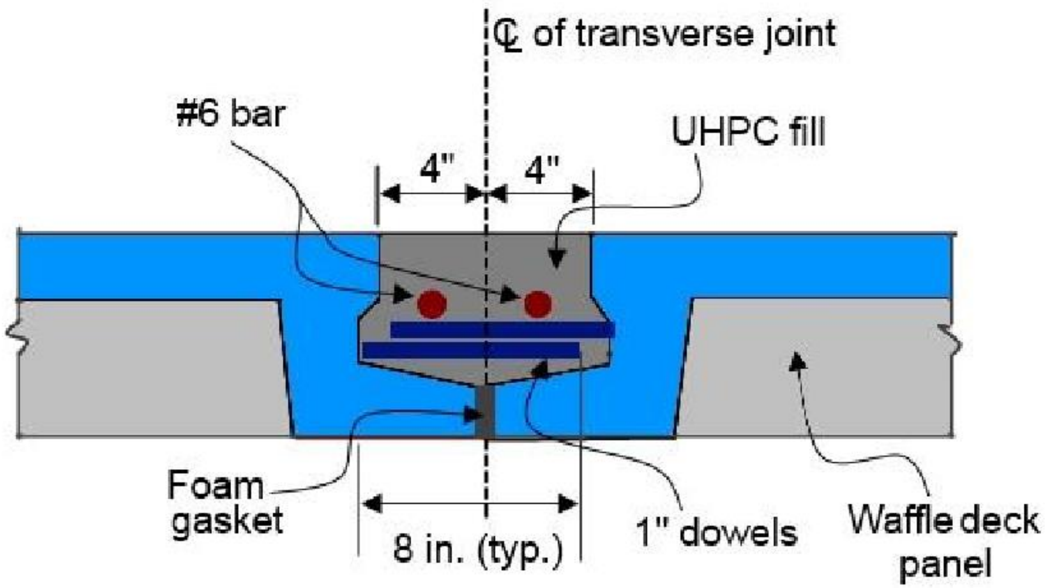
- Deck-level connection between precast deck panels and field casting of UHPC connections

- Small, simple connections without requiring post–tensioning or large volumes of field–cast concrete

Despite the cost , UHPC is still the economical solution



Deck and girder connections



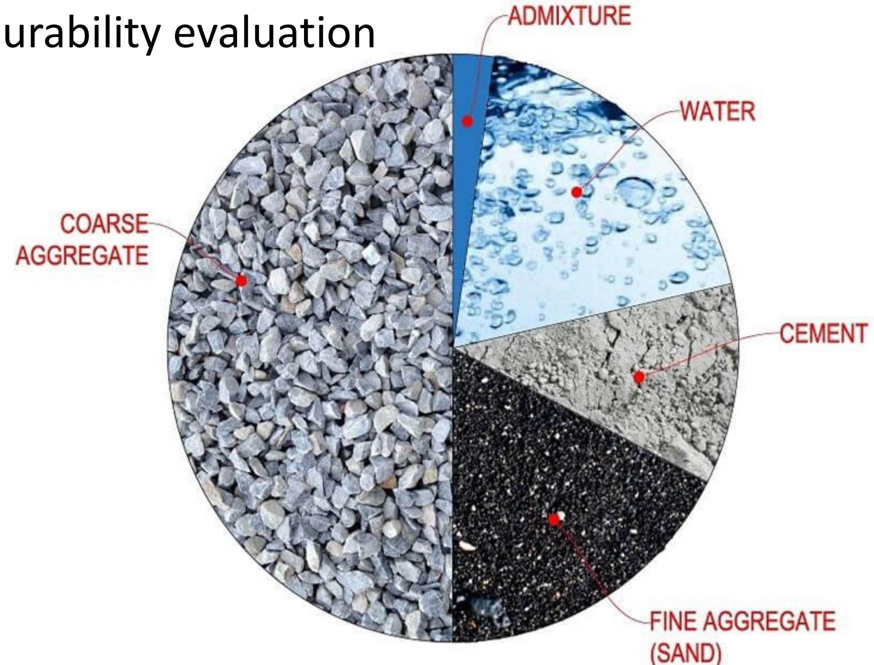
Connection between deck panels

Material design challenges

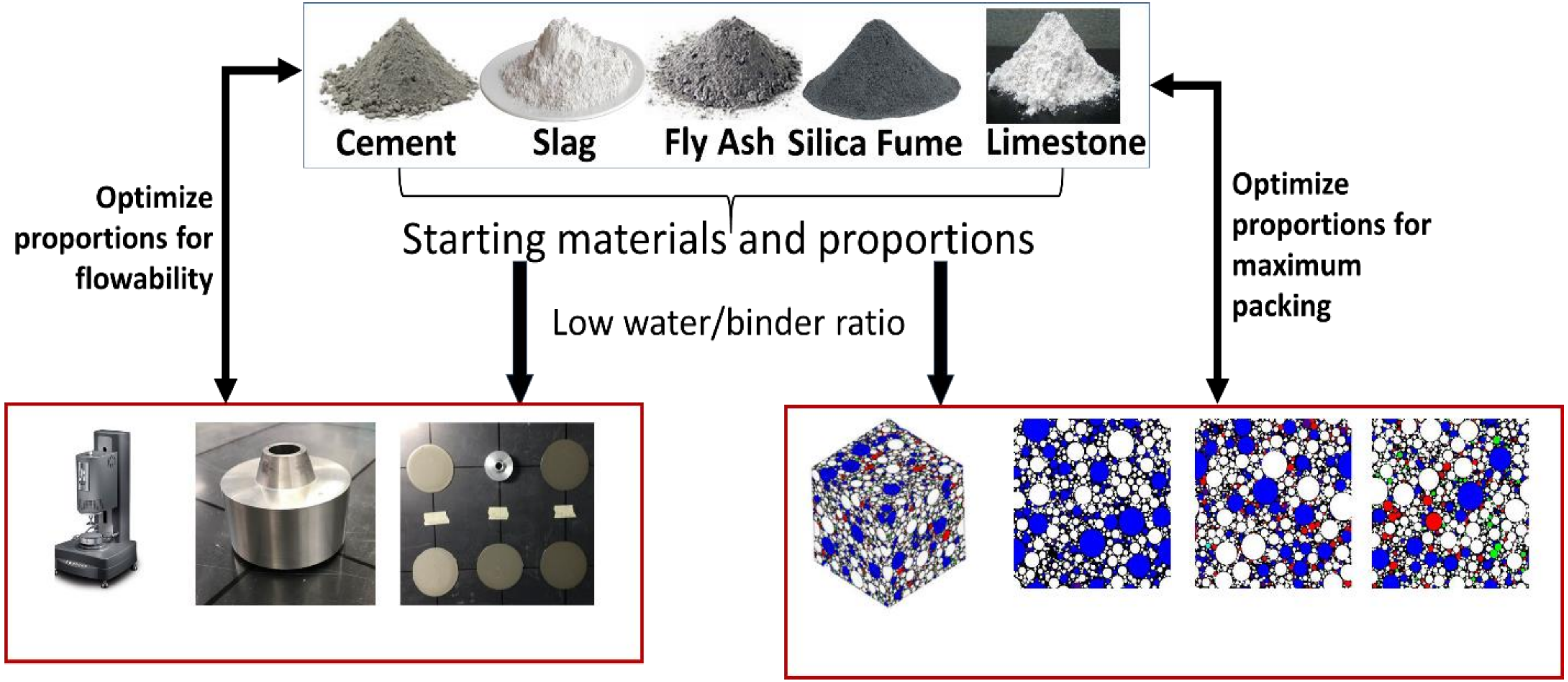
- Commercial UHPC mixtures cost > $9000/cy installed
- Need to use a very low w/b to obtain strengths > 150 MPa
  - Large admixture demand and associated costs/other issues
- Need to be self-compacting for bridge deck connections
  - Large admixture demand and other associated issues
- Need extremely fine powders to ensure particle packing and reactivity
  - More admixtures at low w/b, several types of fine powders
- Need small aggregate sizes and high binder content
  - Cost, shrinkage etc.

A Rational material design procedure

- Rational binder design based on performance characteristics
  - Selecting binder materials, admixtures and w/b for: (a) optimal packing of particles; (b) necessary reactivity, and (c) self-compacting flow
- Rational aggregate class and quantity selection based on packing
  - Select aggregate sizes and amounts (many UHPCs are basically mortars, but aggregates provide dimensional stability and economy, if properly designed)
- Evaluation of material properties and conformance with design requirements
  - Mechanical testing (compression, tension, flexural, fracture) and durability evaluation (resistance to freezing and thawing, chloride penetration)



Paste design



Cement Slag Fly Ash Silica Fume Limestone

Starting materials and proportions

Optimize proportions for flowability

Low water/binder ratio

Optimize proportions for maximum packing

Rheology (flowability)

Packing of particles

Common UHPC mixtures

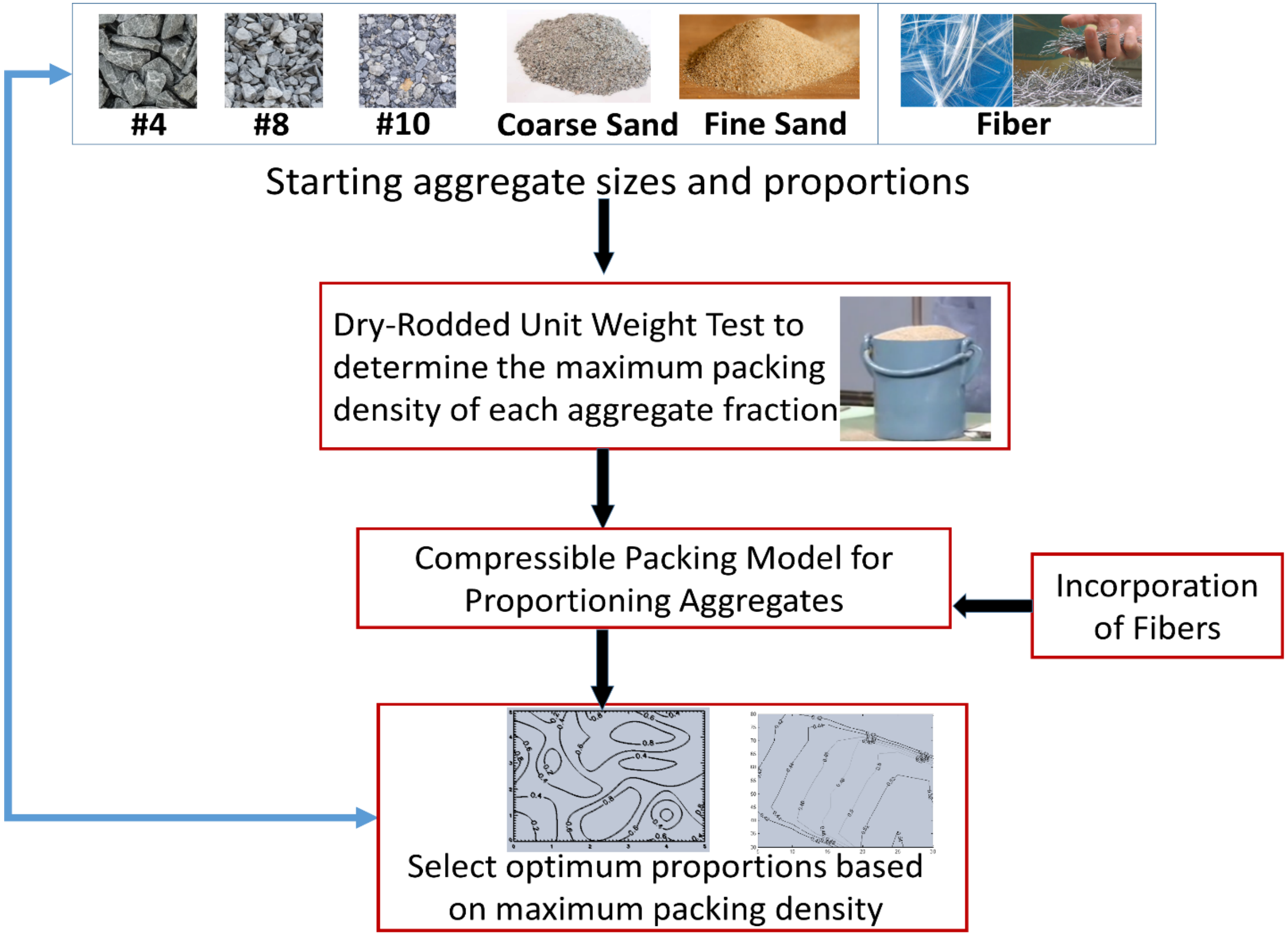
1 lb/yd^3 = 0.593 kg/m^3

Material	Amount (kg/m^3 (lb/yd^3))	Percent by Weight
Portland Cement	712 (1,200)	28.5
Fine Sand	1,020 (1,720)	40.8
Silica Fume	231 (390)	9.3
Ground Quartz	211 (355)	8.4
Superplasticizer	30 (51)	1.2
Steel Fibers	156 (263)	6.2
Water	130 (218)	5.2

	Mix 1		Mix 2	
Material	lb/yd^3	kg/m^3	lb/yd^3	kg/m^3
Cement	1,235	733	978	580
Silica Powder	388	230	298	177
Fine Quartz 1	308	183	503	131
Fine Quartz 2	0	0	848	325
HRWR	55.5	32.9	56.2	33.4
Sand	1,699	1,008	597	354
Basalt	0	0	1,198	711
Steel Fibers	327	194	324	192
Water	271	161	238	141
Water-Binder Ratio	0.19	0.19	0.21	0.21

Material	lb/yd^3	kg/m^3
Portland Cement	1,770	1,050
Sand	866	514
Silica Fume	451	268
HRWR	74	44
Steel Fibers	1,446	858
Water	303	180

Aggregate packing design



#4 **#8** **#10** **Coarse Sand** **Fine Sand** **Fiber**

Starting aggregate sizes and proportions

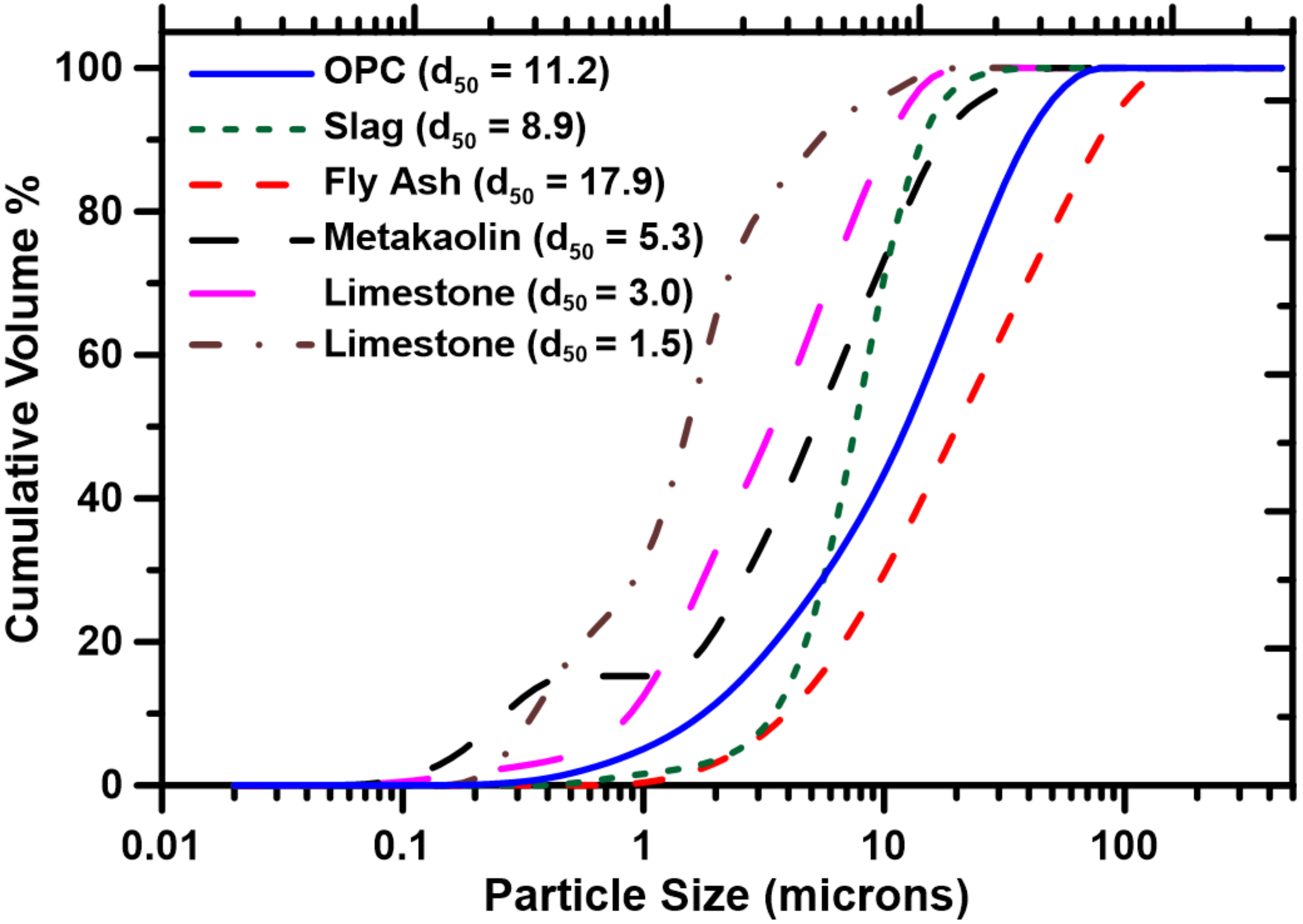
Dry-Rodded Unit Weight Test to determine the maximum packing density of each aggregate fraction

Compressible Packing Model for Proportioning Aggregates

Incorporation of Fibers

Select optimum proportions based on maximum packing density

Materials for Binder design



Materials selected

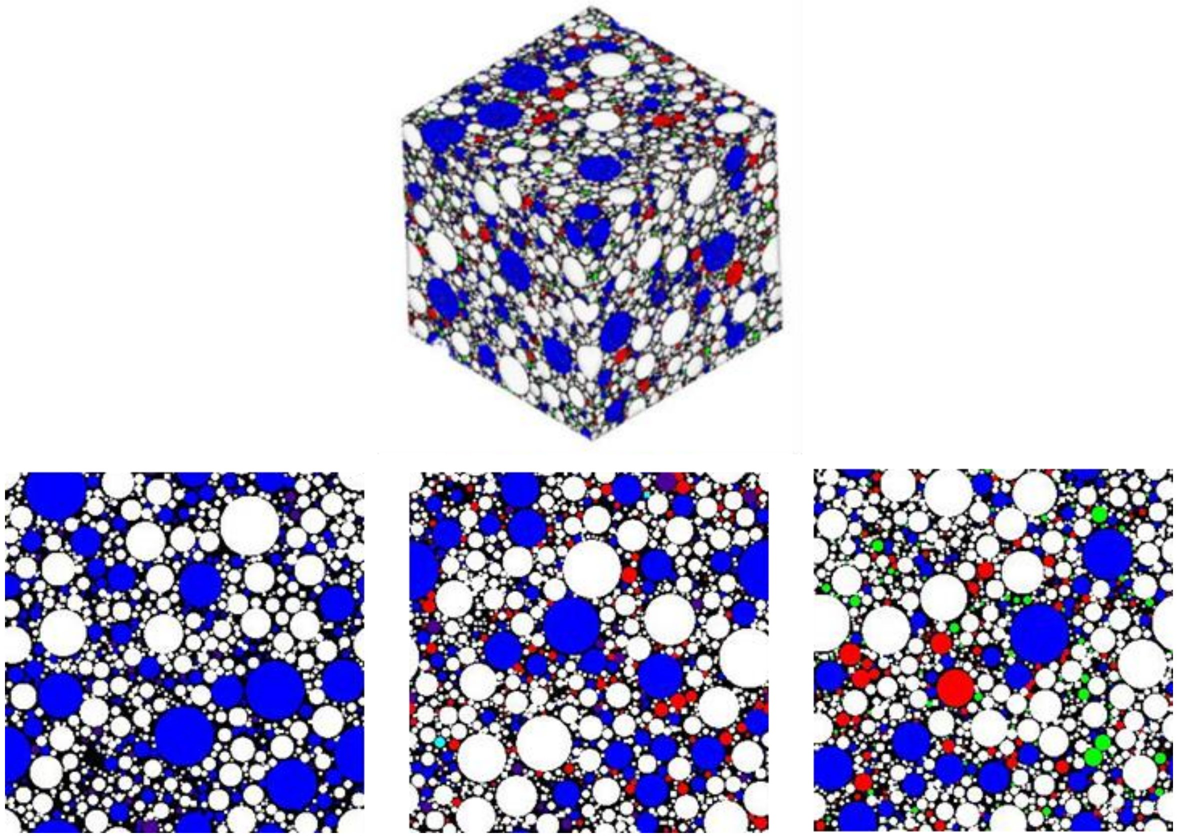
- ➢ **OPC** – ASTM C150 cement
- ➢ **Slag, Metakaolin** (pozzolanic, and alumina sources – to react with carbonates present in the system)
- ➢ **Limestone** – 3.0 micron and 1.5 micron median sizes. Fine limestone help with dense packing of microstructure
- ➢ **Fly Ash** – pozzolanic, spherical particles aid with workability

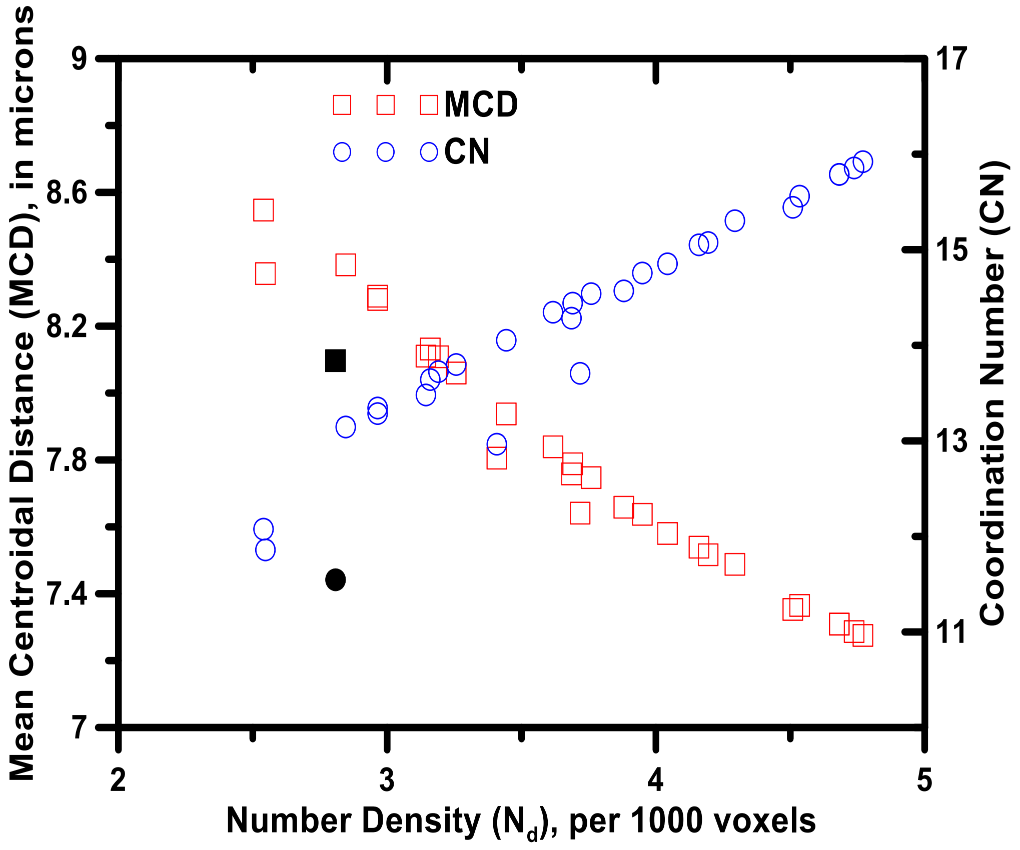
Aggregate Packing - Challenges

v/s

- Aggregates are irregularly shaped – rounded, angular, flat, elongated.
- In a concrete mixture, aggregates cannot be placed one by one, so virtual maximum packing density can never be achieved in practice.
- The packing density of aggregates increases with the degree of compaction/vibration, the more you compact/vibrate, the more aggregates you can add in a fixed volume.

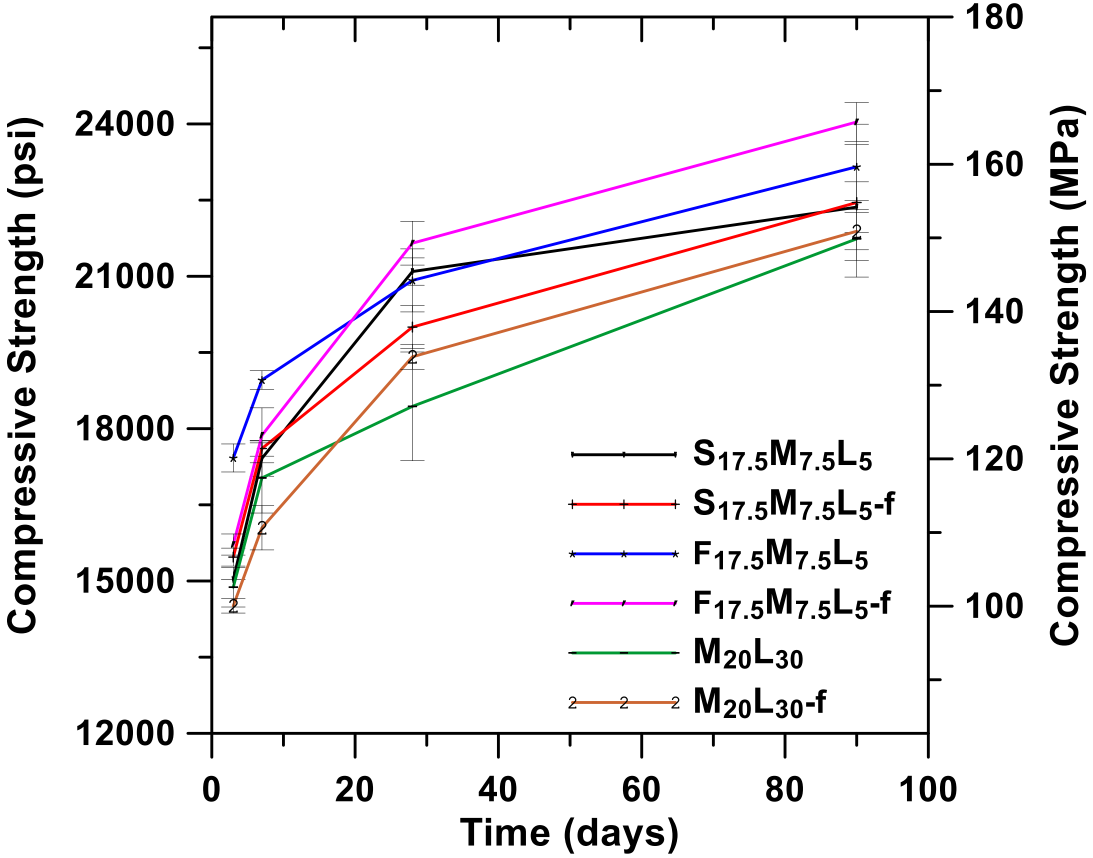
Microstructural packing parameters





Coordination number (CN)
Number density (N_d)
Mean Centroidal Distance (MCD)

Mortar strengths



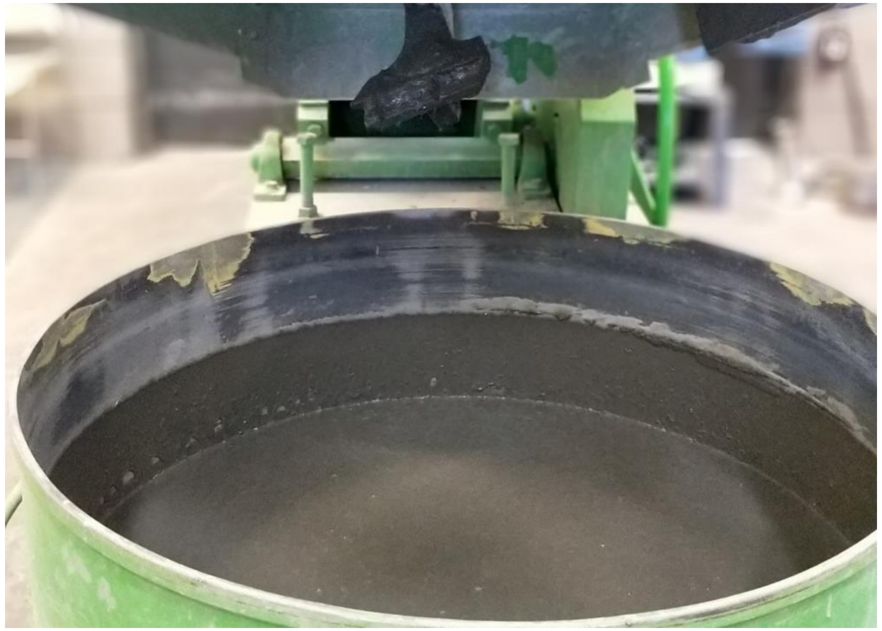
- Close to 150 MPa mortar strengths by 28 days for selected binders
- As high as 170 MPa after 90 days curing depending on binder composition and replacement level

Aggregate Classes Used

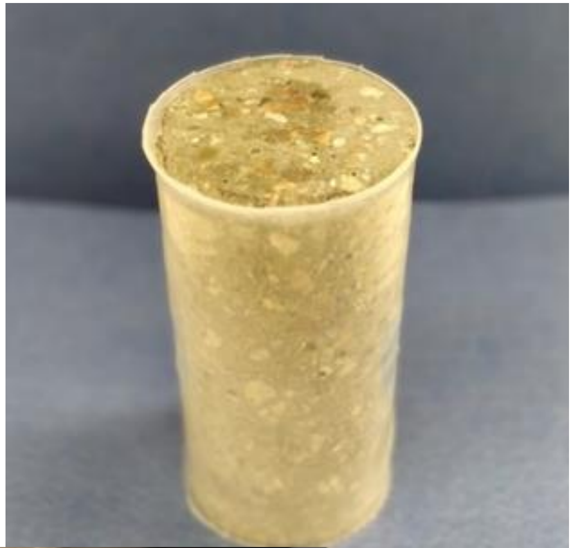
- 5 different aggregate classes were used corresponding to sizes - #4, #8, #10, coarse sand with a d_{50} = 0.6 mm, fine sand with a d_{50} = 0.2 mm
- Steel fibers – d = 0.6 mm, l = 13 mm.

Mechanical Splitter used to obtain uniform gradation of particles

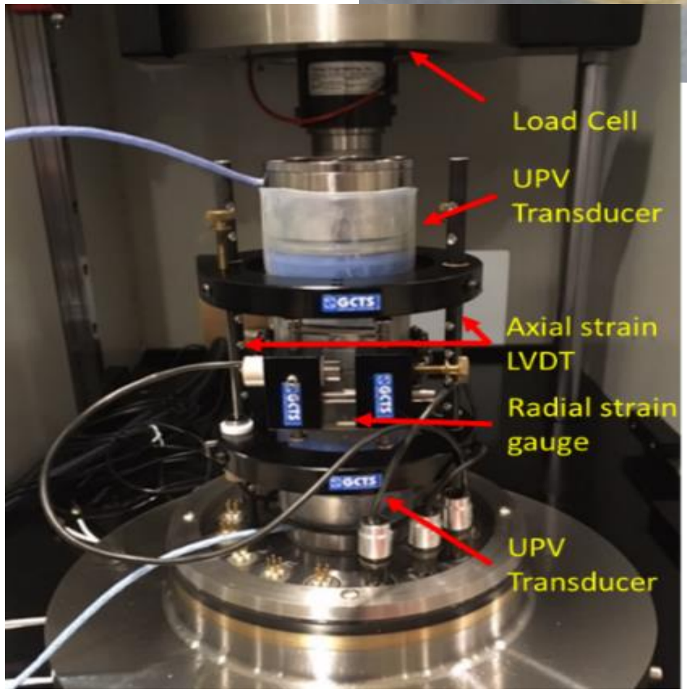
Scaled-up mixtures



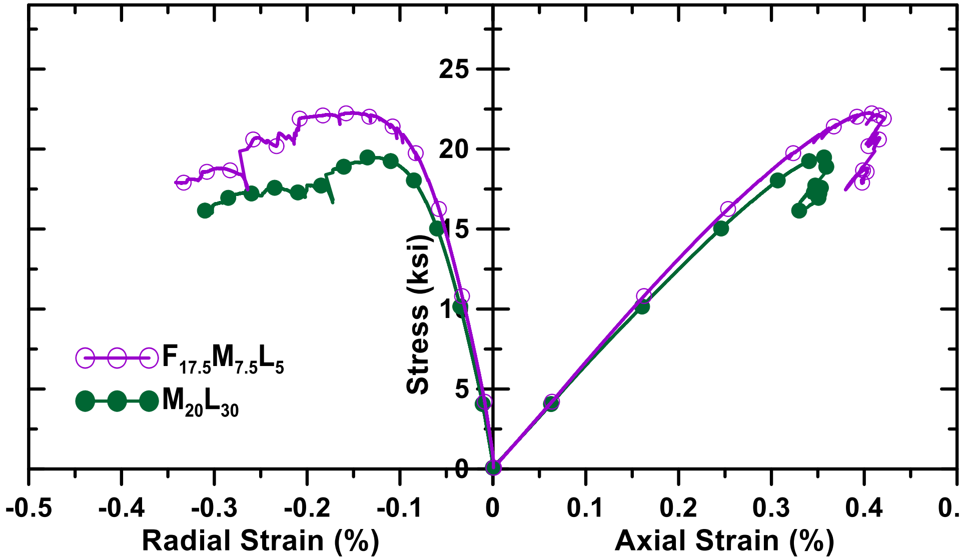
Compressive Strength

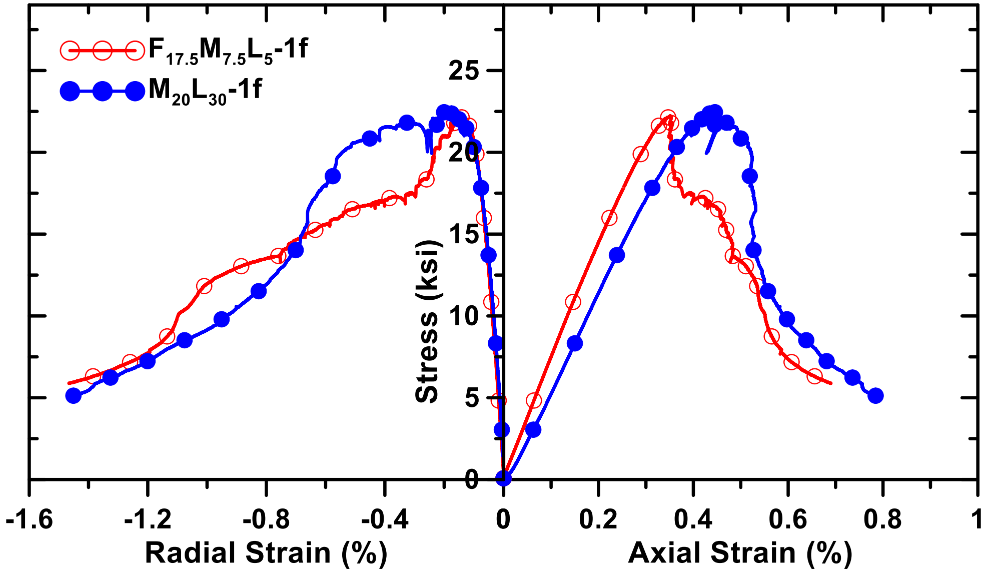


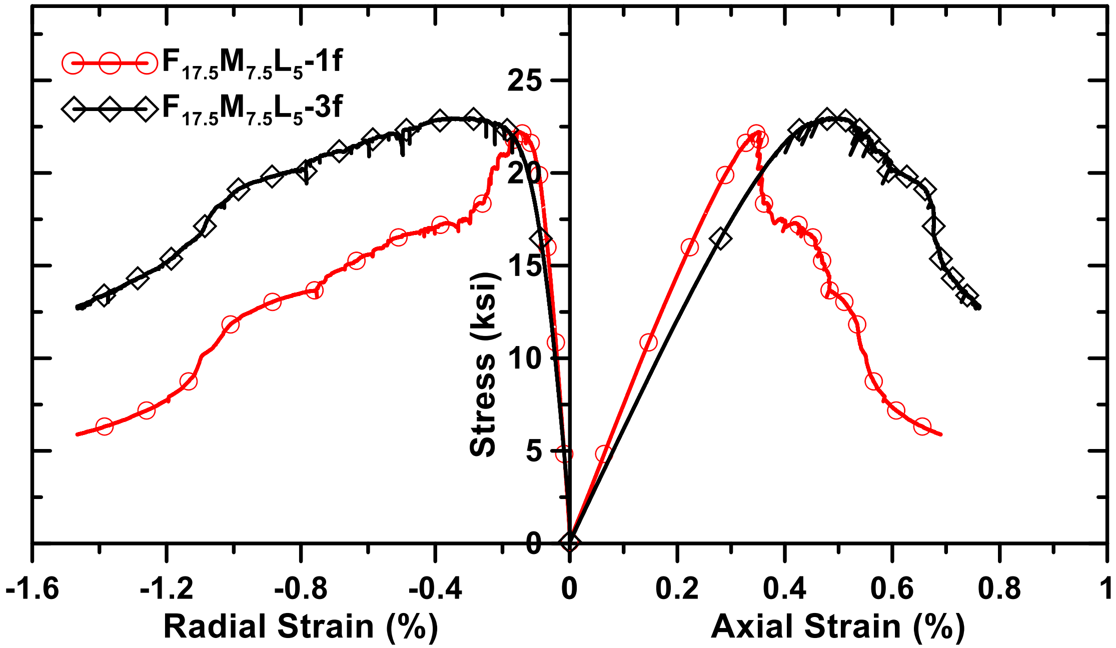
- 2” x 4” cylindrical specimens were cored from 3” x 6” concrete specimens to be used for the evaluation of stress-strain response.
- Ends of the cylinders were ground to extremely low surface roughness (< 0.007 inches).
- In-situ ultrasonic pulse velocity (UPV) testing was also conducted during the compression test and velocity measurements were recorded at successive stress intervals of 10 MPa



Stress-Strain Response in Compression and the influence of fibers





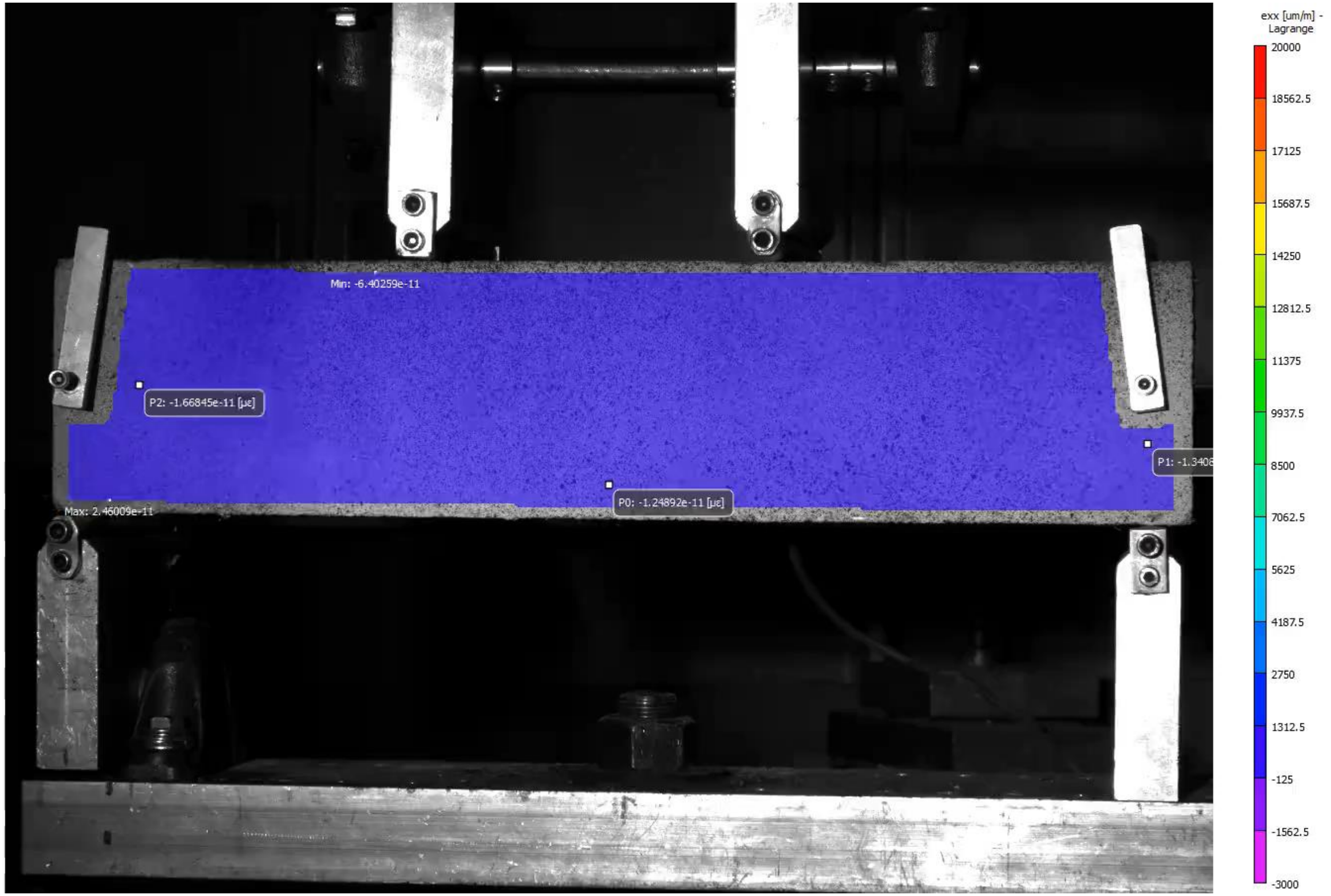


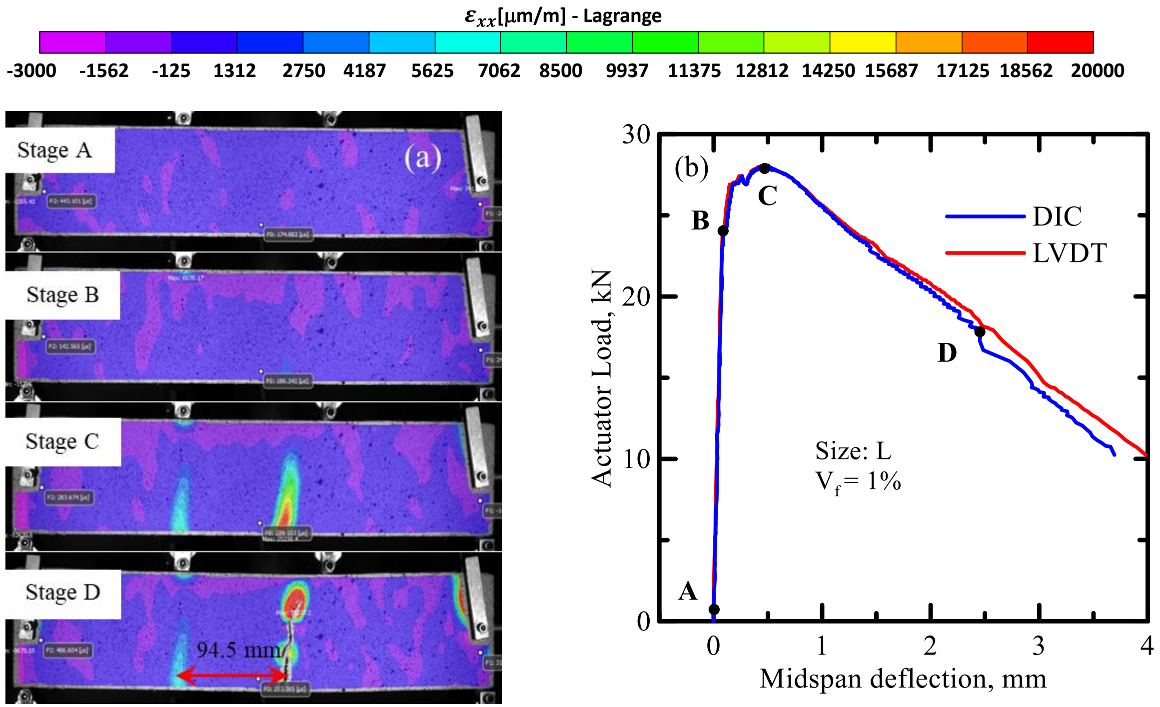
Note that the strain axes are not the same

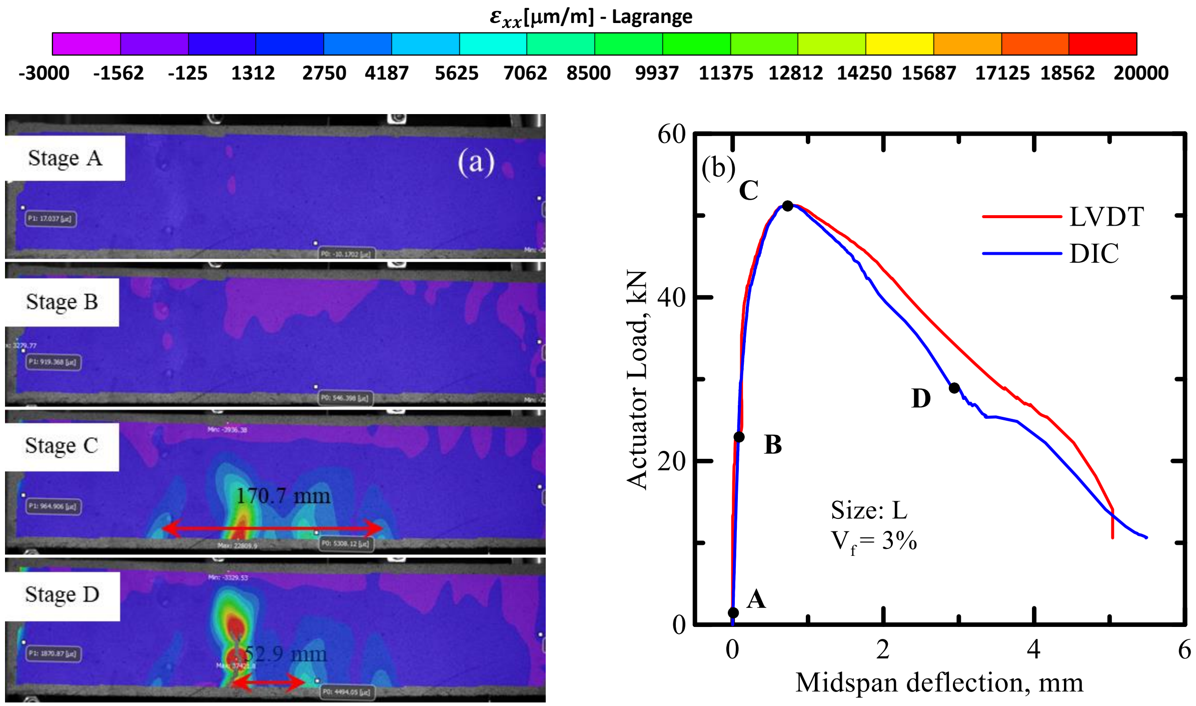
1 MPa = 145 psi or 0.145 ksi

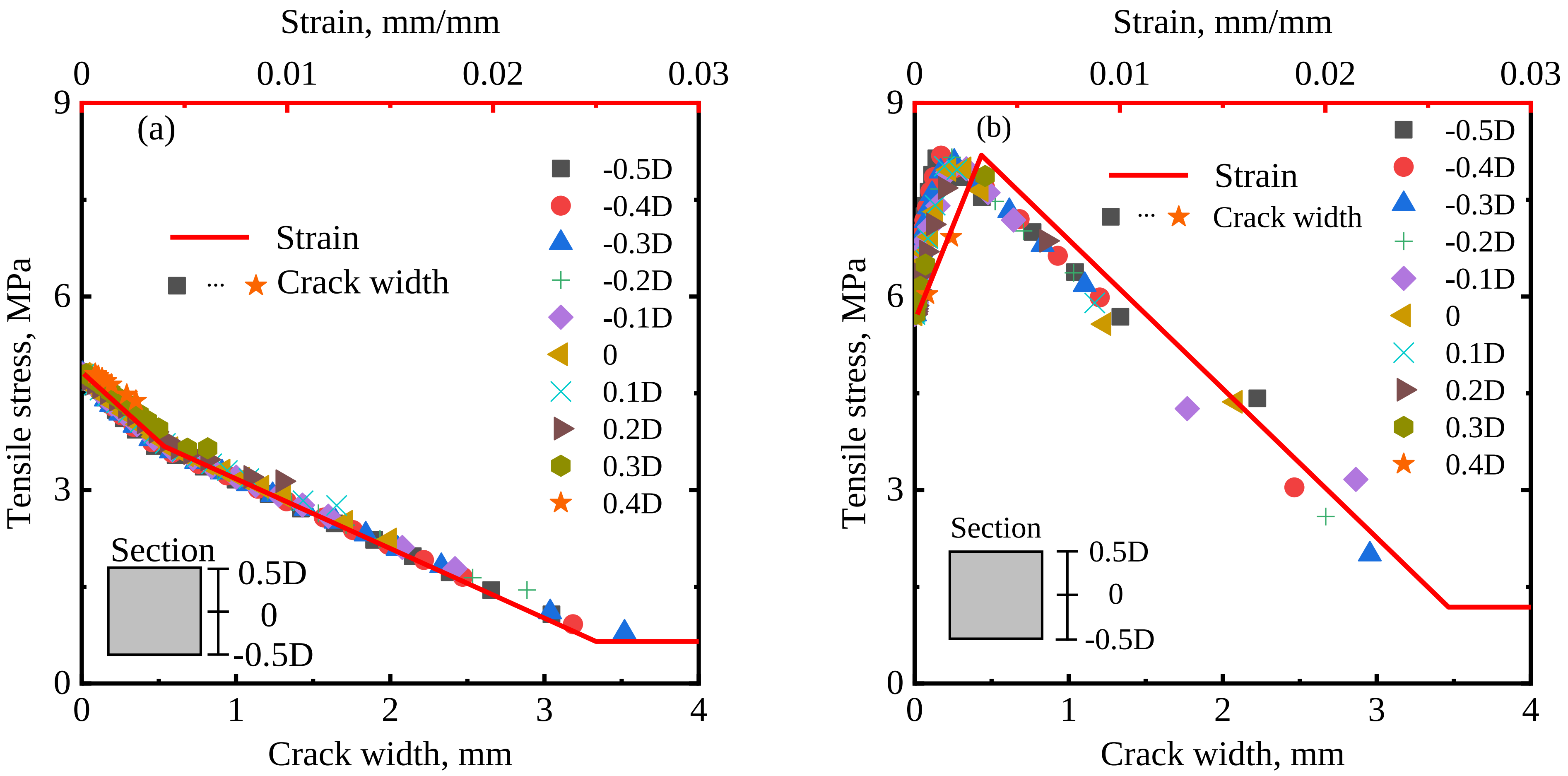
Flexural failure and the effect of fibers in UHPC

Characterization of Crack Growth Mechanisms Using Digital Image Correlation (DIC)

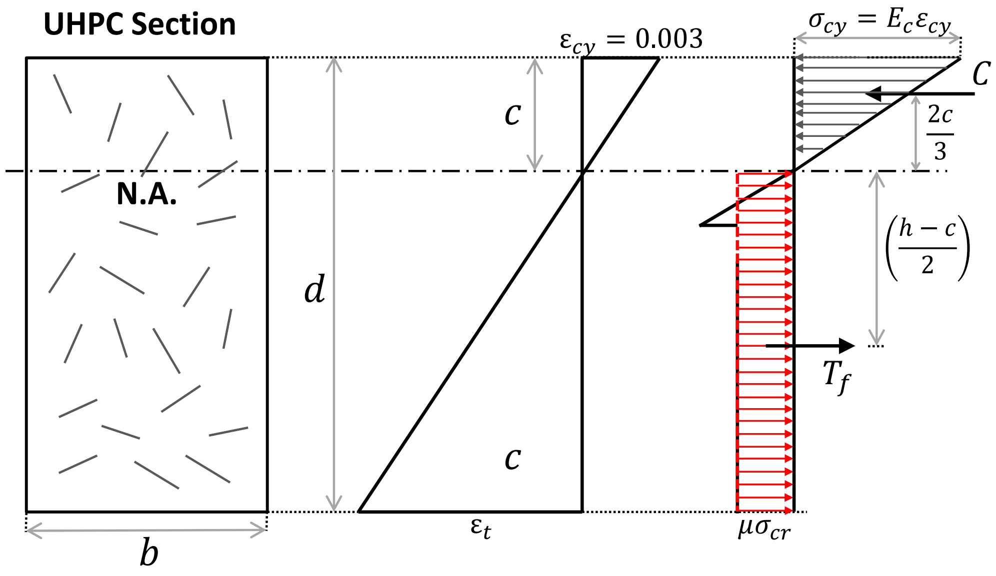


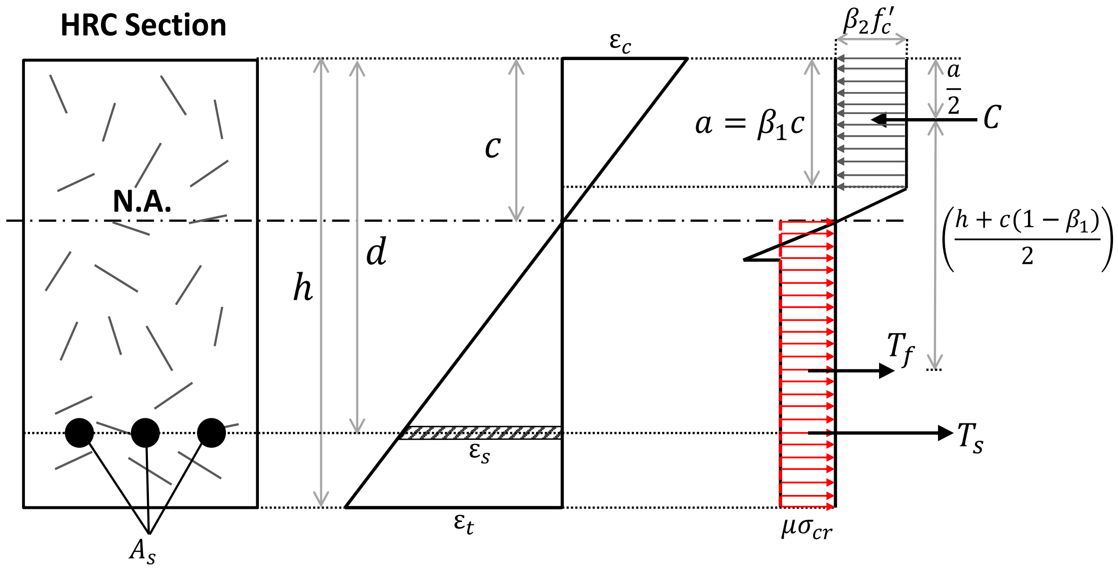

ε_{xx}[µm/m] - Lagrange
-3000
-1562
-125
1312
2750
4187
5625
7062
8500
9937
11375
12812
14250
15687
17125
18562
20000
Stage A
(a)
Stage B
Stage C
Stage D
94.5 mm
(b)
A
B
C
D
DIC
LVDT
Size: L
V_f= 1%
Actuator Load, kN
Midspan deflection, mm
0
10
20
30
0
1
2
3
4

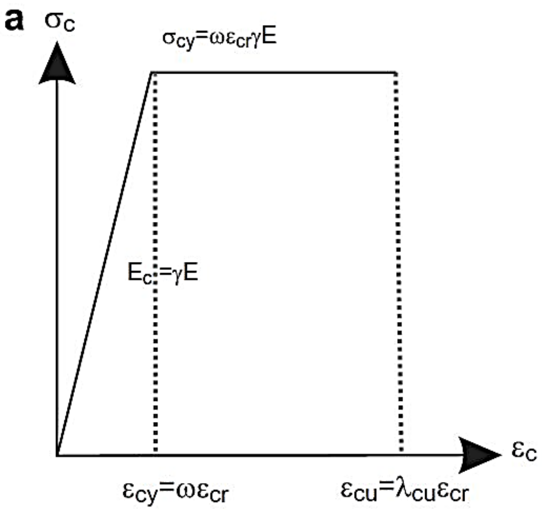

ε_{xx}[µm/m] - Lagrange
-3000
-1562
-125
1312
2750
4187
5625
7062
8500
9937
11375
12812
14250
15687
17125
18562
20000
Stage A
(a)
Stage B
Stage C
170.7 mm
Stage D
52.9 mm
(b)
A
B
C
D
LVDT
DIC
Size: L
V_f= 3%
Actuator Load, kN
Midspan deflection, mm
0
20
40
60
0
2
4
6

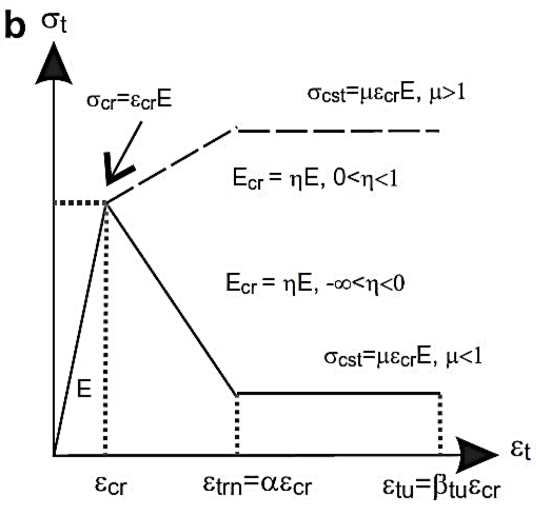

Strain, mm/mm
0
0.01
0.02
0.03
(a)
Strain
■ ··· ★ Crack width
-0.5D
-0.4D
-0.3D
-0.2D
-0.1D
0
0.1D
0.2D
0.3D
0.4D
Section
0.5D
0
-0.5D
Tensile stress, MPa
0
3
6
9
0
1
2
3
4
Crack width, mm
(b)
Strain
■ ··· ★ Crack width
-0.5D
-0.4D
-0.3D
-0.2D
-0.1D
0
0.1D
0.2D
0.3D
0.4D
Section
0.5D
0
-0.5D
Tensile stress, MPa
Crack width, mm

UHPC Flexural Design


UHPC Section

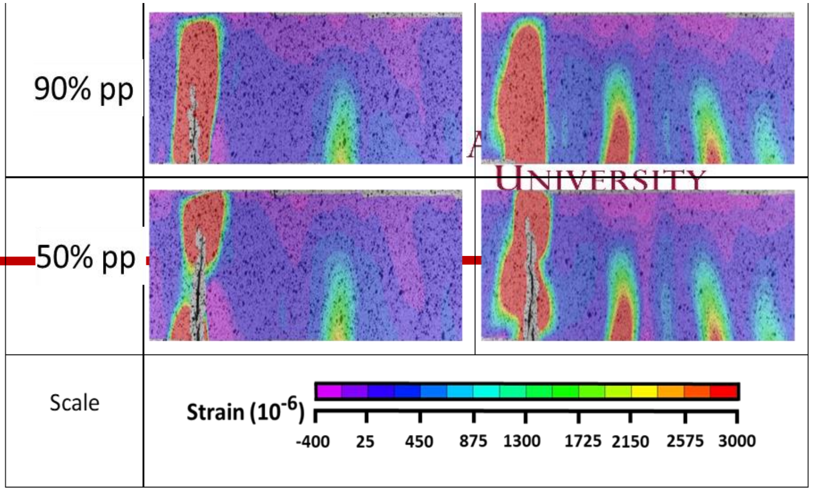

HRC Section

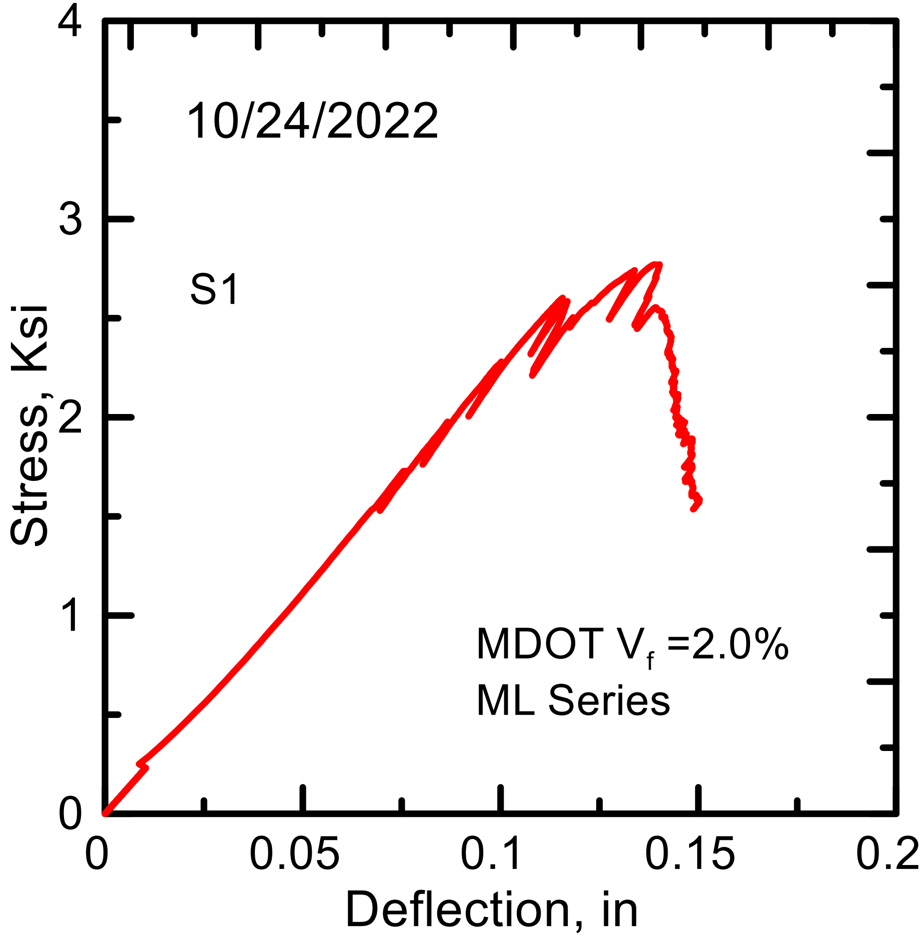


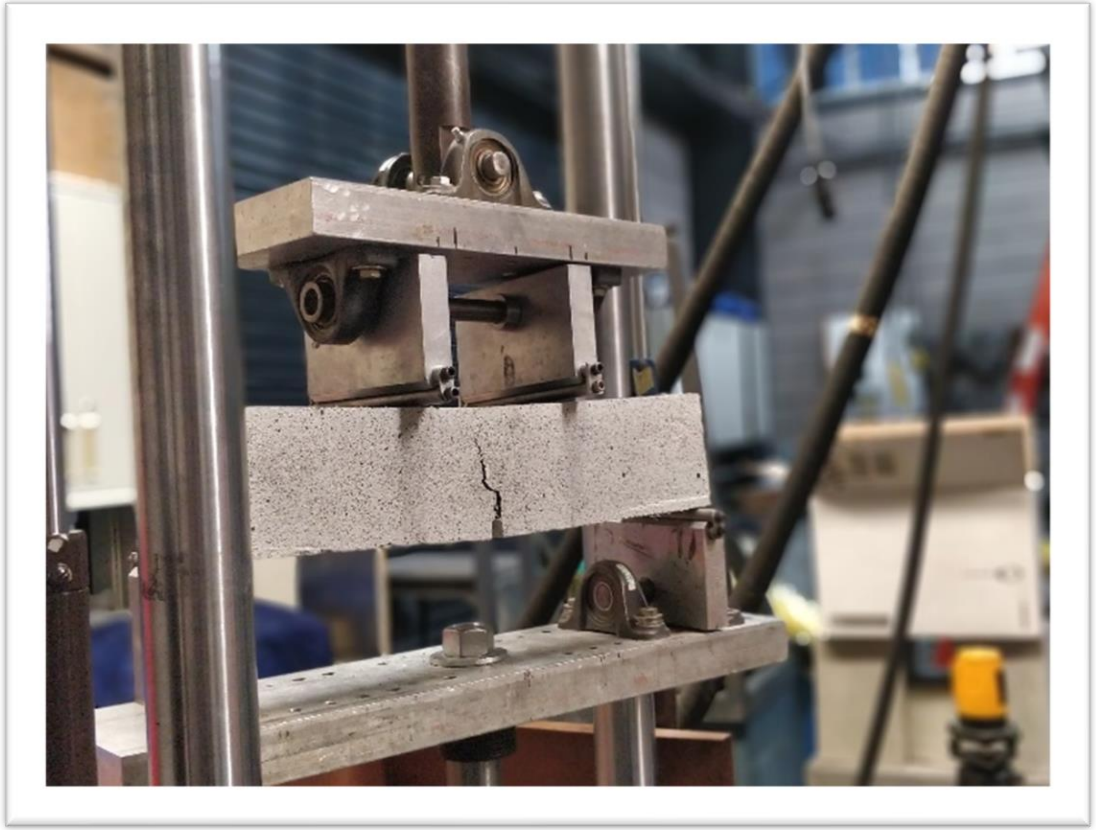


MARICOPA
COUNTY

Flexural strength 2800 psi (20 MPa)

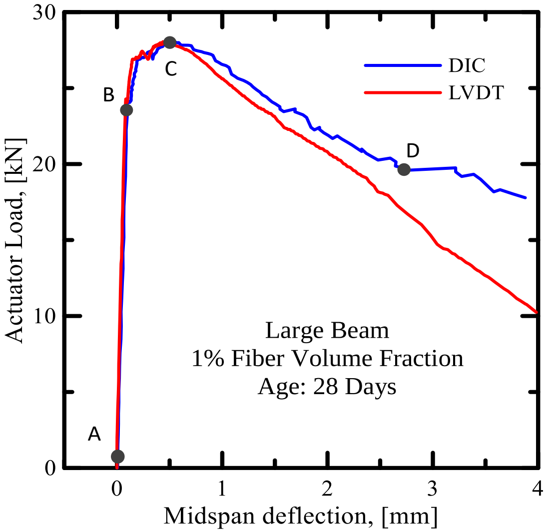


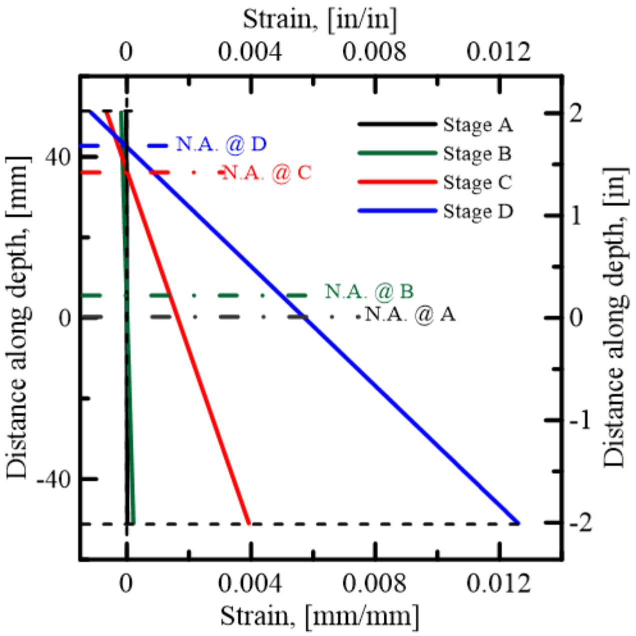


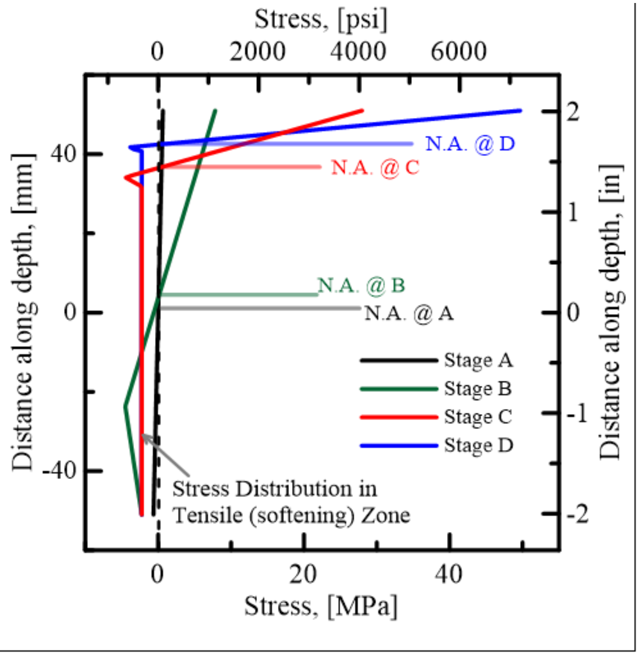


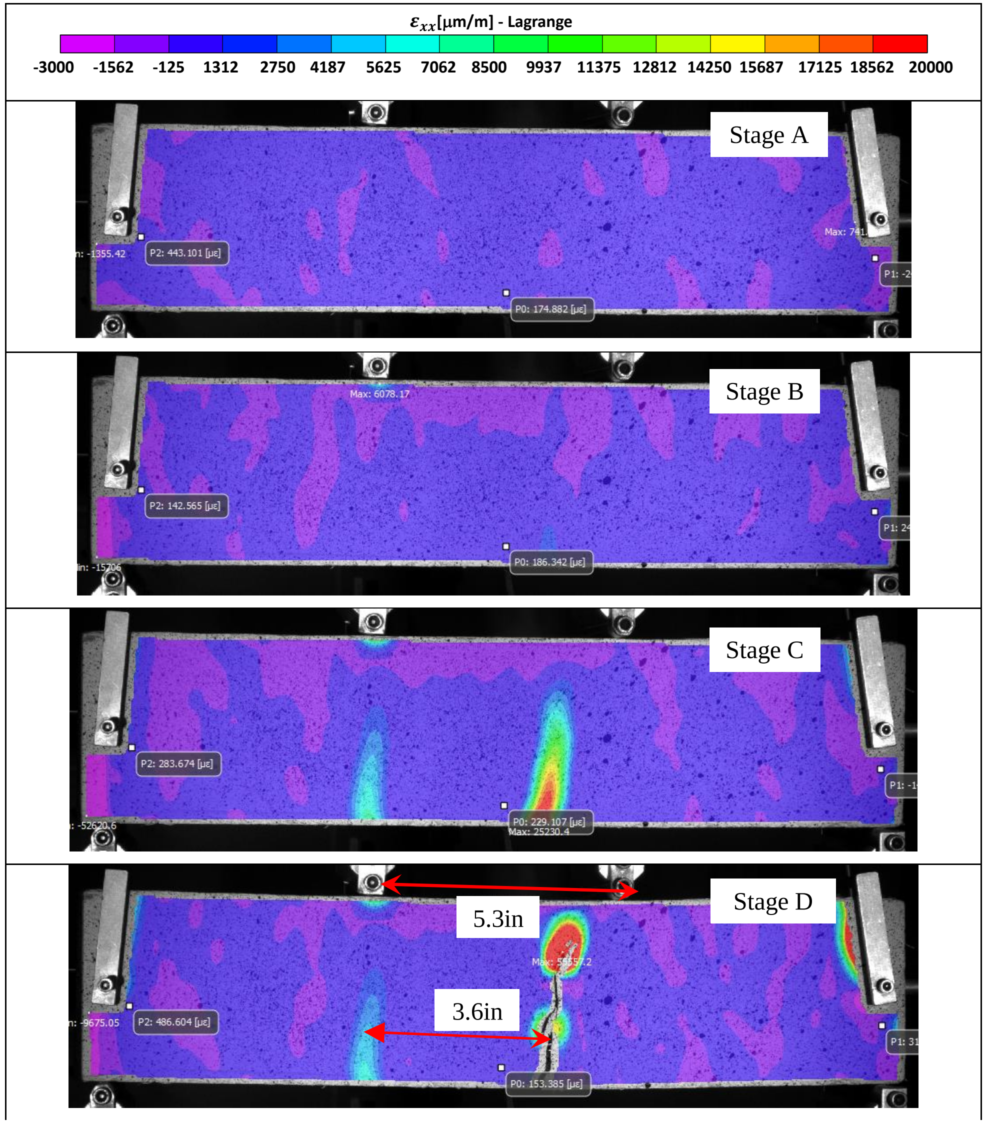
UHPC Design Model

Stage	Characteristic
A	Initiation of the deformation
B	Initiation of the non-linear response
C	Response to the peak load
D	beam failure









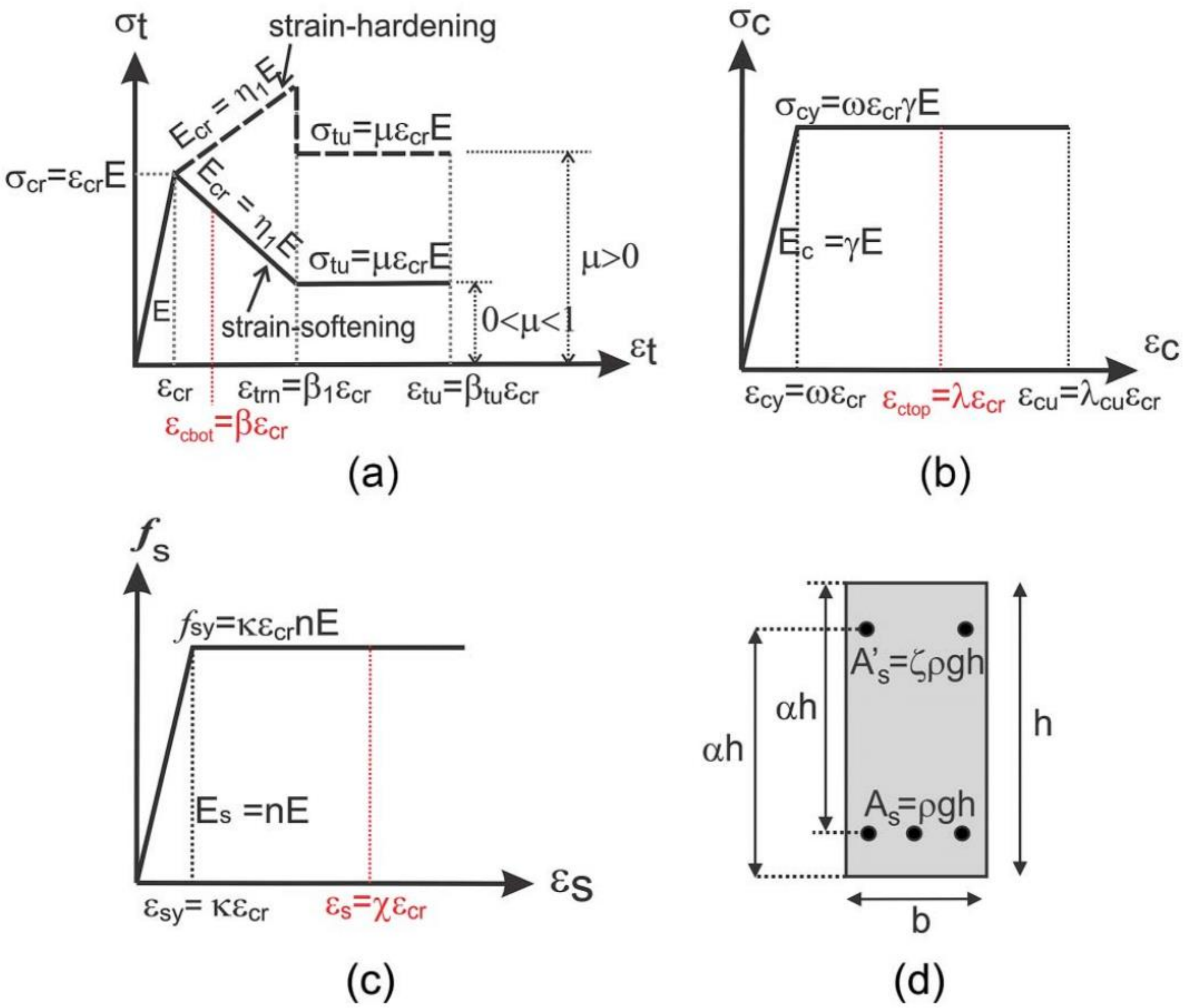
Palo Verde Bridge Project, November 2022

Palo Verde Bridge Project, November 2022


JLG LIFT
HUSKY
Contractor Clean-Up Bags

Material model for doubly reinforced concrete

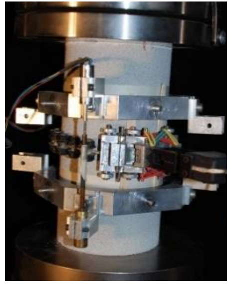
(a) tension; (b) compression; (c) steel; and (d) beam cross section.



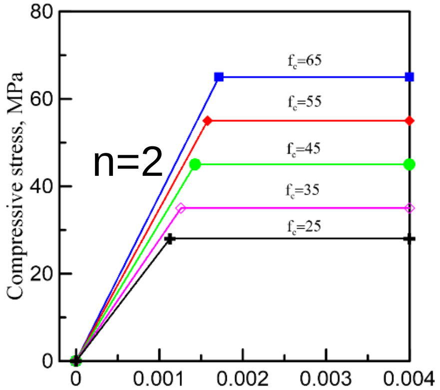
From laboratory to structure scale

Laboratory Scale

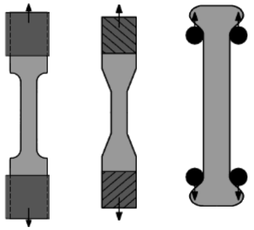
Compression



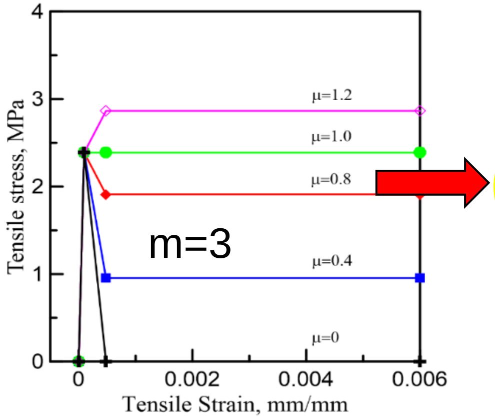
Uniaxial Compression

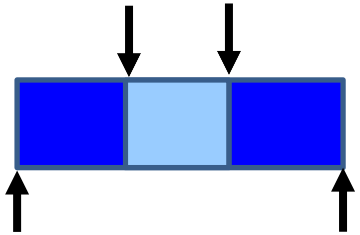


Tension



Uniaxial tension



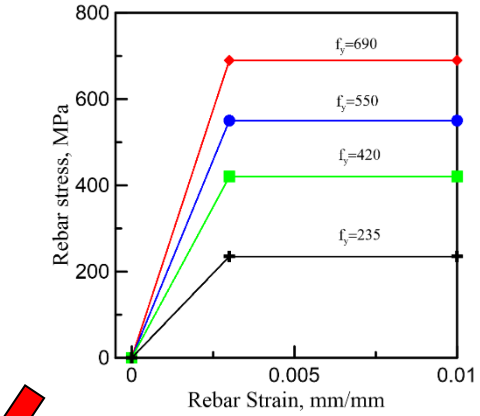


-ASTM C1609

-EN14561

Standard
Flexural test

??

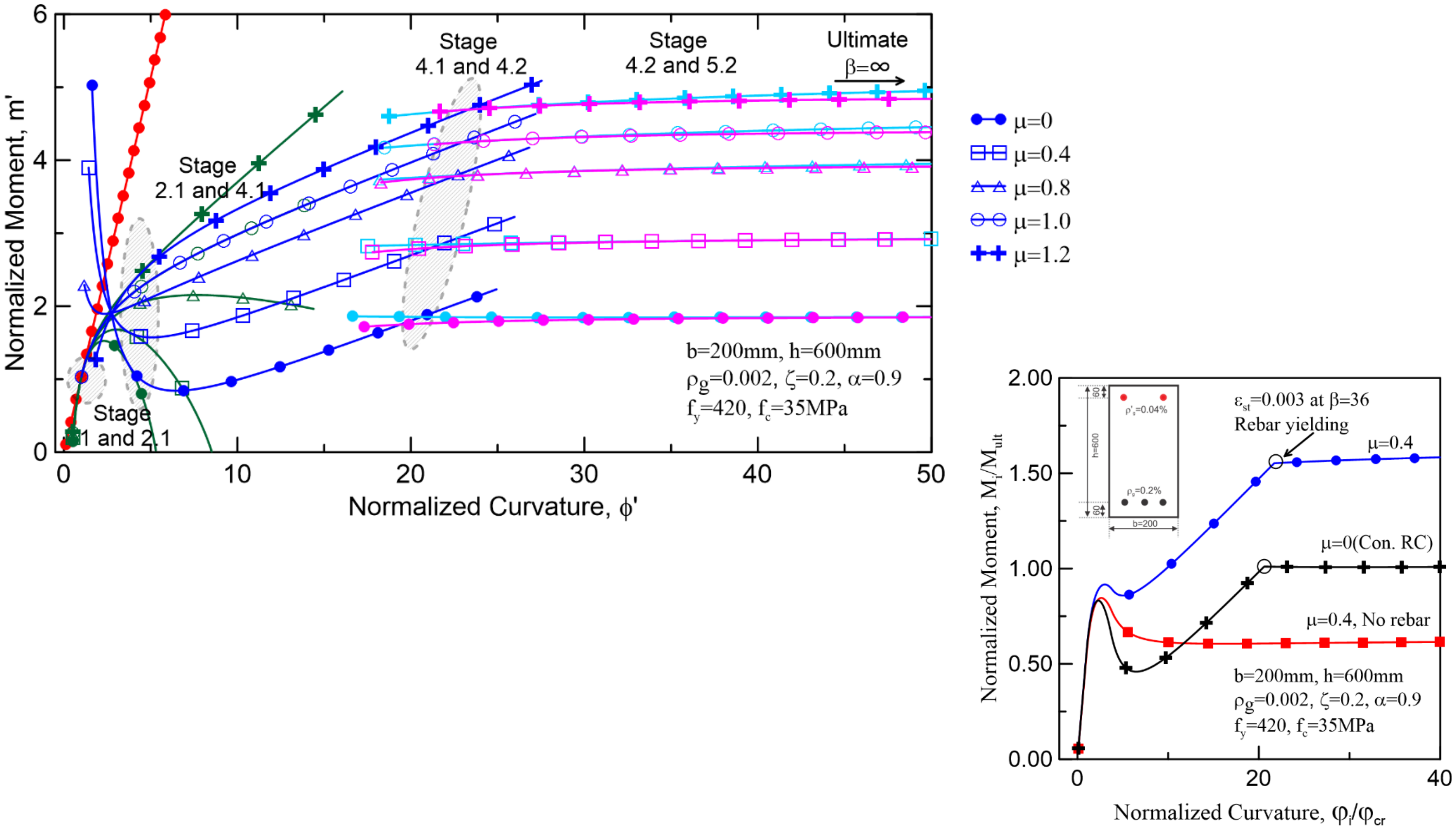


reinforcement

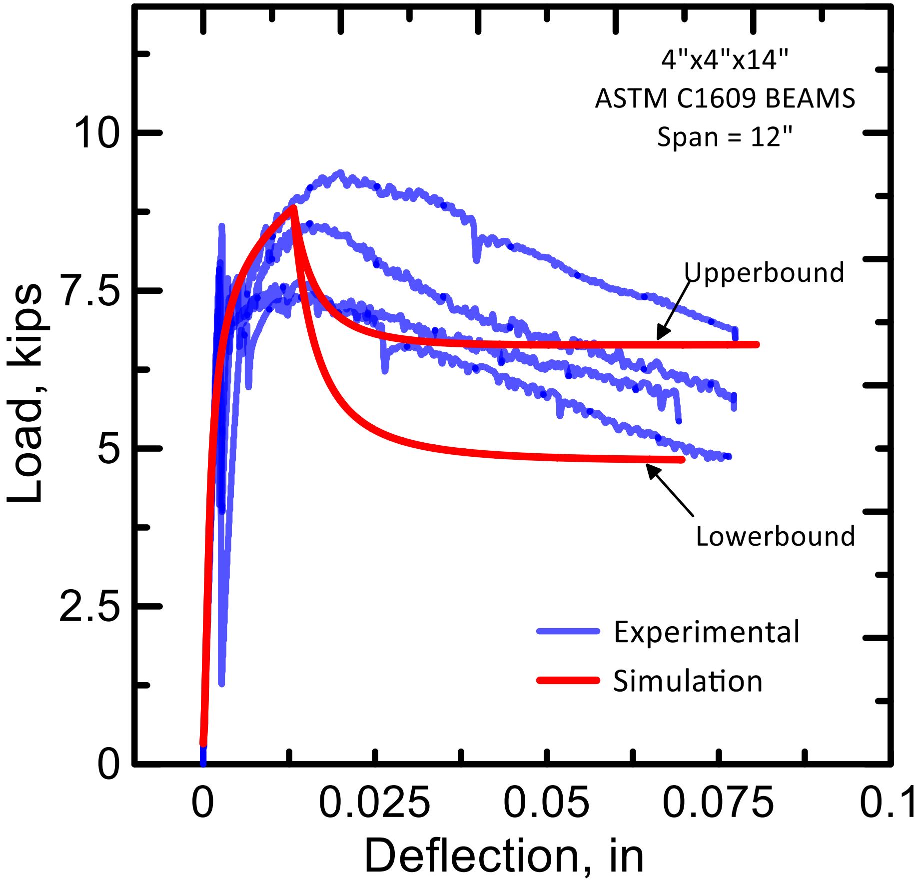
Closed-Form Solutions

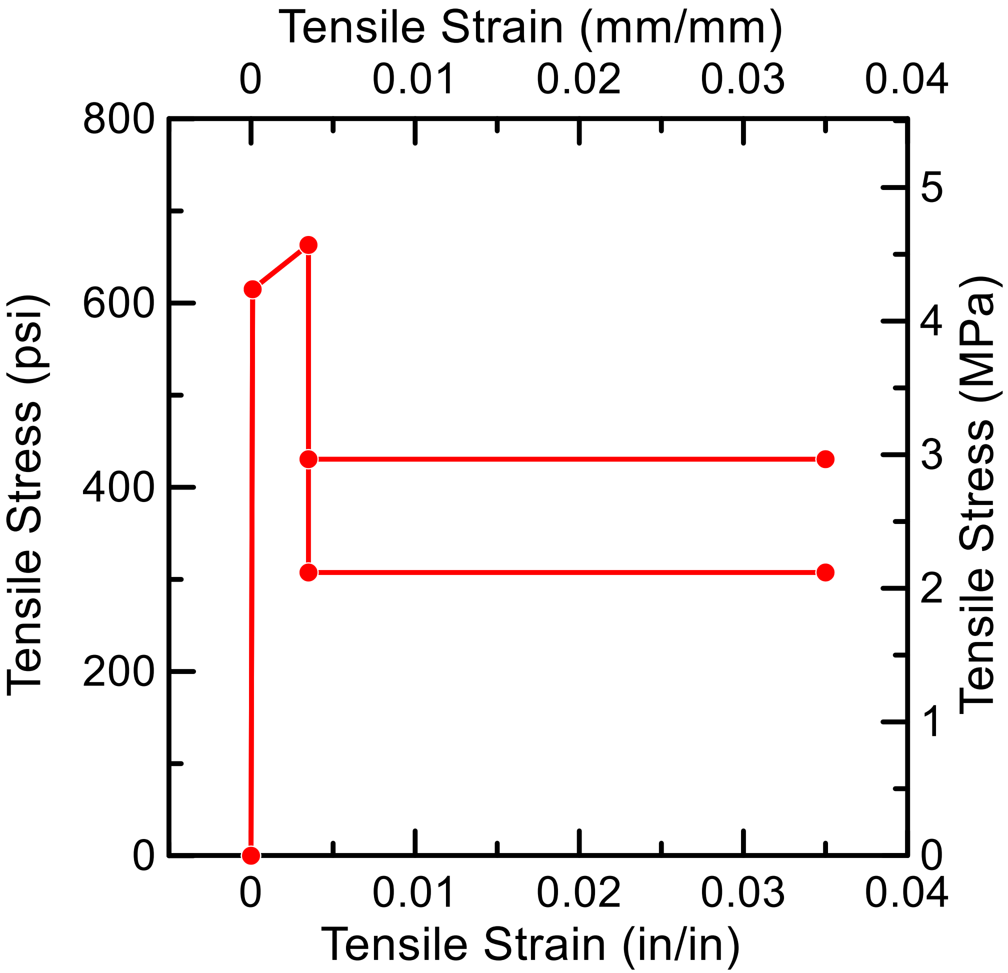
(Mudadu et al., 2019)

Envelope Moment-Curvature

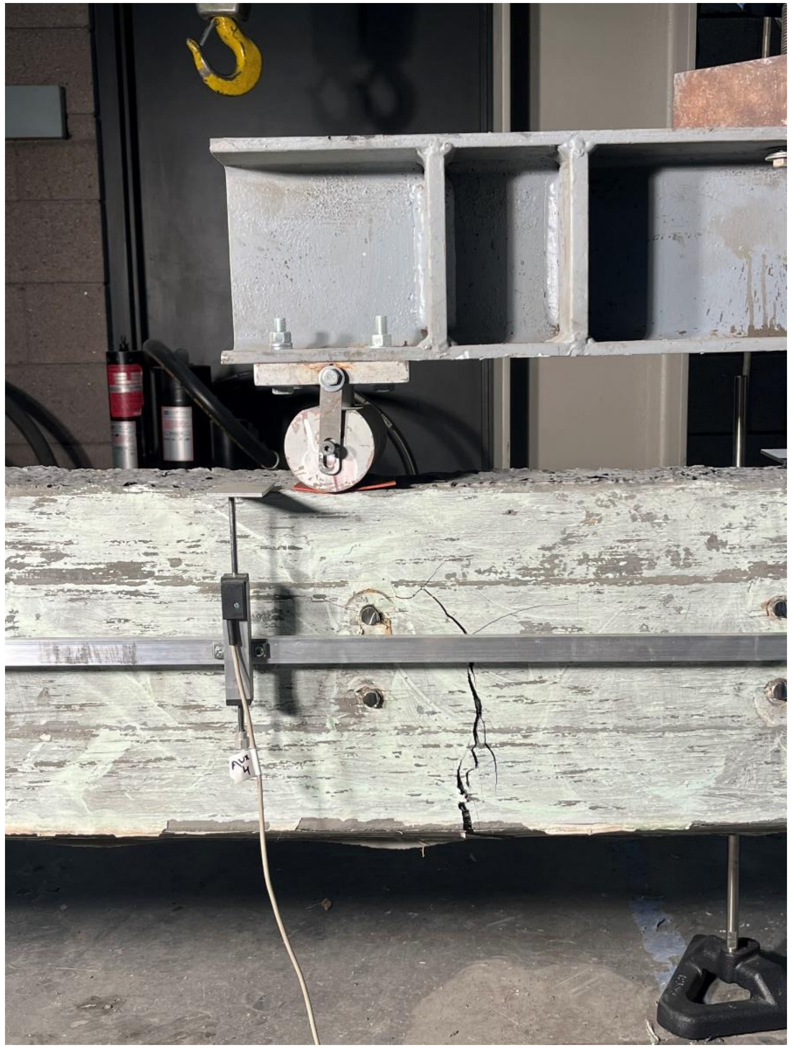


Back-calculation



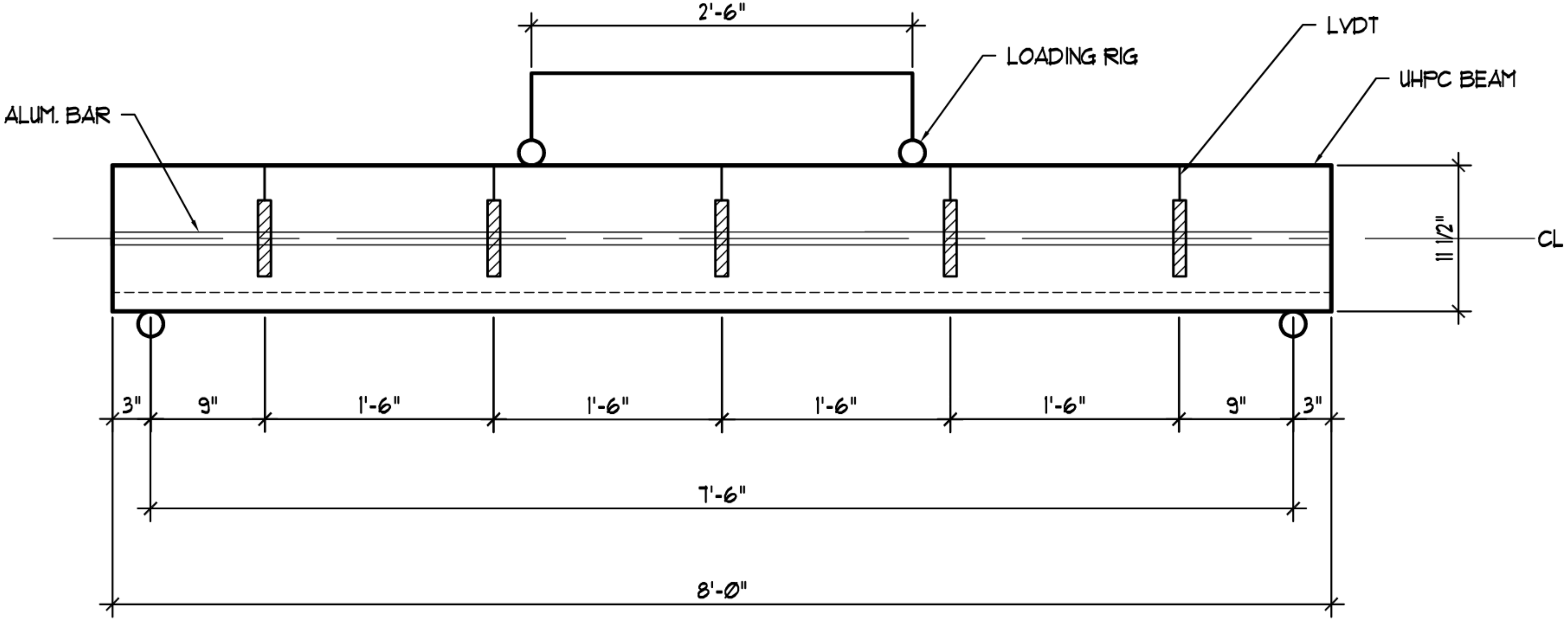


UHPC BEAM TESTS



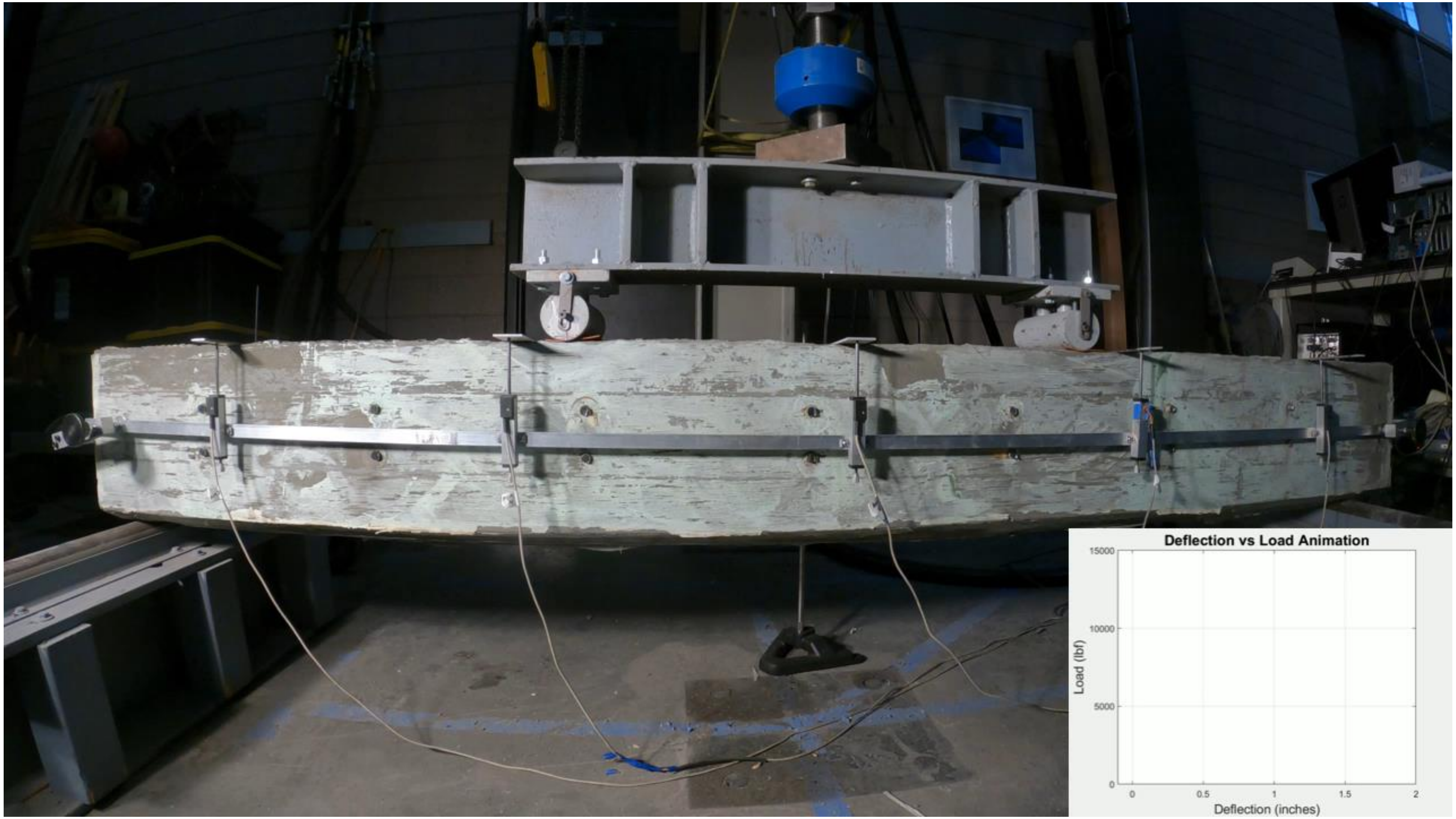
MDOT – UHPC BEAM TESTS

Test Setup



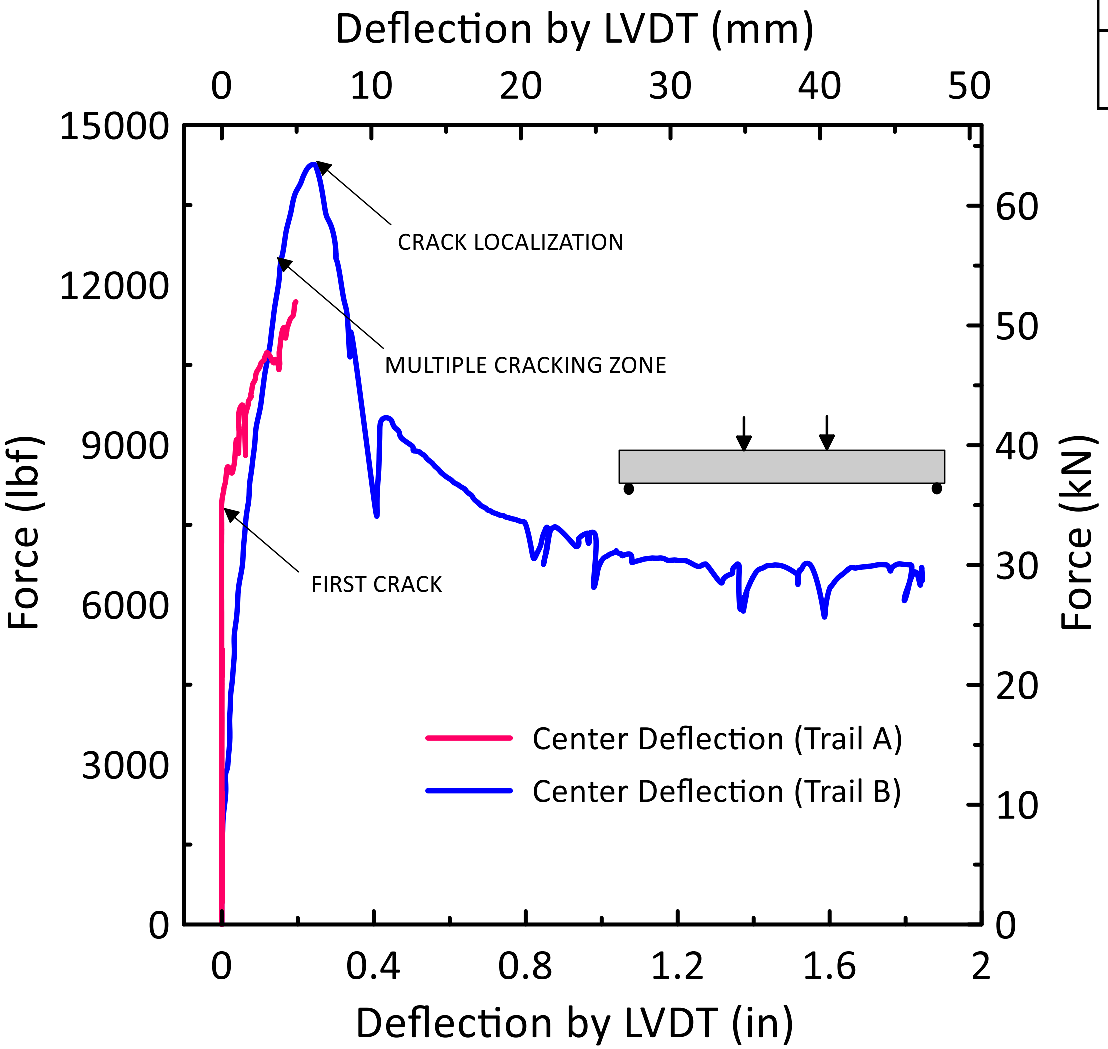
Total 6 LVDTs To Measure Complete Deflection Profile

UHPC BEAM TESTS

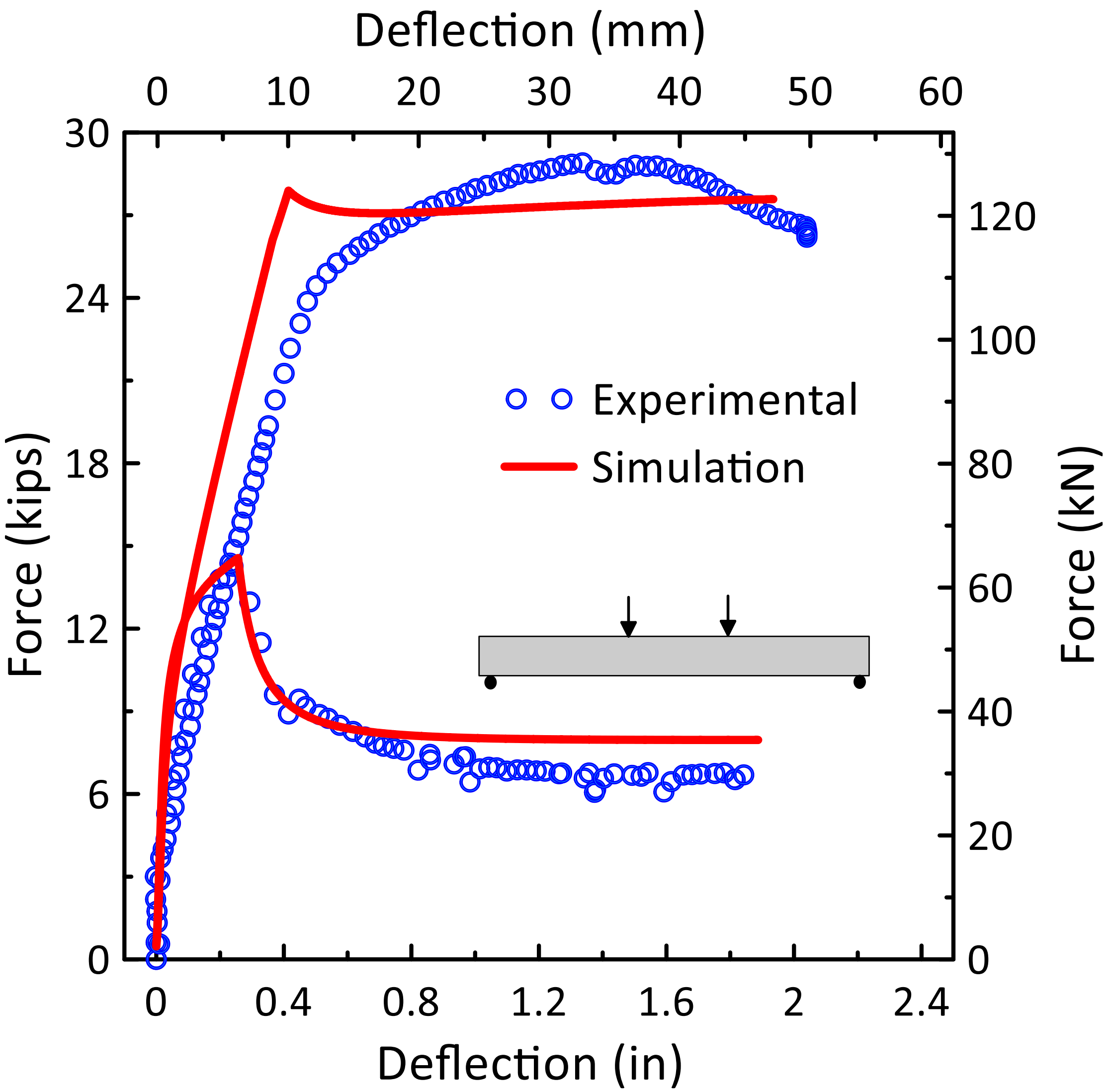


UHPC BEAM TESTS

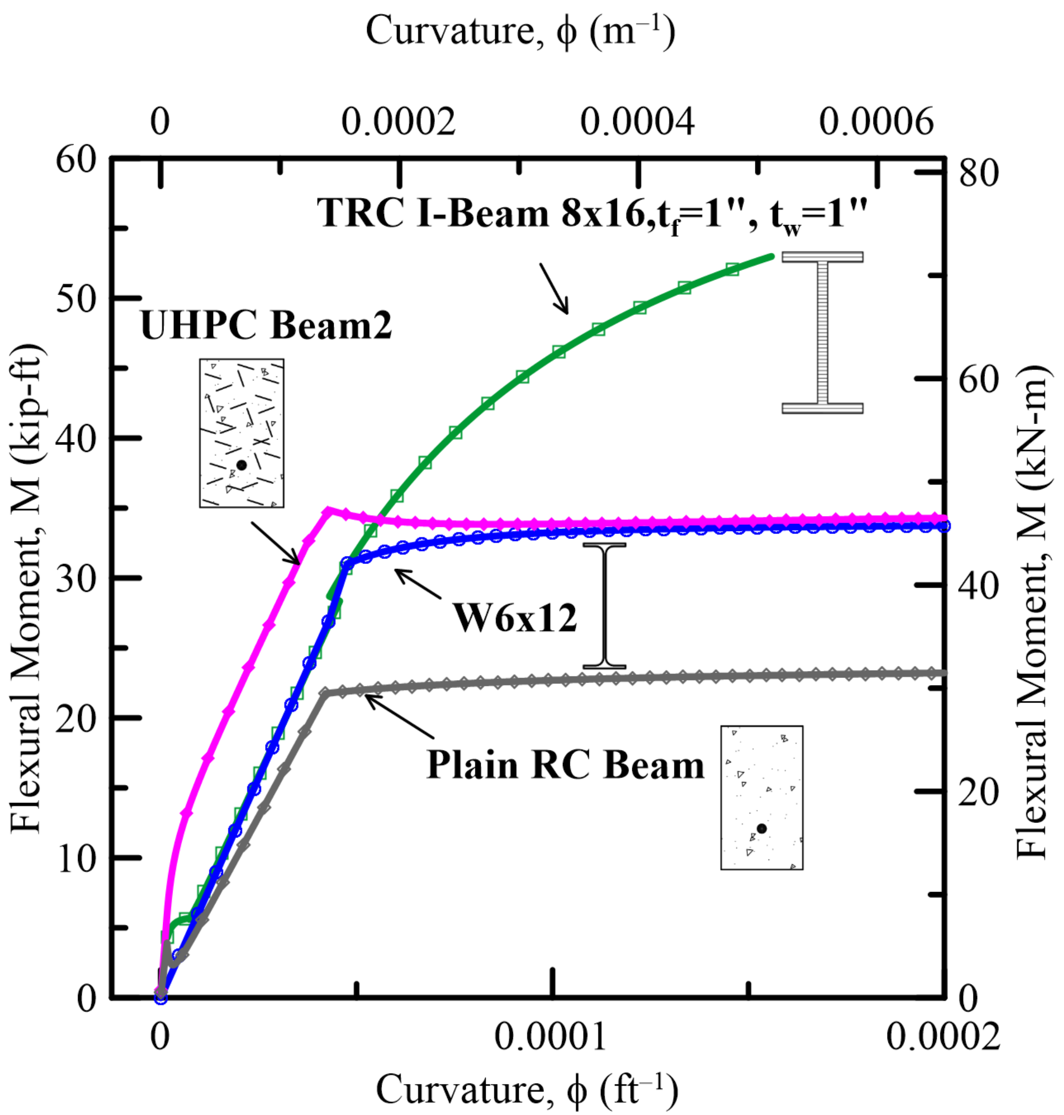
	Load (lbf)	Deflection (in)
First Crack	7952	0.0008
Max. Load	14300	0.23
Post Crack Min.	6652	1.8



Simulation of beams 1 and 2



Comparison of UHPC with Structural Steel, and TRC sections



Summary and Conclusions

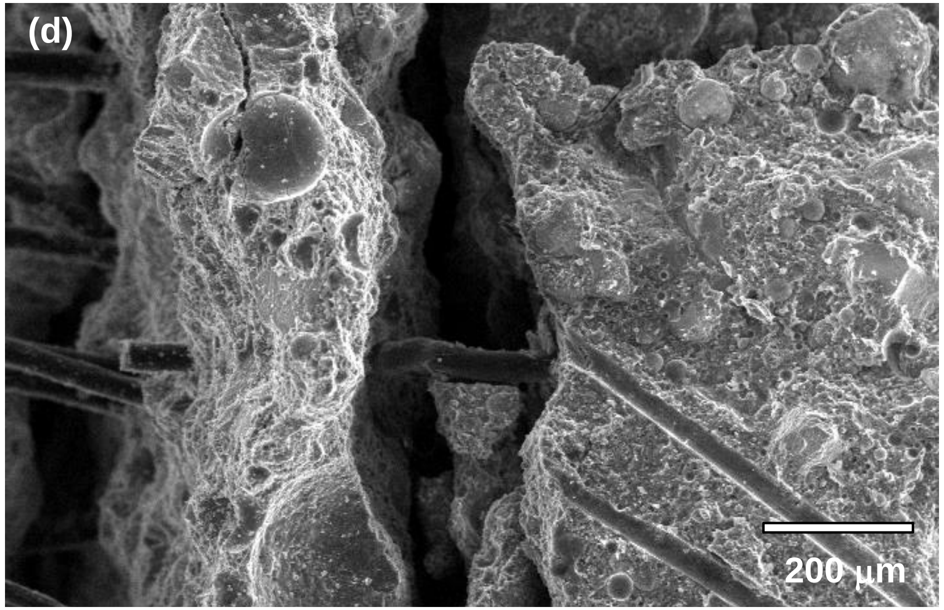
- Cost-effective UHPC designed through multi-level particle packing approach
- > 150 MPa compressive strength and ~20 MPa flexural strength
- High ductility and durability
- Can be accomplished only by a robust, rational mixture design procedure and a modified mixing regime
- Careful material design helps reduce UHPC cost
- New and improved design models for UHPC – integration into codes an standards

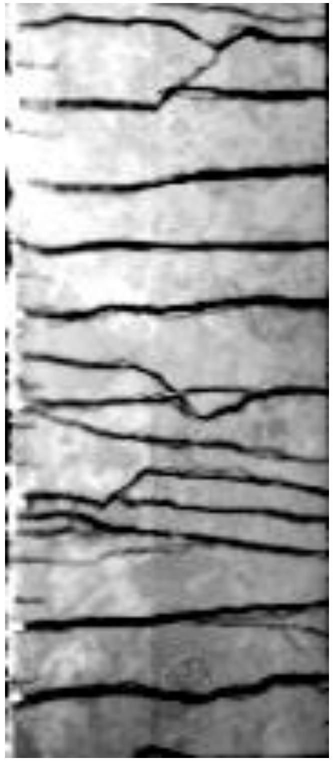
Opportunities in use of FRC in Serviceability Based Structural Design Applications

- The phenomenal growth of fiber reinforced concrete market is a key motivator for addressing sustainability-based design
- Economy, labor, time, materials characteristics and performance
- Recent developments have played a significant role in developing documents to showcase the performance of FRC materials
- Design opportunities:
  - Ductility, durability, crack width, stiffness, cracked section modulus.
  - Shear
  - A hybrid approach of combining reinforcement and fibers is the key to addressing sustainability
  - Minimum reinforcement requirements.

Materials characteristics

- Ductility
- Toughening
- Improved tensile strength
- Increase level of energy absorption
- Fatigue life, impact/explosive loading
- Seismic resistance
- Steel work, labor, construction time.
- Corrosion damage
- Long-term repair and maintenance.



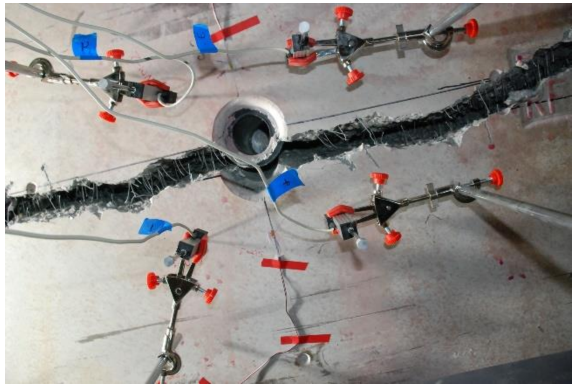


Design at the microstructure level will have a profound impact at the macro-structural level

ASU Large Scale Structural Testing Lab

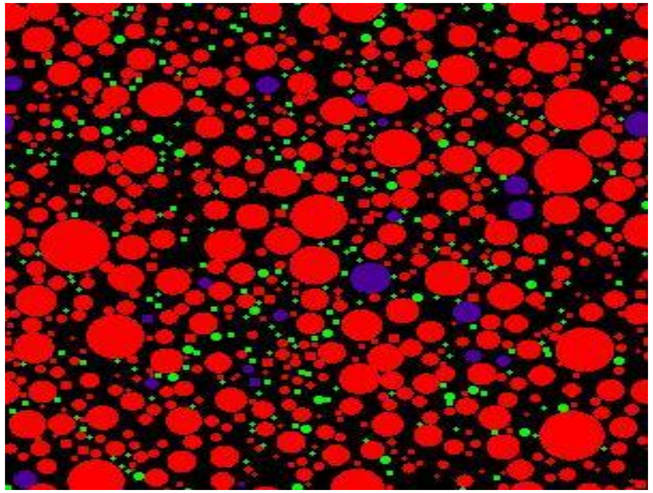
- Develop Sustainable Materials, analyze Solid Mechanics, material formulations, Structural components, and Systems.
- Full scale testing and Modeling in order to promote innovative and sustainable construction systems.
- solutions for composite materials for transportation, water treatment facilities, pipes, tunnel lining, thin sections, Structural Shapes

1) Up to 200 kips in Bending and 800 kips axial capacity
2) Failure mode modeling, Effect of hybrid reinforcement
3) Design tools for Tension, compression, and flexure.
4) A wide range from a 40 µm fiber to a 4 meter tunnel segment
5) Long term serviceability by addressing permeability, creep, and corrosion.



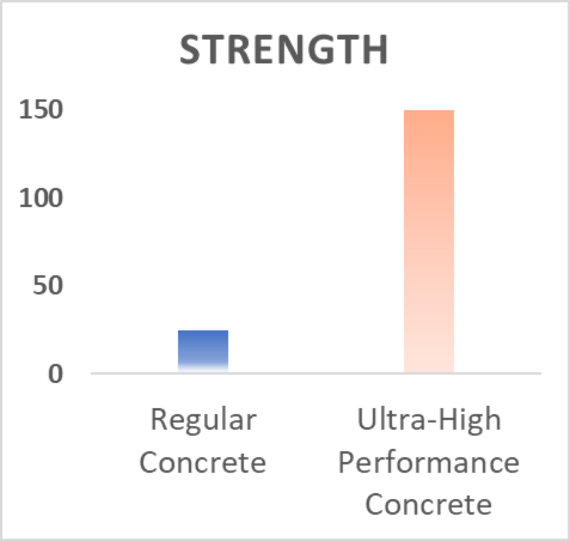
Task 1: Non-Proprietary Mix Designs

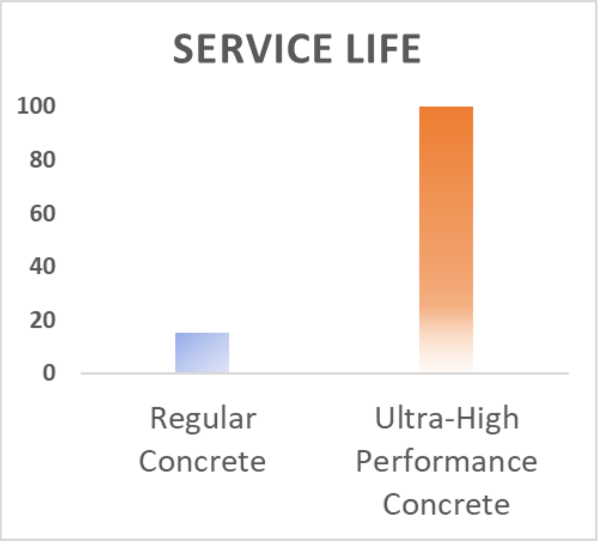
- Microstructure and Rheology Guided Design of Ultra-High Performance Binders
- Designing the ideal paste phase for UHPC to address
  - Local materials and their combinations, low cost
  - Particle packing methods, workability
  - Experiments and simulations
- Rheological properties
- Conducted under a three tier approach, paste, mortar, and concrete

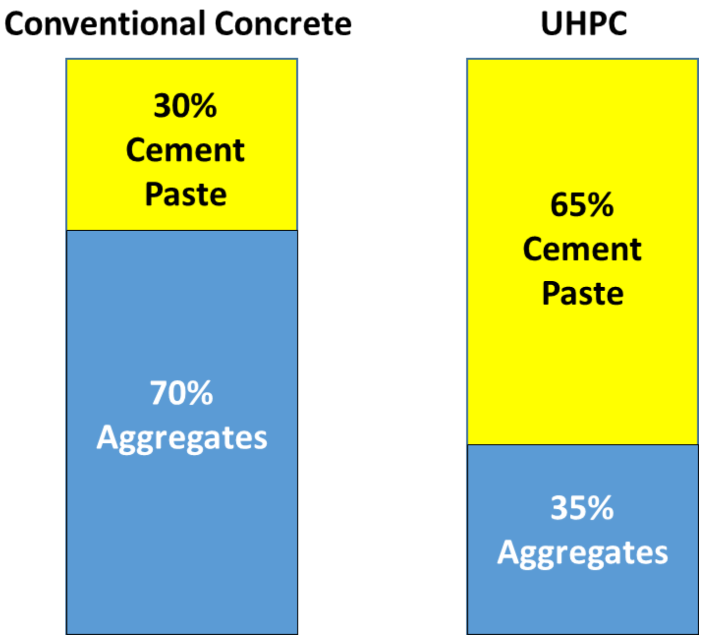


Anticipated Benefits for ADOT Groups

- UHPC mix will accelerate construction time and increase the concrete’s durability, strength, ductility, and longevity, making structures available for traffic use faster and producing cost savings
- Proprietary UHPC mixtures commonly used
- Tends to be very expensive and does not account for local raw materials
- Groups involved at ADOT included Construction-Materials Group, Bridge Group , Contracts and Specifications



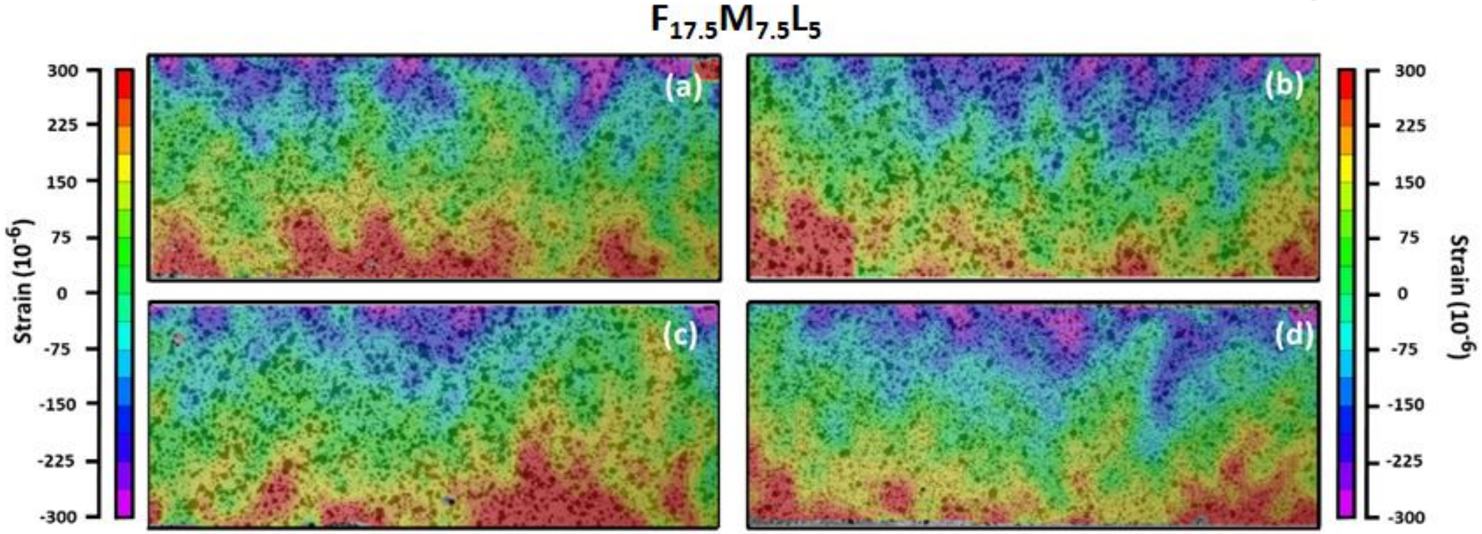




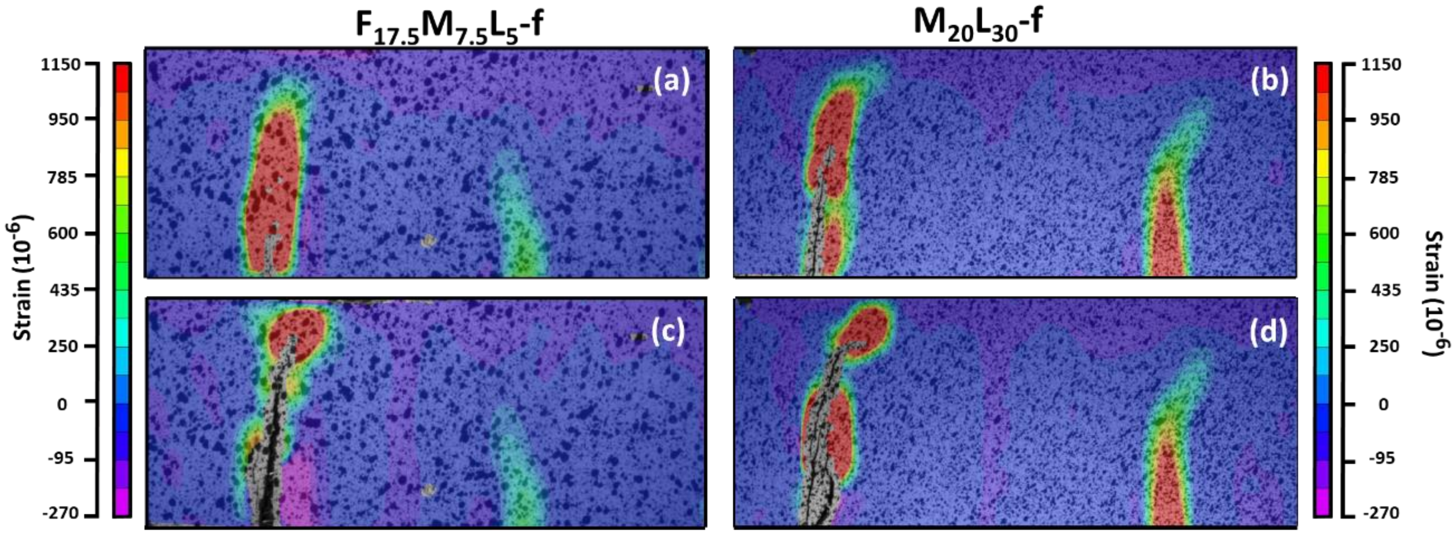
Outline

- Microstructure and Rheology Guided Design of Ultra-High-Performance Binders
  - Microstructure packing
  - Rheology of Pastes
  - Selection Criteria
- Particle Packing Based Design of UHPC
  - Compressible Packing Model
  - Concrete Design Considerations
- Mechanical testing - Compression and Flexure
  - Test results

Flexural Test Results of Strain Hardening UHPC Beams

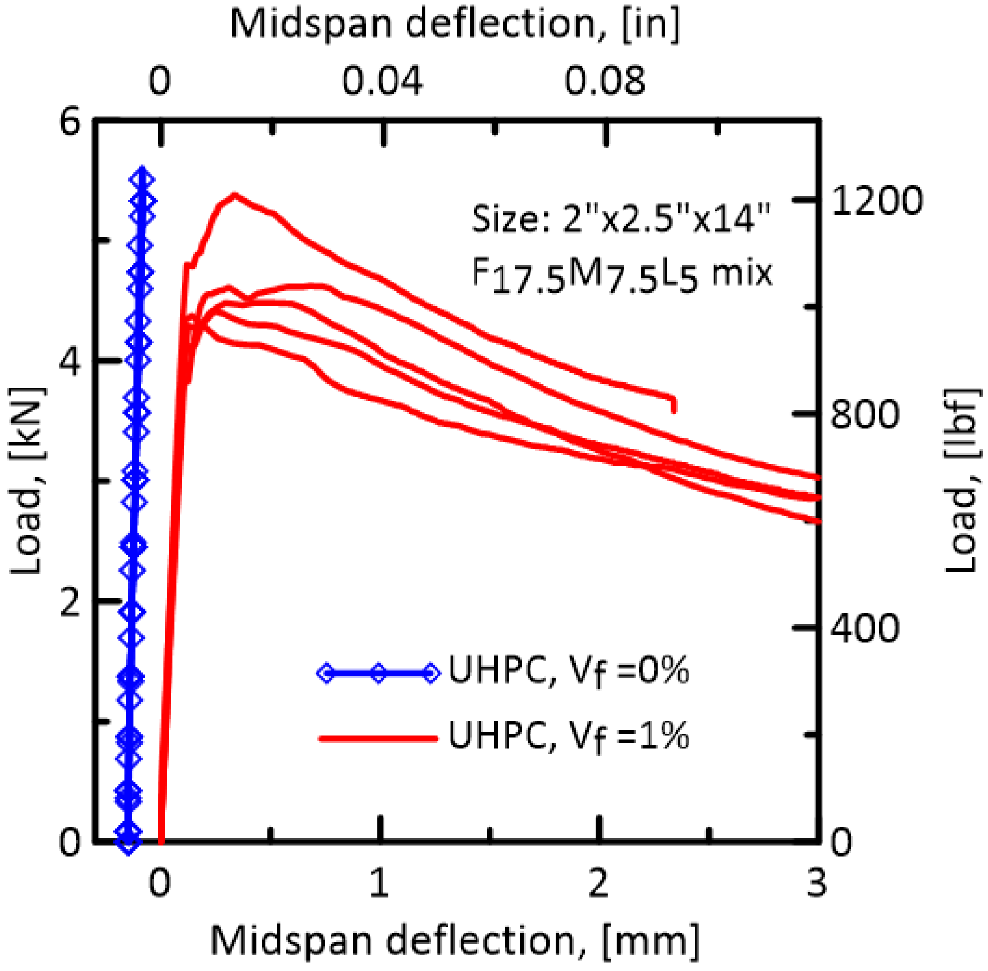


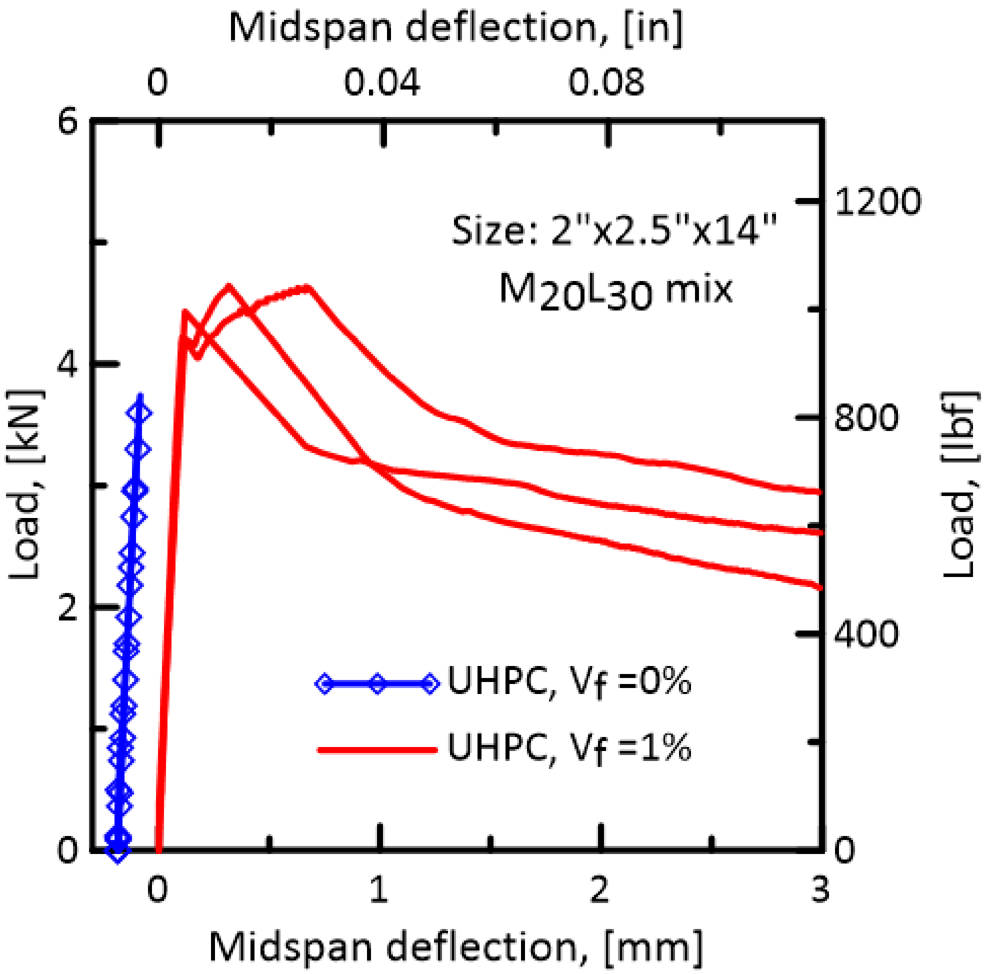
strain distribution in UHPC beams at peak load just prior to failure



Strain distribution in FRC beams with 1% steel fiber, post peak stress (a,b) 90% and (c,d) 50% post-peak stress.

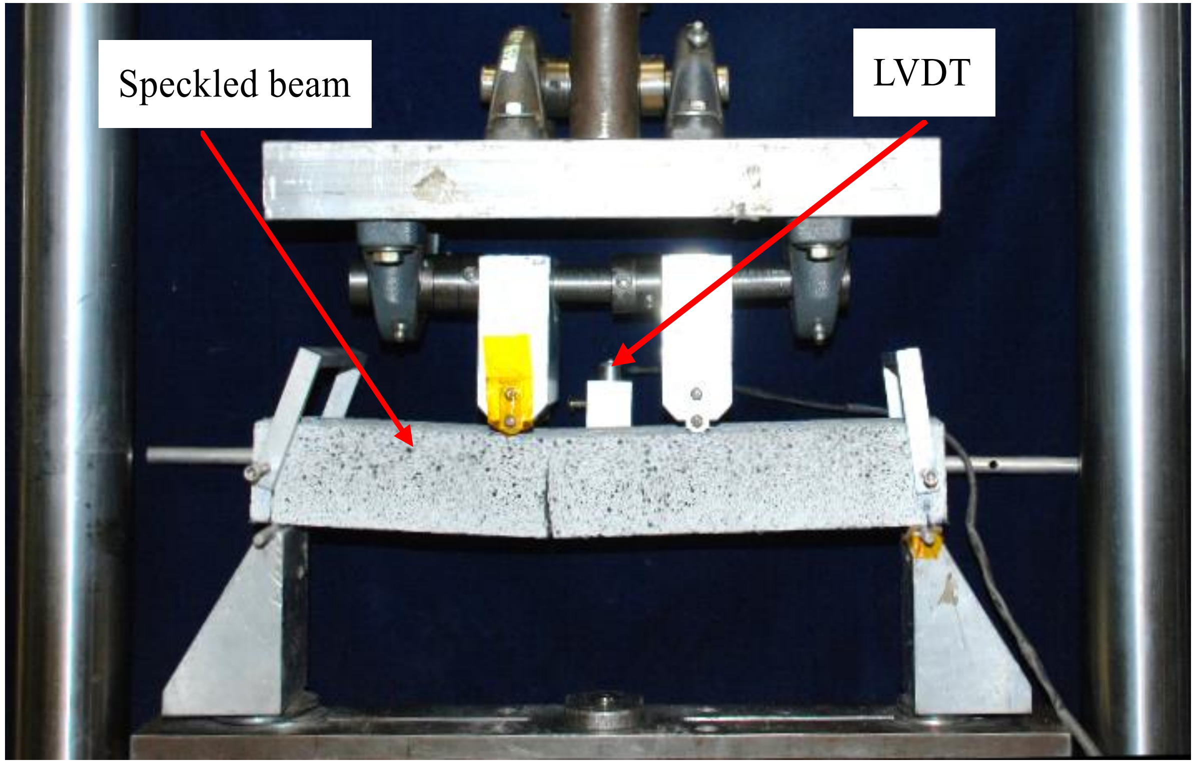
Plain UHPC and Effect of Fiber Reinforcement on Strain Hardening Behavior



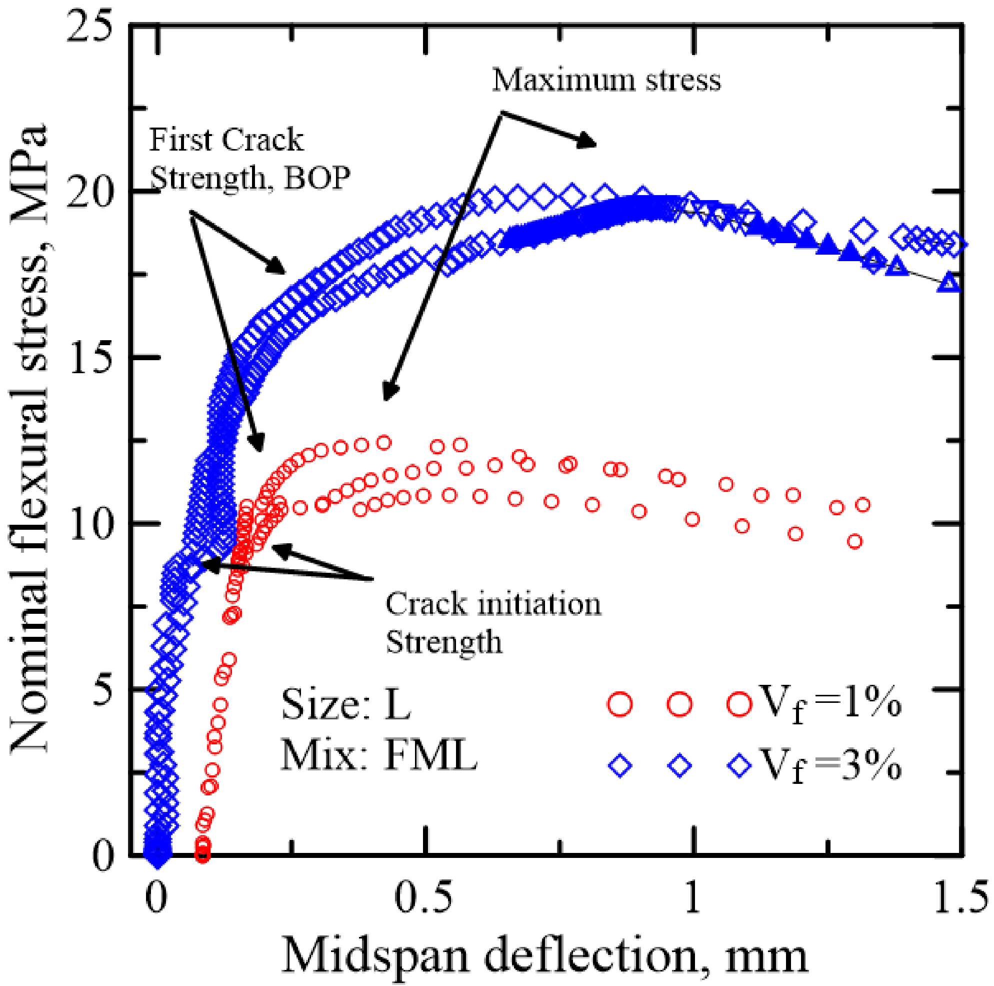


- No post-peak response for the brittle unreinforced specimen
- Considerable non-linear response after the occurrence of the first crack with 1% fibers

Four-point bending test of Strain Hardening materials



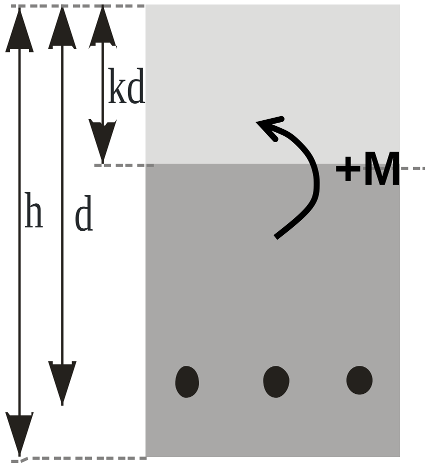
Set up for flexural Four-point bending test



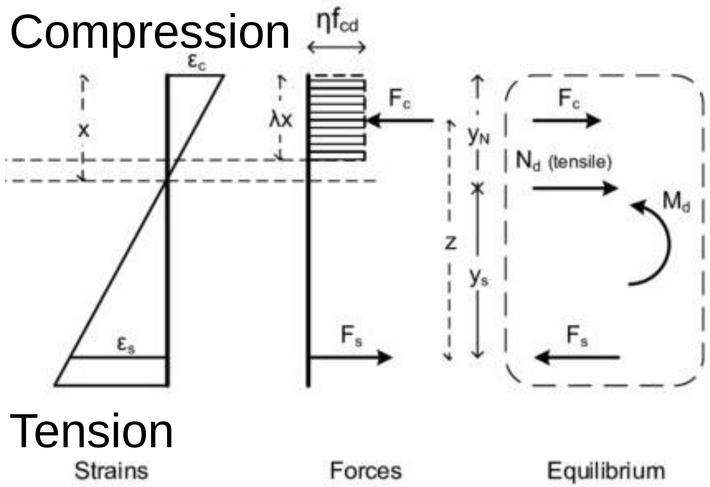
Tensile contribution of FRC to the Flexural Response

- Can not fully replace the rebars, but can enhance their contribution
- The tensile strength in plain concrete is only about 10% of its compressive strength, so it is primarily ignored in many engineering calculations such as in RC where only the contribution of steel reinforcement is taken into account

Beam section



Conventional RC



FRC+Rebar=Hybrid RC(HRC)