Low-Carbon Aspects of Alternative Reinforcement Systems: Fibers, Textiles, and Hybrid-based Design

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Disclaimer

As with all concrete mixtures, trial batches should be performed to verify concrete properties. Results may vary due to a variety of circumstances, including temperature and mixture components, among other things.

You should consult your materials, cement, and concrete professionals for design assistance. Nothing contained herein shall be considered or construed as a warranty or guarantee, either expressed or implied, including any warranty of fitness for a particular purpose.

Today's Speaker

Barzin Mobasher is a Professor in the School of Sustainable Engineering and the Built Environment at Arizona State University. He has over 35 years of experience in R&D of cement and concrete materials, composites, and structures and has led research in materials formulation, durability, mechanics, and full-scale structural testing of construction and structural materials. With more than 180 peer-reviewed research papers in leading professional journals and conference proceedings, he is the author of two textbooks, and five edited books. His fundamental contributions are in the field of fiber-reinforced concrete and mechanics of toughening in cement-based systems, mechanical properties, and durability of materials. He has worked with National, and international research agencies and served ACI TAC and as Chair of the ACI, committee 544 on Fiber Reinforced Concrete, RILEM Committee MCC-292 on TRC, and Associate Editor of the Journal of Materials and Structures.

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Outline of the Presentation

- Strategies to increase the efficiency of structural concrete

- Efficiency of concrete as a structural material (Stress to strength ratio for both tension and compression)
- Tools for quantification of carbon footprint in structural terms (Specific Strength per volume of material)
  - Fiber reinforced concrete
    - Applications addressing min. reinforcement
  - Textile reinforced Concrete
    - Repair and New construction applications/products
  - Hybrid and UHPC Reinforced Concrete
    - Structural design with fibers, Precast tunnel lining, track slabs, environmental applications
  - Design of Resilient and Ductile Systems
    - Combination of GRP rebars and fibers, TRC sections, UHPC, Structural FRP sections

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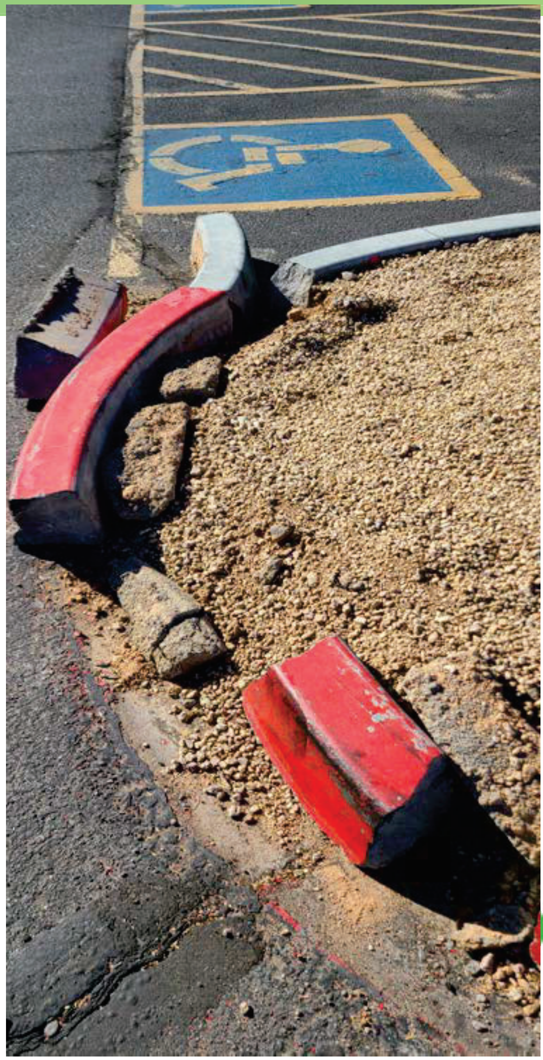
Hypothesis #1: Reinforcement Strategy is the Cornerstone of Concrete Sustainability



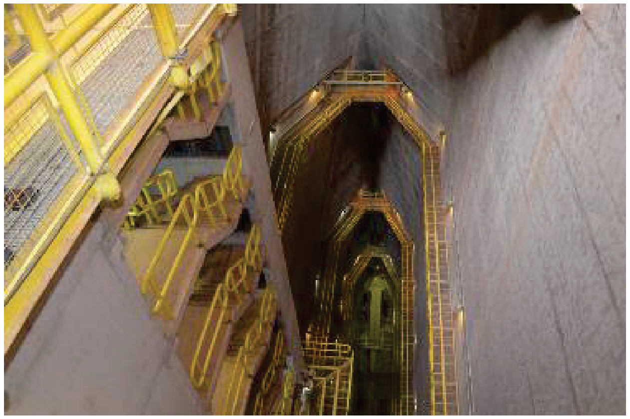
How to approach the serviceability design criteria:

1) Open discussion of sustainability through reinforcement strategy
2) Why focus on the serviceability criteria?
3) What are the challenges with the current FRP technology?
    a. Domination of steel rebars controlling 99.9% of the market
    b. Cost competitiveness of carbon, Glass, FRP, and Textiles
    c. Lack of Design Strategies
4) What are the potential near future goals?
    a. 1-5 year design changes and methodologies for various product lines
    b. Prove the effectiveness of alternative reinforcement systems

1. Address the Need for Efficient Concrete Consumption

- 30 billion tons of concrete used per year. 1 ton of CO_2 released per ton of cement produced
- All plastics produced in the past 60 years = 8bn tons = Cement industry's production in 2 two years.
- Majority of the focus on the Carbon footprint has concentrated on the Cement production and its use
- China's Cement use in 3 years > US use in the past 100 years [6.6 GT (2011-2013) vs. 4.5 GT 1901-2000)]
- About 60-75% of the concrete volume used in any beam does not participate in carrying loads since its contribution is ignored due to cracking

Itaipu Dam, Brazil



Itaipu Dam, Brazil

Three Gorges Dam, China

USGS Cement statistics 1900-2012, mineral industry of China 1990-2013)
https://www.gatesnotes.com/About-Bill-Gates/Concrete-in-China

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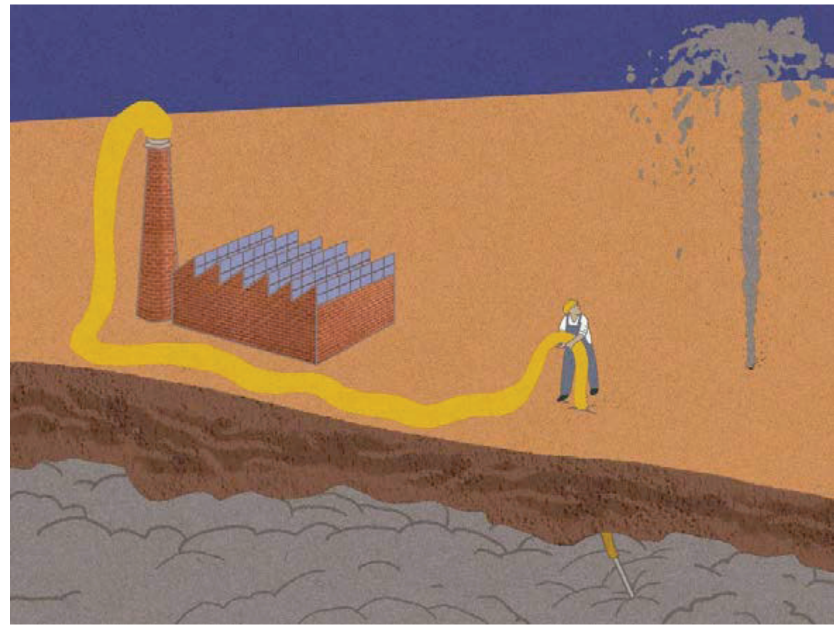
Changing Societal Attitude towards Concrete

Guardian, Best of 2019,

Concrete: the most destructive material on Earth

https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth



Scientific American, March 1, 2024,

The False Promise of Carbon Capture as a Climate Solution

Fossil-fuel companies use captured carbon dioxide to extract more fossil fuels, leading to a net increase in atmospheric CO_2

https://www.scientificamerican.com/article/the-false-promise-of-carbon-capture-as-a-climate-solution/

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Statistics of Concrete Consumption

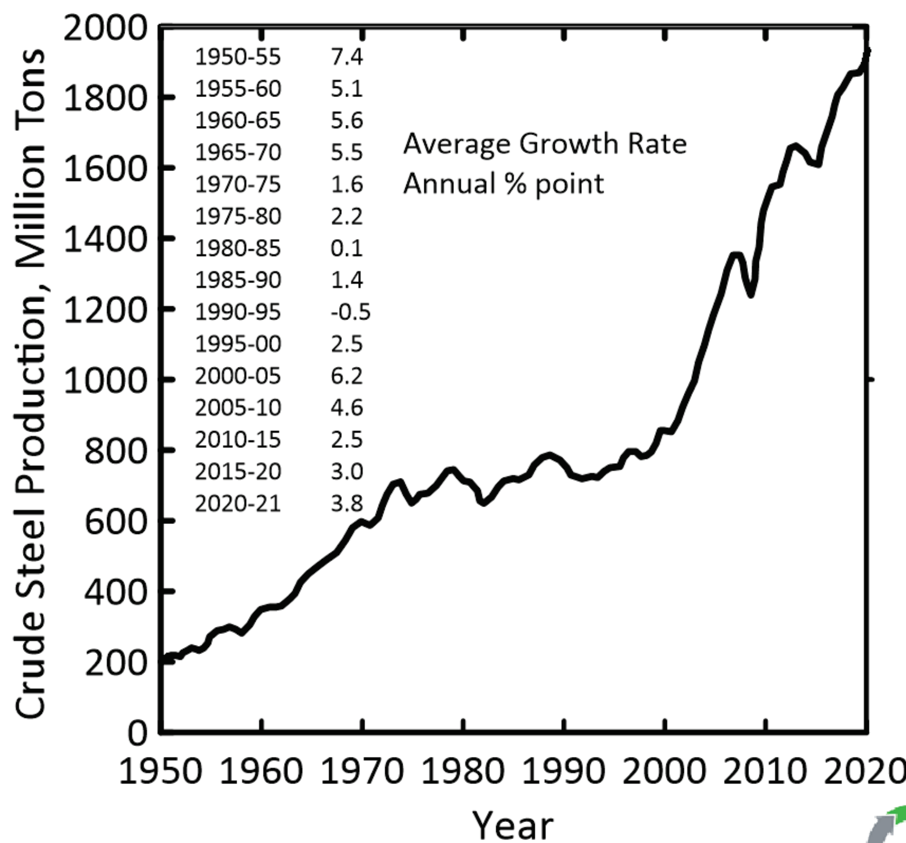
- Compared to all countries, concrete industry is the third-largest CO_2 emitter
- 4-8% of the world's CO_2 emission,
- Fourth in ranking as a source of greenhouse emission after coal, oil and gas.
- Annual use of about 4 billion tons of cement creates 3 B tons of CO_2

- Uses 10% of the world's industrial water, affecting drinking and irrigation.
- 75% of water consumption is in drought and water-stressed regions; adding to the heat-island effect
- Carbon capture by storage or mineralization has yet to show any promise, ($27B spent since 2017)
- Very little has been done about efficient structural design of concrete

https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth
https://www.cnbc.com/2021/01/31/carbon-capture-technology.html
https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus#growing-ccus-momentum

World Production of Steel in the past 70 years

- Crude steel production has increased from 800 to 2000 million tons per year since 1990
- One-half of the current production of 1 billion tons a year is by China, 10 times more than India, the second producer.
- assuming annual concrete consumption of 10Bt Total volume of rebar will be 522 million tons
- 7.5 lbs of steel rebar per ft^3 of concrete
- Although recyclable, the raw feed supplies of steel ore will be exhausted due to increasing demand.



https://www.crsi.org/reinforced-concrete-benefits/economy-of-construction/

Rebar footprint

Metric	Cost Category	Rebar Share	Direct/indirect cost
Rebar density by building type	a) Heavy industrial b) Commercial c) Institutional	130 kg/m^3 100 kg/m^3 90 kg/m^3	Direct
Weight of Rebar by volume of concrete	Average weight for all categories	7.57-10.93 lb/ft^3 120 -175 kg/m^3	Direct
Volume of Rebar, %	Average % volume of Rebar reinforcement for all concrete	1.56 – 2.41%	Direct
Average % component cost as cost of overall structure	Formwork Concrete Steel rebar	50% 30% 20%	Indirect Direct Direct

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Phases of a product life cycle: from cradle-to-grave

- Raw Material Extraction
- Manufacturing & Processing
- Transportation
- Usage & Retail
- Waste Disposal

Building Life Cycle Information Modules																
Product stage			Construction Process stage		Use stage							End-of-life stage			
Raw Material supply	Transport	Manufacturing	Transport	Construction/Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	De-Construction/ Demolition	Transport	Waste processing	Disposal
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4

- Due to the complexity and large volume of construction, general Rules do not Apply
- Site Specific Building Design and Construction, extremely low cost of concrete, high factors of safety.
- Design changes to improve the material efficiency will have a cascading effect on all follow up costs.
- Compressive strength is the primary metric used for the quality of concrete, and only one variables in the Design
- Tensile properties dominate the major volume of concrete used, but are not used in the design

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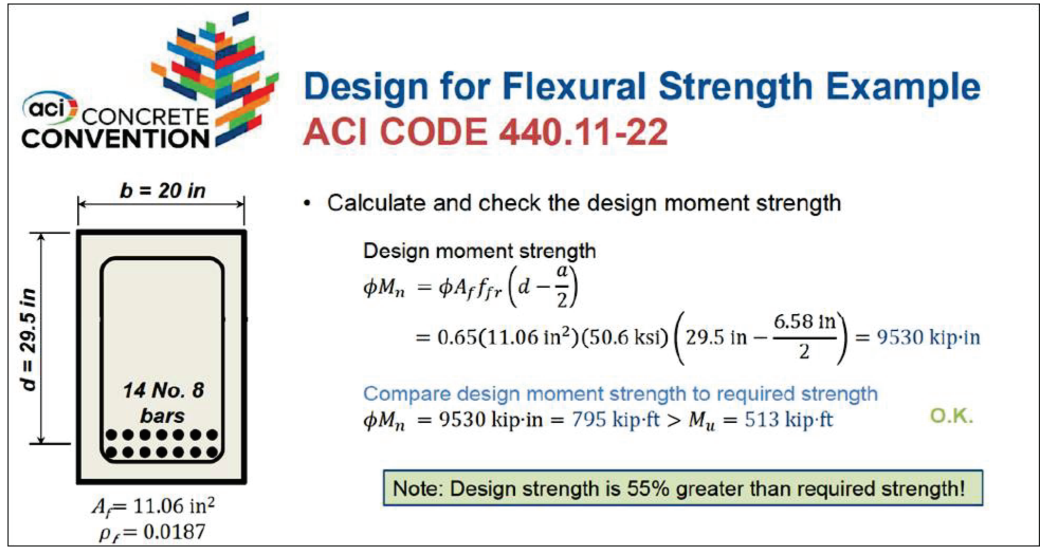
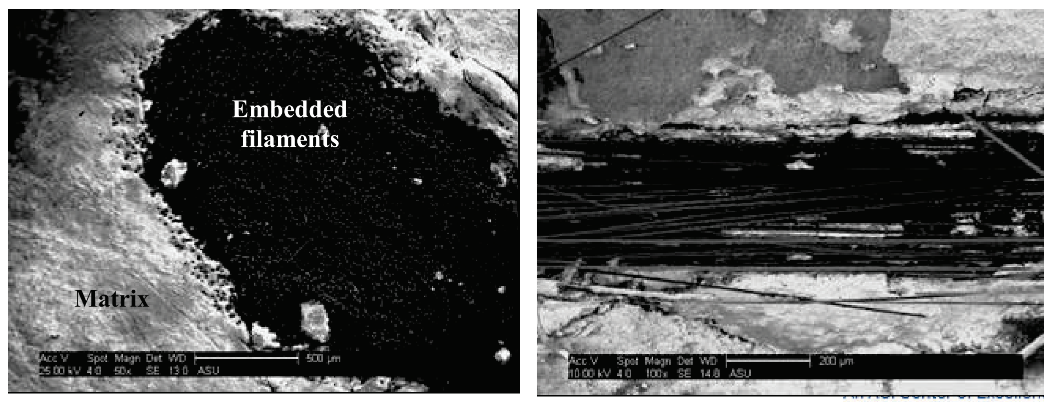
2. Barriers to growth of High-performance Composites, FRP, Glass, Carbon, Basalt, and Textiles

- UV degradation, fire, moisture, debonding of FRP
- Lack of an integrated approach toward design rules
- Fragmented design of reinforcement for shear, flexure, and pullout
- Dominated by the codes developed for the steel, How to arrive at a cost-competitive carbon fibers
- Lower stiffness and strength, except for carbon fibers
- Simplify the sizing of polymeric coatings
- Stiffness mismatch with the base of FRP rebar
- Design for Ductility
- Lack of inspection, and guidelines for design



Large size tows reduce the potential for proper bonding and load transfer



(a) (b)

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3. Proposed Unified design approach for Alternative reinforcement

- FRC- Short Chopped Fibers, 3-5 mm in length semi-soluble polymeric coating with good dispersion quality for use as a strengthening, crack arrest mechanism
- TRC- Development of textile applications for new products, repair, and strengthening. Product development, automation for new structural shapes
- FRP- Traditional bar sizes, limited to number 5, development of technology for forming and bending with thermo-plastic and shape changes
- UHPC- development of high-performance FRP for matching the strength and stiffness of UHPC
- Hybrid-RC- Development of a Supplementary fiber system to work in combination with the primary reinforcement

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A perspective on the history of Reinforced Concrete Design

Arch bridge at Châtellerault, France, 1899, Francois Hannebique -1905, Engineer and builder, who patented reinforced-concrete construction in 1892.

Model T, Developed in 1908

World's first transatlantic passenger service by Pan American on 28 June 1939

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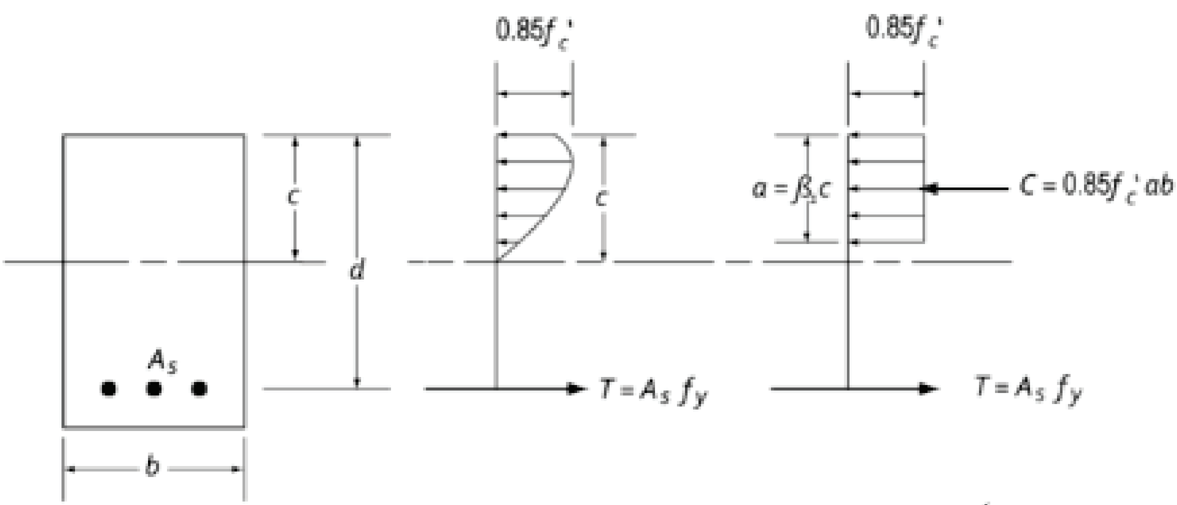
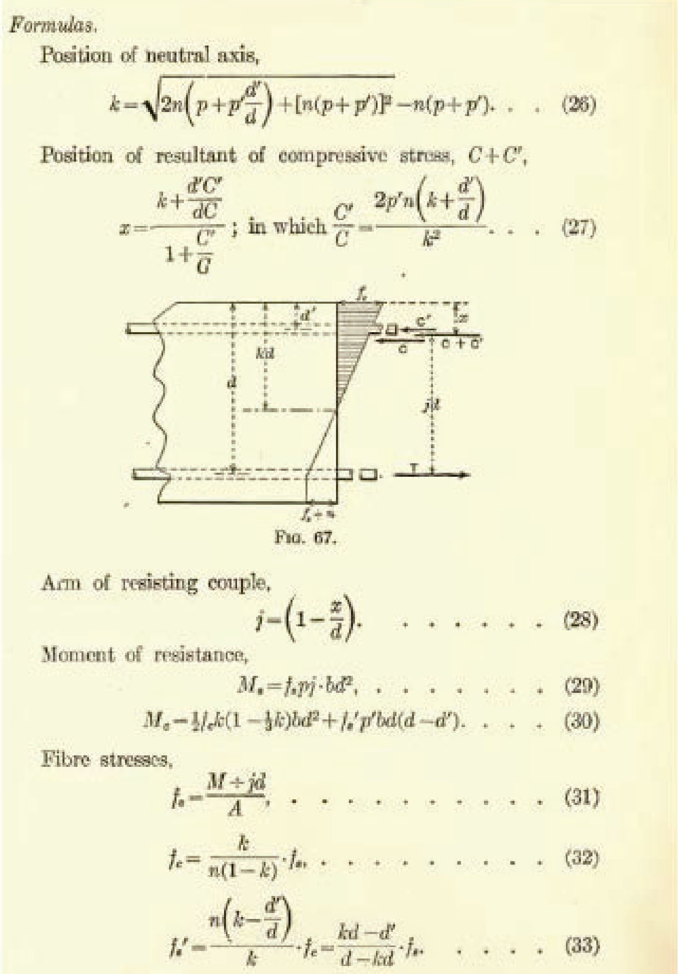
4. Concepts for the structural design are more than 120 years old

- Structural Design of reinforced concrete has been practically unchanged in 120+ years
- Guidelines developed in 1907, modified in 1930s, and codified in 1940s.
- Approximately 60-70% of concrete's volume that is subjected to tensile stress is still ignored and thus a waste of resource, providing no contribution other than providing a cover for the steel rebar.



Rectangular Stress Block
Charles S. Whitney, 1930s

$$M_u = \phi A_s f_y d\left(1 - 0.59\frac{\rho f_y}{f_c'}\right)$$



Formulas.

Position of neutral axis,

$$k = \sqrt{2n\left(p + p'\frac{d'}{d}\right) + [n(p+p')]^2} - n(p+p'). \quad (26)$$

Position of resultant of compressive stress, $C+C'$,

$$z = \frac{k + \frac{d'C'}{dC}}{1 + \frac{C'}{C}}; \text{ in which } \frac{C'}{C} = \frac{2p'n\left(k + \frac{d'}{d}\right)}{k^2}. \quad (27)$$

Fig. 67.

Arm of resisting couple,

$$j = \left(1 - \frac{z}{d}\right). \quad (28)$$

Moment of resistance,

$$M_s = f_s pj \cdot bd^2, \quad (29)$$

$$M_c = \tfrac{1}{2} f_c k(1 - \tfrac{1}{3}k)bd^2 + f_s' p' bd(d - d'). \quad (30)$$

Fibre stresses,

$$f_s = \frac{M \div jd}{A}, \quad (31)$$

$$f_c = \frac{k}{n(1-k)} \cdot f_s, \quad (32)$$

$$f_s' = \frac{n\left(k - \frac{d'}{d}\right)}{k} \cdot f_c = \frac{kd - d'}{d - kd} \cdot f_s. \quad (33)$$

Ultimate Loads formula by Tuneaure 1907

5. Challenges in the Traditional Structural Design Limit States

- Structural elements are designed by performance requirements by codes at ultimate and serviceability limit states (ULS and SLS), with partial factors used to ensure reliability.
- Codes do not establish upper limits to these criteria. Requiring structural designers to design the embodied energy efficiently is not enforced.
- Over-conservative code language results in materially inefficient structures.
- Primary approaches to decrease the environmental impact of concrete structures.
  - A. Optimize the geometry by better definition of serviceability and durability design basis. Using topology optimization, decrease cement consumption due to targeted goals.
  - B. Efforts concentrated on efficient cement substitution products such as pozzolans, lime cements to replace the hydraulic Portland cement.
  - C. Innovative design guidelines by using high-performance materials with high strength and stiffness properties. FRP reinforcement, hybrid design, textiles. These are however not mandated, or codified.

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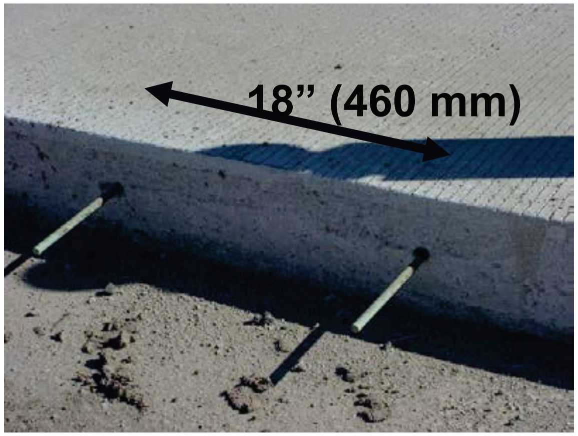
Why Should we move towards Supplementary Reinforcement?

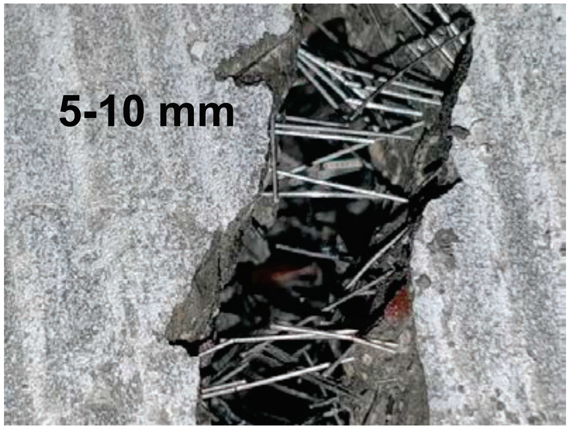
Strengthening at the microstructure level will have a profound impact at the macro-structural level strength and durability

Concrete reinforcement at a microscale a game changer in terms of Carbon footprint



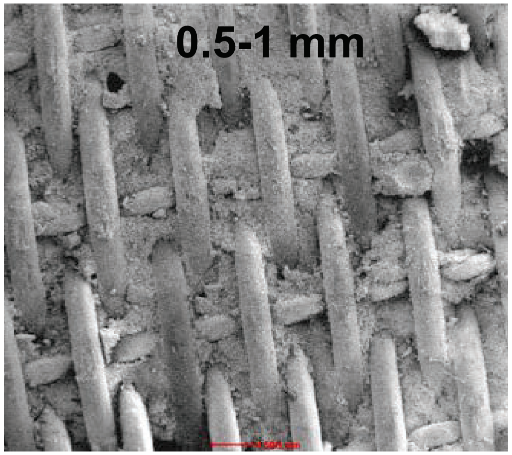
Ordinary reinforced concrete slab, 5-10” thick, standard rebars, 12”-18” apart

Reinforcing Bars: Macro-structure reinforcement



Fiber reinforced Concrete (FRC), at the meso-structure with ½” long fibers, ½” (10mm) millimeters apart

Fiber reinforced Concrete: Meso-structure reinforcement



Textile reinforced Concrete (TRC), at the micro-structure with long fibers, woven, only millimeters apart

Textile Reinforced Concrete: Micro-structure reinforcement

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What are the potential mechanisms for toughening Concrete?

- Additional cracking that correlates with creation of surface area results in energy dissipation
- Any process that delays localization and nominally increases the strength of concrete in tension
- Delays in crack initiation, reducing w/c , porosity, and improving interfaces

- Mechanisms:
- Crack path tortuosity
- Crack deflection
- Crack bridging, fiber pullout, yielding
- Delamination cracks
- Multiple cracking
- Tension stiffening

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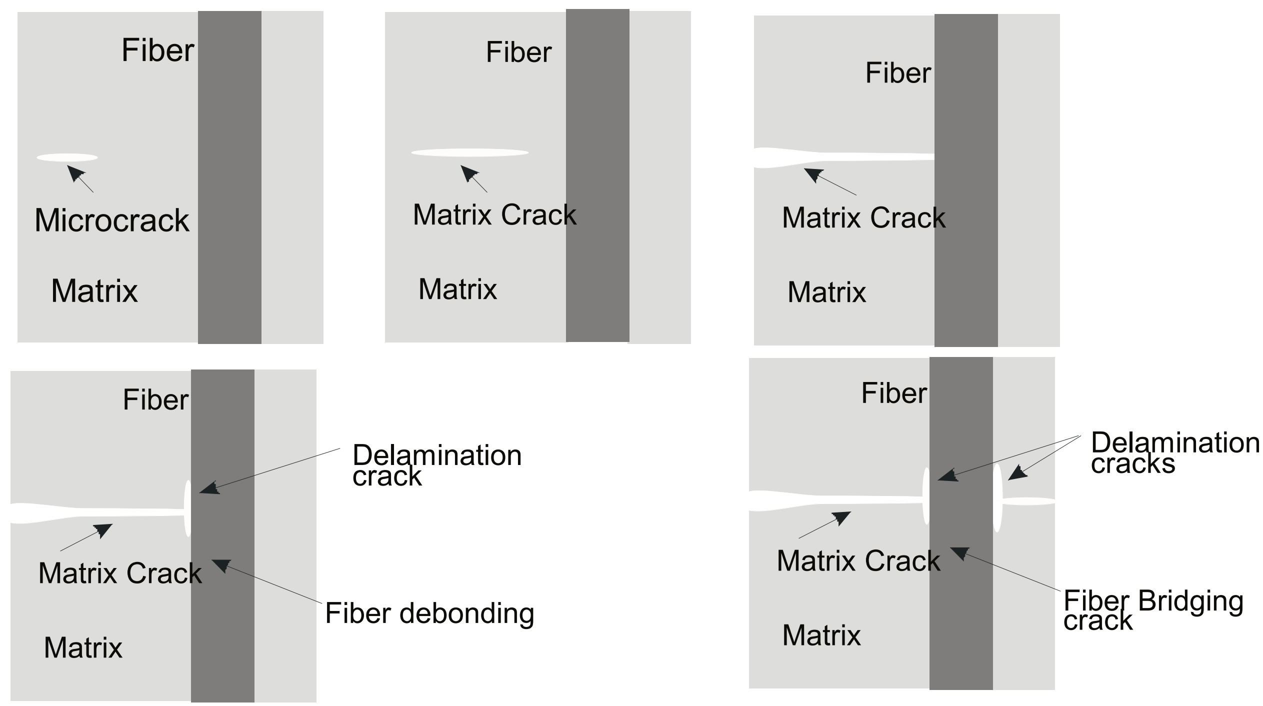
Sequence of cracking from initiation and growth, deflection, & Bridging perspective

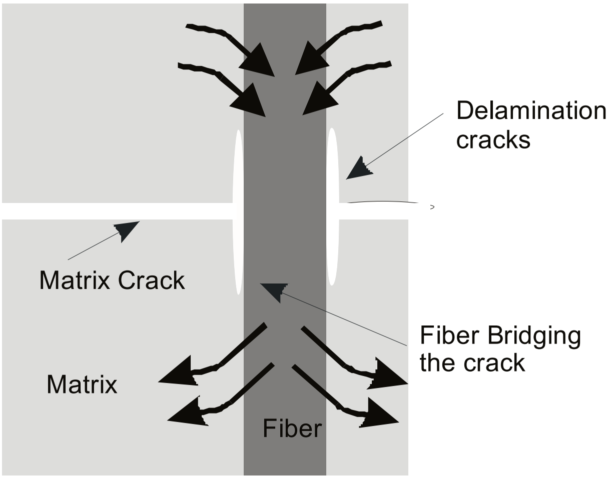
The cracking process starts from slow crack growth of a microcrack from a pore or aggregate interface, crack propagation, hindered by fibers, resulting in crack deflection, delamination, fiber bridging, pullout

1. Stable microcrack to macro crack growth
2. Crack coalescence and growth
3. Crack arrest by fibers
4. Fiber debonding and crack deflection
5. Interface debonding
6. Full fiber debonding growth
7. Fiber bridging

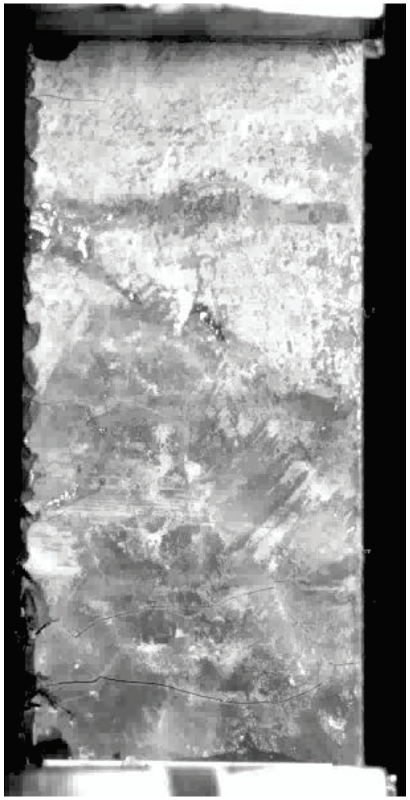


None of these mechanisms are present when the concrete is not reinforced at the microstructural level

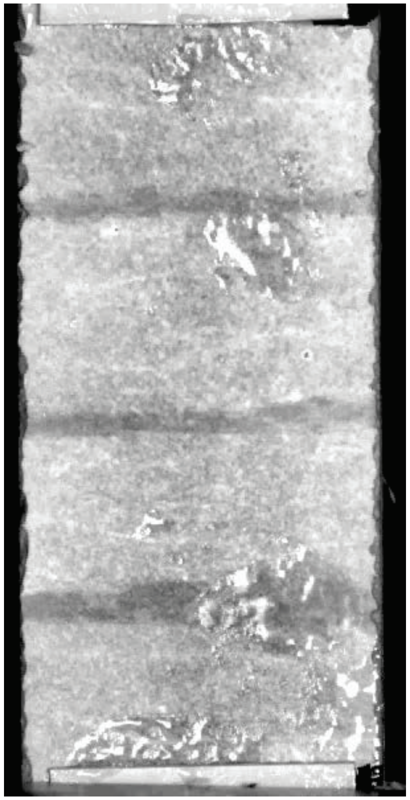
Tension Stiffening is the Fifth major mode of toughening



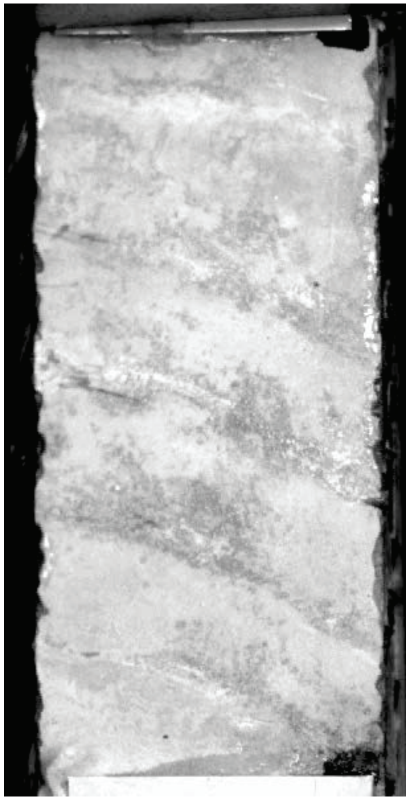
PE, Glass, and Carbon Composites



PE Composite with Silica Fume



AR-Glass Composite



Carbon Composite (plain cement)

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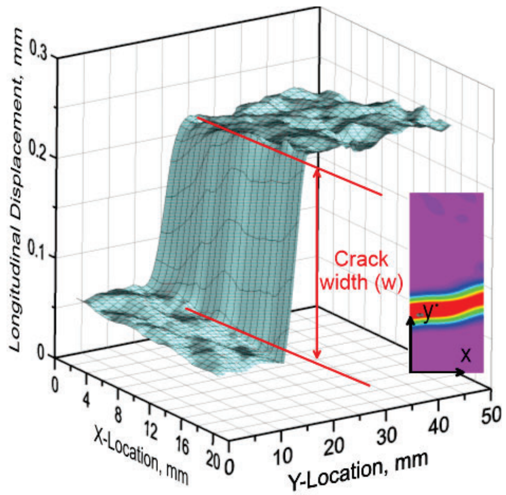
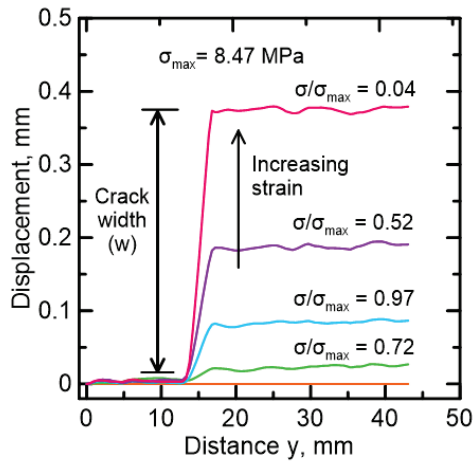
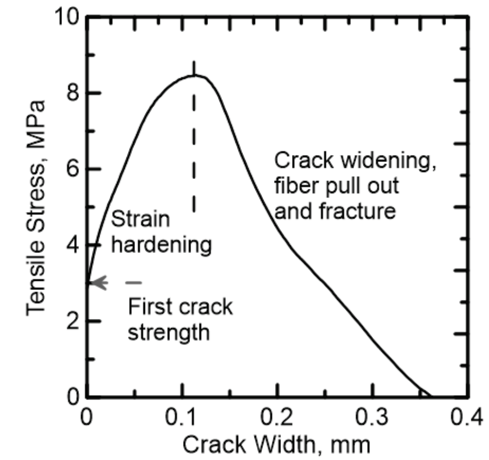
Crack Width Measurement for Strain Hardening in TRC



Displacement Field



Displacement Distribution Along Specimen



Stress-Crack Width Relationship

- Non-contact measurement
- Quasi-static to high speed
- Single crack and multiple cracks

Rambo, D. A. S., Yao, Y., et al. (2017). Experimental investigation and modelling of the temperature effects on the tensile behavior of textile reinforced refractory concretes. Cem. Concr. Compos. 75, 51-61.

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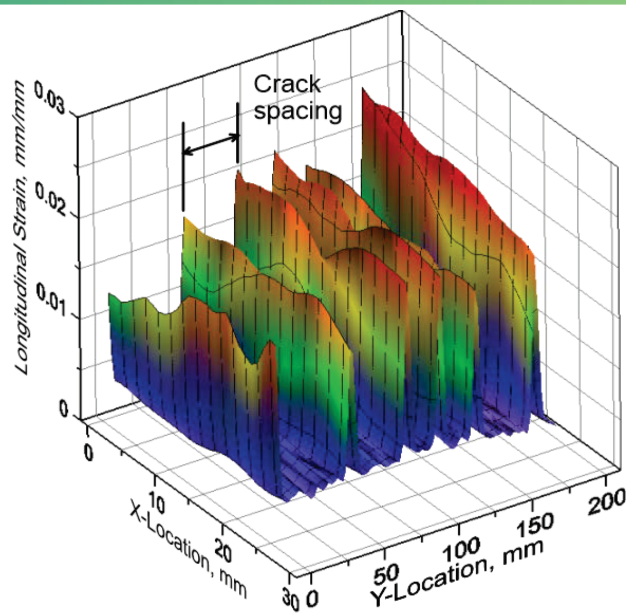
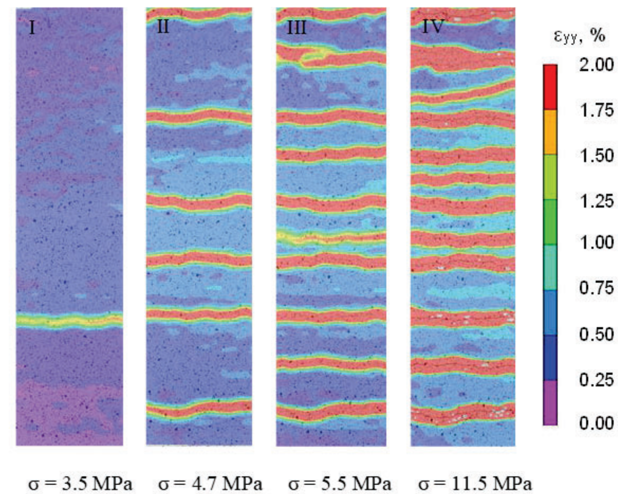
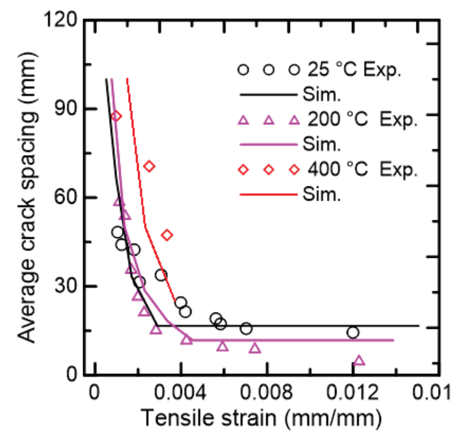
Ductility Induced enhanced behavior for structural composite applications

- Evolution of Crack Spacing in TRC
- Multiple cracking in tension
- Tension stiffening
- Development of parallel cracks

- Indication of toughening mechanisms
- Characteristic length in numerical modelling







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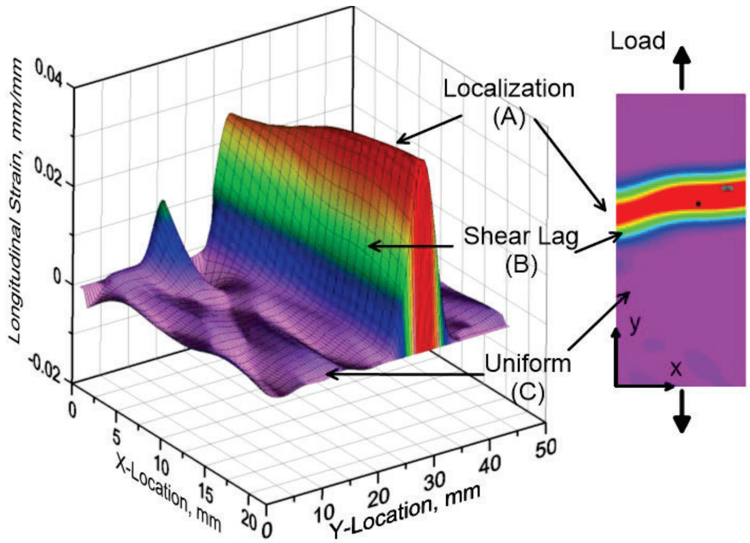
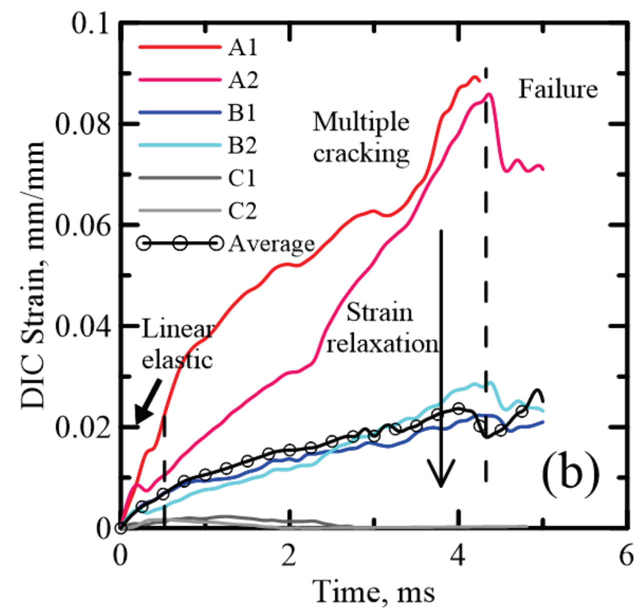
Crack Bridging capability, Ductility, and enhanced strength under impact conditions - Carbon TRC high speed tensile response





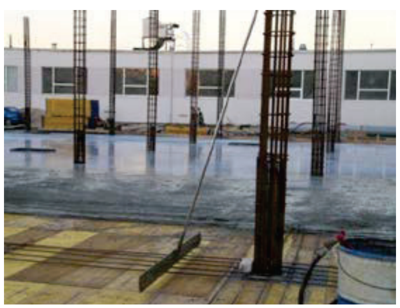
- A: Localization Zone – Fiber debonding
- B: Shear Lag Zone – Shear lag bonding stress distribution
- C: Uniform Zone – Fiber and matrix are perfectly bonded

DIC strain versus time histories at different zone

Rambo, D. A. S., Yao, Y., et al. (2017). Experimental investigation and modelling of the temperature effects on the tensile behavior of textile reinforced refractory concretes. Cem. Concr. Compos. 75, 51-61.

Elevated slabs with FRC

Section size reduction, Volume reduction, Labor, construction scheduling, Speed of construction



ACI 544-6R 2015

Elevated slabs for multistory floors without steel reinforcement, ACI 544-6R

Addressing Reinforcement aspects of precast market








Top row Left to right

1. Septic tanks and vaults
2. Elevated slabs
3. Shotcrete and tunnel lining
4. Pavement applications

Bottom row Left to right

1. Pipes
2. Industrial strong floors
3. Corrosion protection
4. Wiremesh replacement

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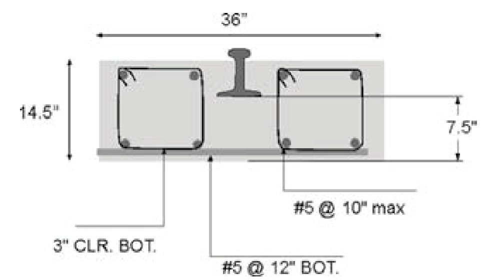
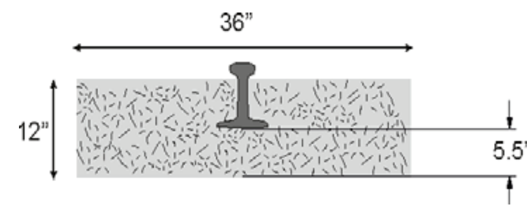
Case Study: City of Phoenix Light Rail System, (Valley Metro)

Provide alternative solution to the design of reinforced concrete rail slabs, cost savings, stray current corrosion mitigation plan



Conventional Design section



FRC Section

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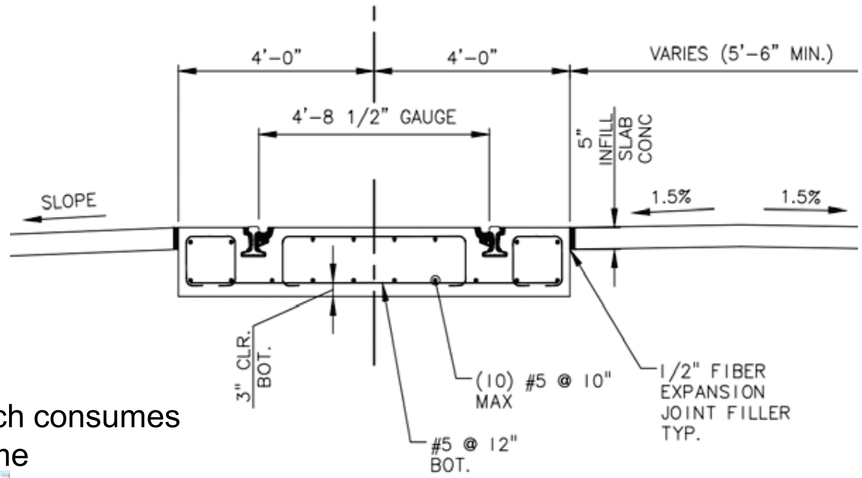
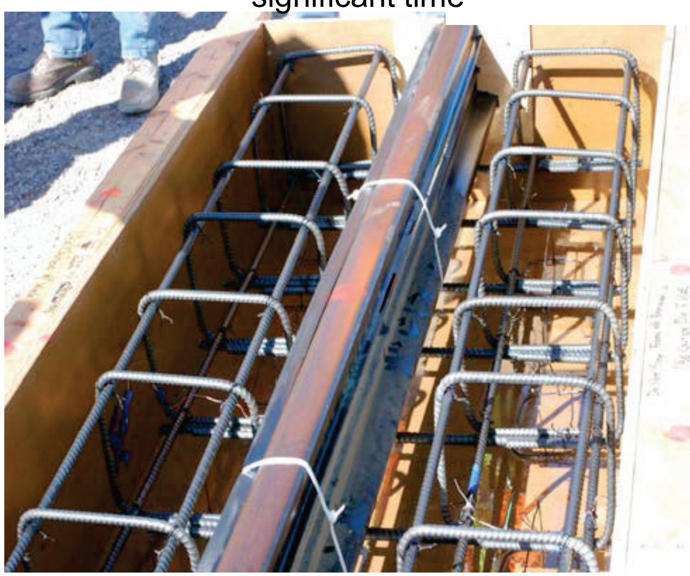
-Conventional Rebar section (0.37mx0.9mx2.5m)
-SFRC, 65 PCY Dosage (0.3"x0.9mx2.5m)

Alternative Design of Embedded Track Section

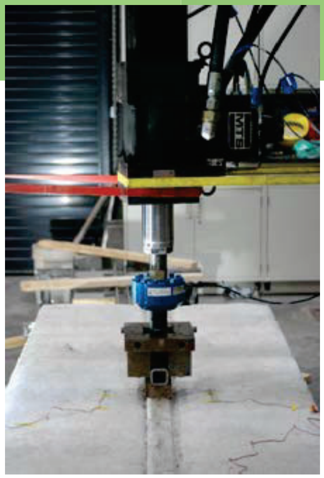


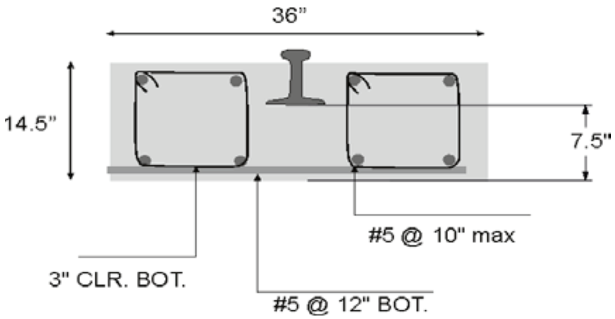
Current Design approach consumes significant time



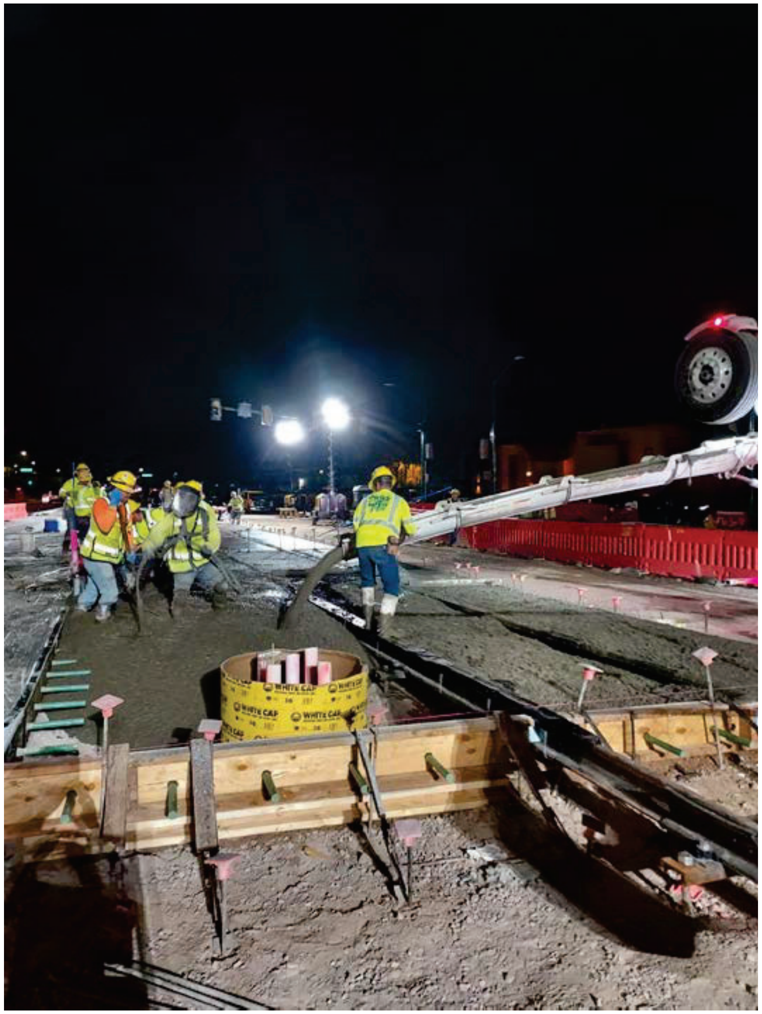
FRC design increases ductility and saves time and cost.

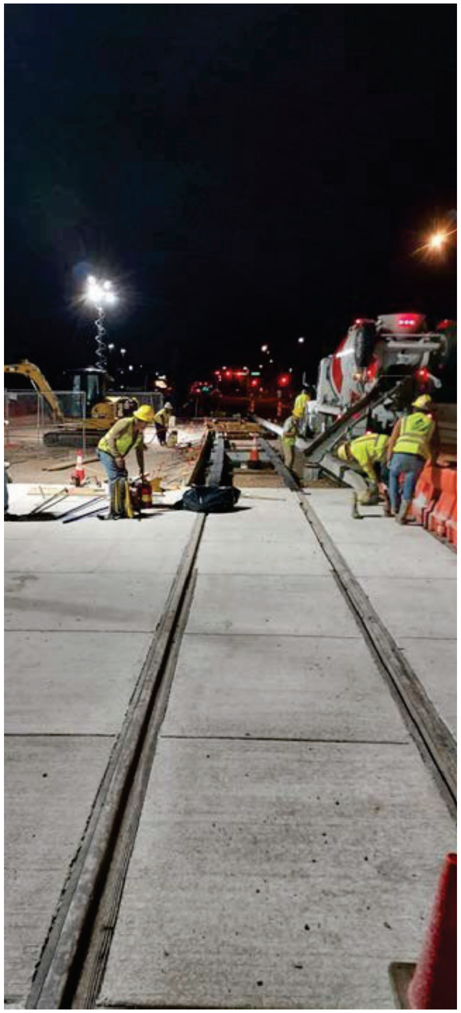
Full size Track Slab Fatigue testing 2.5 million cycles

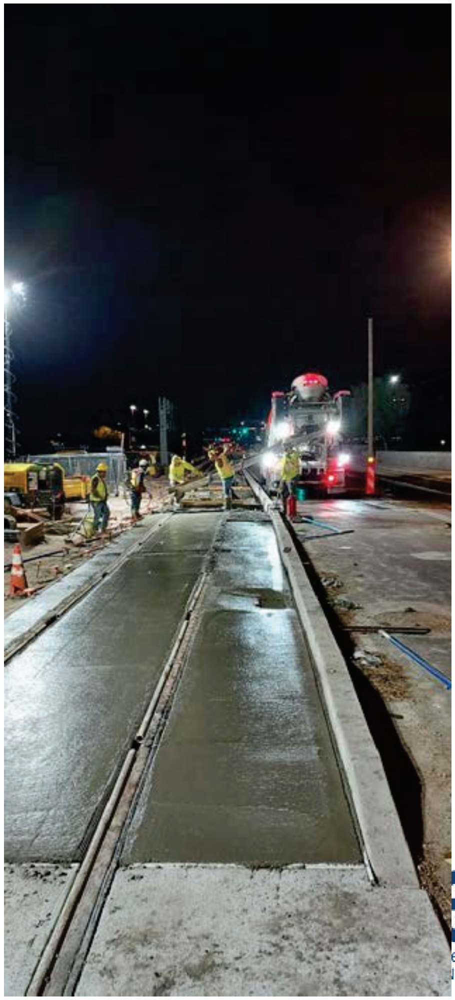




Project Implementation, Valley Metro light rail Extension, Phoenix







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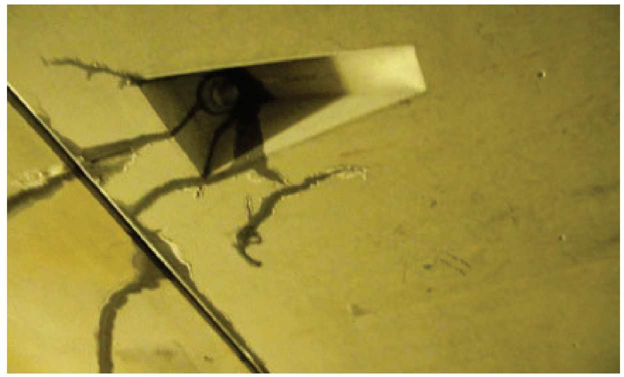
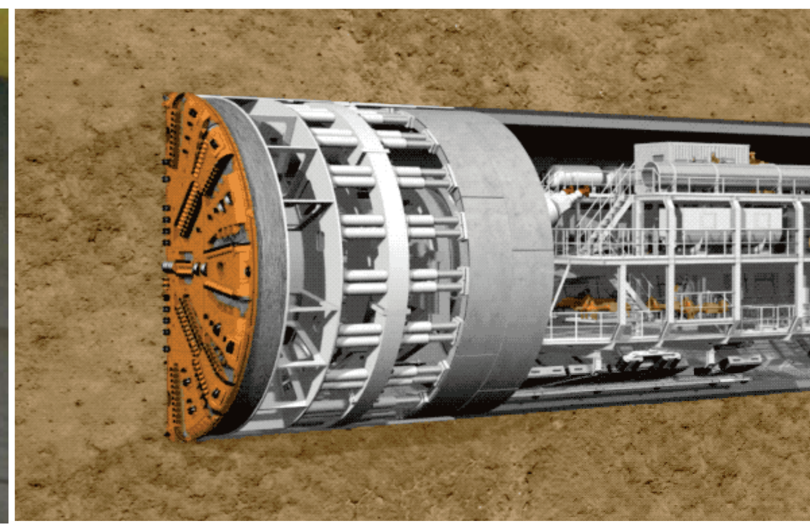
Case Study #2 Precast Tunnel Lining using Fiber Reinforcement

Serviceability Based Analysis, Design, and Testing of Hybrid Structural Sections

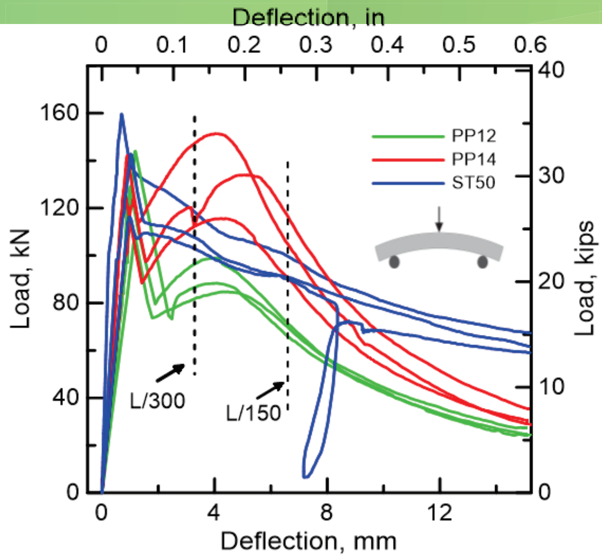
- Use of Polymeric fibers and/or FRP for precast tunnel lining in TBM equipment
- Elimination of steel reinforcement
- Full scale testing and Modeling in order to promote innovative and sustainable construction systems.

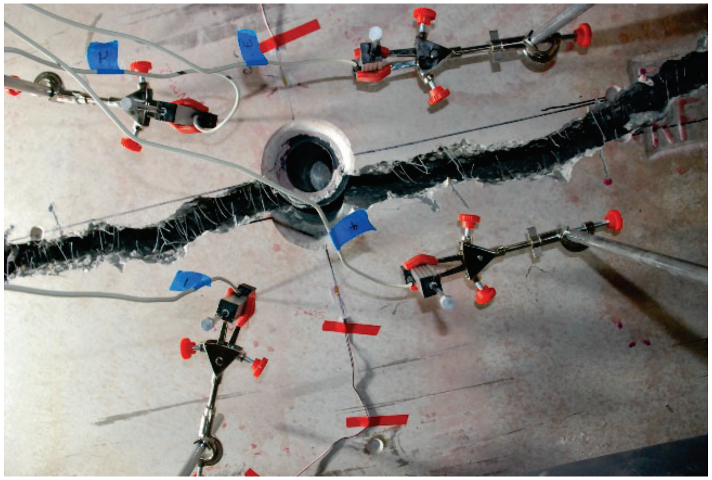


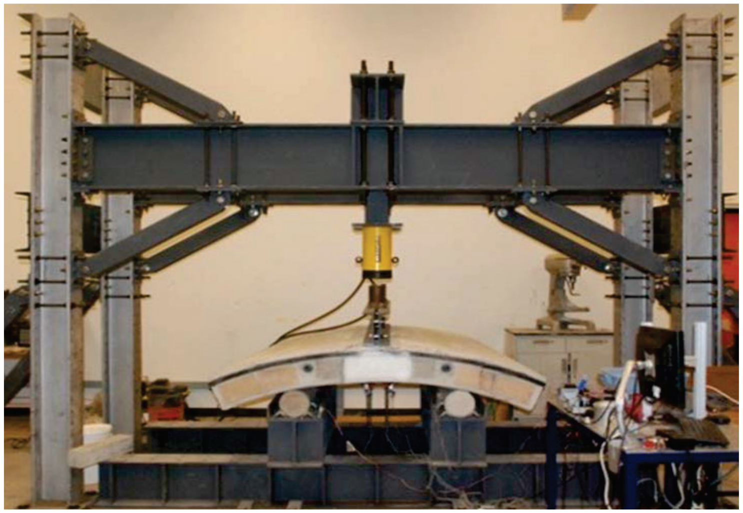


Precast Tunnel Lining Applications, ACI 544-7R

- The question is no longer rebar vs. fibers, but what type and volume fraction?
- Increased energy absorption, fatigue life, seismic, impact conditions, edge cracking
- Ductility, Durability, Sustainability







Patel, D., Pleesudjai, C., Bui V., Pridemore, P., Schaef, S. and Mobasher, B. 2023. “Mechanical Response of Precast Tunnel Segments with Steel and Synthetic Macro-Fibers.” *Cement and Concrete Composites* 144 (November): 105303. https://doi.org/10.1016/j.cemconcomp.2023.105303.

Area 2- Hybrid Based Serviceability Based Design

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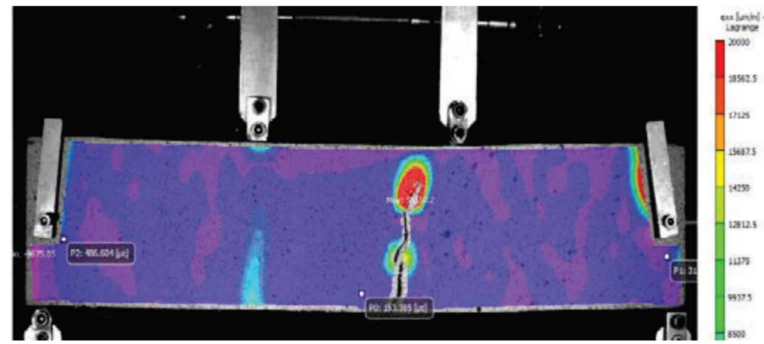
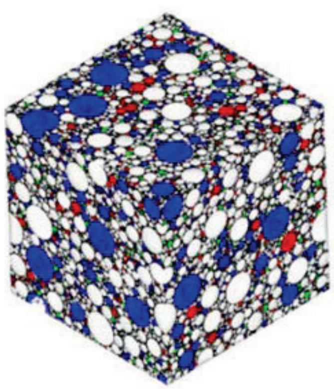
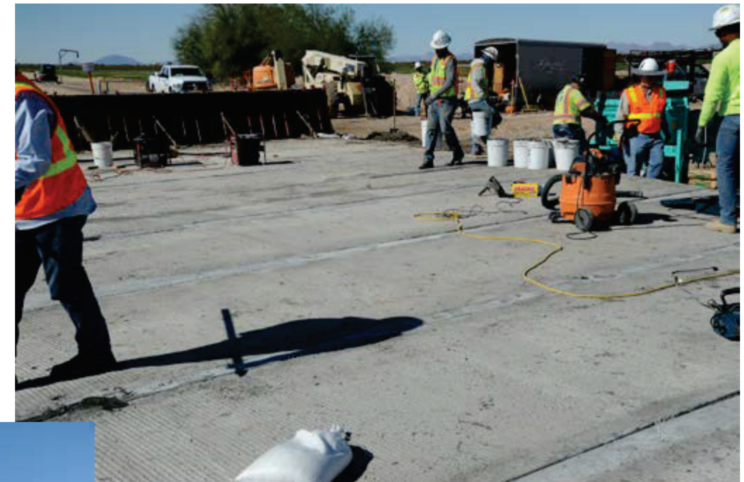
Case #3 Non-Proprietary UHPC Concrete Mixtures, ADOT and Maricopa County, Arizona, 2022

- Life cycle cost and economic advantages of using UHPC systems in terms of structural applications.
- Precast UHPC elements reduce operational complications, labor-intensive tasks. From a design perspective, elastoplastic behavior improves durability, ductility, load redistribution, and weight reduction.
- Develop Sustainable Materials, using solid mechanics, material formulations, structural components, and systems.
- solutions for composite materials for transportation, water treatment facilities, pipes, tunnel lining, thin sections, Structural Shapes





UHPC Joint Implementation for Bridge rehabilitation with MDOT



Y Yao, B Mobasher, J Wang, Q Xu, "Analytical approach for the design of flexural elements made of reinforced ultra-high performance concrete", Structural Concrete, 2021

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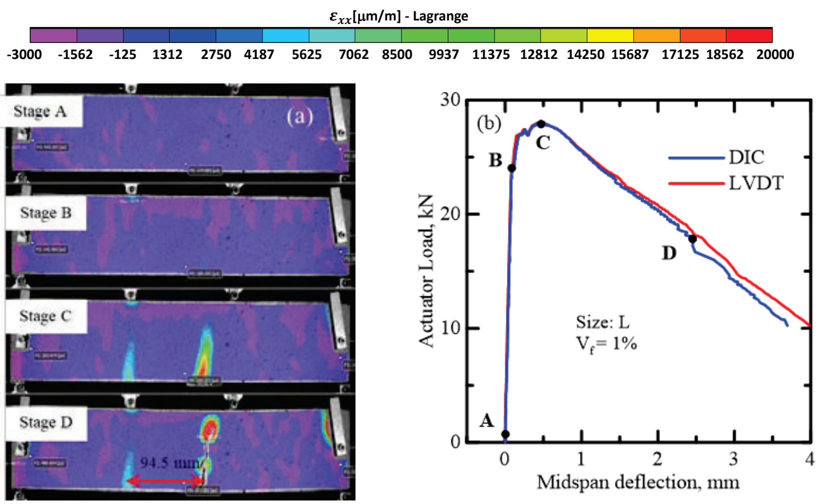
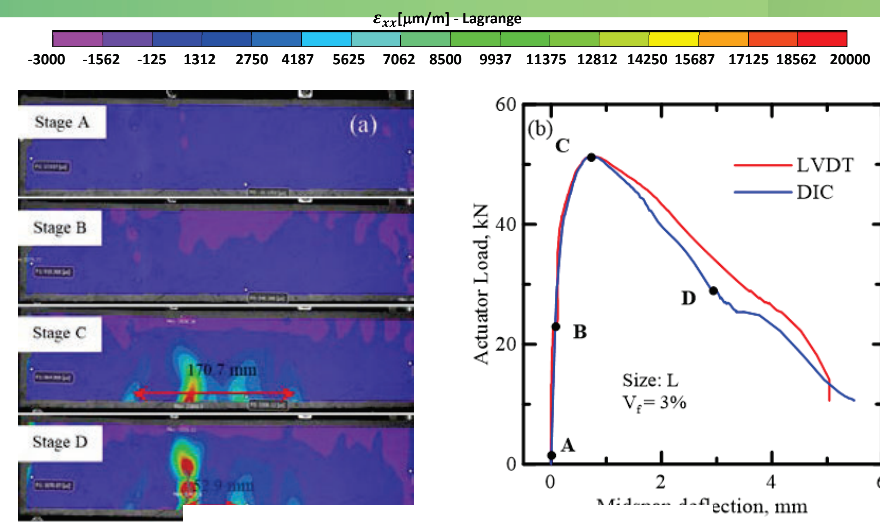
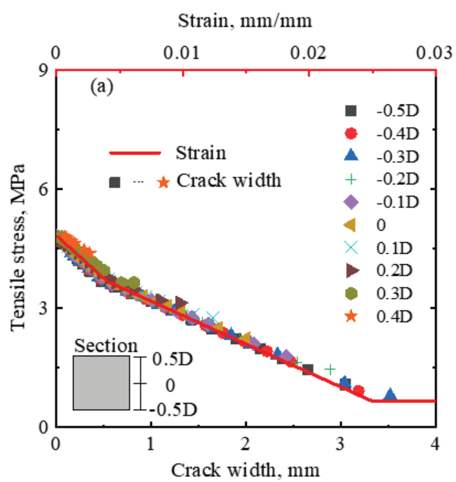
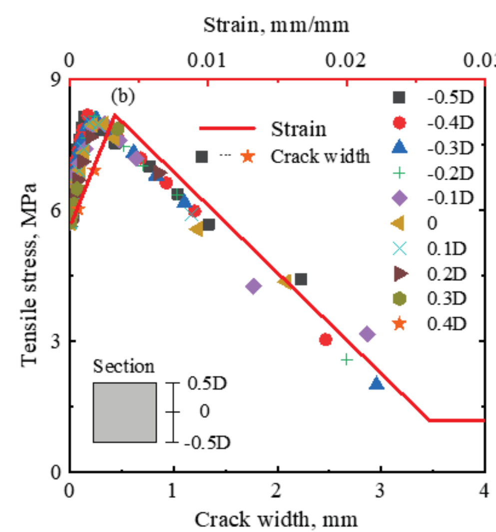
UHPC with 1% and 3% steel fibers, Stress Crack width Response







1% steel fibers



3% steel fibers

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Connection Beams for Precast Bridge Precast Slabs MDOT – UHPC

Arizona State University

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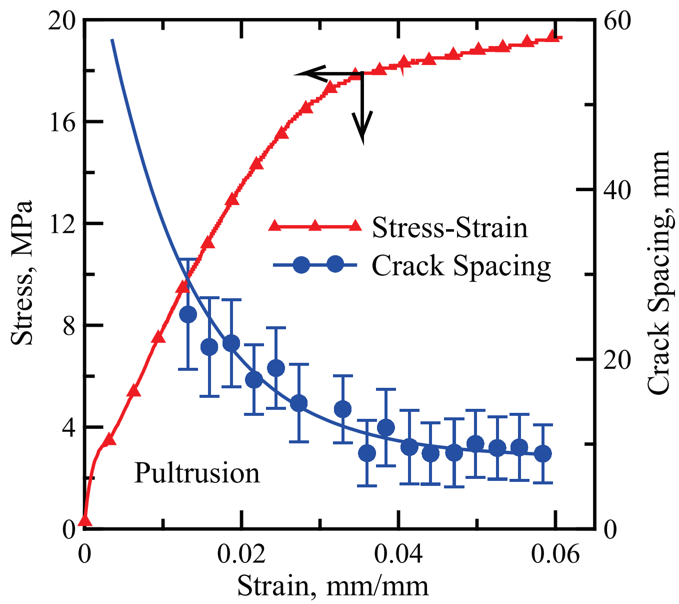
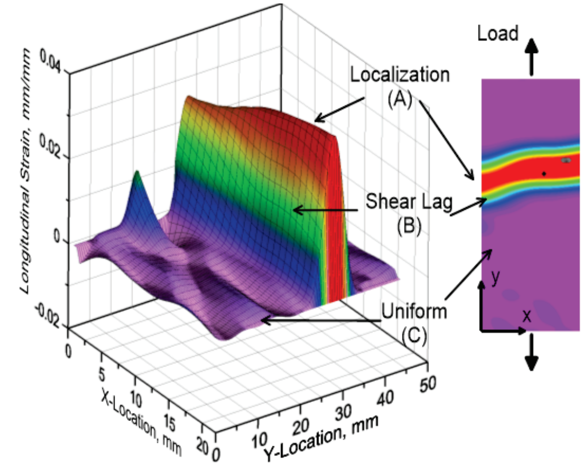
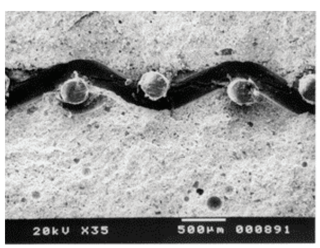
Textile Cement Composites

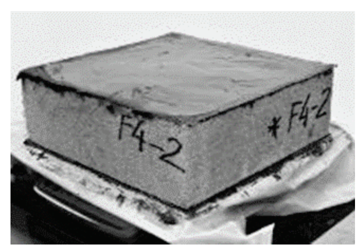
- Automated pultrusion system for manufacturing full scale TRC structural shapes from laminates
- large strain capacity and ductility





Peled, A. and Mobasher, B., (2005), “Pultruded Fabric-Cement Composites,” ACI Materials Journal, Vol. 102 , No. 1, pp. 15-23.





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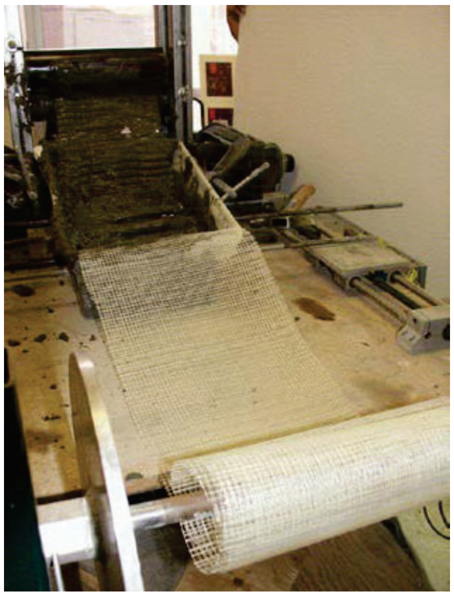
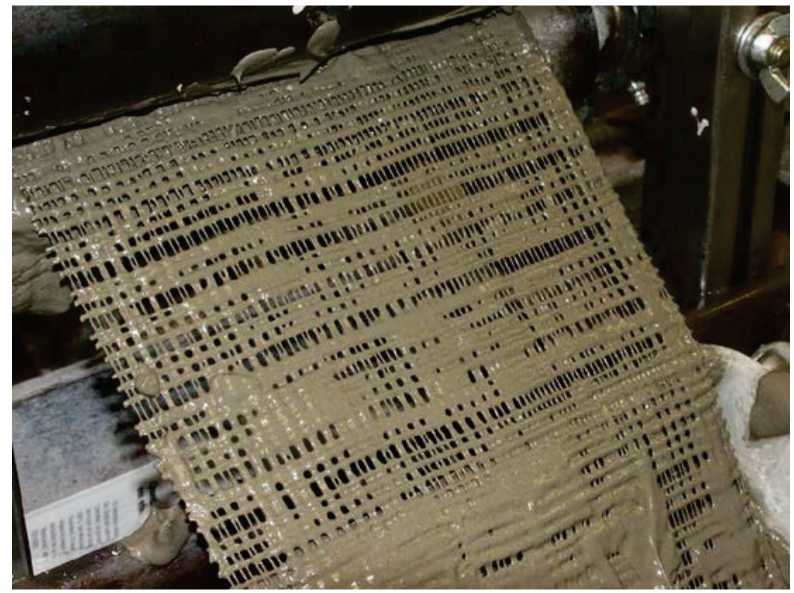
Pultrusion based approaches





Mobasher, B., and Pivacek, A.,”A Filament Winding Technique for Manufacturing Cement Based Cross-Ply Laminates,” *Journal of Cement and ConcreteComposites*,20 (1998) 405-415.

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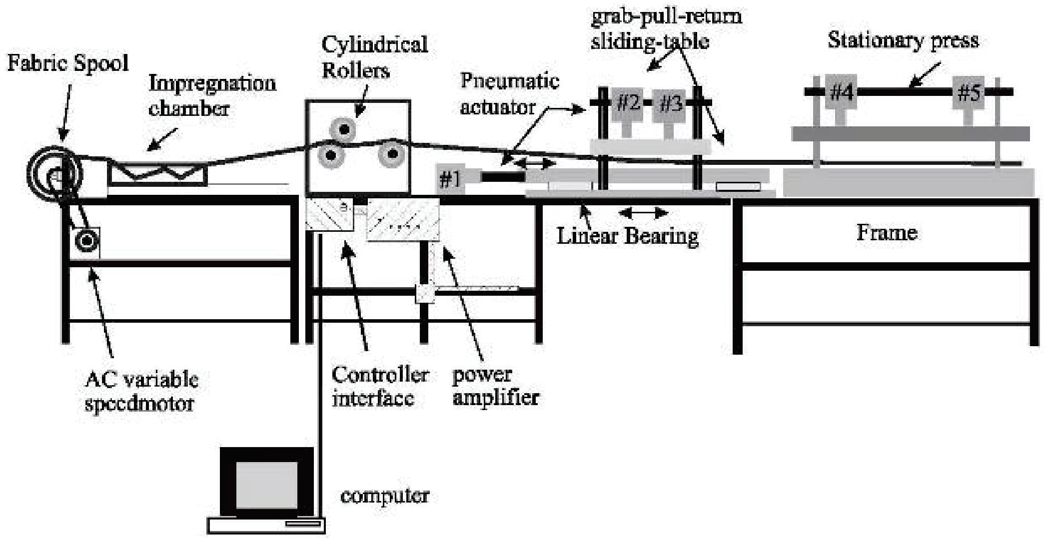
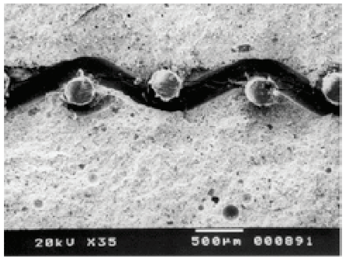
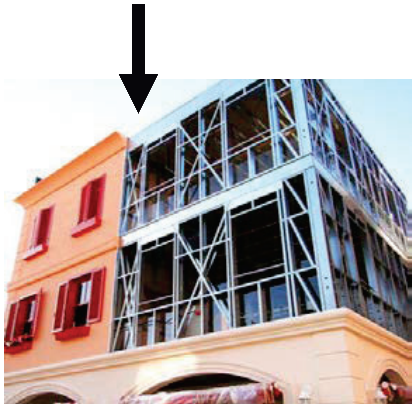
Structural Shapes using Textile Cement Composites

- Automated pultrusion system for full scale structural shapes with TRC laminates
- Competitive to wood and Light gage steel sections



Pultrusion Process Schematic Diagram

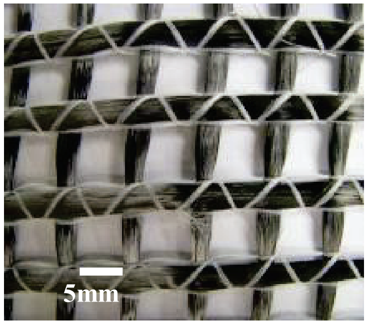


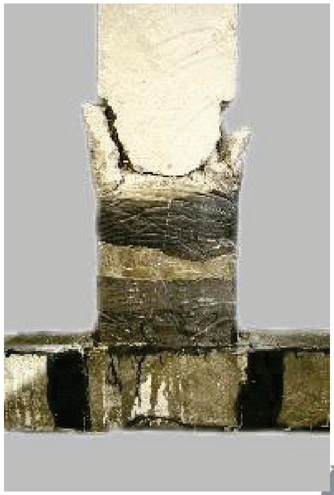


Peled, A., Mobasher, B., & Bentur, A. (2017). Introduction. In *Textile Reinforced Concrete* (pp. 1–12). https://doi.org/10.1201/9781315119151-1

Mobasher, B. (2011). Mechanics of fiber and textile reinforced cement composites.

Case Studies addressing Textile Reinforced Concrete





First row from Left to right

1. Aerated concrete textile Sandwich composites
2. Ductile response of sandwich composite Panels
3. Carbon textile
4. 4. Carbon textile beam-column repair

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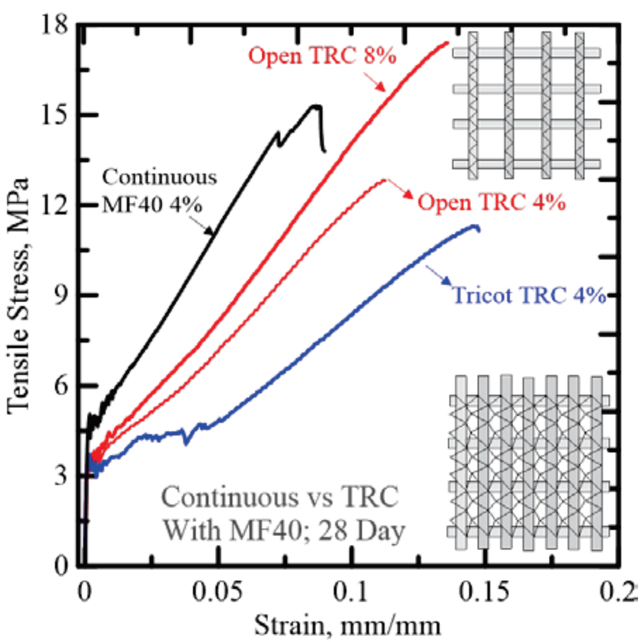
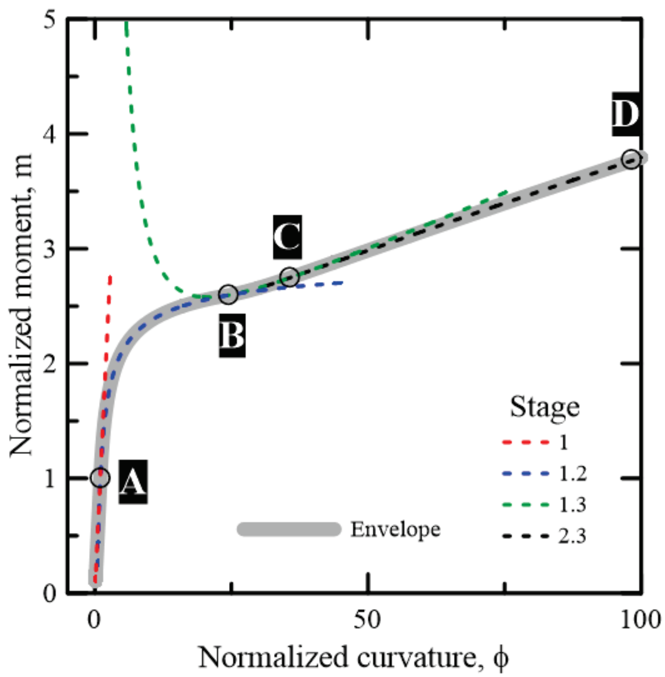
Development of Structural shapes with Textile Reinforced Concrete (TRC)





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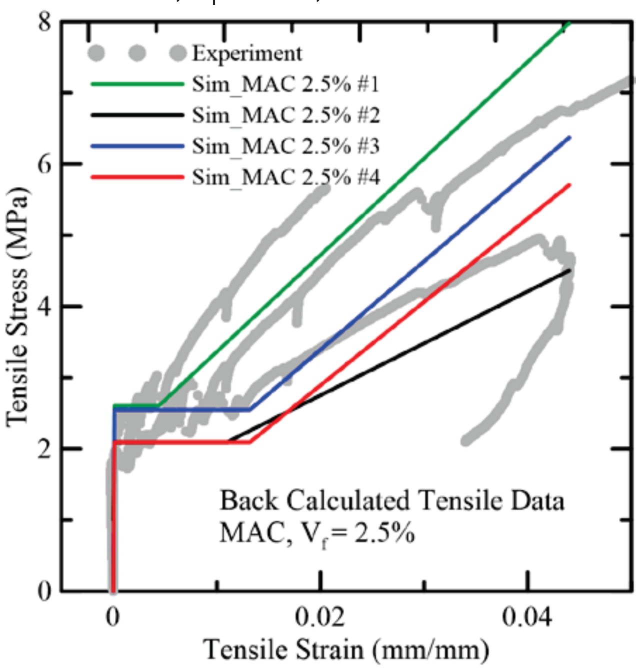
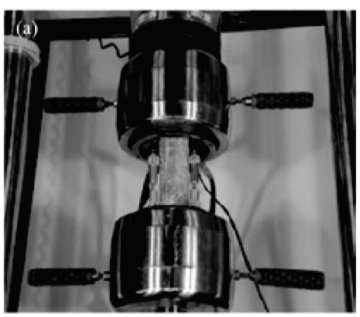
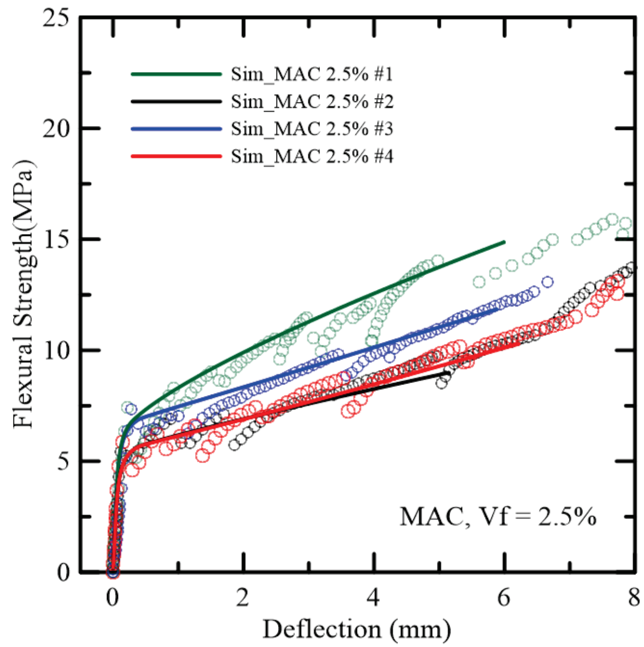
Tension and flexural response of PP Composite , V_f=2.5%, with Analytical modeling

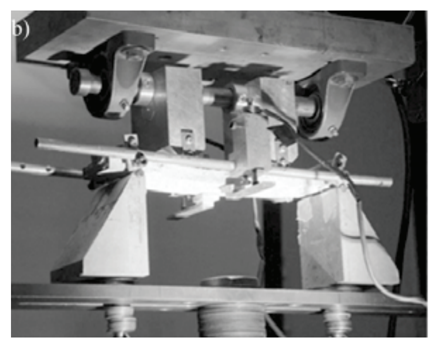
MAC, V_f=2.5% , Tension Test





MAC, V_f=2.5% , Flexural, simulation of test





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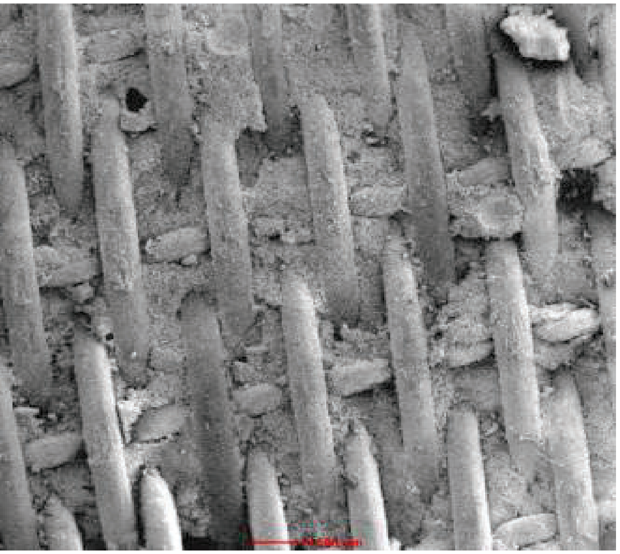
Fabrics in Paste

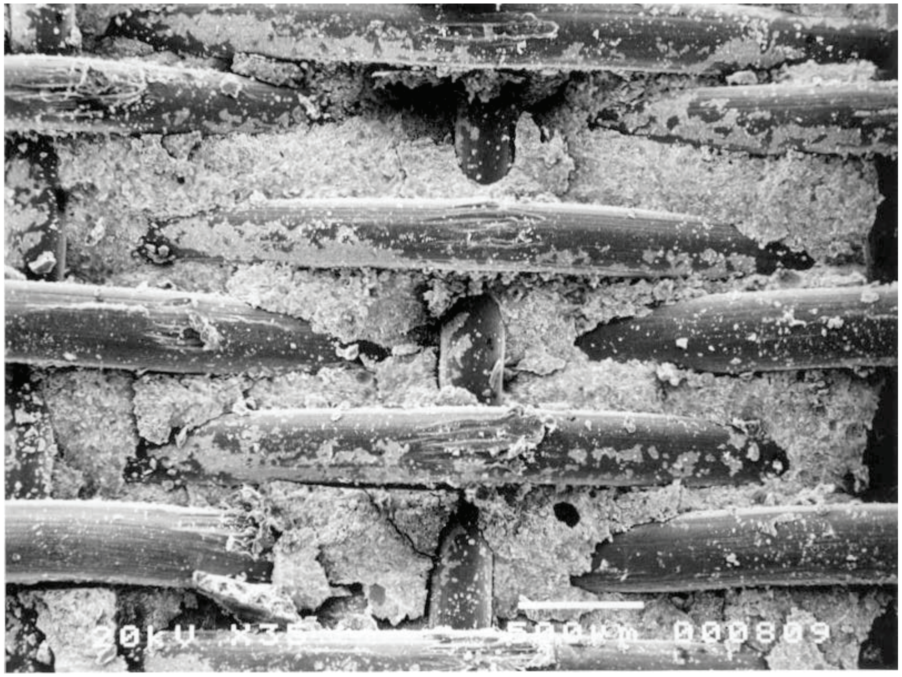


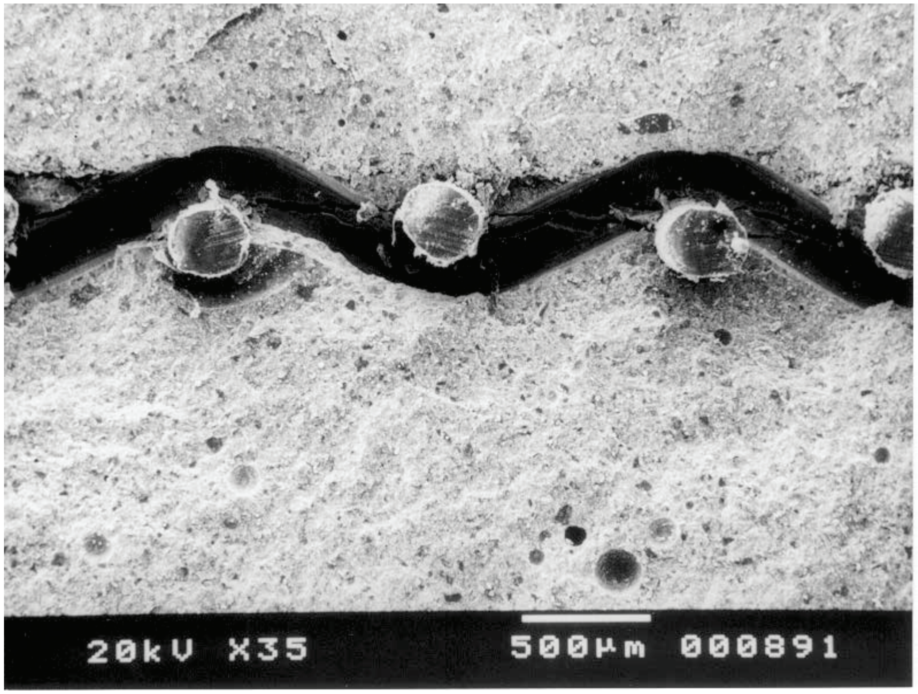
Polyethylene (PE)
Woven Fabric

AR Glass
Bonded Fabric

Polypropylene (PP)
Knitted Fabric

Anchorage of polymeric based fabrics is the primary advantage for fabrics as reinforcement





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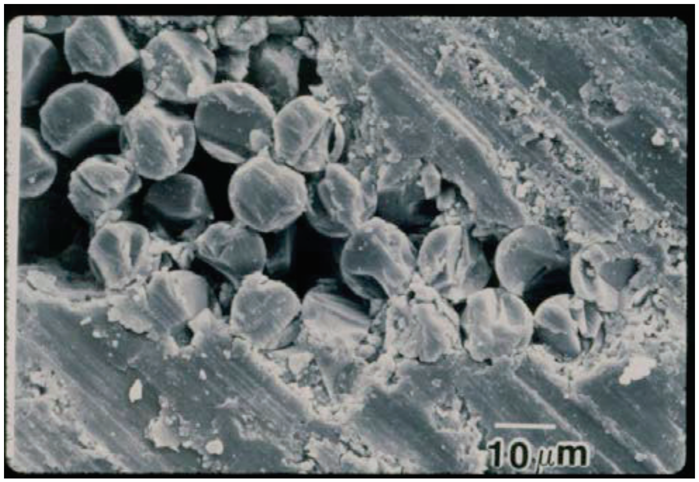
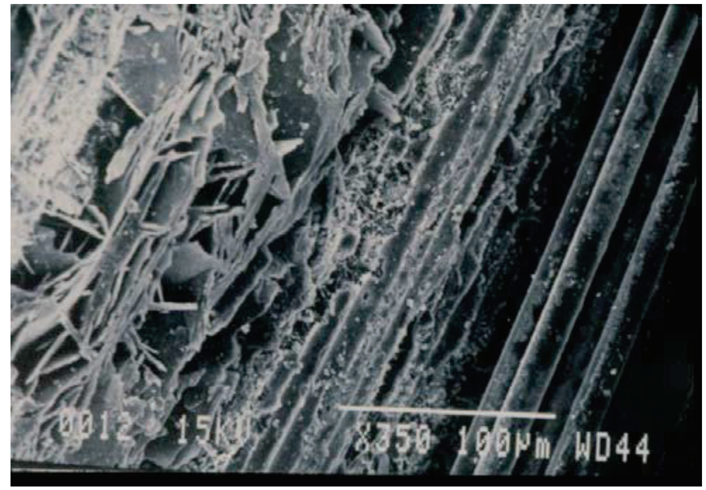
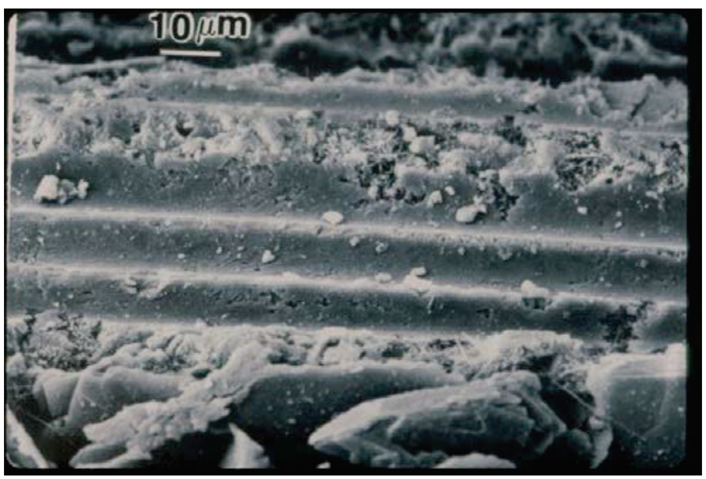
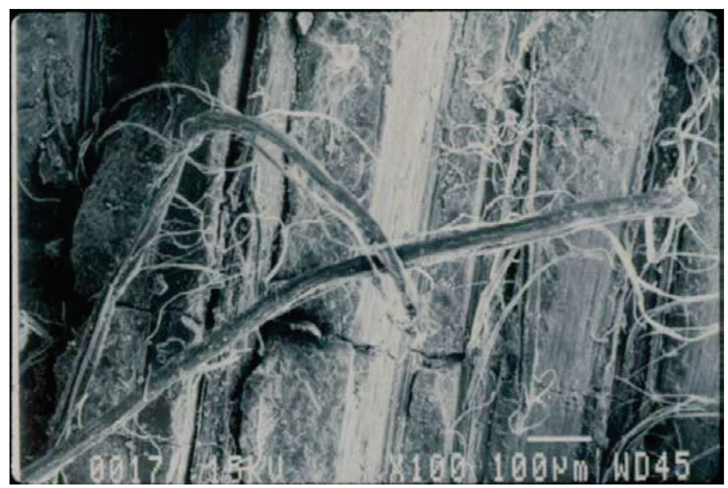
Interface Transition zone









Pultruded Full Size TRC Structural Shapes

Cross section of pultruded shapes with TRC laminates

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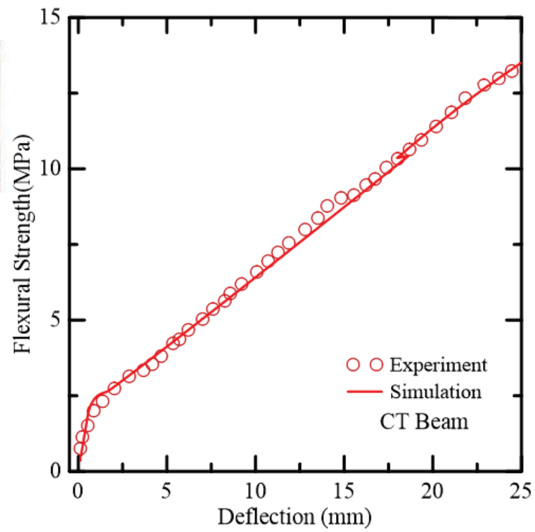
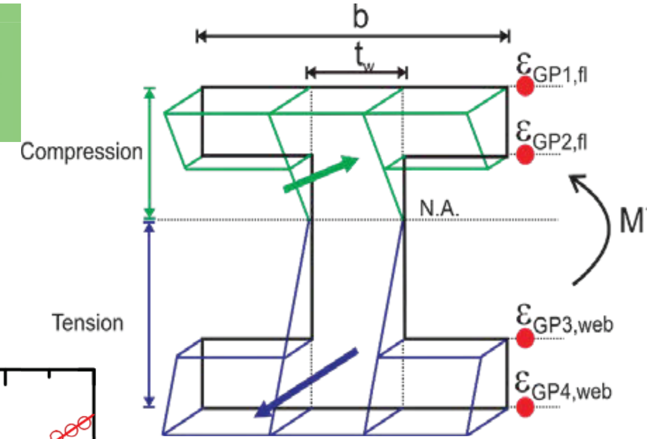
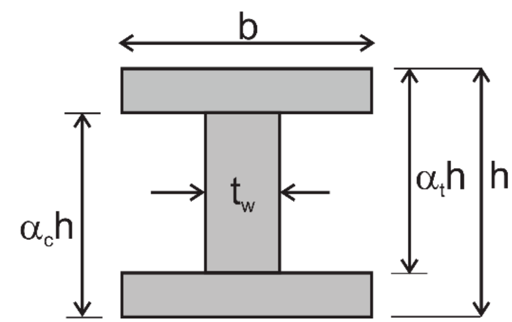
Model Development for FRP and TRC Structural Shapes

- I-section under Four-point bending test
- 80(b) × 180(d) × 1800(L) mm, t_w and t_f =12.5mm
- Textile fabrics: Carbon Textile Reinforcement





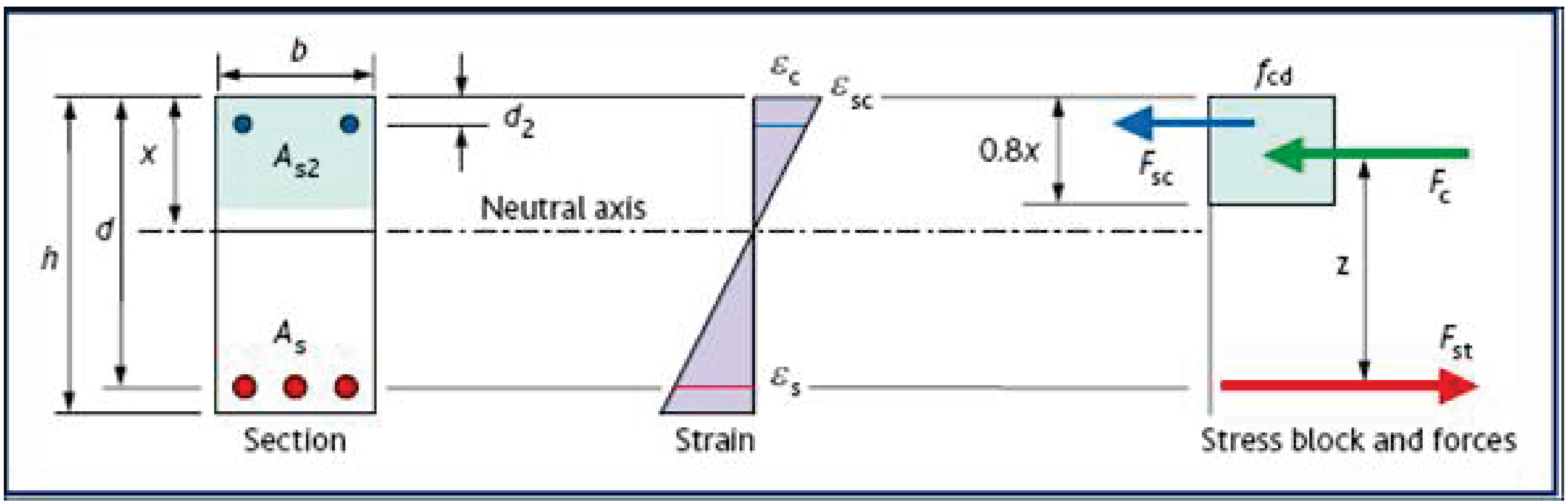


Goliath, K. B., Cardoso, D. C. T. and Silva. 2021, F. A. "Flexural Behavior of Carbon Fiber Textile-Reinforced Concrete I-Section Beams." *ACI*, no. SP-345: Materials, Analysis, Structural Design and Applications of Textile Reinforced Concrete/Fabric Reinforced Cementitious Matrix Correlation: 230–42.

Pleesudjai, C., & Mobasher, B. (2023). Analytical moment-curvature solutions for generalized textile-reinforced concrete sections. *Engineering Structures*, *276*, 115317. https://doi.org/10.1016/j.engstruct.2022.115317

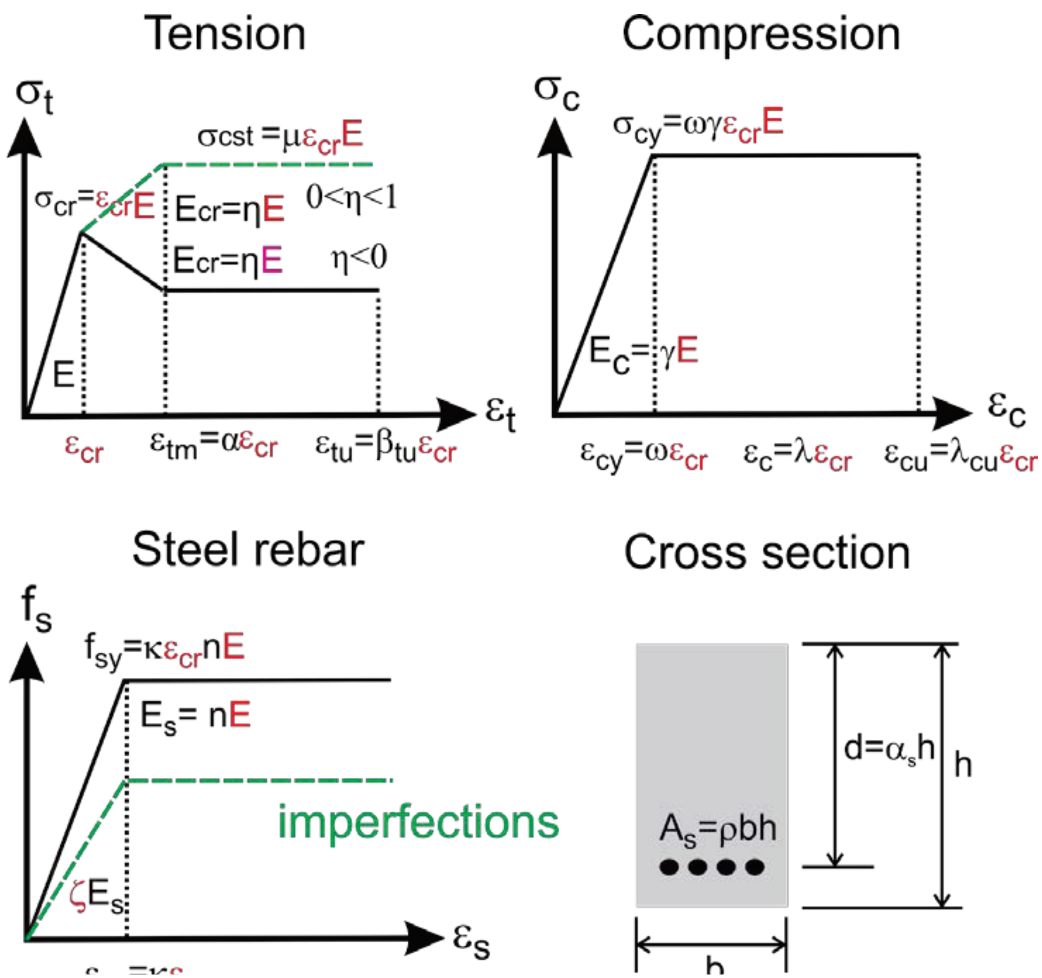
Traditional Flexural design of RC

- Cross-sectional analysis
- Plane section remains plane
- Compression: stress block method
- **Tension: ignored, only steel rebar contributes**
- **Serviceability limit state: ill-defined**
- Ultimate limit state: moment capacity
- Ductility: ratio of ultimate curvature to curvature at steel yielding



New Design Methodologies to account for the contribution of fibers

Parameterized Material Models



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Derivation of Moment-Curvature Relationship

Impose $0 \leq \varepsilon_t \leq \varepsilon_{tu}$

↓

Strain Distribution

Stress Delivery

↓

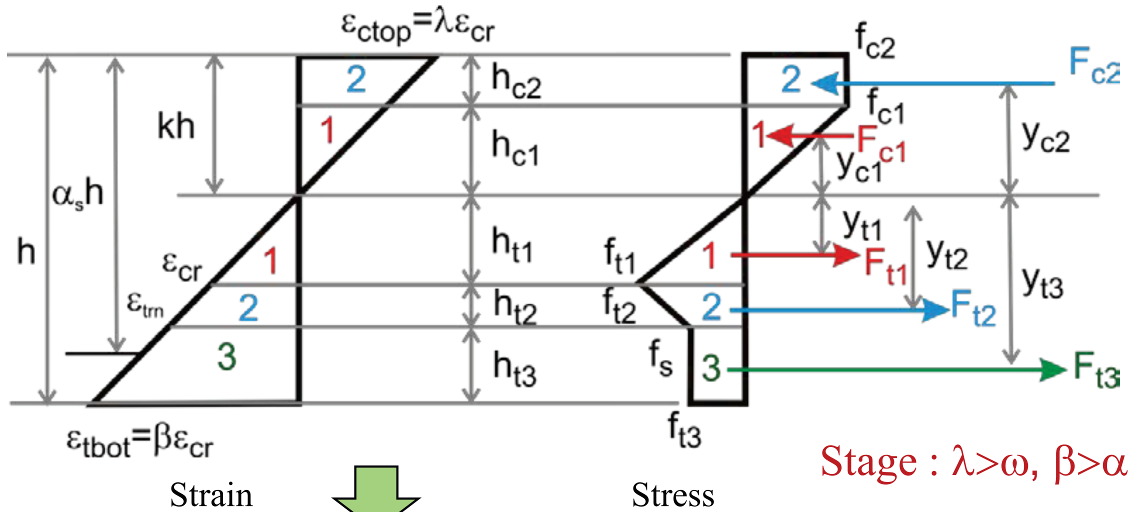
$\Sigma F = 0$, determine k

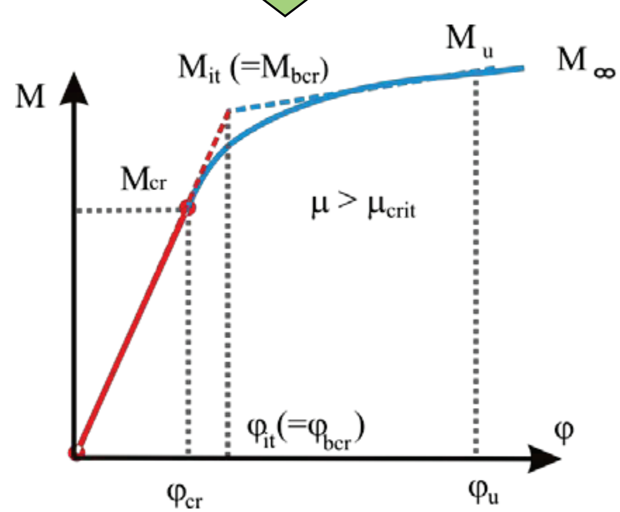
↓

Moment:

$M = \Sigma F_{ci} y_{ci} + \Sigma F_{ti} y_{ti}$

Curvature: $\varphi = \varepsilon_c / kh$





Simplified bilinear moment-curvature

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Stress and Strain Distributions in Different Stages

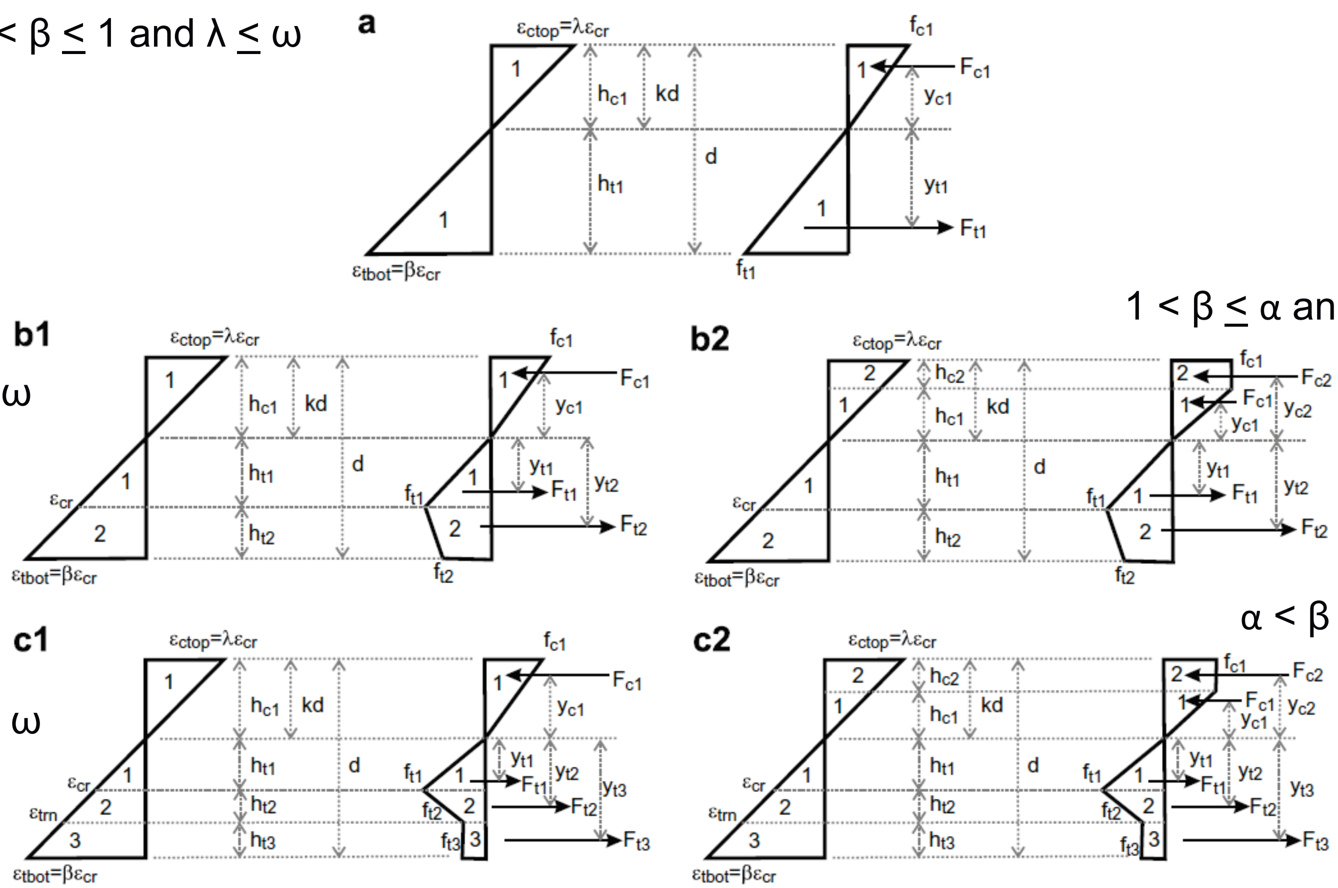
$0 < \beta \leq 1$ and $\lambda \leq \omega$

$1 < \beta \leq \alpha$ and $\lambda \leq \omega$

$1 < \beta \leq \alpha$ and $\lambda > \omega$

$\alpha < \beta \leq \beta_{tu}$ and $\lambda \leq \omega$

$\alpha < \beta \leq \beta_{tu}$ and $\lambda > \omega$



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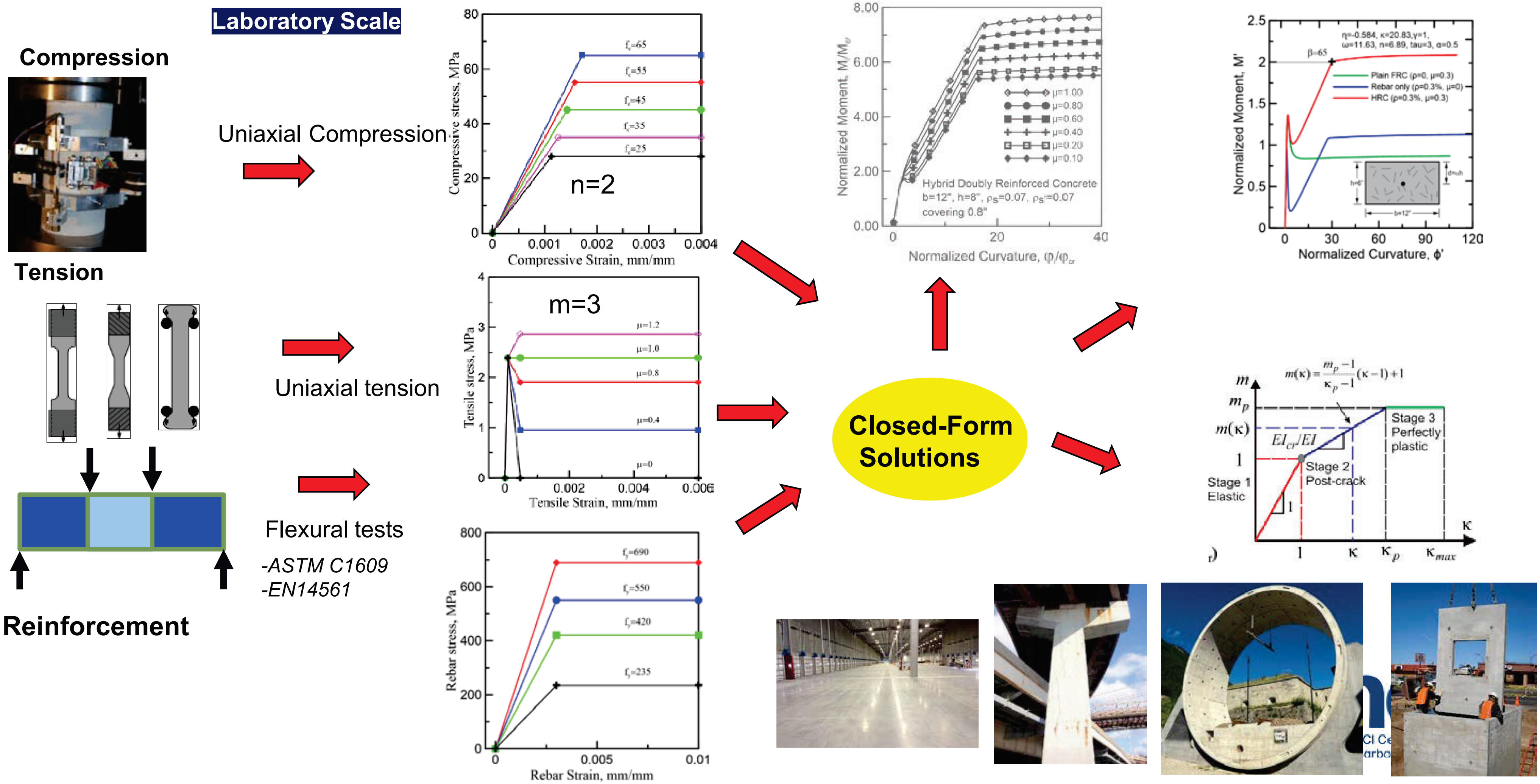
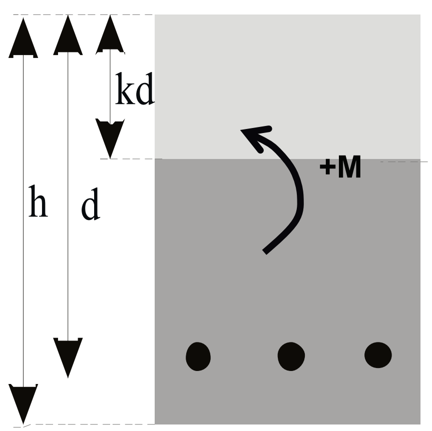
Mechanical Characterization and Design From laboratory to structure scale



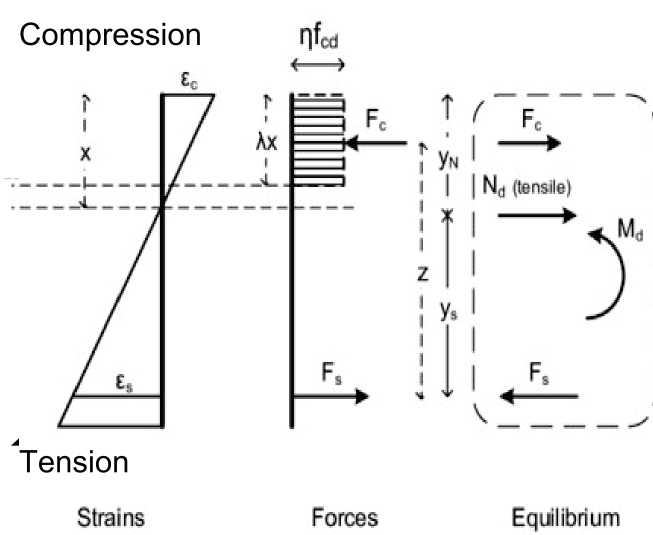
Tensile contribution of FRC to the Hybrid Flexural Response

- Tensile strength of concrete (at 10% of its compressive strength), is ignored in structural calculations
- Steel reinforcement is expected to carry all the tensile loads immediately after concrete cracks
- Can’t fully replace the rebars, but can enhance their contribution significantly
- Efficiency of total concrete volume is in the single digits.

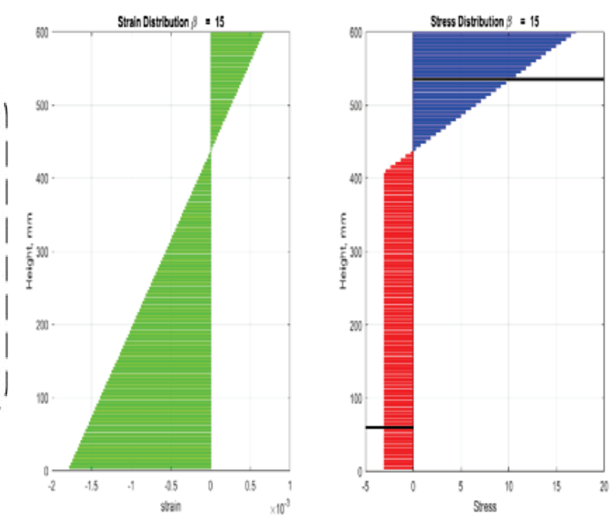
Beam section



Conventional RC



FRC+Rebar=Hybrid RC(HRC)



Soranakom, C., & Mobasher, B. (2008). Correlation of tensile and flexural responses of strain softening and strain hardening cement composites. Cement and Concrete Composites, 30(6), 465–477. https://doi.org/10.1016/j.cemconcomp.2008.01.007

ACI Committee 544.4R. (2018). ACI 544.4 R-18 -Guide to Design with Fiber-Reinforced Concrete.

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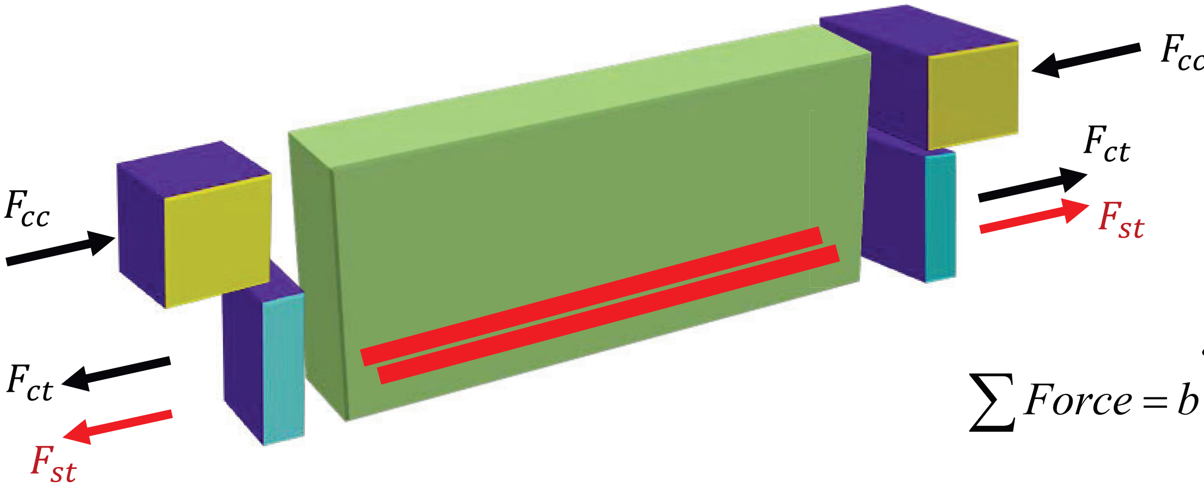
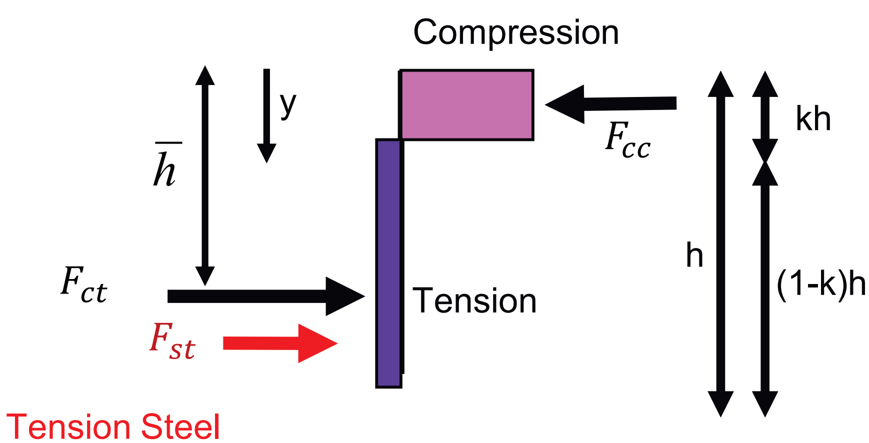
Mean Equivalent Stress distribution in an intermediate stage



$$\sum Force = b\int_0^{\varepsilon_i} \sigma(\varepsilon)\frac{(1-k)h_0}{\beta\varepsilon_{cr}}d\varepsilon = F_{cc}+F_{ct}+F_{st}+F_{sc}=0$$



$$\bar{h} = \frac{b\int_0^{\varepsilon_i} h(\varepsilon)\sigma(x)dh}{\sum F_{ct}} = \frac{\int_0^{\varepsilon_i} h(\varepsilon)\sigma(\varepsilon)\frac{(1-k)h_0}{\beta\varepsilon_{cr}}d\varepsilon}{F_{ct}}$$

$$\sum M = b\int_0^{\varepsilon_i}\sigma(\varepsilon)\frac{y(1-k)h_0}{\beta\varepsilon_{cr}}d\varepsilon = M_{cc}+M_{ct}+M_{st}+M_{sc}=\bar{M}$$

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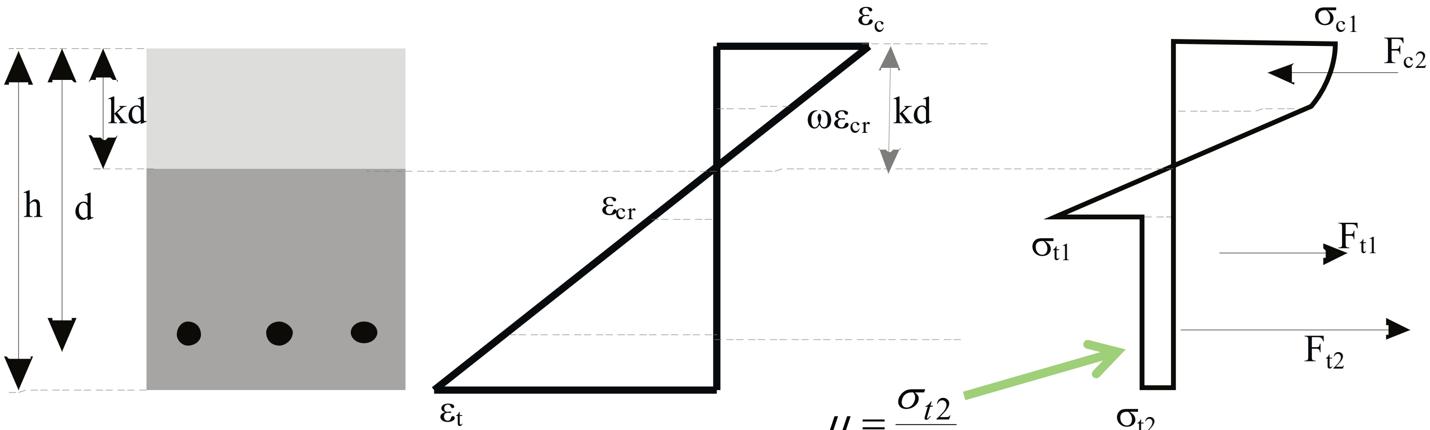
Simplified Design Approach for FRC

- materials model, testing techniques, and design codes
- Simplifies FRC Flexural design assumption for a beam with traditional and fiber reinforcement.
- Use a stress distribution analogous to Whitney's stress block diagram
- Tensile stresses in accordance with stress-strain response applied over the tensile domain
- Integrate to compute the moment capacity



$$\mu = \frac{\sigma_{t2}}{\sigma_{t1}}$$

$$M_{ult} = \left[\frac{\mu\sqrt{f_c'}}{15.55\mu + 2\sqrt{f_c'}}\right] bd^2 E\varepsilon_{cr}$$

tensile stress transmitted by the fibers across the flexural crack. A measure of residual tensile stress strain response.

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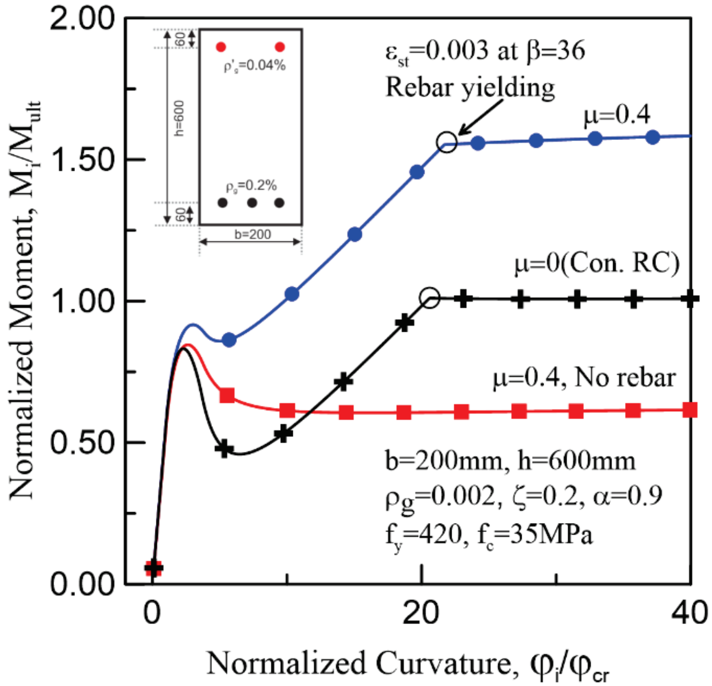
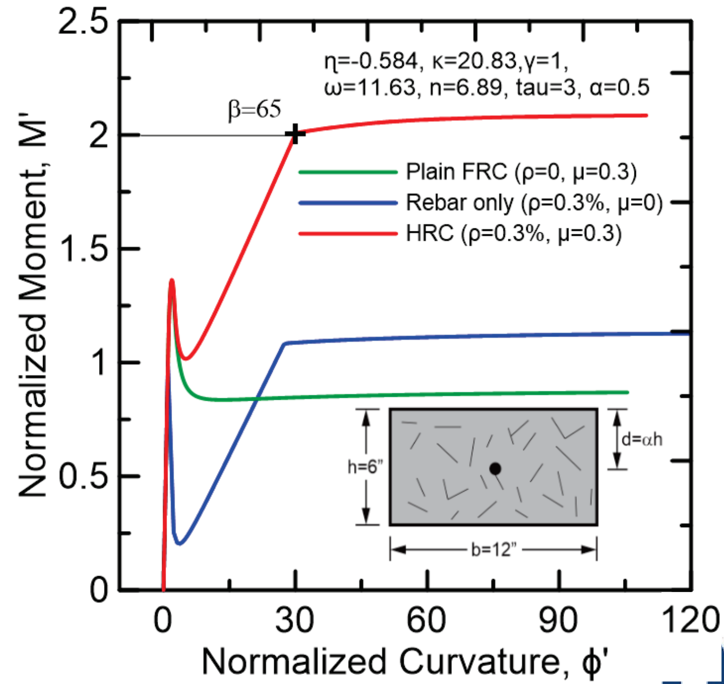
The Hybrid Composite effect

Reinforced concrete beams



Reinforced Slabs



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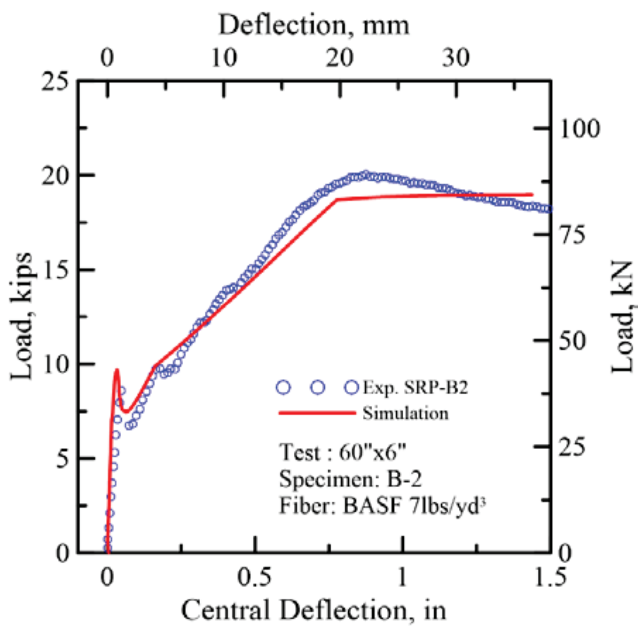
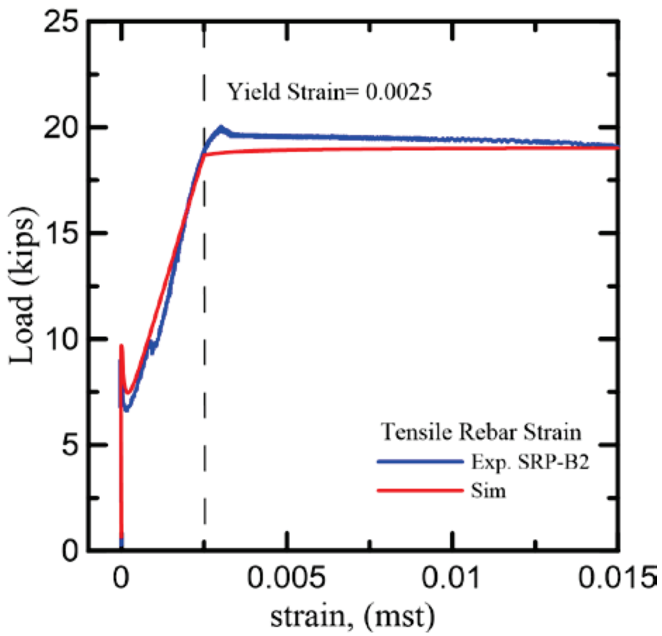
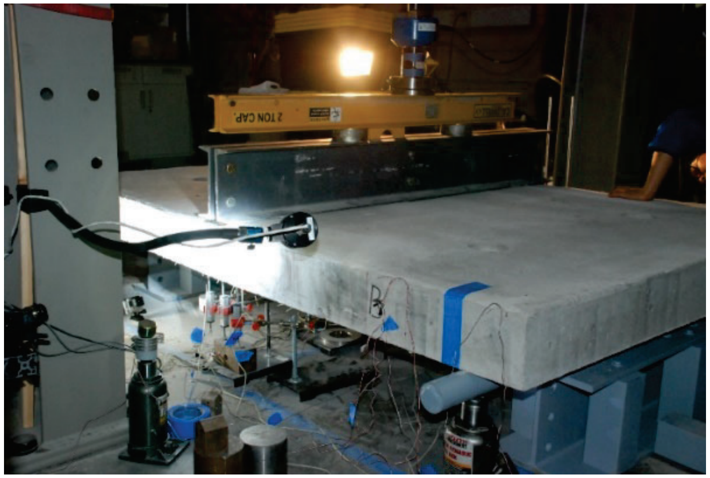
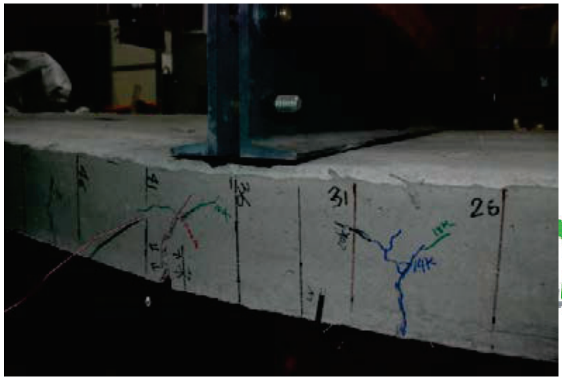
One way slab Experimental and Simulation Comparison of Hybrid Slabs



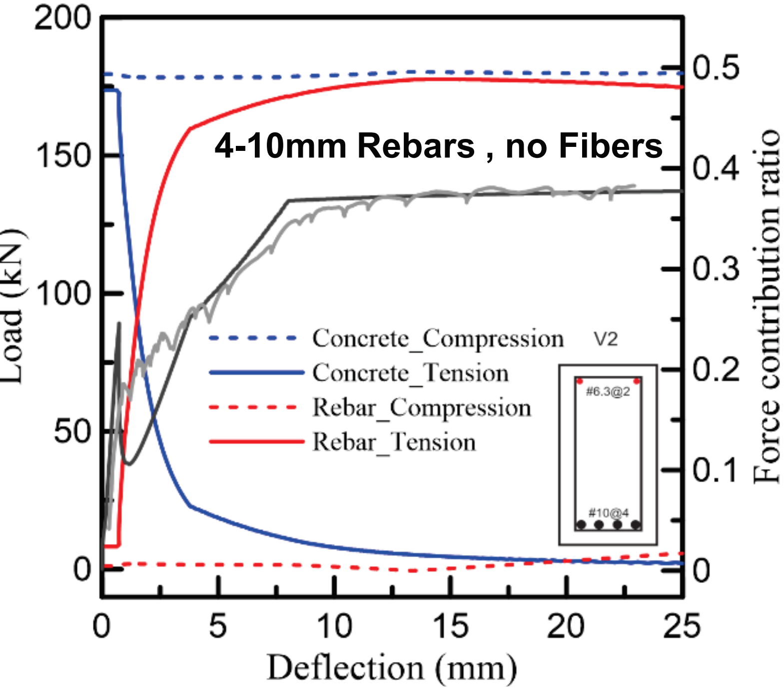


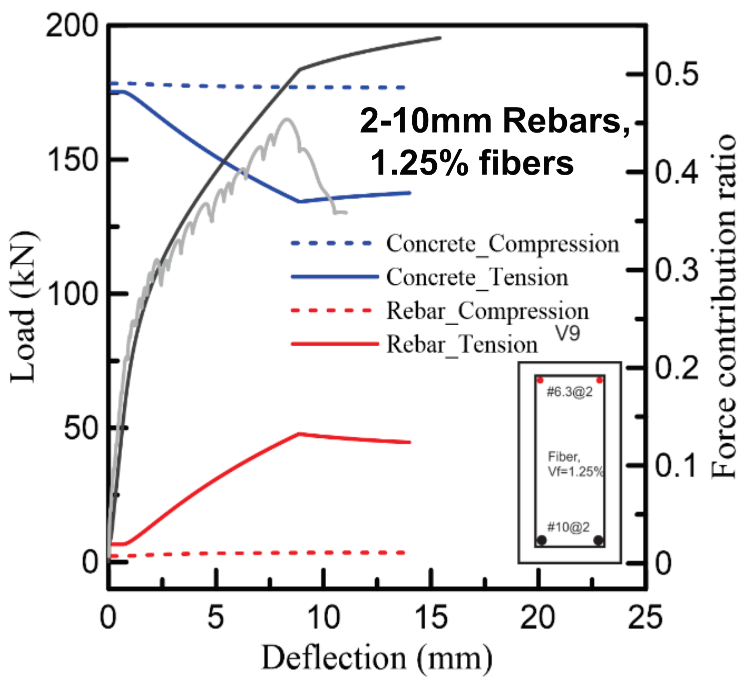




Synergy of fiber and rebar combination as Hybrid Reinforcement

- As soon as post cracking starts, concrete contribution diminishes to less that 10% in plain RC concrete
- With only half the amount of steel in the hybrid system, the rebars in hybrid extend the serviceability range to a higher overall stiffness and extend to twice the deflection range
- Improving the efficiency of the reinforcement in delaying the yielding of steel
- Even after yielding of steel, Concrete in the hybrid system is carrying more than twice the steel





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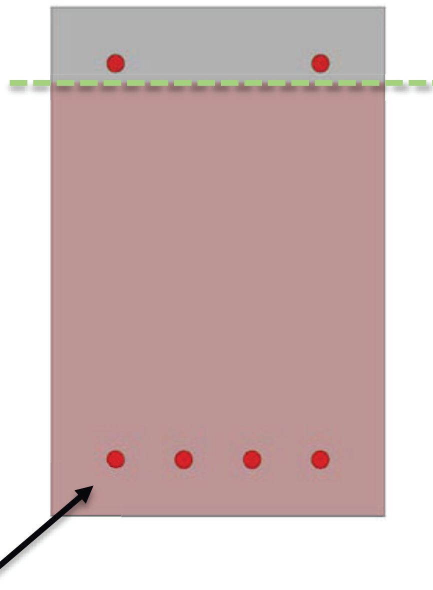
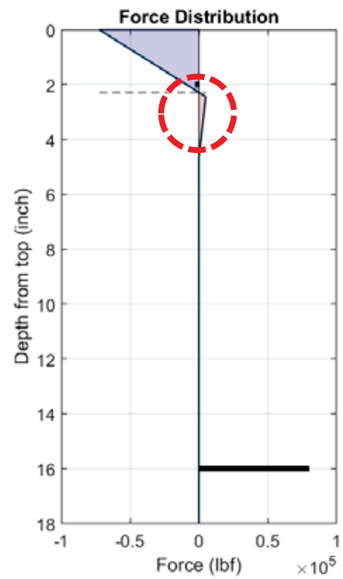
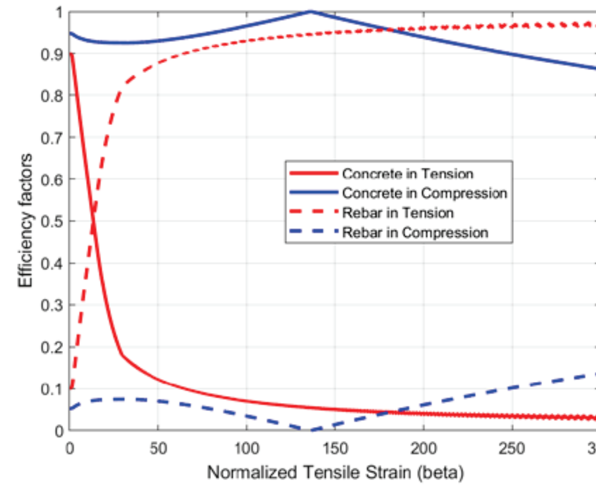
Contribution of Fibers

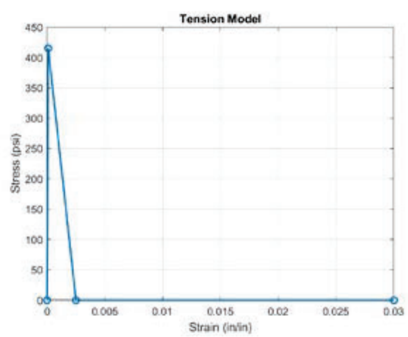
Conventional Beam







No contribution from concrete in Tension



ρ = 0.57%

μ = 0 No residual strength

Size = 12” x 18”

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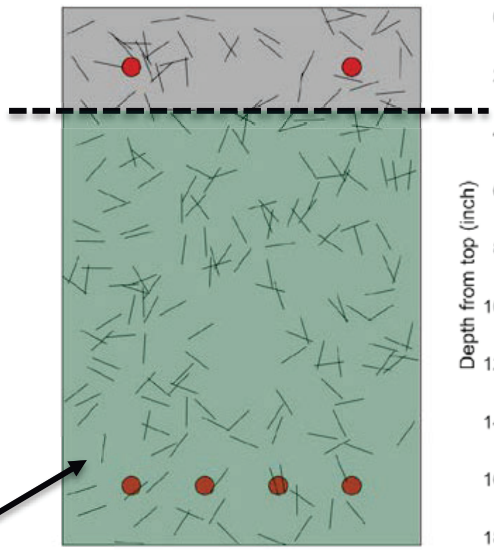
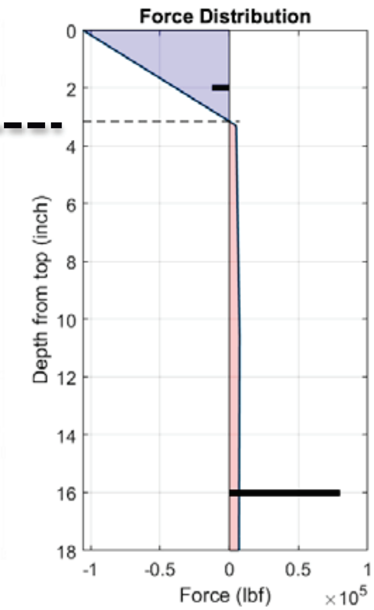
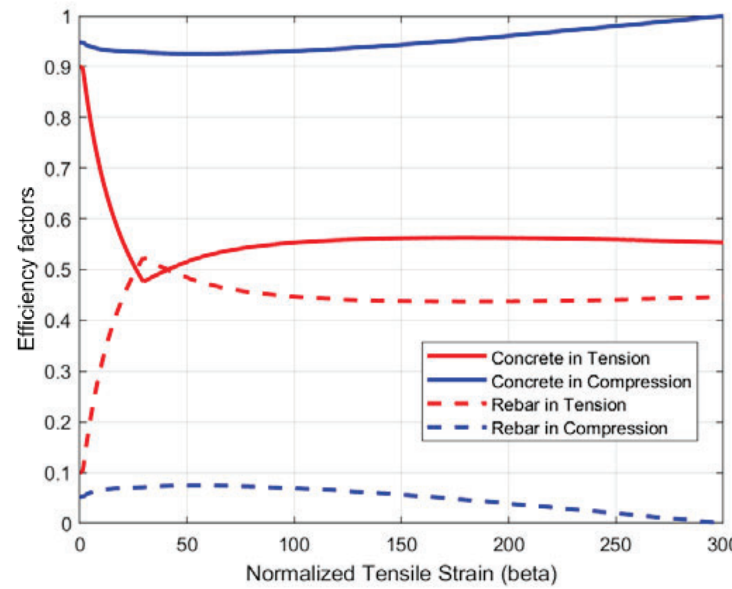
Hybrid Reinforced Section

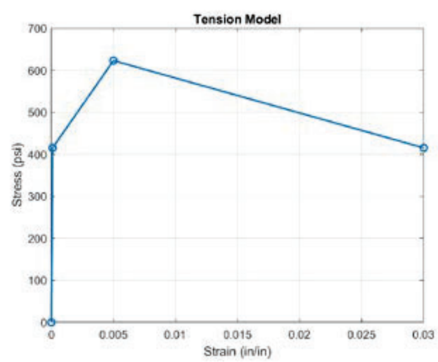
HRC Beam



Concrete in Tension
carrying load







ρ = 0.57%
μ = 1.5 residual strength
Size = 12” x 18”

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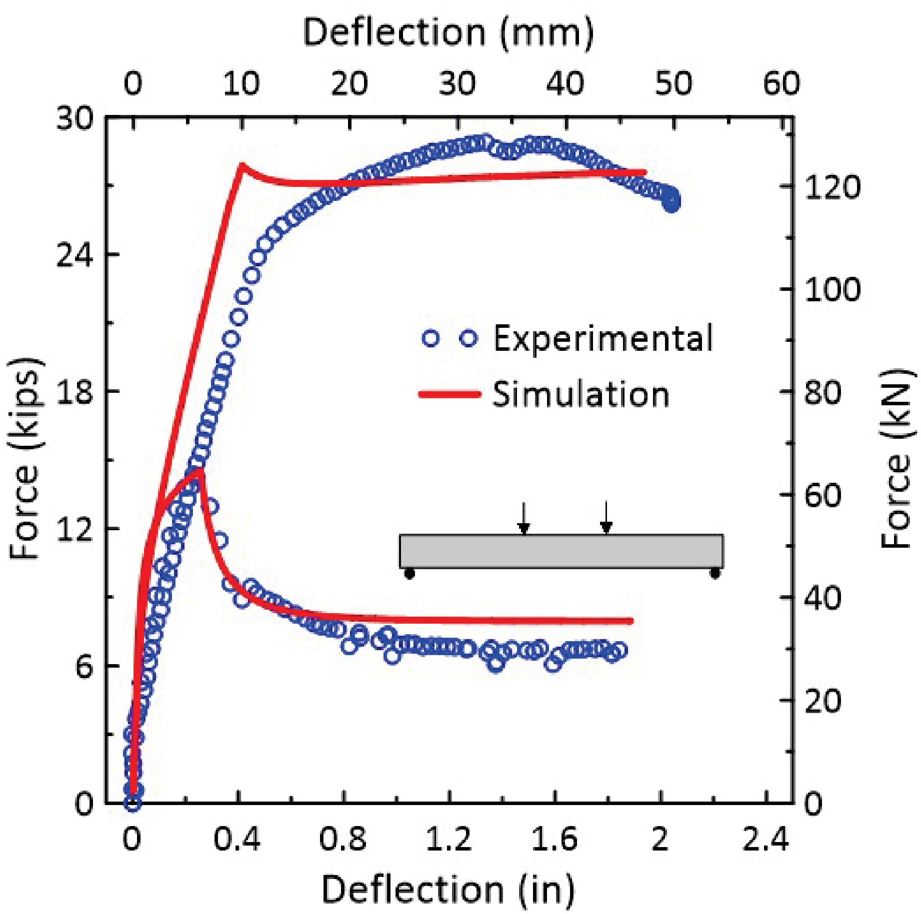
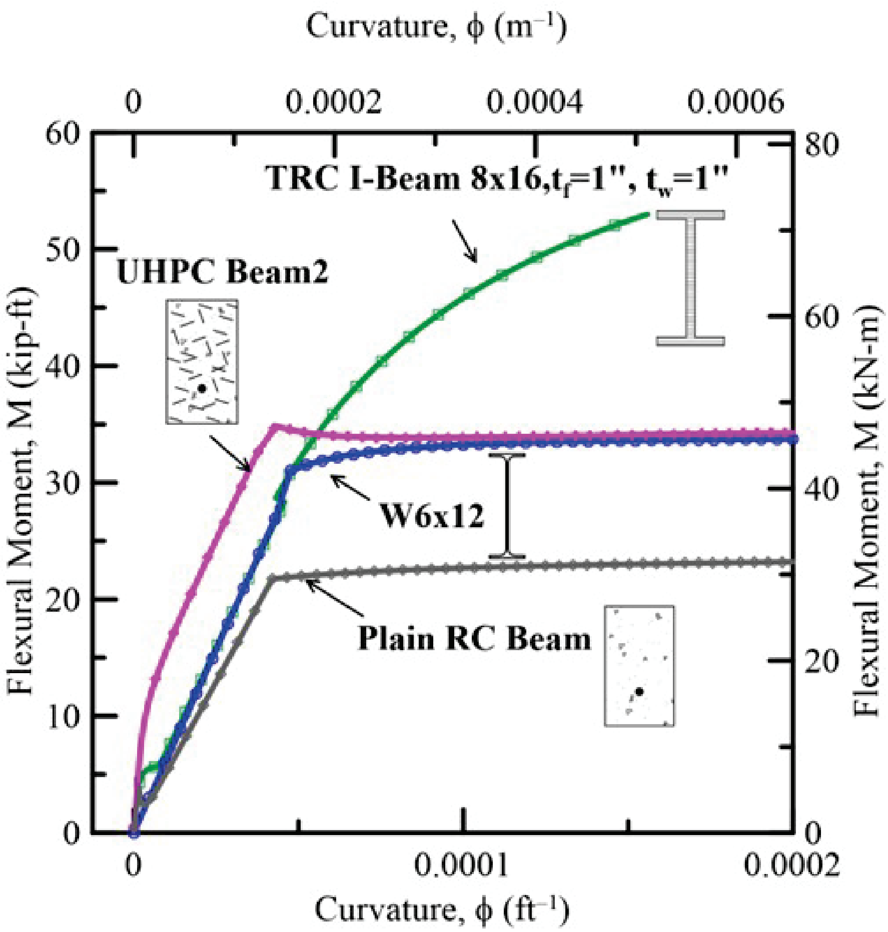
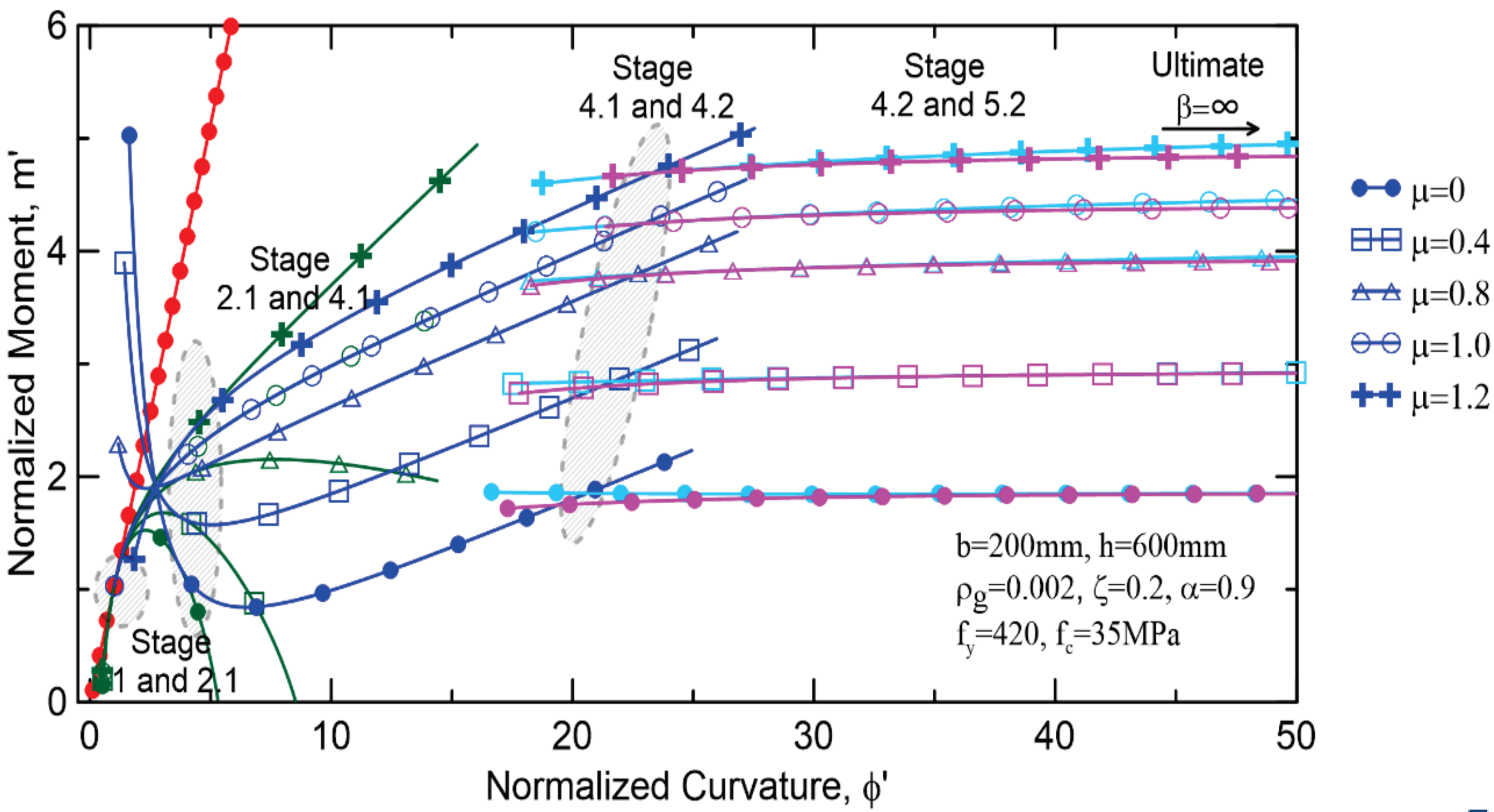
Simulation of UHPC, TRC, Hot rolled Steel, and Conventional RC





Envelope Moment-Curvature



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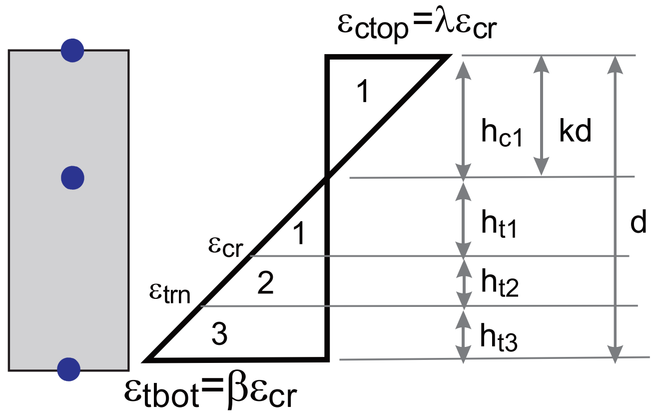
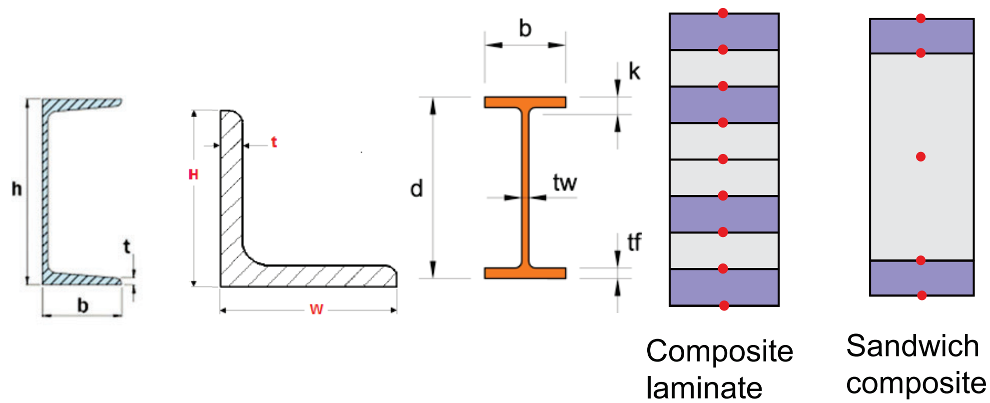
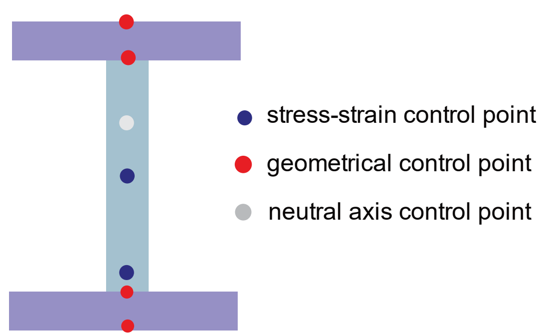
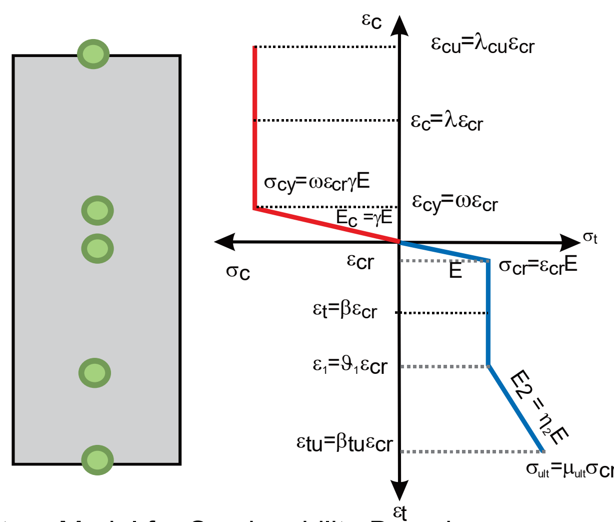
Geometrical and Material Control Points



Rectangular section







Pleesudjai, C., Patel, D., & Mobasher, B. (2023). Generalized Nonlinear Moment–Curvature Model for Serviceability-Based Design of Hybrid Reinforced Concrete. *Journal of Structural Engineering*, *149*(12). https://doi.org/10.1061/JSENDH.STENG-12235

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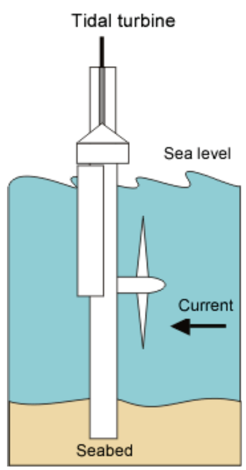
Near-future Opportunities for Supplementary Reinforcement

- Implementation of efficient design equations as the low-hanging fruit
- Need to prove the economics of the effectiveness of supplementary fiber systems
- Analytical tools to justify a blend of Fiber, Rebar, and textile to meet the ductility requirements
- Reduced carbon footprint of steel, carbon, and concrete materials structural design
- Enhanced durability that correlates with potential crack width reduction
- Feasibility of low cost-low mechanical properties (stiffness and strength) use in concrete

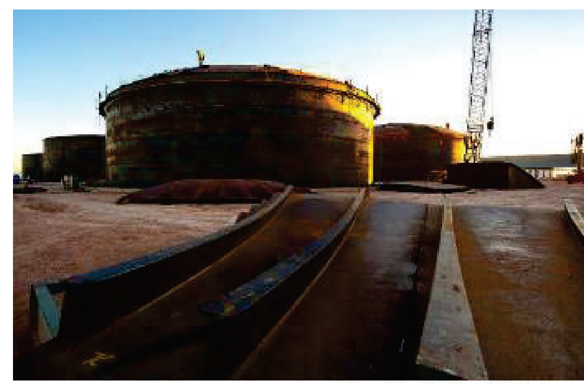
Infrastructure for energy generation requires a robust reinforcement system

- Major renewable energy sources: Solar, Geothermal , Wind energy, Wave and tidal energy converters, Hydropower.
- Marine based infrastructure made with reinforced concrete
- Global Wind Turbine Foundation size $7.1B in 2021, and expected to double by 2028
- 17-30% of the cost of monopole wind turbines is in foundation
- Abengoa Solar molted Salt tank foundation in Gila Bend, AZ,



Floating/ secured wind turbines

Wave generator, HPC *



Molten salt storage 33 times cheaper than lithium-ion batteries

Acknowledgements

- Colleagues, Former and current graduate students
- Narayanan Neithalath (ASU), Subramaniam Rajan (ASU), Alva Peled (BGU), Flavio Silva (PUC), Romildo Toledo Filho (UFRJ), Steve Schaef (MBS), Jimmy Camp and Mozaffor Biswas, (MDOT)
- Yiming Yao, Mehdi Bakhshi, Deju Zhu, Chote Soranakom, Devansh Patel, Chidchanok Pleesudjai, Kenneth Williams, Barbara Ramirez, Jacob Bauchmoyer, Vikram Dey

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Product Categories with Hybrid FRC

- Standard structural section
  - beams, columns, foundations, specialty power generation
- Transportation Structures,
  - bridge decks, superstructure and substructure components, Train platforms, sleepers, vaults, septic tanks, pipes, box culverts
- Precast sections,
  - tunnel lining, buried structures, tilt up Panels, prestressed sections, structural components, barriers, impact & energy absorbing barriers
- Corrosion and Durability management
  - Steel rebar free structures, welded wire mesh applications, temperature and shrinkage reinforcement, environmental structures, lightweight sandwich panels, industrial floor, composite metal deck, loading dock, shotcrete, slope stabilization, and retaining walls
- Textile reinforced concrete
  - structural shapes, W- C- L- Z- shapes , panels, sandwich elements, corrugated sheets

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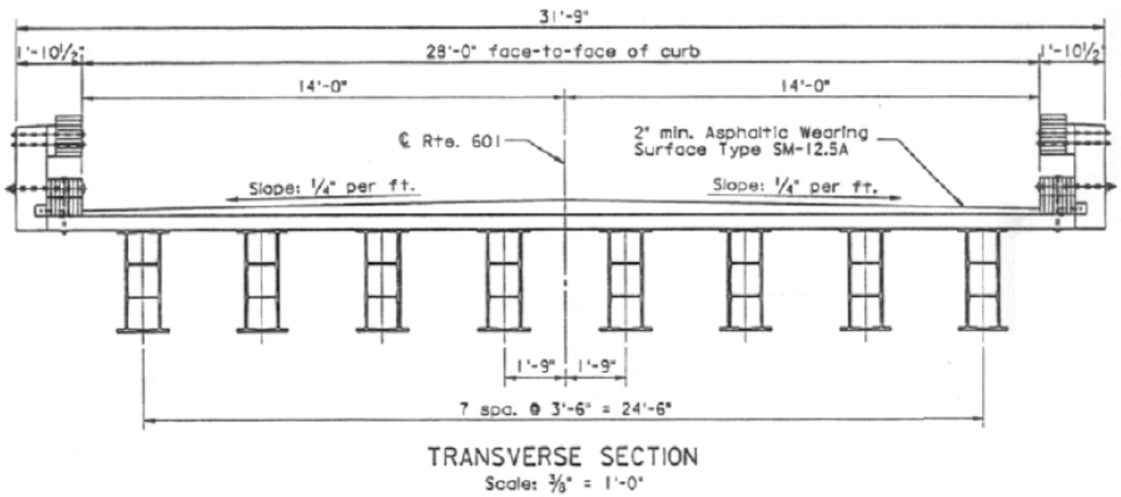
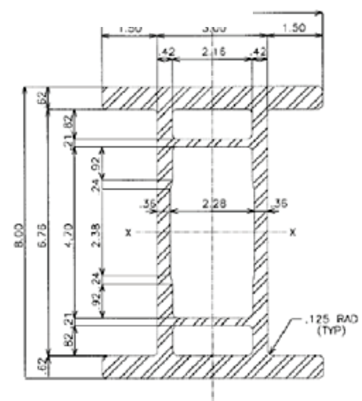
Presentation Overview

- Redefine the efficiency of concrete as a structural material
- Design by quantification of carbon footprint (Specific Strength)
  - Fiber reinforced concrete
    - Applications addressing min. reinforcement
  - Textile reinforced Concrete
    - Repair and New construction applications/ products
  - Hybrid and UHPC Reinforced Concrete
    - Structural design using high volume fibers, Precast, tunnel lining, environmental applications
  - Serviceability based Structural design
    - FRP Systems, GRP rebars and fibers, Structural FRP sections

Closed form Solutions and Simulation of experimentally obtained FRP Structural Sections Double Web beam

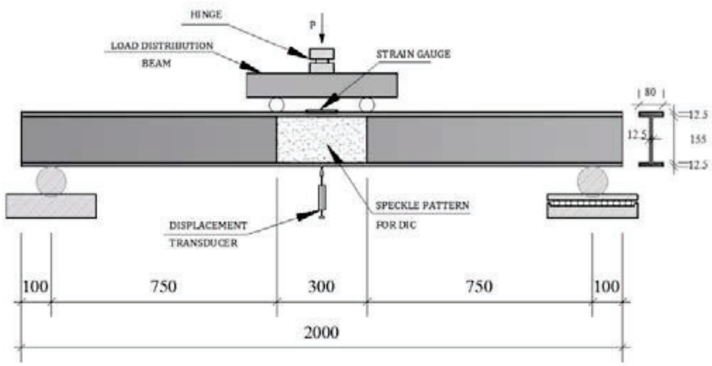
Brown, J., Daewon, K., & Ali, T. (2018). *Bridge Girder Alternatives for Extremely Aggressive Environments*. Daytona Beach, Florida.

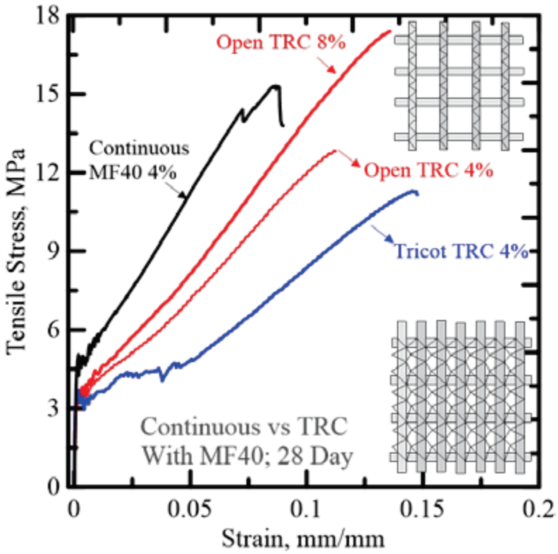




Pultruded FRP bridge girders by Strongwell, Inc. (A) 8"x6" EXTREN DWB

Modeling of TRC W sections





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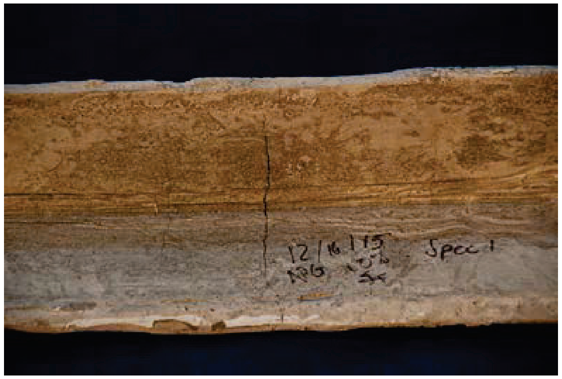
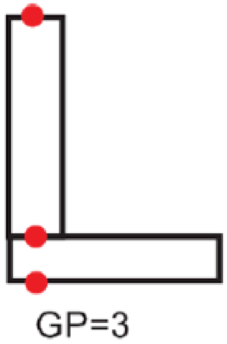
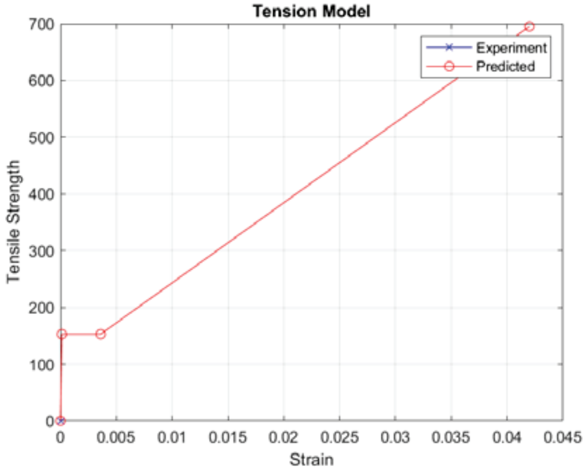
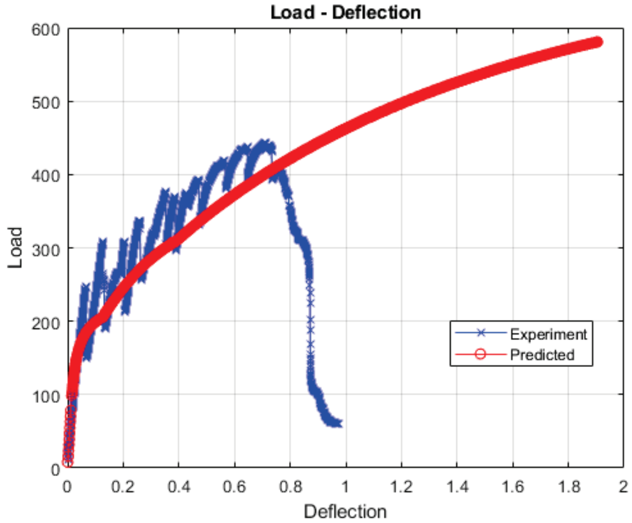
Angles in Flexure









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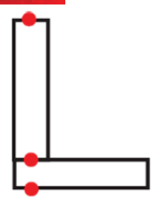
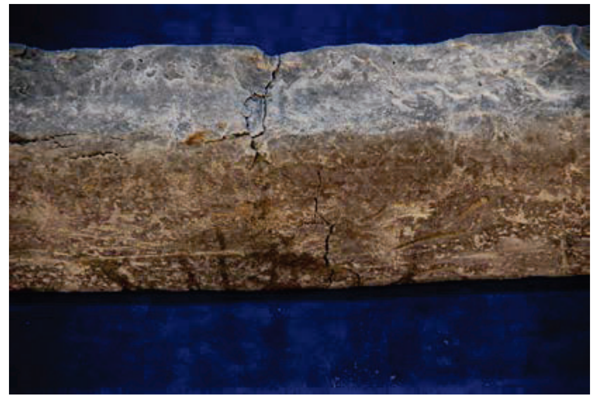
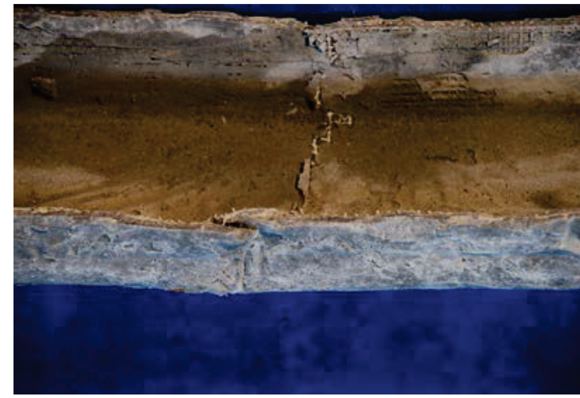
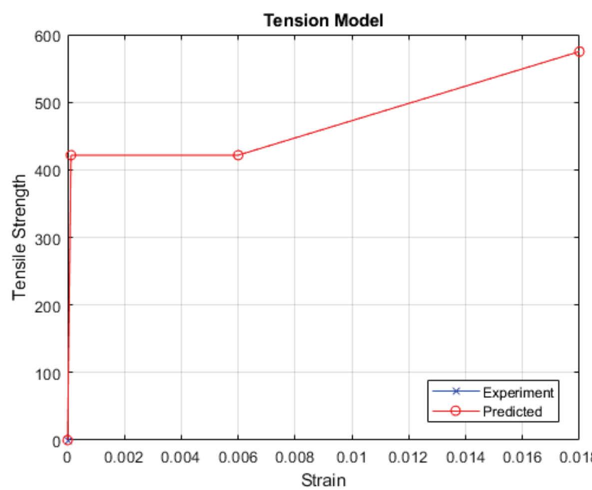
US unit

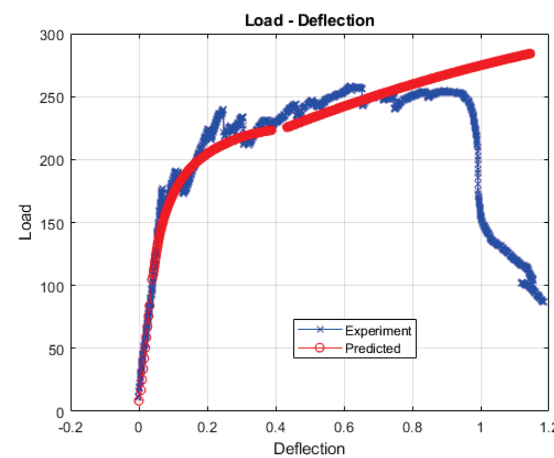
Channel Sections











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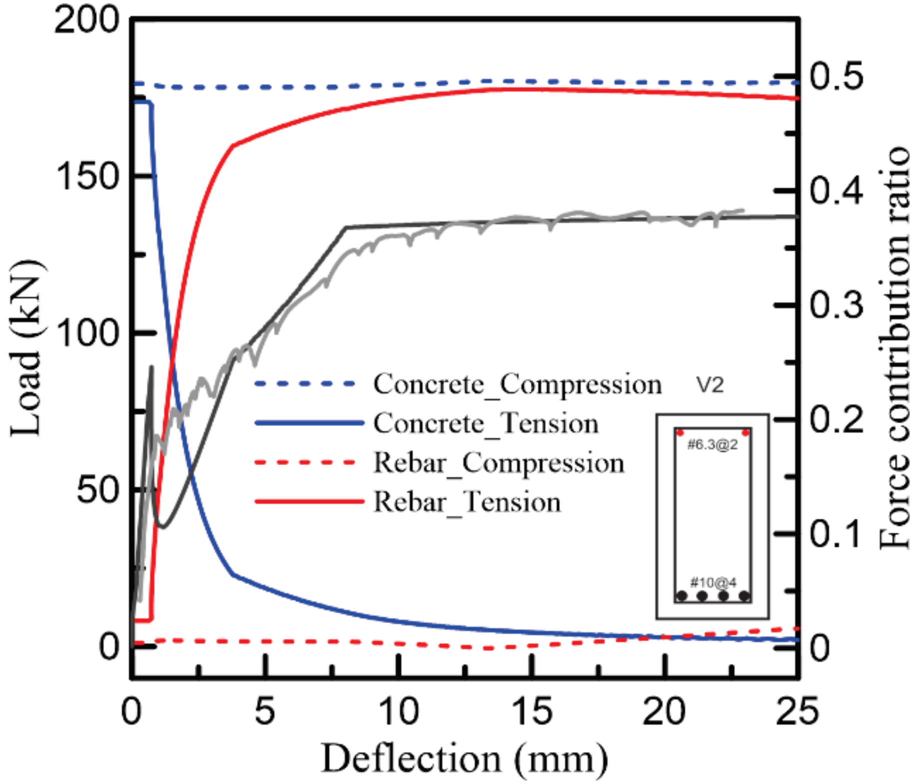
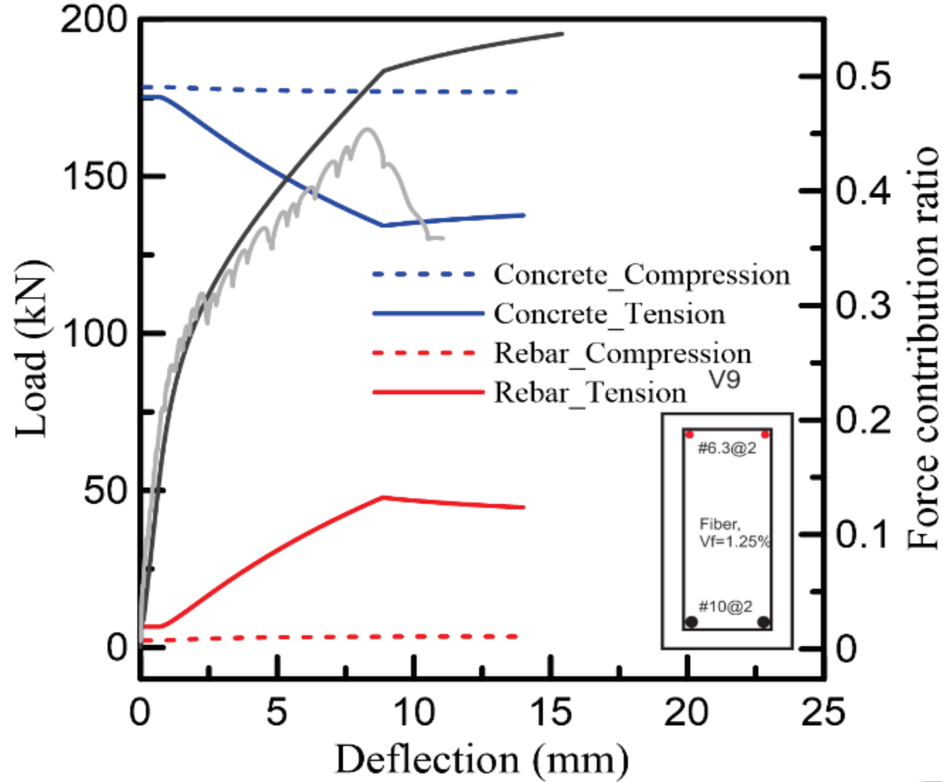
Force distribution in conventional RC and HRC





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Low-Carbon Aspects of Alternative Reinforcement Systems: Fibers, Textiles, and Hybrid-based Design

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