Improving the Efficiency of Concrete Structural Design through Alternative Reinforcement: A Serviceability Based Design Approach

NRMCA-SESSION 21- DECARBONIZATION STRATEGIES

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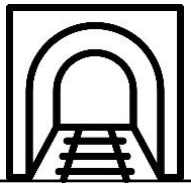
Strategies to increase the efficiency of concrete construction

- Define the efficiency of concrete as a structural material
- How can compressive strength as measure of concrete quality mislead us?
- Tools for quantification of carbon footprint by structural (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, and environmental applications
  - Design Procedures of RC, and FRP Systems
    - Combination of GRP rebars and fibers, Structural sections from Concrete



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

How shall we approach the serviceability design criteria:

1) Status of concrete sustainability and reinforcement strategy
2) Why should our focus on the serviceability criteria?
3) What are the problems with 100-year history of steel and FRP technology?
   a. Domination of steel rebars controlling 99.9% of the market
   b. Cost competitiveness of carbon, Glass, FRP, distributed fibers, 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
5) What is the potential success of low cost-low mechanical properties (stiffness and strength)

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 textiles 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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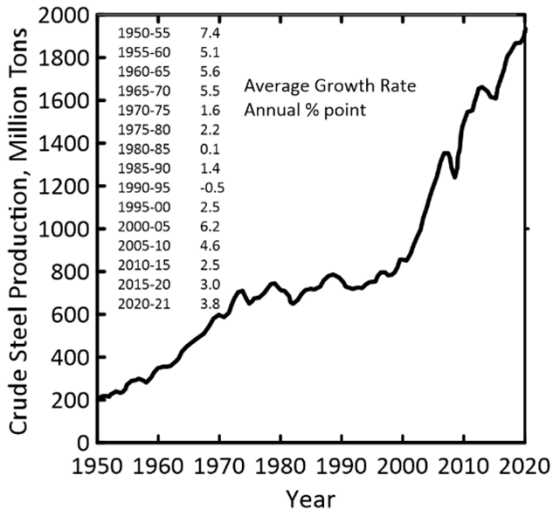
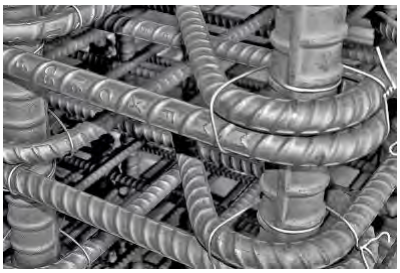
World Production of Steel in the past 70 years

- Since 1990 crude steel production has increased from 800 to 2000 million tons per year.
- 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 the demand.



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

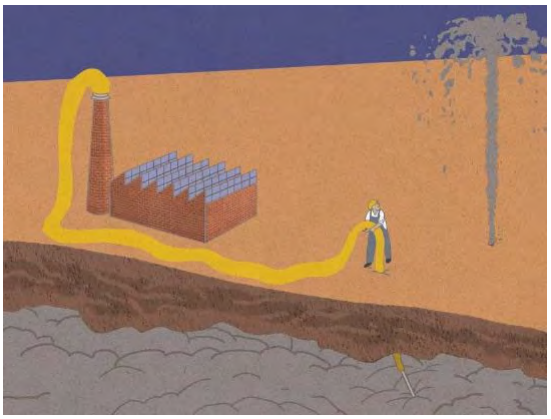
Steel is used in a majority of Concrete applications



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/

Statistics of Concrete Consumption

- Responsible for 4-8% of the world's CO_2 emission,
- Compared to all countries, concrete industry is the third-largest CO_2 emitter
- 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
- Full electrification of cement production can reduce 40% of concrete's CO_2 emissions
- 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
- Amazon and Microsoft have both invested with a goal to sequester 500 million metric tons of carbon dioxide annually by 2030 — equivalent to taking 100 million cars off the road each year.
- Carbon capture and utilization by mineralization of cement has yet to show any promise, proposed CO_2 capture by concrete have yet to yield a meaningful amount. ($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

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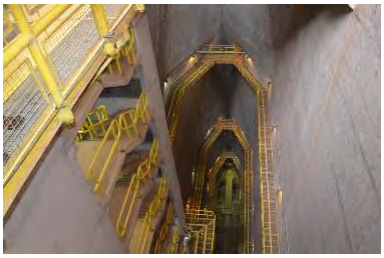
1. Address the Need for efficient Concrete Consumption

- 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.
- 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

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

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

- Actual building and pavement Design and Construction
- Compressive strength is the primary metric used for the quality of concrete. However, it controls many other variables in the Load Resistance Factor Design (LRFD), and durability.
- A change in the design to reduce the volume of the materials will have a cascading effect on all other follow-up costs.

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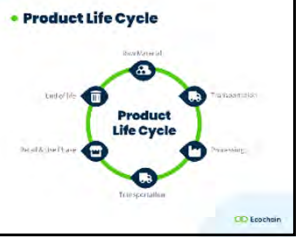
Majority of the focus on the Carbon footprint has concentrated on the Cement production and its use

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

Rebar footprint

Metric	Cost Category	Rebar Share	Direct/indirect cost
Rebar density by building type	a) Heavy industrial b) Commercial c) Institutional	130 kg/m³ 100 kg/m³ 90 kg/m³	Direct
Weight of Rebar by volume of concrete	Average weight for all categories	7.57-10.93 lb/ft³ 120 -175 kg/m³	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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A perspective on the history

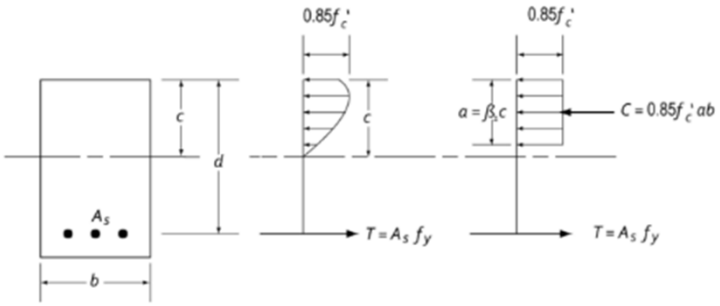
Arch bridge at Châtellerault, France, 1899, Francois Hannebique -1905, Engineer and builder, who patented reinforced-concrete construction in 1892.

Model T, Developed in 1908

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

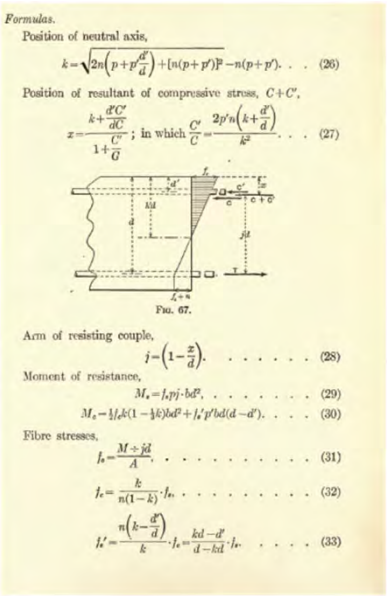
3. Concepts for the structural design are more than 110 years old

- The structural Design of reinforced concrete has been practically unchanged.
- Using 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 covering 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, $C+C'$,

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

Fig. 67.

Arm of resisting couple,

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

Moment of resistance,

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

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

Fibre stresses,

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

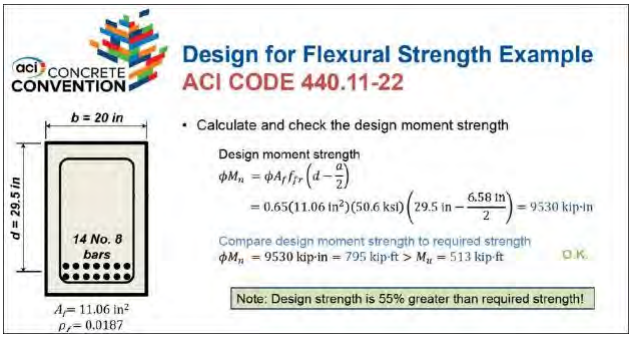
$$f_c = \frac{k}{n(1-k)} \cdot f_s, \quad (32)$$

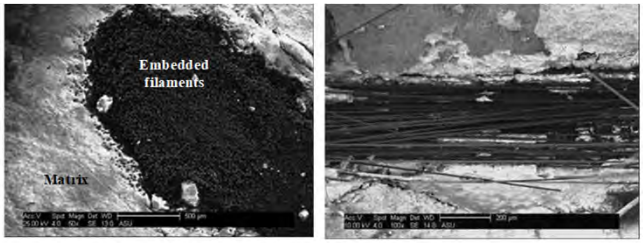
$$f_c' = \frac{n\left(k - \frac{d'}{d}\right)}{k} \cdot f_s = \frac{kd - d'}{d - kd} \cdot f_c. \quad (33)$$

Ultimate Loads formula by Tuneaure 1907

2. Barriers to growth of current FRP technology, Glass, Carbon, Basalt FRP, and Textiles

- UV degradation, fire, moisture, debonding of FRP
- Lack of an integrated approach towards design rules
- Fragmented design of reinforcement for shear, flexure, pullout
- Dominated by the codes developed for the steel How to arrive at a cost competitive carbon fibers,
- Lower stiffness and strength, less polymerized pitch fiber would be applicable
- Reduce, simplify the sizing as compared to the polymeric coatings and matrices
- Stiffness mismatch with the base of FRP rebar
- Design for Ductility
- Definition of market needs
- Lack of inspection, and guidelines for design

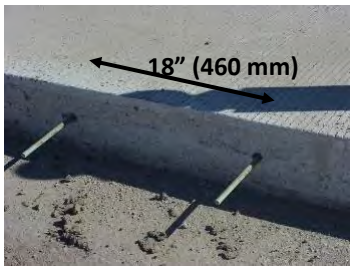




Large size tows reduce the potential for proper bonding and load transfer

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

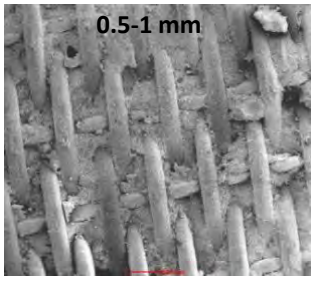


Ordinary reinforced concrete slab, 5-10" thick, standard rebars, 12"-18" apart

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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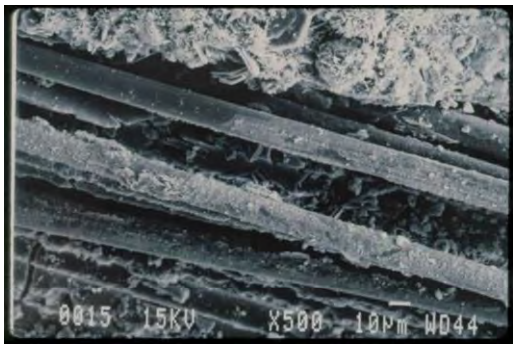
Weak interfaces make ductile and energy absorbing composites

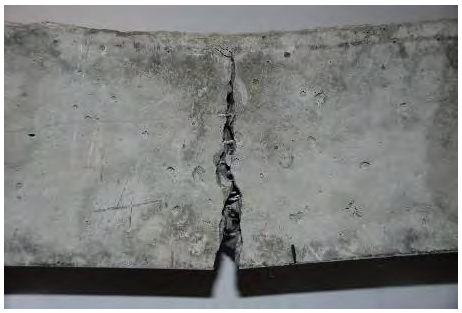
- Three phases, fiber, matrix, and the interface region, the failure of interface is beneficial to many degrees.
- Strong interfaces make very brittle composites, Weaker interfaces make ductile composites
- Five orders of magnitude difference in reinforcement

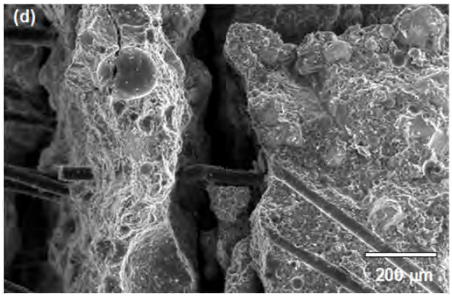


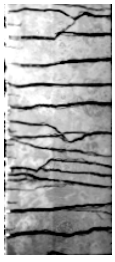
Strong Solids - A. Kelly (Author), N. H. Macmillan, 1987

Fiber toughening - Materials characteristics

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

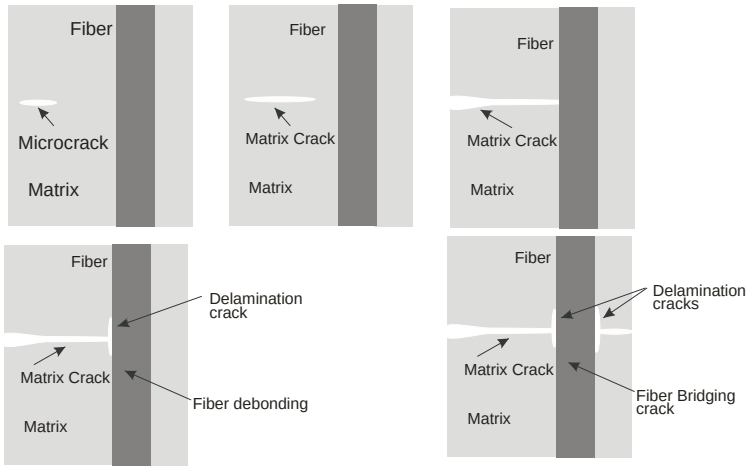




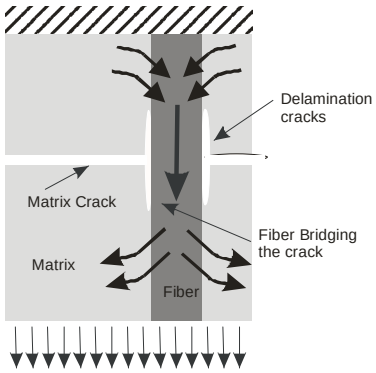


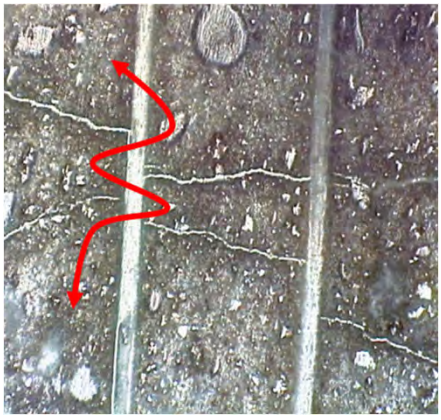
How many mechanisms are operative for toughening Concrete?

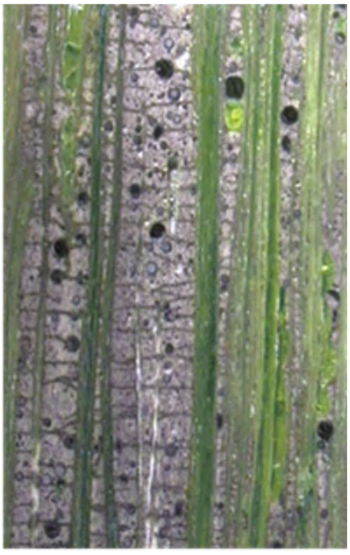
Sequence of cracking from initiation and growth, deflection, Bridging perspective



Tension Stiffening is the Fifth major mode of toughening







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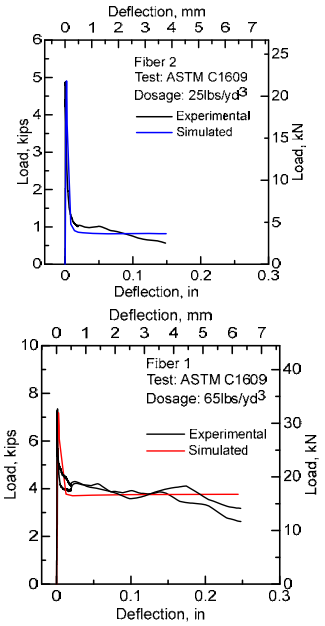
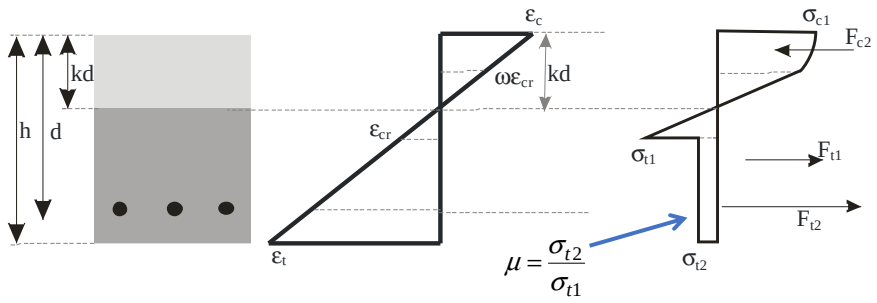
Concept of Residual Strength using Material Property tests



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

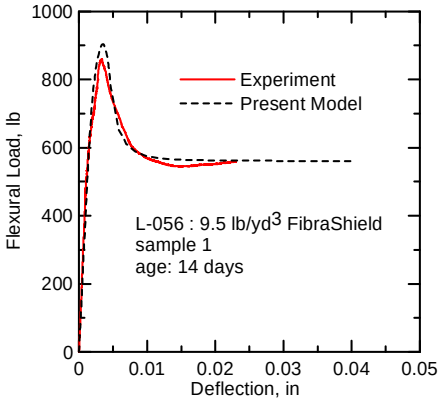


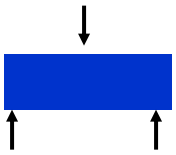
tensile stress transmitted by the fibers across the flexural crack. A measure of residual tensile stress strain response.

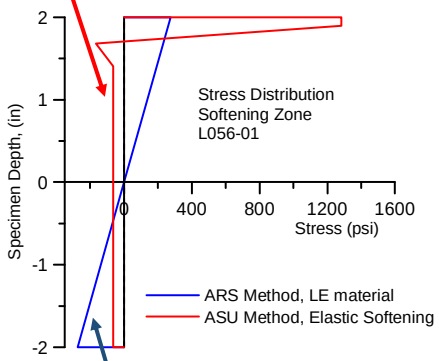
$$M_{ult} = \left[\frac{\mu\sqrt{f_c'}}{15.55\mu + 2\sqrt{f_c'}} \right] bd^2 E\varepsilon_{cr}$$

Stress distribution for a cracked material with Strain-Softening FRC

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







$$\sigma = \frac{Mc}{I} = \frac{3PL}{2bd^2}$$

Fiber Products Database are readily available

Primary Use	Reduce plastic and hardened concrete shrinkage, improve impact strength, marginally increase fatigue resistance, and toughness, incorporation in structural design
Products	Major Fiber Types polymeric and Steel fibers
Product Description	Polypropylene, a polymer consisting of identical monomer units as monofilament or fibrillated fibrous concrete reinforcement. Specified by type, collated fibrillated (network) form and Denier finish content (linear density) per ASTM D7508.
Codes/ Specifications	ASTM, AASHTO, ACI, other specifications
Testing Lab	name, location, Certification status
Additional Information	Technical data sheet provided. Provides comprehensive details regarding product

Test	Results vs. ASTM Limits	ASTM Limits	Check
ASTM C1116	Compliance check		OK
Material	Virgin polypropylene		OK
Specific gravity	0.91-1.0	N/A	OK
Fiber length	0.125” to 2” (3mm to 50 mm)		OK
Tensile strength	Typical 83-96 ksi, or specified/ required		OK
Alkali resistance	Resist deterioration due to moisture, alkalis throughout the anticipated life		OK

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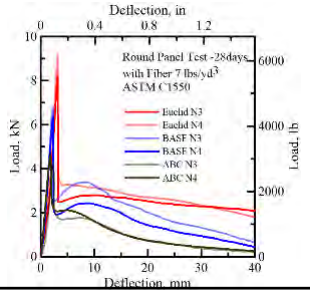
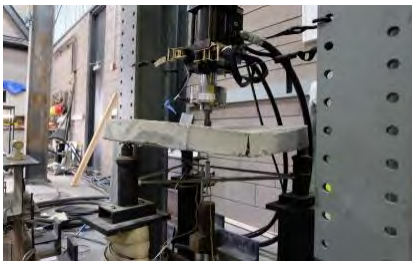
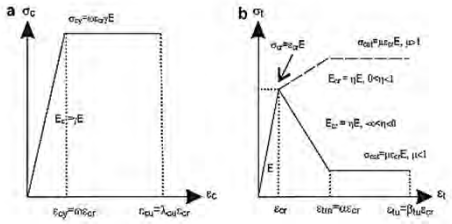
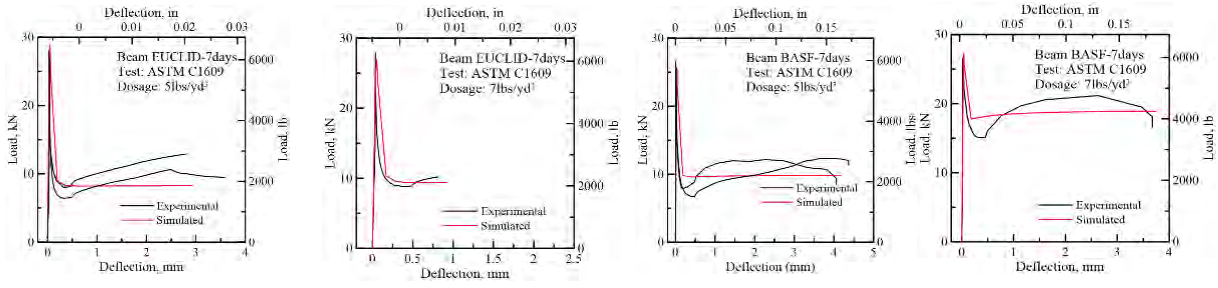
Round Panel tests



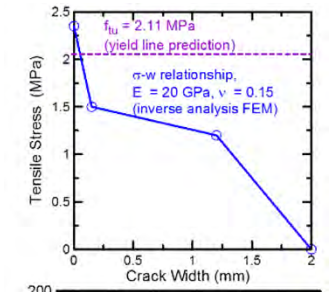


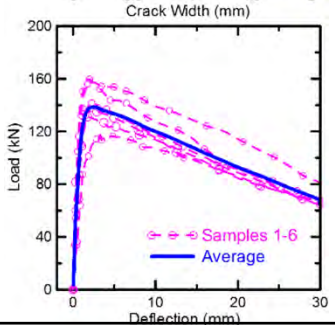
Material Models and Back-calculation

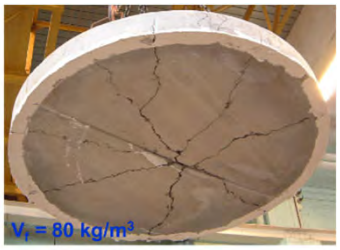


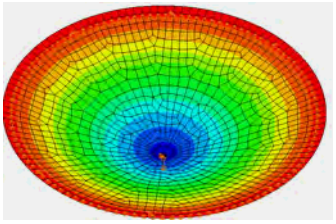


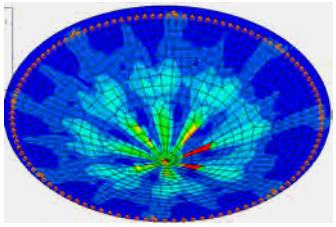
Round Panel Continuous Support Specimens











Rehabilitation of infrastructure

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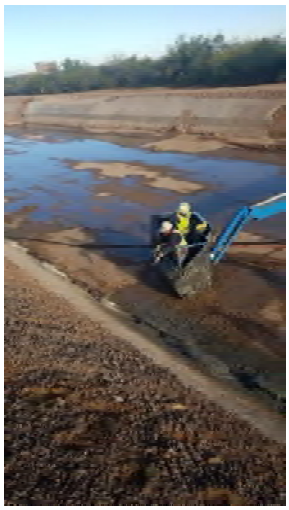
Shotcrete canal lining



New Canal lining, WWF, or rebar replacement

Traditional #5 rebar layout
Photo: Pulice Construction

Fiber Reinforced Concrete Mix
Photo: Pima-Maricopa Irrigation Project, Sacaton, AZ

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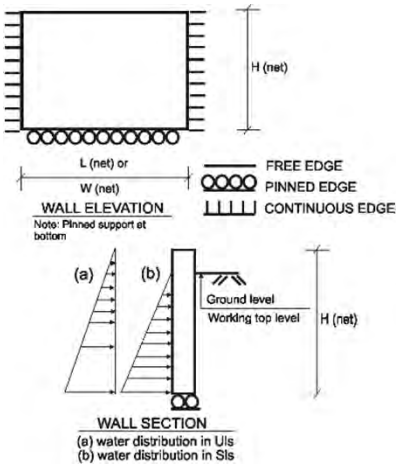
Safety, and Cost savings due to reduced section sizes, labor, mobilization costs, Logistics

Precast Wall Panels

- Assume continuous wall, pin connection at the bottom and free at the top
- Lateral water pressure in ultimate and serviceability limit states



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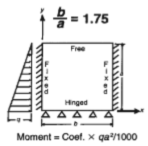
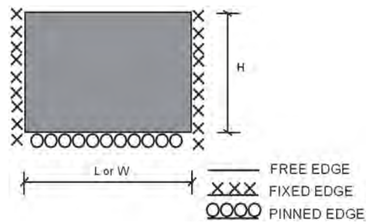
Structural analysis of the Panels using PCA method

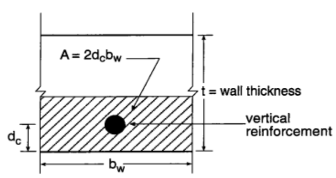


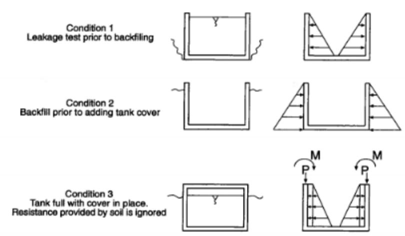
M_x	END	0.1b / 0.9b	0.2b / 0.8b	0.3b / 0.7b	0.4b / 0.6b	0.5b
TOP	-12	0	0	0	0	0
0.9a	-15	-5	0	2	4	4
0.8a	-15	-6	1	6	9	10
0.7a	-15	-5	4	11	15	16
0.6a	-15	-4	7	16	21	22
0.5a	-15	-2	11	20	26	28
0.4a	-15	0	14	24	30	32
0.3a	-13	2	16	25	30	32
0.2a	-10	4	16	23	27	28
0.1a	-6	4	11	15	17	18
BOT.	0	0	0	0	0	0

M_y	END	0.1b / 0.9b	0.2b / 0.8b	0.3b / 0.7b	0.4b / 0.6b	0.5b
TOP	-58	-36	-4	19	33	37
0.9a	-75	-34	-3	19	32	36
0.8a	-75	-33	-1	20	32	36
0.7a	-77	-31	0	20	32	35
0.6a	-77	-29	2	21	31	34
0.5a	-77	-26	4	21	30	32
0.4a	-73	-21	6	20	27	29
0.3a	-65	-16	6	18	23	25
0.2a	-51	-10	6	14	17	18
0.1a	-30	-5	4	8	10	10
BOT.	0	0	0	0	0	0

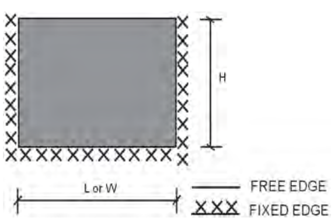
M_{xy}	END	0.1b / 0.9b	0.2b / 0.8b	0.3b / 0.7b	0.4b / 0.6b	0.5b
TOP	0	2	4	5	3	0
0.9a	0	0	3	3	2	0
0.8a	0	0	2	3	2	0
0.7a	0	1	3	4	3	0
0.6a	0	2	5	5	3	0
0.5a	0	4	8	8	5	0
0.4a	0	8	11	10	6	0
0.3a	0	12	15	13	7	0
0.2a	0	16	19	15	8	0
0.1a	0	20	22	17	9	0
BOT.	0	21	23	18	10	0







magnitude of moment in x & y axis using PCA method

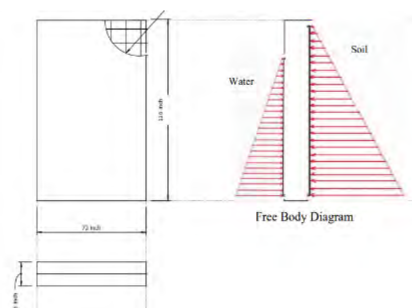


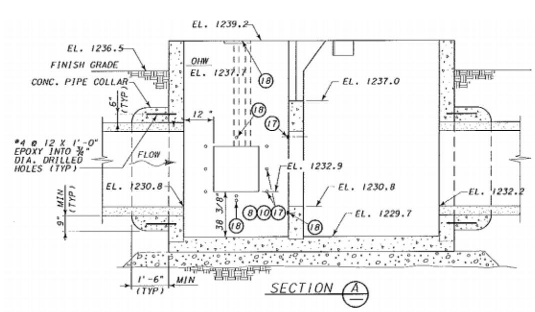
M_x (lb-in/in)

0	-125	-499	-748	-997	-1122	-1246	-1246	-1371	-1371	-1246
-1994	-748	-125	125	125	0	-125	-374	-499	-374	0
-4985	-2119	-374	499	872	997	748	499	249	0	0
-7353	-3365	-872	623	1371	1620	1496	1122	623	249	0
-8724	-4237	-1246	623	1620	1869	1869	1496	997	499	0
-9098	-4487	-1371	499	1620	1994	1994	1620	997	499	0
-8724	-4237	-1246	623	1620	1869	1869	1496	997	499	0
-7353	-3365	-872	623	1371	1620	1496	1122	623	249	0
-4985	-2119	-374	499	872	997	748	499	249	0	0
-1994	-748	-125	125	125	0	-125	-374	-499	-374	0
0	-125	-499	-748	-997	-1122	-1246	-1246	-1371	-1371	-1246

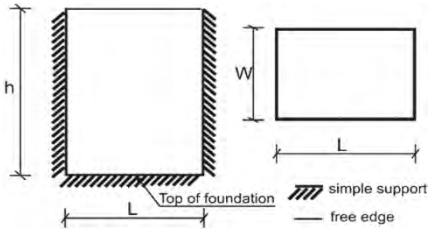
M_y (lb-in/in)

0	-748	-2368	-3864	-4985	-5858	-6231	-6481	-6730	-6855	-5982
-374	-249	-374	-748	-1246	-1620	-1994	-2368	-2617	-2866	-3116
-997	-374	125	374	499	499	374	249	125	0	-125
-1496	-499	249	872	1246	1496	1620	1745	1745	1745	1745
-1745	-748	125	997	1496	1994	2243	2493	2617	2742	2866
-1869	-748	125	997	1620	2119	2493	2742	2866	2991	3116
-1745	-748	125	997	1496	1994	2243	2493	2617	2742	2866
-1496	-499	249	872	1246	1496	1620	1745	1745	1745	1745
-997	-374	125	374	499	499	374	249	125	0	-125
-374	-249	-374	-748	-1246	-1620	-1994	-2368	-2617	-2866	-3116
0	-748	-2368	-3864	-4985	-5858	-6231	-6481	-6730	-6855	-5982





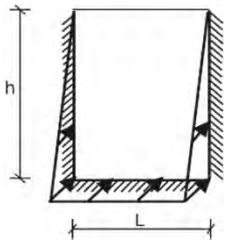
Limit Analysis Approach

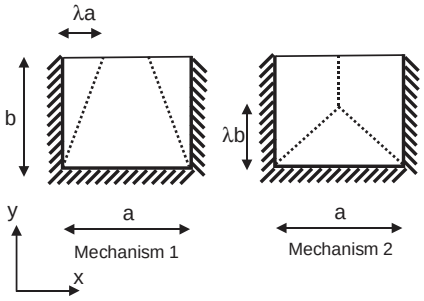


$$m = \frac{qh^2}{12}\left(\sqrt{\frac{9L^2}{4h^2}+1}\ -1\right)$$ Demand Equation

$$M_n = \left[\frac{6\mu\sqrt{f_c'}}{\xi\mu+2\sqrt{f_c'}}\right]M_{cr}$$ Capacity Equation

ξ = 15.8 for U.S. units; ξ = 1.32 for SI





ACI-related International Committee Reports

ACI 544.5R-10 “Physical Properties and Durability of Fiber-Reinforced Concrete,” Report, ACI Committee, p. 31, (2010).

ACI 544.6R-15 Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs (2015)

ACI 544.7R-16 Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments (2016)

ACI 544.8R-16: Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete (FRC), ACI Committee 544 ACI 544.8R (2016)

ACI 544.9R-17: Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete, (2017)
https://www.concrete.org/Portals/0/Files/PDF/Previews/544.9R-17_preview.pdf

ACI 544.10R-17: Report on Measuring Properties of Fresh Fiber-Reinforced Concrete, (2018)

ACI 544-4R ACI 544.4R-18: Report on Structural Design with Fiber-Reinforced Concrete (2018)

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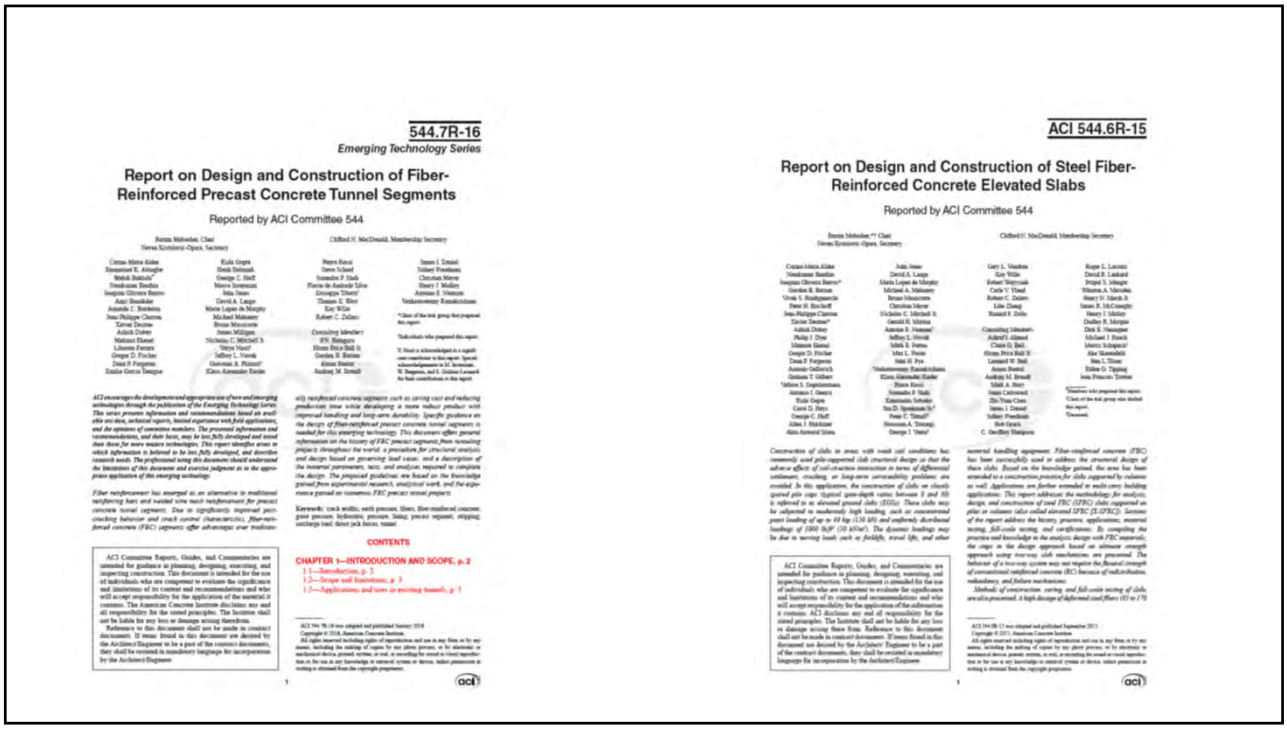

544.7R-16
Emerging Technology Series

Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments

Reported by ACI Committee 544

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ACI 544.6R-15

Report on Design and Construction of Steel Fiber-Reinforced Concrete Elevated Slabs

Reported by ACI Committee 544

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Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete

Reported by Committee 544

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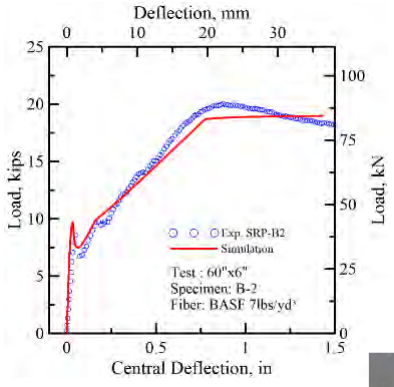
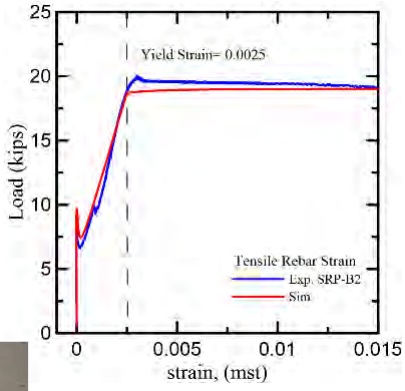
ACI 544.8R-16

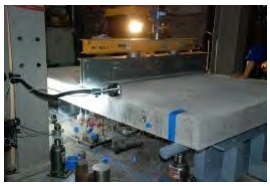
Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete (FRC)

Reported by ACI Committee 544

One way slab Experimental and Simulation Comparison







Elevated slabs with FRC

- Structural Design with Hybrid FRC Materials: testing, modeling, analysis and Design ACI 544-6R 2015
- Section size reduction, Volume reduction, Labor, construction scheduling, Speed of construction

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

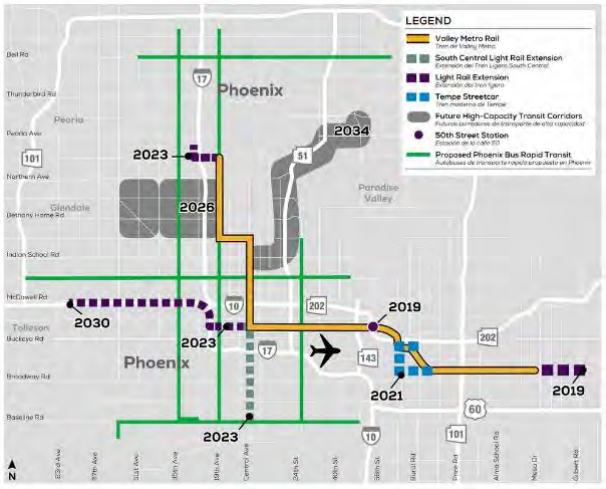
1. Pipes
2. Industrial strong floors
3. Corrosion protection
4. Wiremesh replacement

Information about Valley Metro, valleymetro.org

- The Valley Metro Regional Public Transportation Authority, is the unified public brand of the regional transit system in and around the Phoenix, Arizona, metropolitan area, responsible for public transit.
- **Founded:** 1993
- **System length:** 26.3 miles (42.3 km) (light rail)
- **Number of lines:** Light rail: 1;
  Express/RAPID bus: 6; Bus: 102
- **Annual ridership:** 65,958,074
- **Daily ridership:** 219,406
- (March 2017; avg. weekday boardings)

City of Phoenix South Central/NW Extension project

Northwest Phase 2 project with 12,000 feet and 8’ South-Central Phase with 55,000 feet of the 8’ wide track slab



Project Objectives

- Phoenix Metro Light Rail adding several stations and track lines.
- Construction costs and scheduling creates a significant pushback
- The track slabs are 14.5” thick and 8’ wide reinforced concrete sections
- Given the size and cost of the project, the time required for the setting of the rebars, and the volume of the materials used
- Proposed to consider the cost savings by switching the reinforcement from continuous bars to fibers.
- Validate the deign by Full-scale fatigue tests
- Project was in collaboration with: Kiewit McCarthy, a Joint Venture (NWE2), Mr. Gary Sanders, Project Manager

x

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Stray Current Corrosion Potential is a Concern

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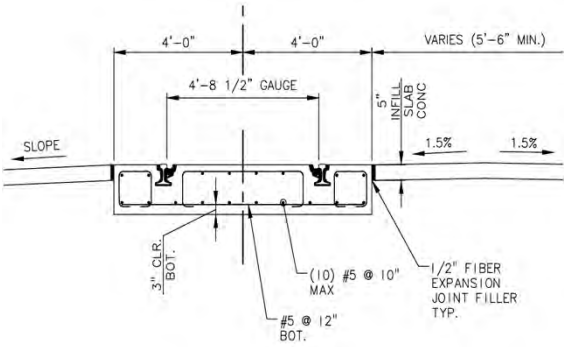
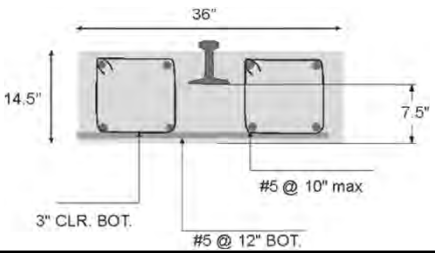
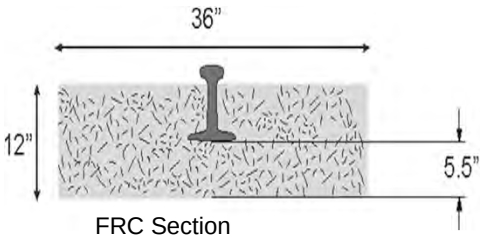
Design Alternatives

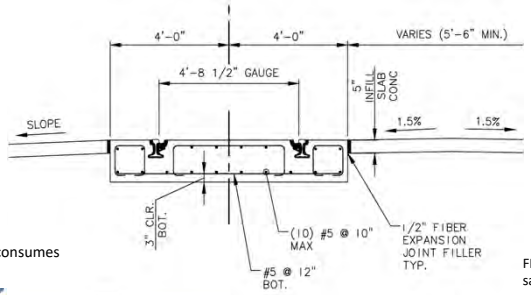






FRC Section

Alternative Design of Embedded Track Section



Current Design approach consumes significant time

FRC design increases ductility and saves time and cost.

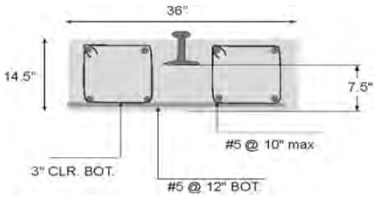
Sample Preparation

Definition of Serviceability Criteria in terms of Fatigue

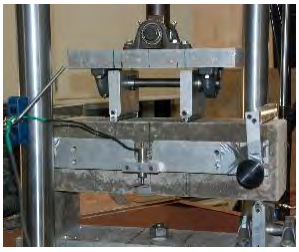
- Simulate the response under fatigue load, a loading history for a service life was considered:
- A service life of 45 years
- Significant ground settlement
  - Ex: water line failure the slab, loss of ground support, 8’ long section for the entire width
- Design Wheel loading, fully loaded train with triple capacity is 9000 lbs.
- Factor of safety of 1.7-2.0, set the load at 18-24 kips.
- Train runs on schedule 24/7, every 6 minutes for the entire service life
- Preload the specimen to full cracking phase before the fatigue testing starts

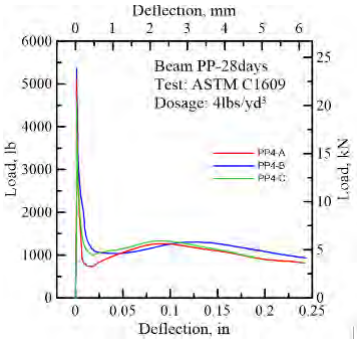
- Results: 2.0 million cycles of loading. From zero load to full capacity of the fatigue loads.

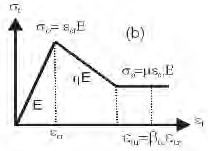
Full size Slab testing

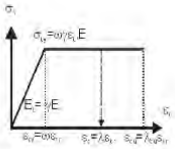


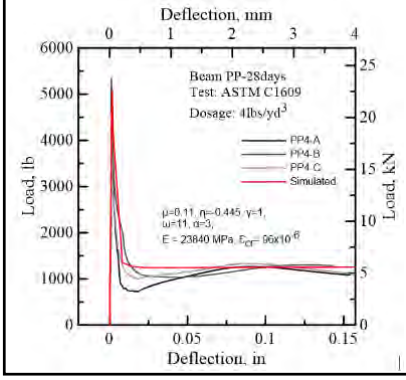
Standard Design Procedure using ACI 544.4R method (Parametric-based design)



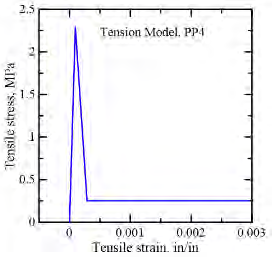


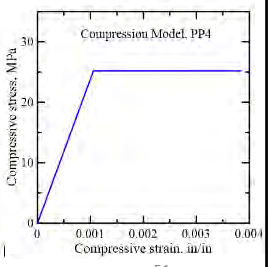






Using these parameters, the location of neutral axis, moment capacity, and curvature of the section can be obtained at any imposed strain





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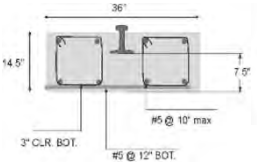
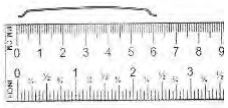
Full scale mockup specimen testing

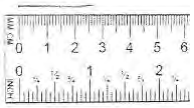
3 type of mockup sections

-Conventional Rebar section (14.5”x3’x8’)
-FRC, Steel Fiber, #1, 65 PCY Dosage (12”x3’x8’)
-FRC, Steel Fiber #2, 25 PCY Dosage(12”x3’x8’)





Type 1



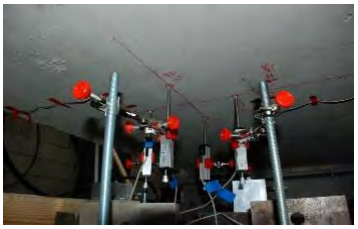
Type 2

Testing Plan

- Monotonic (3PB flexure) testing of mockup specimens
-Fatigue testing at 4Hz loading frequency

Instrumentation

-4 LVDT at bottom
- 4 strain Gages (2 @ Compression zone, 2 @ Tension zone)



55 kip load frame setup

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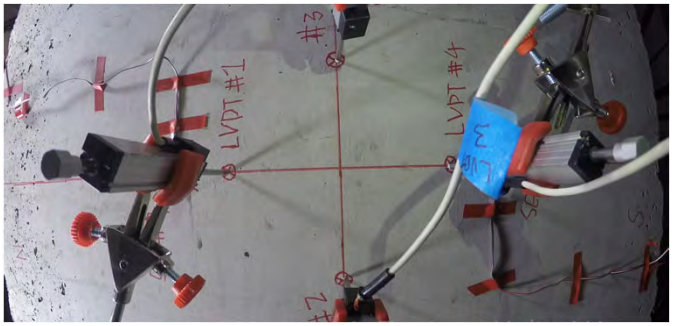
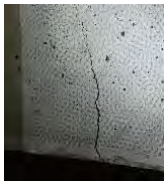
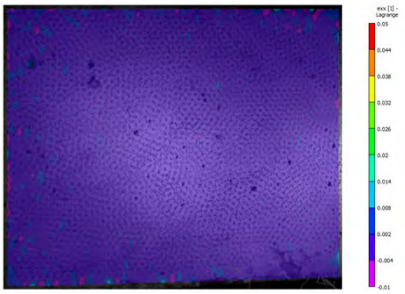
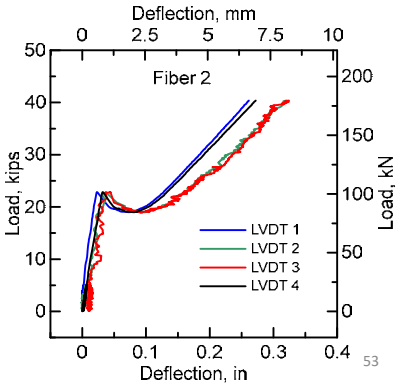
Full scale mockup specimen testing

Monotonic Testing:









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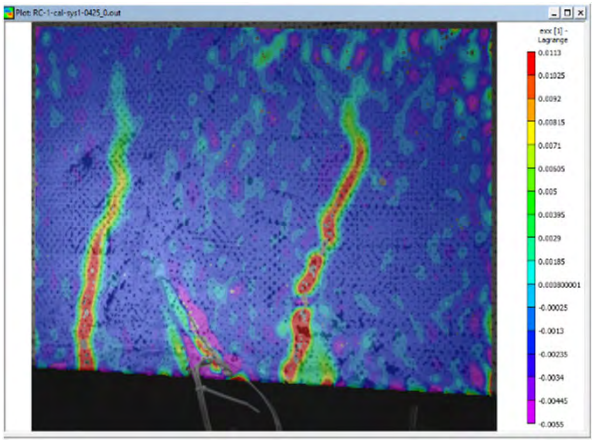
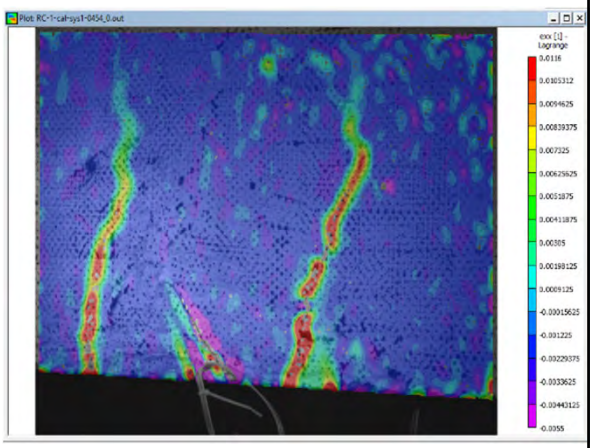
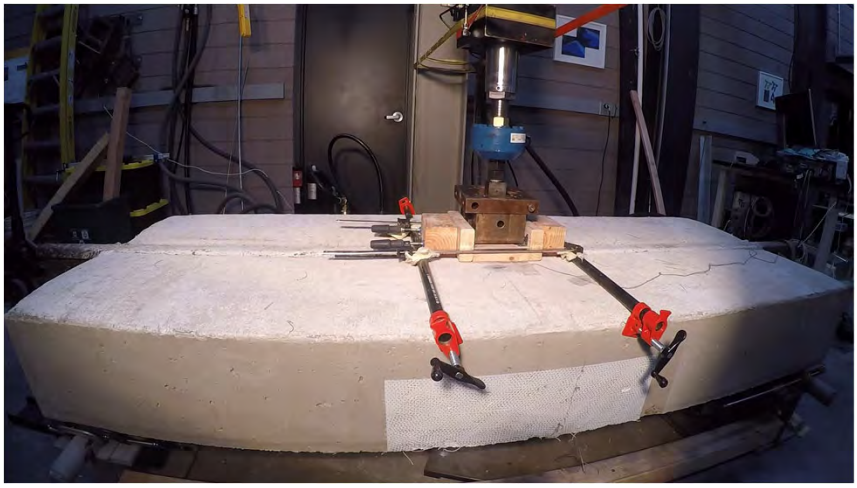
DIC measurements of level of cracking



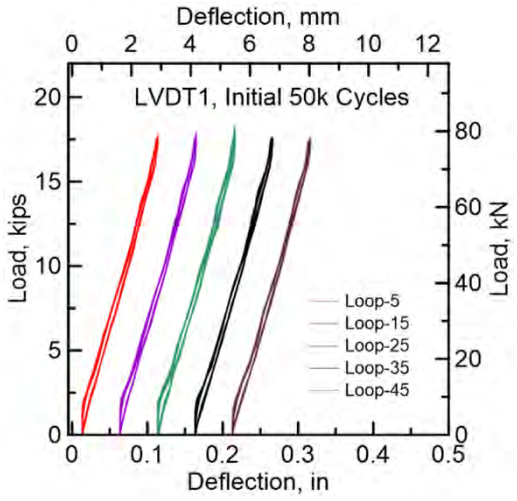


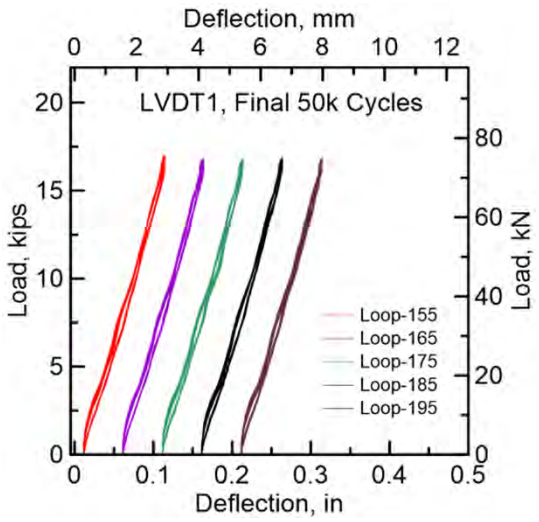
Full-scale Fatigue Testing (2 Million Cycles , 4Hz)



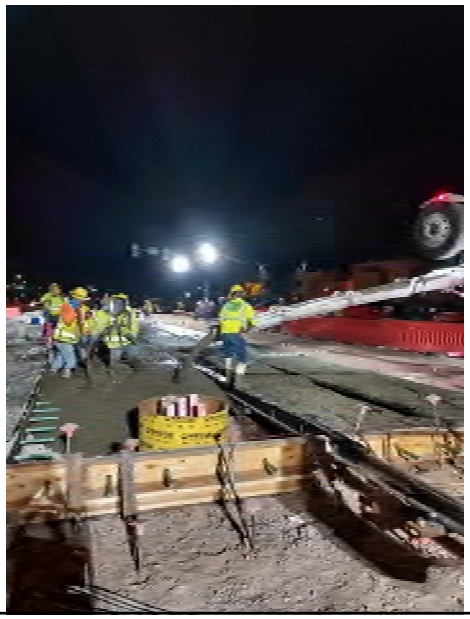
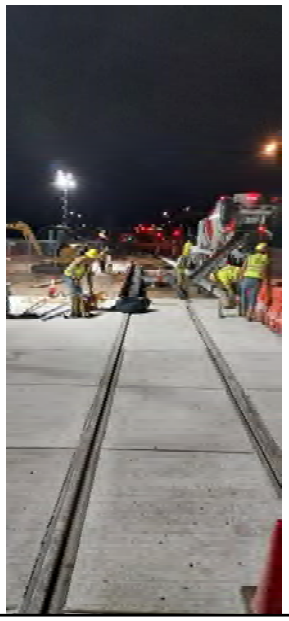
-Loading : 17.5 kips
-Data Acquisition of 100 cycles per 10,000 cycles,
2.0 million cycles, 8 days at 4 Hz

55





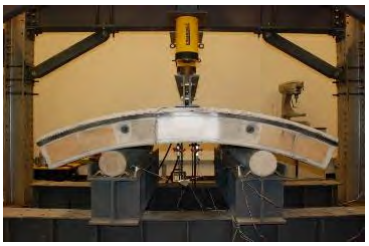
Project Implementation, Valley Metro light rail Extension, Phoenix

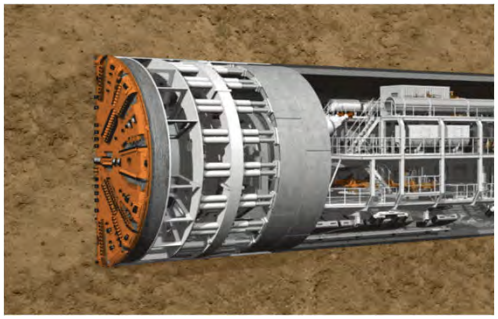




Serviceability Based Analysis, Design, and Testing of Hybrid Structural Sections

- Use of Polymeric fibers and/or FRP for precast tunnel lining in TBM equipment
- Elimination of steel reinforcement





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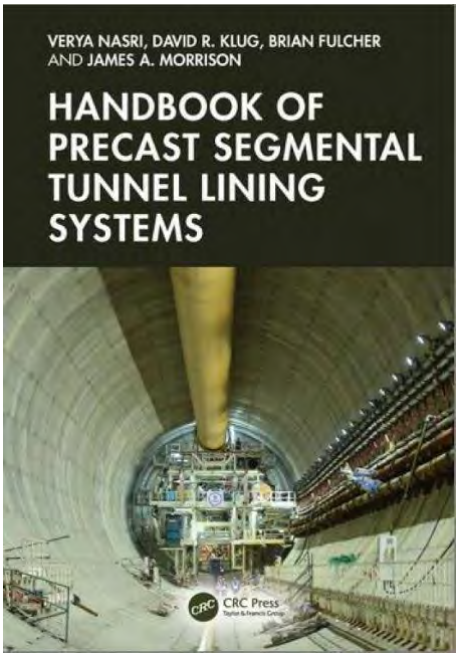
Precast Tunnel Lining using no rebar



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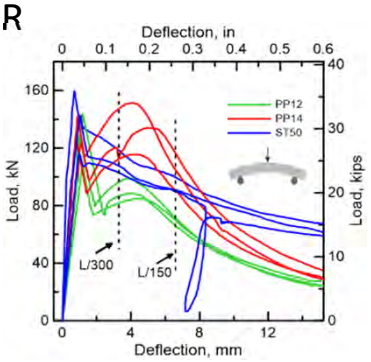
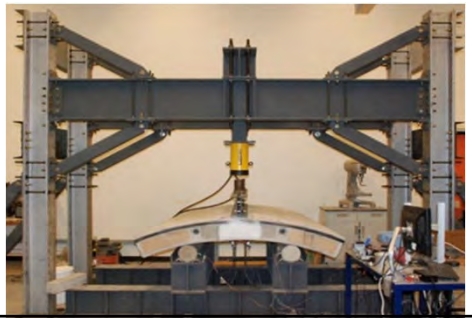
Precast Tunnel Lining Applications ACI 544-7R

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

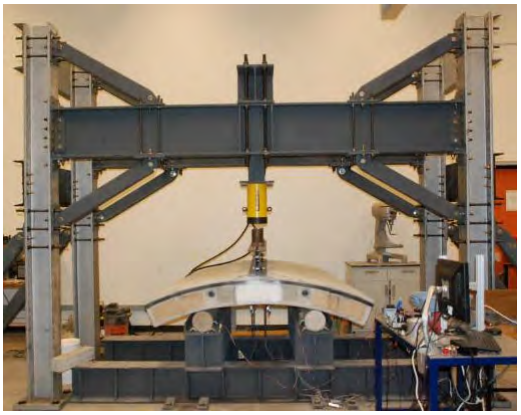




Patel, D., Pleesudjai, C., Bui V., Pridemore, P., Schaef, S. and Mobasher, B. 2023. "Mechanical Response of Precast Tunnel Segments with Steel and Synthetic Macro-Fibers." *Cement and Concrete Composites* 144 (November): 105303. https://doi.org/10.1016/j.cemconcomp.2023.105303.

Analysis of PCTLs through full-scale testing

- Flexure 3 or 4 Point Bend Test Setup
- Max. flexure loading capacity of 400 kips (1780 kN)



Load Frame for full scale testing

Hydraulic rams with 200 kips max. loading capacity, each

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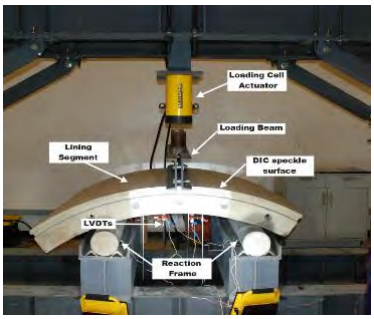
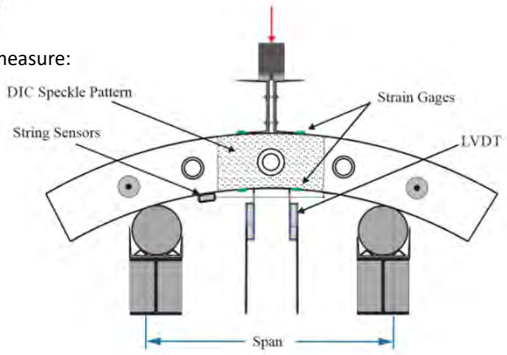
Analysis of PCTLs through full-scale test

Total Instrumentation in Flexure Testing to measure:

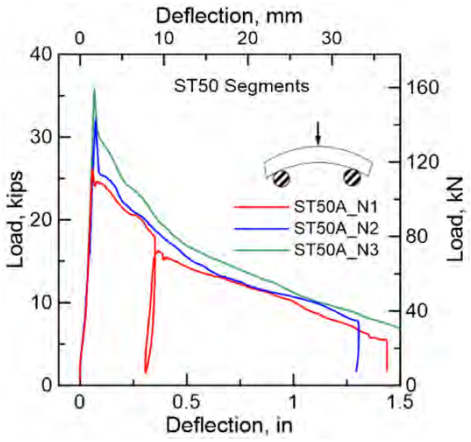
- Deflection (LVDT x4)
- Crack-Width (String Sensor x4)
- Strain in Tension and Compression (Strain gage x4)
- Digital Image Correlation (DIC)





Strain gage in Tension zone, Bottom view

Load Deflection Response, SFRC



Cracked SFRC segment

Edge Compression Testing

- Point Load Compression Test Setup
- Max. Loading capacity of 400 kips (1780 kN)

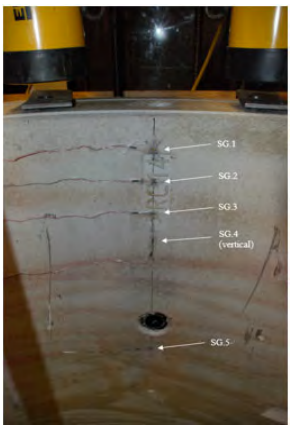
Load Frame for compression testing

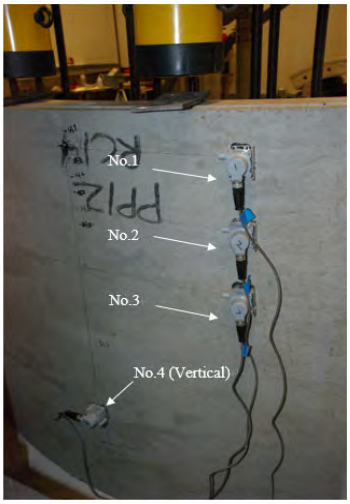
Hydraulic rams with 200 kips max. loading capacity, each

Instrumentation of Edge Compression testing

Total Instrumentation in Compression Testing to measure:

- Displacement (String Sensor x4)
- Strain (Strain gage x5)





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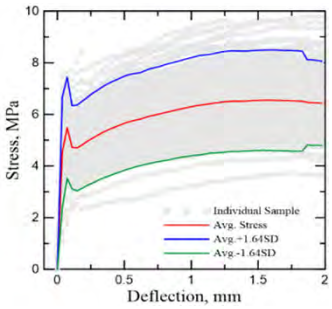
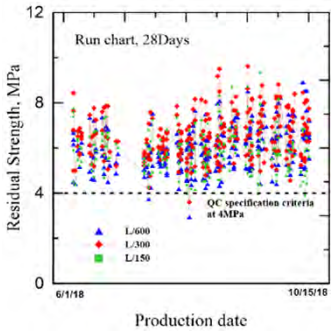
Statistical Process Control Of Residual Strength

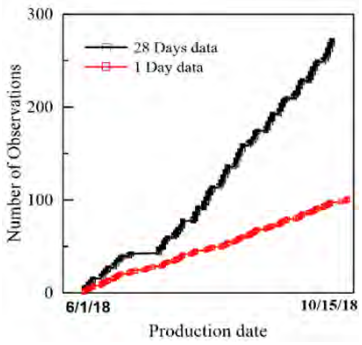
- Analysis of QC data to Improve production efficiency of PCTLs



Stress vs. deflection plot of 270 C1609 test data



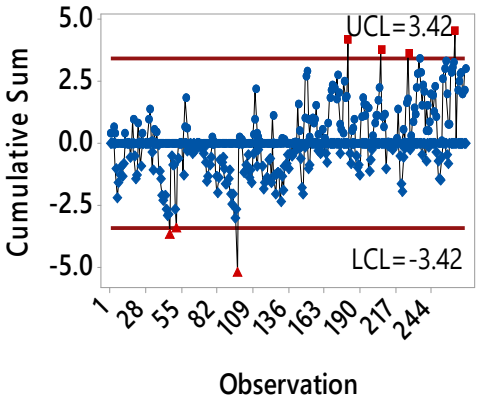
Run Chart for residual strength



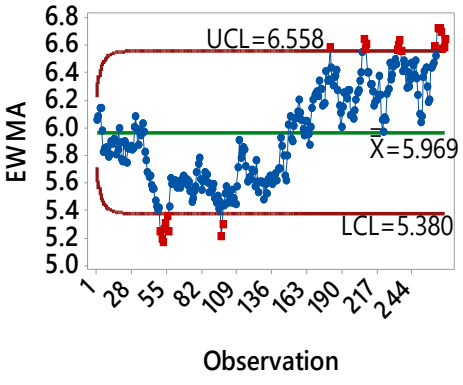
Sample collection data points

Statistical Process Control Of Residual Strength

- A control chart for individual observations monitors concrete residual strength
- One can distinguish between a significant change (real change in slope) and non-significant change (error of aberration).



CUSUM of L/600 stress at 28day, h=4, k=0.5



EWMA of L/600 stress at 28day, h=3 , l=0.1

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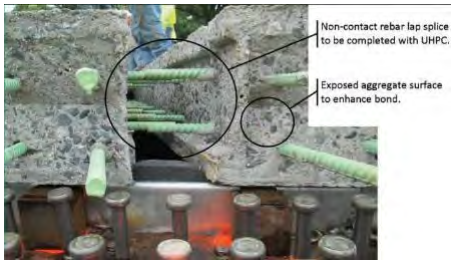
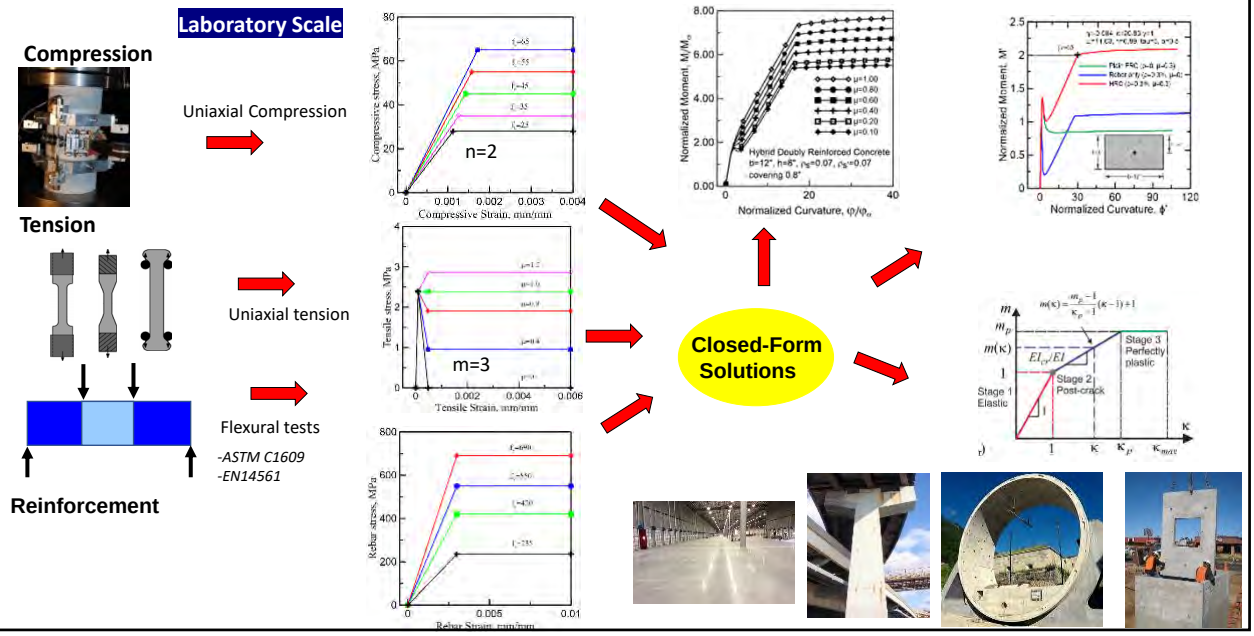
UHPC girders and decks



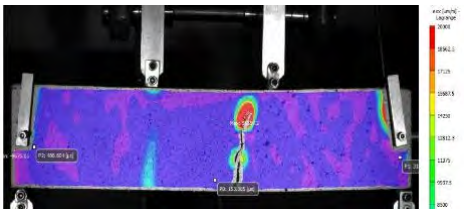
Y Yao, B Mobasher, J Wang, Q Xu, "Analytical approach for the design of flexural elements made of reinforced ultra-high performance concrete", Structural Concrete, 2021

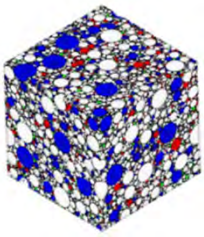
Mechanical Characterization and Design From laboratory to structure scale



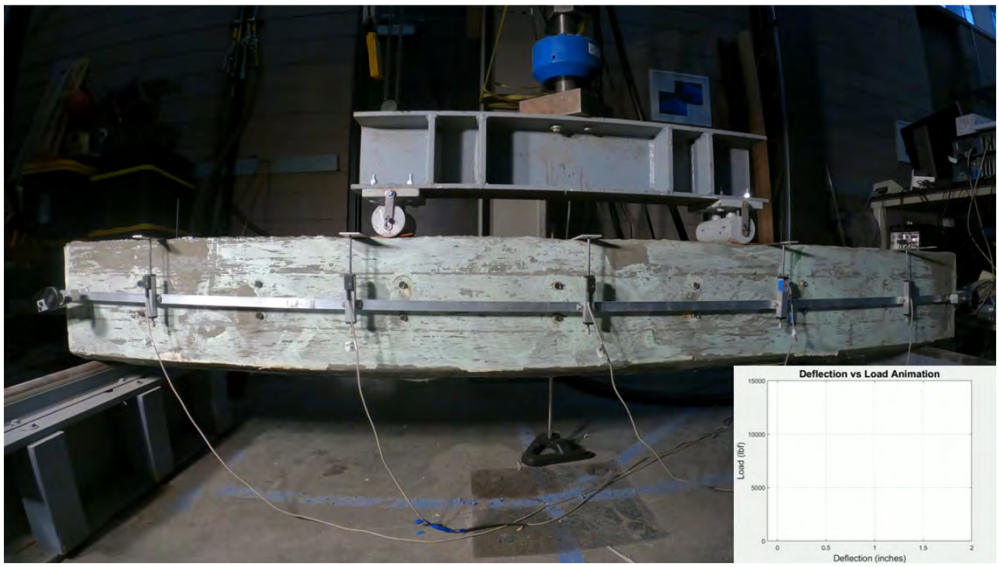
Non-Proprietary UHPC Concrete Mixtures, Maricopa County, Arizona, 2022

- Life cycle cost and economic advantages of using UHPC systems in terms of structural applications.
- Precast UHPC elements reduce the overall operational complications, labor-intensive tasks. From a design perspective, elastoplastic behavior supports durability initiatives, ductility, allows load redistribution, and weight reduction.





MDOT – UHPC BEAM TESTS



Arizona State University

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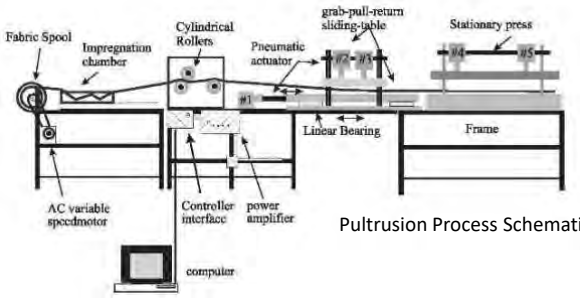
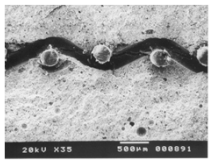
Structural Shapes using Textile Cement Composites

- Using an automated pultrusion system, full scale structural shapes composed of TRC laminates are efficiently manufactured.
- Competitive to wood and Light gage steel sections



Pultrusion Process Schematic Diagram

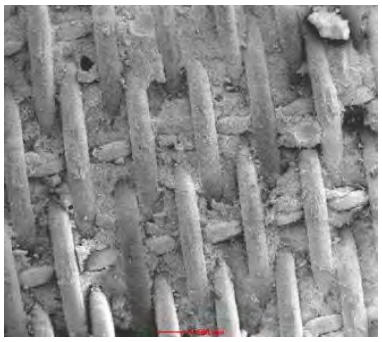


Pultrusion based approaches

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.

© National Ready Mixed Concrete Association

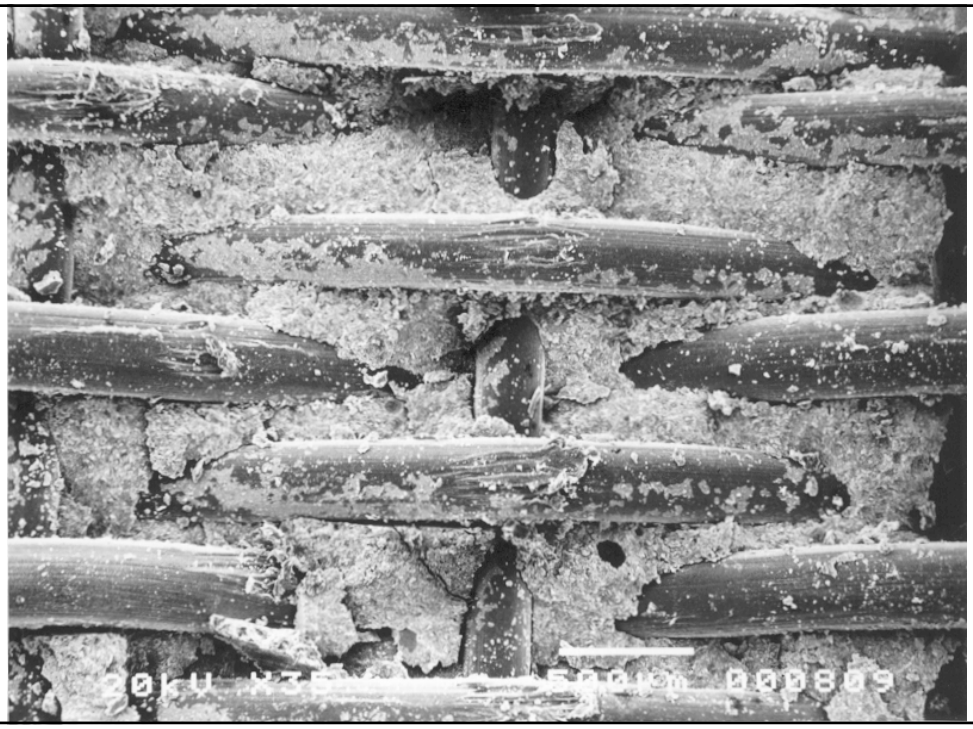
Fabrics in Paste



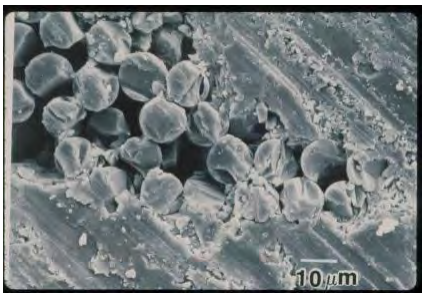
Polyethylene (PE)
Woven Fabric

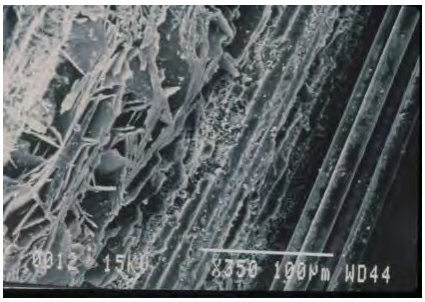
AR Glass
Bonded Fabric

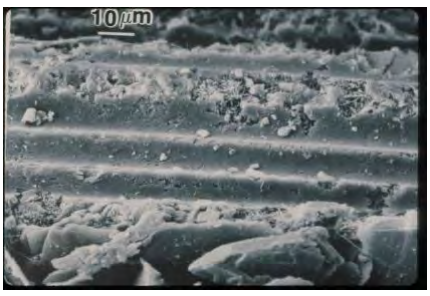
Polypropylene (PP)
Knitted Fabric



Interface Transition zone







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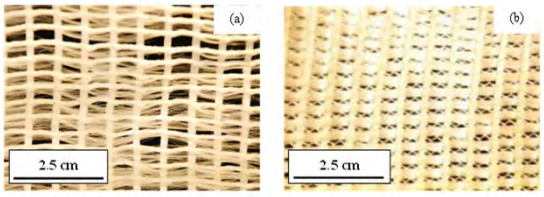
Pultruded Full Size TRC Structural Shapes

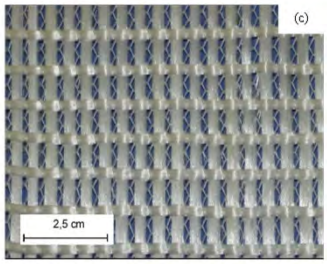
Cross section of pultruded shapes with TRC laminates

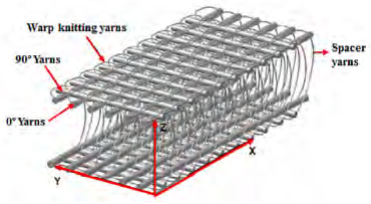
Woven textiles from PP microfibers and 3D textiles

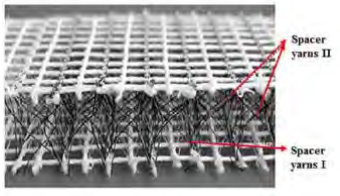
(a) Open weave pattern



(b) & (c) tricot weave pattern

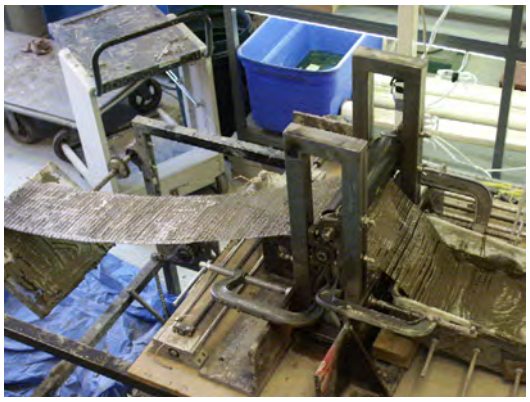


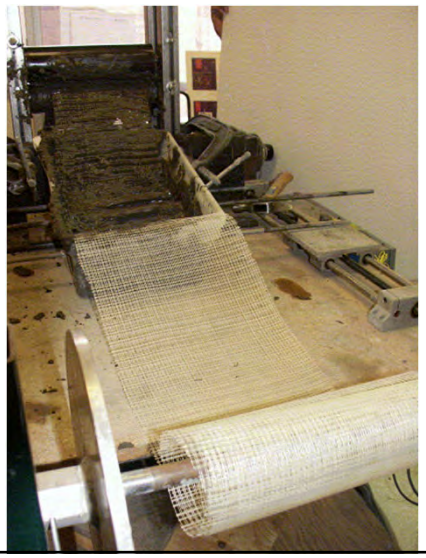




3-D Textiles

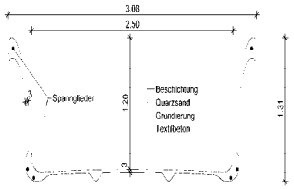
Pultrusion of Fabric Composites



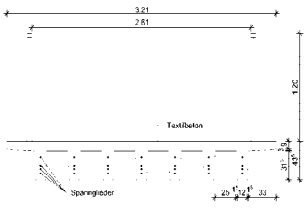


Structural Applications: TRC Showcase Studies, C3-Germany

When materials with high specific stiffness and strength are used, size reduction reduces the dead loads a structure is expected to carry as well



U-shaped cross section of the textile reinforced concrete bridge in Oschatz

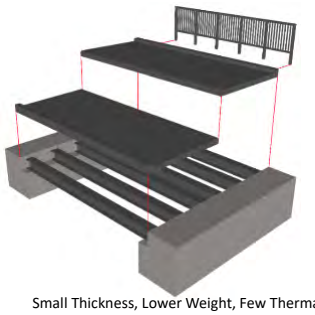


Textile reinforced concrete bridge in Kempten, Photo: Harald Michler

TRC pedestrian bridge with Multiple web cross section of in Albstadt-Lautlingen

Repair & Retrofit

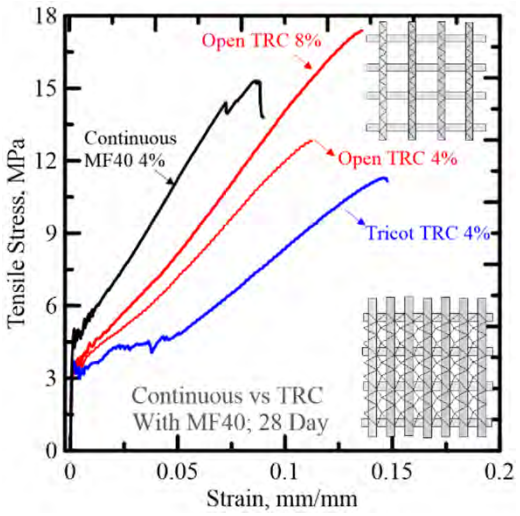
Compared to FRP, a cement-based matrix for repair and retrofit offers: compatibility with substrate, moisture, UV, fire, and delamination resistance



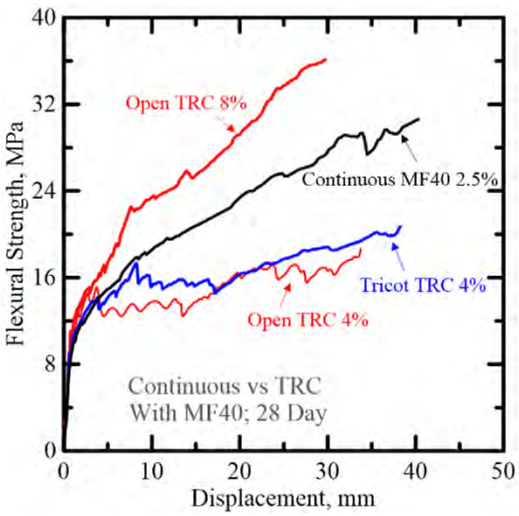
Small Thickness, Lower Weight, Few Thermal Bridges, Few Fixtures, 3d Adjustability For Set Up

Bridge in Naila rehabilitated with textile reinforced concrete, Photo: Frank Schladitz

Tensile response



Flexural response



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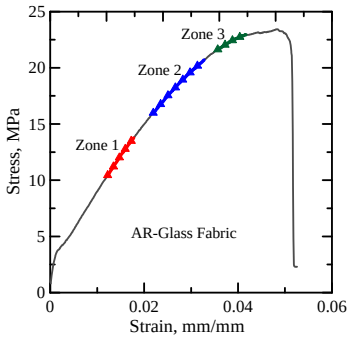
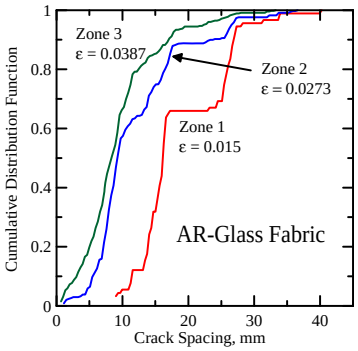
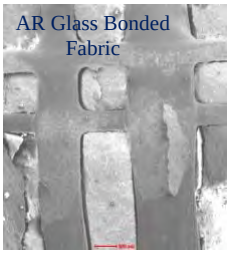
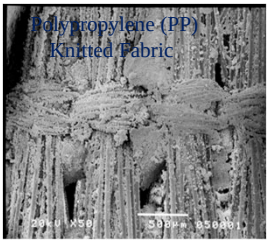
Homogenization of Crack spacing –Mechanical interlock









T Section

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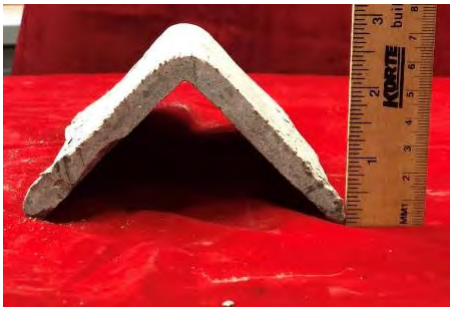
I-Beam with Different Flange Thickness



Channel and Angle Sections

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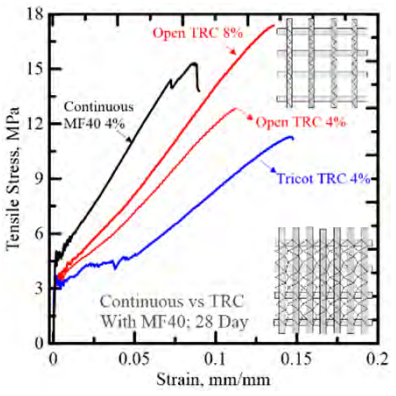
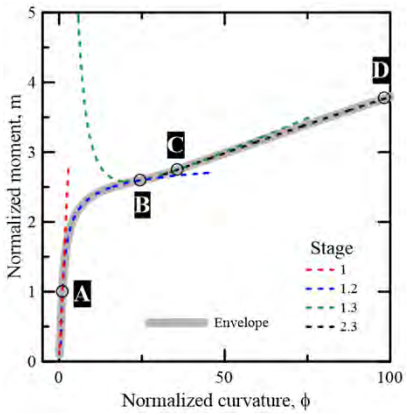
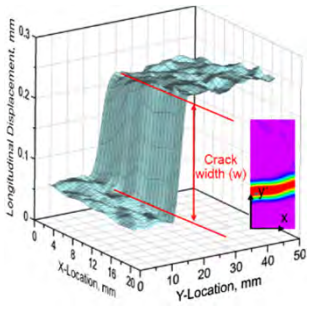
Development of Structural shapes with Textile Reinforced Concrete (TRC)

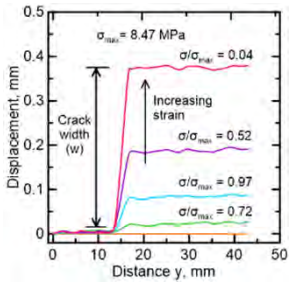




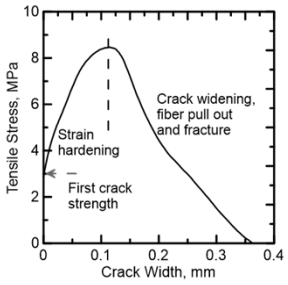
Crack Width Measurement



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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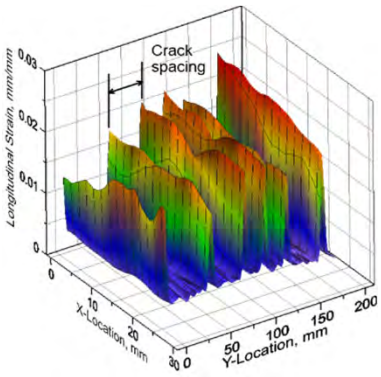
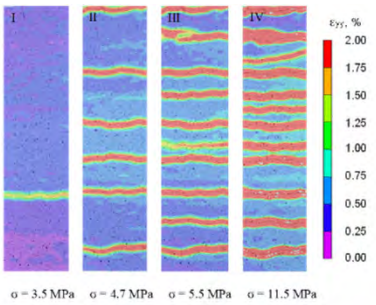
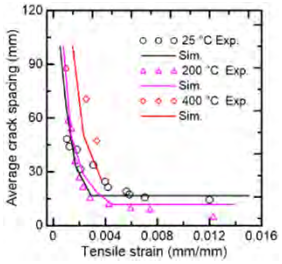
Extreme ductility and enhanced behavior for structural composite applications

- 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



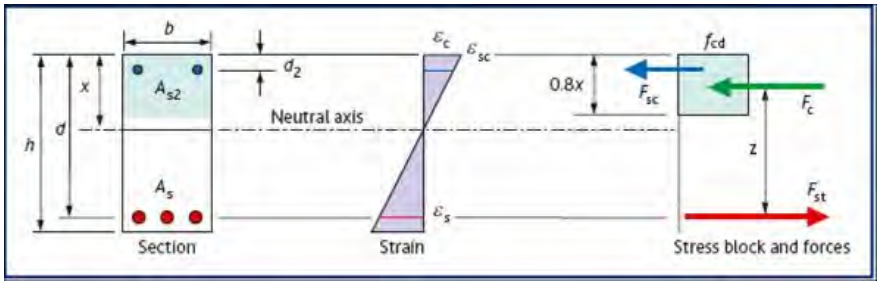




Rambo, D. A. S., Yao, Y., et al. (2017). Experimental investigation and modelling of the temperature effects on the tensile behavior of textile reinforced refractory concretes. Cem. Concr. Compos. 75, 51-61.

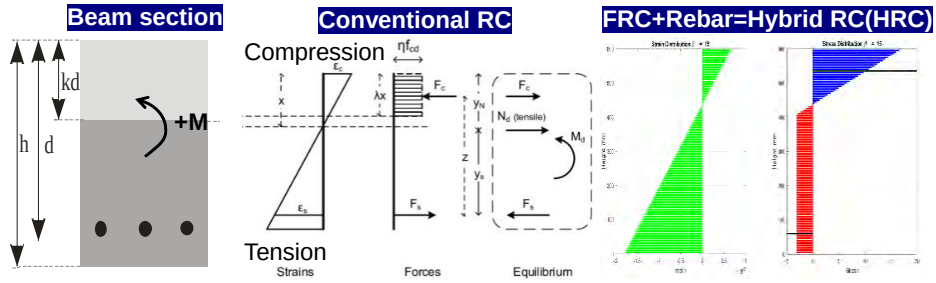
New Design Methodologies for taking into account the contribution of fibers

- Cross sectional analysis
- Plane section remains plane
- Compression: stress block method
- **Tension: ignored**
- Ultimate limit state: moment capacity



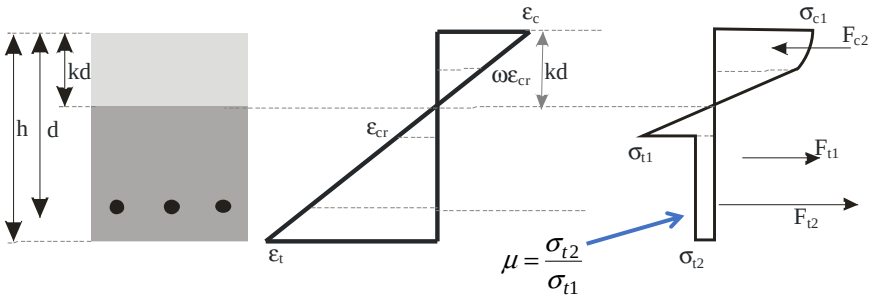
Tensile contribution of FRC to the Hybrid Flexural Response

- 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



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

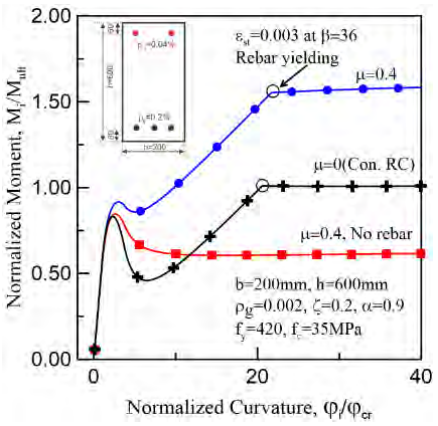


$$M_{ult} = \left[\frac{\mu\sqrt{f_c'}}{15.55\mu + 2\sqrt{f_c'}} \right] bd^2 E\varepsilon_{cr}$$

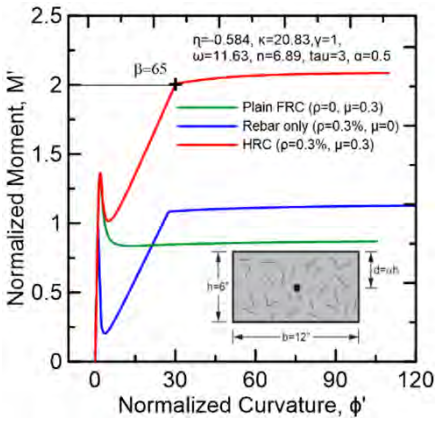
tensile stress transmitted by the fibers across the flexural crack. A measure of residual tensile stress strain response.

The Hybrid Composite effect

Reinforced concrete beams

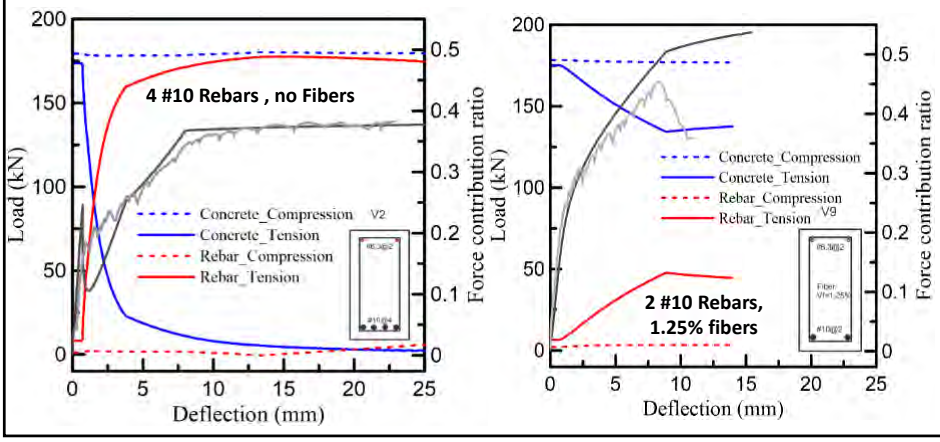


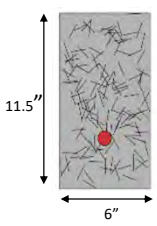
Reinforced Slabs

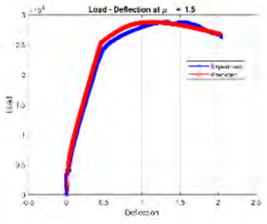


The efficiency of the reinforcement in delaying the yielding of steel main
Synergy of fiber and rebar combination

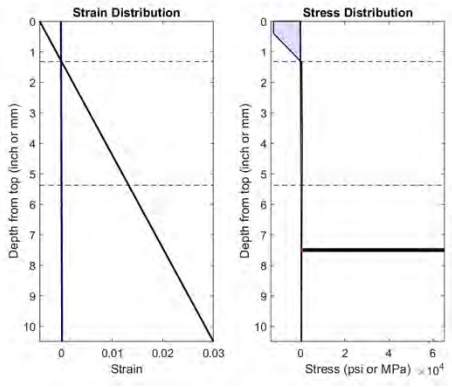
- As soon as post cracking starts, concrete contribution diminishes to less that 10% in plain RC concrete
- Even after yielding of steel, Concrete in the hybrid system is carrying more than twice its steel
- With only half the amount of steel in the hybrid system, the rebars in hybrid extend the serviceability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



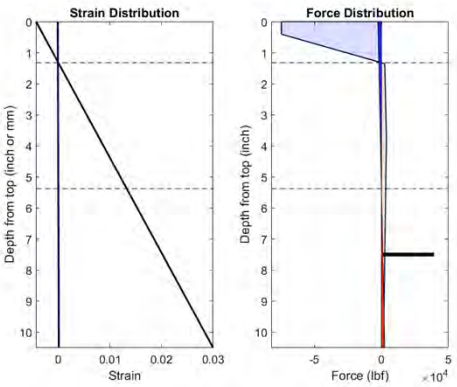


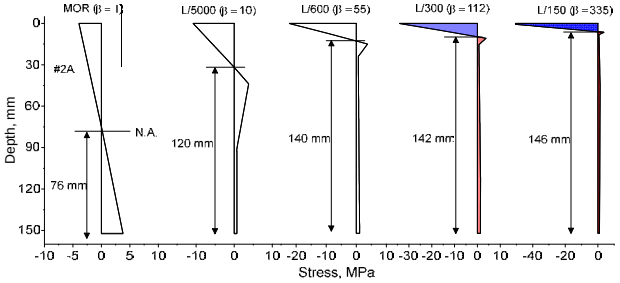


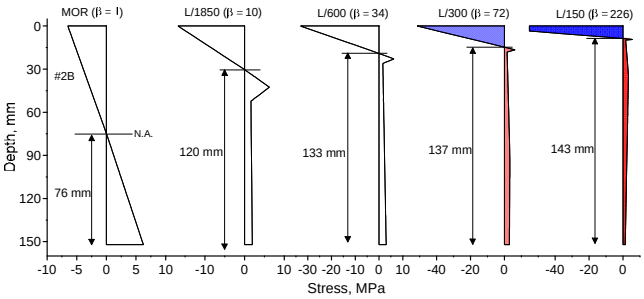
STRESS DISTRIBUTION

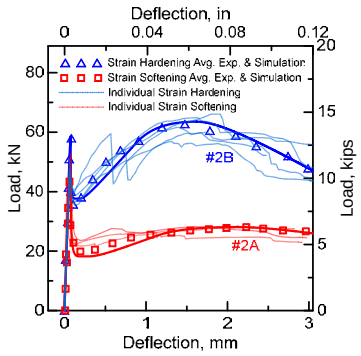


FORCE DISTRIBUTION



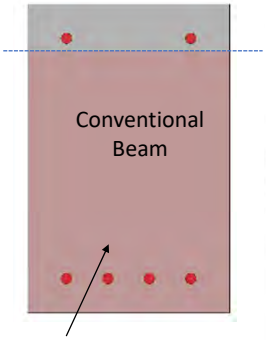




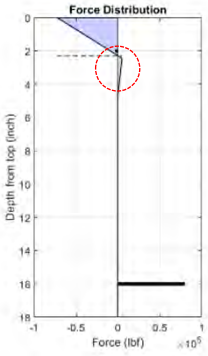


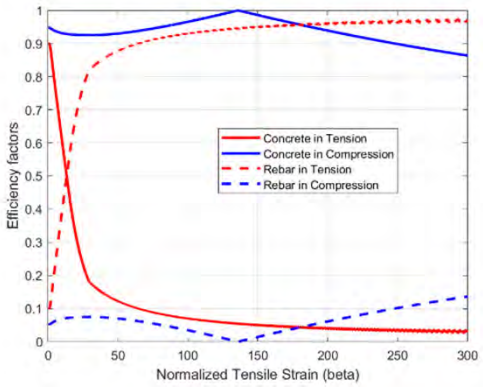
Add efficiency

Plain Reinforced Concrete, ACI 318 Code

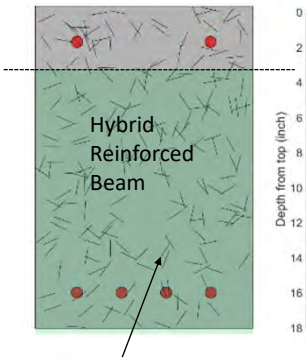


No contribution from concrete in Tension.

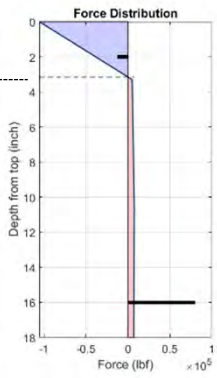


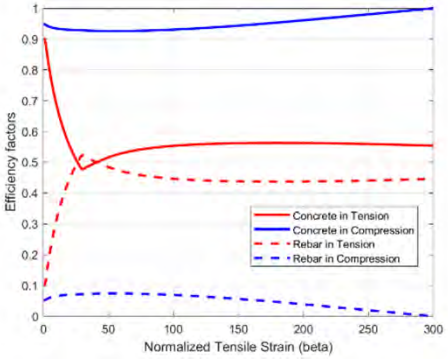


Hybrid Reinforced Concrete with Fibers



Concrete in Tension
Starts carrying load





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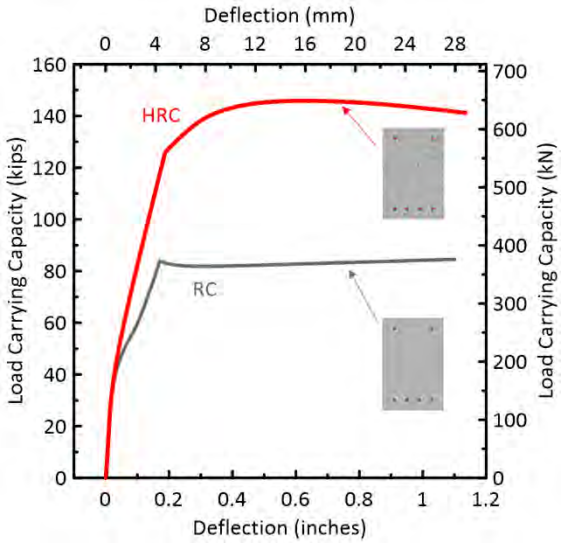
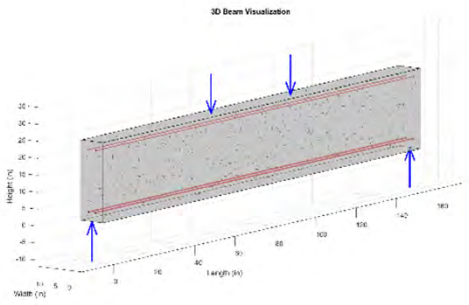
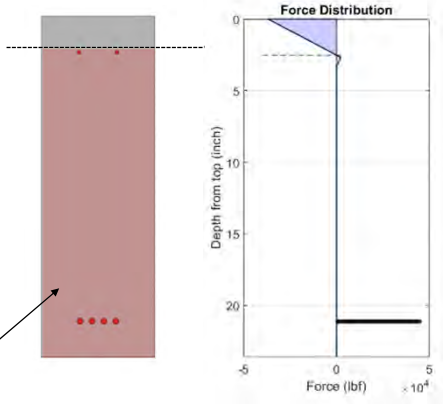
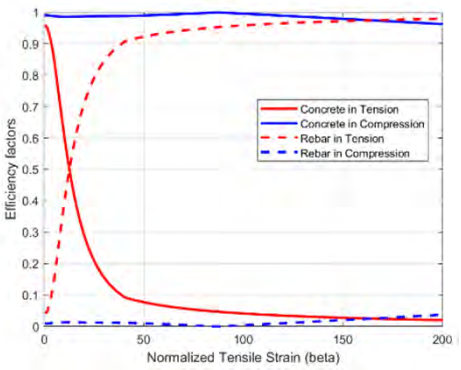




Standard RC Beam



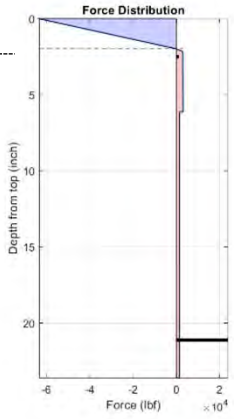


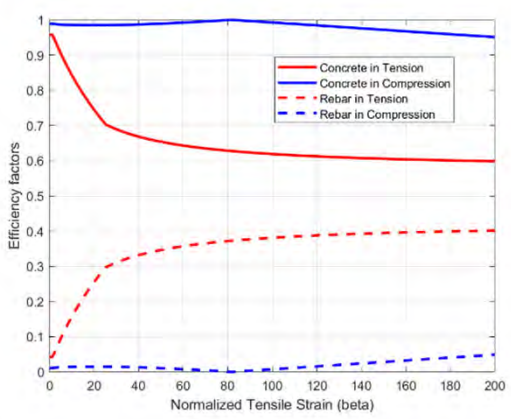
No contribution from concrete in Tension.

Rho (bottom) = 0.28%

Beam size: 7.5” x 23.5”

Hybrid section, with fibers



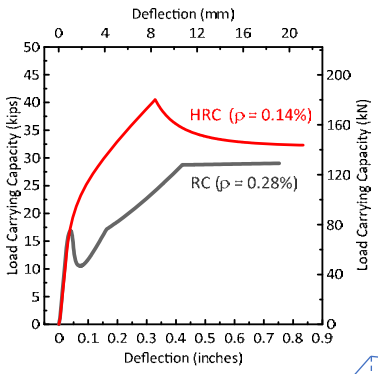


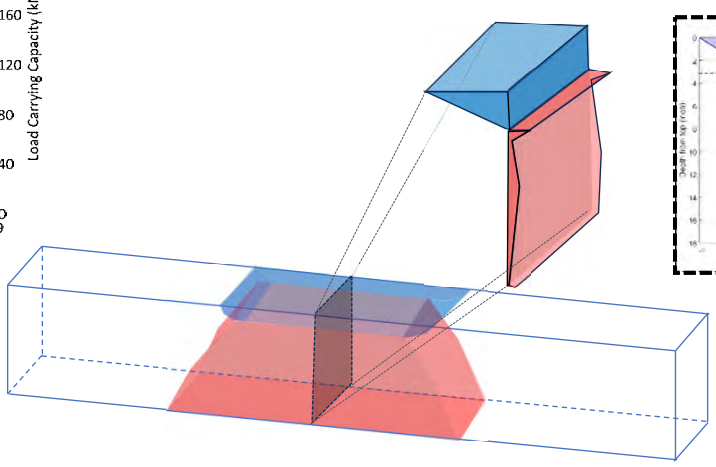
Concrete in Tension
Starts carrying load

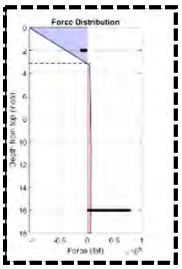
ρ = 0.14%

Beam size: 7.5” x 23.5”

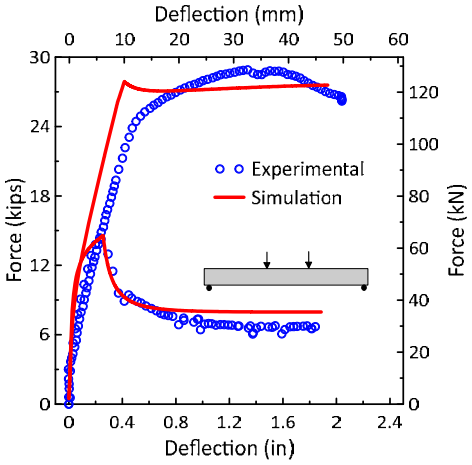
RC vs HRC (with 50% rebar content)

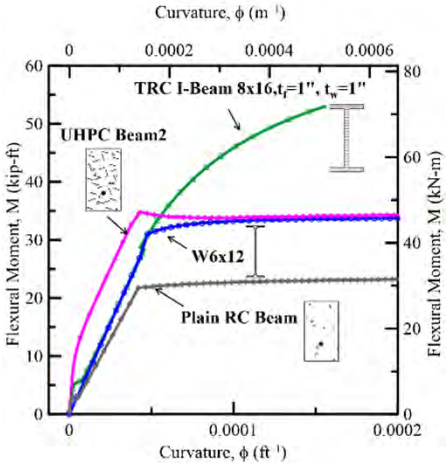






Simulation of Flexural UHPC beams Compared with W sections and TRC





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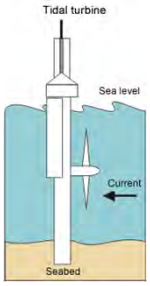
Closure- Infrastructure for non-fossil energy generation requires a robust reinforcement system

- 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, Alva Peled, Subramaniam Rajan, Flavio Silva, Romildo Toledo Filho, Steve Schaef

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- **Recent Publications by Mobasher's Team Related to Supplementary Reinforcing Systems**
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