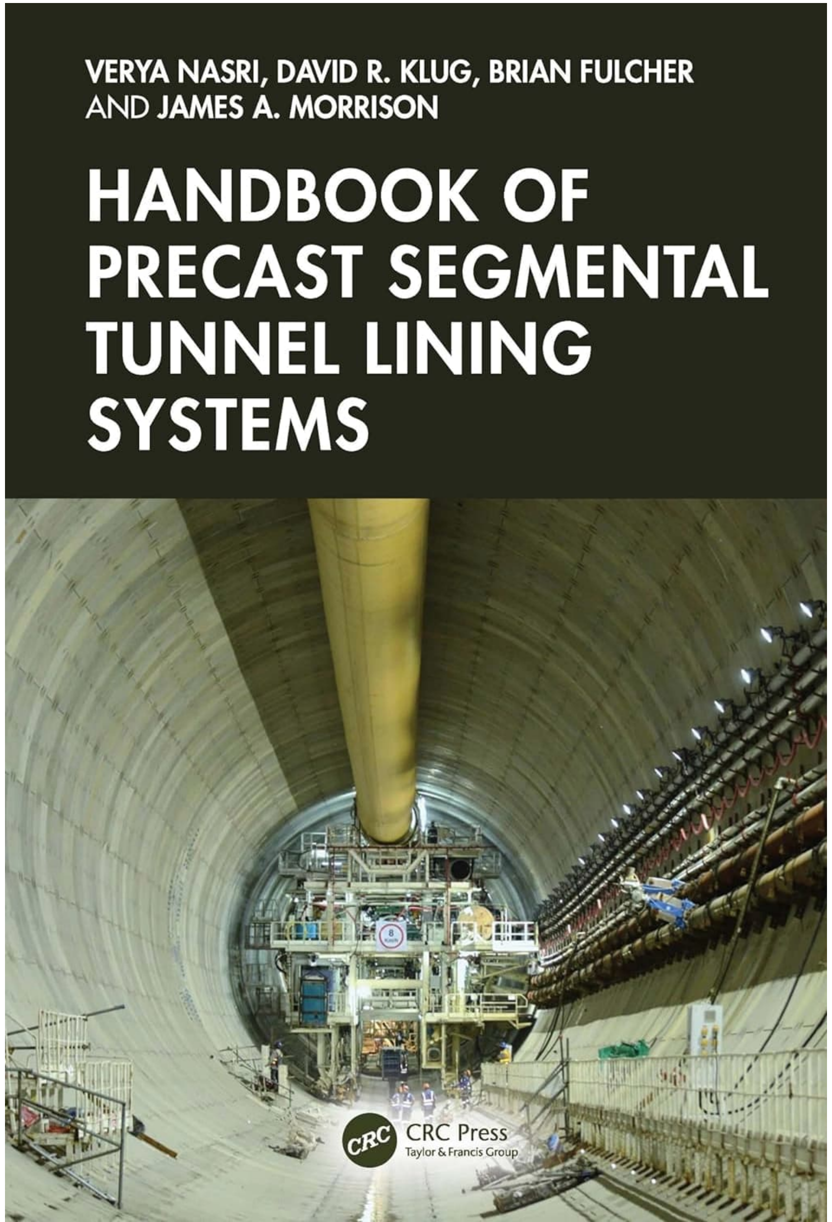
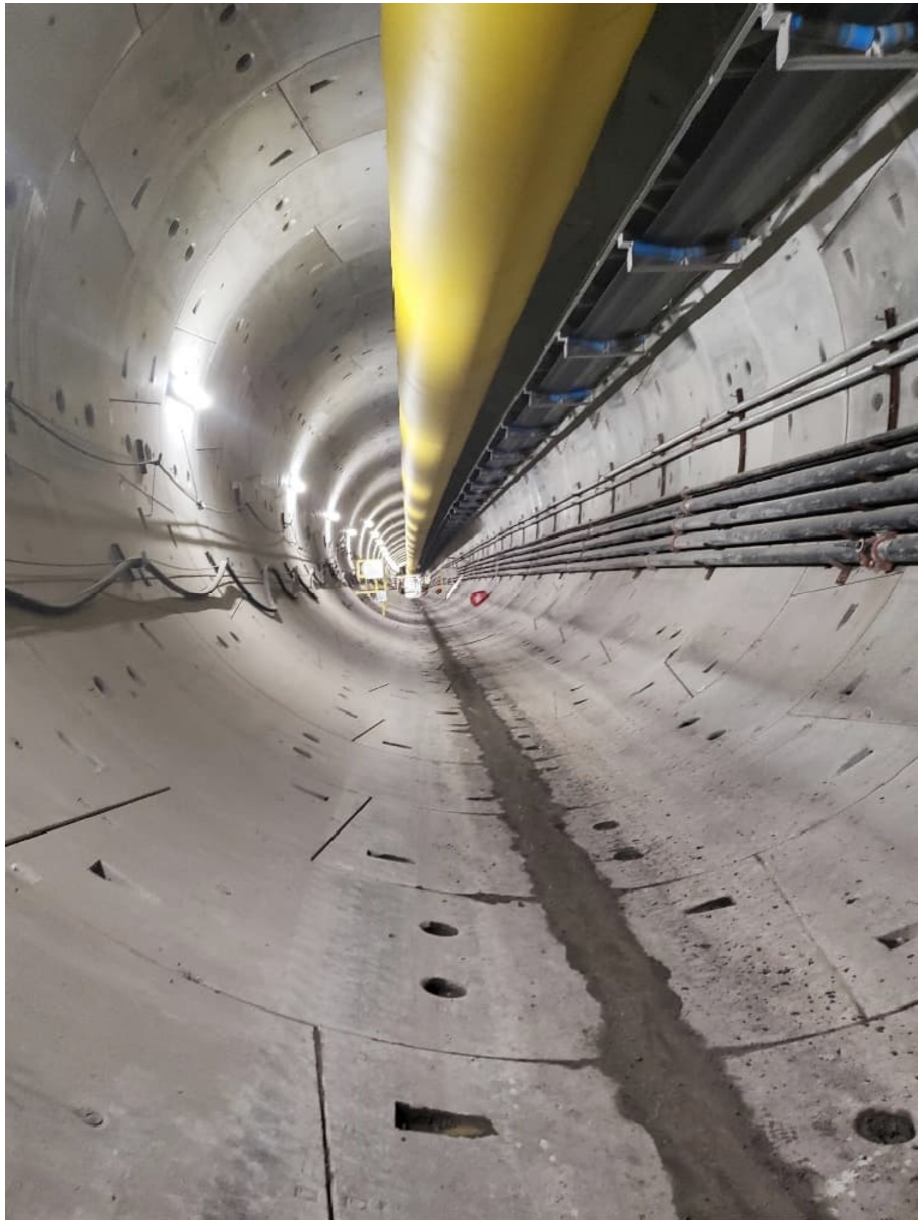
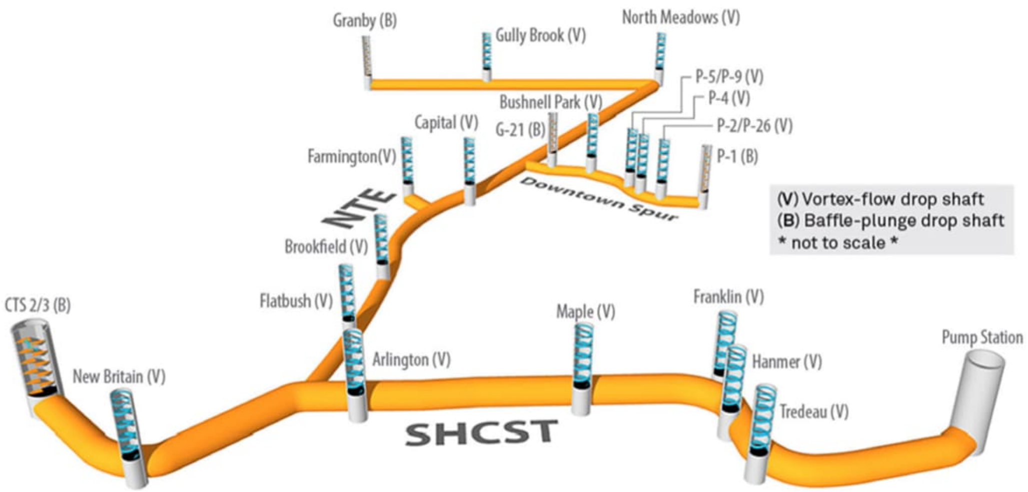
Precast Tunnel Sections

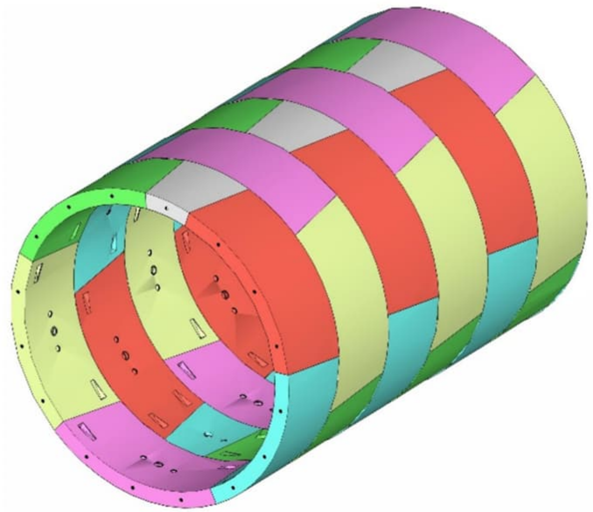




Sustainability of Concrete Structures

- Compared to all countries, concrete industry is the third-largest CO_2 emitter (4-8% of the world's 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





South Hartford Conveyance Storage Tunnel (SHCST), flagship infrastructure project in Connecticut managing combined sewer overflows, 6.6 km, 6 m in diameter

Fundamentals of Concrete Technology

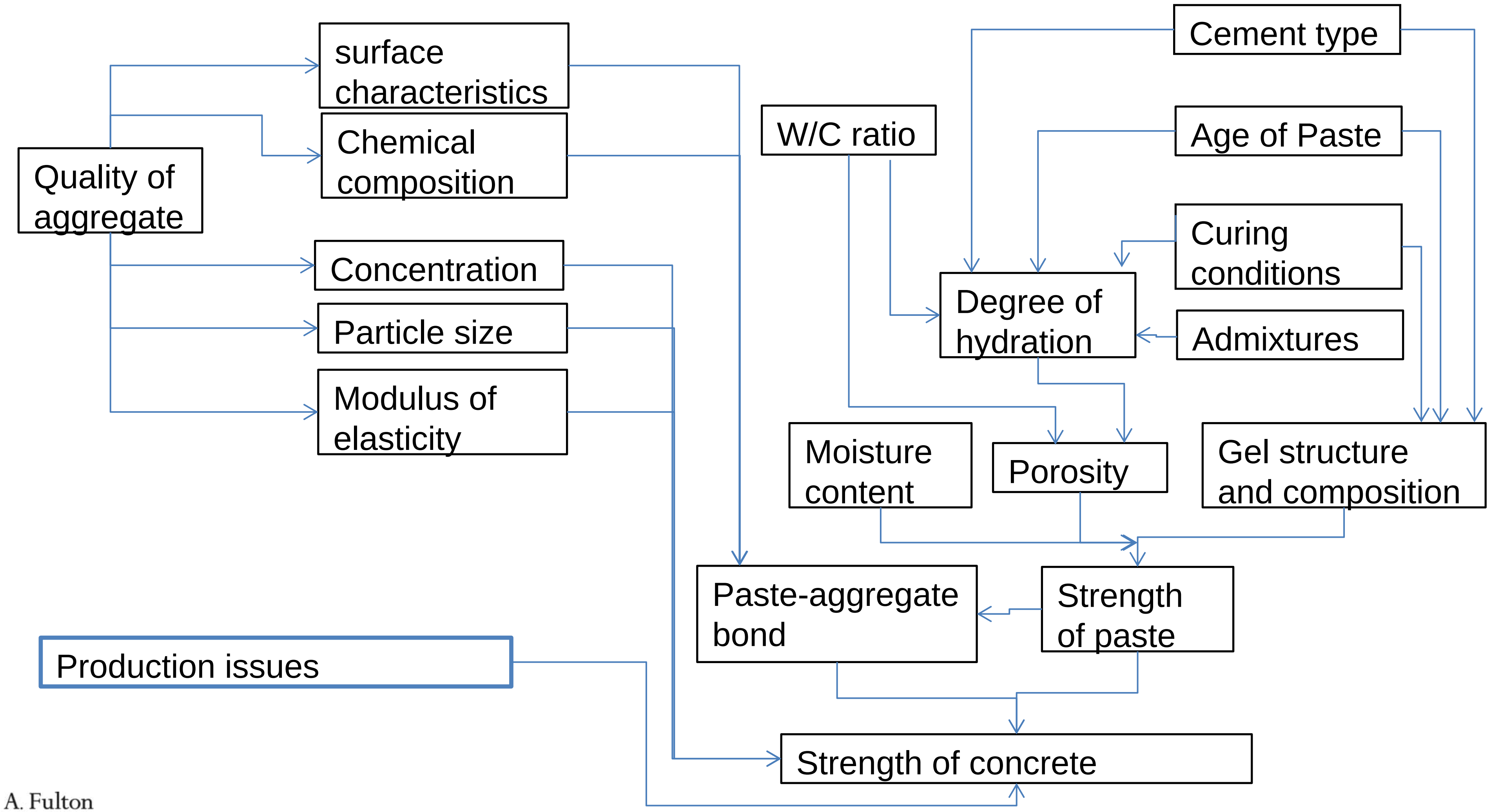
Fresh Concrete

- Constituents: Portland cement, aggregates, water, admixtures
- Mix Design
- Rheology & flow, consolidation, packing factors, slump, bleeding
- Production speed, placing, finishing.
- Curing, early age plastic shrinkage cracking
- Temperature effects

Hardened Concrete

- Factors affecting strength
- Choice of reinforcement
- Physical and chemical properties
- Mix design: Strength, permeability
- Durability, freeze-thaw, creep, shrinkage, permeability, corrosion, alkali-silica reaction, sulfate attack, carbonation, chloride induced corrosion of rebar.
- Specifications and quality control

Factors Affecting Strength of Concrete

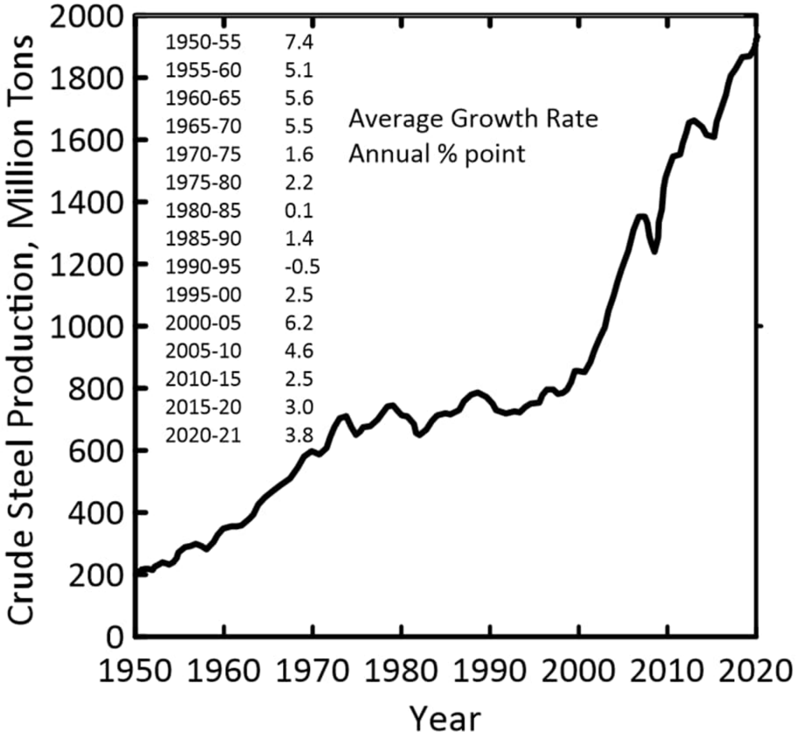


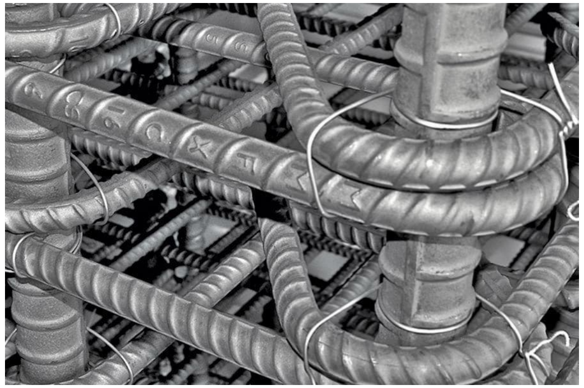
Testing, Material Properties, and QC

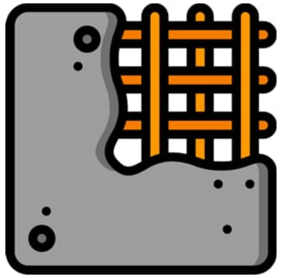
- Why do the testing, materials, from Mix design component, to sample strength testing, and full-scale testing, as well as system testing
- How do we obtain and control the Material properties used in the design process
- What tools to use to utilize the multiple fundamental parameters in the Material Properties in the structural design.
- How to conduct Quality Control Processes using Statistical Process control
- How to address the variability, when the results look all over the place

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 MT
- 7.5 lbs of steel rebar per ft^3 of concrete
- Although recyclable, raw feed supplies of steel ore will be exhausted due to demand.





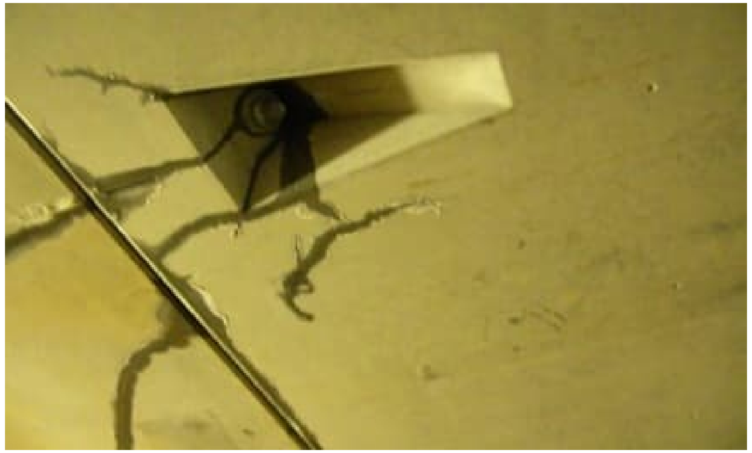


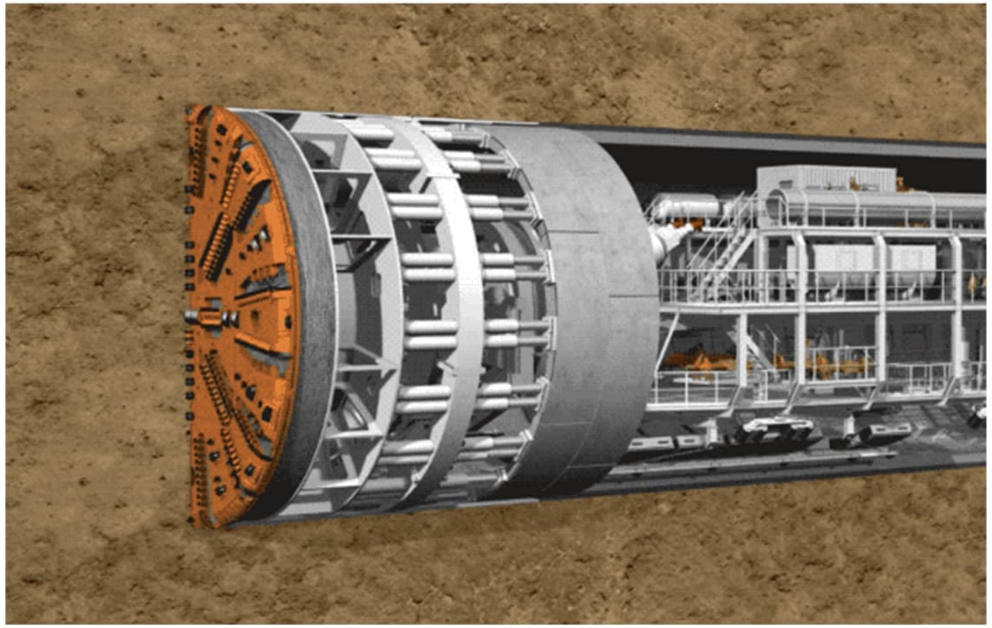
https://www.crsi.org/reinforced-concrete-benefits/economy-of-construction/

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.

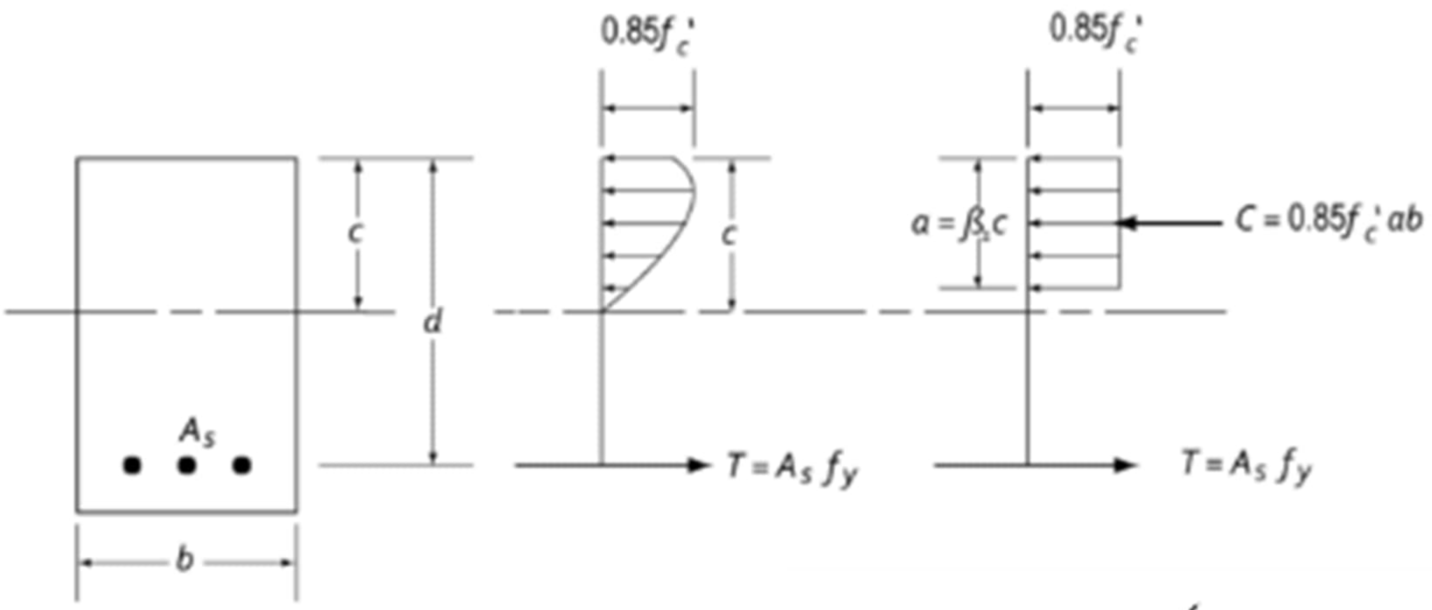




Fully Automated Procedures for robotic handling and installation of the Tunnel sections

Concepts for the structural design are more than 120 years old

- The Structural Design of reinforced concrete, 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.



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

Rectangular Stress Block
Charles S. Whitney, 1930s

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, $C+C'$,

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

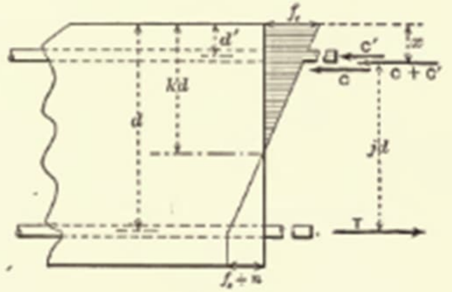


Fig. 67.

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,

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

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

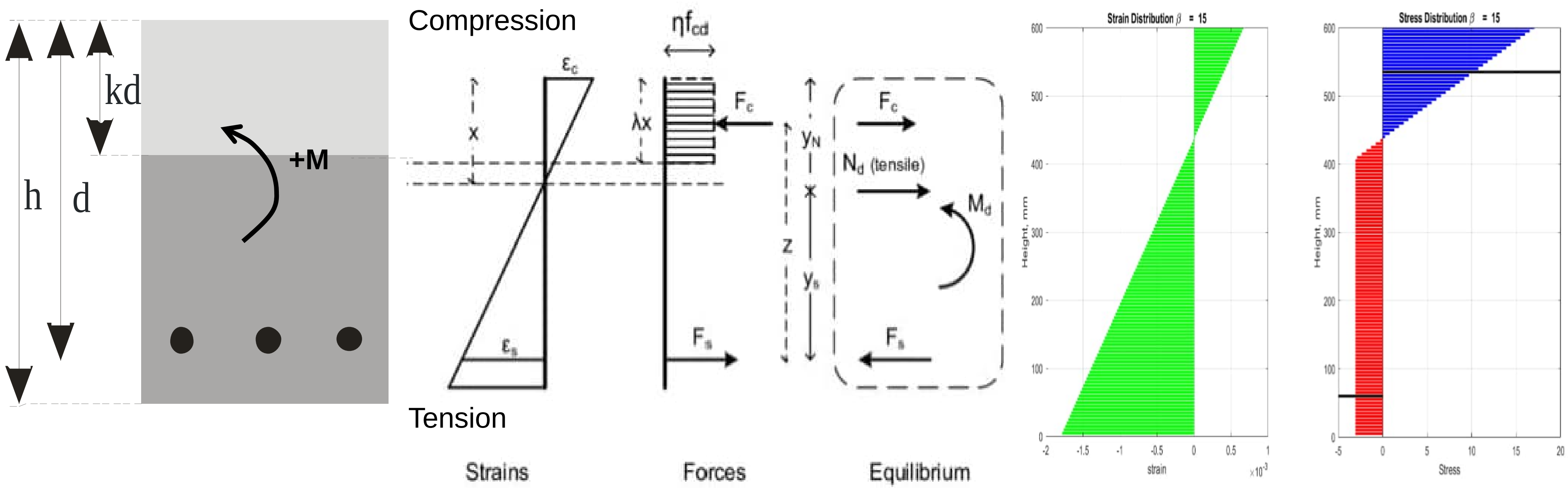
$$f_s'=\frac{n\left(k-\frac{d'}{d}\right)}{k}\cdot f_c=\frac{kd-d'}{d-kd}\cdot f_s. \quad (33)$$

Ultimate Loads formula by Tuneaure 1907

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)**



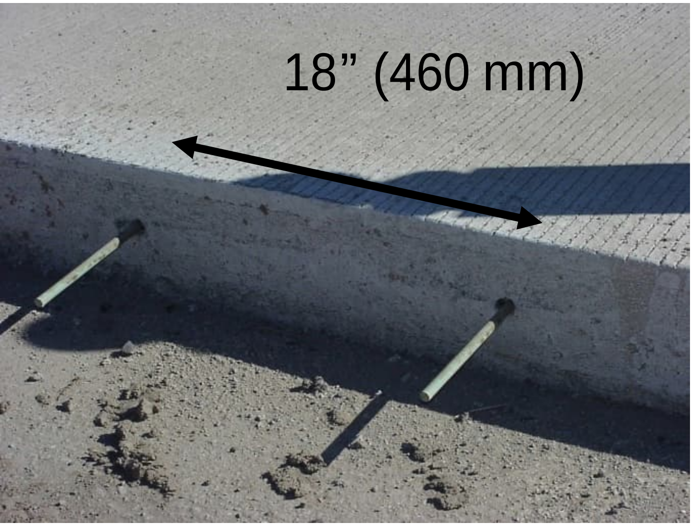
Soranakom, C., & Mobasher, B. (2008). Correlation of tensile and flexural responses of strain softening and strain hardening cement composites. Cement and Concrete Composites, 30(6), 465–477. https://doi.org/10.1016/j.cemconcomp.2008.01.007

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

Role of Supplementary Reinforcement

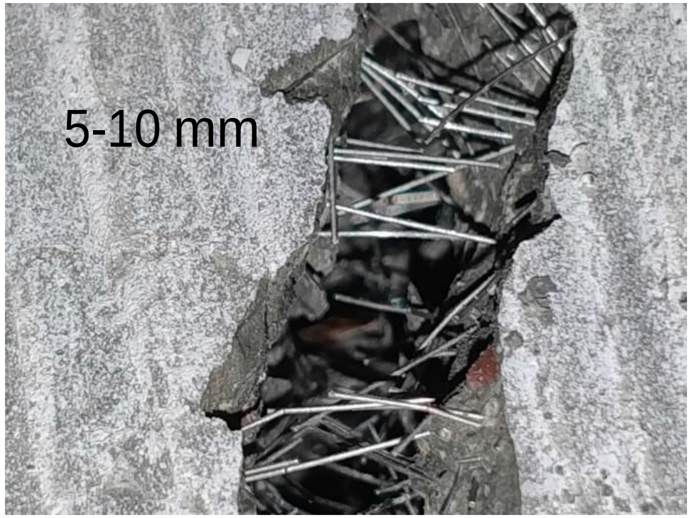
Strengthening at the microstructure level will have a profound impact at the macro-structural level strength and durability

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



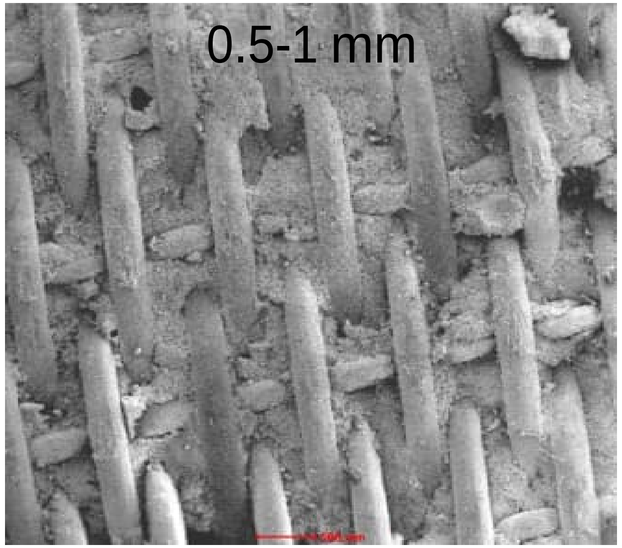
Ordinary reinforced concrete slab, 5-10” thick, standard rebars, 12”-18” apart

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

Delayed Activation of Reinforcement

Inhibited Localization

What are the potential mechanisms for toughening Concrete?

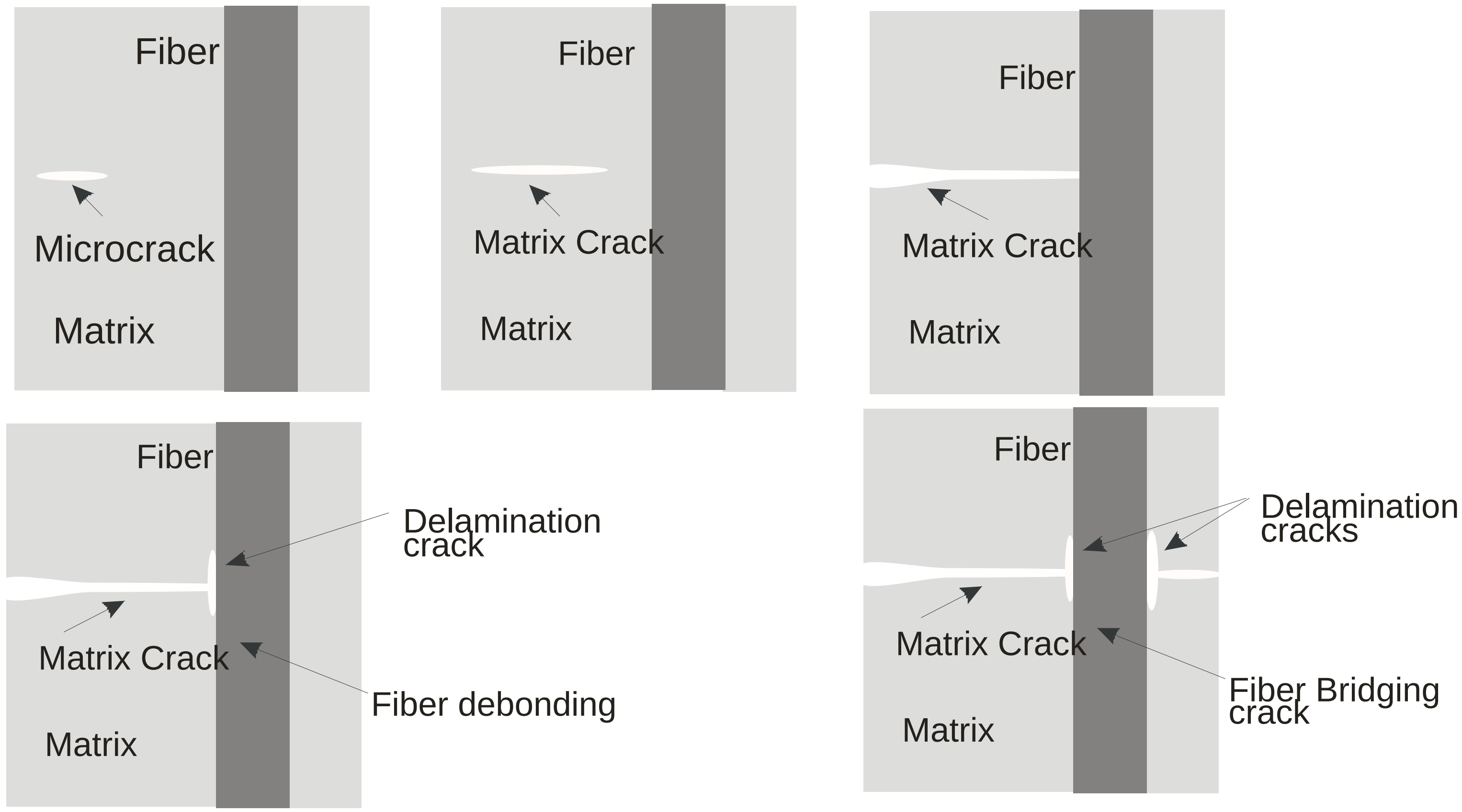
- Mechanisms:
  - Crack path tortuosity
  - Crack deflection
  - Crack bridging, fiber pullout, yielding
  - Delamination cracks
  - Multiple cracking, Tension stiffening

- Structural Redundancy in the Limit States
- Correlation of cracking with creation of new surfaces and energy dissipation
- Delay localization to increase the strength of concrete in tension
- Delays in crack propagation, reducing w/c , porosity, and improving interfaces
- Transverse Yarn anchorage by textiles

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

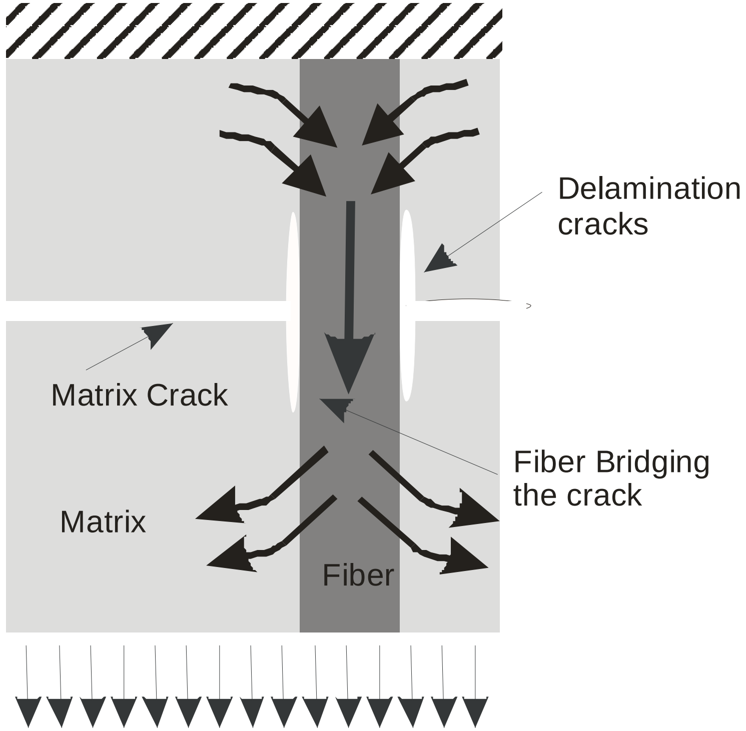
The cracking process starts from slow crack growth of a microcrack from a pore or aggregate interface, crack propagation, hindered by fibers, resulting in crack deflection, delamination, fiber bridging, pullout

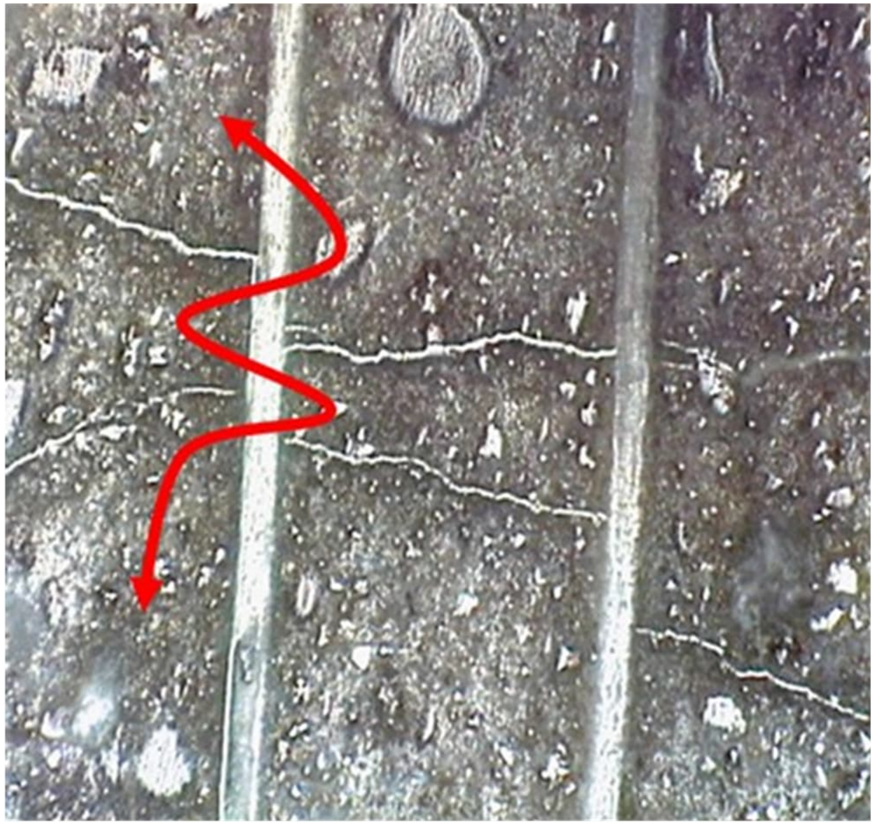
1. Stable microcrack to macro crack growth
2. Crack coalescence and growth
3. Crack arrest by fibers
4. Fiber debonding and crack deflection
5. Interface debonding
6. Full fiber debonding growth
7. Fiber bridging

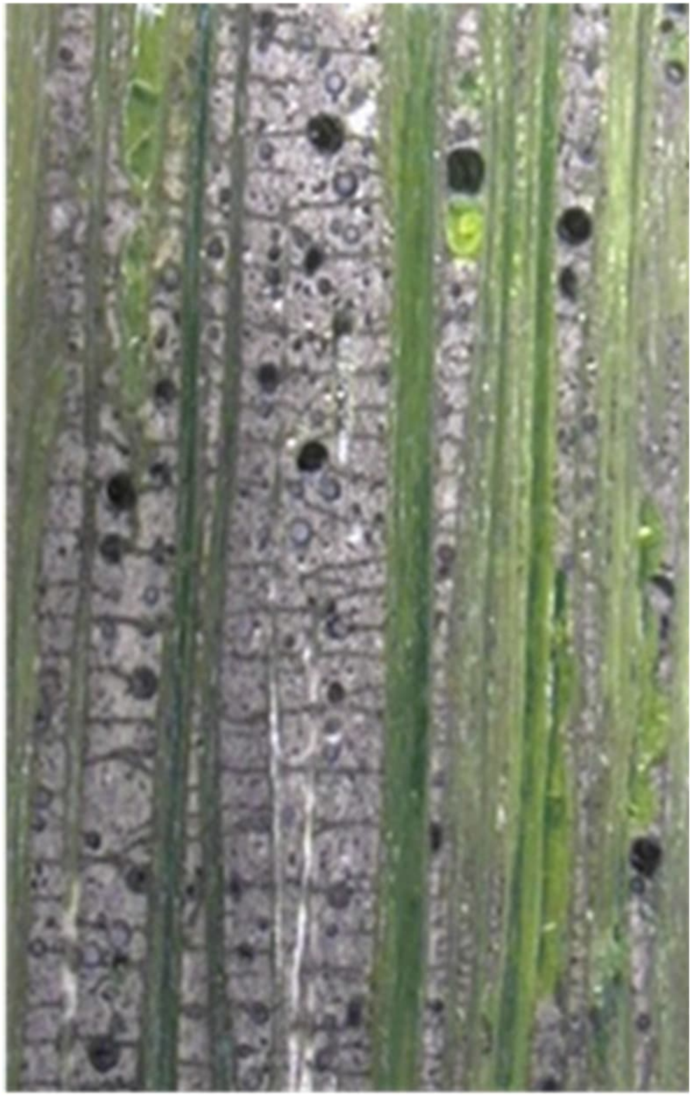


None of these mechanisms are present when the concrete is not reinforced at the microstructural level

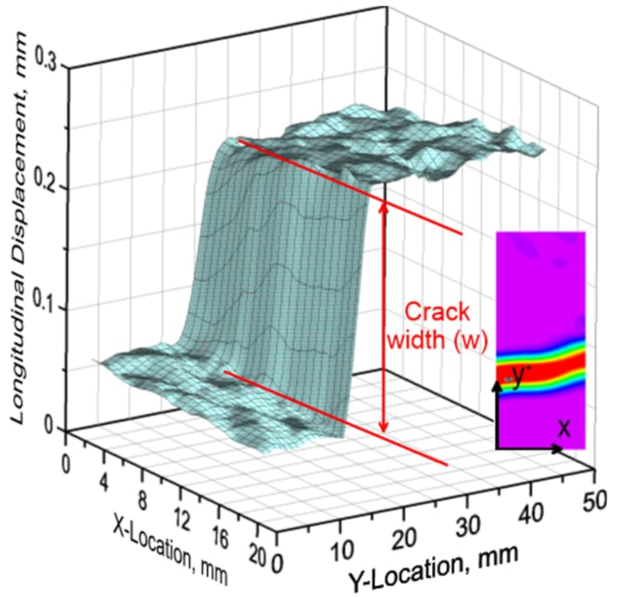
Tension Stiffening is the Fifth major mode of toughening



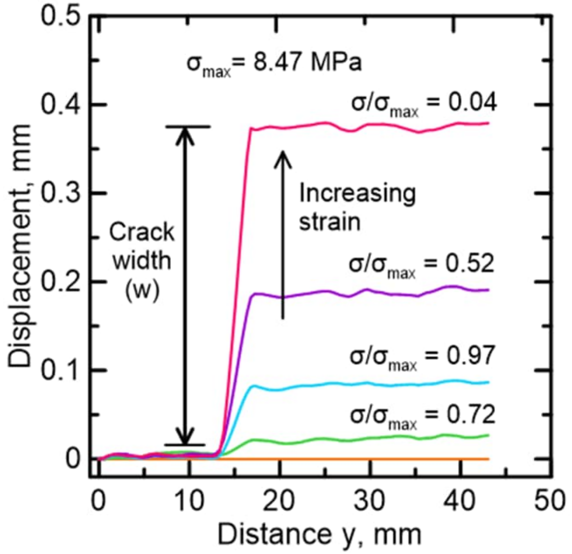




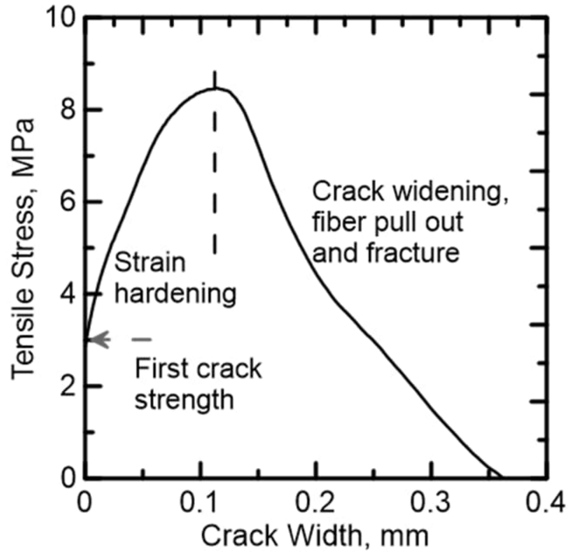
Crack Width Measurement for Strain Hardening Composite



Displacement Field



Displacement Distribution Along Specimen



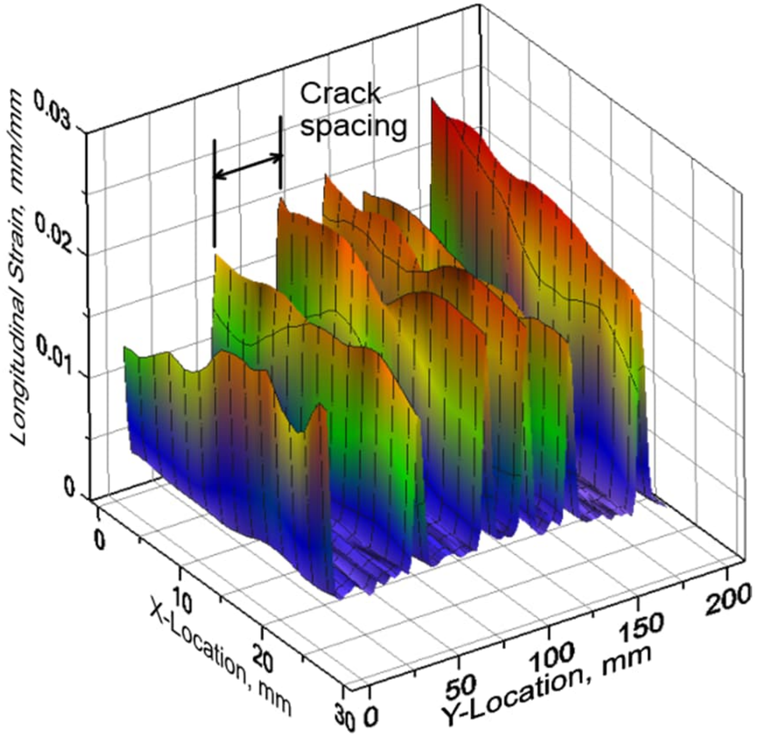
Stress-Crack Width Relationship

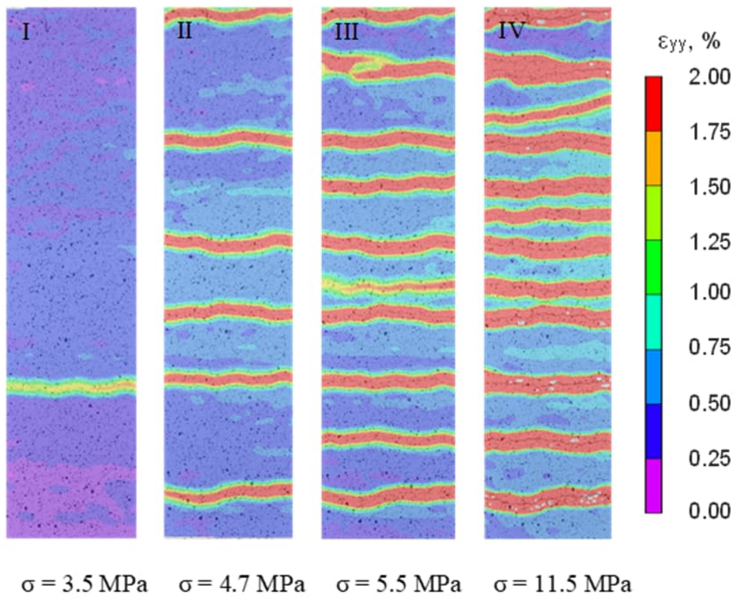
- Non-contact measurement
- Quasi-static to high speed
- Single crack and multiple cracks

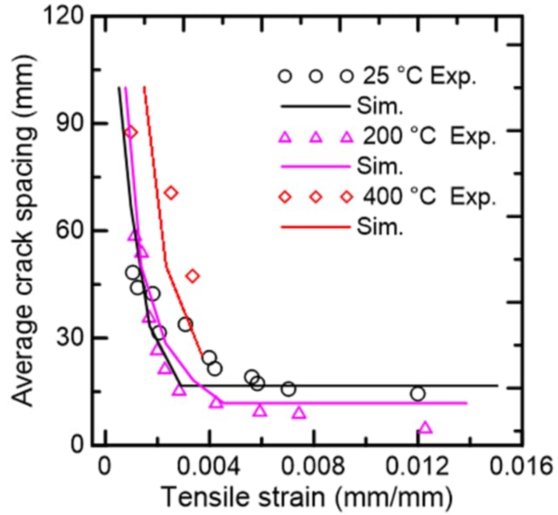
Rambo, D. A. S., Yao, Y., et al. (2017). Experimental investigation and modelling of the temperature effects on the tensile behavior of textile reinforced refractory concretes. Cem. Concr. Compos. 75, 51-61.

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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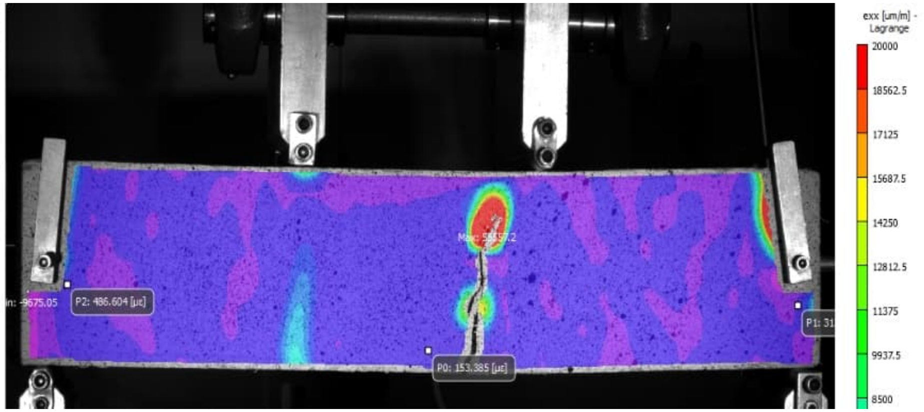
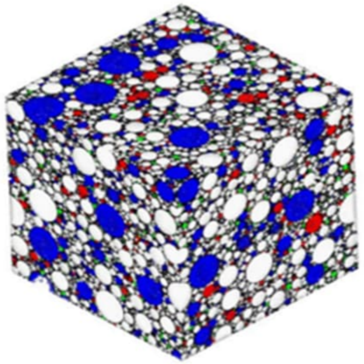
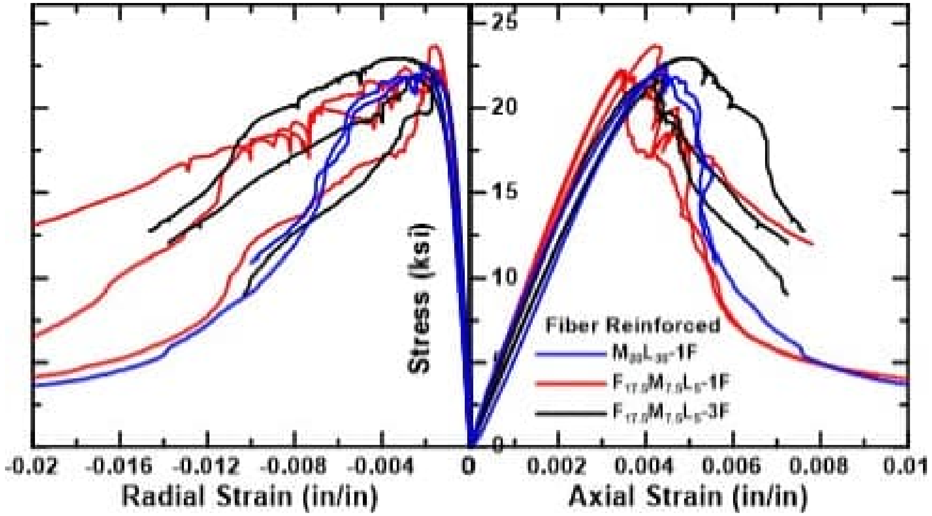
UHPC Concrete Mixtures, Bridge Replacement Strategies McDOT, Arizona, 2022

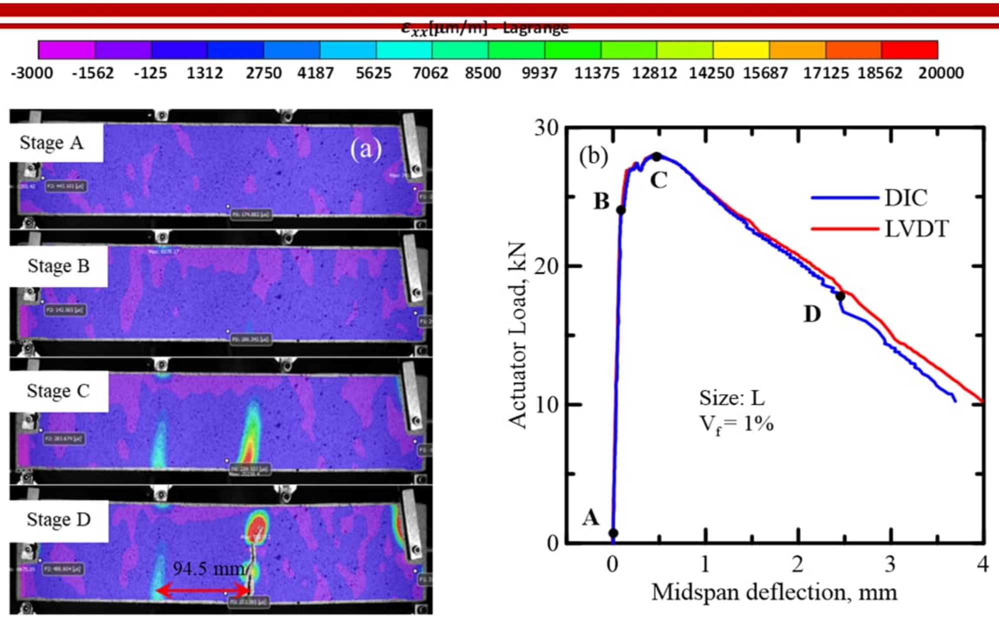
- How to replace an entire corroded Bridge deck in 10 days
- Life cycle cost and economic advantages of using UHPC systems in terms of structural applications.
- Precast UHPC elements reduce operational complications, labor-intensive tasks. From a design perspective, elastoplastic behavior improves durability, 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

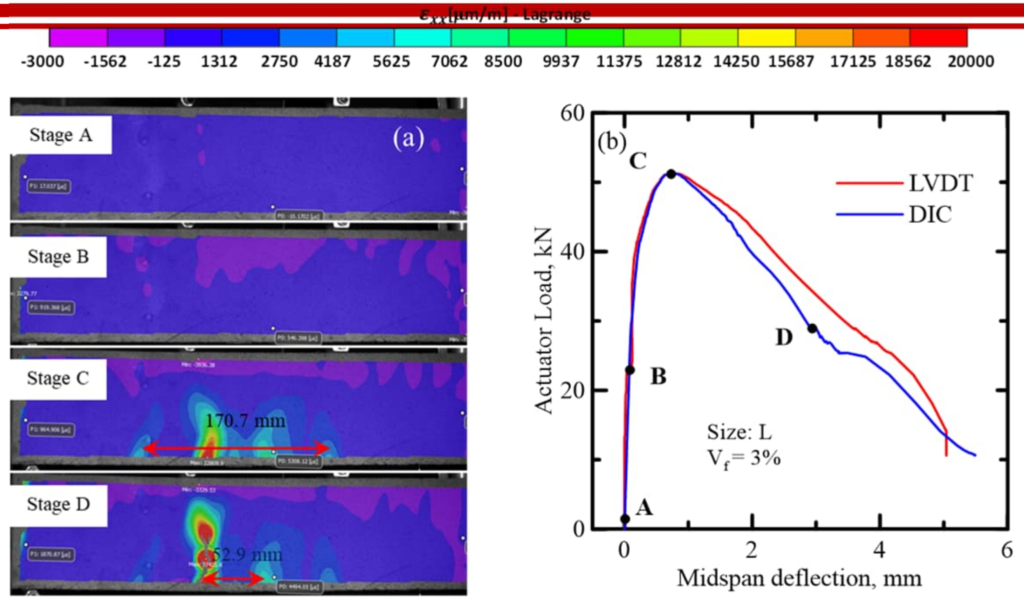




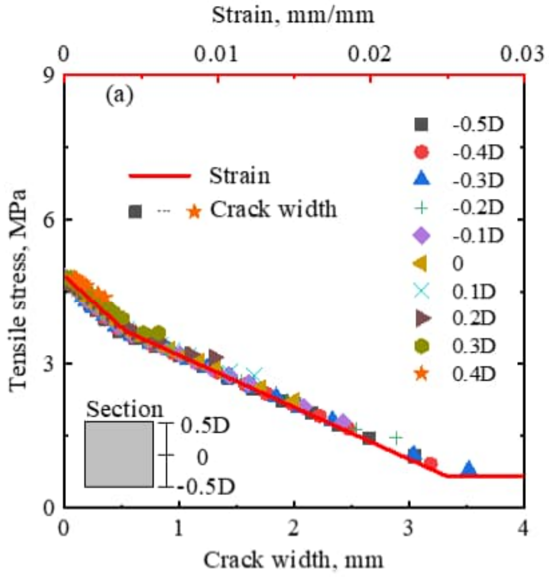


UHPC with 1% and 3% steel fibers, Stress Crack width Response

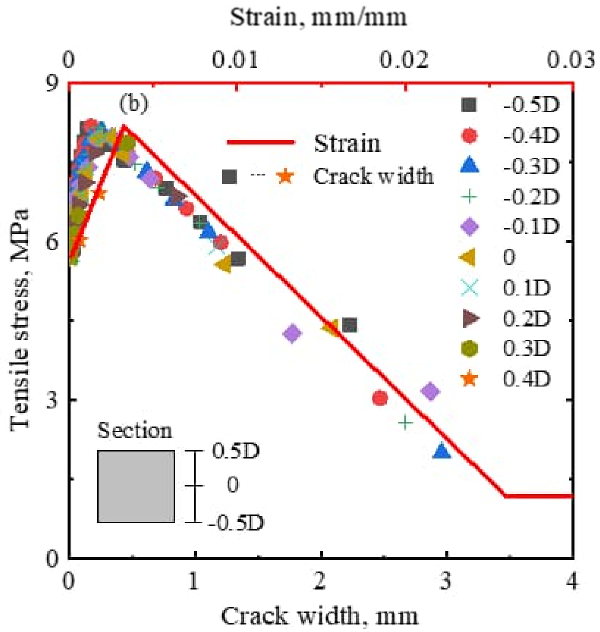




1% steel fibers

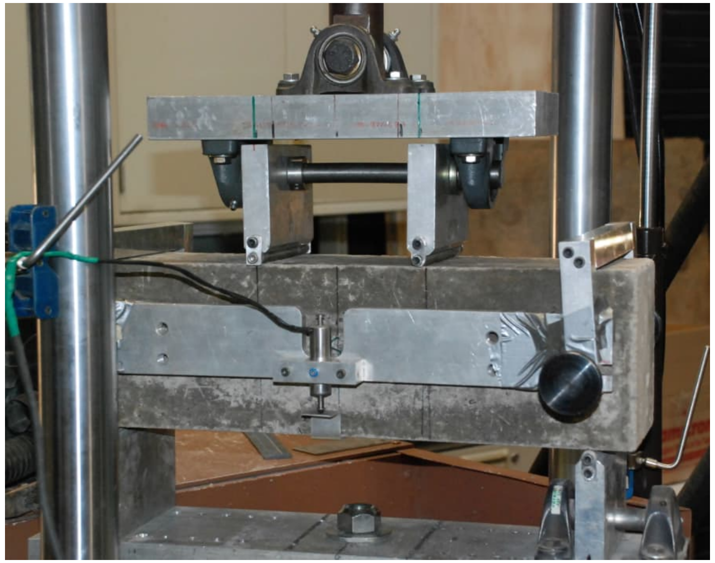


3% steel fibers

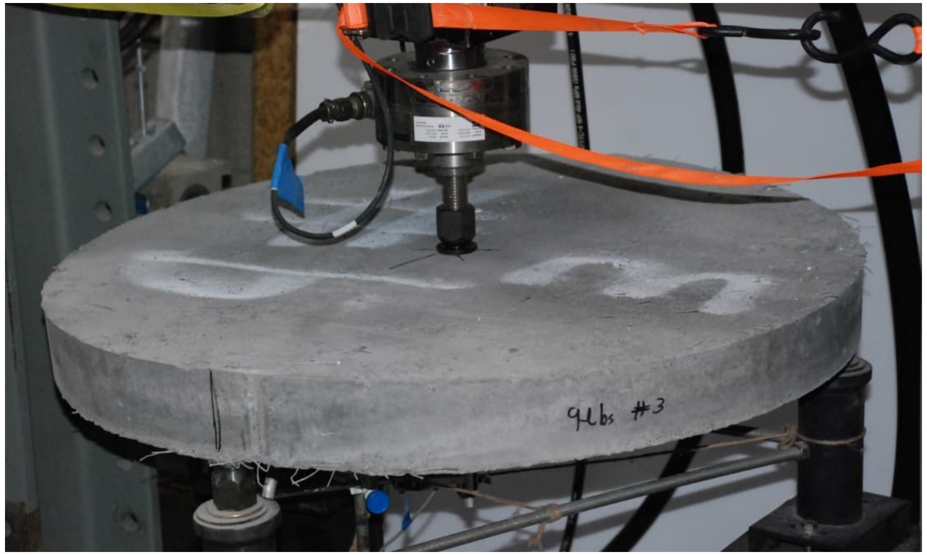


Specimen Level Testing Approaches

- FRC Material properties analyzed using standard closed-loop Testing at ASU
- Developing Closed-form solutions for Parameter Extraction using a parameterized approach
- A host of other characterization techniques



ASTM C1609



ASTM C1550

ASTM C39M

- Load-Deflection response
- Simulate L-D using parametric tension and compression models
- Backcalculation of other geometries using the bilinear/trilinear/quadrilinear approach

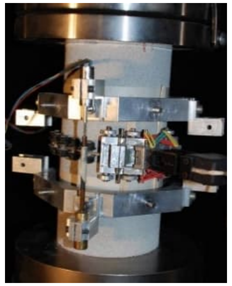
Modelling procedures

- Tension model
- Compression model
- Bond (interface) model
- Stress/strain distribution
- Moment-curvature relationship
- Normalized parameters
- Incorporations of equilibrium equations
- Moment and curvature distributions throughout the volume
- Integration, application of boundary conditions
- Data reduction and solutions for stress, strain, load, deflection distributions

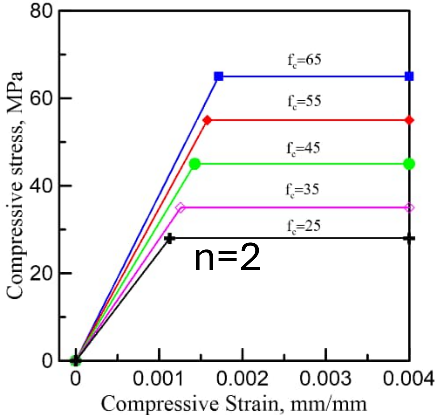
Mechanical Characterization and Design From laboratory to structure scale

Laboratory Scale

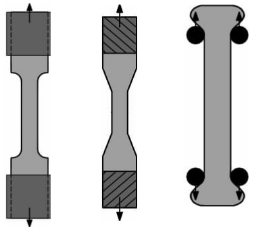
Compression



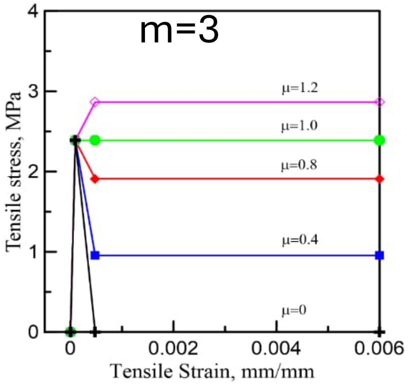
Uniaxial Compression

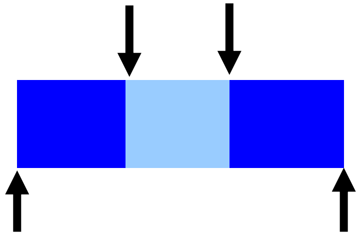


Tension



Uniaxial tension

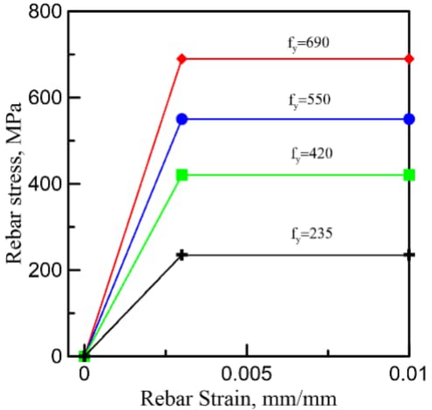


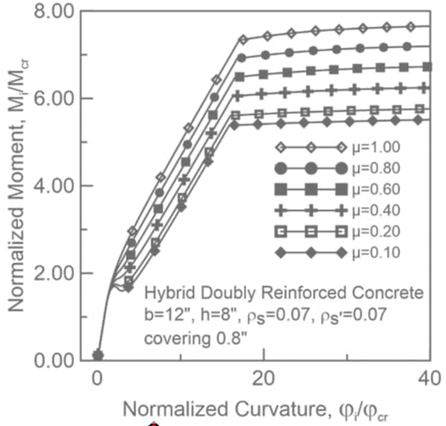


Flexural tests

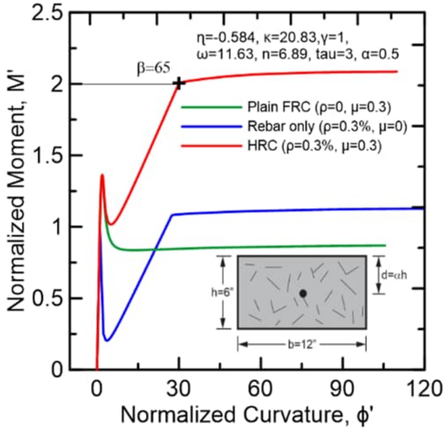
-ASTM C1609
-EN14561

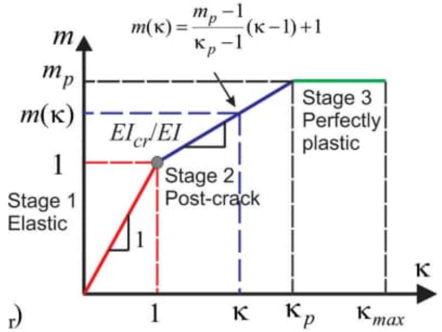
Reinforcement





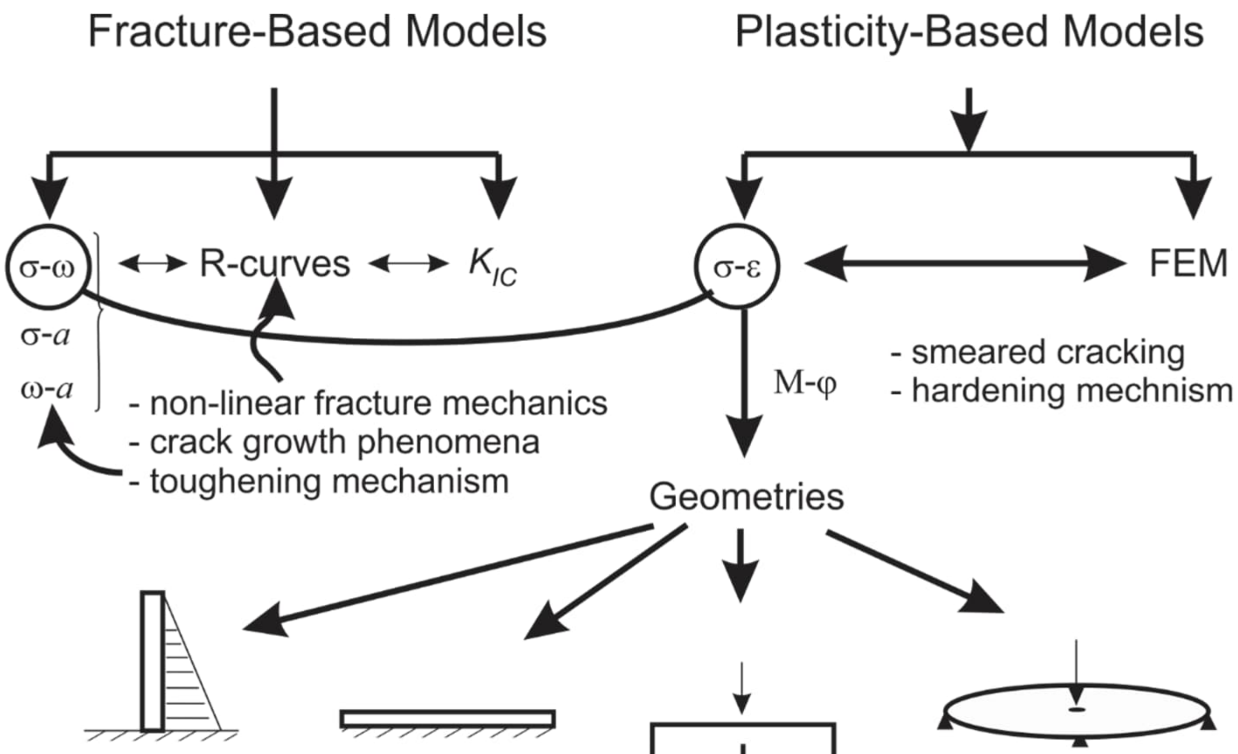
Closed-Form Solutions

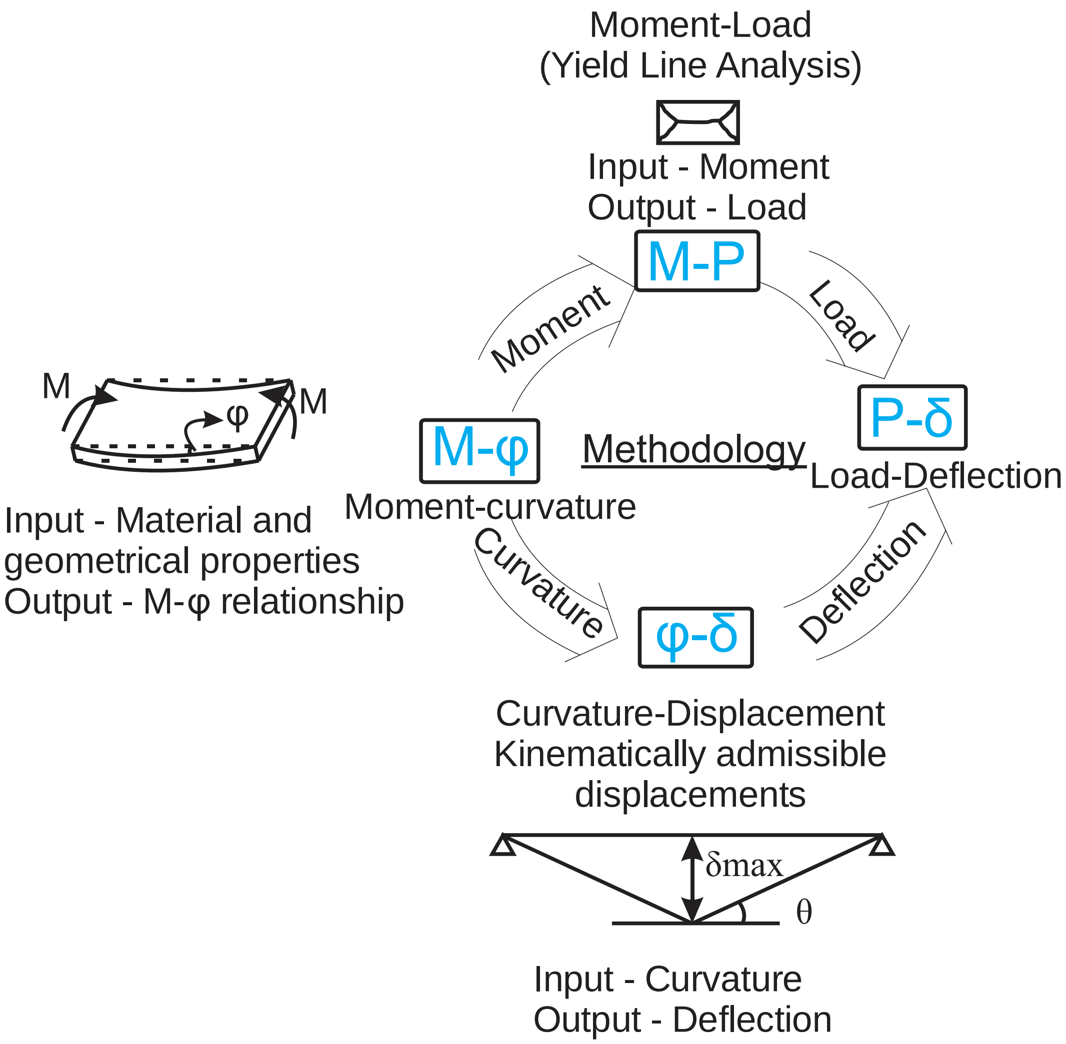




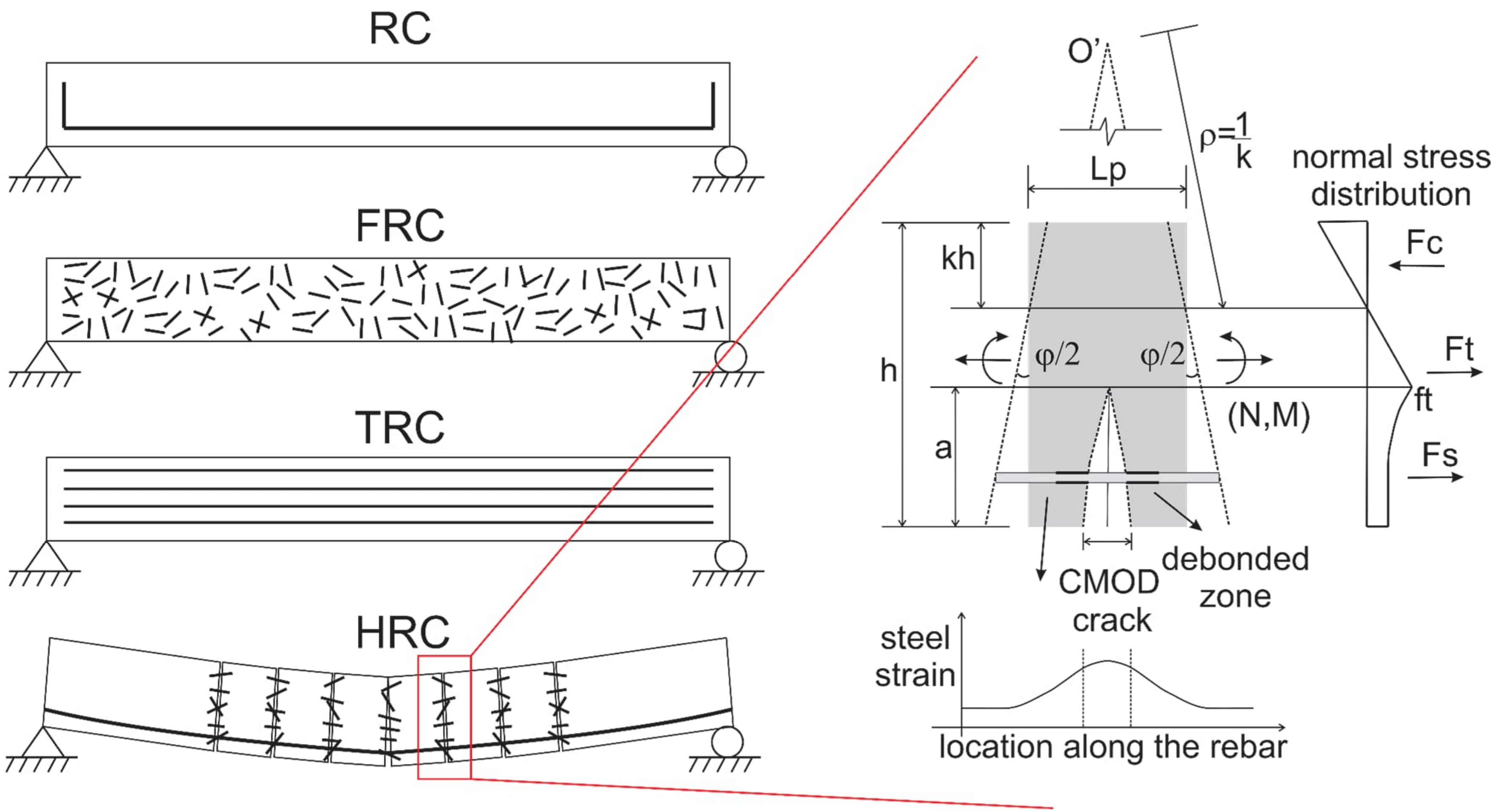
Ira A. Fulton Schools of Engineering
ARIZONA STATE UNIVERSITY

Fracture and plasticity models



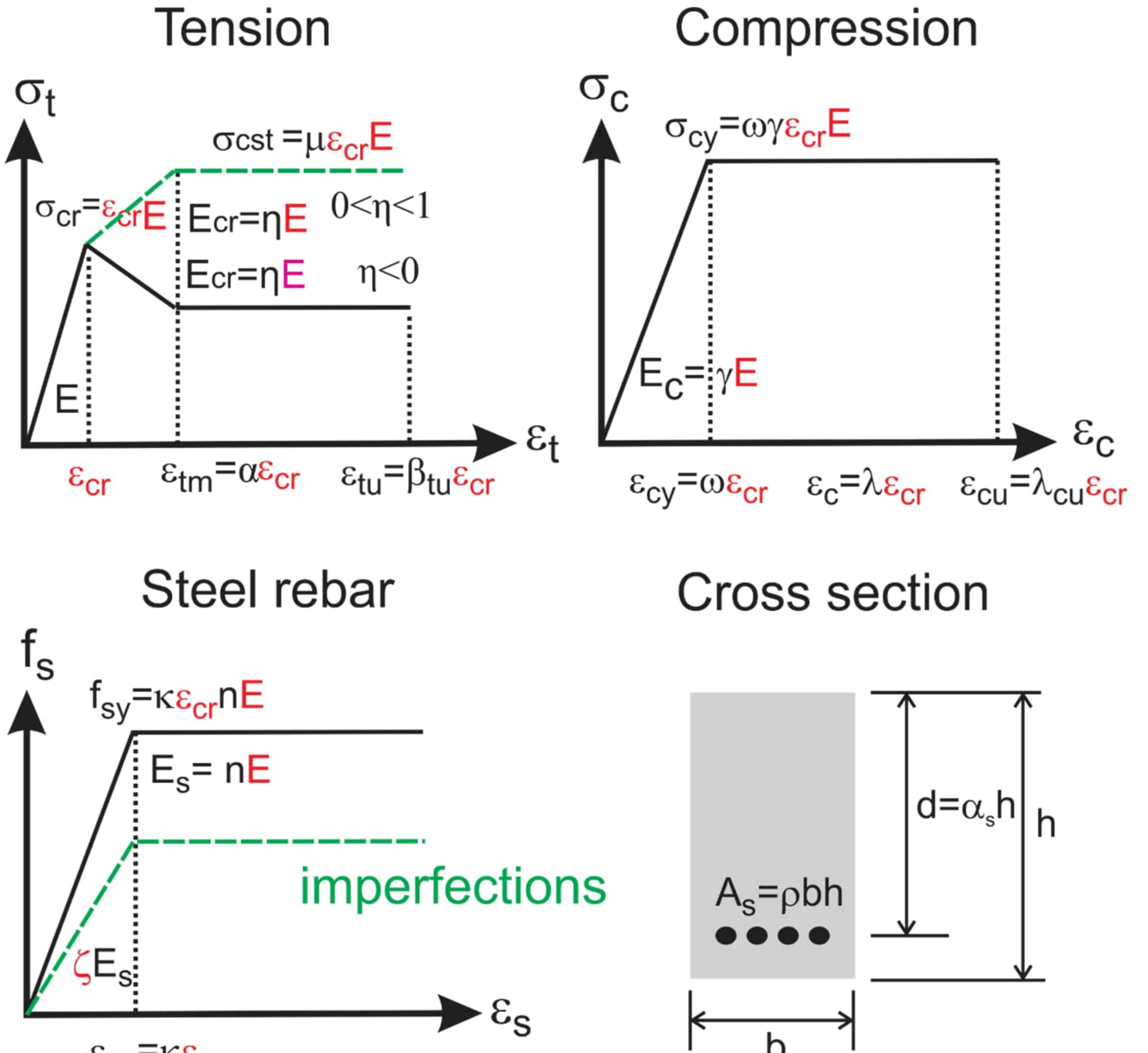


Localized hinge



Methodologies to account for the contribution of fibers

Parameterized Material Models



Moment-Curvature Relationship using the Strain Compatibility Analysis

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

Strain Distribution

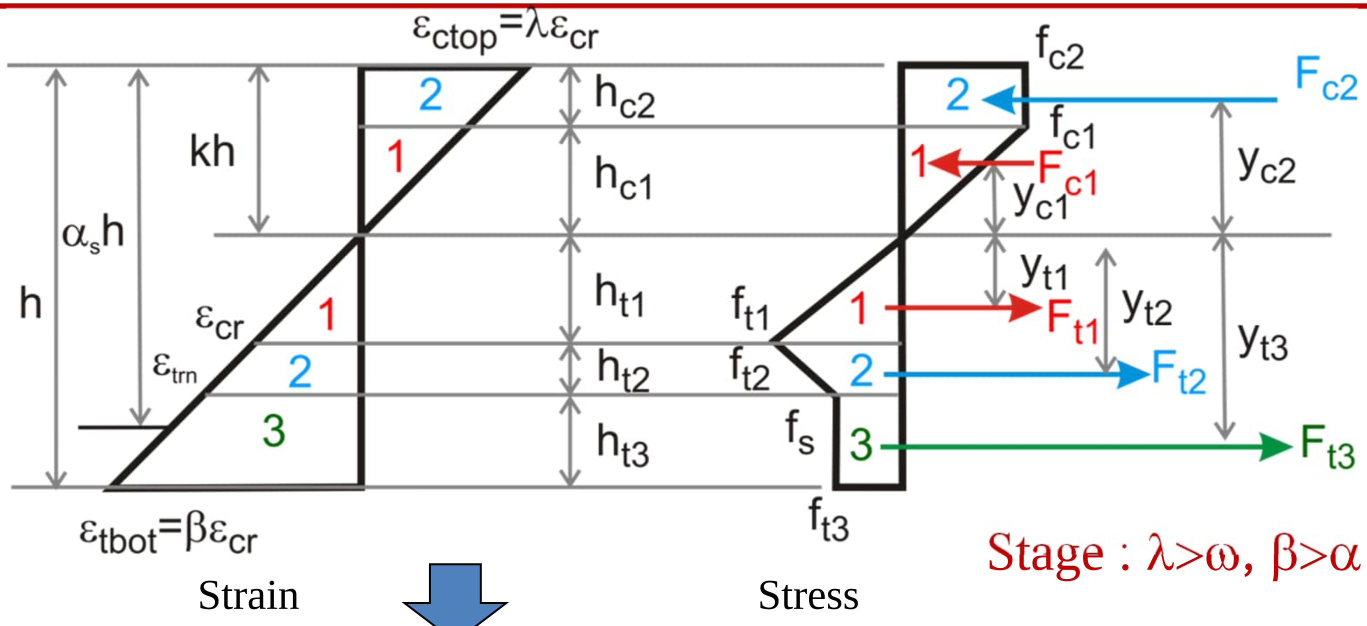
Stress Delivery

$\Sigma F = 0$, determine k

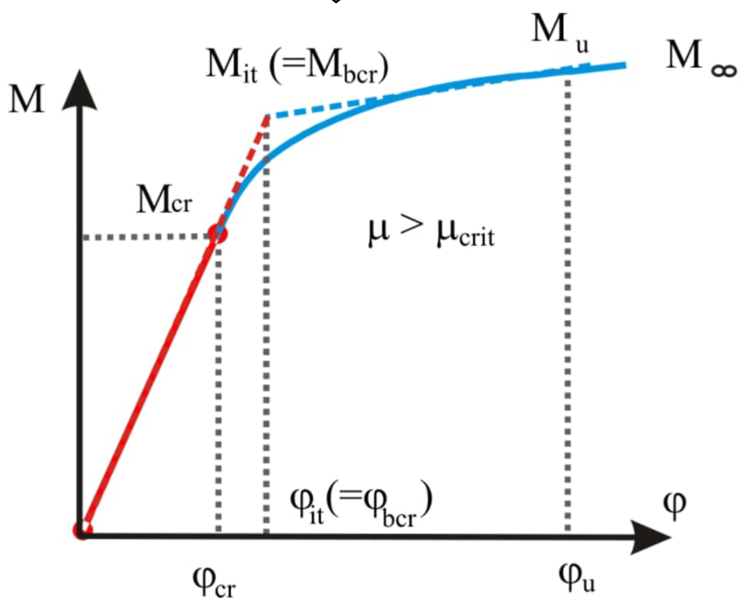
Moment:

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

Curvature: $\phi = \varepsilon_c / kh$



Stage : $\lambda > \omega$, $\beta > \alpha$

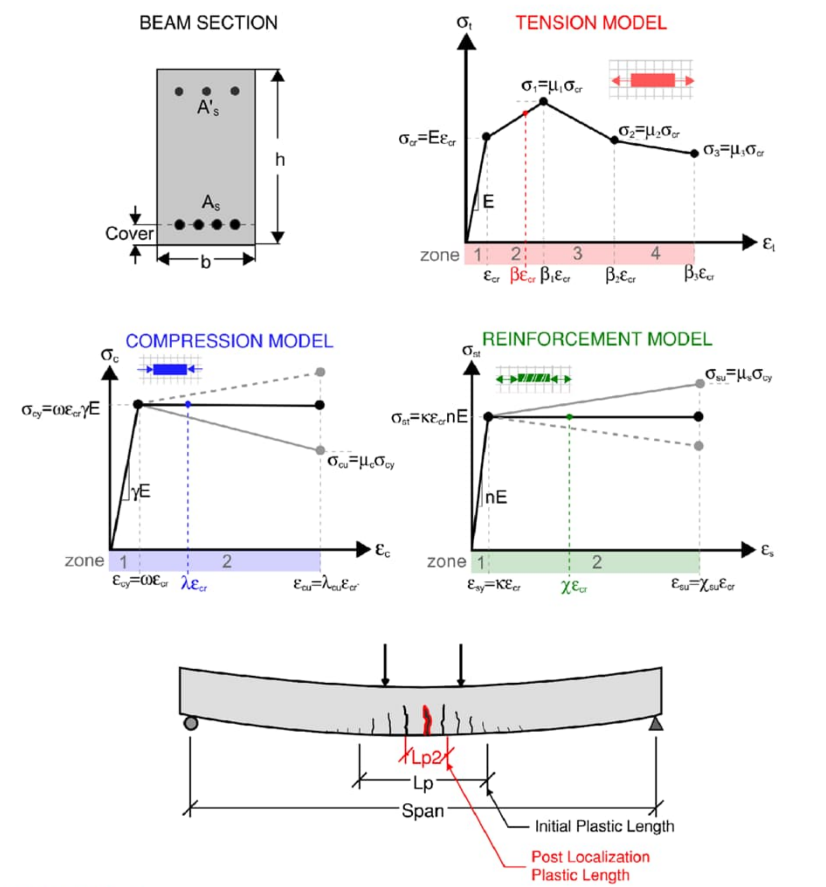


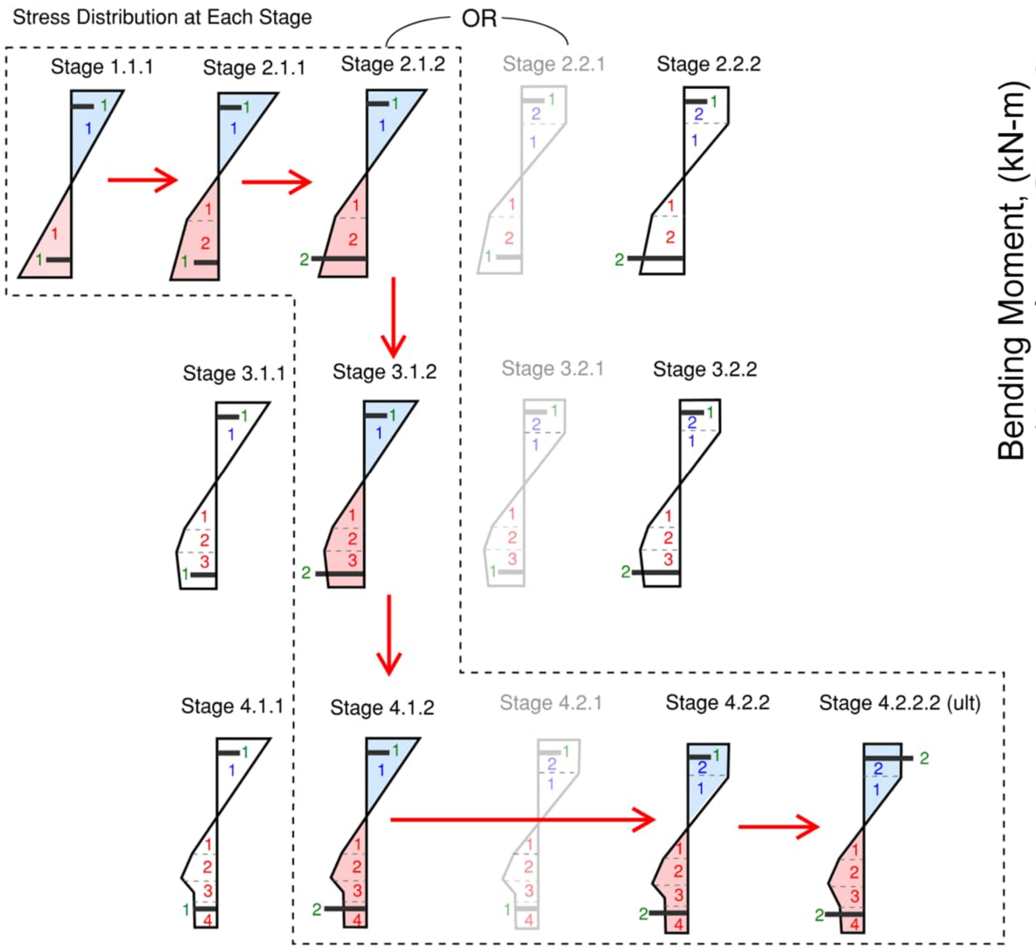
Simplified bilinear moment-curvature

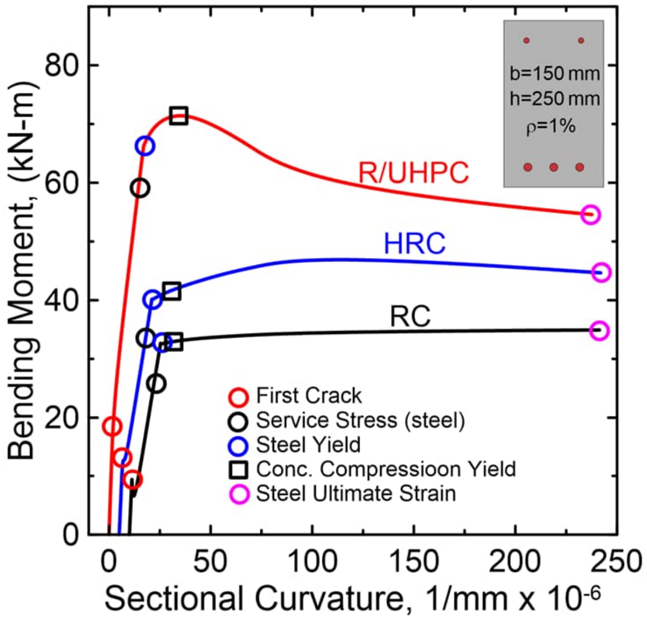
Flexural Modeling of Reinforced FRC/UHPC (Hybrid Approach)

- Closed-from based analytical Model for flexure simulation and Inverse analysis

Parametrized Input Model → Closed-Form Solution for k, M, φ at For all Possible Stages → Full Moment-Curvature Response







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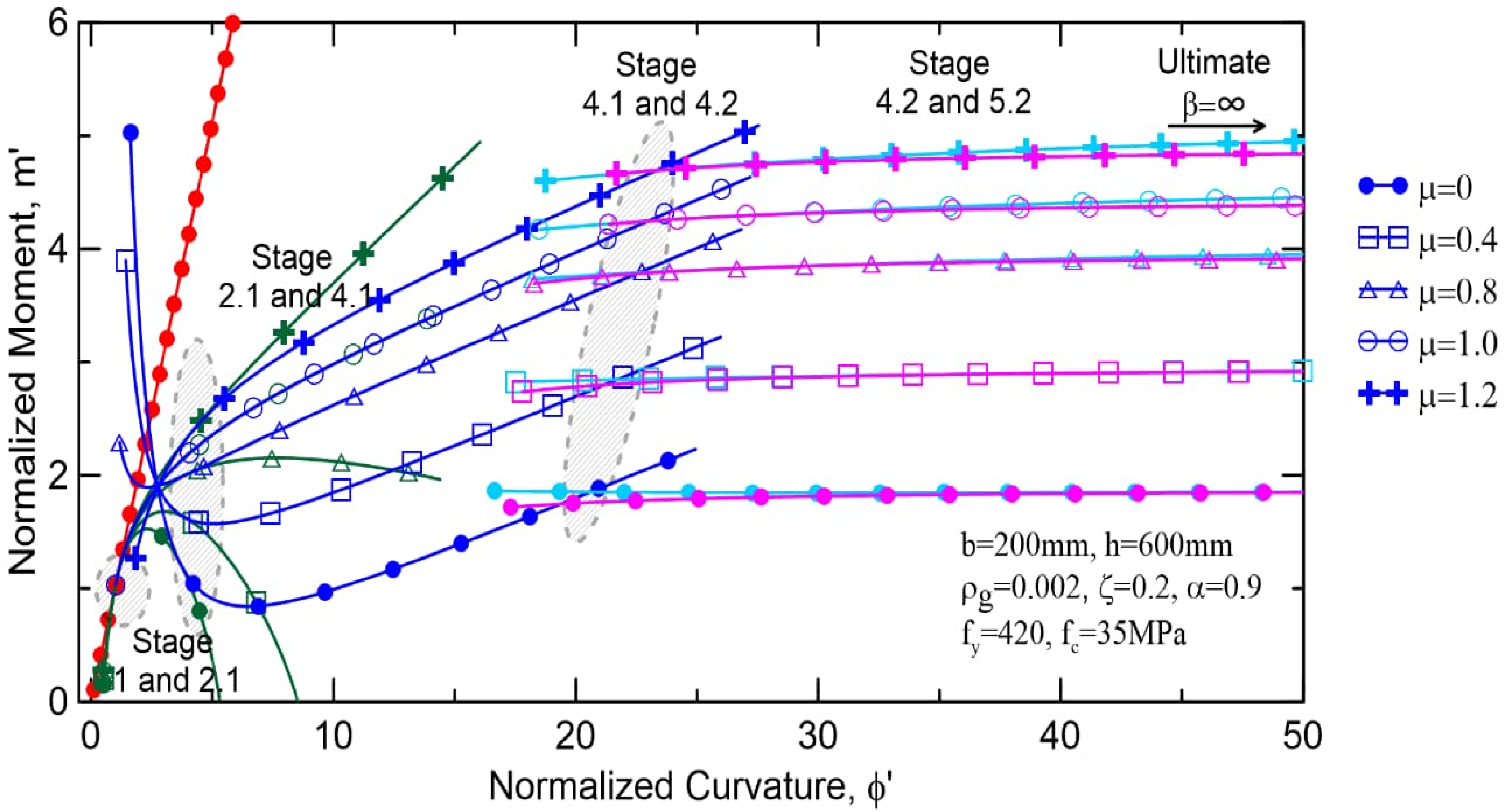
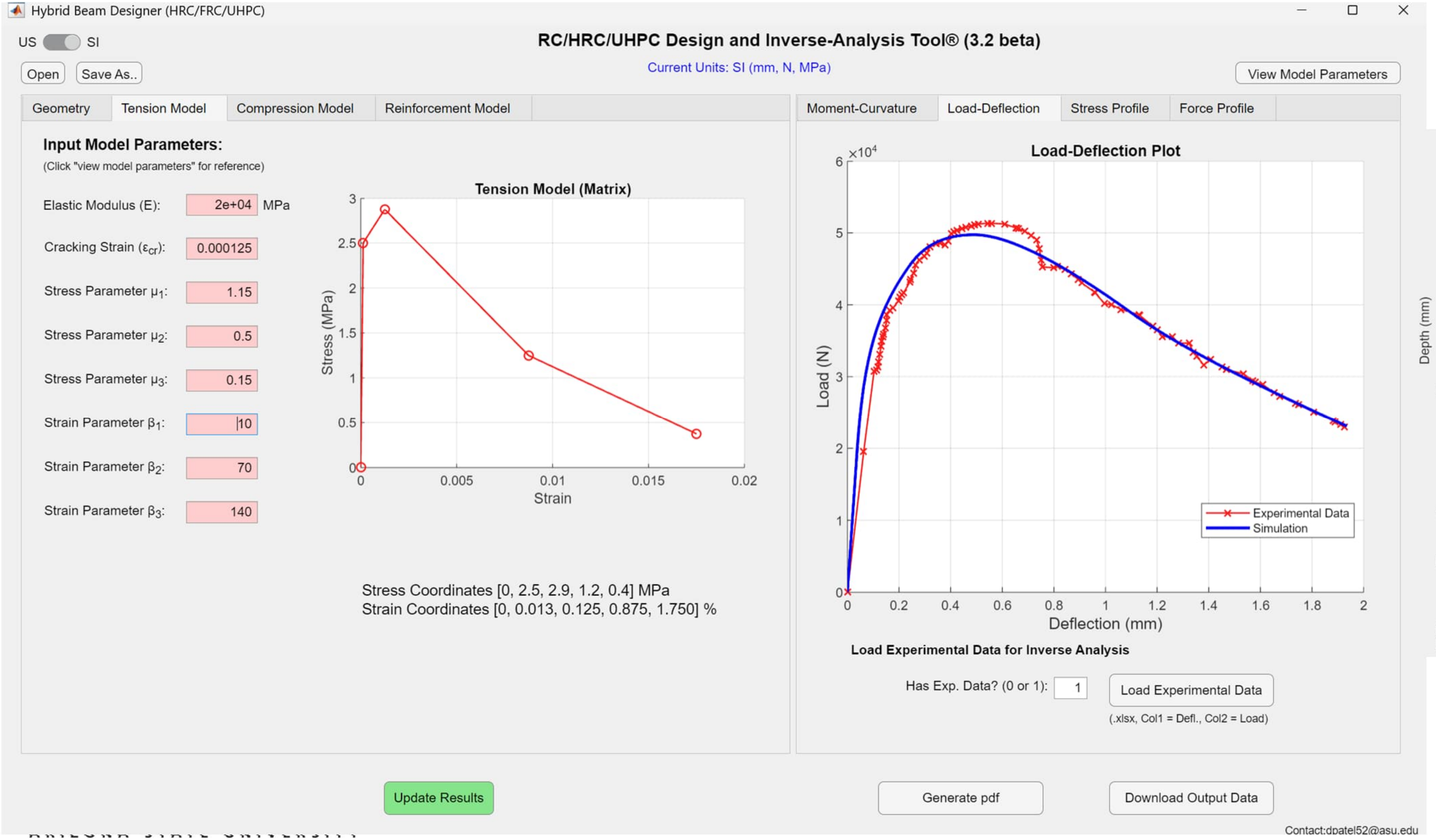
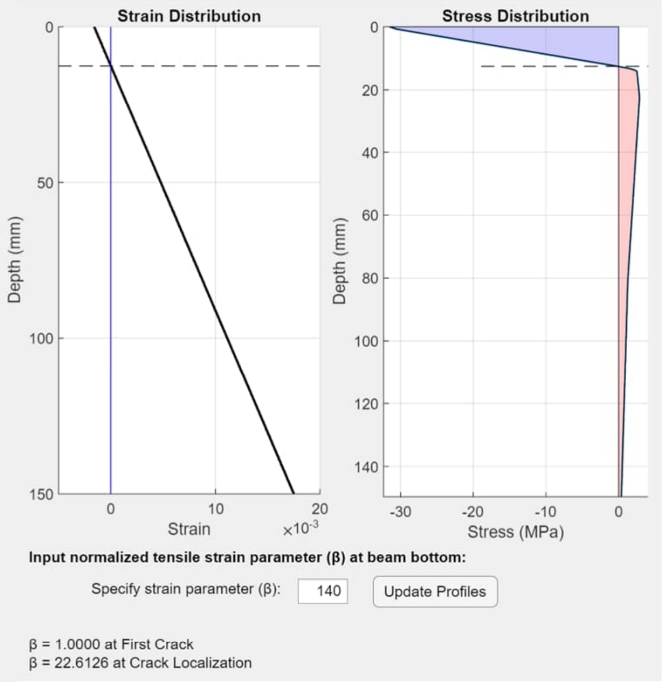
Envelope Moment-Curvature



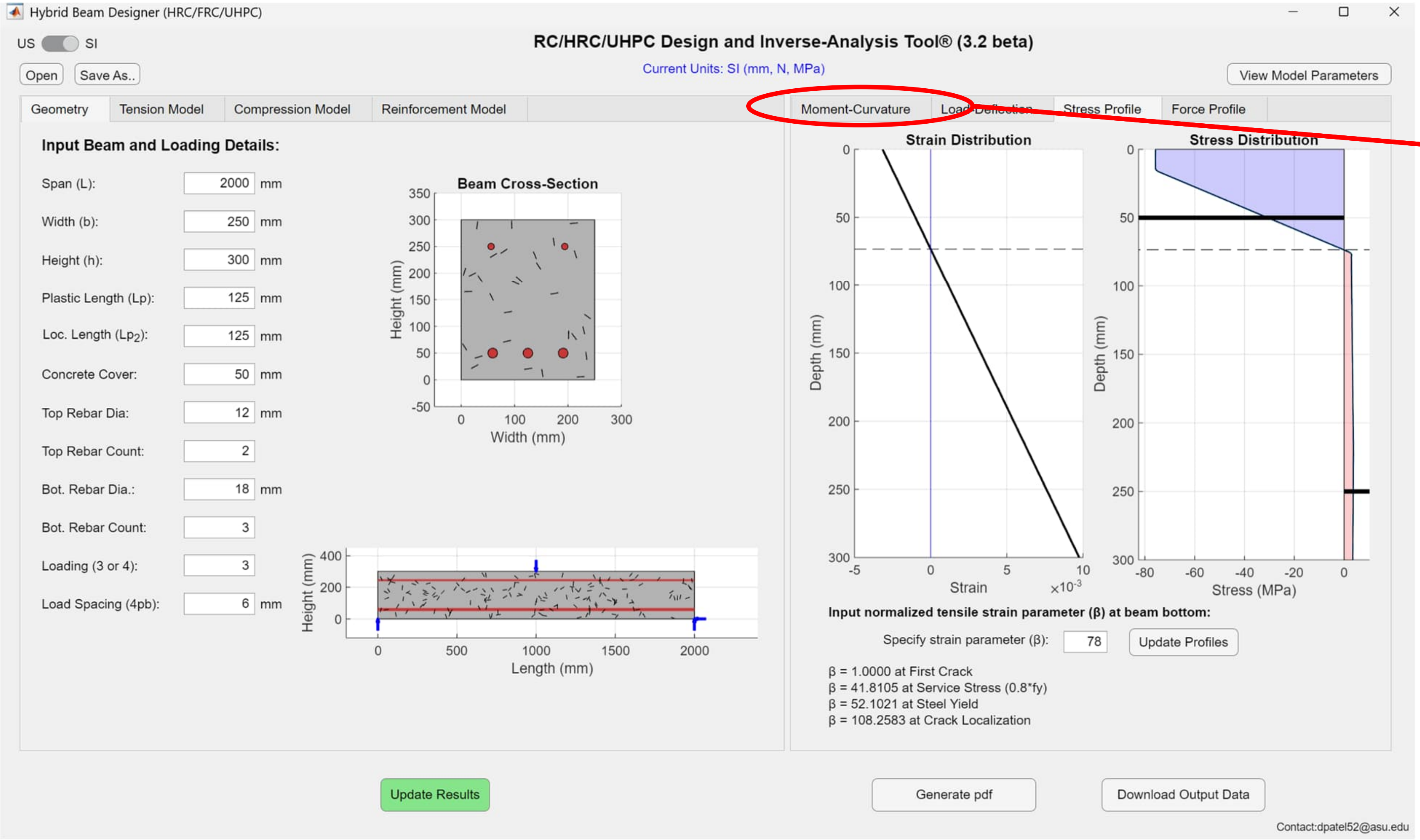
Inverse Analysis for precise characterization

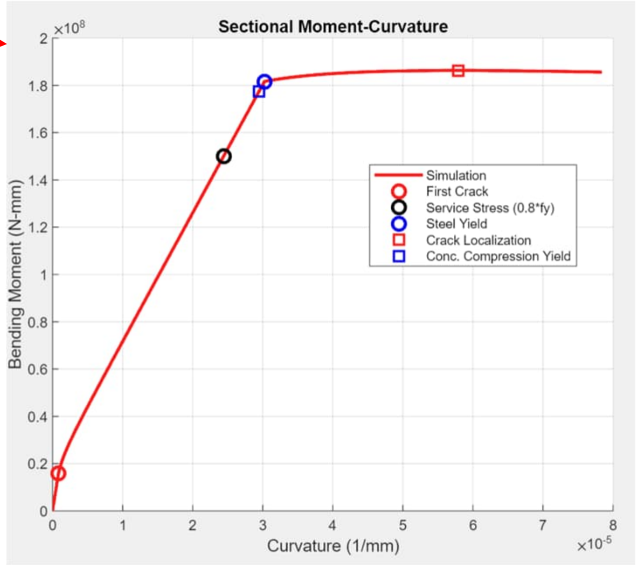
-Quadrilinear model





Design software for Plain FRC, UHPC using parametric Modeling





Load Frame for full scale testing of Precast Tunnel Segment

Hydraulic rams with 900 kN max. loading capacity, each

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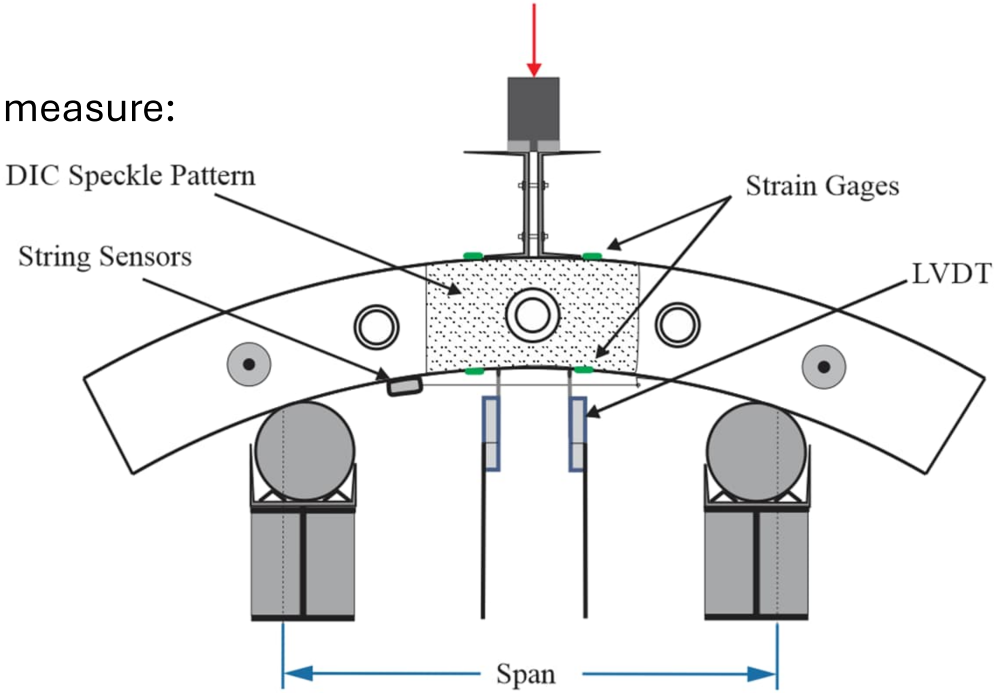
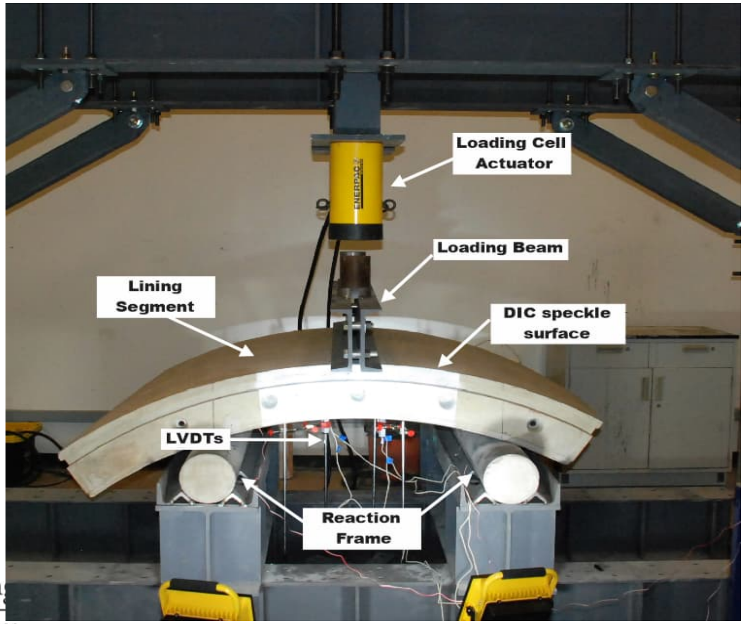
Flexure 3 or 4 Point Bend Test Setup
Max. flexure loading capacity of 400 kips (1780 kN)

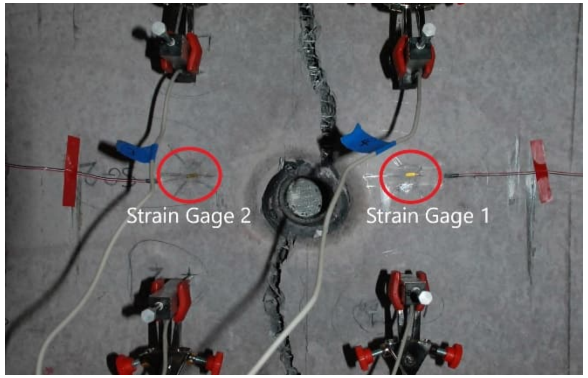
Analysis of PCTLs through full-scale testing

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)

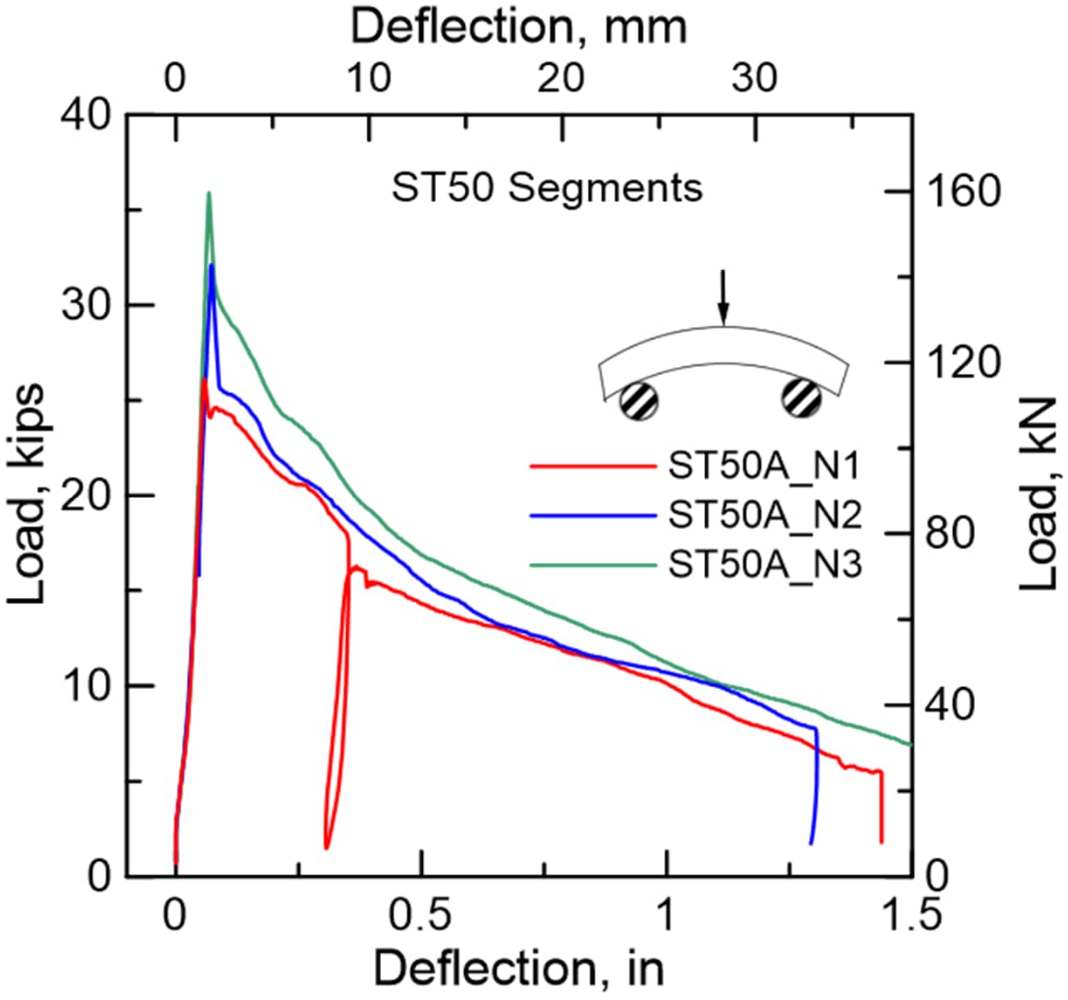






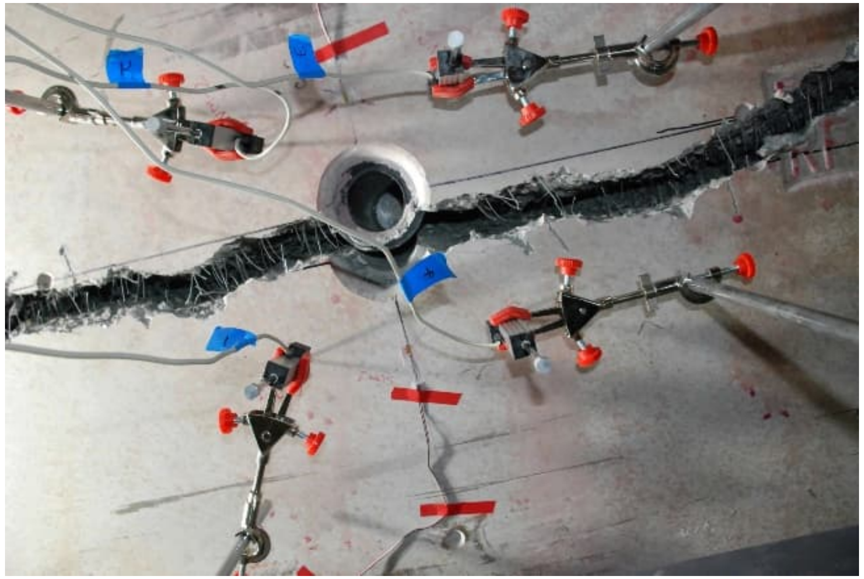
Strain gage in Tension zone, Bottom view

Load Deflection Response, SFRC, Full scale Tunnel Lining, 38kg/m^3



N1,N2, N3 are three replicate Samples, note the variation

Cracked SFRC segment



Full scale Edge Compression Testing of Precast Tunnel Segment

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

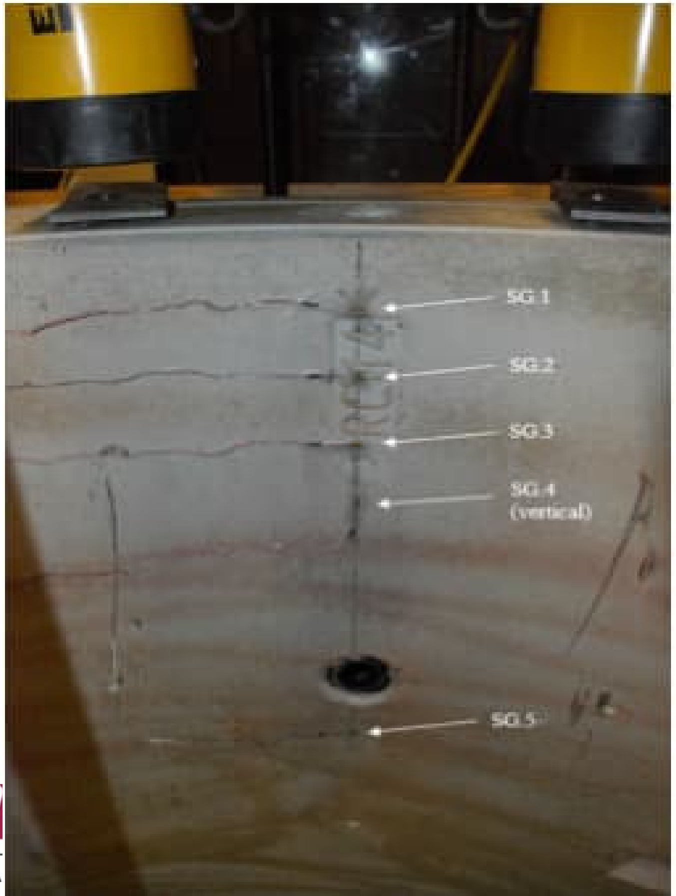
Load Frame for compression testing

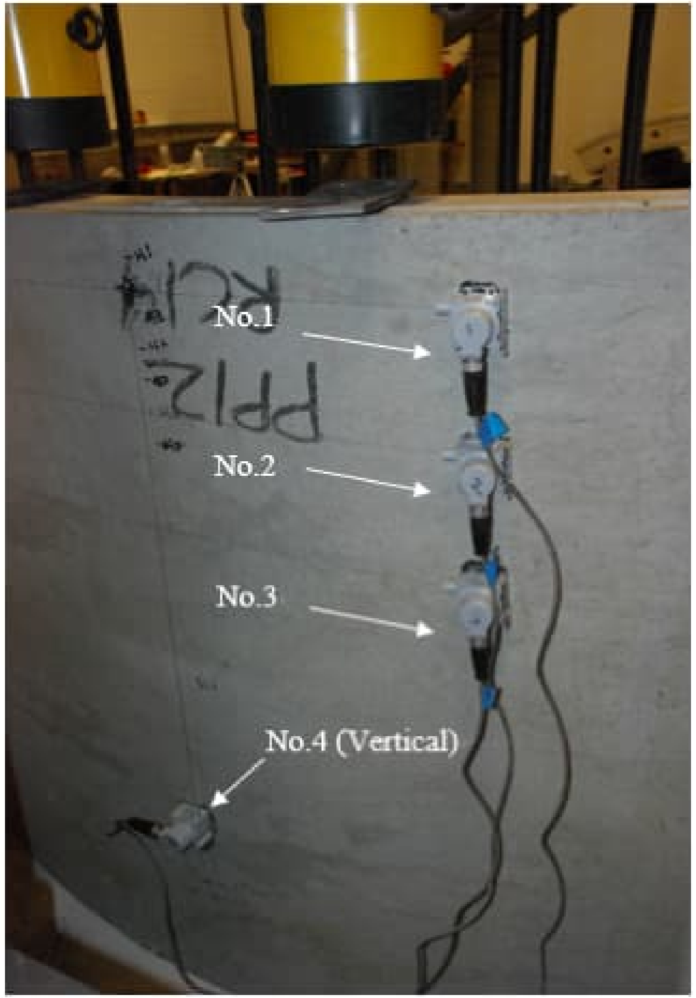
Hydraulic rams with 200 kips max. loading capacity, each

Instrumentation of Edge Compression testing

Total Instrumentation in Compression Testing to measure:

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

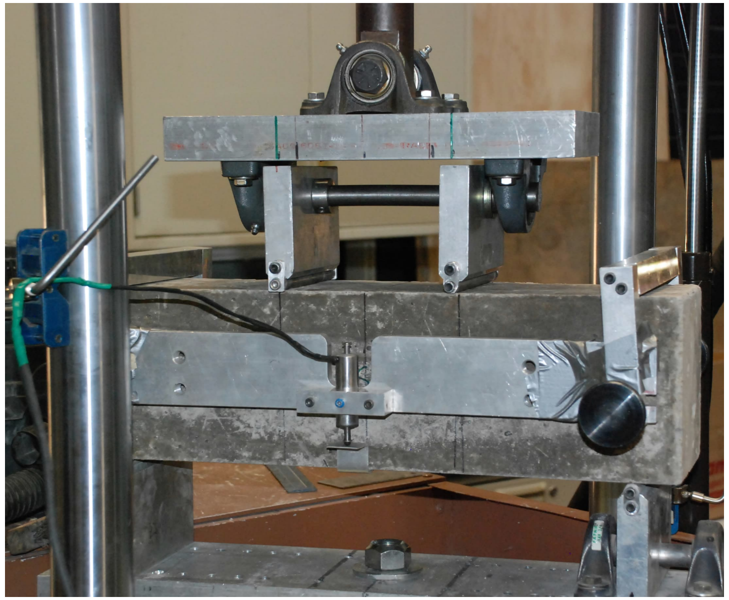


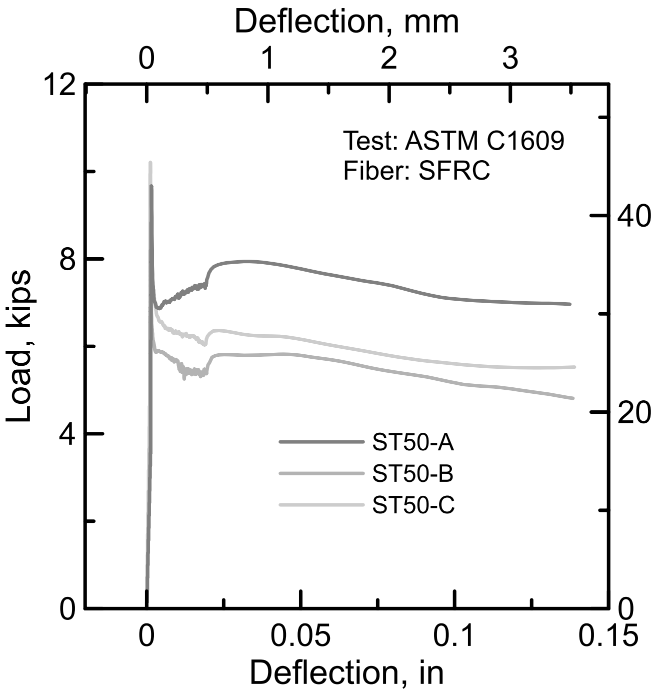


Tensile Cracking during the Edge compression tests

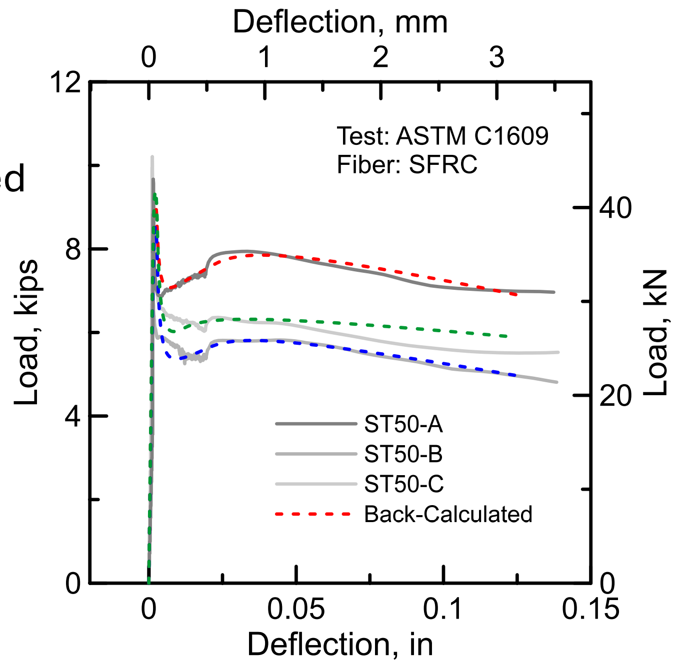
Tracing Cracks at every loading Stage

Quadrilinear Modeling for Simulating the response of tunnel segments based on ASTM C1609 Tests



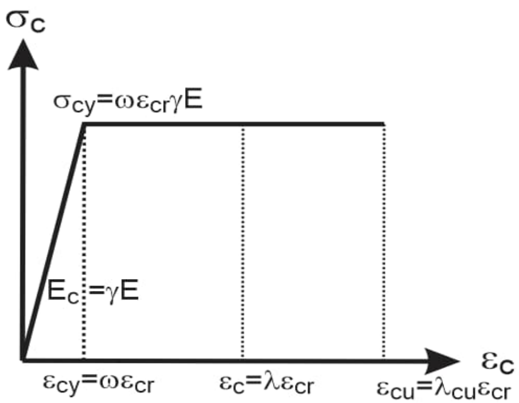


Model Simulated Data

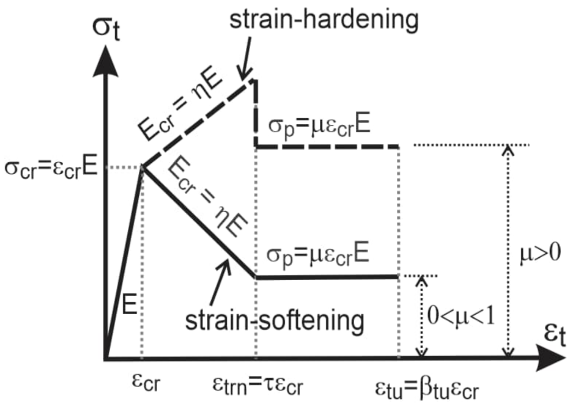


Constitutive Response

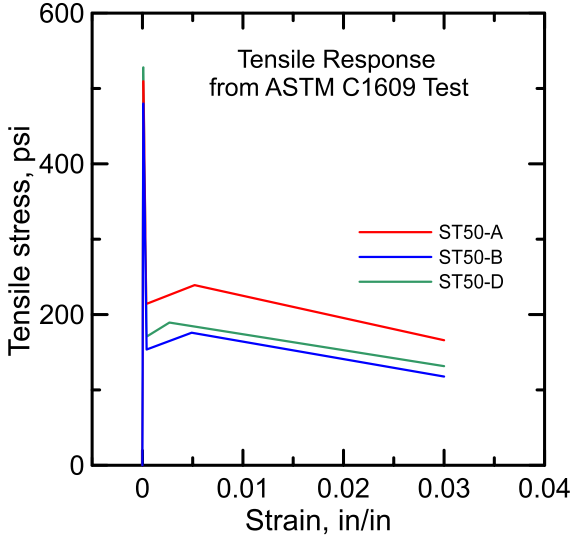
(a) Compression Model



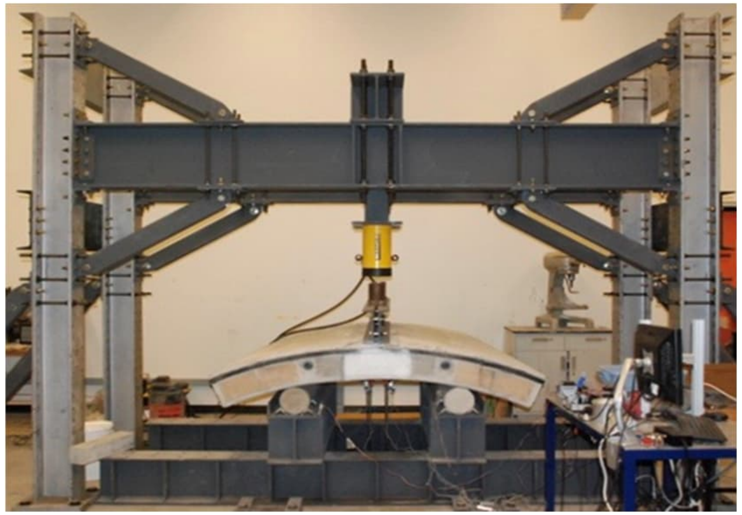
(b) Tension Model

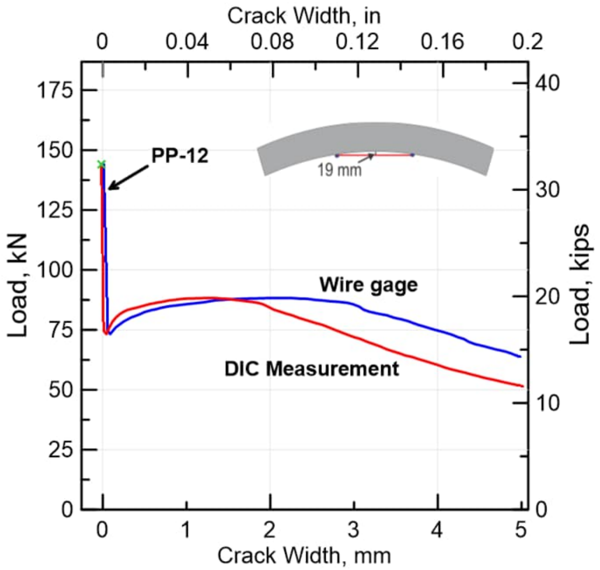


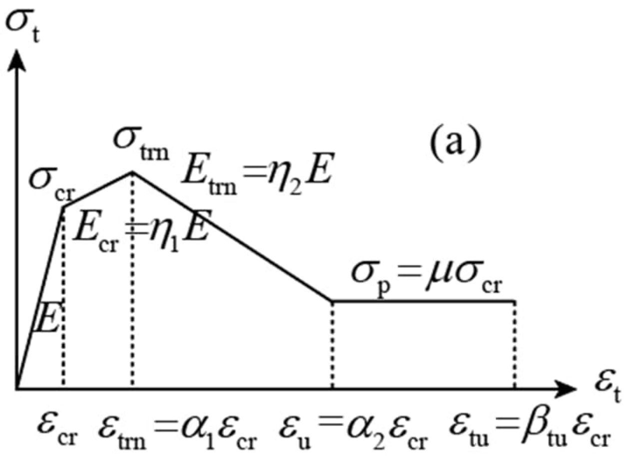
Specimen Level testing

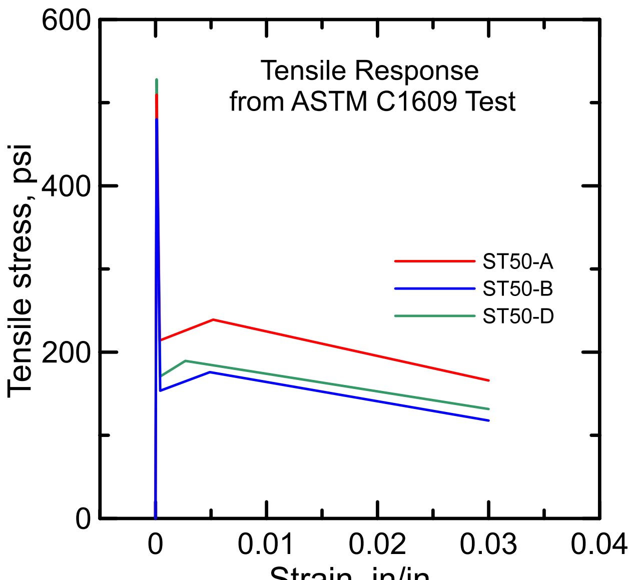


Quadrilinear Modeling for Simulating response of tunnel segments based on ASTM C1609 Tests

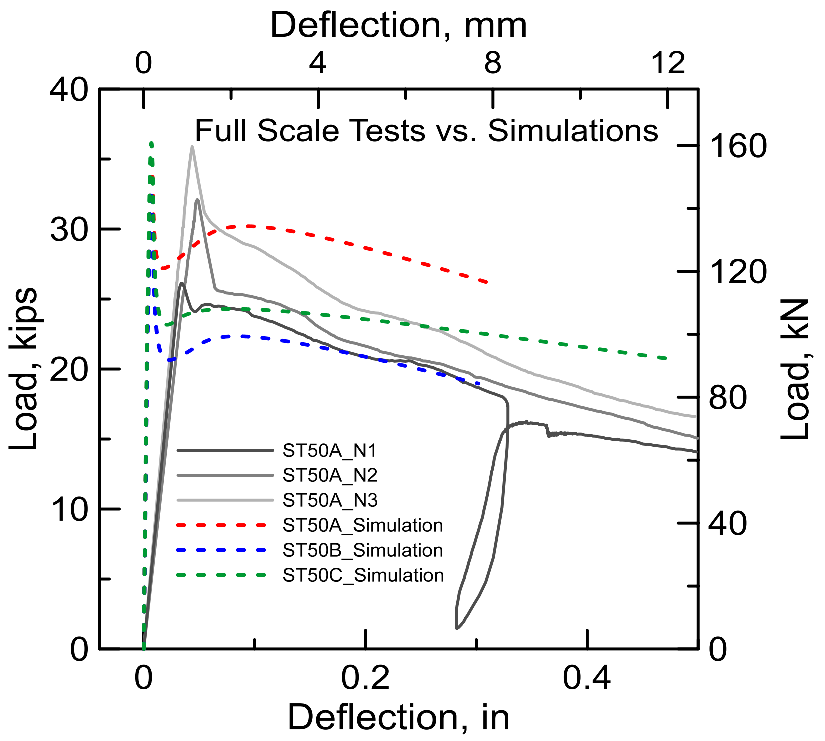






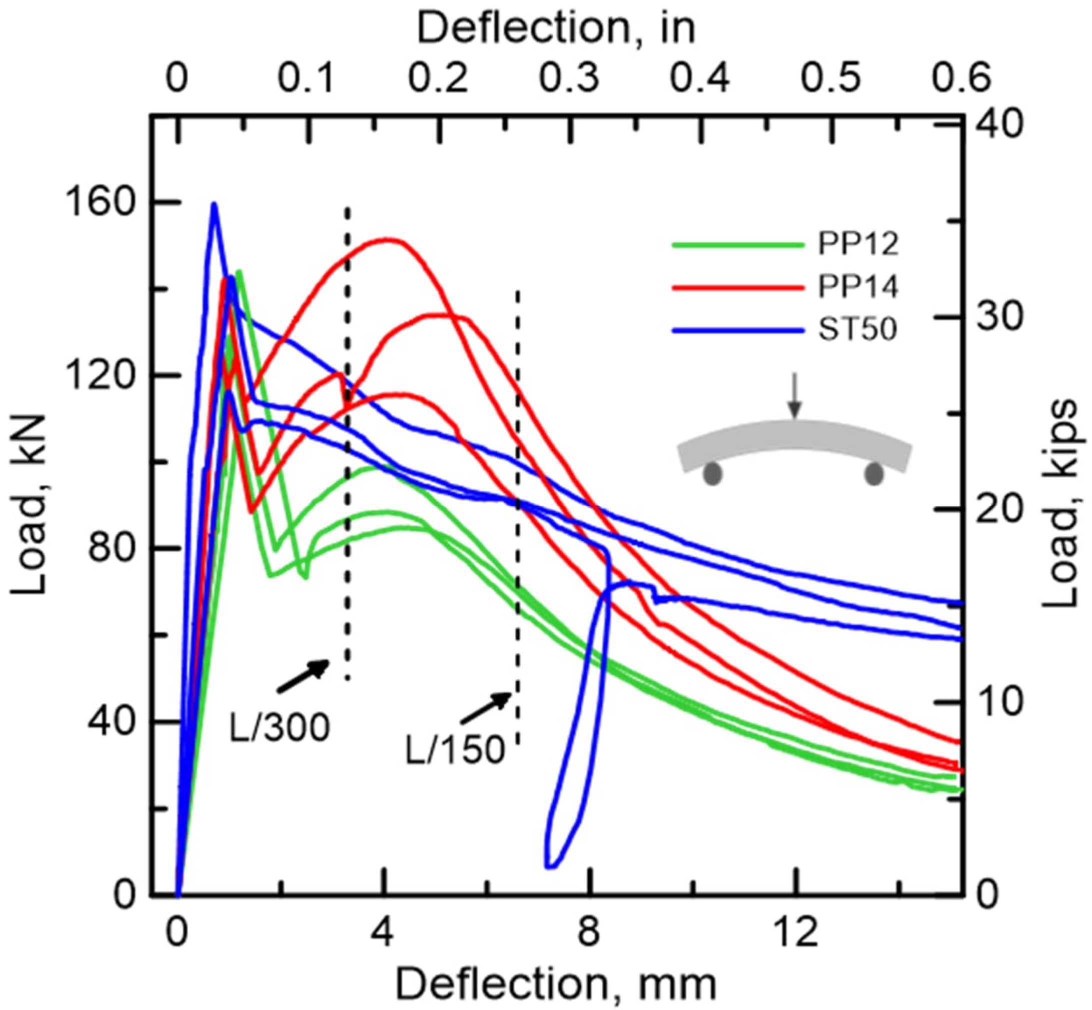


Simulation of the full-scale test



Precast Tunnel Lining Full Scale testing validation, ACI 544-7R

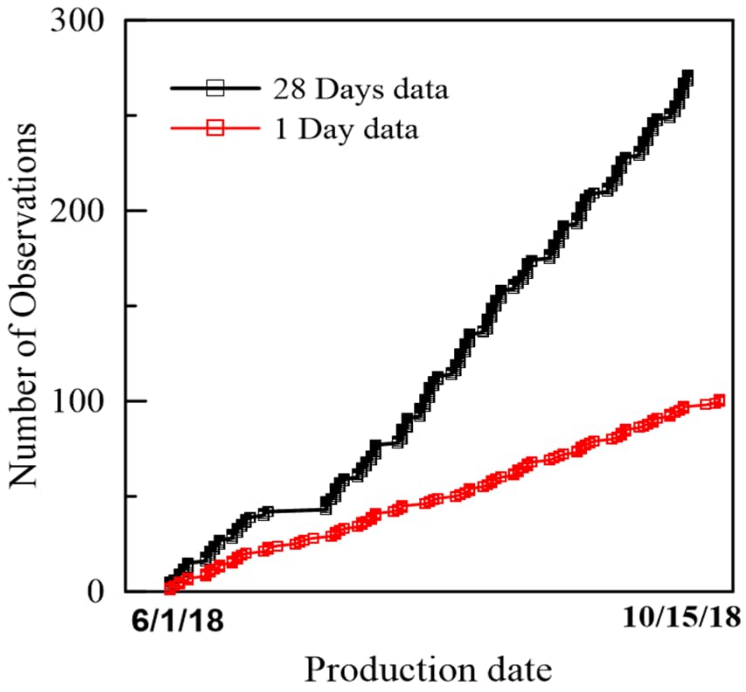
- The question is no longer rebar vs. fibers, but what type of fiber at what volume fraction?
- Increased energy absorption, fatigue life, seismic, impact conditions, edge cracking
- Ductility, Durability, Sustainability



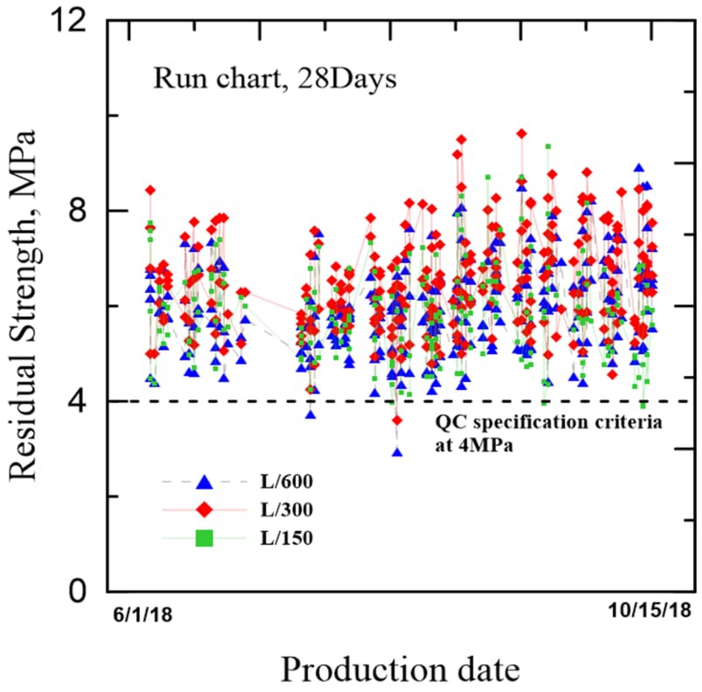
Patel, D., Pleesudjai, C., Bui V., Pridemore, P., Schaef, S. and Mobasher, B. 2023. "Mechanical Response of Precast Tunnel Segments with Steel and Synthetic Macro-Fibers." *Cement and Concrete Composites* 144 (November): 105303. https://doi.org/10.1016/j.cemconcomp.2023.105303.

Statistical Process Control Of Residual Strength measures

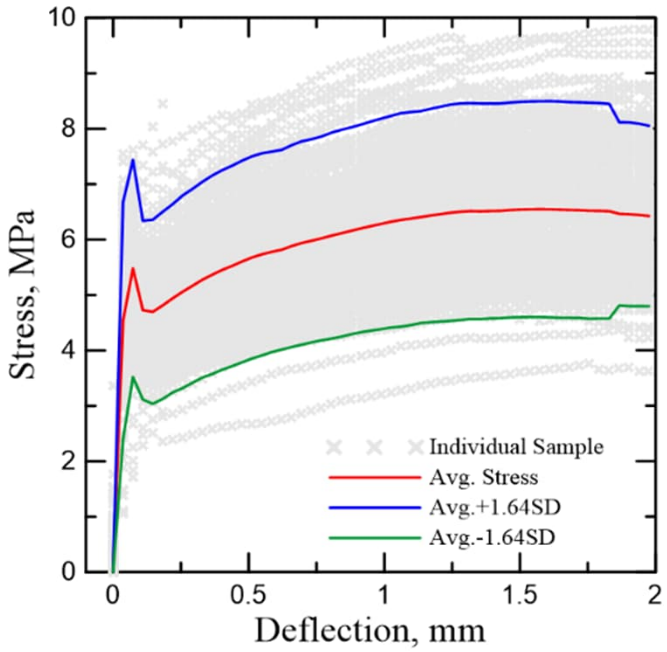
- Analysis of QC data to Improve production efficiency of PCTLs



Sample collection data points



Run Chart for residual strength as a function of Production schedule



Stress vs. deflection plot of 270 C1609 test data

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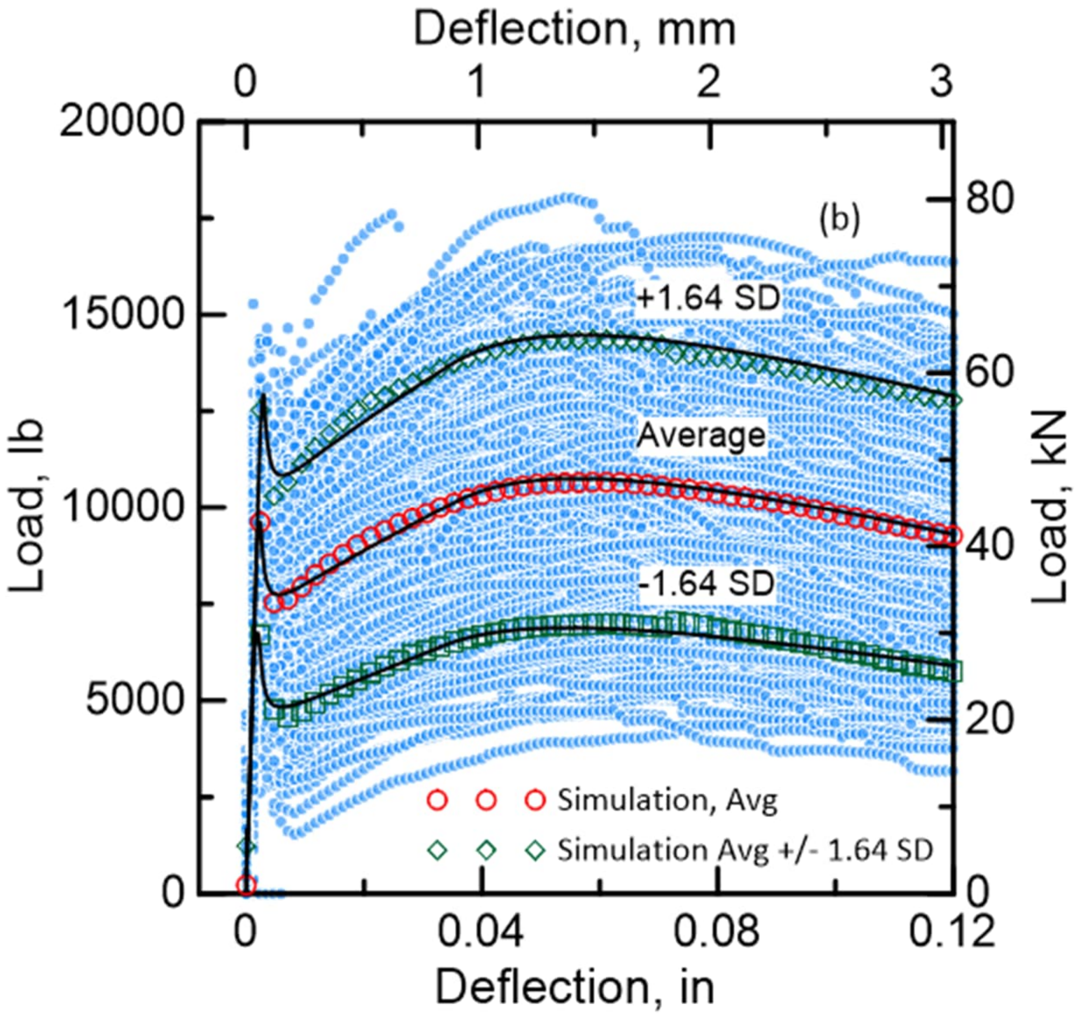
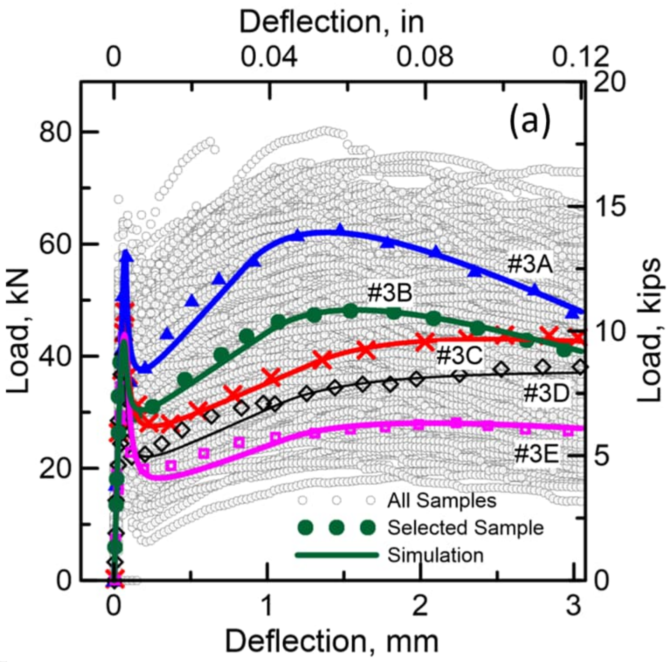
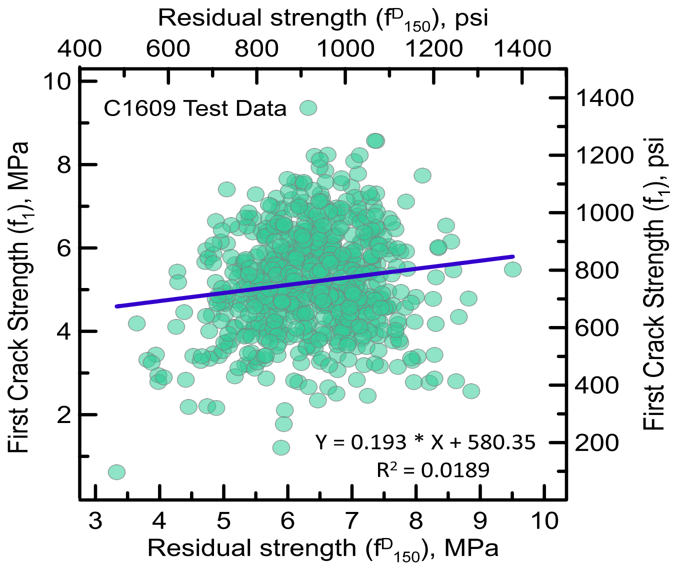
Flexural Testing used for precast Tunnel Linings QC/QA Procedures

- Evaluation of more than 9 months of QC/QA beam samples, 1200+ flexural C1609 beams
- Address the variations using Statistical Process Control tools

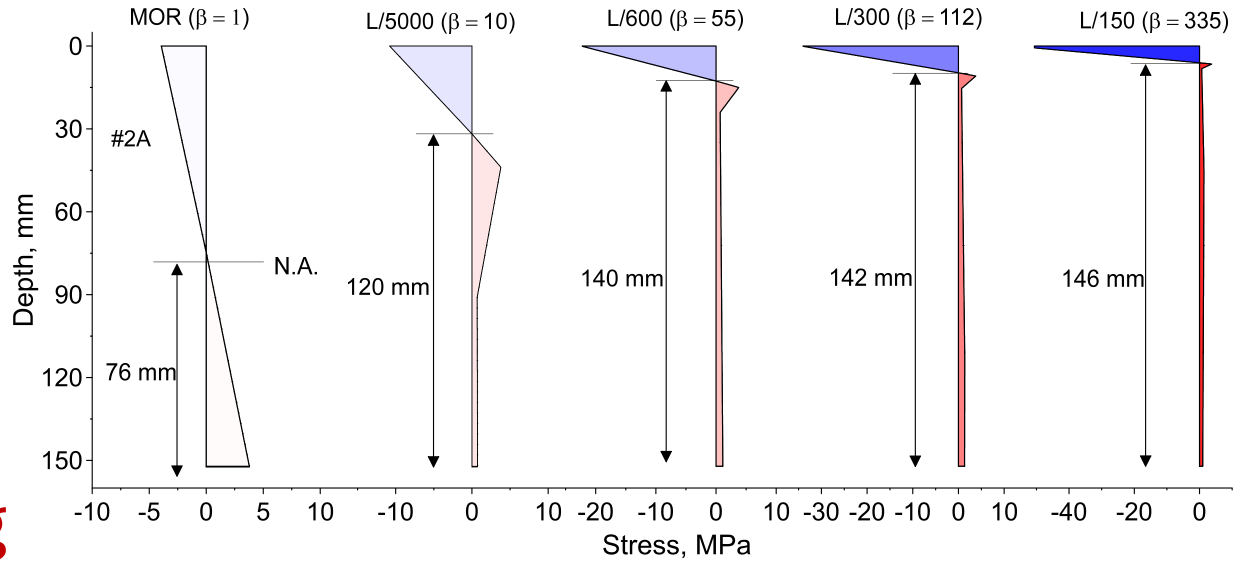


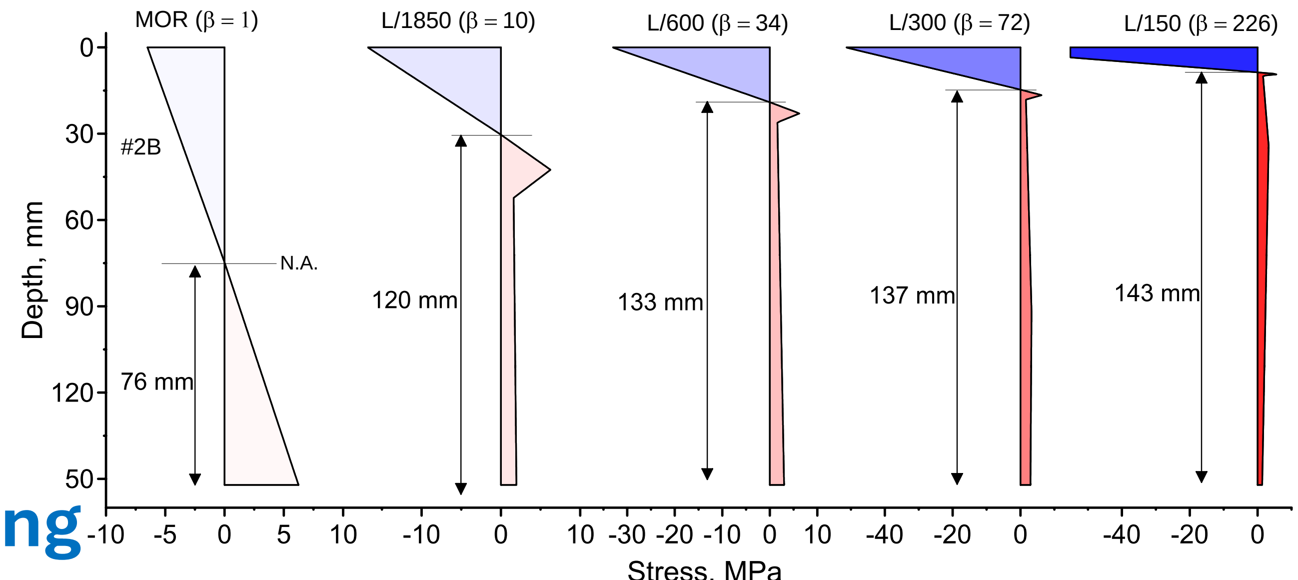




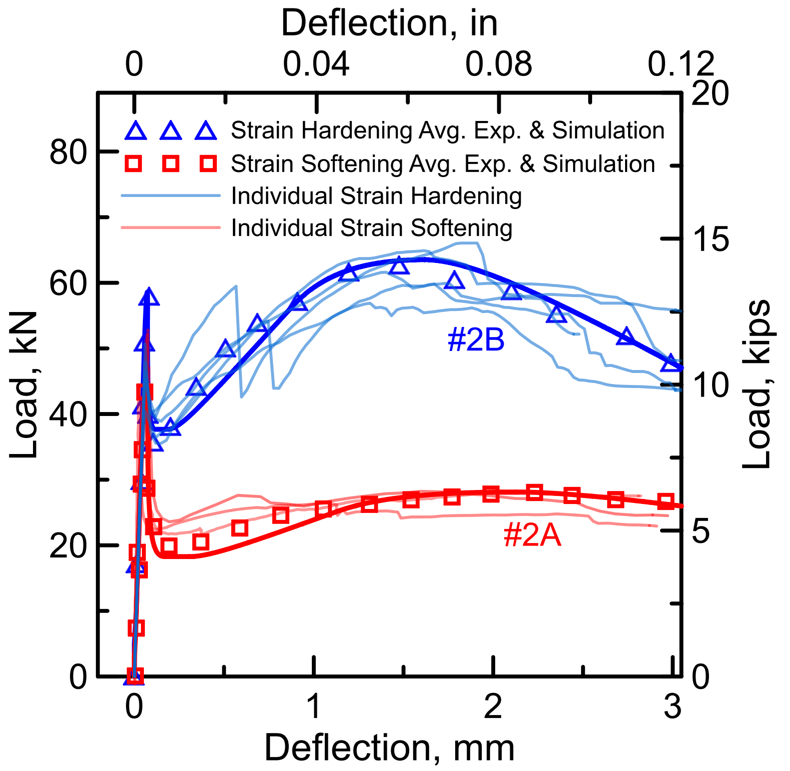
Evolution of Stress Distribution across the thickness

2A-Softening

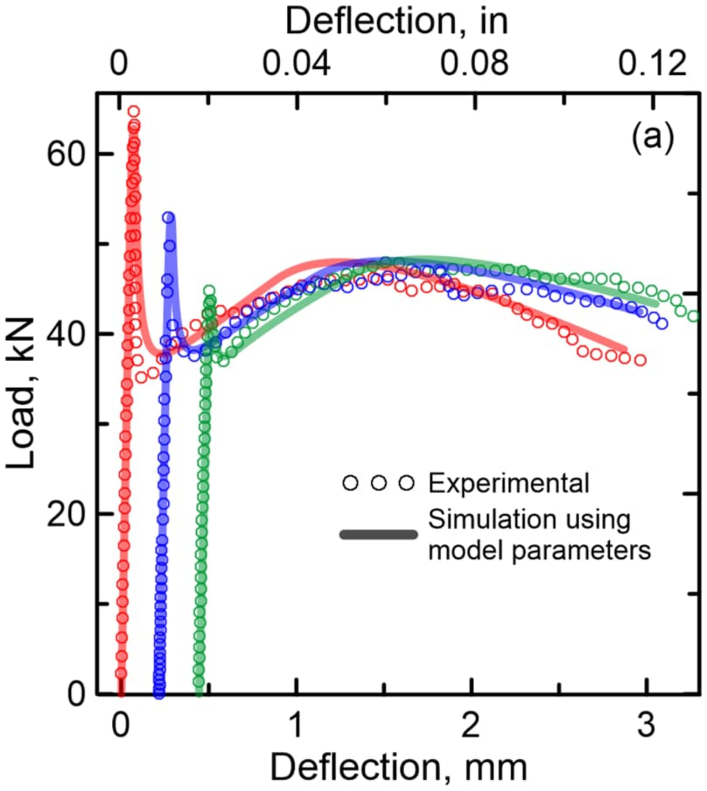


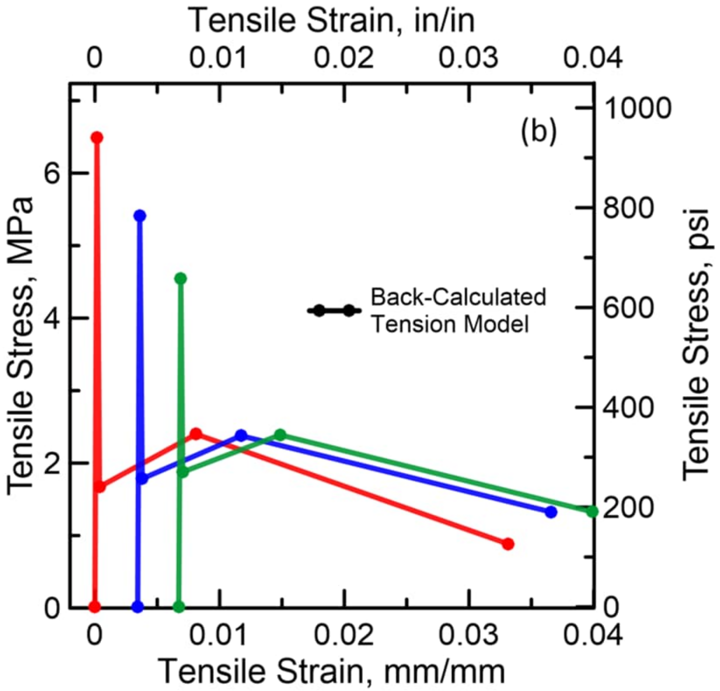


2B-Hardening

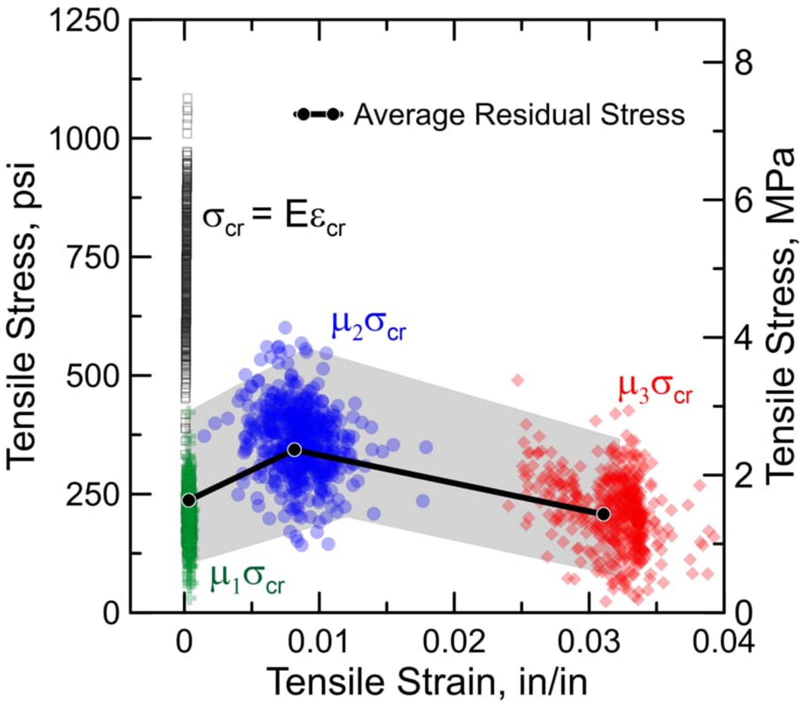


Statistical measures of distribution and correlation



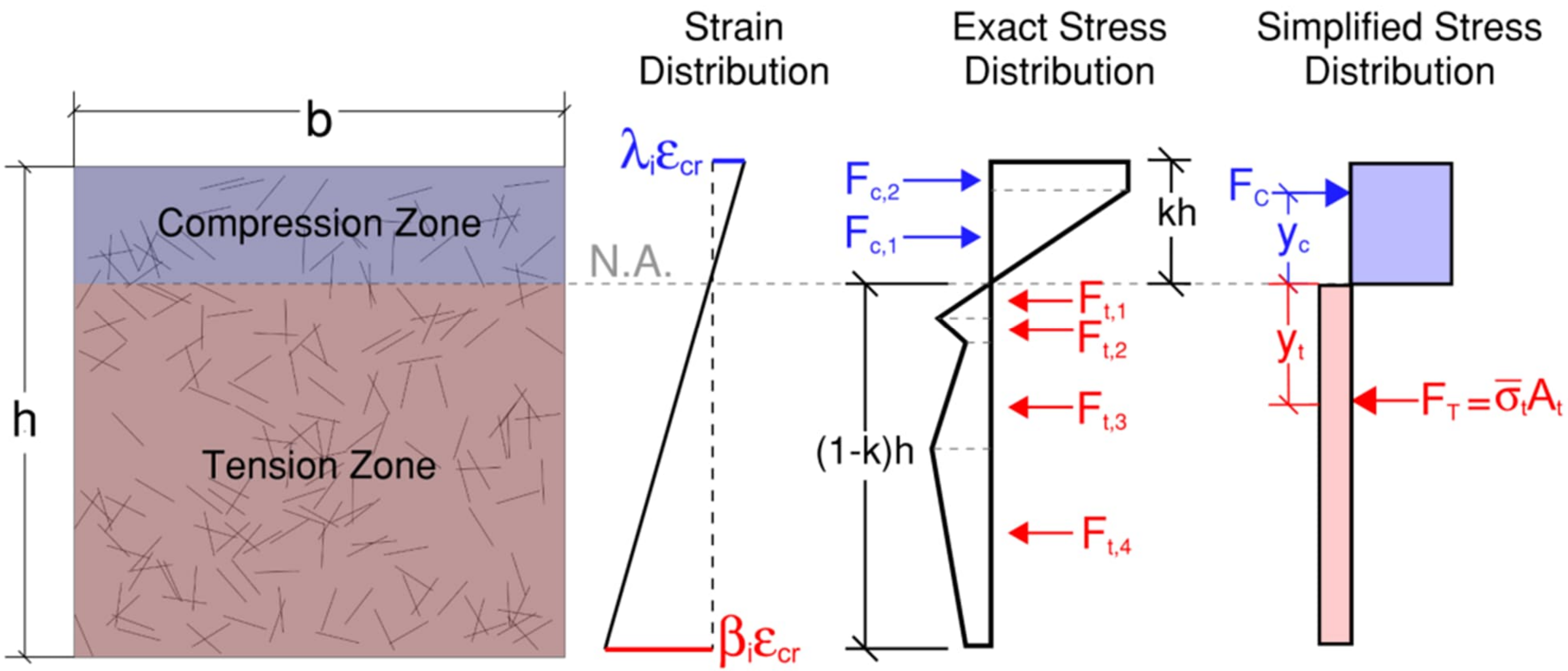


Fit Exp. Data



Backcalculated Tension Model

Definition of Average Tensile Stress for Simplified Design



Total Force in T/C $$F_C = F_T = \sum_0^{(1-k)h} F_t(\varepsilon) = b\int_0^{(1-k)h} \sigma(\varepsilon)dy = bh\int_0^{\beta_i} \sigma_t(\beta_i)\left(\frac{(1-k)}{\beta_i}\right)d\beta_i$$

Avg. Force in T/C $$\bar{\sigma}_t = \frac{F_T}{A_t} = \frac{F_T}{(1-k)hb}$$

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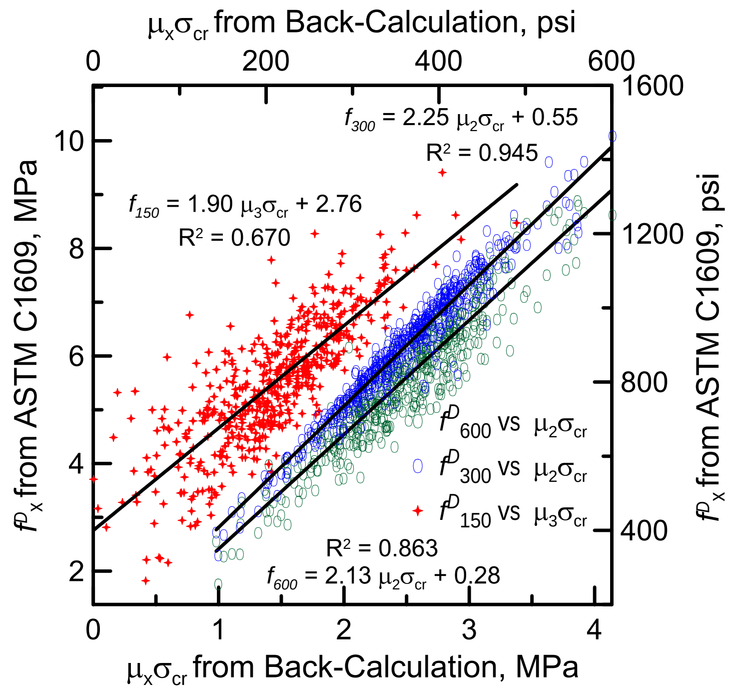
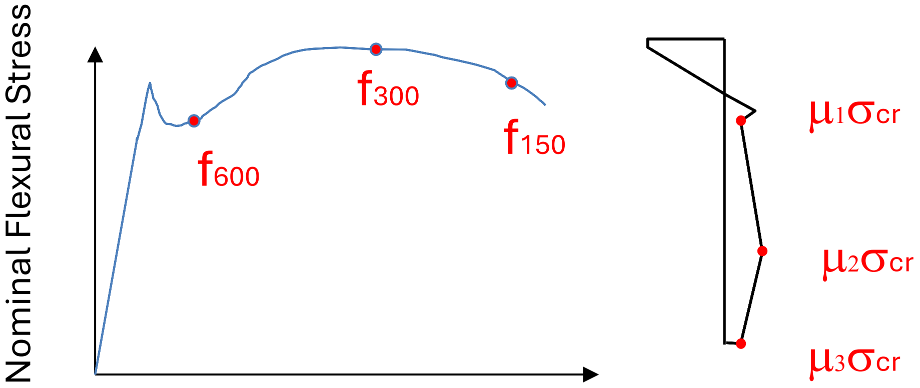
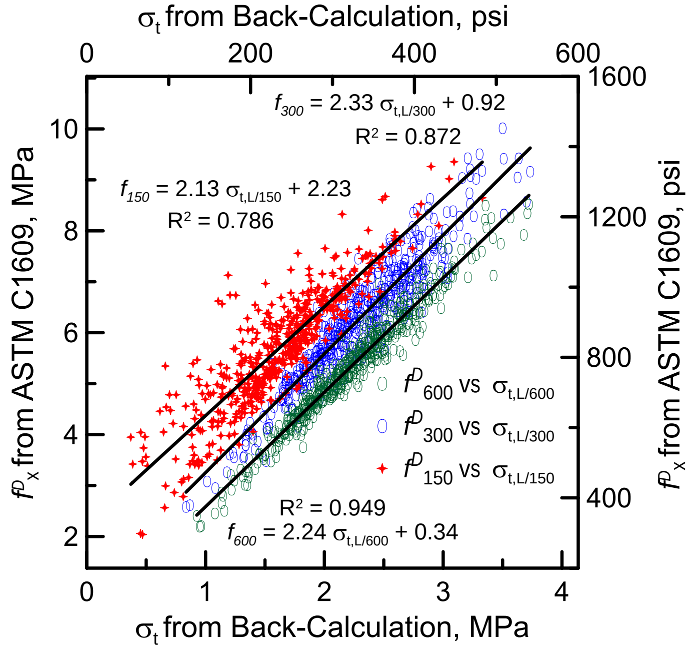
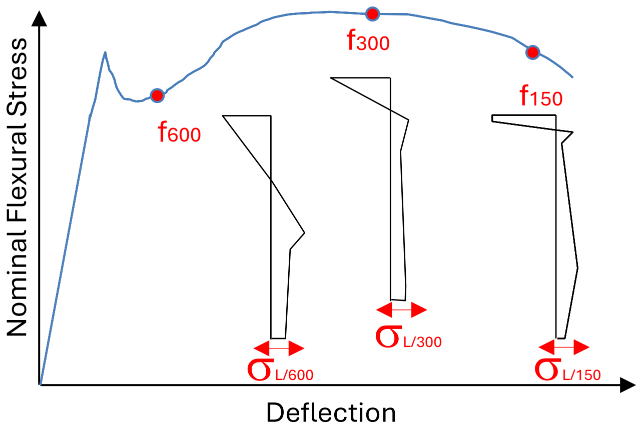
Correlation of experimental and simulation-based stresses at various Deflections





ASTMC1609 Parameters vs Tension Model Parameters

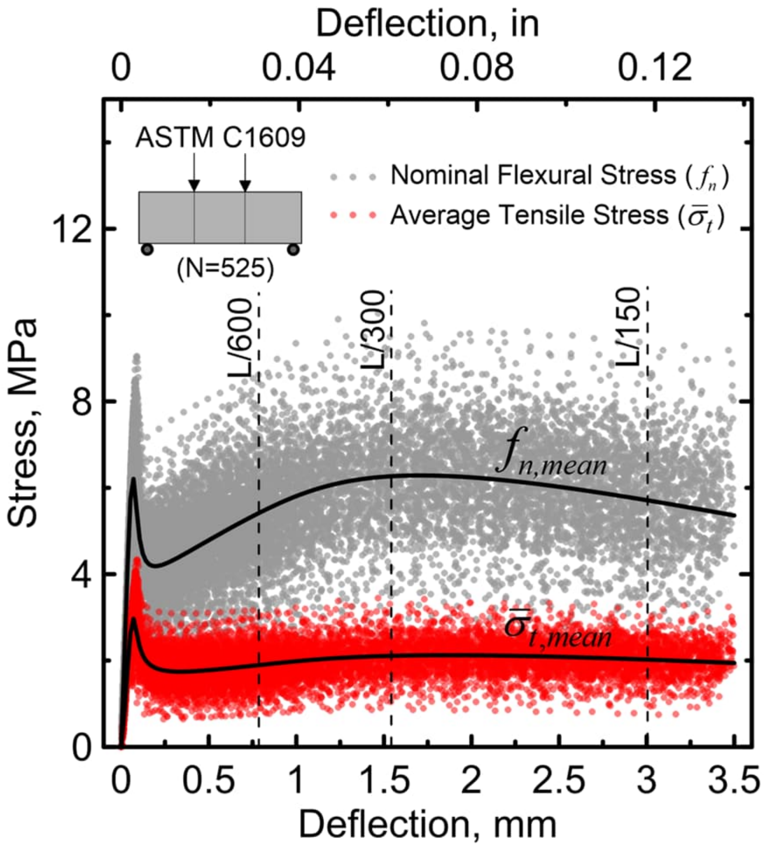


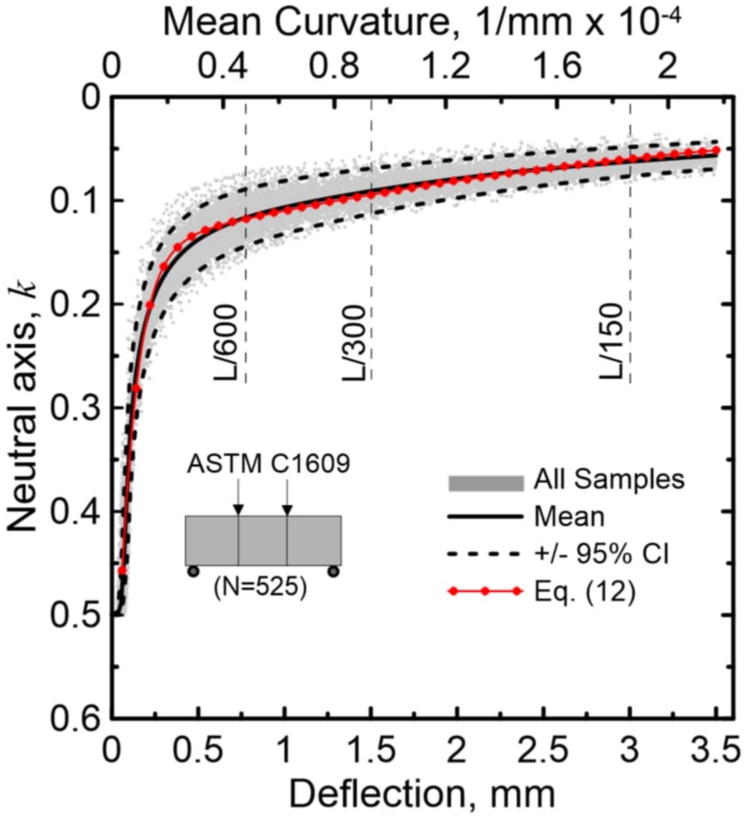


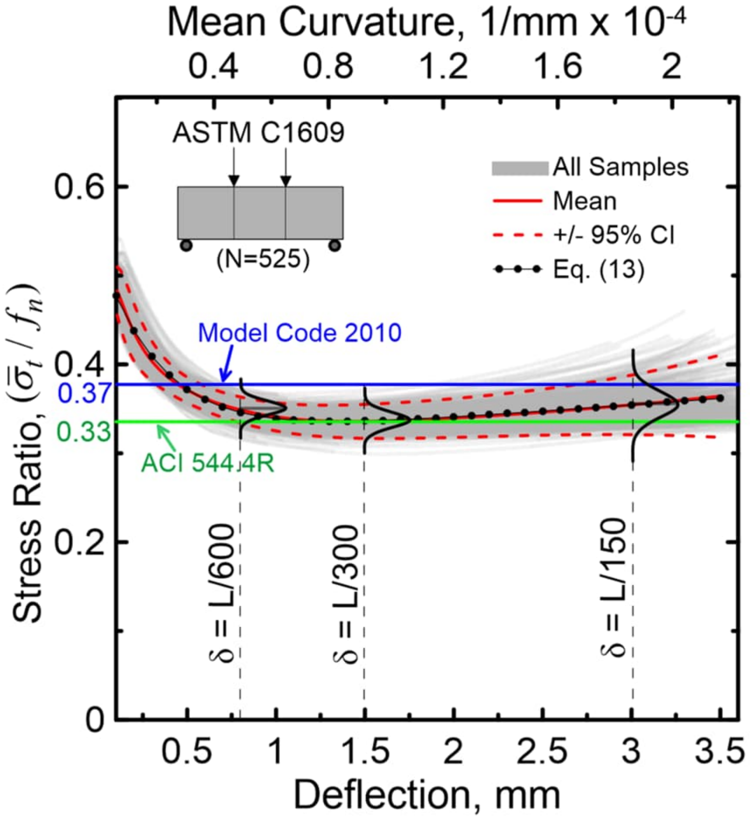
ASTMC1609 Parameters vs stress at extreme fiber

Average tensile stress calculation for simplified design

- ➢The Nominal stress ratio and the neutral axis are relatively consistent compared to the nominal flexural stress which has a high scatter.
- ➢The empirical factors for flexure are not constant and compound the definition of characteristic empirical factors.
- ➢The post-peak response of different fiber types and amounts are fundamentally different.

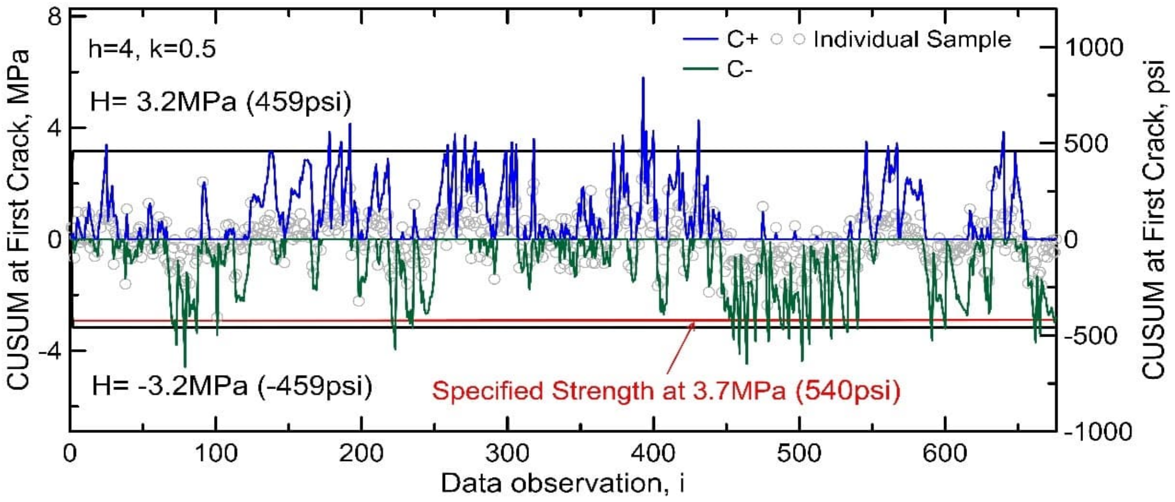


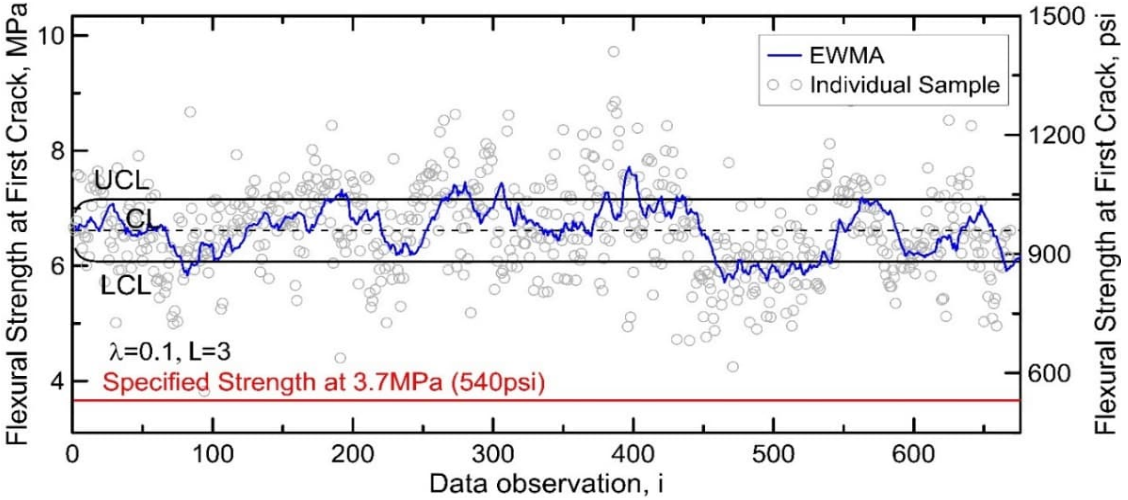




Control Charts and Machine Learning Applications for Production QC

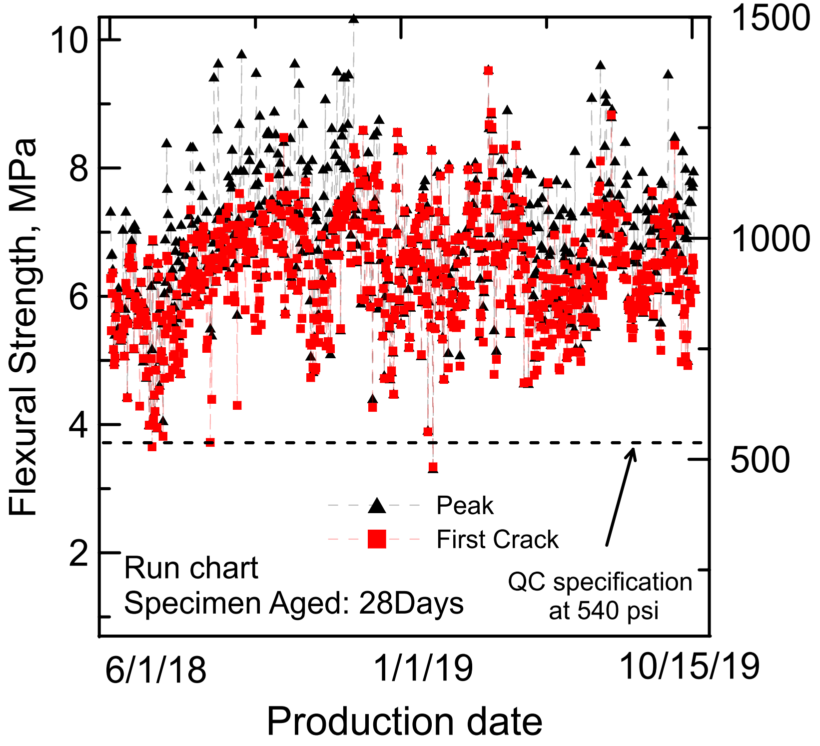
- A control chart for individual observations monitors concrete residual strength by distinguishing between a significant change (real change in slope) and non-significant change (error of aberration).
- CUSUM, cumulative sum of errors as a function of time to hit the limits
- EWMA, Exponential Weighted Moving Average

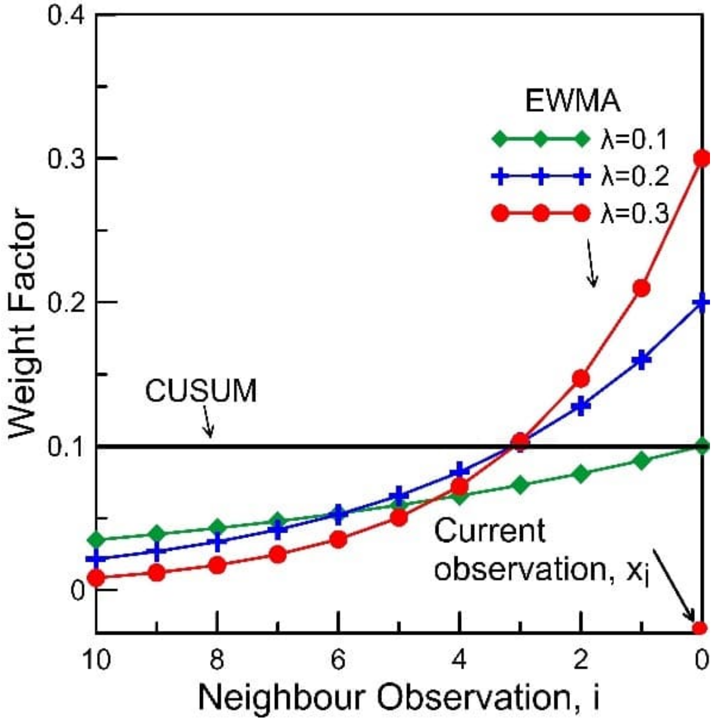


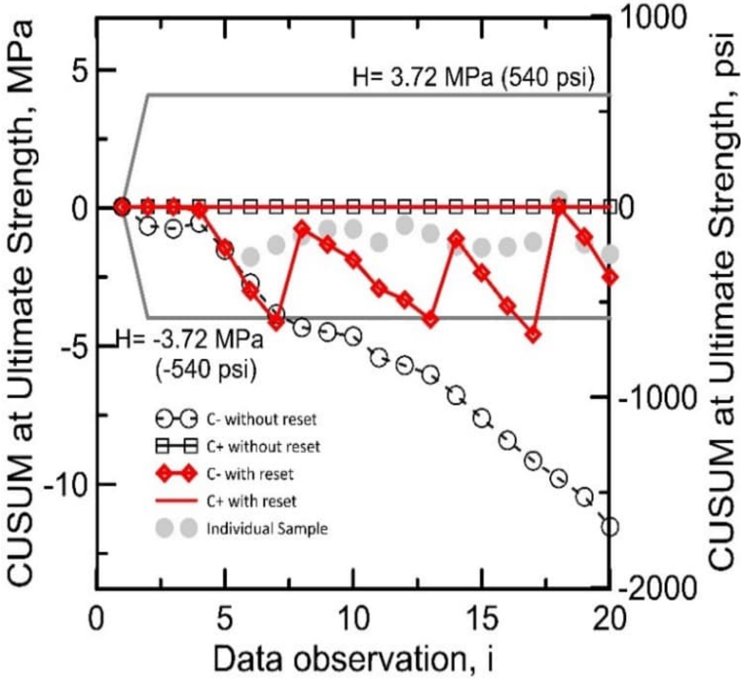


Pleesudjai, et al, 2023 “QC requirements for the construction of South Hartford Conveyance and Storage Tunnel Back-calculation of Mechanical Properties of Fiber Reinforced Concrete in Tunnel Lining Segments, ACI Materials Journal

CUSUM and EWMA Run Charts to monitor and control Production problems and outlier analysis

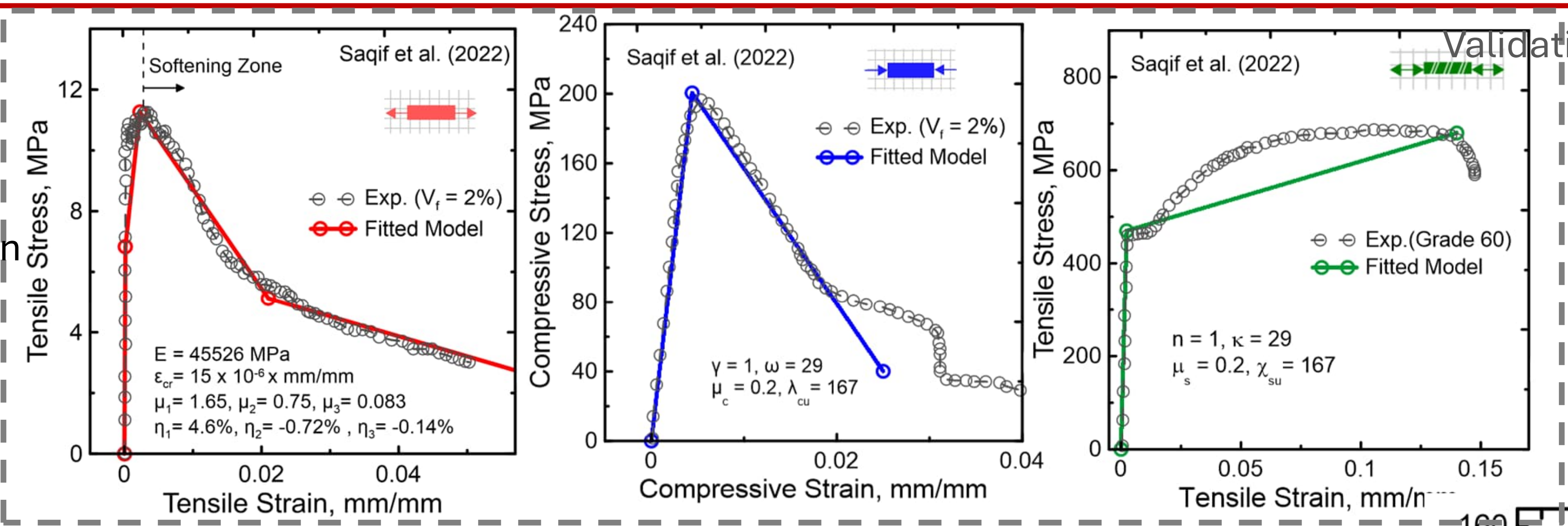




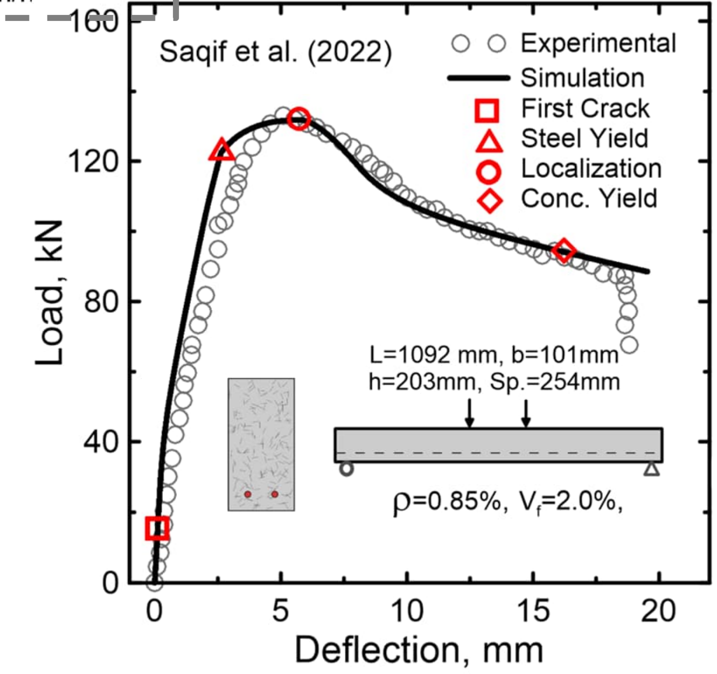


Validation of closed-form approach for Hybrid Members:

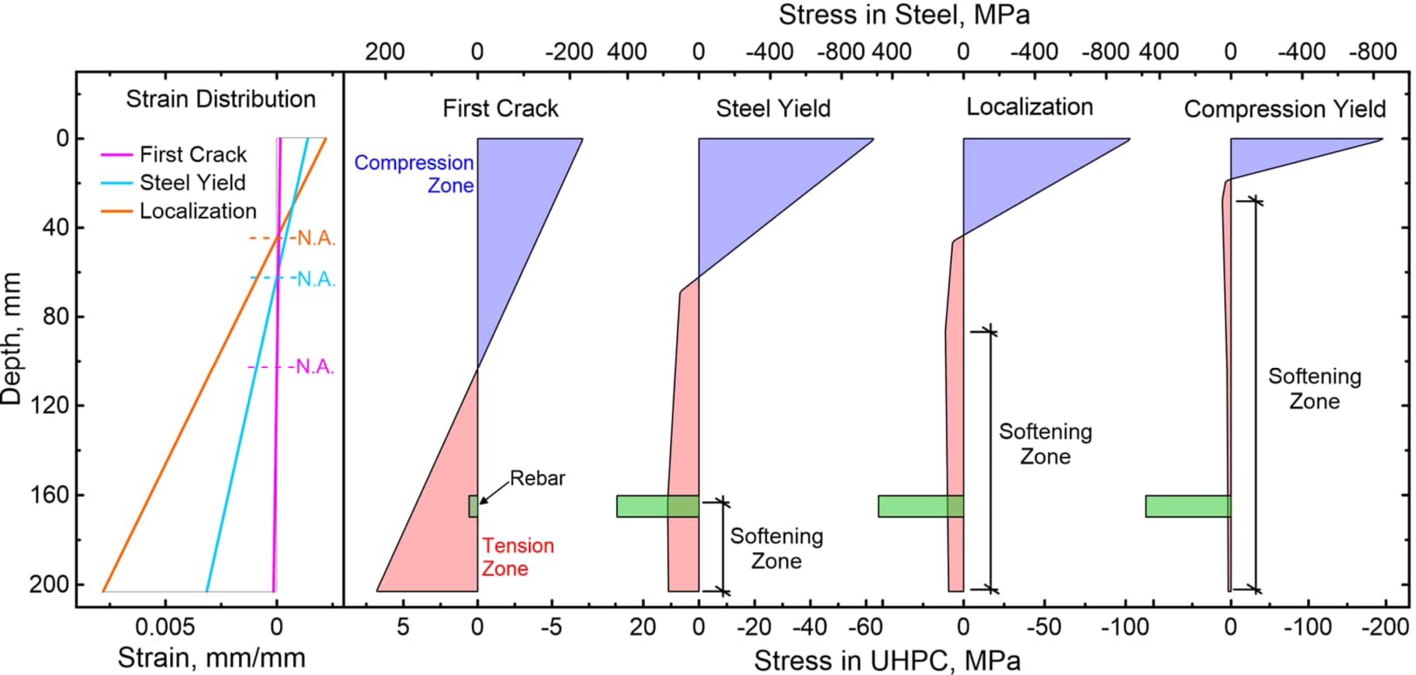
Material Characterization



Validation:

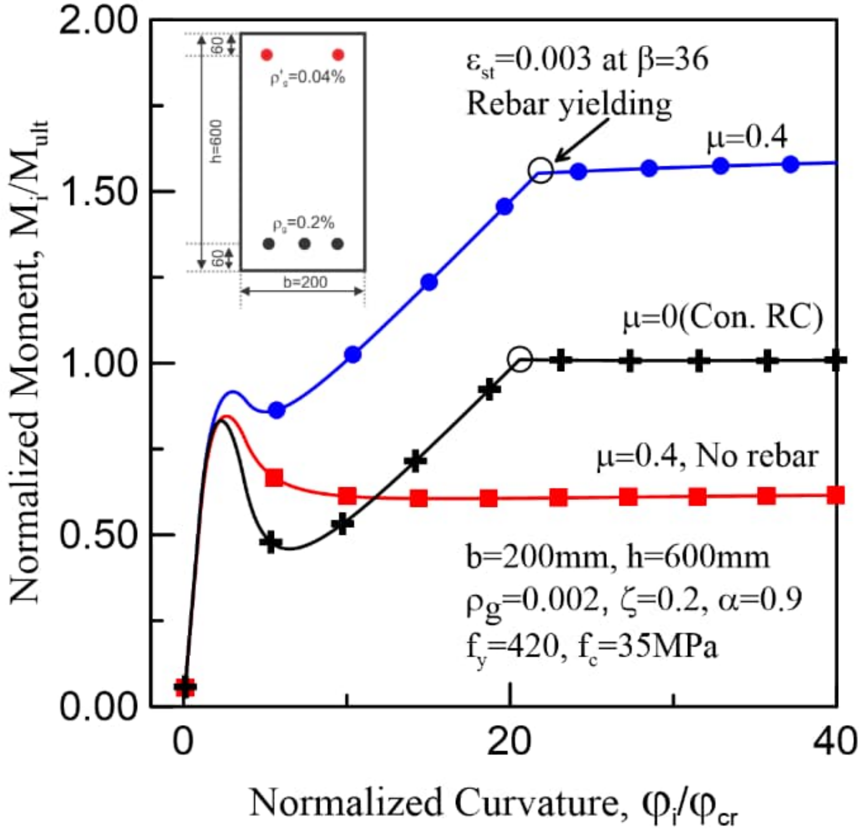


Stress Distribution at Limit States

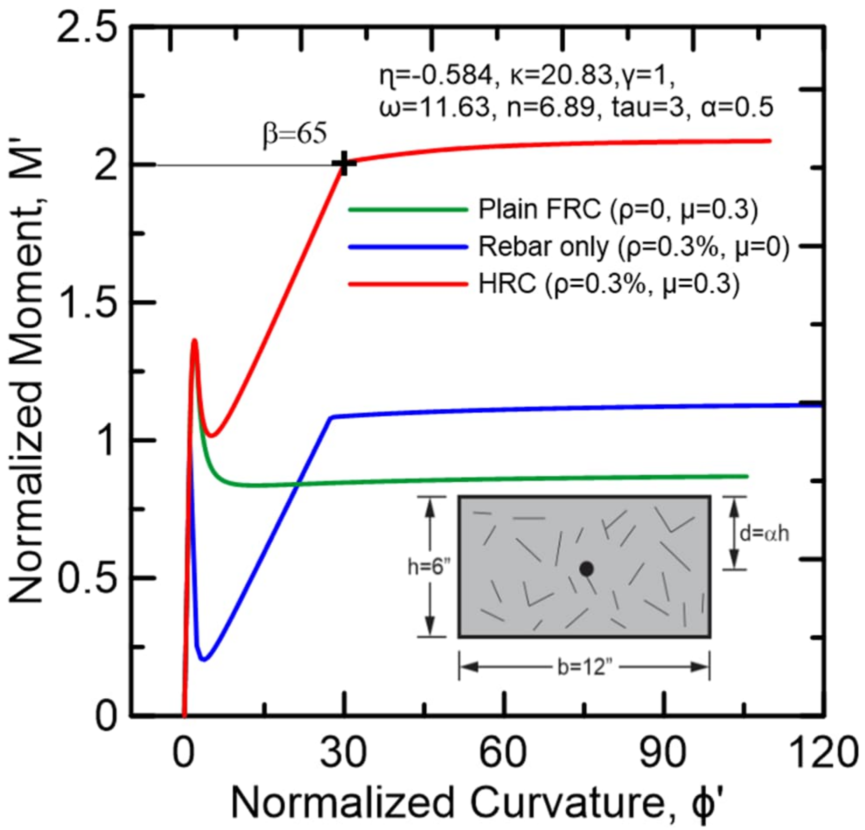


The Hybrid Composite effect

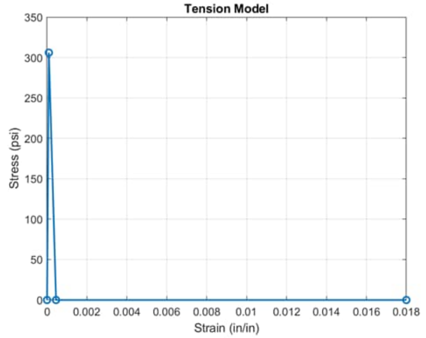
Reinforced concrete beams



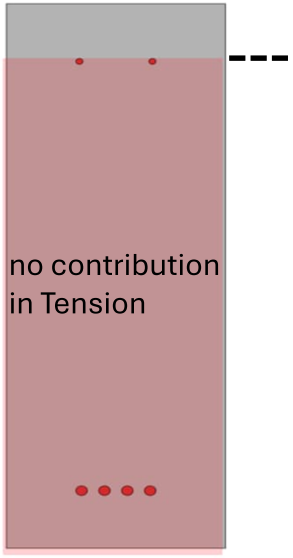
Reinforced Slabs

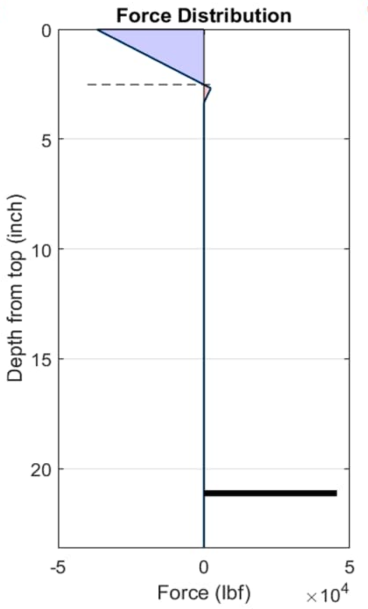


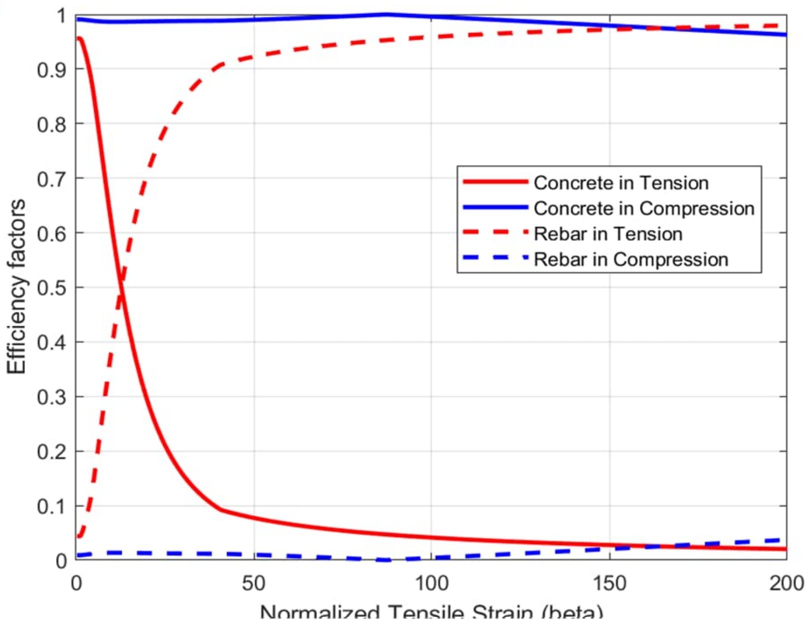
Contribution of Secondary Reinforcement in Conventional Design



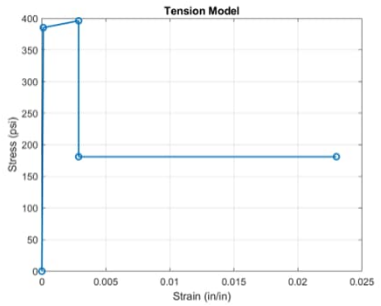
ρ = 0.28%
μ = 0 No residual strength
Size = 7.5” x 23.5”



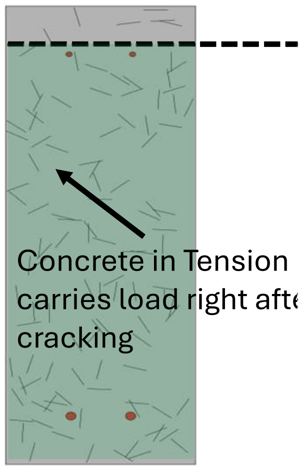


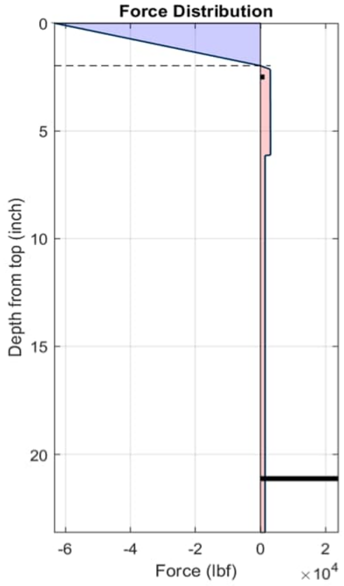


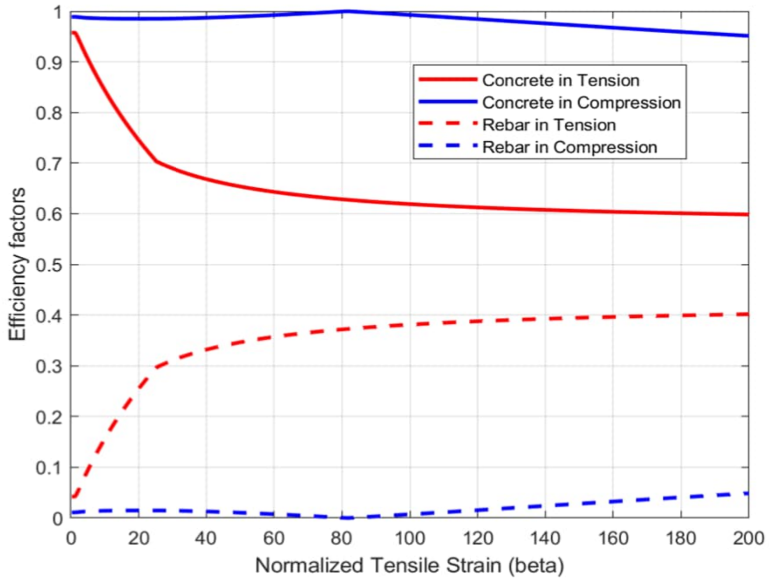
Hybrid Reinforced Section, accounting for Residual Strength



ρ = 0.14%
μ = 0.5 residual strength
(less than 1.4 MPa)
Size = 7.5” x 23.5”



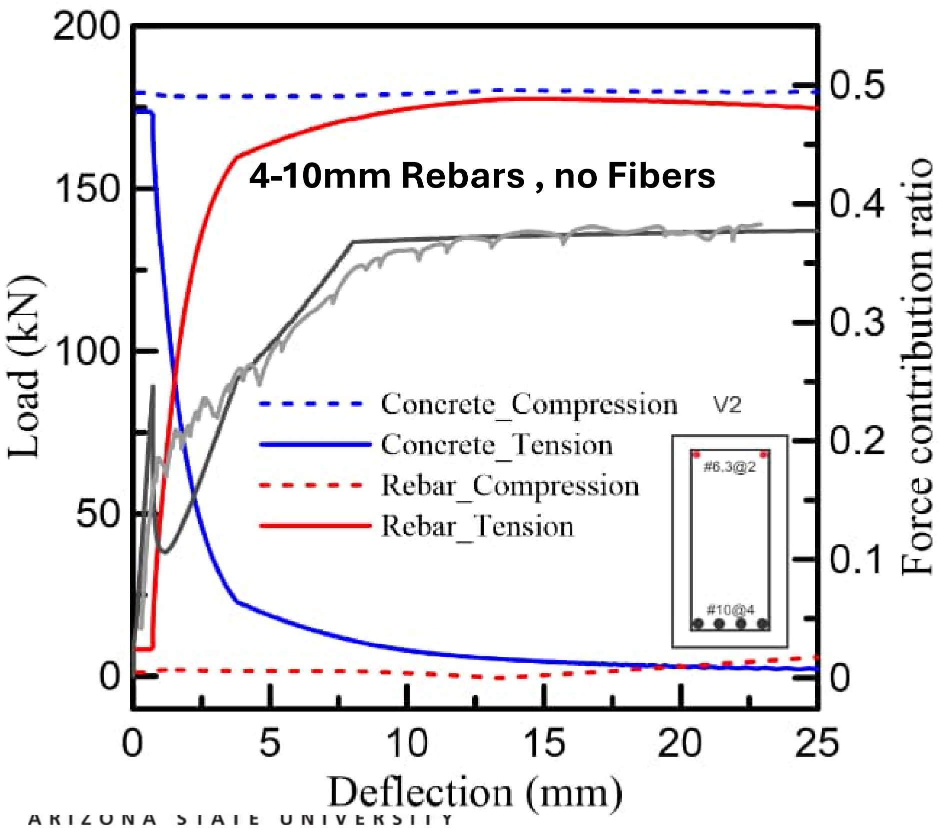


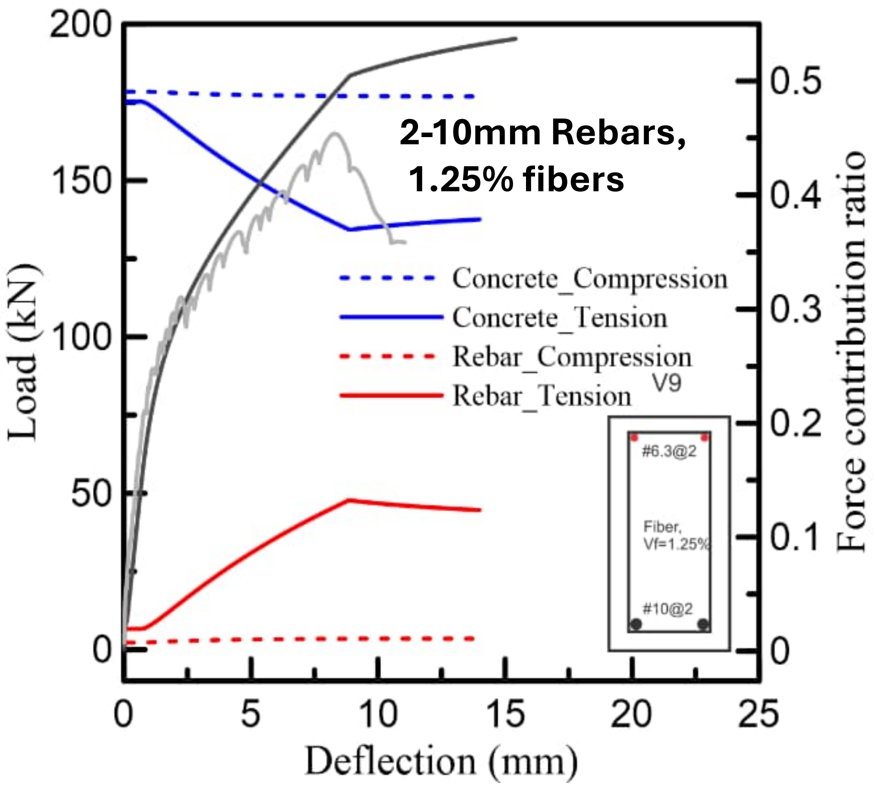


Ira A. Fulton Schools of Engineering
ARIZONA STATE UNIVERSITY

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

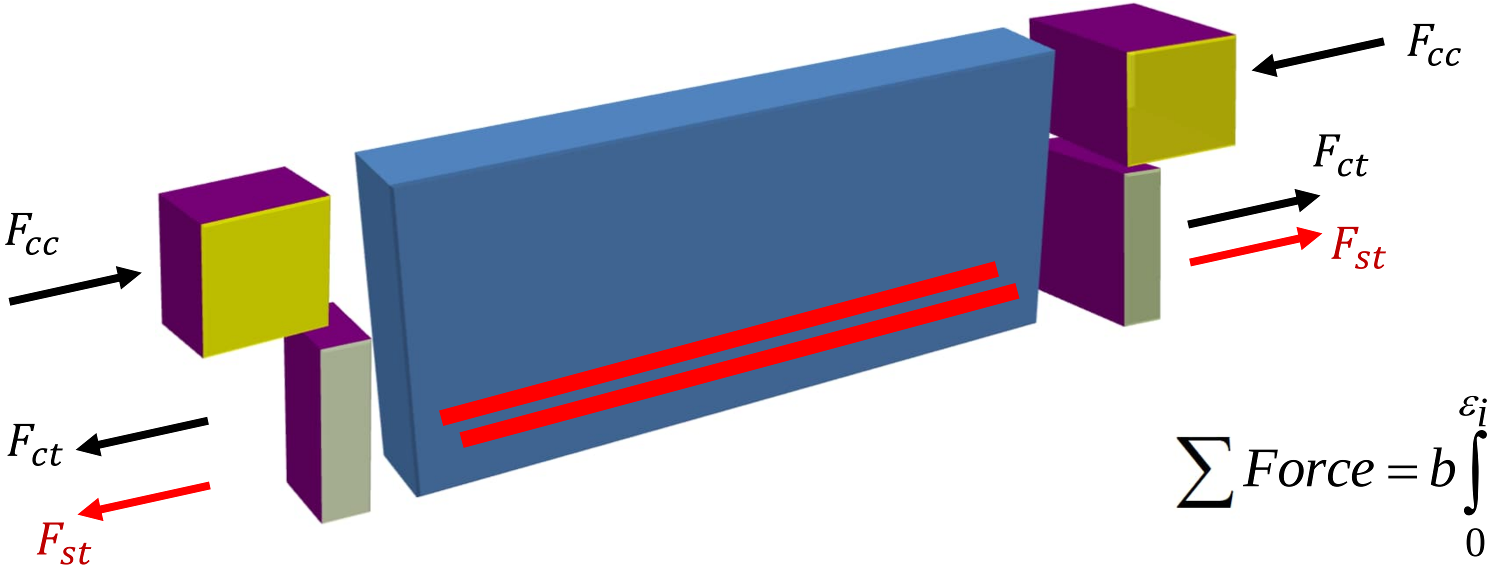




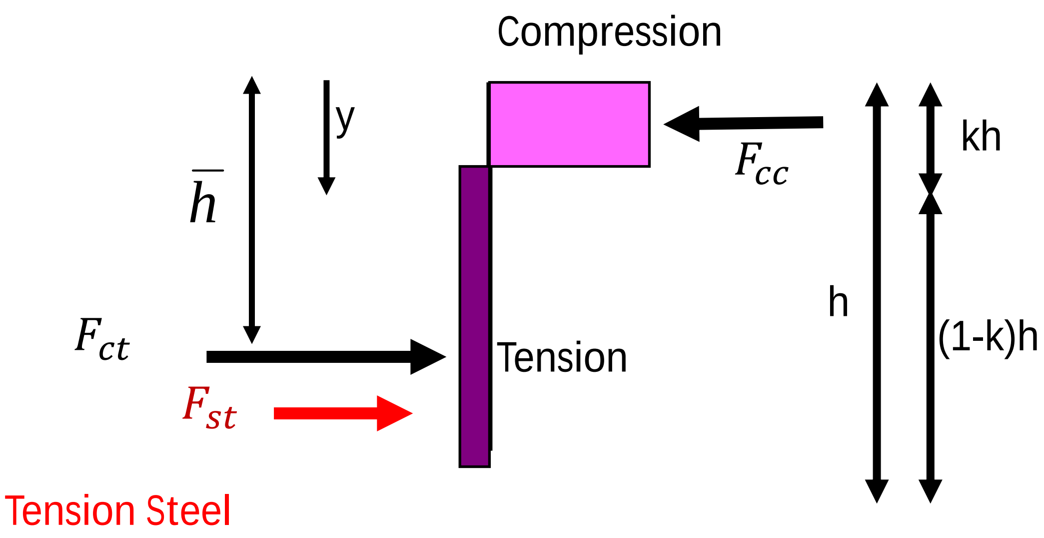
Conclusions

- Cost-effective tunnel lining sections can be developed using fiber reinforced concrete
- Presenting a robust, rational mixture and structural design
- Modeling of the compression and flexural Analysis for design using a closed form solution strategy
- Moment Curvature response can be used to isolate individual force components and obtain the materials efficiency parameters
- Statistical Process control can help QC/QA and material design to increase efficiency compared to Reinforced Concrete
- New and improved design models for Tunnel Section using Ssteel and Polymeric Fibers integration into codes an standards

Mean Equivalent Stress distribution in an intermediate stage



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



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

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