Fiber Reinforced Shotcrete and Earth Retaining Structures for Rockfall Protection

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Mutual Objectives

- ADOT-
  - Providing Safe, Quality Roadways for Arizona
  - Support the Economical Development of the region
  - Costs associated with road closure due to rockfall and ground instability are excessive, unpredictable and can have grave consequences for local industry, tourism, and commerce.
- ASU Research in construction Materials
  - Development of new technologies for direct implementation in infrastructure development

Outline

- Areas of applications for structural use of Fiber Reinforced concrete
  - Rock fall protection, and Slope Stability
  - Applications for Infrastructure development
- Development of Design procedures for Strain softening and hardening FRC
  - Material models, Moment-curvature relationship
  - load-deflection results compared with experiments
  - Toughness based Design
  - Use of post-peak residual strength
- Conclusions

Landslides and Rock fall stabilization

- *News:*
  - *Additional rock falls keep SR 264 closed*
  - *Mudslide on state highway 89A South between Flagstaff and Sedona*
- *Ongoing maintenance projects:*
  - *Kingman District Construction Projects, November 2012*
  - *I-40 MP 48, Rockfall Mitigation*
  - *I-40 MP 102*
  - *Cross Mountain—Jolly Road Rockfall Protection*
  - *Rockfall prevention project set for State Route 78 in Greenlee County's Mule Creek Pass*

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Rockfall protection and Slope Stability Issues- Safety issues

- “A large rock fall has closed State Route 264 southeast of Tuba City. State highway officials now say the earliest the highway will reopen is likely Thursday because the equipment necessary to remove the debris has to be driven up to northern Arizona” January 05, 2010
- “Arizona Department of Transportation crews started clearing the debris Monday but more rocks started falling, and the supervisor on the scene pulled his teams from the area for safety reasons. Then, another large section of the hill fell, covering more of the road.”

STATE ROUTE 87 LANDSLIDES, Payson, Arizona

- Mitigation plans have been in effect during 2004, 2005, 2008, and 2009

ASU- Rio Tinto Project – Magma Copper mine, Superior , Arizona

ASU has helped in evaluating the initial fiber-reinforced shotcrete support design for a 2000 m-deep shaft at Resolution Mine, Arizona.

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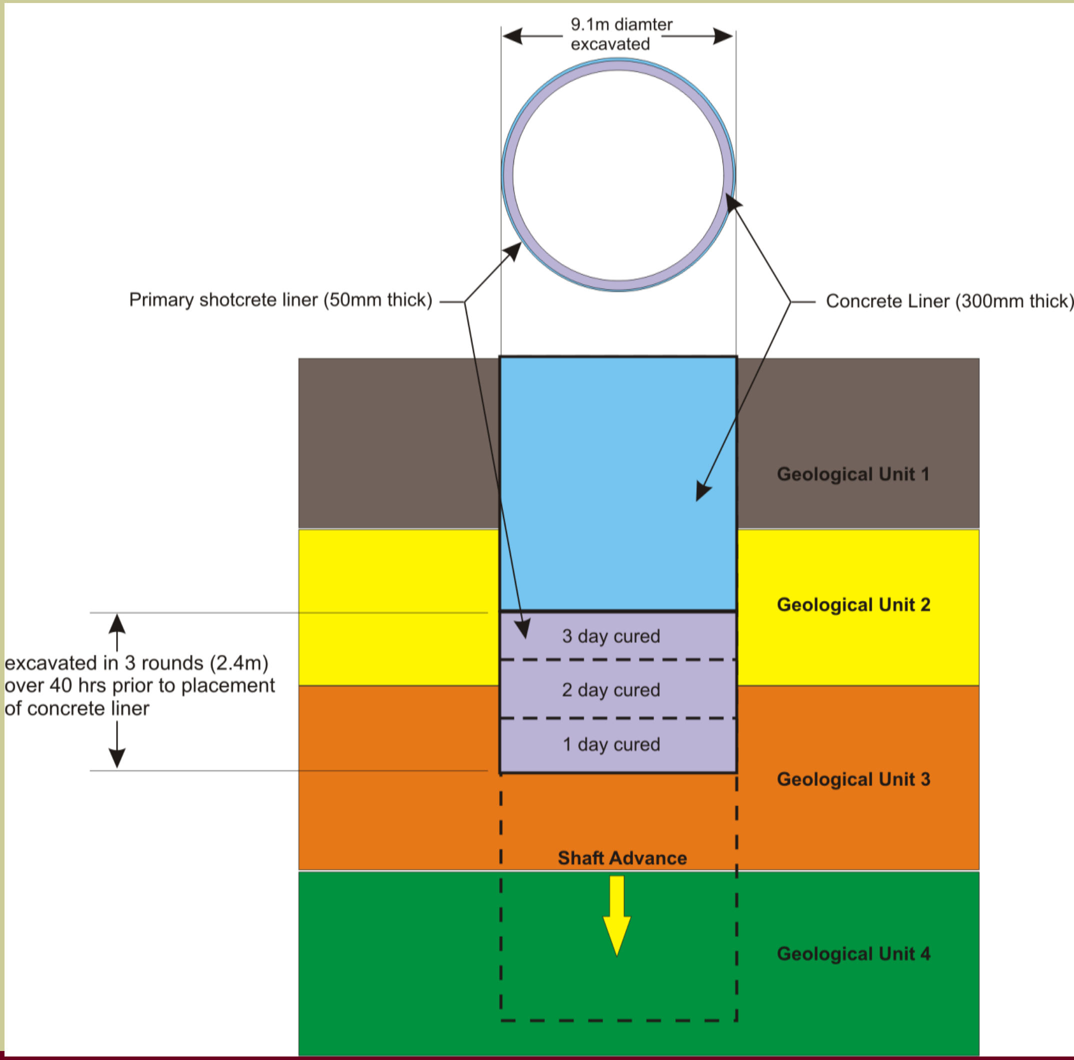
Project Overview

- Evaluate fiber-reinforced shotcrete performance
- No rockbolts planned for initial support.
- Deep shaft (2189 m)
- Three geological units
- A range of stress conditions (increased with depth)
- Several modes of instability: gravity driven, rockmass shear yielding, brittle failure

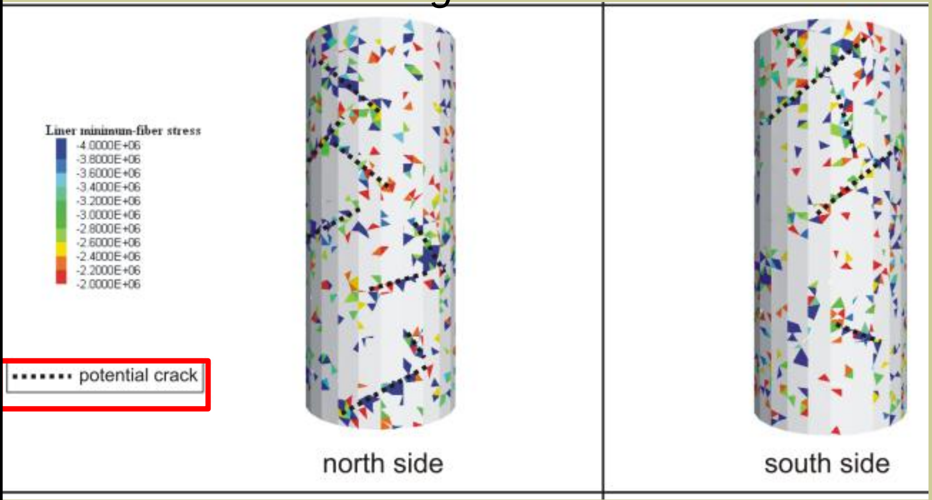


Shotcrete for Tunnel Stabilization-
Resolution Copper Mine, Superior, AZ

- *Shotcrete is applied prior to form setting for permanent lining*
- *No rock bolts planned for initial support*
- *Several modes of instability: gravity driven, rock mass, shear yielding, brittle failure*

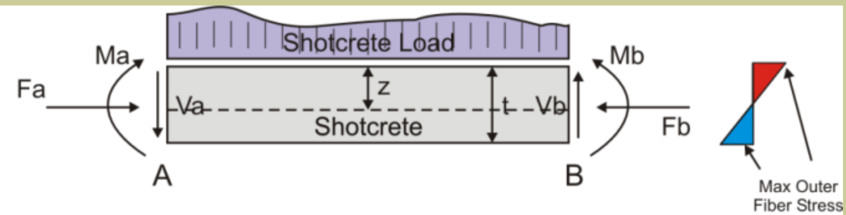
3DEC Evaluation of Shotcrete

Tensile extreme fiber stress exceeding tensile strength of shotcrete



3DEC-predicted liner stresses and potential cracking in TAL unit

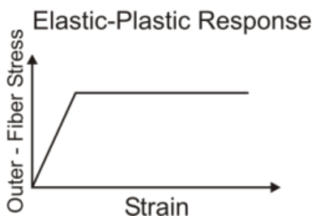
- Linear-elastic shotcrete liner installed in low stress, blocky ground.
- Early age properties use for shotcrete and rock-shotcrete interface along full length of model shaft.
- Extreme fiber stress used to evaluate potential shotcrete cracking.
- Tensile extreme fiber stress exceeding the tensile strength *combined* with tensile thrust at a given liner section indicates potential for a crack to form through the liner.
- Large regions of connected cracks would indicate potential for a block breaking through the shotcrete.



Combines Fluxural Strength:

$F/A \pm Mz/I \leq \sigma_{ten,\ comp\ strength}$

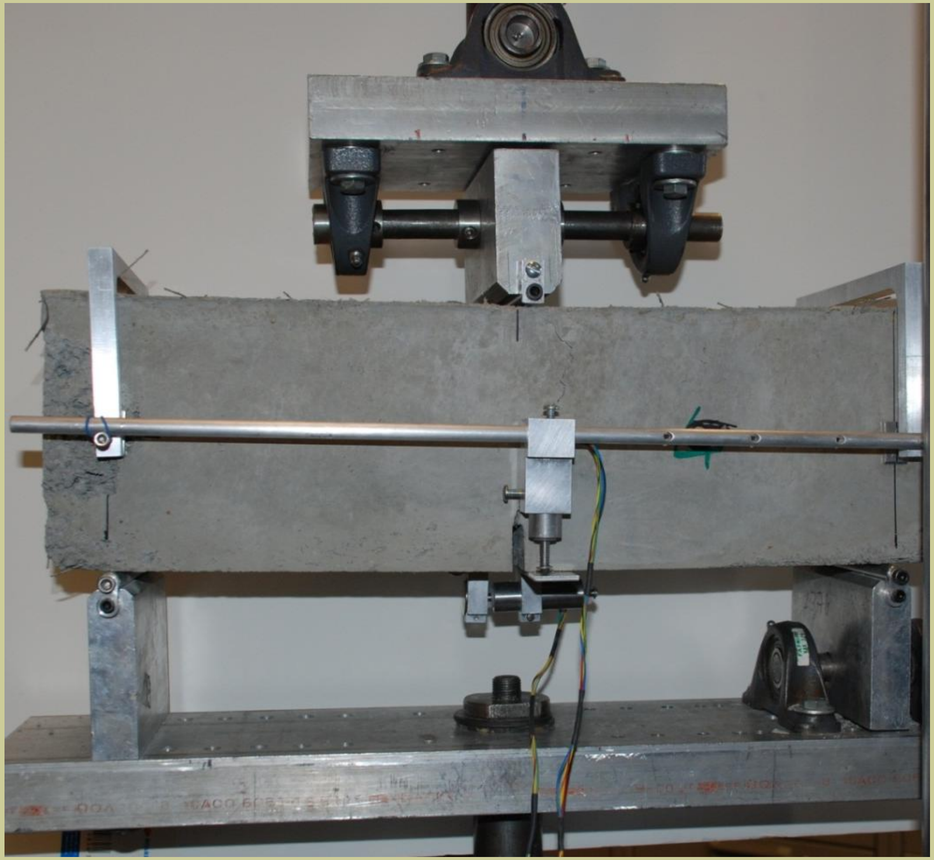
$A = 1*t;\ I = 1*t^3/12$



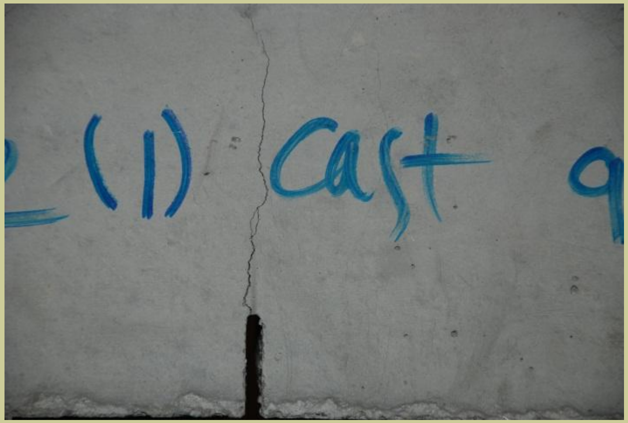
Extreme Fiber Stress

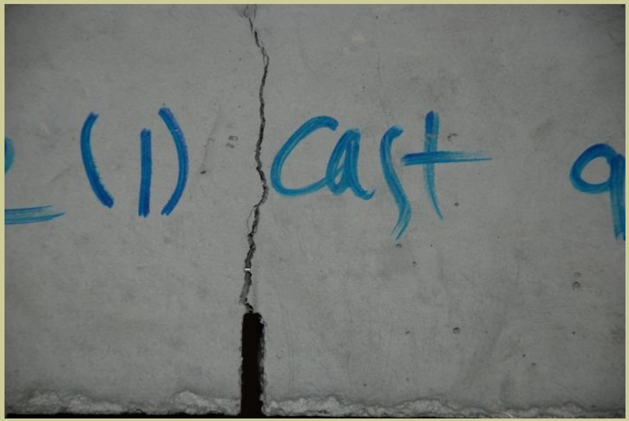
Methodology (Three-Point Bending)

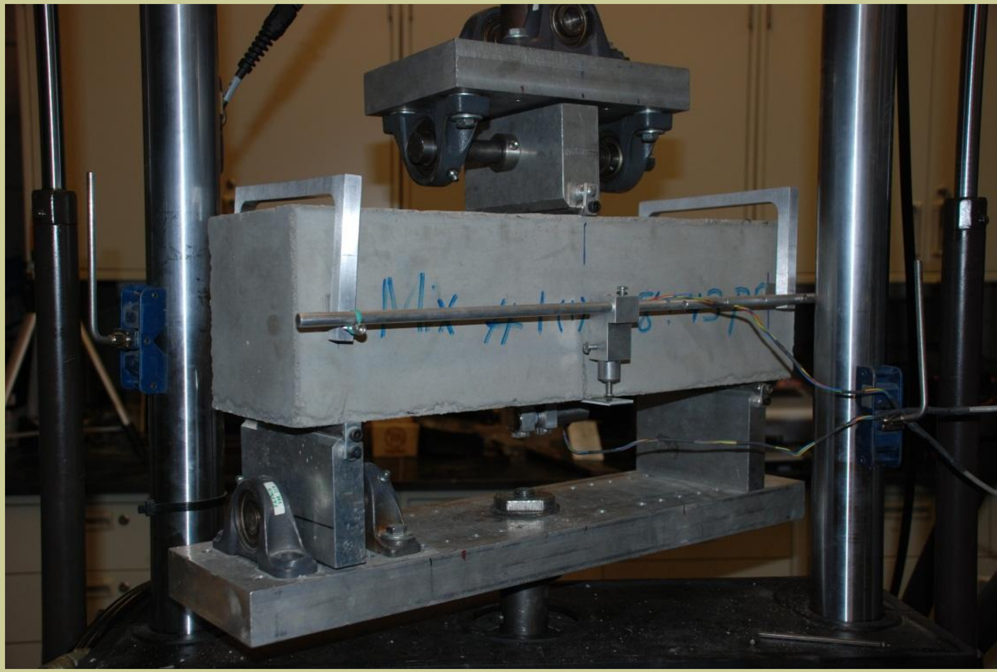
- Beam 53x15x15 cm^3, Span: 45 cm
- Initial notch length: 2.5 cm
- Load is applied along the notch at a single point
- Test performed under closed loop CMOD control at 0.12mm/min
- Results are correlate with Round Panel Tests for material modeling



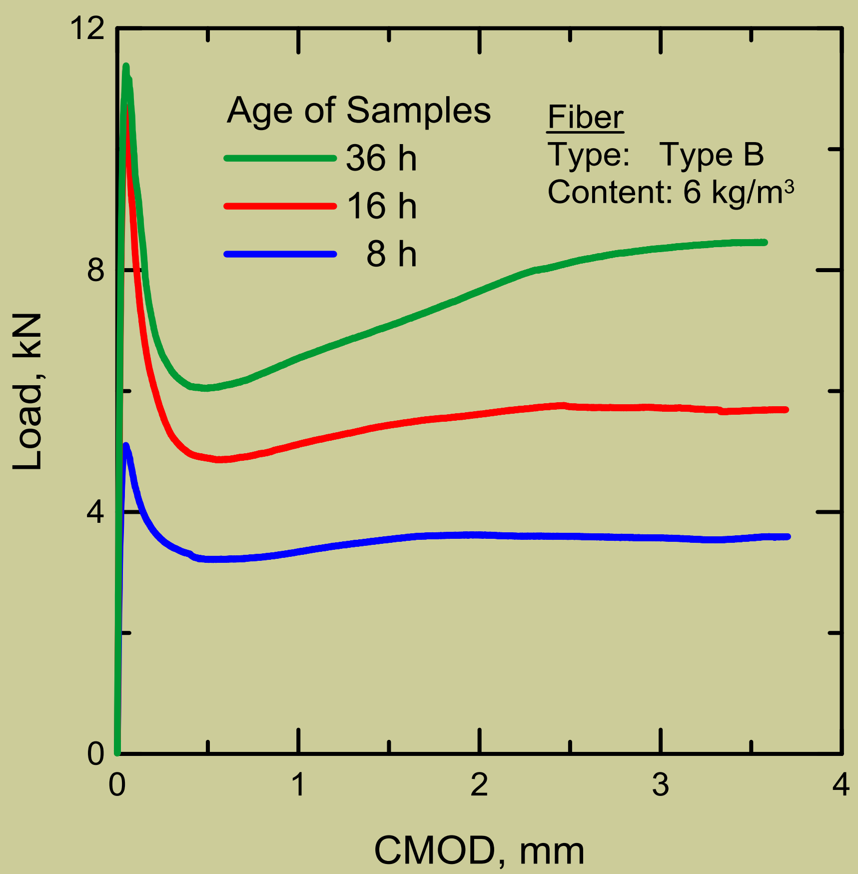
Three Point bending







Effect of Age, minimum requirements for advancing



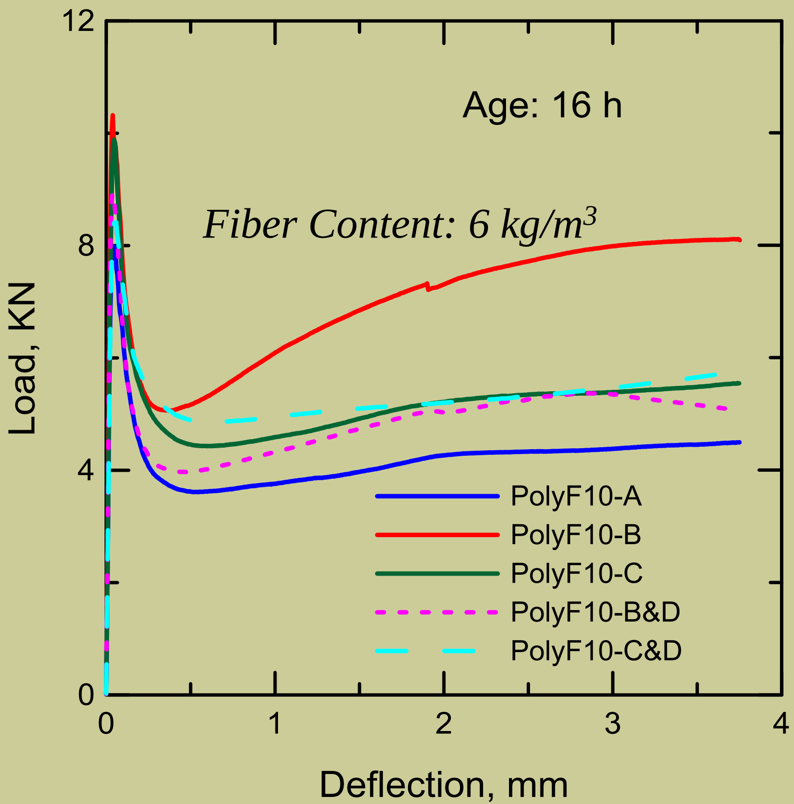
Mix Proportion (kg/m³)

Mix ID	PolyF10-TypeB
Portland Cement	475
Fly Ash	60
Silica Fume	15
Fine Aggregate	1050
Coarse Aggregate	400
Water	220
Fiber	6
Fiber Type	Type 3
Accelerator (%)	4
w/cm	0.40
s/cm	1.9
F'c (28 d), Mpa	27.1[a]

Age, h	K, KN/mm	CMOD at Max Load, mm	f_b, MPa	Max CMOD, mm	Flex. Tough., KN.mm
8	176	0.0431	1.57	3.8	8.05
16	273	0.0406	2.84	3.8	12.28
36	257	0.0431	3.09	3.8	14.60

Soranakom C, Bakhshi M, Bonakdar A, Mobasher, B. "Optimization of early strength shotcrete for rapid shaft sinking", Report to Rio Tinto-Resolution, Tempe, AZ, 2008.

Effect of Fiber Types (Polymeric)

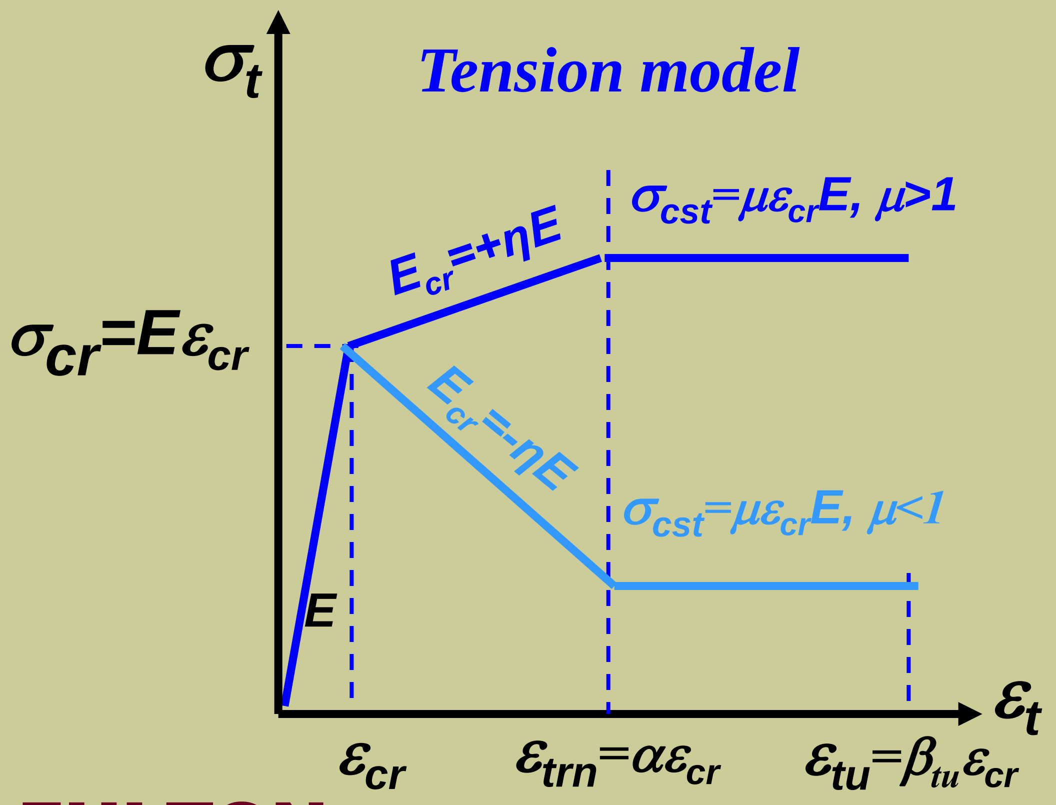


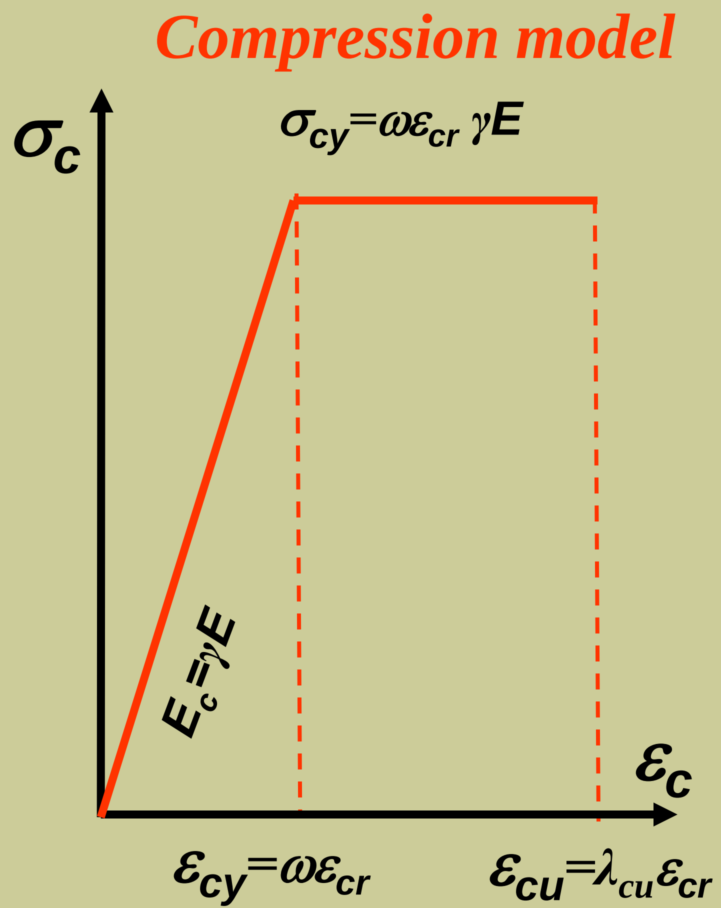
Fiber Type	Type A	Type B	Type C	Type D
Base	Monofilament Polypropylene/ Polyethylene blend	Modified Olefin	Modified Polypropylene Blend	fibrillated polypropylene fiber
S. Gravity	0.92	0.9-0.92	0.91	0.91
E (GPa)	5	10	6.55	5.5
UTS (MPa)	600 -650	550	655	410
Length (mm)	50	50	37.5	50

Mix ID	K, KN/mm	CMOD at Max Load, mm	f_b, MPa	Max CMOD, mm	Flex. Tough., KN.mm	F'c, MPa
PolyF10-A	239	0.0457	2.43	3.83	9.6	29.0[a]
PolyF10-B	281	0.0431	2.76	3.83	15.8	27.1[a]
PolyF10-C	251	0.0457	2.79	3.82	12.3	28.8[a]
PolyF10-B&D	269	0.0609	2.48	3.82	13.8	28.7[a]
PolyF10-C&D	266	0.0508	2.28	3.81	14.0	25.8[a]

Stress-Strain for Hardening and Softening FRC

- Material parameters are described as a multiple of the first cracking tensile strain (ε_{cr}) and tensile modulus (E)



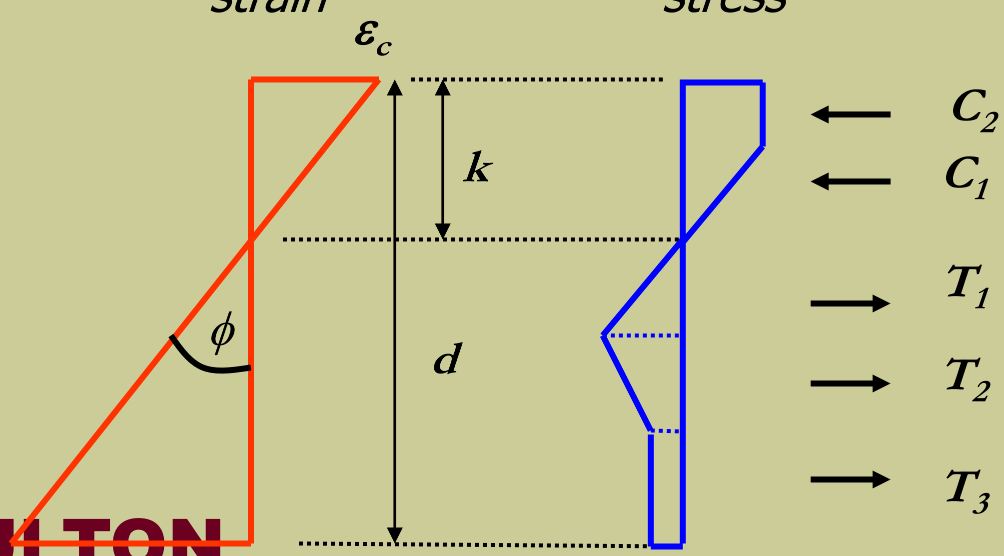


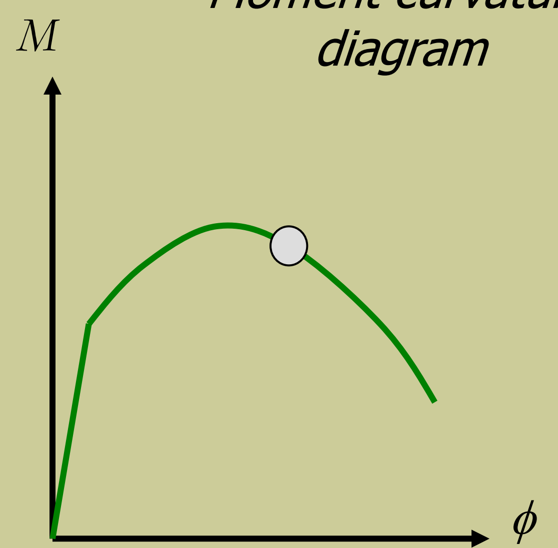
Moment-Curvature Diagram

- Incrementally impose $0 \leq \varepsilon_t \leq \varepsilon_{tu}$
  - Strain Distribution
  - Stress Distribution
- $\Sigma F = 0$, determine k (Neutral axis)
  - $M = \Sigma C_i y_{ci} + \Sigma T_i y_{ti}$ and $\phi = \varepsilon_c / kd$
- Normalization $M' = M/M_0$ and $\phi' = \phi/\phi_{cr}$

$$F_{c1} = b\int_0^{kd} f_{c1}(y)dy$$

$$y_{c1} = \frac{b}{F_{c1}}\int_0^{kd} f_{c1}(y)ydy$$

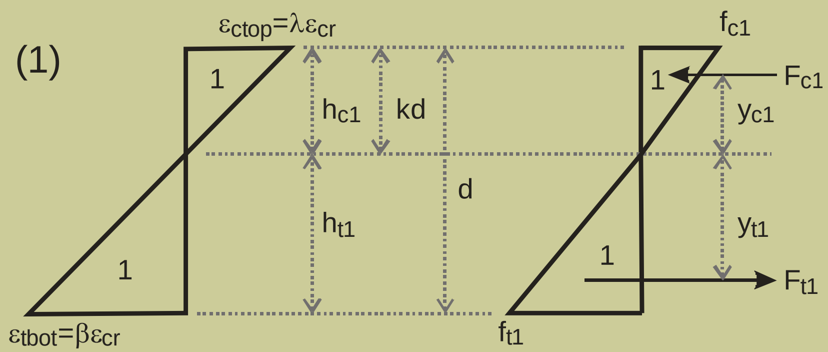




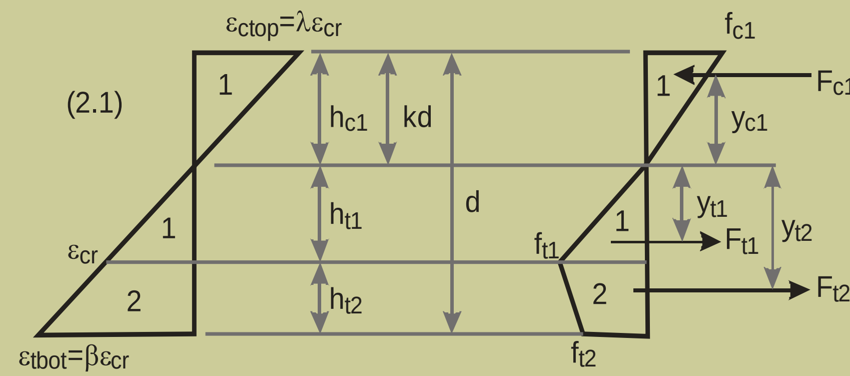
$0 \leq \varepsilon_t \leq \varepsilon_{tu}$

Stress and Strain Distribution Tensile Regions 1.0, 2.1 and 3.1

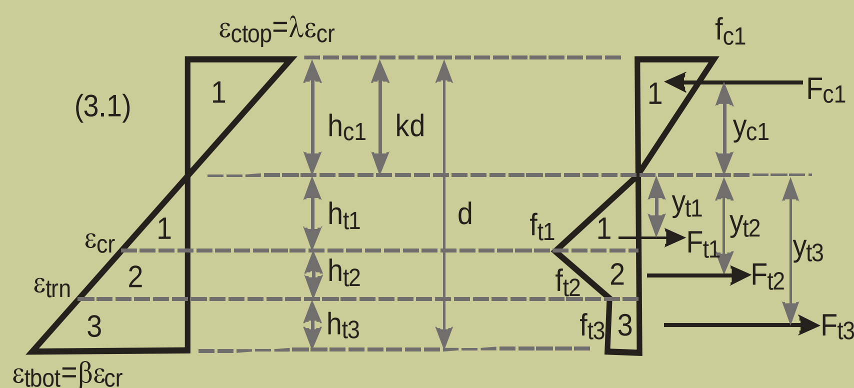
$0 < \beta \leq 1$ and $\lambda \leq \omega$



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



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



Closed Form Solutions for Strain Hardening/Softening material

Stage	k	M'	ϕ'
1	$k_1 = \begin{cases} \frac{1}{2} & \text{for } \gamma=1 \\ \frac{-1+\sqrt{\gamma}}{-1+\gamma} & \text{for } \gamma<1 \text{ or } \gamma>1 \end{cases}$	$M'_1 = \frac{2\beta\left[(\gamma-1)k_1^3 + 3k_1^2 - 3k_1 + 1\right]}{1-k_1}$	$\phi'_1 = \frac{\beta}{2(1-k_1)}$
2.1	$k_{21} = \frac{\beta^2\gamma + D_{21} - \sqrt{\gamma^2\beta^4 + D_{21}\gamma\beta^2}}{D_{21}}$ $D_{21} = \eta\left(\beta^2 - 2\beta + 1\right) + 2\beta - \beta^2\gamma - 1$	$M'_{21} = \frac{(2\beta\gamma + C_{21})k_{21}^3 - 3C_{21}k_{21}^2 + 3C_{21}k_{21} - C_{21}}{1-k_{21}}$ $C_{21} = \frac{-2\eta\beta^3 + 3\eta\beta^2 - 3\beta^2 - \eta + 1}{\beta^2}$	$\phi'_{21} = \frac{\beta}{2(1-k_{21})}$
2.2	$k_{22} = \frac{D_{22}}{D_{22} + 2\omega\gamma\beta}$ $D_{22} = \eta\left(\beta^2 - 2\beta + 1\right) + 2\beta + \omega^2\gamma - 1$	$M'_{22} = (3\omega\gamma + C_{22})k_{22}^2 - 2C_{22}k_{22} + C_{22}$ $C_{22} = \frac{2\eta\beta^3 - 3\eta\beta^2 + 3\beta^2 - \omega^3\gamma + \eta - 1}{\beta^2}$	$\phi'_{22} = \frac{\beta}{2(1-k_{22})}$
3.1	$k_{31} = \frac{D_{31} - \sqrt{\gamma\beta^2 D_{31}}}{D_{31} - \beta^2\gamma}$ $D_{31} = \eta\left(\alpha^2 - 2\alpha + 1\right) + 2\mu(\beta - \alpha) + 2\alpha - 1$	$M'_{31} = \frac{(C_{31} - 2\beta\gamma)k_{31}^3 - 3C_{31}k_{31}^2 + 3C_{31}k_{31} - C_{31}}{k_{31} - 1}$ $C_{31} = \frac{3\left(\mu\beta^2 - \mu\alpha^2 - \eta\alpha^2 + \alpha^2\right) + 2\eta\alpha^3 + \eta - 1}{\beta^2}$	$\phi'_{31} = \frac{\beta}{2(1-k_{31})}$
3.2	$k_{32} = \frac{D_{32}}{D_{32} + 2\omega\gamma\beta}$ $D_{32} = \omega^2\gamma + \eta\alpha^2 + 2(\mu\beta - \eta\alpha - \mu\alpha + \alpha) + \eta - 1$	$M'_{32} = (C_{32} + 3\omega\gamma)k_{32}^2 - 2C_{32}k_{32} + C_{32}$ $C_{32} = \frac{3\left(\mu\beta^2 - \mu\alpha^2 - \eta\alpha^2 + \alpha^2\right) + 2\eta\alpha^3 - \omega^3\gamma + \eta - 1}{\beta^2}$	$\phi'_{32} = \frac{\beta}{2(1-k_{32})}$

$$M = M' M_{cr}$$

$$M_{cr} = \frac{1}{6} b d^2 E \varepsilon_{cr}$$

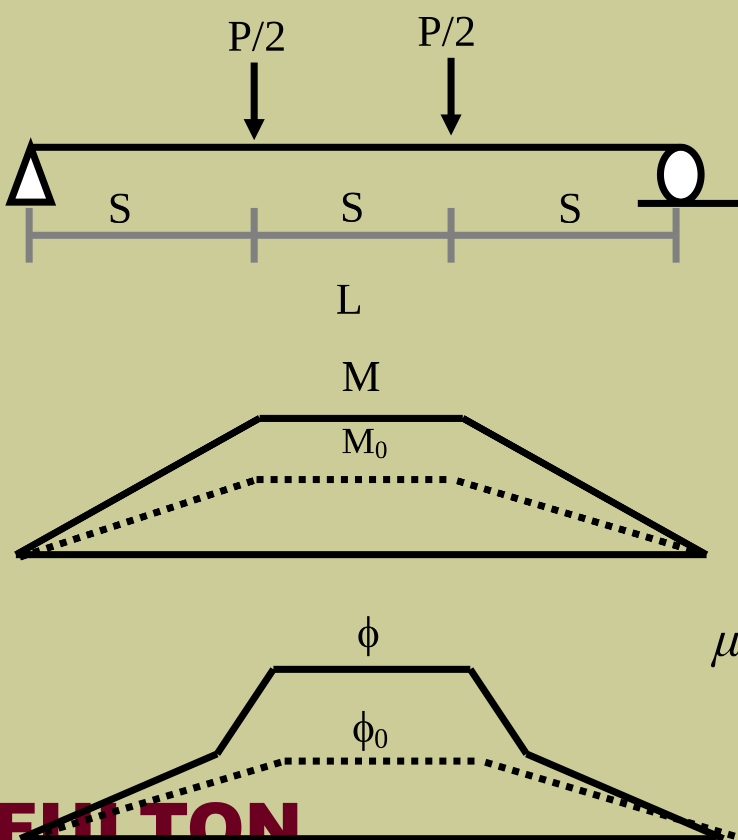
$$\phi = \phi' \phi_{cr}$$

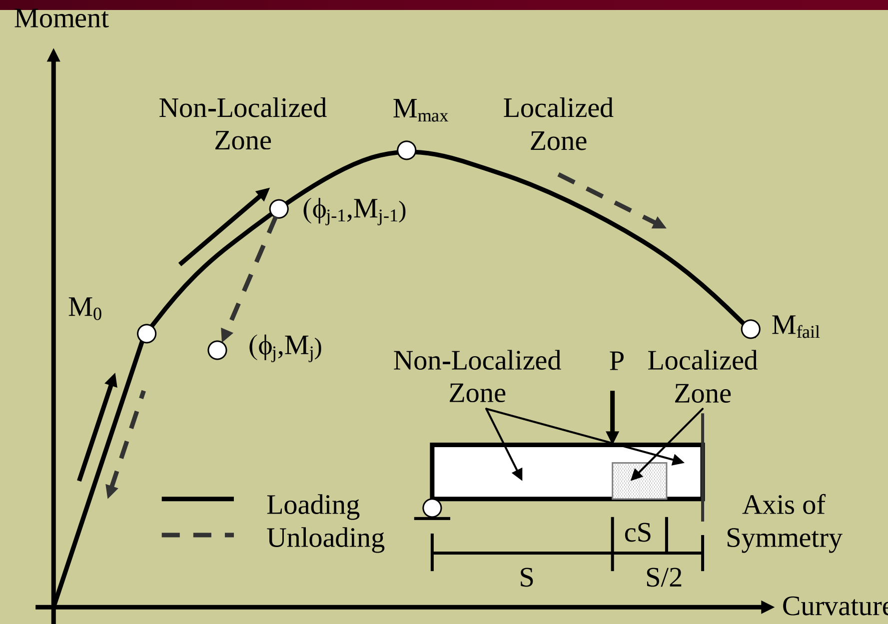
$$\phi_{cr} = \frac{2\varepsilon_{cr}}{d}$$

Soranakom C, Mobasher B. "Correlation of tensile and flexural responses of strain softening and strain hardening cement composites", Cem Concr Comp 2008;30:465–477.

Load Deflection Response Applicable to 3PB and 4PB Tests

- Moment area method
- Crack localization rules





$$\delta_{cr} = \frac{23}{216} L^2 \phi_{cr} \quad \textit{in elastic region}$$

$$\mu > \mu_{crit}: \delta_u = \frac{L^2}{24 M_u^2}\left[\left(2M_u^2 - M_u M_{cr} - M_{cr}^2\right)\phi_u + \left(M_u^2 + M_u M_{cr}\right)\phi_{cr}\right]$$

$$\mu < \mu_{crit} \quad \delta_u = \frac{\phi_u L_p}{8}\left(2L - L_p\right) + \frac{M_u \phi_{cr} L}{12 M_{cr}}\left(L - 2L_p\right)$$

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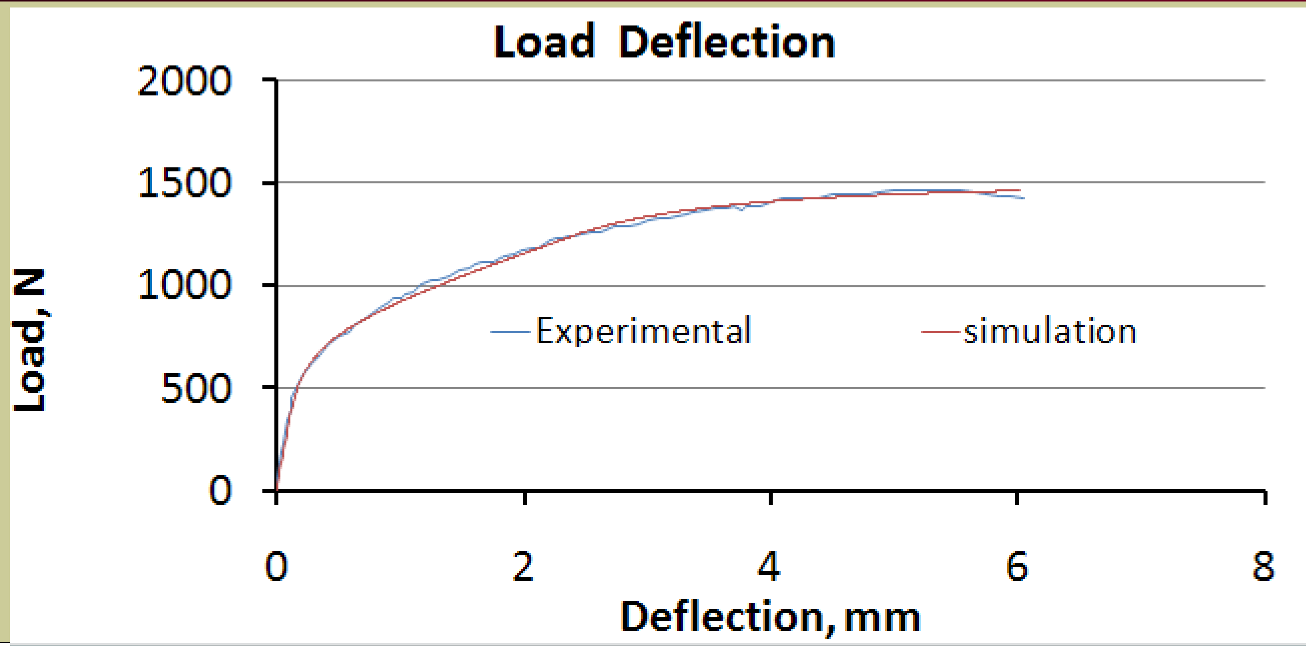
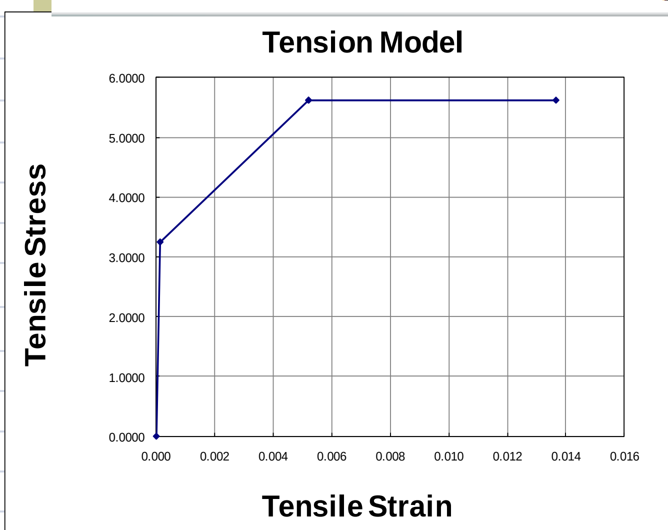
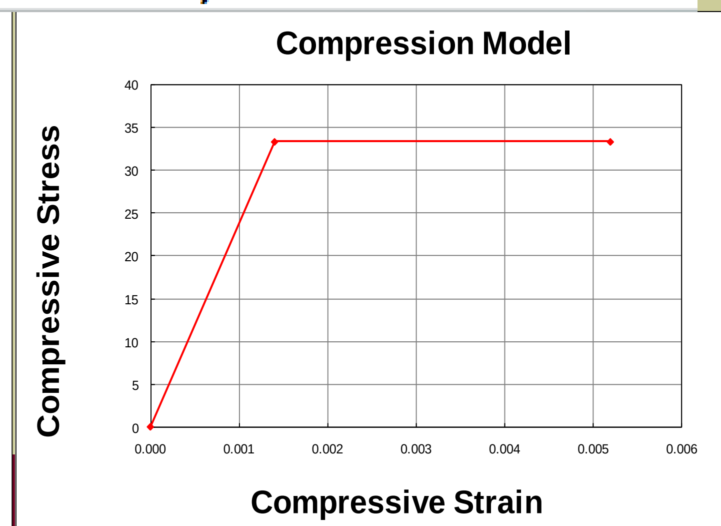
Back Calculation Parameters

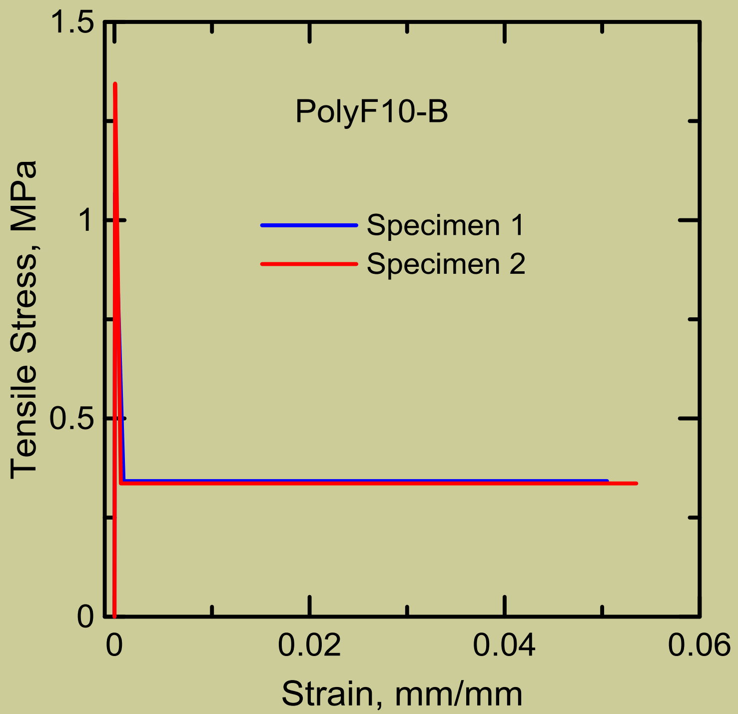
	A	B	C	D
1	**Model Parameters**			
2	**Beam Size**			
3	est Method	4	Point Bending	
4	b =	50		
5	d =	25		
6	L =	300		
7				
8				
10				
11	**Material Model**			
12	E =	25000		
13	εcr =	1E-04		
14	α	40		
15	**Tension**			
16	γ=	0.95		
17	η=	0.019		
18	μ=	1.73		
19	βtu=	105		
20				
21				
22	**Compression**			
23	ω =	10.8		
24	λcu =	40		
25				
26				
27	Units are: **in, lbs, psi**			
28	or: **mm, N, Mpa**			
29	Please Use Units Consistently			

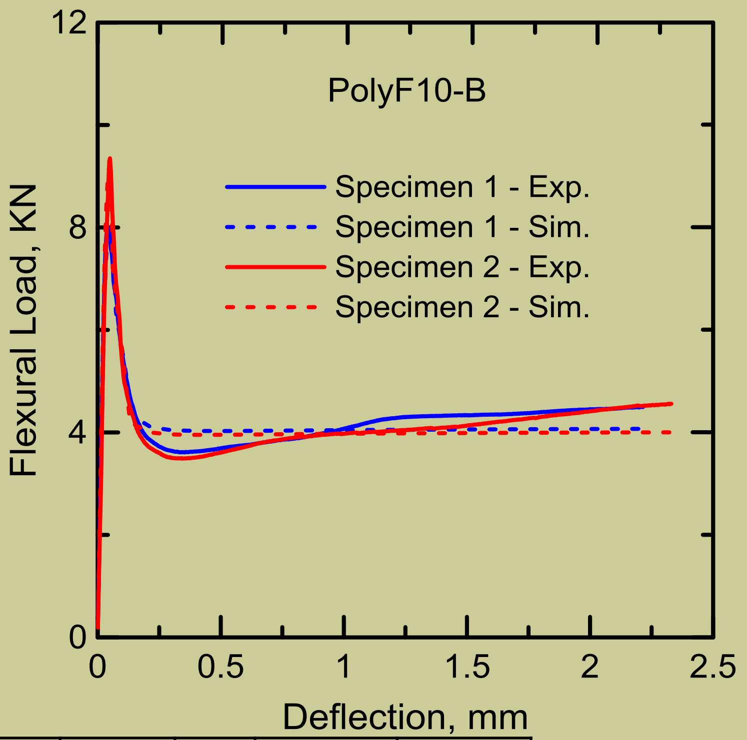






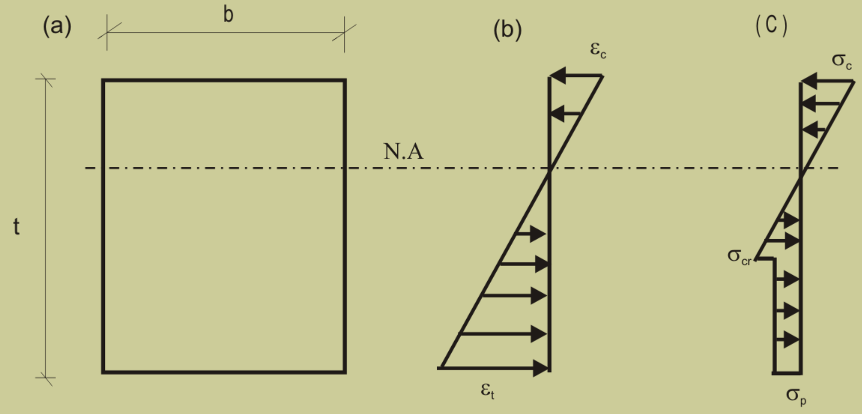
Back Calculated Material Properties and Tensile Parameters

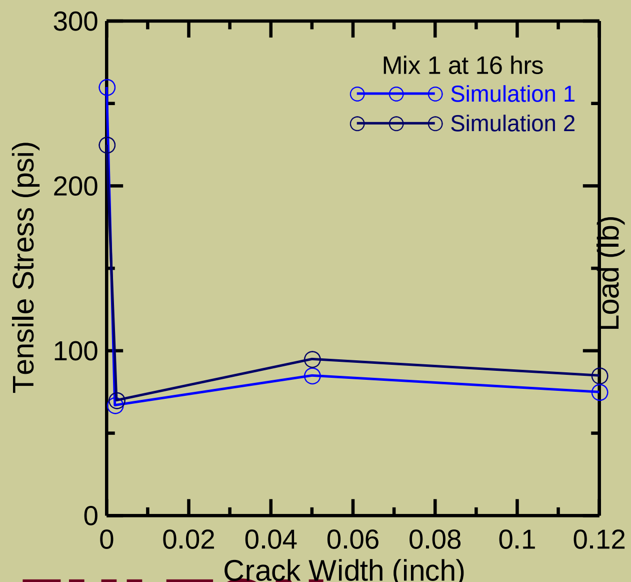


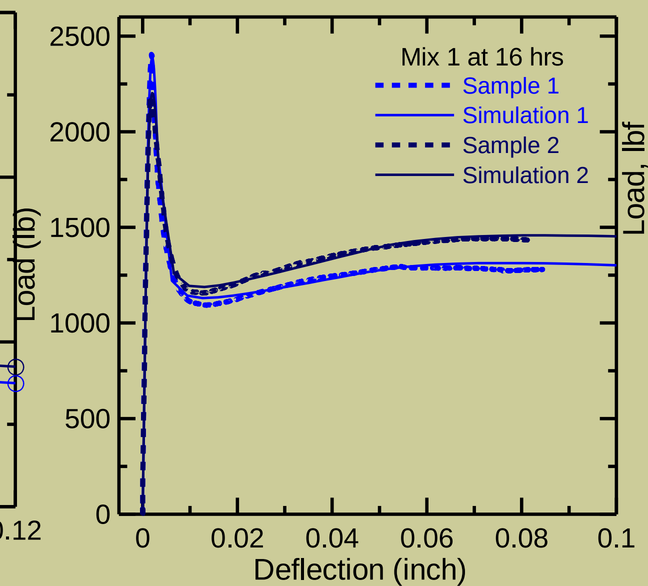


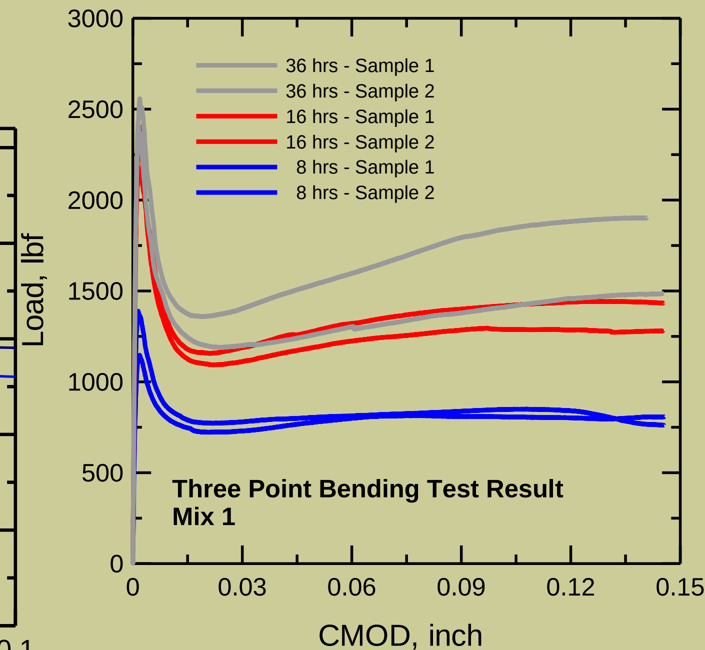
Mix ID	ε_{cr}, μstr	E, GPa	μ	α	ε_{trn}, μstr	ε_{tu}, mm/mm
PolyF10-A	58.5	20.6	0.285	14	793	0.052
PolyF10-B	55	24.1	0.37	14	755	0.050
PolyF10-C	55.5	23.8	0.33	19	1032	0.043
PolyF10-B&D	76	17.2	0.27	9	684	0.0495
PolyF10-C&D	66	17.2	0.39	16	1056	0.054

Effect of age and backcalculation of properties









10-12 lbs/yd^3 of macro fibers

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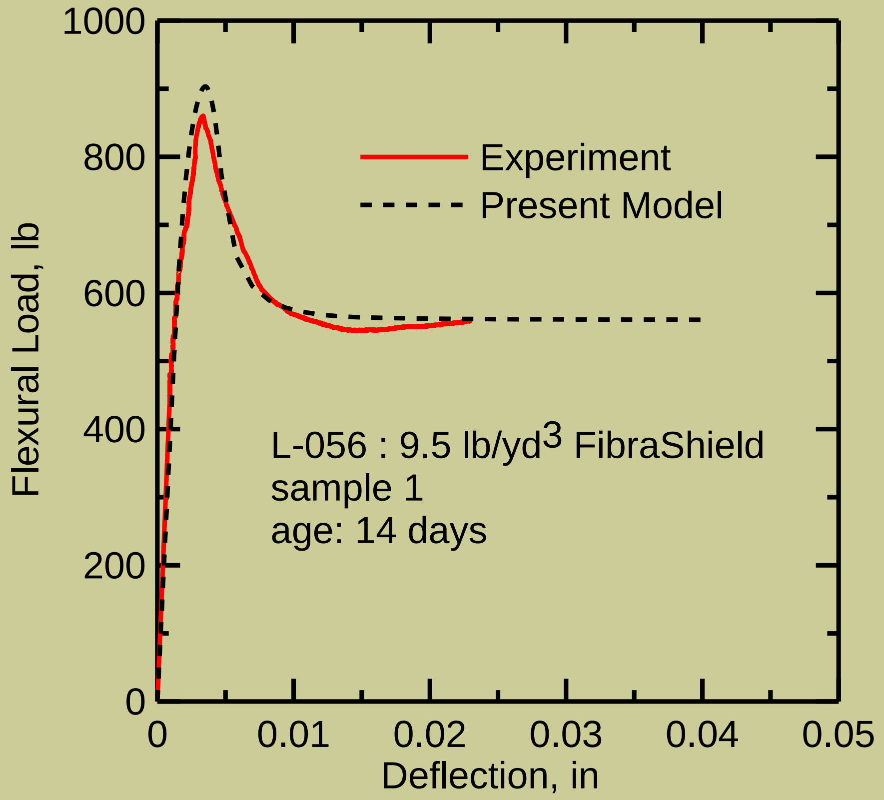
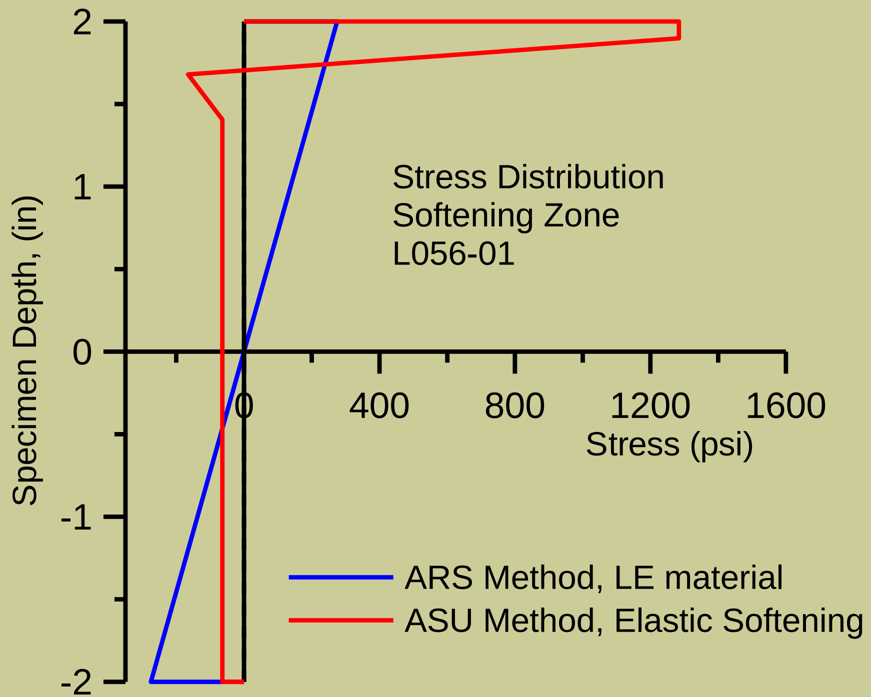
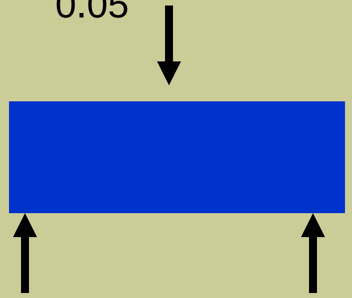
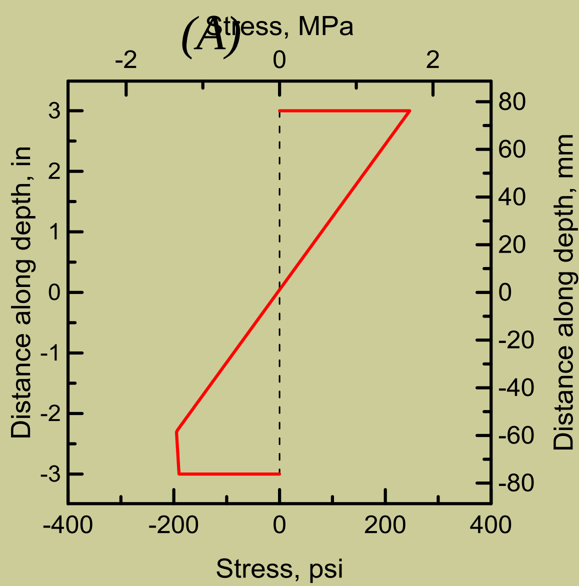
Comparison With ASTM- C1609

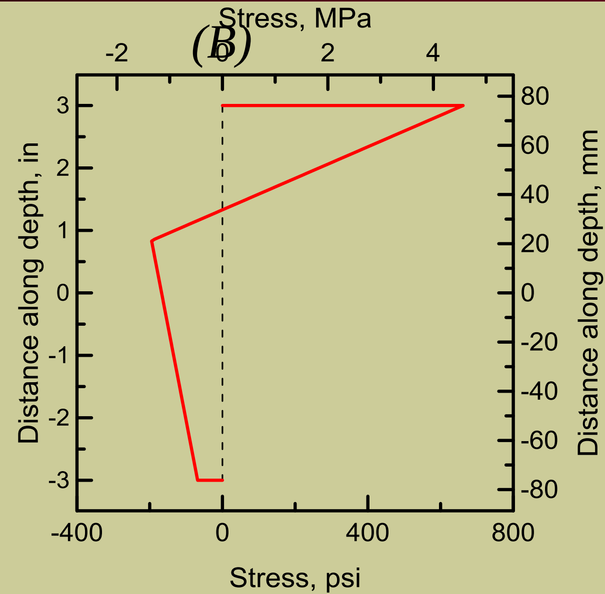


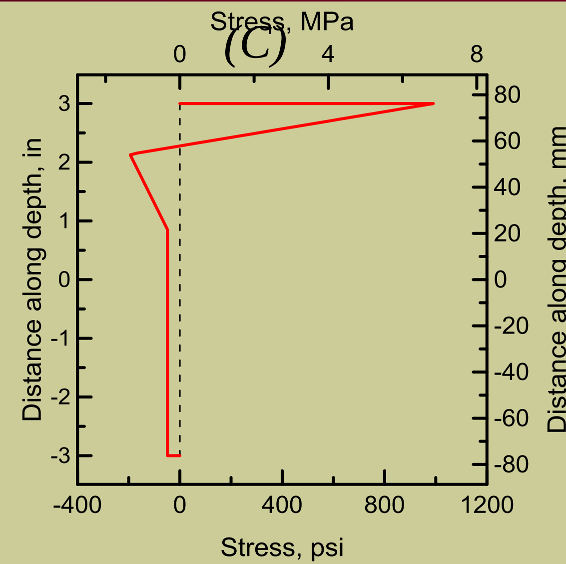


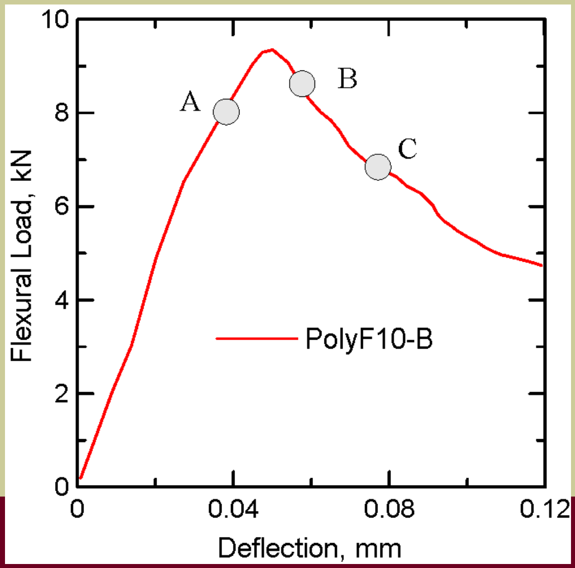


Evolution of Profile of Stress Distribution

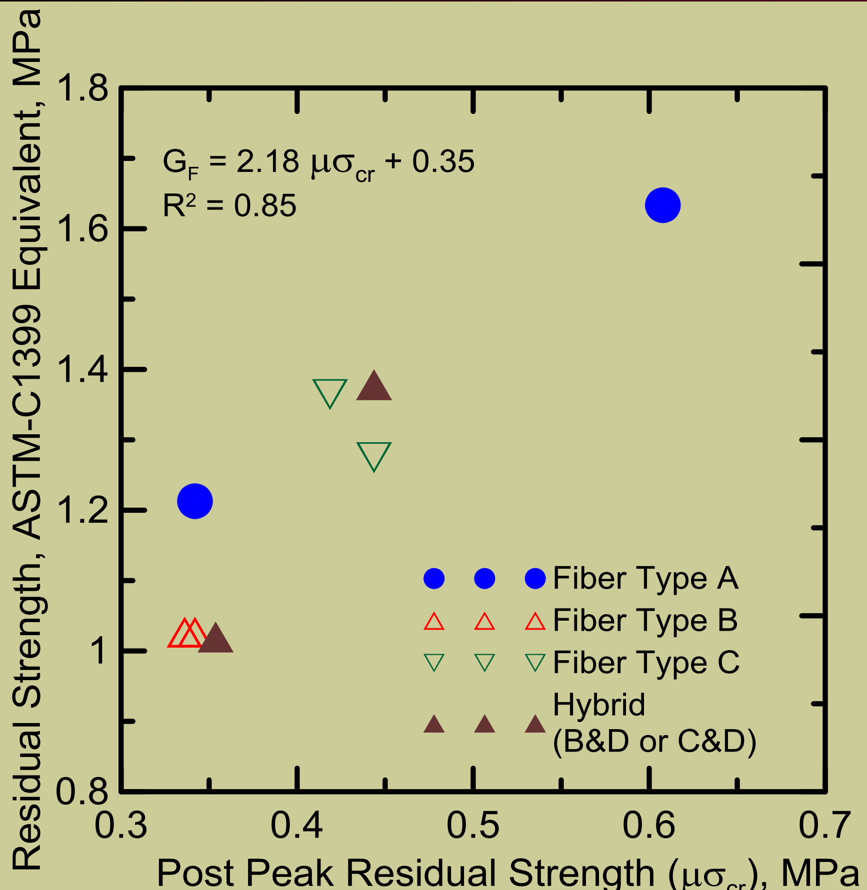


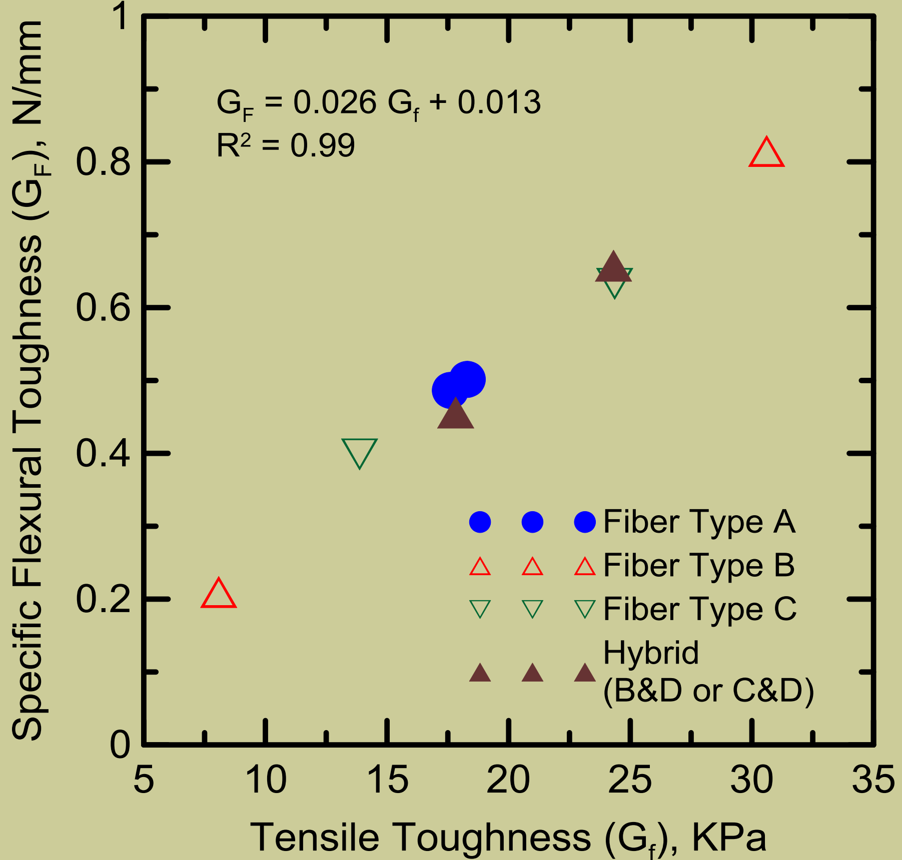






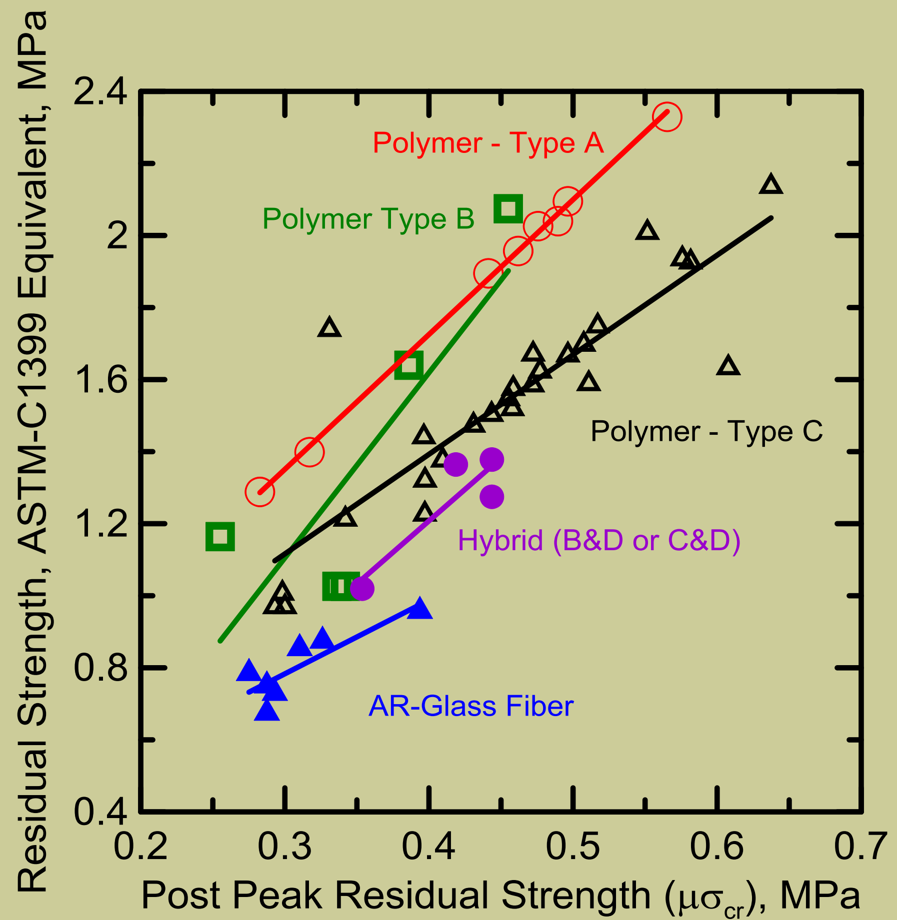
Post Peak Residual Strength ($\mu\sigma_{cr}$), ARS and Toughness Comparison





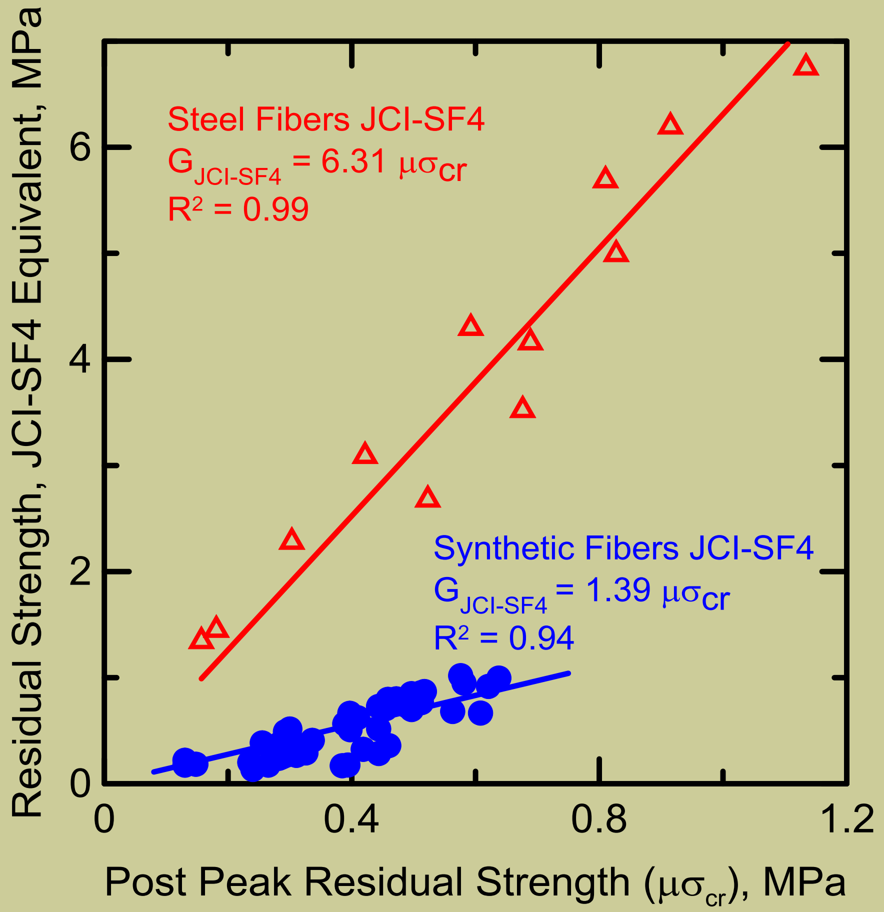
ARS method overestimates the residual tensile strength by 2.2 times

Curve Fitting of ARS versus Post Peak Residual Strength ($\mu\sigma_{cr}$)

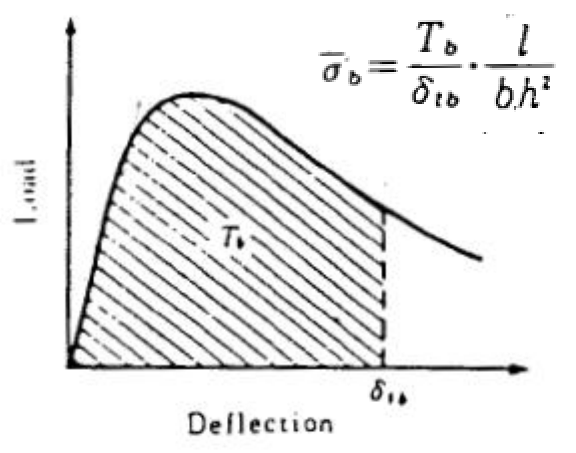


Bakhshi M, Mobasher B. "Sustainable Design of Structural Concrete Materials: a Case Study of Materials Science, Structural Mechanics, and Statistical Process Control", A Report (SR-633) to Arizona Department of Transportation, Tempe, AZ, 2010.

Comparison with JCI Method



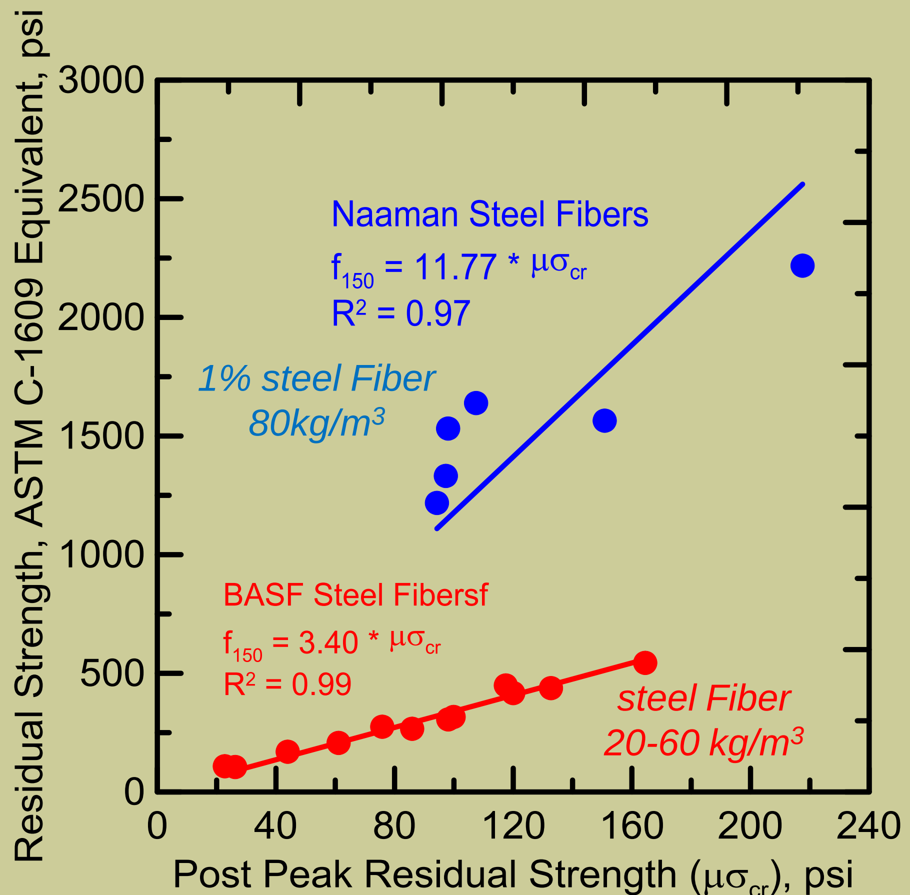
- JCI method overestimates the residual strength of
  - synthetic fibers by 1.4 times
  - steel fibers by 6.3 times



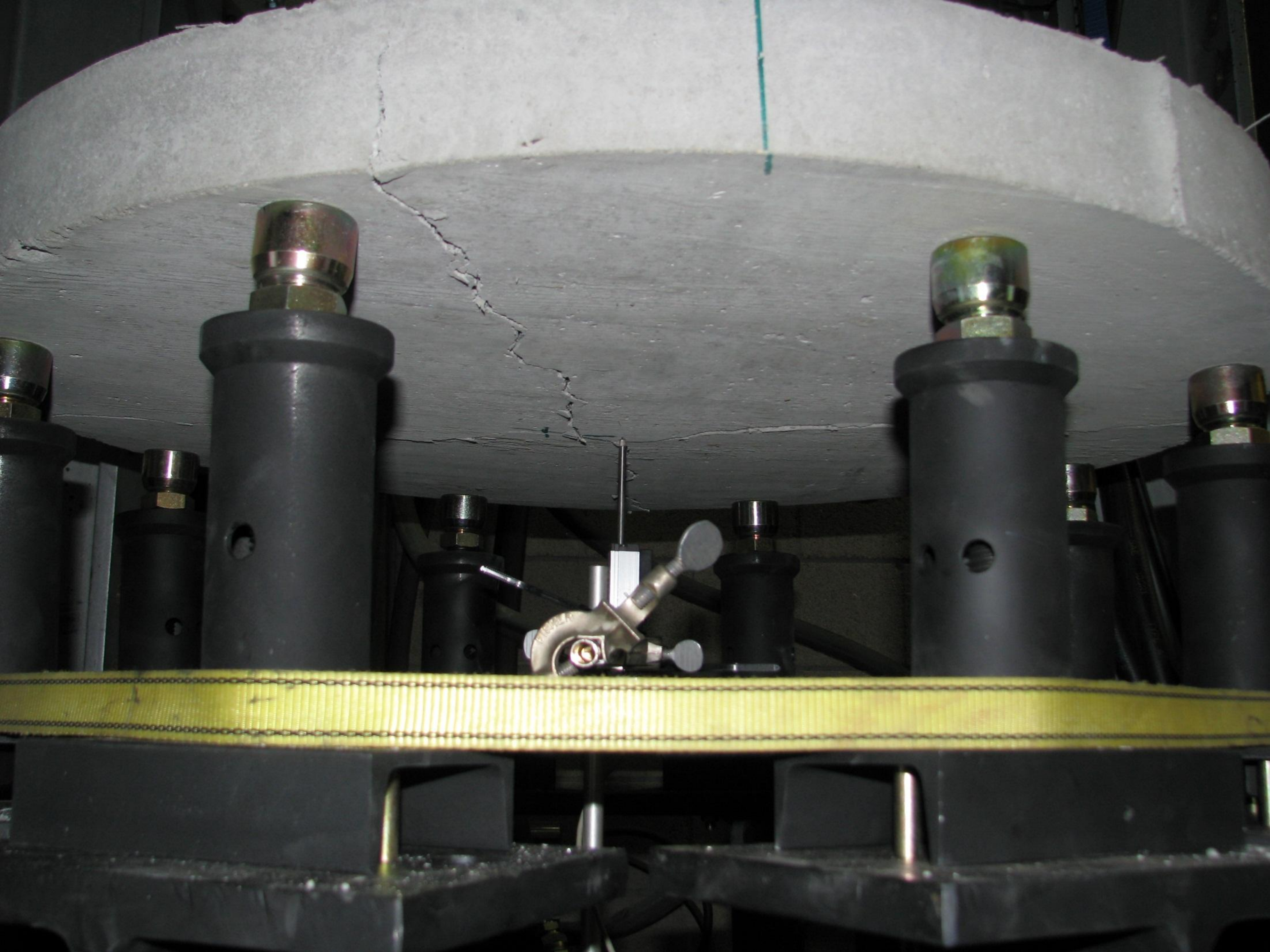
δ_{tb} : deflection of 1/150 of span

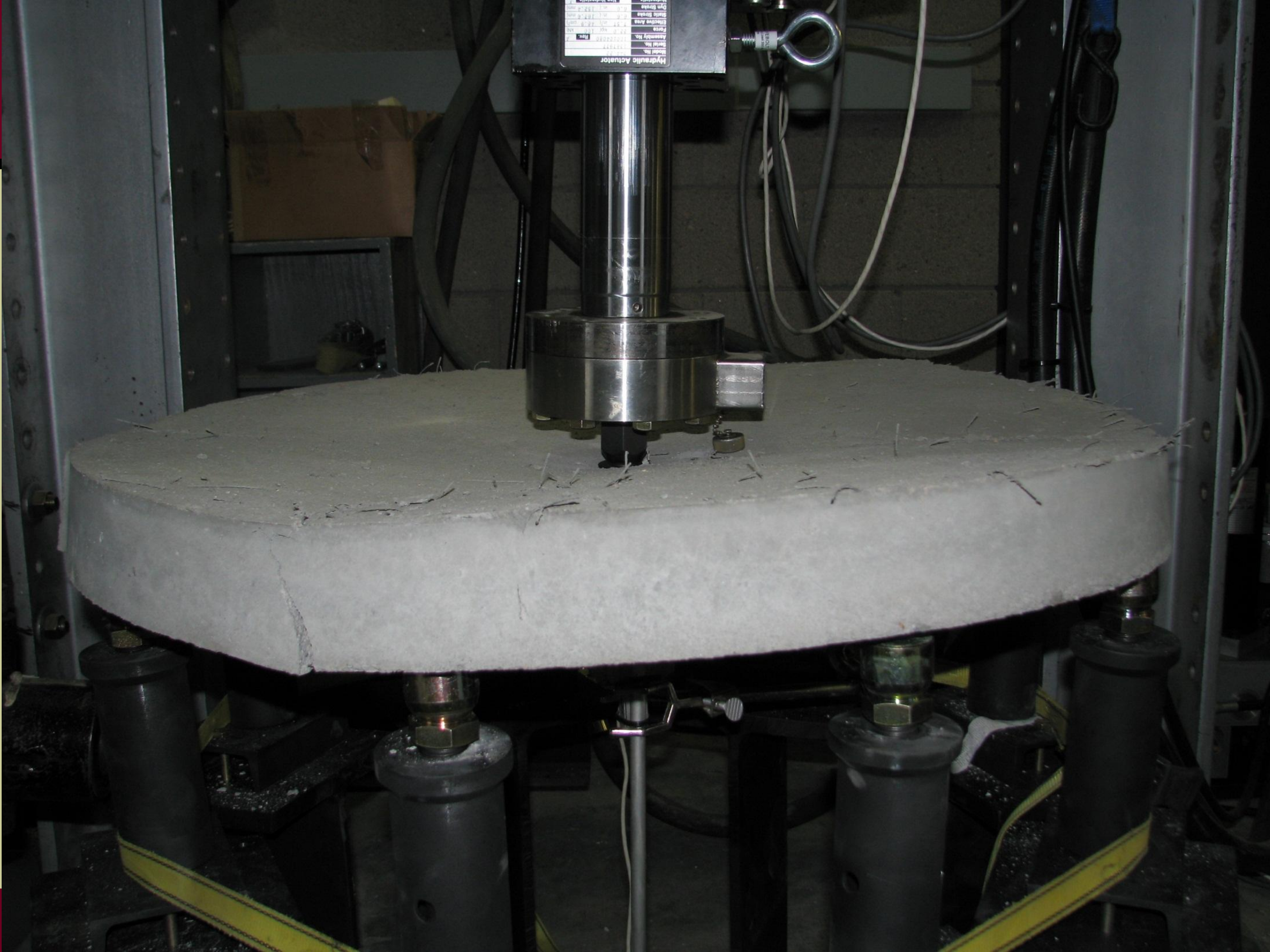
Bakhshi M, Mobasher B. "Sustainable Design of Structural Concrete Materials: a Case Study of Incorporating Materials Science, Structural Mechanics, and Statistical Process Control", A Report (SR-633) to Arizona Department of Transportation, Tempe, AZ, 2010.

Ultra-High Performance FRC-

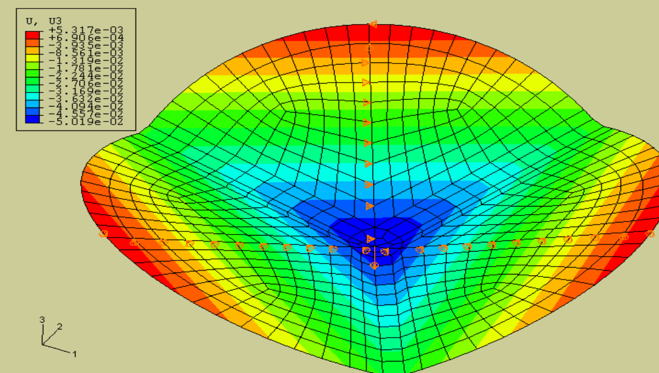


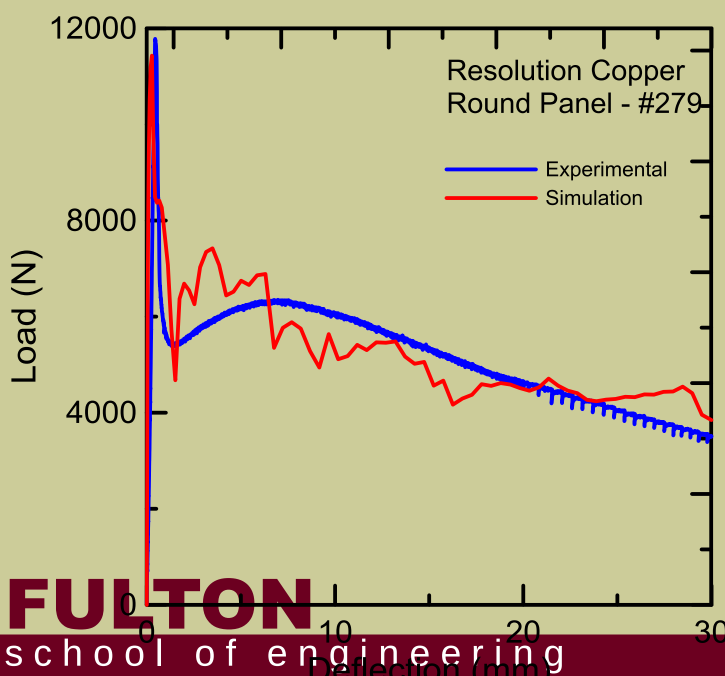
Kim D-J, Naaman AE, El-Tawil S. "Correlation between Tensile and Bending Behavior of FRC Composites with Scale Effect", Proc FraMCoS-7, 7th International Conference on Fracture Mechanics of Concrete and Concrete Structures, May 23-28, 2010, Jeju Island, South Korea

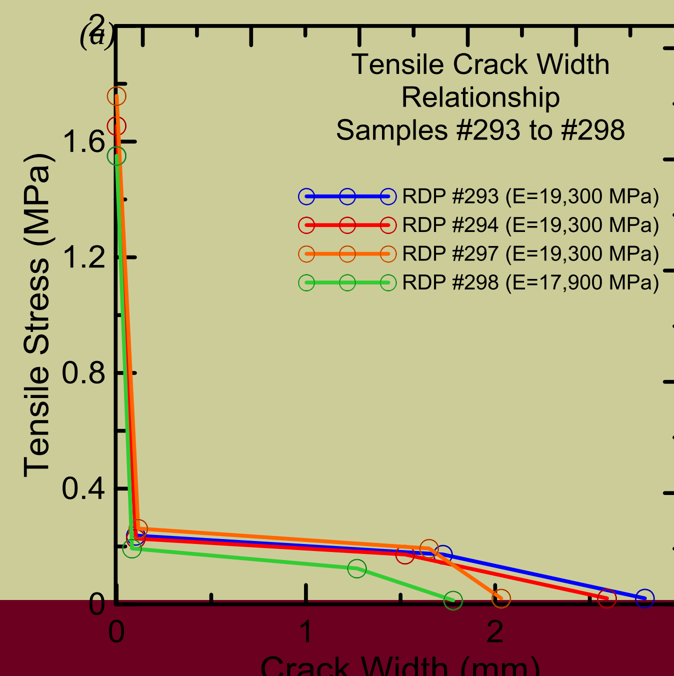



Hydraulic Actuator

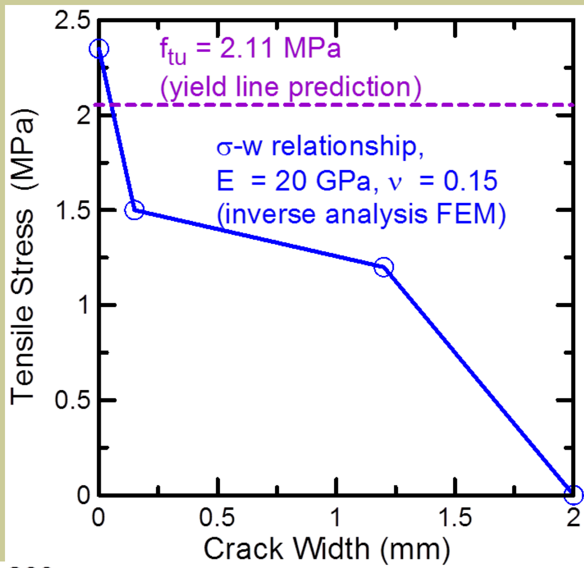
Round Panel 3P-support specimen, ASTM C1550

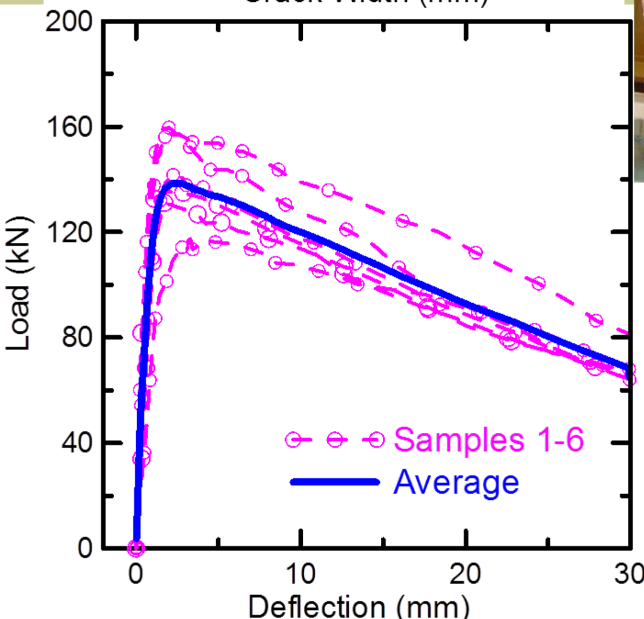


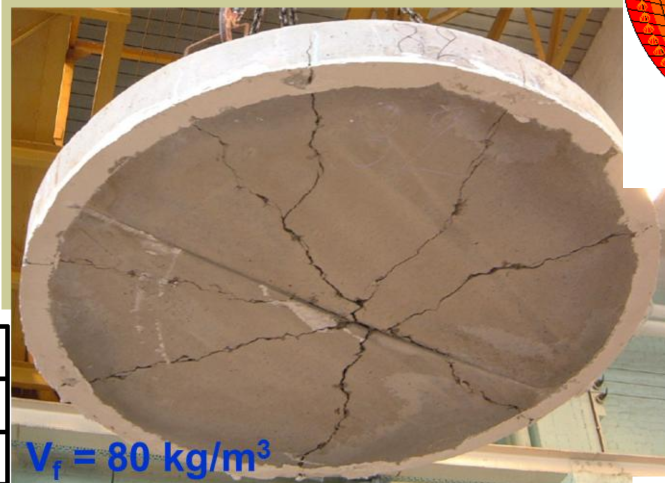


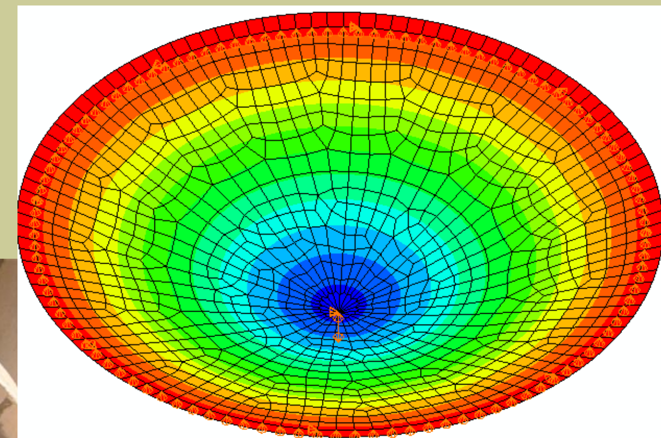


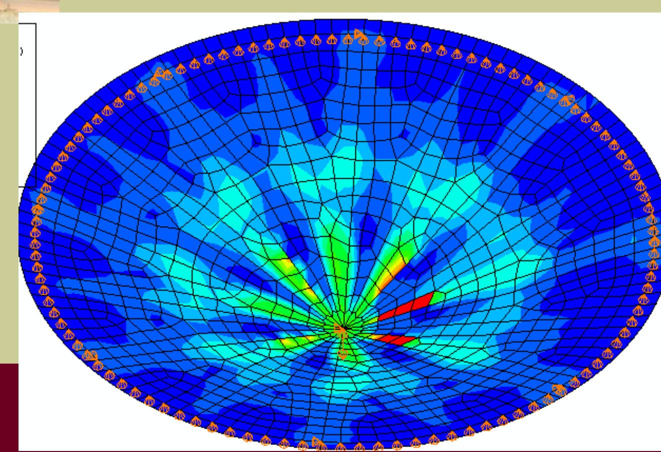
Round Panel specimens-Continuous support

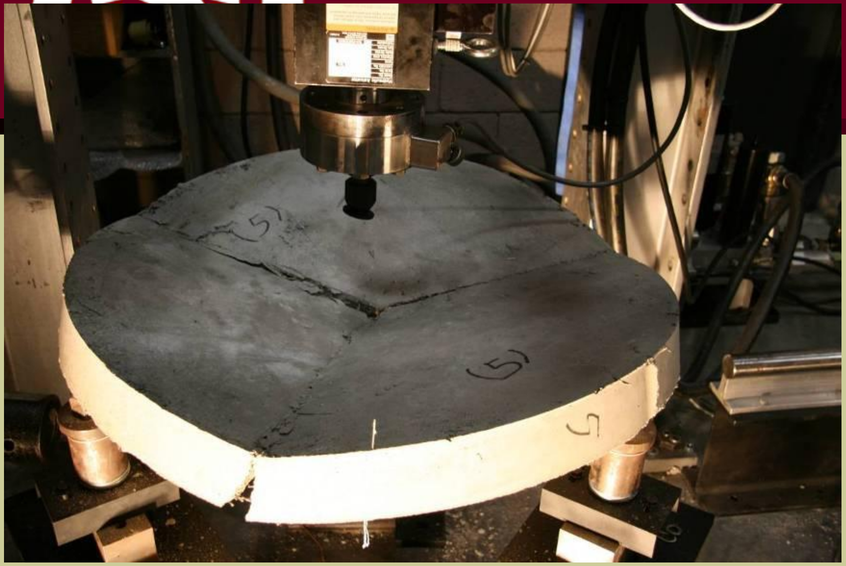






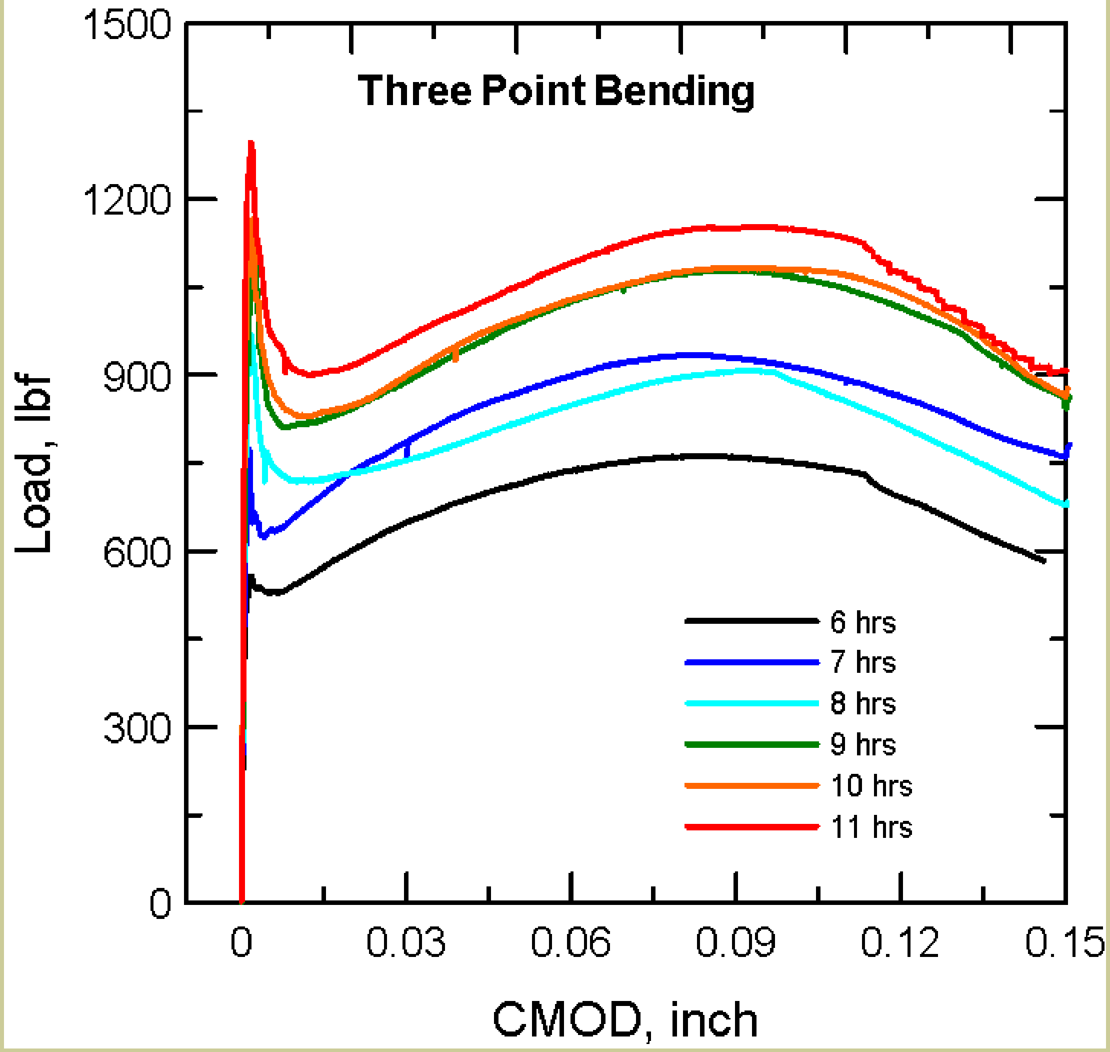




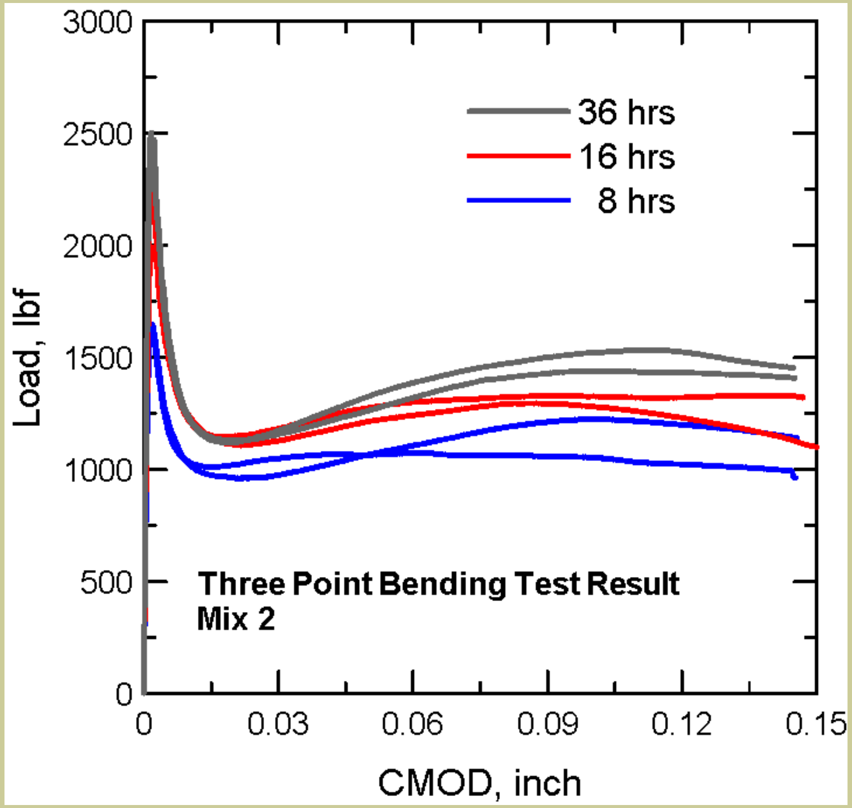


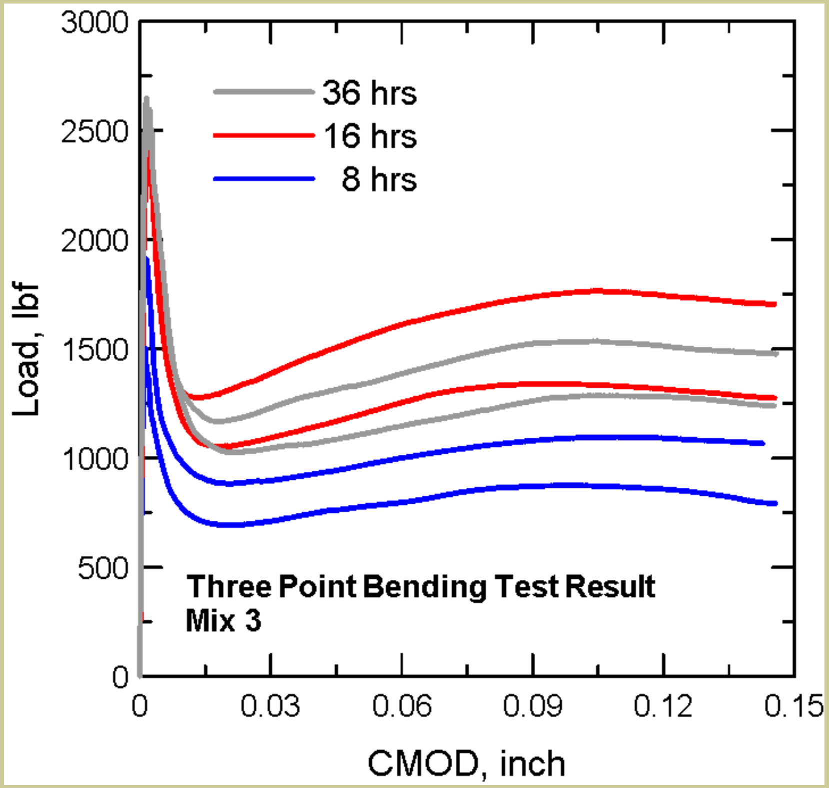
Item	Sample No.	Id	Type	Fiber Type	Fiber Dosage lb/yd^3	Curing Condition	Age
1	(dummy)	I-3	sprayed	PP	5.5	moisture, 75^{o}F	6+2
2	2		sprayed	PP	9.625	moisture, 75^{o}F	5+2
3	3	I-5	sprayed	PP	5.5	moisture, 75^{o}F	6+2
4	4	I-4	sprayed	PP	5.5	moisture, 75^{o}F	6+2
5	5		sprayed	PP	9.625	moisture, 75^{o}F	5+2
6	6		sprayed	PP	9.625	moisture, 75^{o}F	5+2

Gradual strength gain as a function of time

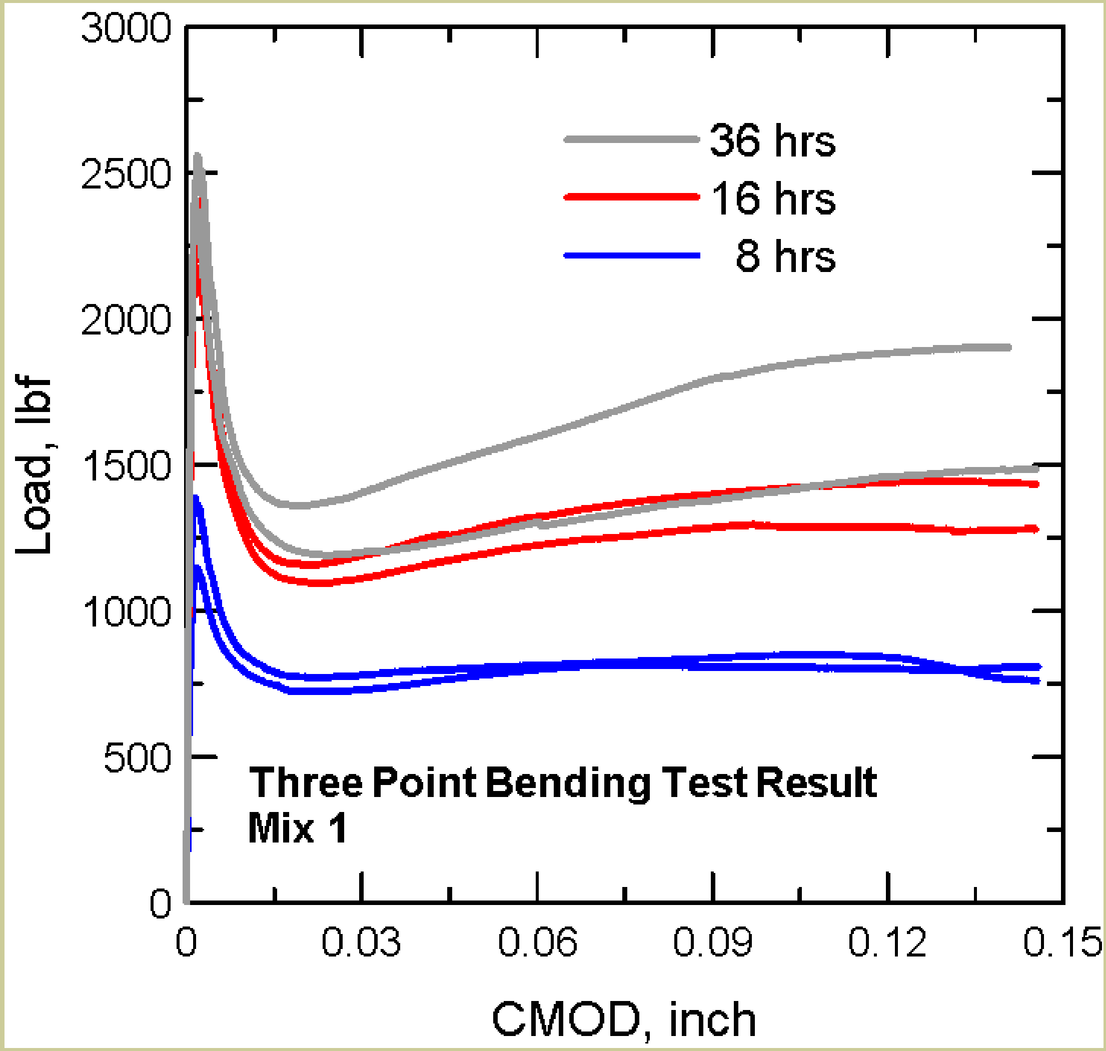


Preliminary test results

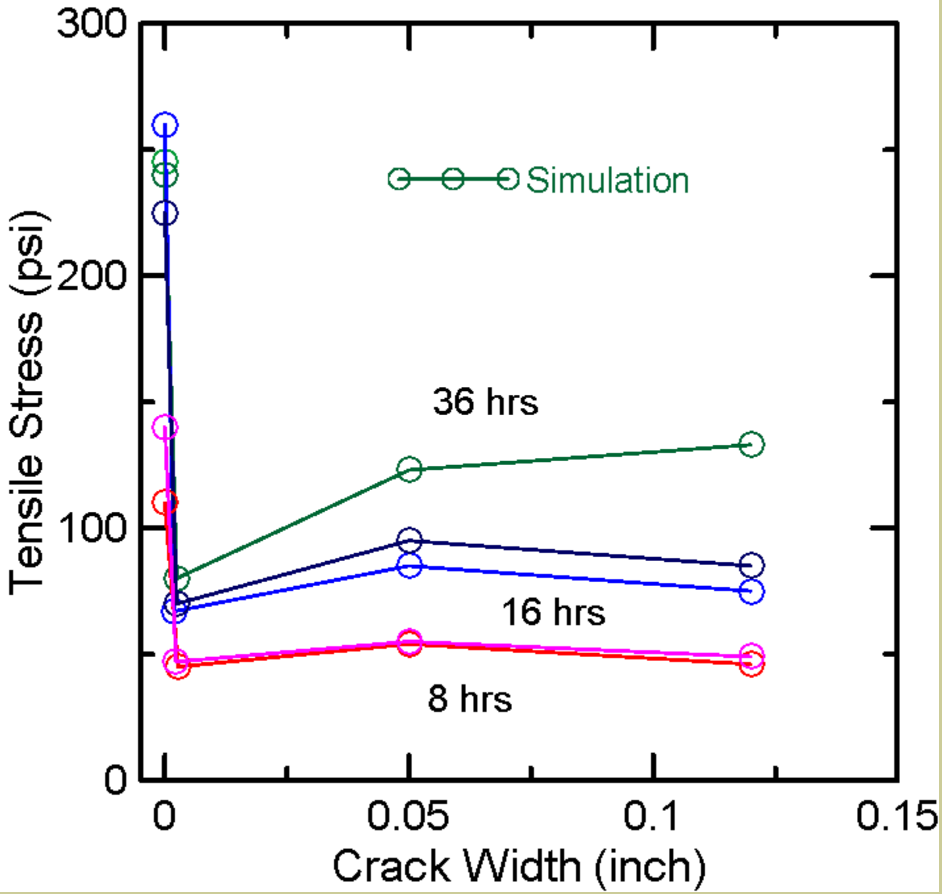


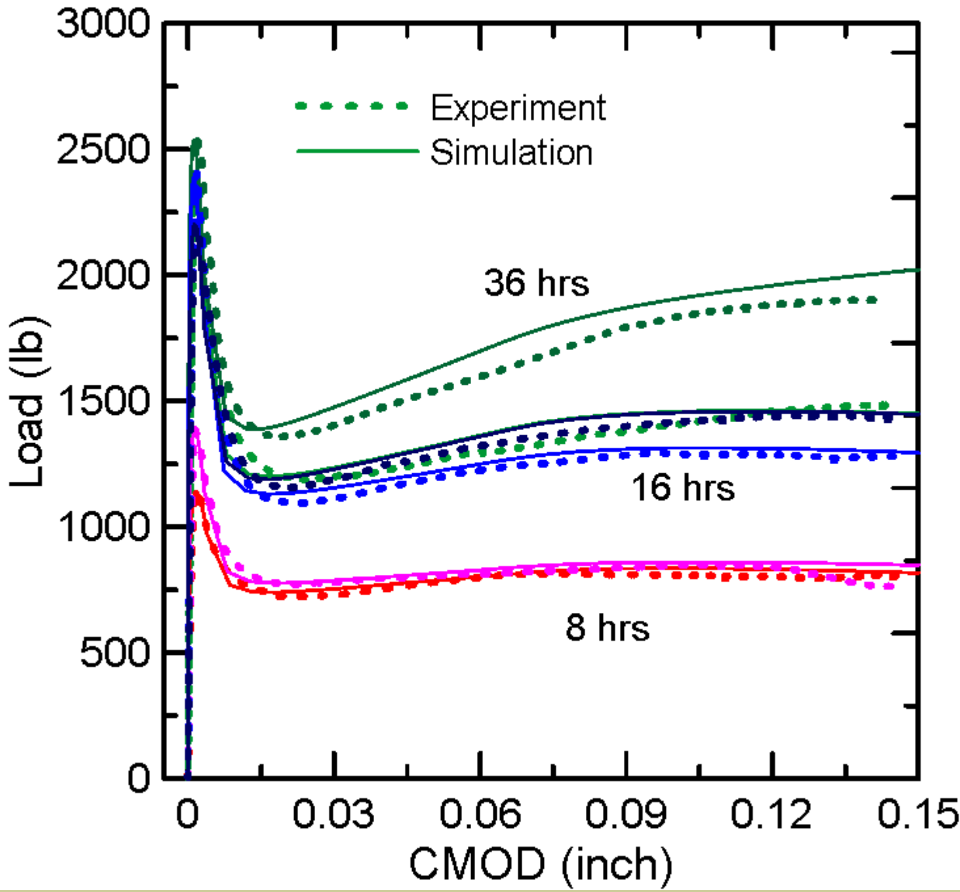


Effect of Age on the post crack Mechanical response

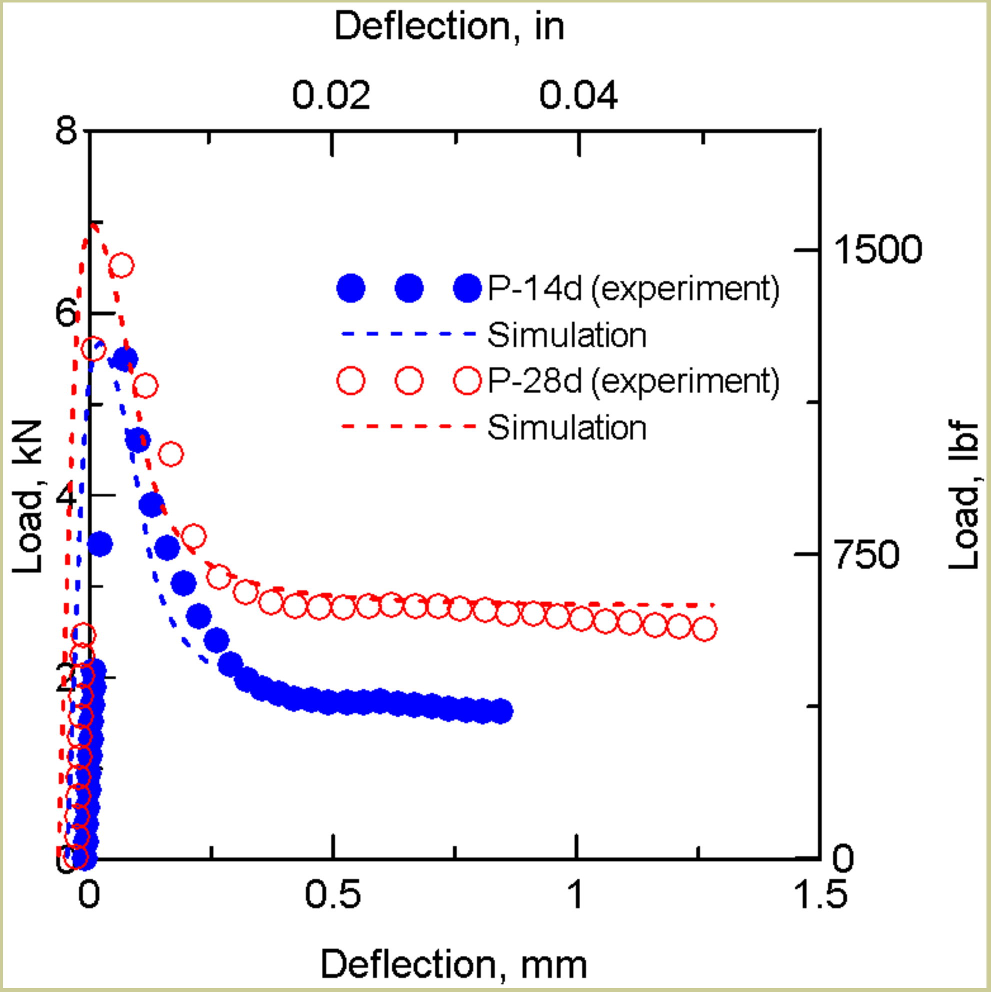


Simulation vs. Experiment

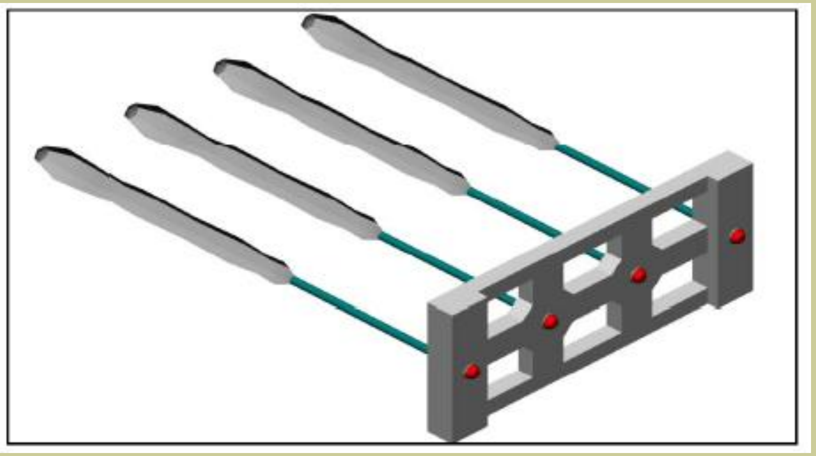


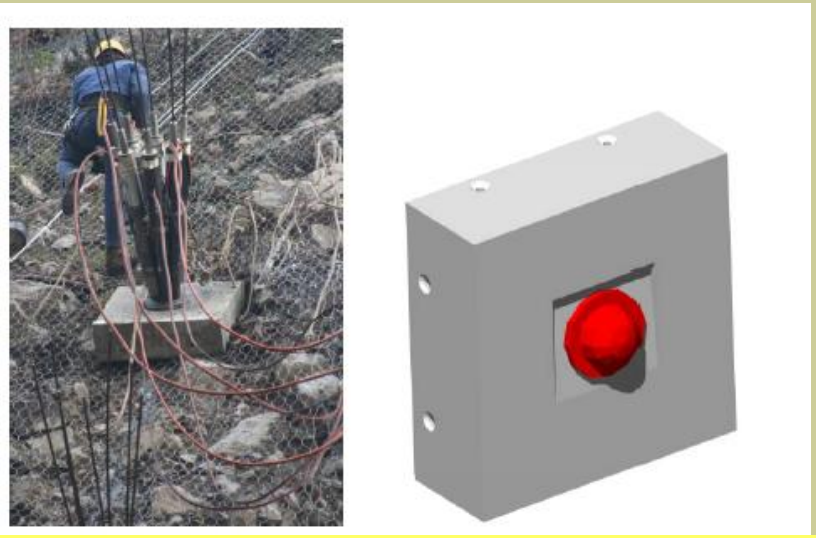


Effect of curing up to 28 days

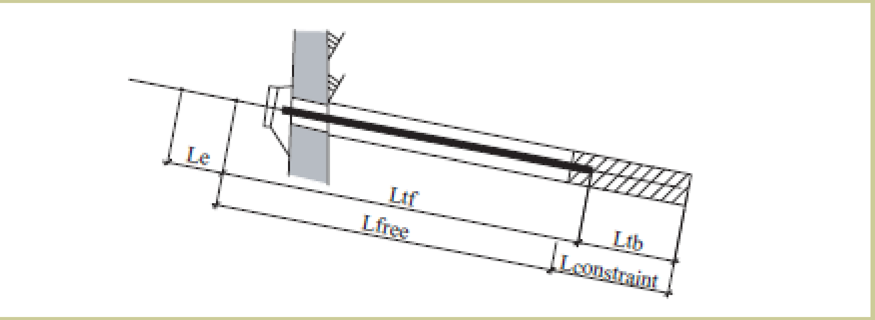


Slope Stability and Rockfall stabilization





ASSESSMENT AND CONTROL OF A SFRC RETAINING STRUCTURE: MECHANICAL ISSUES, di Prisco, M., di Prisco, C., Dozio D., Galli, A., Lapolla, S., Department of Structural Engineering, Politecnico di Milano, Italy.


Le
Ltf
Lfree
Ltb
Lconstraint


SOC. TRASPORTI BERGAMO

Structural Design with FRC Materials Requires proper guidelines for testing, analysis and Design

Elevated slabs

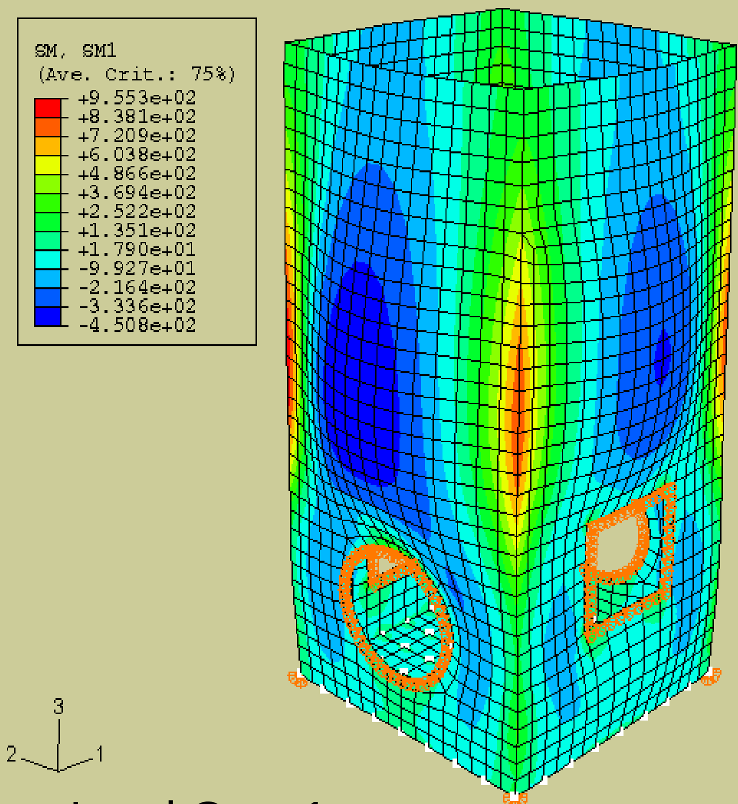
Precast panels

Shotcrete applications

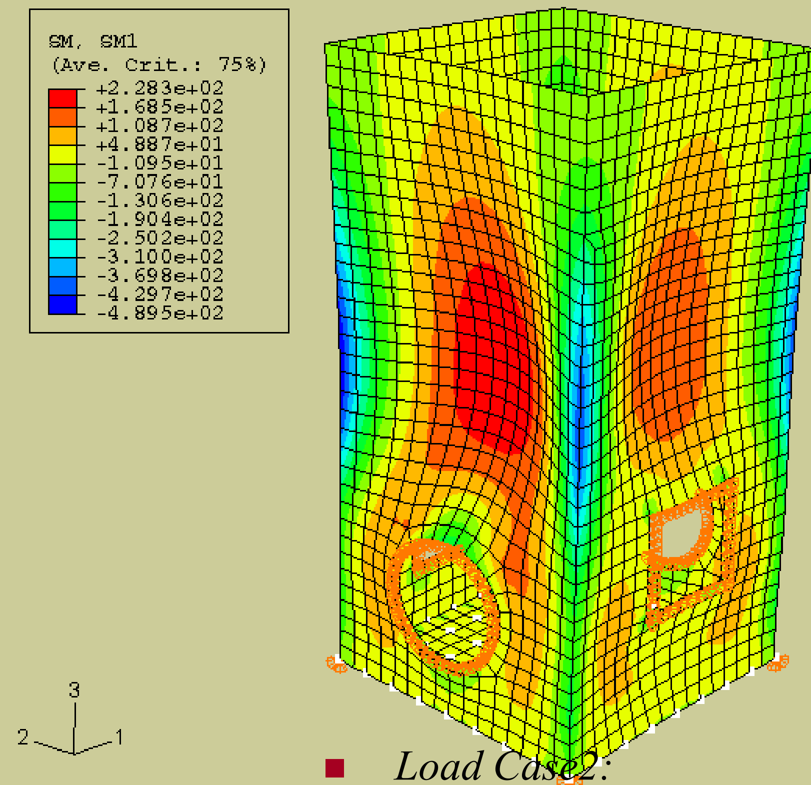
Installation of precast water tank

- Panels are assembled on site
- The wall joints are connected using bolts and epoxy
- The base slab is connected to the periphery walls by friction through slots

Analysis Results



- Load Case1:
  - 1.4 Self weight + 1.4 Water pressure
  - Moment in short span direction SM1



- *Load Case2:*
  - *1.4 Self weight + 1.7 Earth pressure + 1.7 Uniform pressure due to surcharge*
  - *Moment in short span direction SM1*

Conclusions

- Proposed approach for backcalculation of stress train response is applicable to both Strain hardening and Strain softening Fiber reinforced concrete (FRC)
- Major physical parameters define tensile response of fiber reinforced cementitious materials
- back calculation procedures allow one to obtain tensile response from three-point and four-point bending tests
- The material parameters can be used for design, or finite element analysis of structural members
- Post peak residual strength of FRC is overestimated by available experimental methods such as ARS, JCI and RILEM.

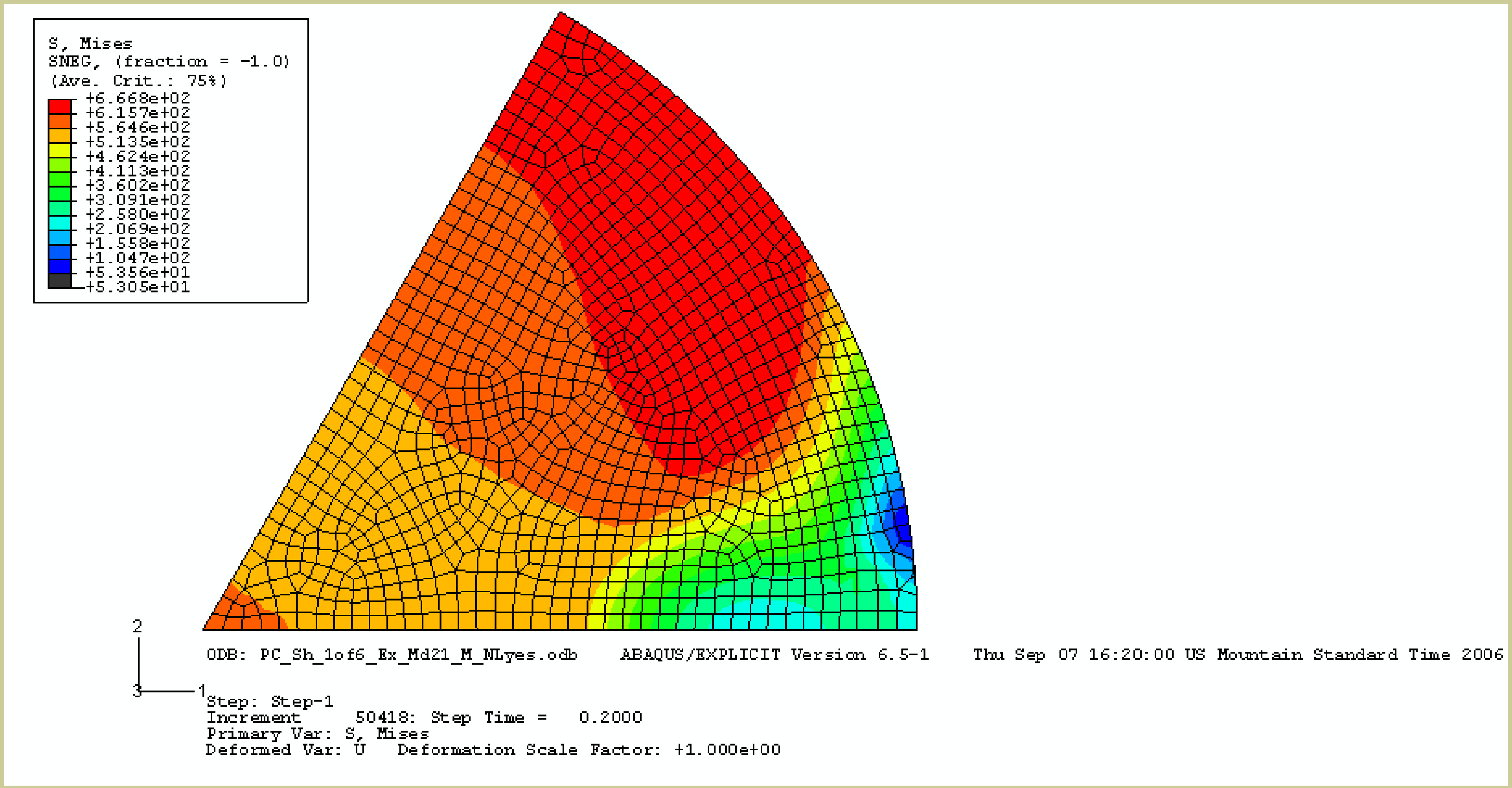
Stay Safe, be creative


CLAUDIO

- Mix 1,2,3,4 are CSA, CSB, HAS, HSB respectively.
- C = control mix, H = high performance mix, S = shogun fiber
- A = fiber dosage level 10 lb/yd^3, B = fiber dosage level 12 or 15 lb/yd^3
- Beam is 6” x 6” x 18” (clear span) with a one inch notch at the center.
- Assume localized plastic length L_p = 0.5h, where h is reduced depth 5”
- Assume compressive modulus is always elastic. Young’s modulus in compression and tension are equal.
- Use load-deflection response instead of load-CMOD to back calculate tensile stress crack width relationship. Using load-CMOD in back calculation gives low *E* in the range of 500,000 to 900,000 psi while the load-deflection gives *E* in the range of $1.5x10^6$ to $4x10^6$ psi.
- The simulations of load-CMOD are also plotted with the experimental load-CMOD.
- Tensile stress crack width evaluated up to 0.15 inch due to the experimental load-deflection response is terminated around 0.1 inch. The corresponding fracture energy is therefore evaluated up to 0.15 inch.

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Shogun	10.0			8.5		10.0
Tufstrand		10.0				
Mac 200			10.0		8.5	
F100				1.5	1.5	
P900	8.0	8.0	8.0	8.0	8.0	8.0
Delvo	1.5	1.5	1.5	1.5	1.5	1.5
G7101	13.0	15.0	15.0	15.0	17.0	
PT1552						13.0
NC534	20.0	20.0	20.0	20.0	20.0	20.0
Spread	19.5	17.0	21.5	21.0	22.5	21
Unit Wt	138.6	137.0	138.4	137.6	136.8	137.1
Air	2.6	3.4	3.1			
Temp	73	72.0	74	75	70	72
16 hr Temp	95	99	106	103	89	91
16 hr Break	3168	3167	3320	3104	2170	2873
24 hr Temp	82	82	73	73	73	74

ix No.	Code	Tensile Parameters					Compressive Parameters		
		e_{cr} (in/in)	s_{cr} (psi)	E_t (psi)	m	b_{tu}	e_{cy} (in/in)	e_{cu} (in/in)	s_{cu} (ps
Mix 1	1-1	0.00013	351	2.7E6	0.16	940*	0.001275	0.004250	3442
	1-2	0.00015	405	2.7E6	0.24	2200	0.001500	0.005000	4050
	Average	0.00014	378	2.7E6	0.2	2200	0.001388	0.004625	3746
Mix 2	2-1	0.000105	283.5	2.7E6	0.2	3200	0.0011250	0.003750	3037
	2-2	0.000115	310.5	2.7E6	0.18	2900	0.0012750	0.004250	3442
	Average	0.00011	297	2.7E6	0.19	3050	0.001200	0.004000	3239
Mix 3	3-1	0.00014	378	2.7E6	0.19	1500*	0.0013500	0.004500	3645
	3-2	0.000135	364.5	2.7E6	0.19	2450	0.0013500	0.004500	3645
	Average	0.000138	371.25	2.7E6	0.19	2450	0.0013500	0.004500	3645
Mix 4	4-1	0.000125	337.5	2.7E6	0.19	2650	0.0012000	0.004000	3240
	4-2	0.000125	337.5	2.7E6	0.15	2650	0.0011250	0.003750	3037
	Average	0.000125	337.5	2.7E6	0.17	2650	0.001163	0.003875	3138
Mix 5	5-1	0.000115	310.5	2.7E6	0.23	2800	0.001200	0.004000	3240
	5-2	0.00011	297	2.7E6	0.18	3000	0.001125	0.003750	3037
	Average	0.000113	303.75	2.7E6	0.205	2900	0.001163	0.003875	3138


S, Mises
SNEG, (fraction = -1.0)
(Ave. Crit.: 75%)
+6.668e+02
+6.157e+02
+5.646e+02
+5.135e+02
+4.624e+02
+4.113e+02
+3.602e+02
+3.091e+02
+2.580e+02
+2.069e+02
+1.558e+02
+1.047e+02
+5.356e+01
+5.305e+01
2
3
1
ODB: PC_Sh_1of6_Ex_Md21_M_NLyes.odb ABAQUS/EXPLICIT Version 6.5-1 Thu Sep 07 16:20:00 US Mountain Standard Time 2006
Step: Step-1
Increment 50418: Step Time = 0.2000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +1.000e+00