Civil and Environmental Engineering Department
University of California, Berkeley, CA 94720

High Performance Fiber Reinforced cement-based Composites

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Outline

I. *Future Challenges*
II. *Characteristics of High Performance Fiber Reinforced cement-based Composites (HPFRCCs)*
III. *Damage Resistance of Bridge Structures due to HPFRCCs*
IV. *Reservations/Concerns towards HPFRCCs*
V. *Summary*

I) Future Challenges

Structures need to be safe under seismic loading conditions

And in addition:

I. Structures need to be damage resistant to reduce repair cost

II. Structures need to last longer to enhance their service life

III. Structures need to be sustainable hence preserve our resources & have low carbon foot print

Problems with many current bridge structures: Deterioration

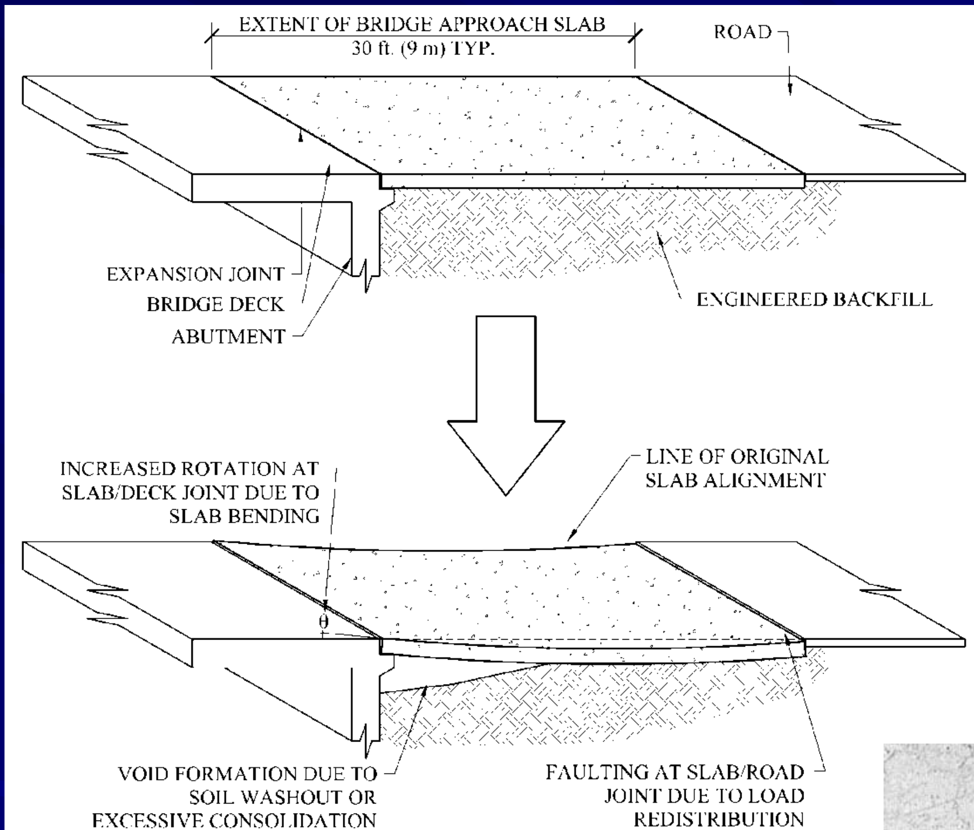
Example #1: Bridge Columns

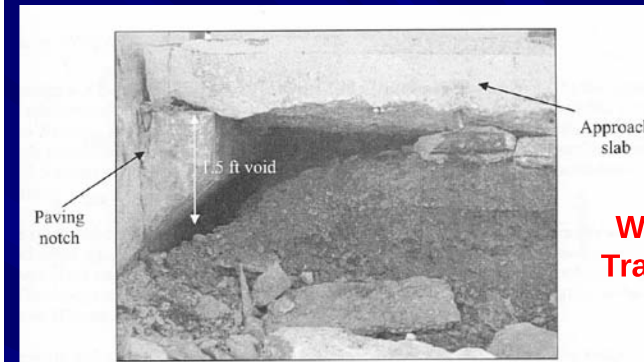
(ASR) Environmental Damage (Corrosion)

Seismic Damage

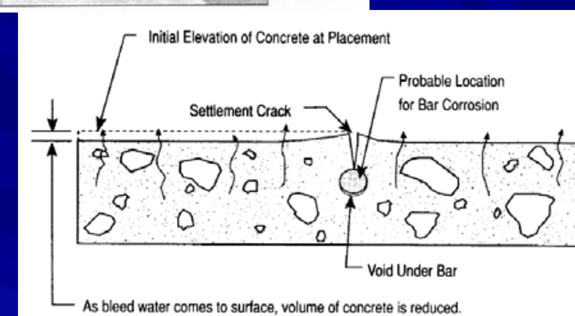
Deterioration caused by both environmental and seismic loading conditions.

Problems with many current bridge structures:
Deterioration
Example #2: Bridge Approach Slabs



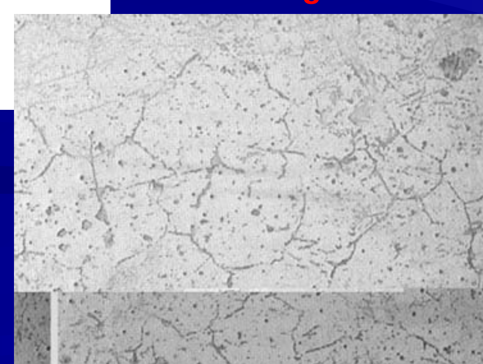


Washout and Traffic Loading



Subsidence

Plastic/Drying Shrinkage



Spalling from Rebar Corrosion and Frost Damage

Cracks = Reduced Flexural Stiffness and Durability

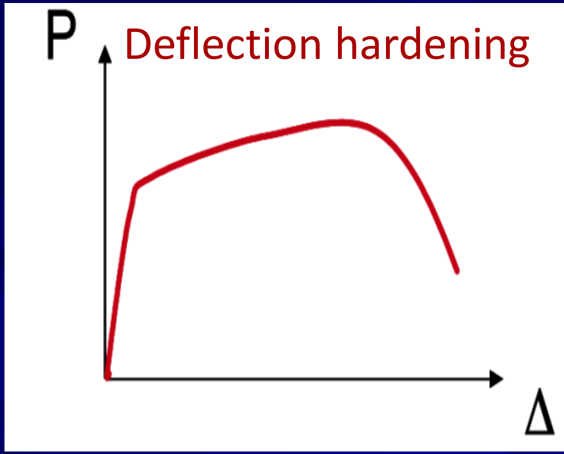
Deterioration due to both mechanical and environmental loading conditions

Effective Solution

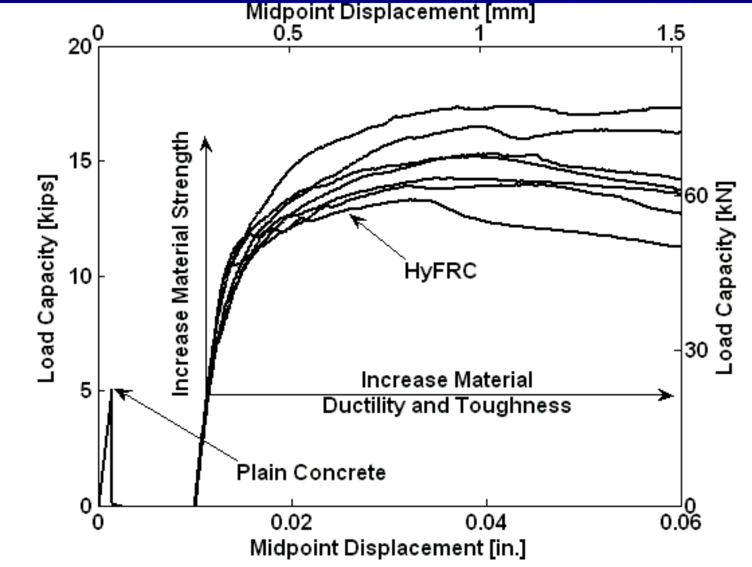
The use of High Performance Fiber Reinforced Cement-based Composites in Concrete Structures for

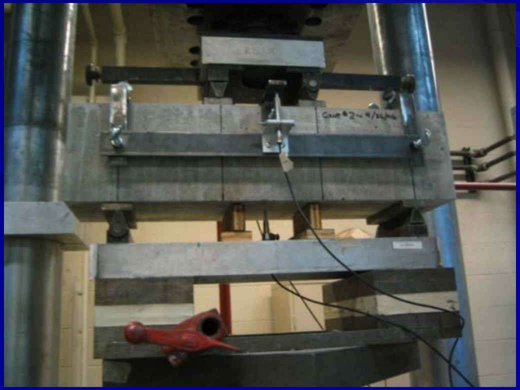
- **Higher Damage Resistance when exposed to both seismic <u>and</u> environmental loading conditions**
- **Extended Service Life and more Sustainable Structures**
- **Enhanced Performance**

II) Characteristics of High Performance Fiber-Reinforced cement based Composites



Example: Hybrid fiber reinforced concrete composite (HyFRC)

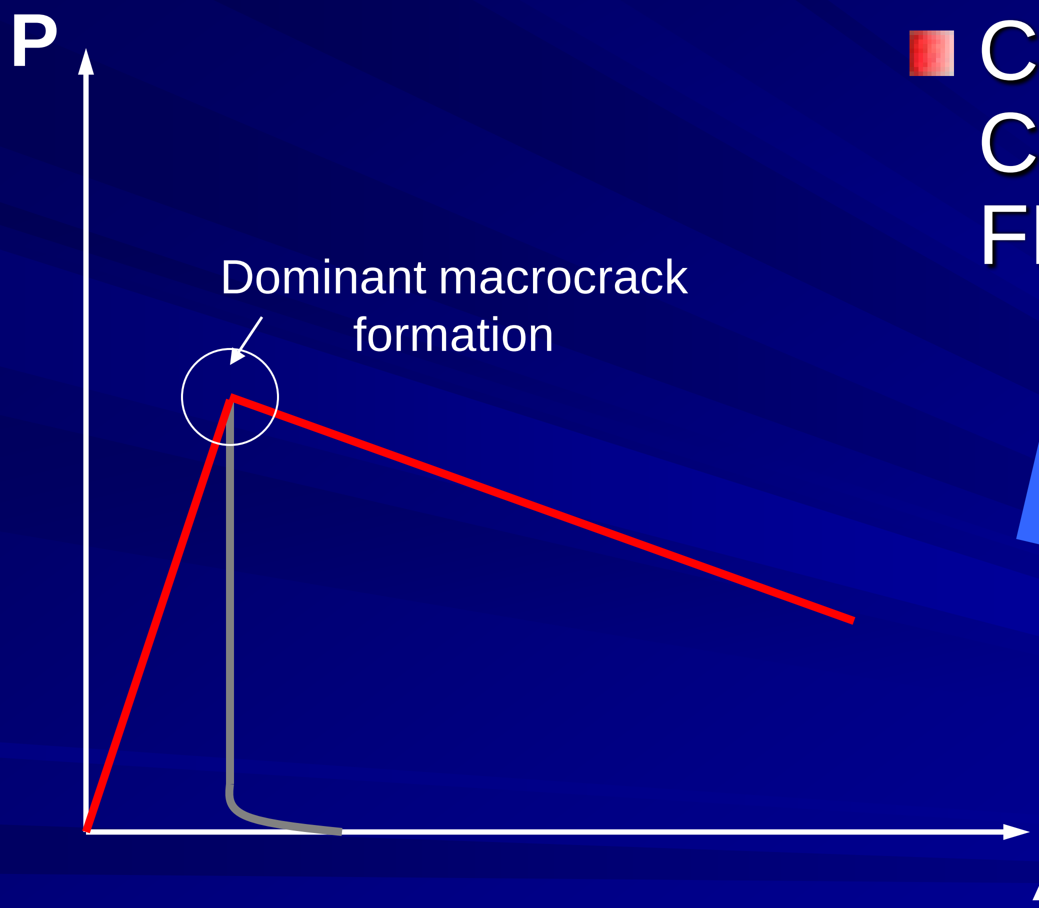




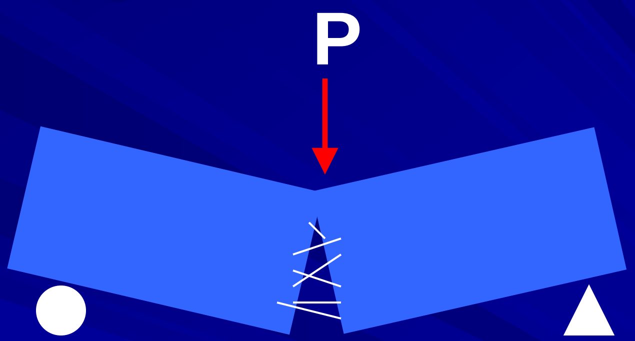
Flexure beams:
6”x6”x28”
Vf=1.5vol%

Conventional FRC

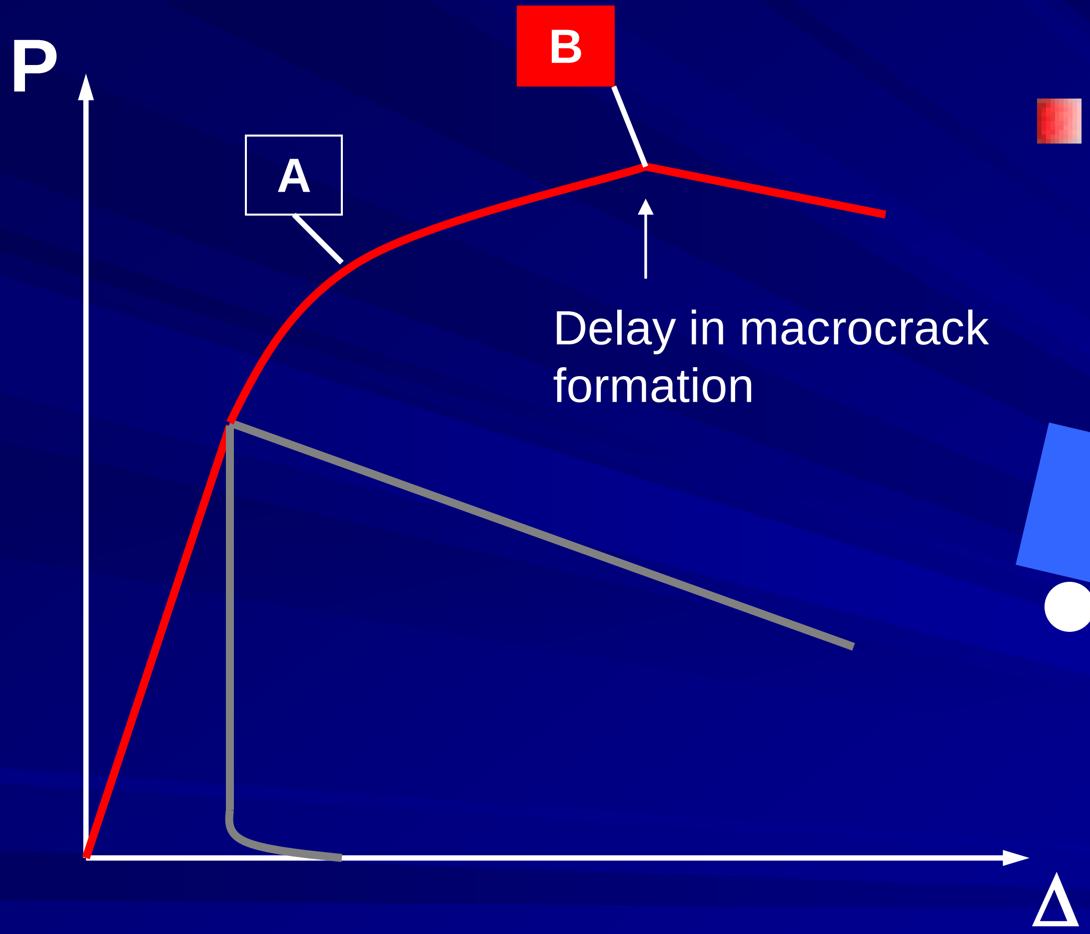
Dominant crack forms at same load level as in plain concrete



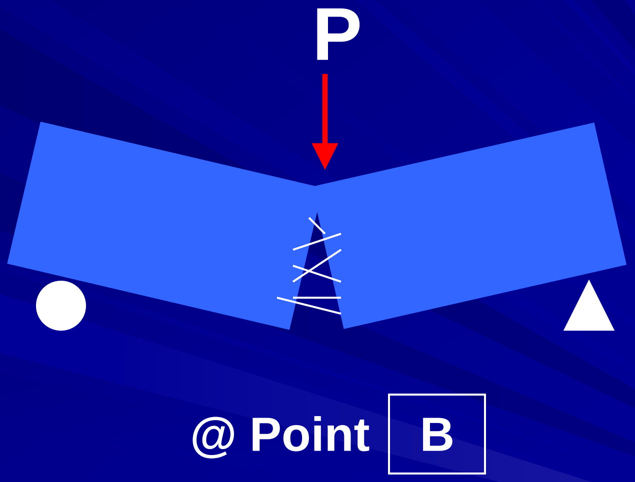
- Concrete and Conventional FRC



HPFRC

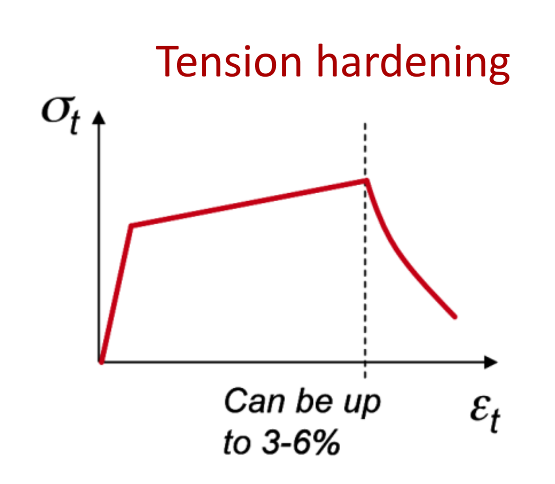


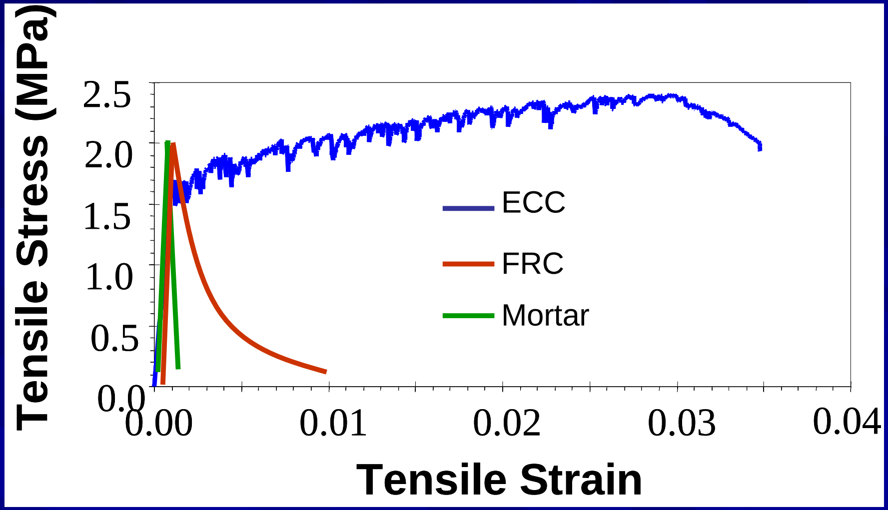
- HyFRC

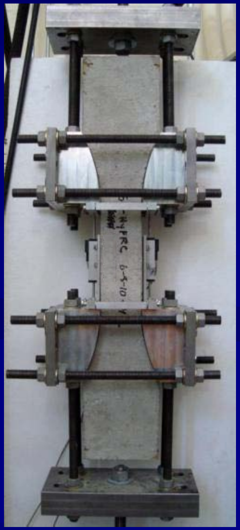


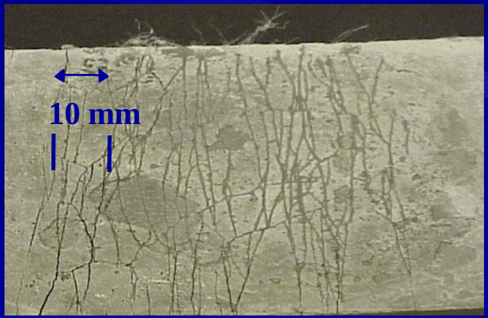
II) Characteristics of High Performance Fiber-Reinforced cement based Composites

Example: Engineered Cementitious Composite (ECC)





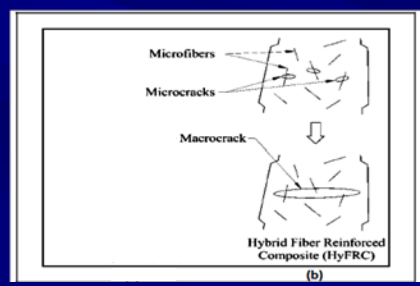




Examples of HPFRCCs that have been used for structural applications

ECC: **mortar matrix** without coarse aggregate, 2 vol% PVA fiber (developed by Prof. Li at University of Michigan)

HyFRC: **concrete matrix** with 9.5mm coarse aggregates, 1.5 vol% fibers (developed by Prof. Ostertag at UC Berkeley)



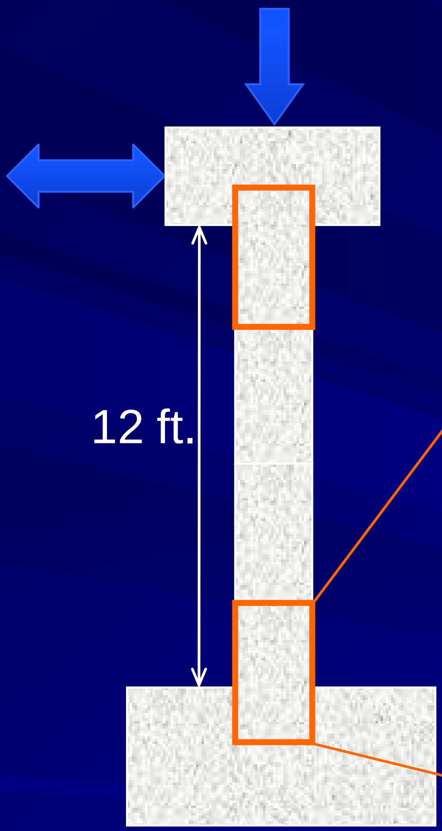
	RECS 15x8	ZP305	RC-80/60-BN
Material	PVA	Steel	Steel
Length [mm]	8	30	60
Diameter [mm]	0.04	0.55	0.75
Aspect Ratio [L/d]	200	55	80
Elastic Modulus [GPa]	42	200	200
Tensile Strength [Mpa]	1600	1100	1050
Volume Fraction [%]	0.2	0.5	0.8
Fiber Spacing [mm]	0.79	6.89	7.43

- 1st generation of HyFRC: Bridge Approach Slabs for Area III (CalTrans)
- 2nd generation of HyFRC: Self-compacting HyFRC: Bridge Columns (PEER)
- 3rd generation of HyFRC: Service Life Enhancement and Reduction in Carbon Footprint of Highway Structures (FHWA)

III) Damage Resistance of bridge structures due to HPFRC

- Example #1: Precast ECC segmental bridge piers (Billington)
- Example #2: Bridge columns with Self-compacted HyFRC (SC-HyFRC); (PEER: Ostertag & Panagiotou)
- Example #3: Bridge Approach slabs in Area III with HyFRC (CalTrans: Ostertag)

Example #1
Damage Reduction with ECC



Precast Segmental Bridge Piers with Unbonded Post-tensioning for self-centering

ECC Hinge Region

After ~4% drift

Reinforced Concrete Hinge Region

After ~2% drift

(Rouse, 2003; Billington & Yoon, 2004; Lee & Billington, 2008)

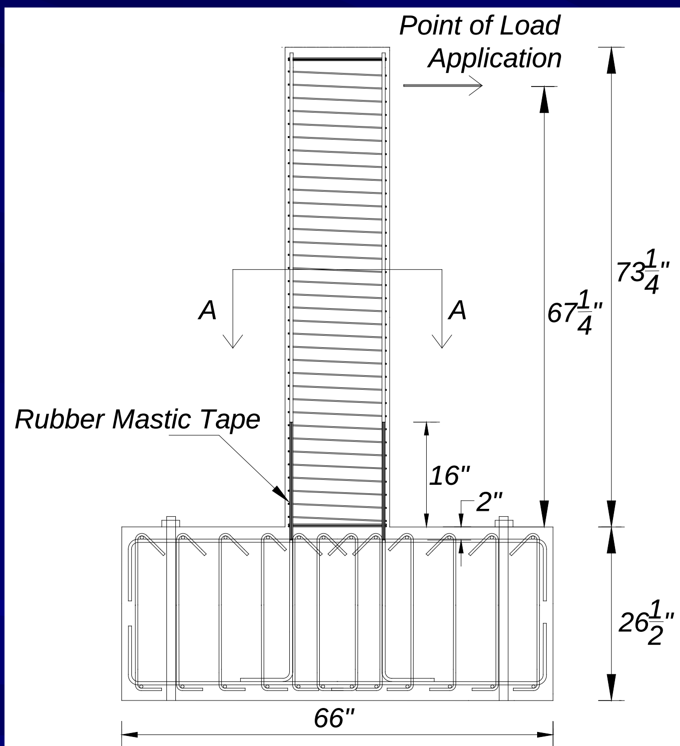
Example #2:

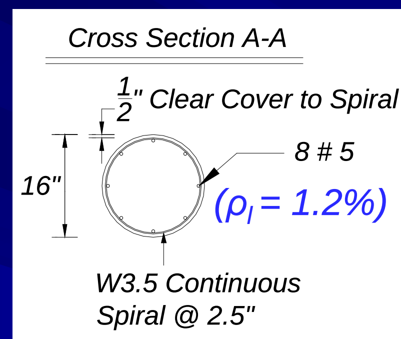
Damage & Spalling Resistance of Bridge Columns with self-compacting HyFRC (SC-HyFRC)

PEER funded project (Ostertag& Panagiotou)

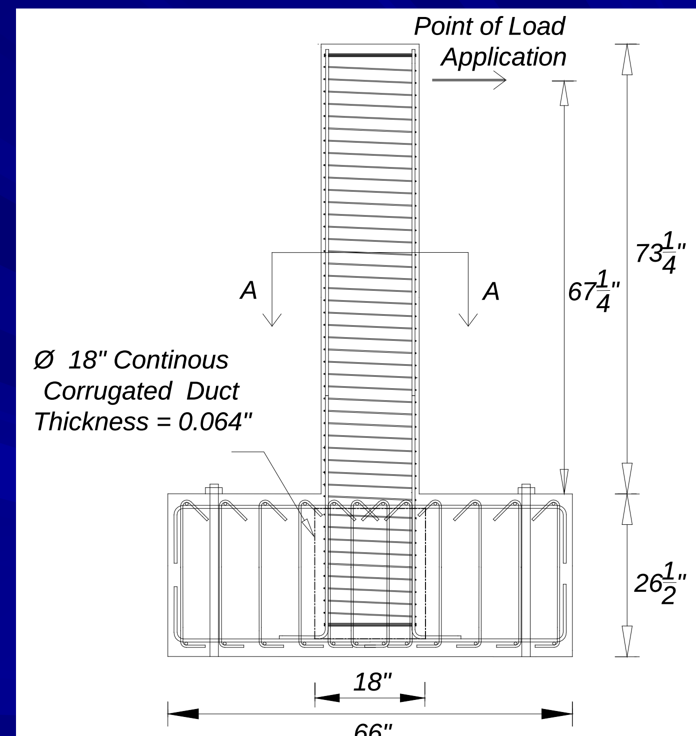
SC-HyFRC TEST SPECIMENS

- *1:4.7 Scale Specimens*
- *Aspect Ratio, H / D = 4*
- *Axial Load Ratio, $N / f'_c A_g = 0.1$*





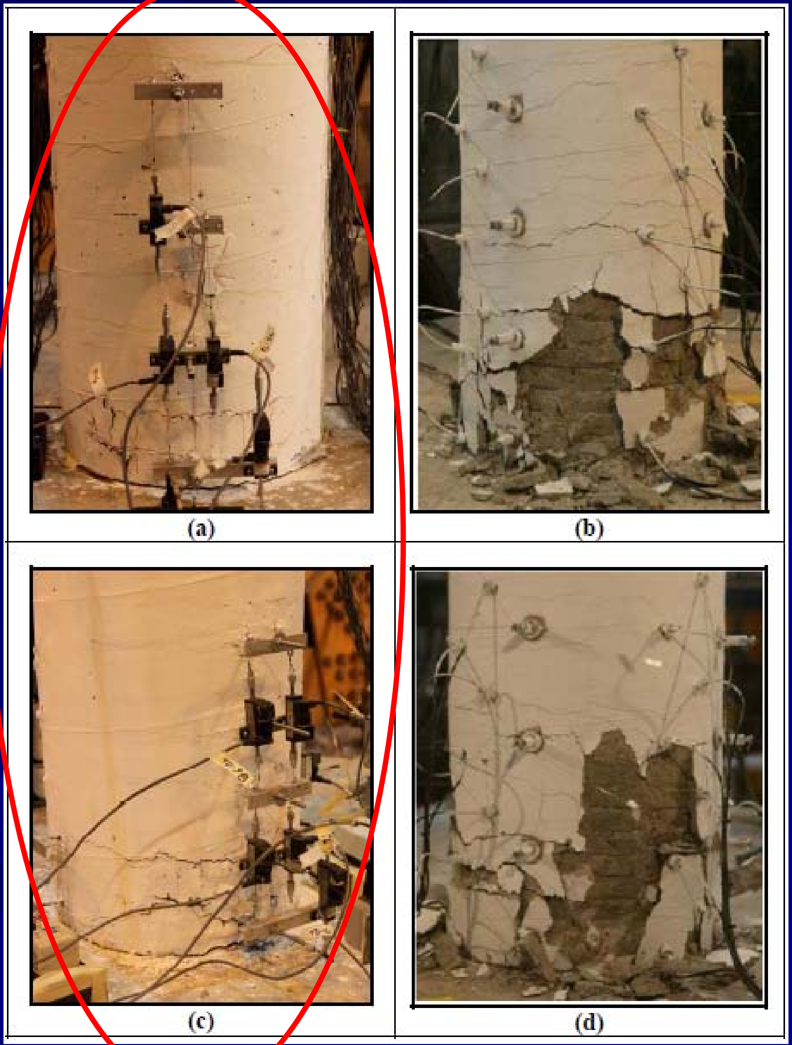
($\rho_v = 0.37\%$)



Designed to rock at column/foundation interface

Designed for plastic hinge formation

SPALLING & DAMAGE Resistance in SC-HyFRC Bridge Columns compared to conventional concrete columns



TS-1(a), TS-2 (c); ρ_v= 0.37%;

Conv. Concrete ρ_v= 0.7%

- *Damage resistance of SC-HyFRC Columns, compared to conventional Concrete Columns after being subjected to approx. same drift ratio of 4%*
- *In SC-HyFRC columns spalling of cover occurs only locally and is delayed up to 3.6% drift ratio despite half the transverse reinforcement ratio, (ρ_v), 0.37% vs. 0.7%).*

Ostertag and Panagiotou (PEER 2011/106)
Terzic et al, (2009)

Damage and Spalling Resistance due to SC-HyFRC

Self-compacted HyFRC column during 11% drift

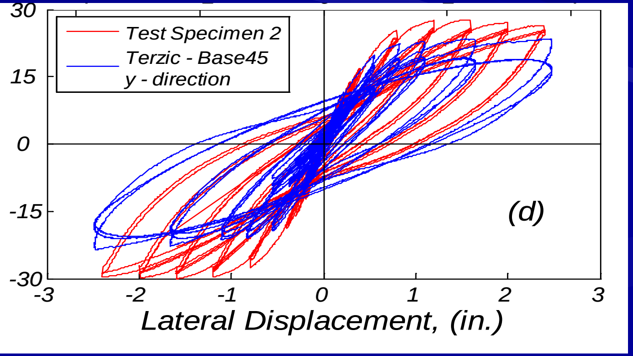
PEER (Ostertag & Panagiotou)

Drift ratio: 3.6%

Self-compacted HyFRC column ρ_v=0.37%

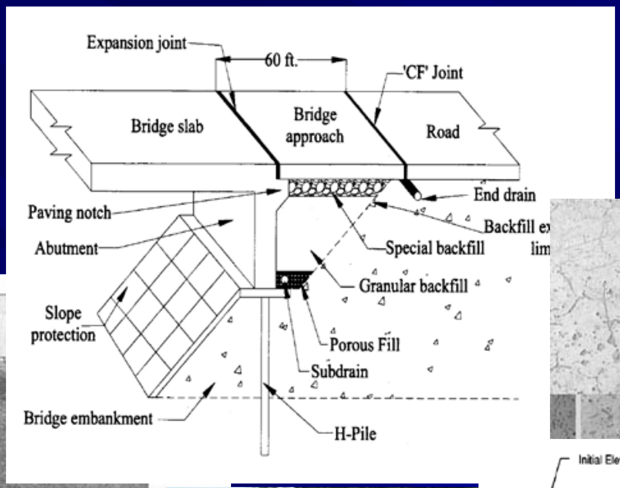
4.0%

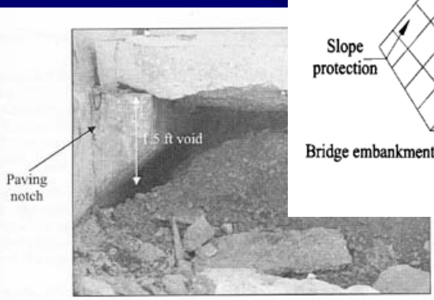
Conv. reinforced concrete column ρ_v=0.70%

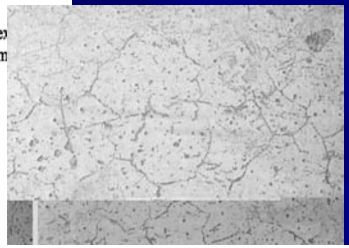


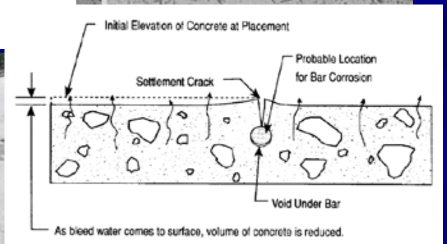
PEER

Example #3: Damage Resistance of bridge approach slabs in area III due to HyFRC









Mechanically induced

Truck loading

Soil Consolidation

Fatigue

Environmentally induced

Corrosion

Frost Action

Alkali Silica Reaction

Early Age Cracking

Shrinkage

Subsidence

Mitigate deterioration caused by:

early age cracking, environmental, & mechanical loading conditions.

CalTrans project (Ostertag)

Multi-scale crack control in HyFRC on

Flexural Performance of ½ scale bridge approach slabs

Material	PVA	Steel	Steel
Length [mm]	8	30	60
Diameter [mm]	0.04	0.55	0.75
Aspect Ratio [L/d]	200	55	80
Elastic Modulus [GPa]	42	200	200
Tensile Strength [Mpa]	1600	1100	1050
Volume Fraction [%]	0.2	0.5	0.8
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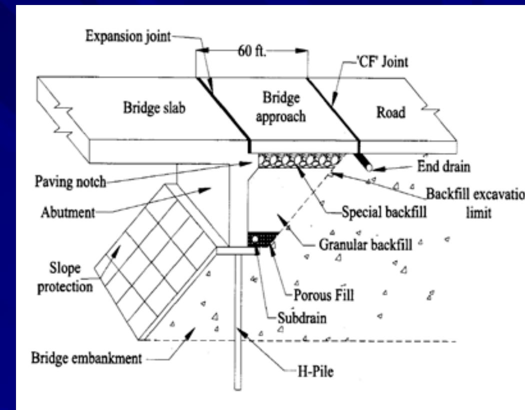
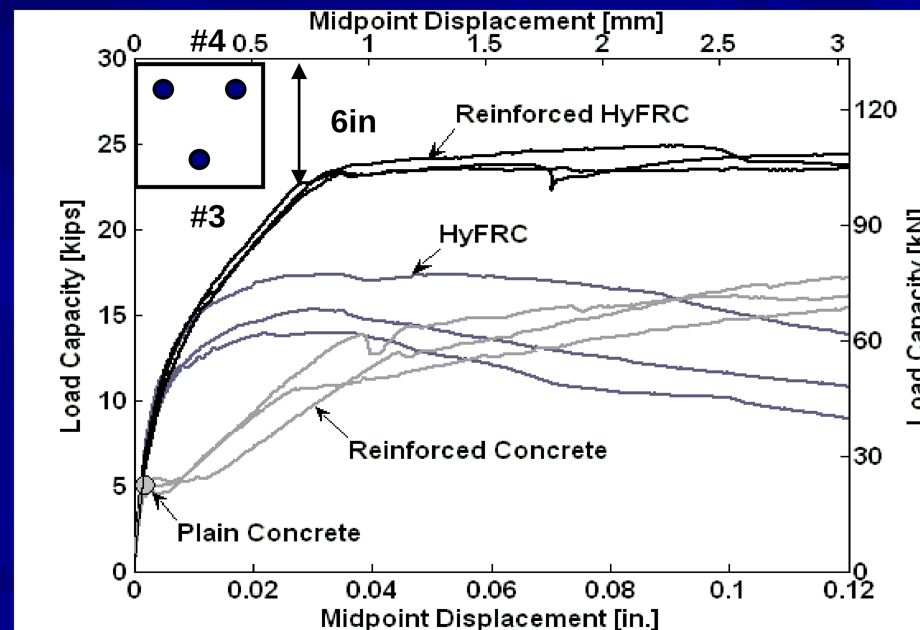


Beam size: 6”x6”x24” (15cm x15cm x60cm)
Fibers: PVA microfibers and steel macrofibers (V_f=1.5%)

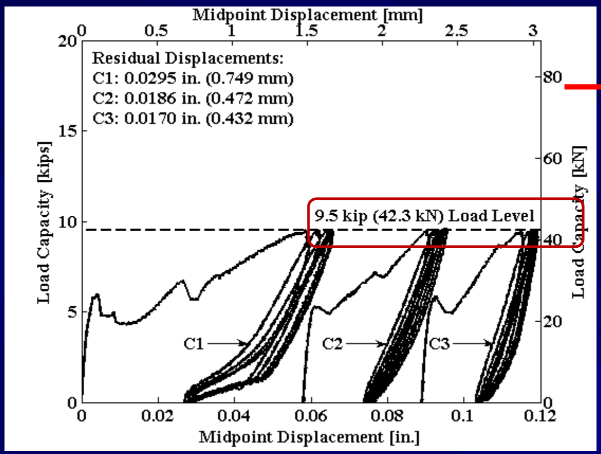


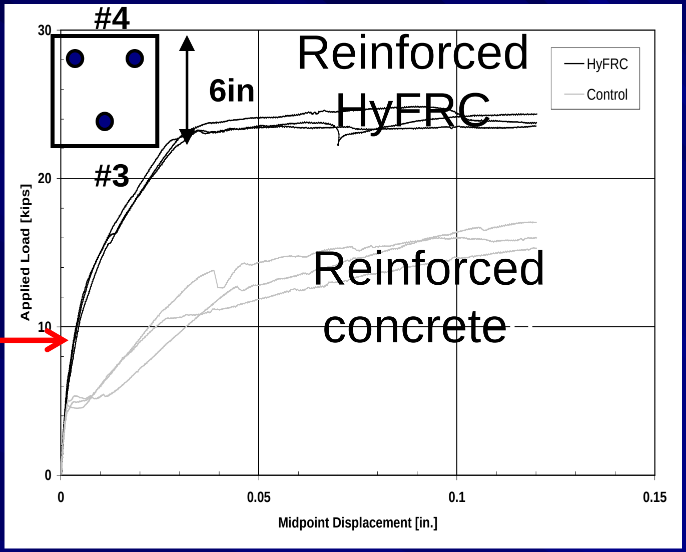
HyFRC versus reinforced concrete
½ scale bridge approach slab

Blunt & Ostertag, ACI, Vol. 106, p. 265 (2009)
Blunt & Ostertag, ASCE, Vol. 135, p. 978 (2009)
CalTrans Report No. CA09-0632, 2008.

Damage Resistance of Reinforced HyFRC

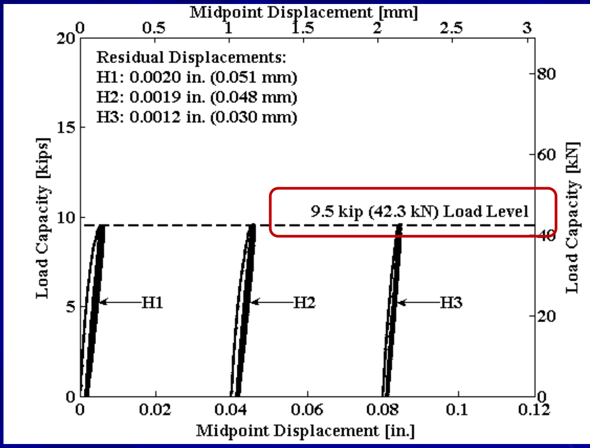
Reinforced Concrete

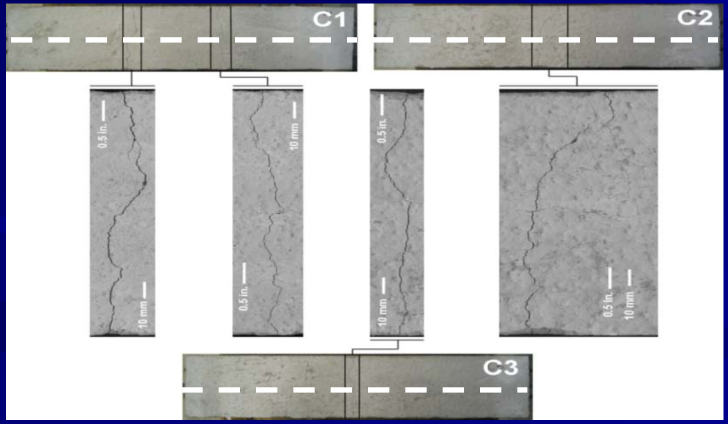




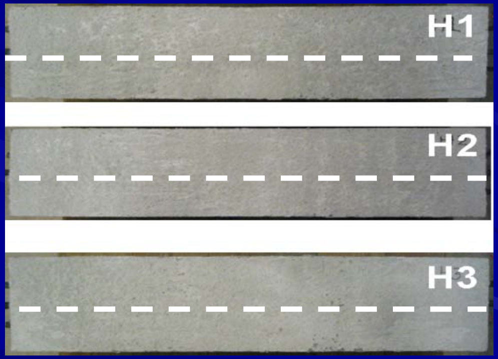
Flexural Performance of ½ scale bridge approach slabs

Reinforced HyFRC





Macrocrack formation after 5 cycles of **9.5** kip loading

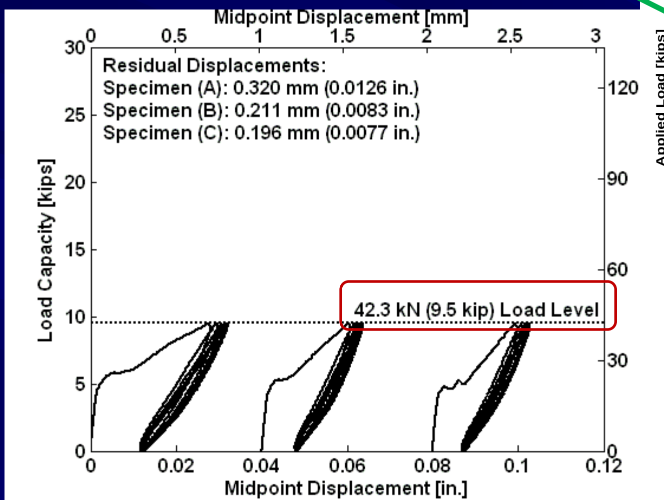


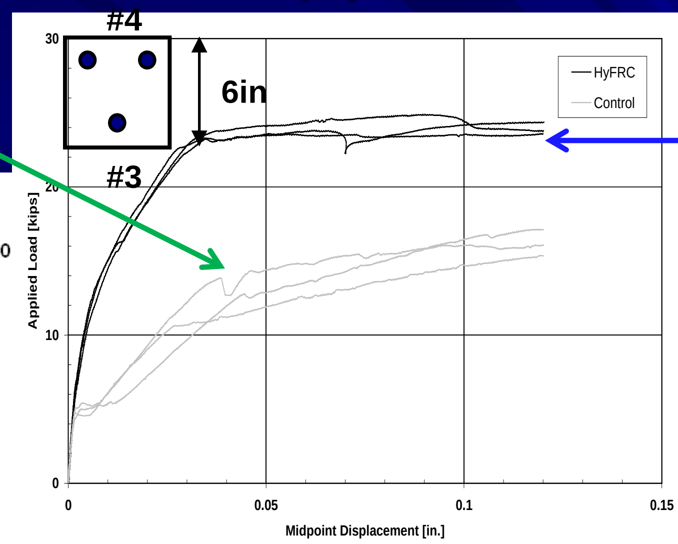
No crack formation after 5 cycles at 9.5 kips

Ostertag and Blunt, FraMCoS-7 Jeju Korea, 2010
Blunt and Ostertag, ACI J. Engrg. Mech., 2009

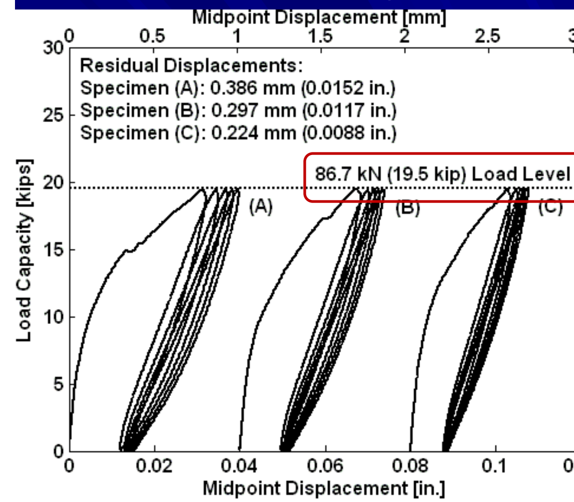
Damage Resistance of Reinforced HyFRC despite 2x the applied load

Reinforced Concrete

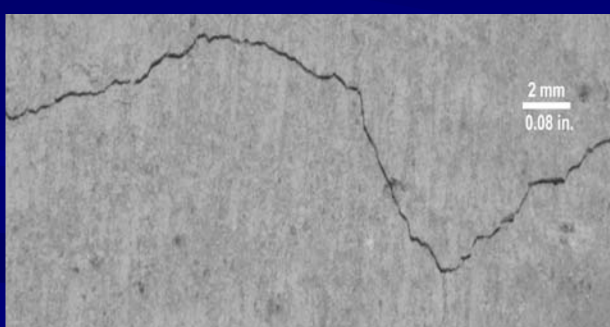




Reinforced HyFRC

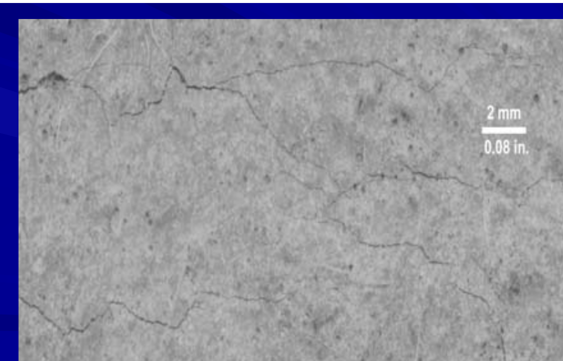


Flexural Performance of ½ scale bridge approach slabs



Macro crack formed in control concrete after 5 cycles of **9.5** kip loading

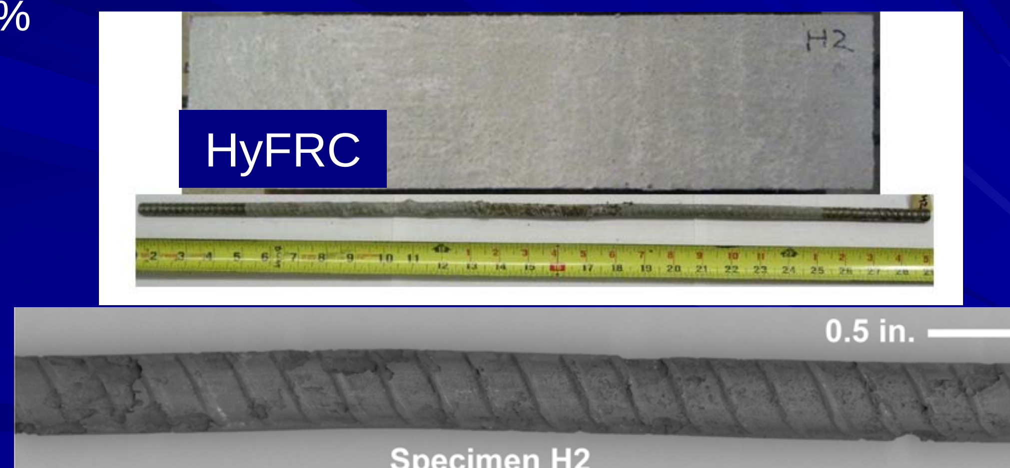
Ostertag and Blunt, FraMCoS-7 Jeju Korea, 2010
Blunt and Ostertag, J. Engrg. Mech., 2009



Only Microcracks formed in HyFRC after 5 cycles despite **double the load level**

Exposure of pre-loaded Control and HyFRC beams to 3% NaCl ponding solution

Tensile Surface (in flexure) exposed to 3% NaCl ponding solution in hot chamber (50°C at 50% RH)



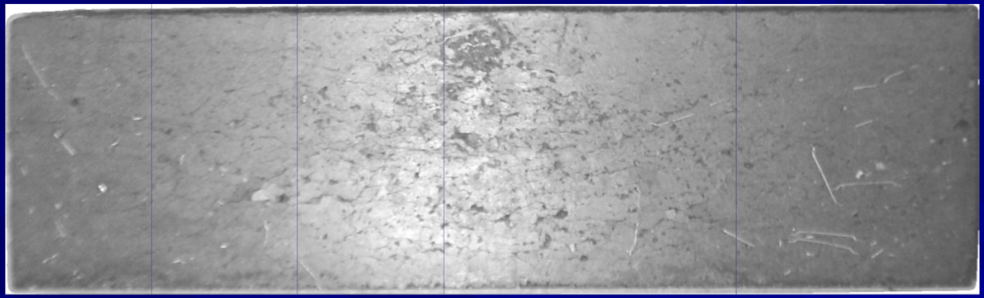
Electrochemical measurements:

- Corrosion potential measurements
- Polarization resistance measurements
- Galvanic current flow measurements

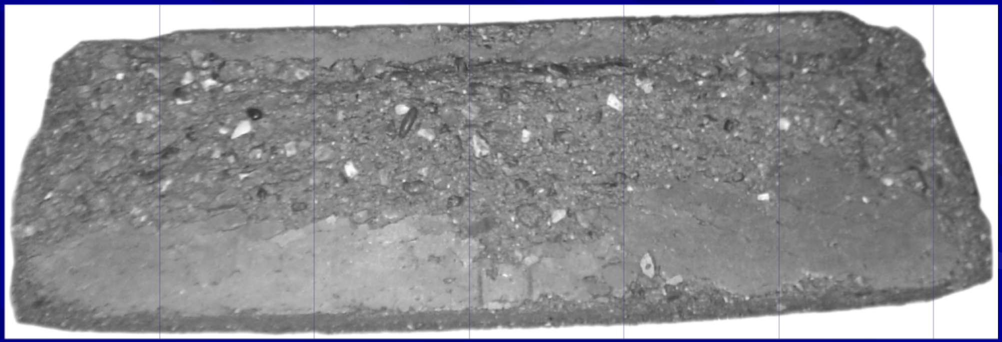
Effect of HyFRC on
Frost Resistance

ASTM C666 test

Cycling temperature:
+4°C to –18°C



HyFRC: after **220 cycles**



Plain Concrete: after 50 cycles

HPFRCCs enhance damage resistance and durability plus:

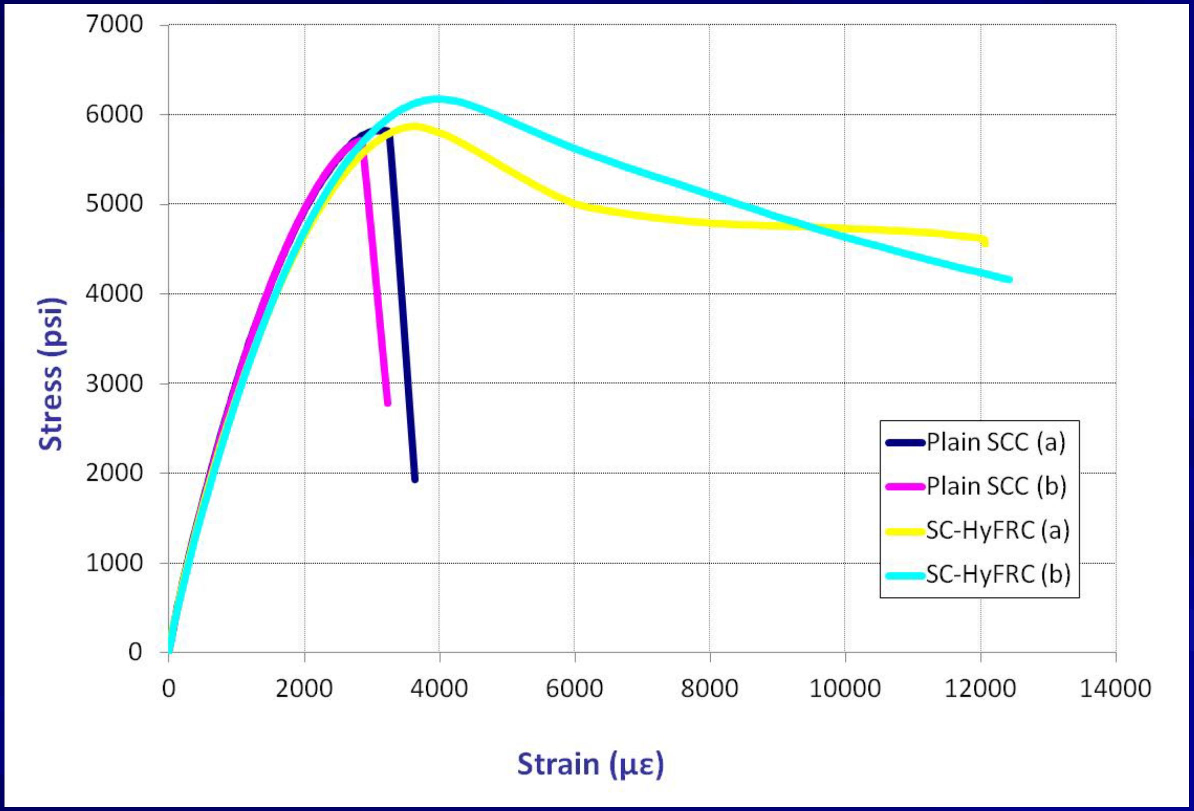
- Provide Internal confinement and tension-stiffening [see student Poster (PEER funded project Billington & Ostertag on ECC and HyFRC]

SC-HyFRC provides **internal confinement** which

i) Leads to stable softening behavior

ii) Provides spalling and damage resistance &

iii) Allows reduction in transverse reinforcements



Unconfined SC-HyFRC and Control (SCC) in compression

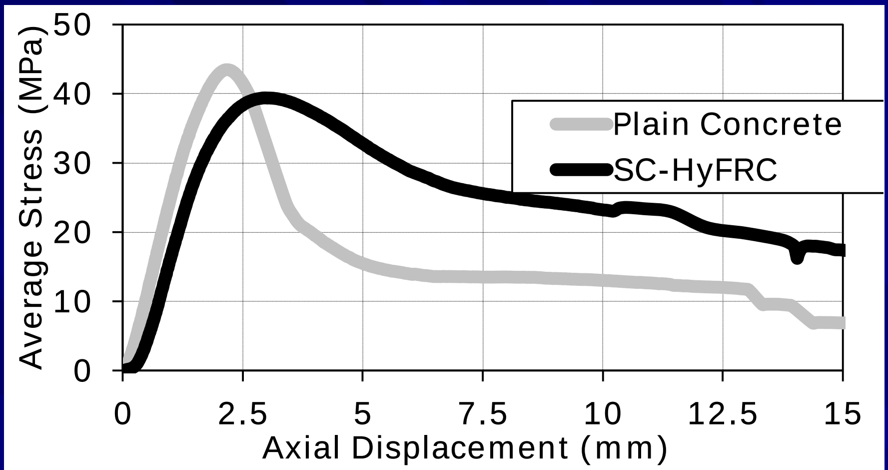
Internal Confinement of HyFRC leads to spalling and damage resistance

Confined specimens tested in compression

$\rho_s = 0.5\%$

Cylinders: 6"x12"

PEER project Billington & Ostertag



Peak Load | 7.5 mm | 12.5 mm

Concrete: extensive spalling

SC-HyFRC: delay in damage initiation and damage progression

Large-Scale Verification

- Better performance in SC-HyFRC with **half the spiral reinforcement**

Self-compacted HyFRC column during 11% drift

PEER (Ostertag & Panagiotou)

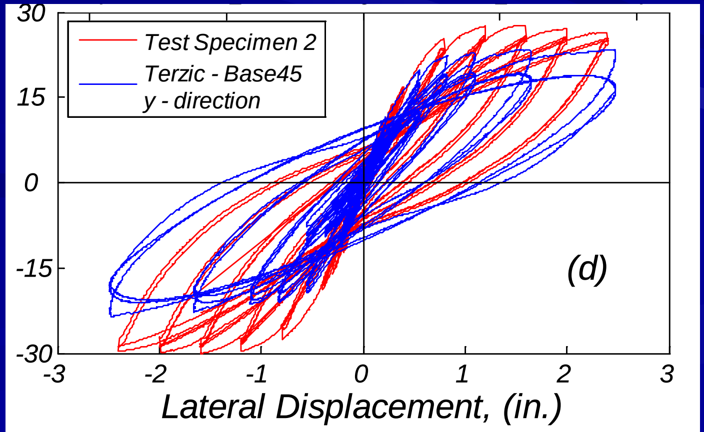
Drift Ratio

3.6%

4.0%

Self-compacted HyFRC column ρ_s = 0.37%

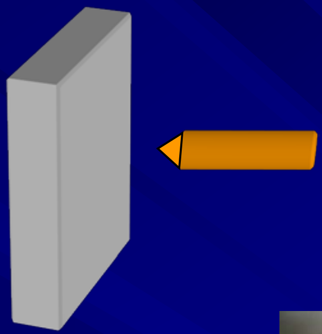
Conv. reinforced concrete column, ρ_s = 0.70%



HPFRCCs enhance damage resistance and durability plus:

- Provide Internal confinement and tension-stiffening (see Poster by Billington & Ostertag on ECC and HyFRC)
- Provide Shear resistance (Prof. Billington in TSRP session on High Performance materials and Sustainable Structural Design)
- Provide Impact Resistance (Dr. Vossoughi in TSRP session on High Performance materials and Sustainable Structural Design)

Multi-scale Crack Control in HyFRC on **Impact Resistance**

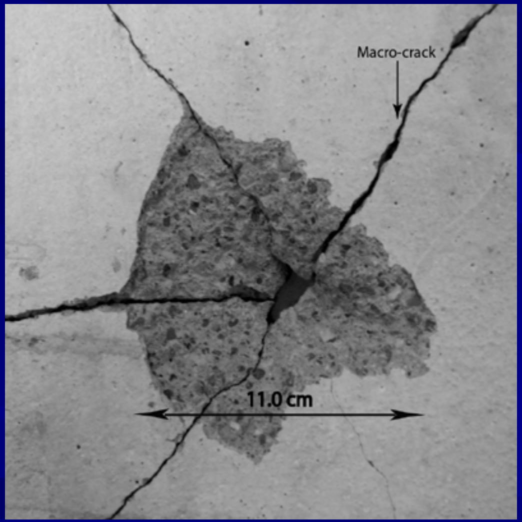


Panel size:
12”x12”x1”

Plain Concrete

HyFRC

Back Face



Velocity of projectile: 127m/s

Back Face

Velocity of projectile: 167m/s

Vossoughi et al

Reservations towards HPFRCCs

"…**HPFRCs in structures will lead to higher initial cost…"**

True…… but:

- HPFRCCs allow new design possibilities due to enhanced performance and allow reduction in steel reinforcement
- Less Repair and extended Service Life

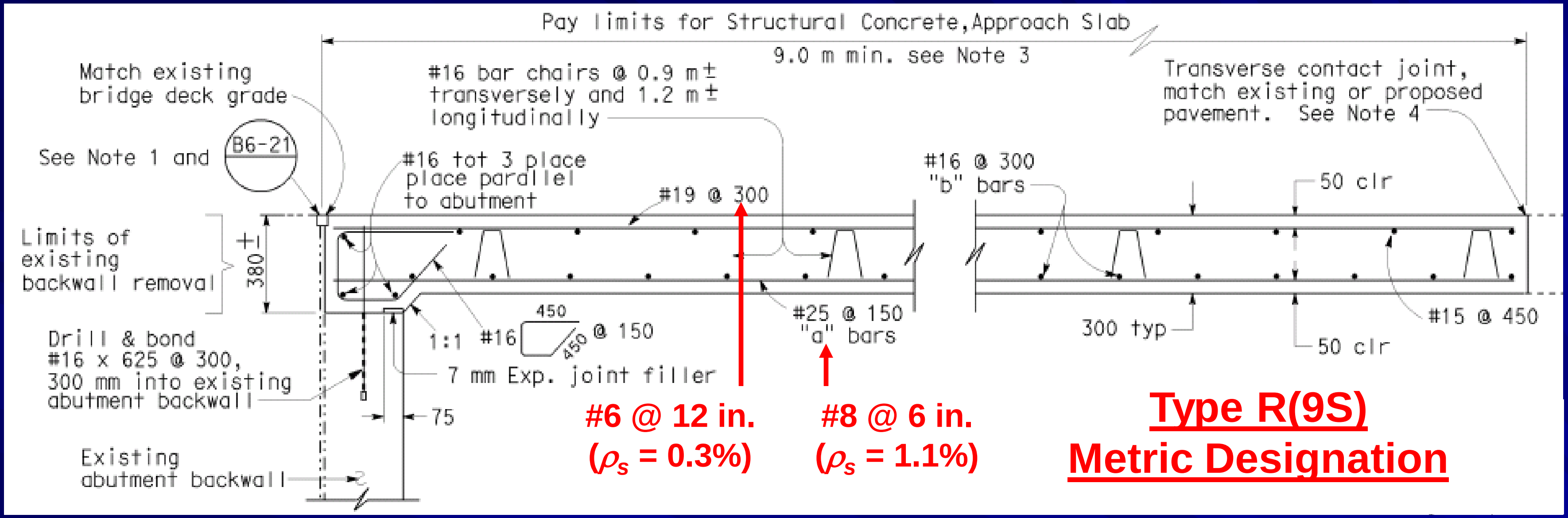
Reservations towards HPFRCCs

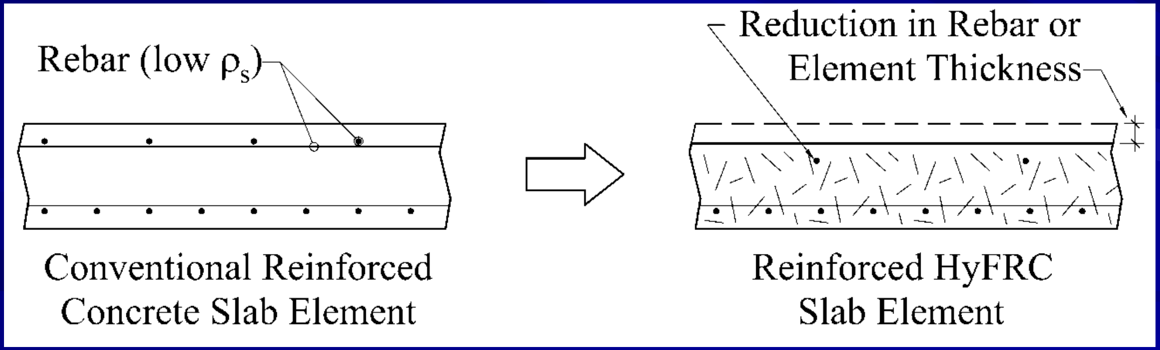
"…**HPFRCs in structures will lead to higher initial cost…"**

True…… but:

- HPFRCCs allow new design possibilities due to enhanced performance and allow reduction in steel reinforcement
- Less Repair and extended Service Life

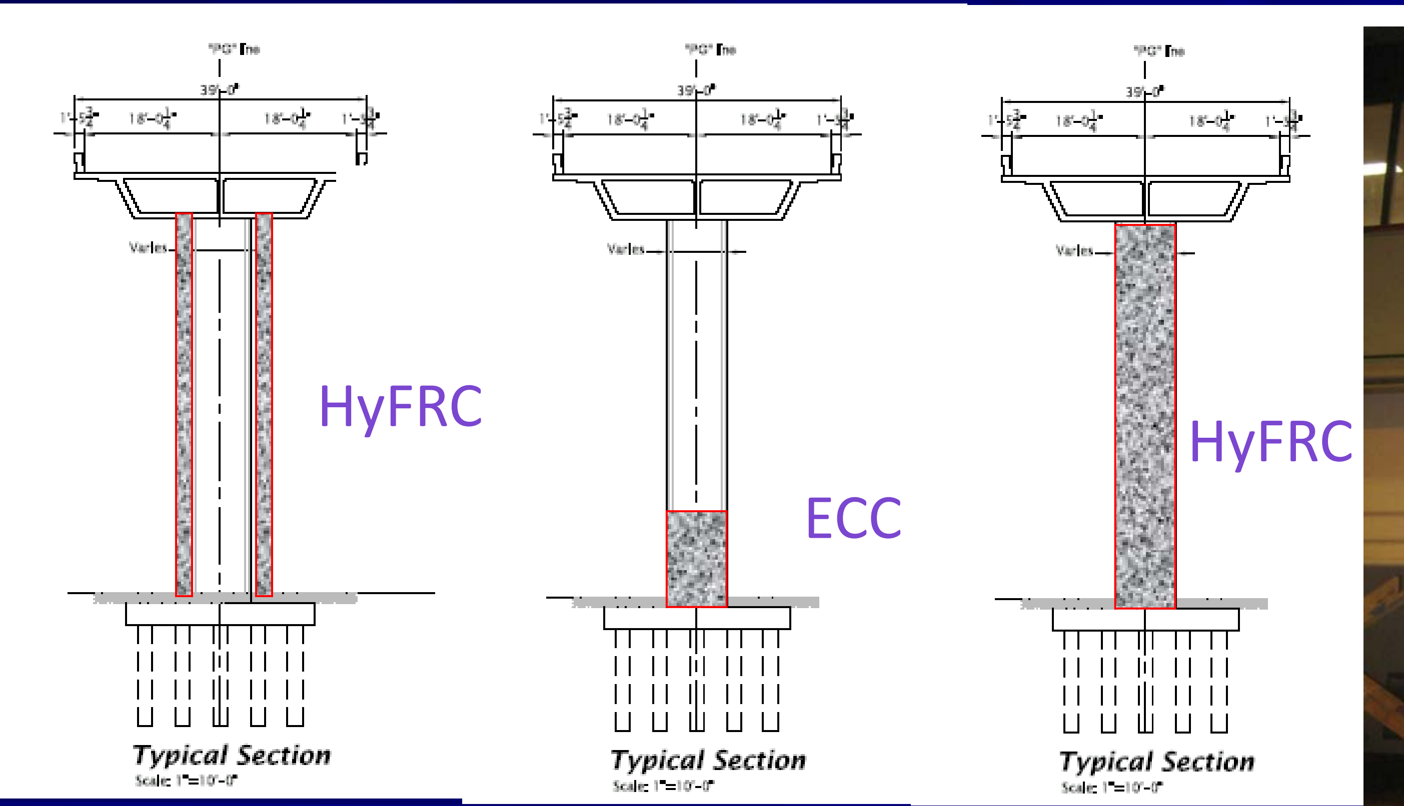
BAS Detail Modification due to HyFRC





CalTrans project

HPFRC allow new design possibilities due to enhanced performance



Current PEER Project on precast structural HyFRC tubes as permanent formwork

Reservations towards HPFRCCs

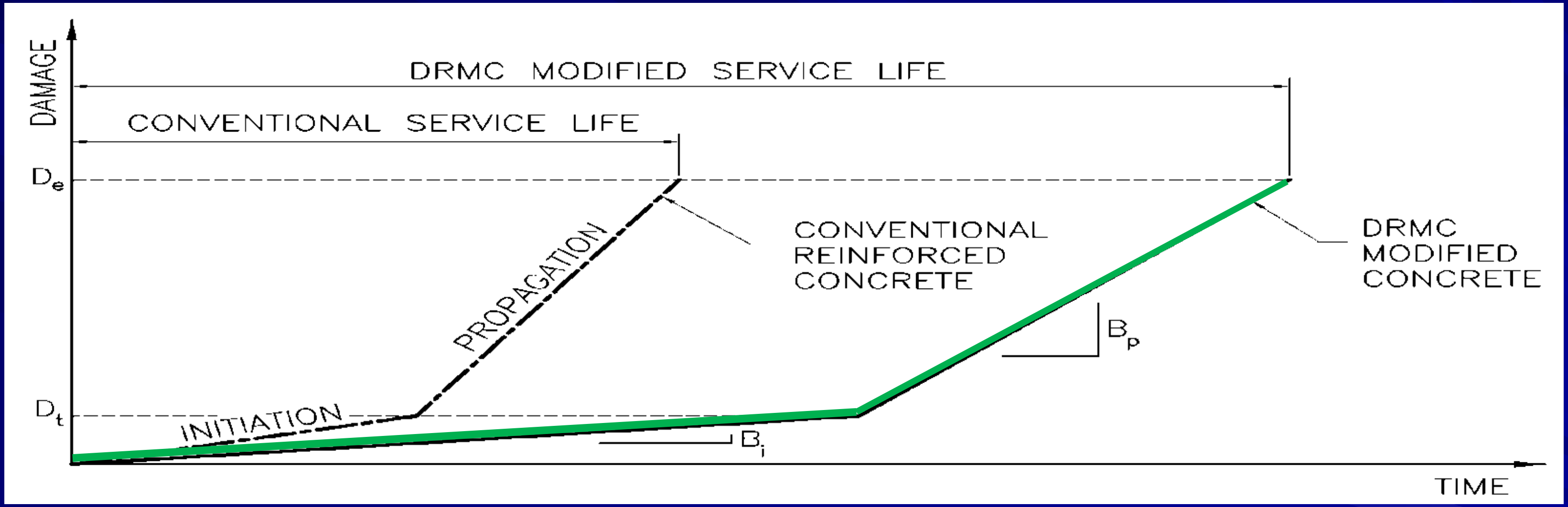
"…**HPFRCs in structures will lead to higher initial cost…"**

True…… but:

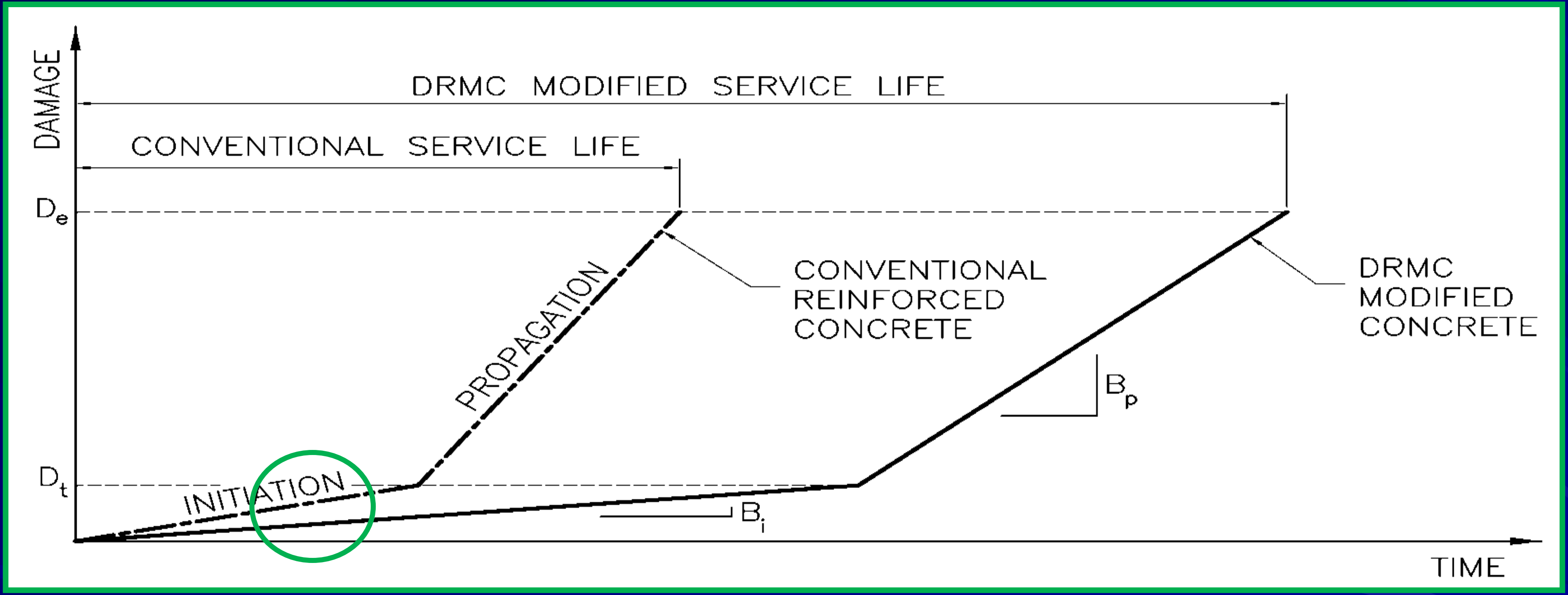
- HPFRCCs allow new design possibilities due to enhanced performance
- HPFRC allow reduction in steel reinforcement
- Less Repair and extended Service Life

Higher initial cost but less repair and Extended Service Life

HPFRCCs have the potential to extend the initiation phase and slow down the propagation phase of damage



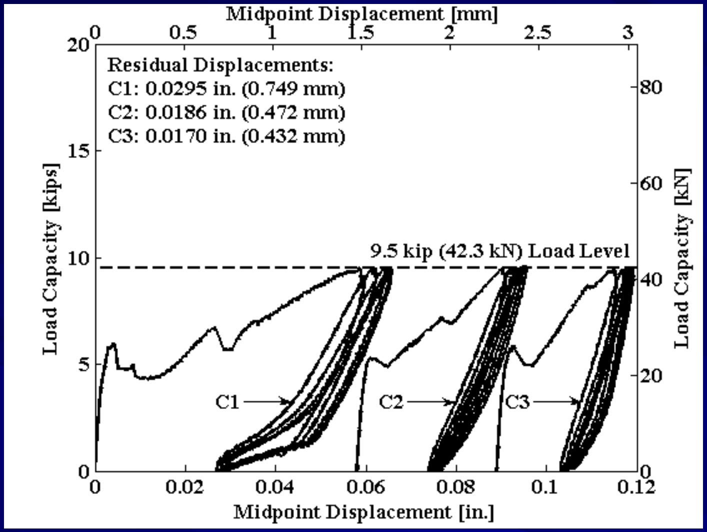
HPFRCCs extend the Damage Initiation Phase

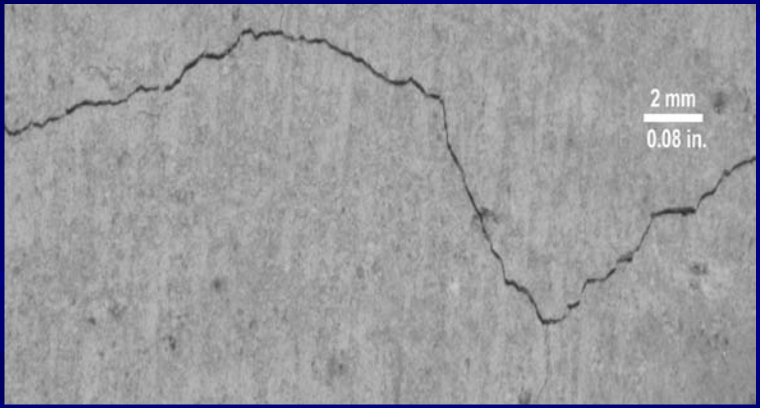


Because HPFRCCs provide the necessary crack resistance and thereby minimize ingress of aggressive agents into the concrete

Extending Damage Initiation Phase due to HyFRC

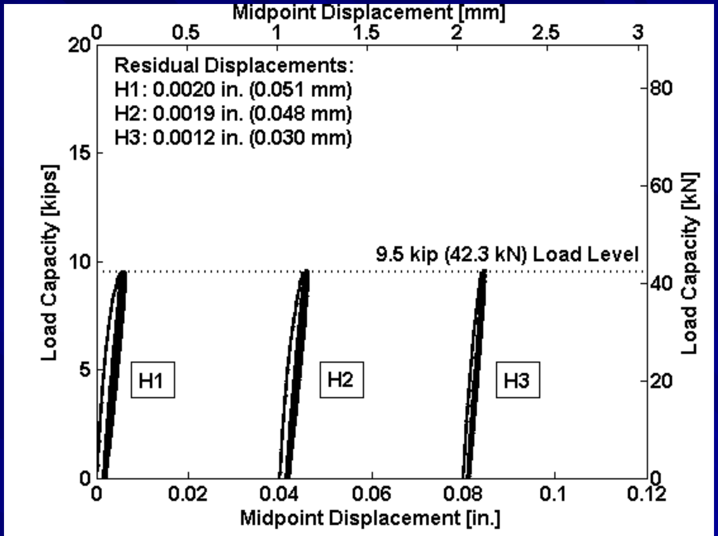
Control BAS

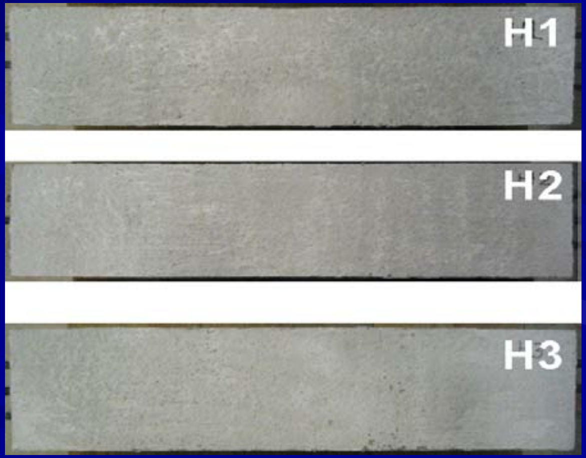




Dominant crack in control specimens after 5 cycles

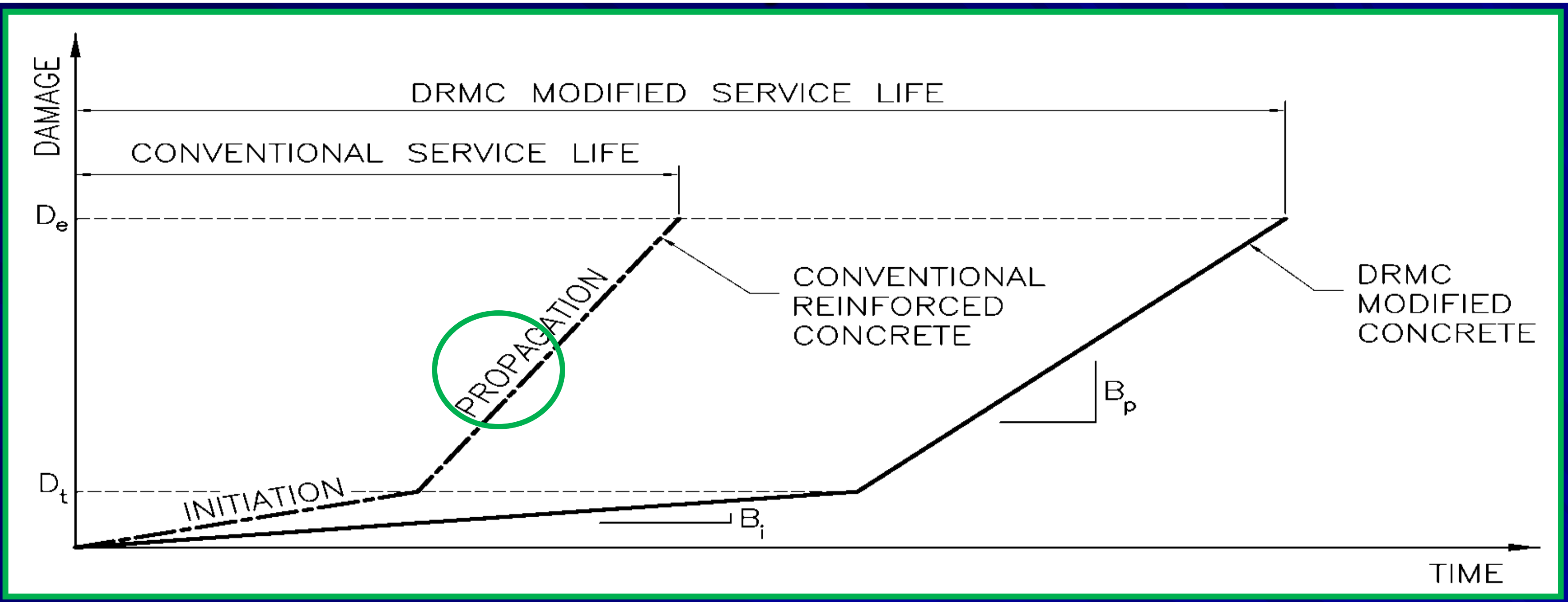
HyFRC BAS

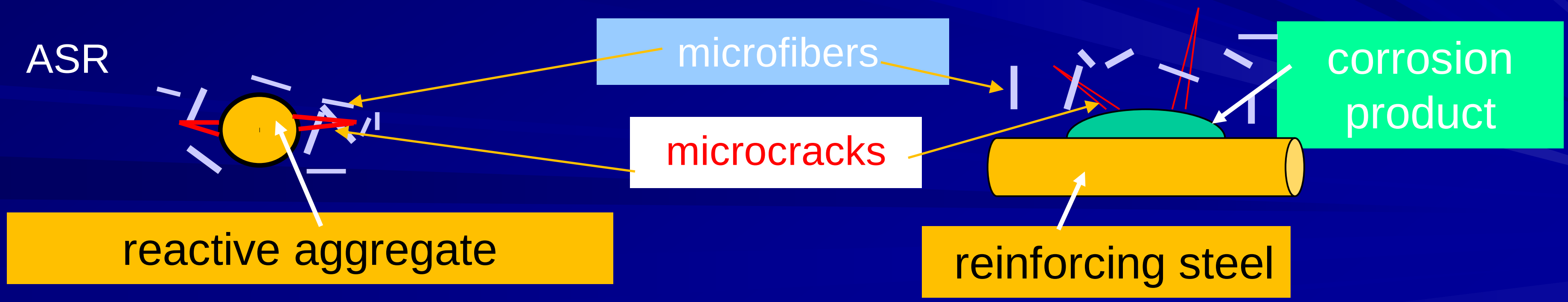




No cracks in HyFRC after 5 cycles (same load)

Slowing down Damage Propagation Phase with HyFRC





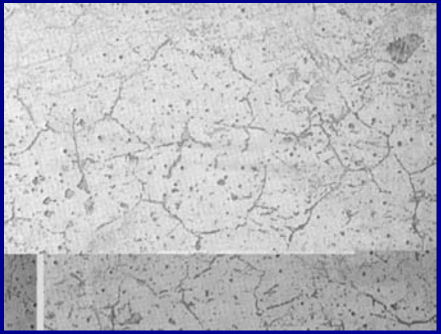
Microfibers bridge these microcracks in close vicinity to the reaction site at onset

Reservations towards HPFRCCs

"… for Corrosion resistance why not using stainless steel rebars..."

Yes…. but

- not effective in regards to other environmental deterioration processes such as ASR, damage due to frost action, sulfate attack etc…

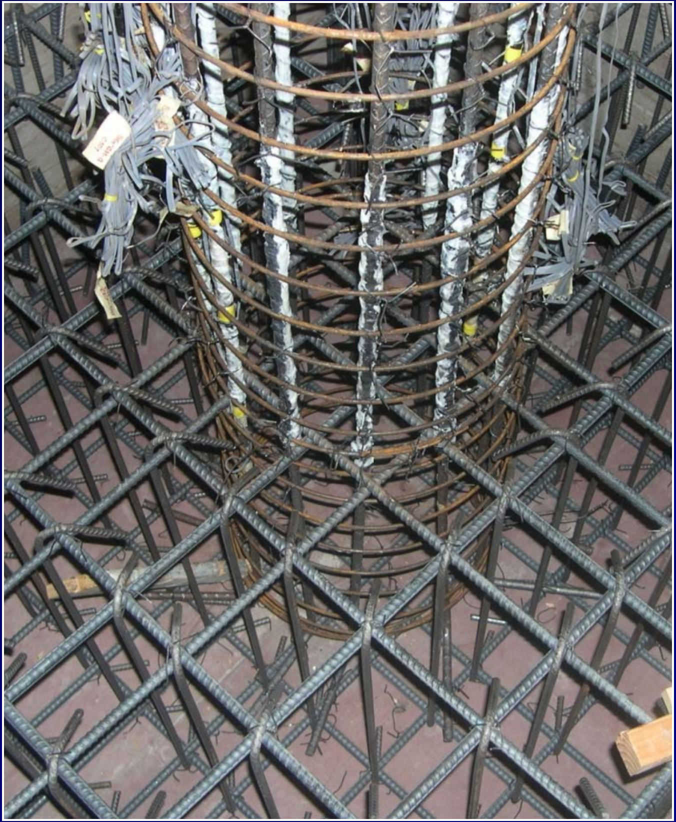


Concerns in regards to HPFRCCs

"…Adding fibers reduces workability … makes it more difficult for CIP applications specially for structures in seismic prone regions that are heavily reinforced... "

- In principle true … but not anymore … due to self-compacting HPFRCs

SC-HyFRC FOR BRIDGE COLUMNS



Casting of Self-compacting HyFRC bridge columns without external and internal vibration (PEER funded project; Ostertag & Panagiotou).

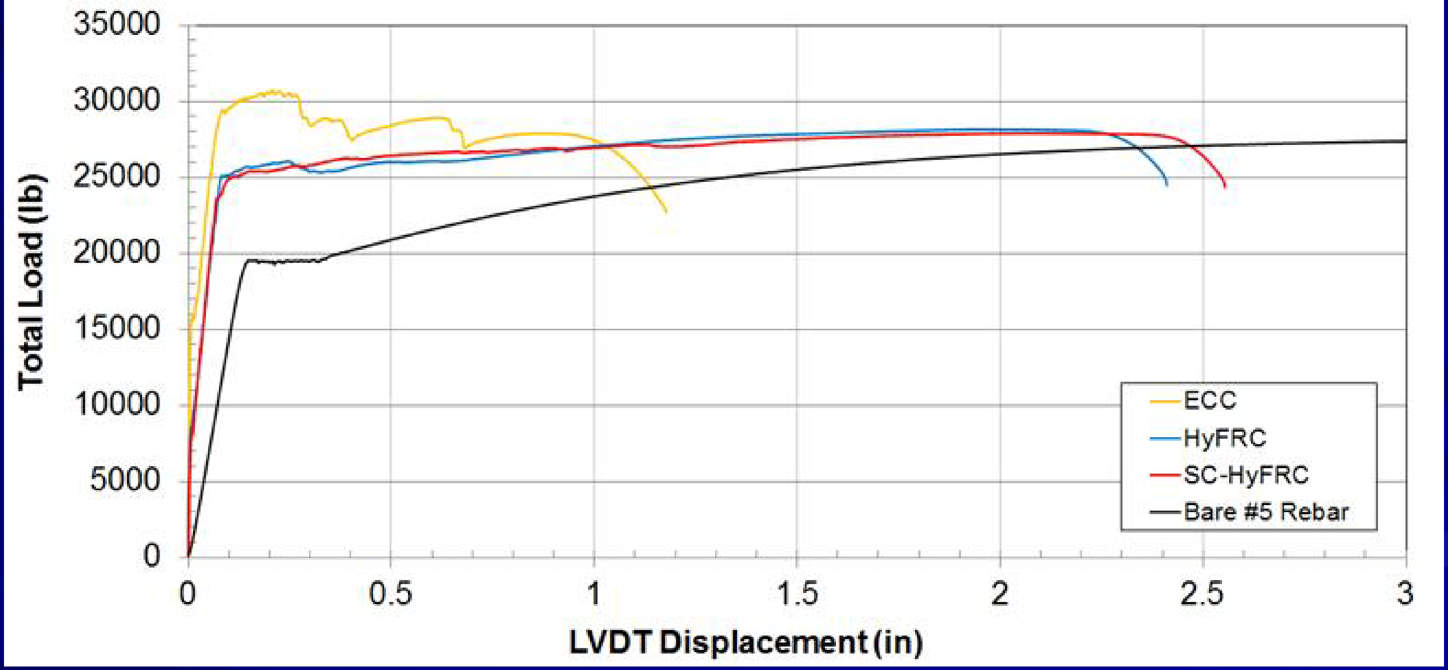
Concerns in regards to HPFRCCs

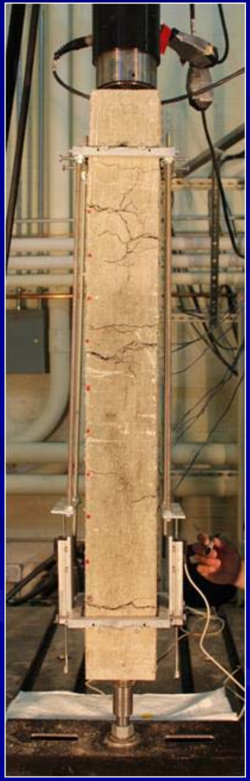
"HPFRCC matrix grabs onto rebar and cause localization and premature failure of rebar"

- True for UHPFRC … but not for ECC and HyFRC (see PEER student poster on confinement and tension stiffening; PEER project: Billington & Ostertag)

Tension stiffening and high ultimate load capacity of ECC, HyFRC and SC-HyFRC

ECC, HyFRC and SC-HyFRC are able to carry tension to strains far greater than the yield strain of the steel reinforcing bar

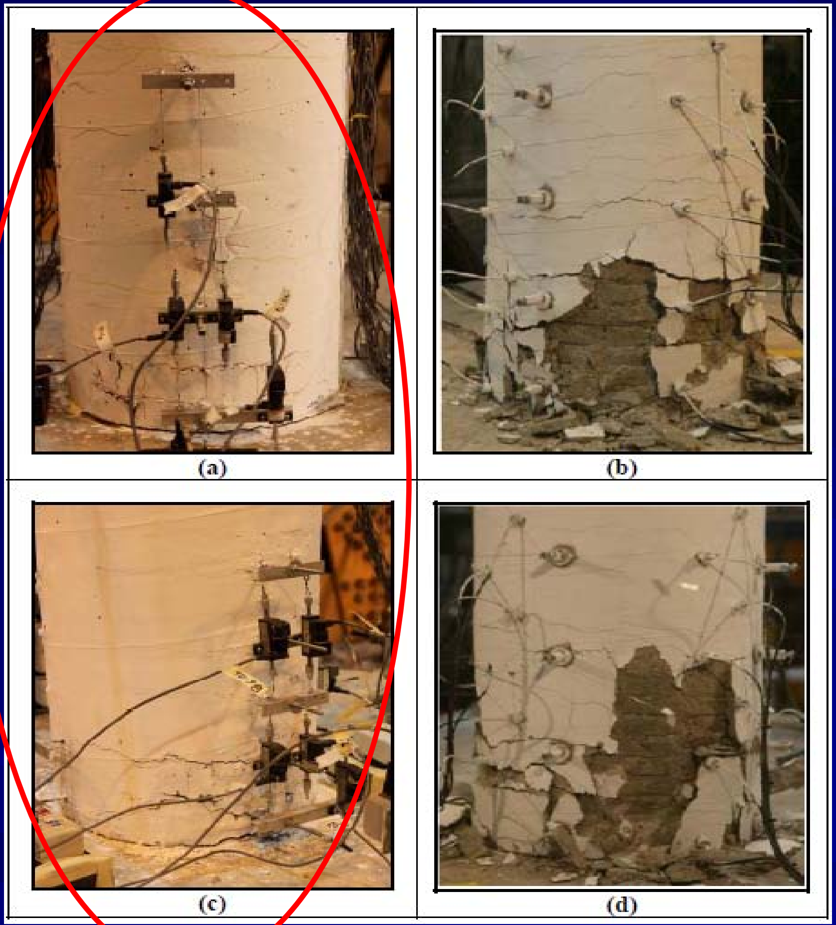




PEER Poster session: “Tension stiffening and Confinement in HPFRCCs”: Billington & Ostertag; Poster presenter: Will Trono (UCB)

41” long with 5”x 5” cross-section
ρ=1.2%

Summary



TS-1(a), TS-2 (c); *Conv. Concrete*
ρ_v= 0.37%; *ρ_v= 0.7%*

HPFRCCs

- Enhance Damage Resistance (when exposed to both seismic and environmental loading conditions)
- Extend Service Life of concrete structures
- Make Structures more sustainable (by preserving our resources)

Summary

HPFRCCs

- Provides a **Holistic Approach** towards enhancing the Durability of concrete structures

  (i.e. it does not only mitigate corrosion but also ASR, frost damage, salt scaling, drying shrinkage… etc).

Research NEEDS:

Whereas mechanical properties of plain HPFRCCs have been studied and are well documented,

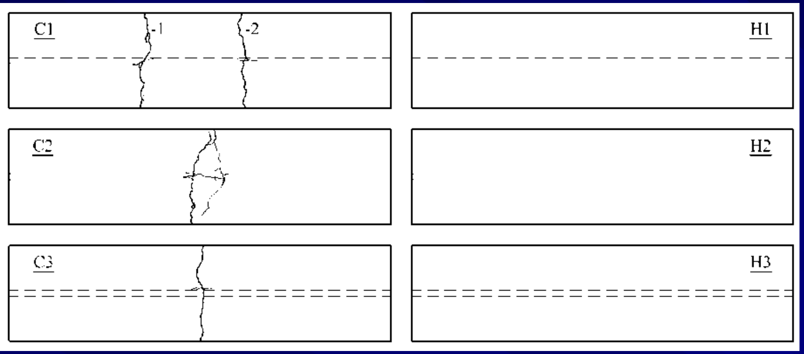
- Few studies exist on synergy between HPFRCC matrix and steel rebar.
- Model development and establish design guidelines
- Need large scale test verification for HPFRCCs in CIP and ABC applications

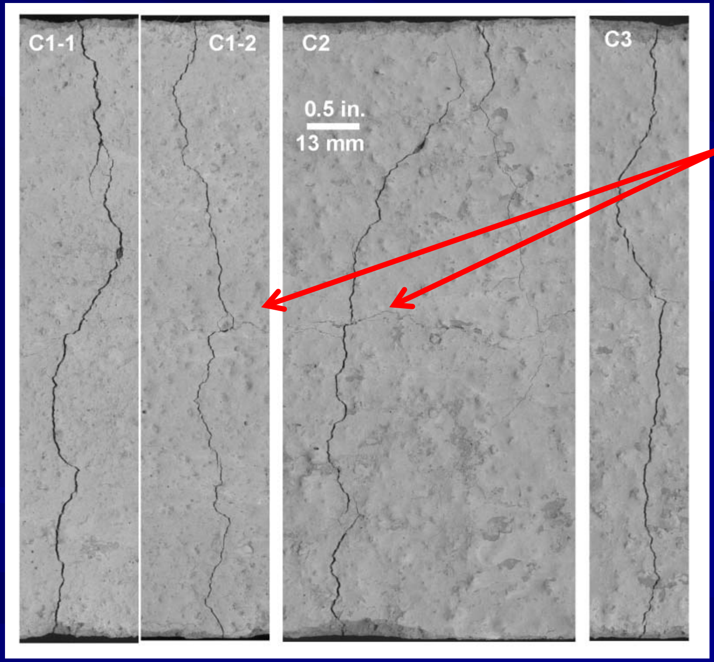
TSRP session on High Peformance Materials & Sustainable Structural Design; Session Chair: Prof. Billington (Sa afternoon)

Speakers	Affiliation	Title of presentation
Phil Hoffman	Structural	Design and Usage of Micro-Reinforced Concrete (Ducon) for Seismic jacketing and other Applications
Ying Zhou	Tongji University, Shanghai, China	High Performance Concrete Structural Walls for Tall Buildings
Fariborz Vossoughi	Ben C. Gerwick, Inc.	Impact Resistance of High Performance Materials
Sarah Billington	Stanford University	Performance and Modeling of Damage Tolerant Fiber-reinforced Concrete in Seismic Retrofits
Claudia Ostertag	UC Berkeley	Durable and Damage Resistant High Performance Fiber reinforced Bridge Structures
Lindsey Maclise	Forell/Elsesser Engineers, Inc	Sustainable Materials Certification
Arpad Horvath	UC Berkeley	Principles of Sustainable Design for Structures
Michael Lepech	Stanford University	Life Cycle Assessment of Concrete Structures in Multi-hazard Environments

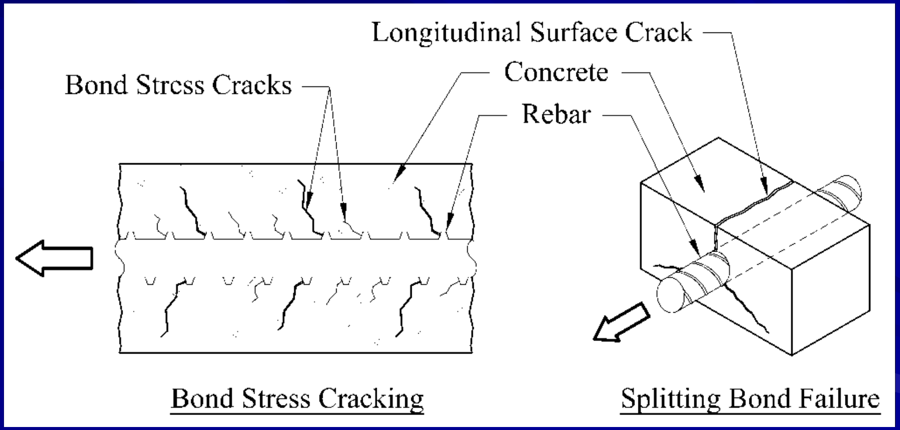
Thank you for your attention

Corrosion Experiments revealed that splitting bond cracks in reinforced concrete increase Cl ingress





Fine cracks parallel to rebar (splitting bond cracks) in control specimens



Splitting bond cracks **not** observed in HyFRC due to :

1)Fibers reduce load demand on rebar thereby reducing bond stresses

2)Fibers effective in reducing crack propagation and growth of bond cracks