Fatigue Evaluation of Light-Rail and Structural Precast Panels Fiber-Reinforced Concrete

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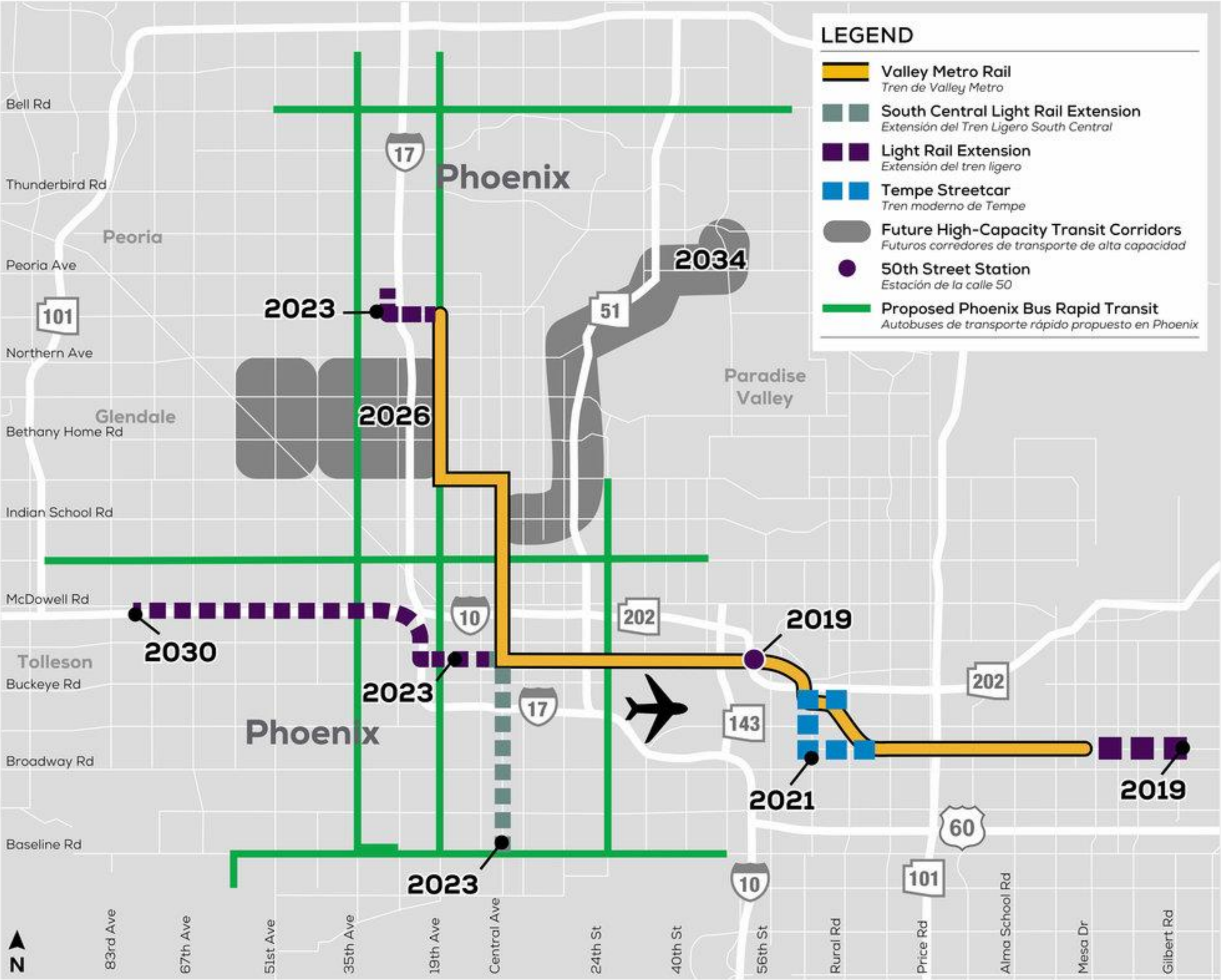
City of Phoenix South Central/NW Extension project

- 12,000 feet (3.6 km) of 8’ (5.3 m) wide track slab, 0.4 m thick
- Volume 10,000 yd^3 (7799 m^3)



Project Objectives

- Phoenix Metro Light Rail adding several stations and track lines.
- Construction costs and scheduling creates a significant pushback
- The track slabs are 14.5” (0.4 m) thick and 8’ (2.5 m) wide RC sections
- Size and cost of the project, the location, time required for forming of rebars, and the total volume.
- Propose cost savings by switching continuous bars to fibers.
- Validate the deign by Full-scale fatigue tests
- Project in collaboration with: Kiewit McCarthy, a Joint Venture (NWE2), Mr. Gary Sanders, Project Manager

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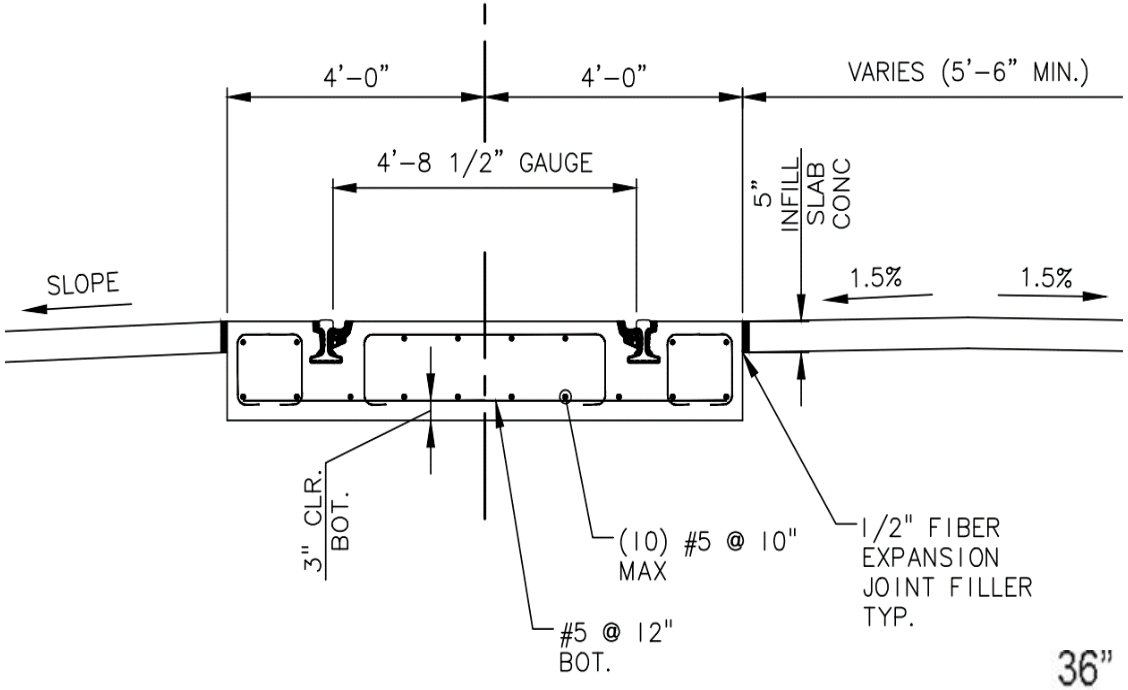
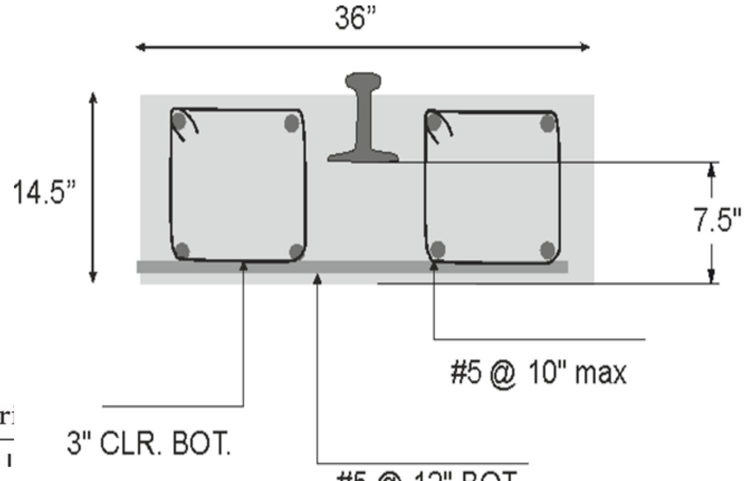
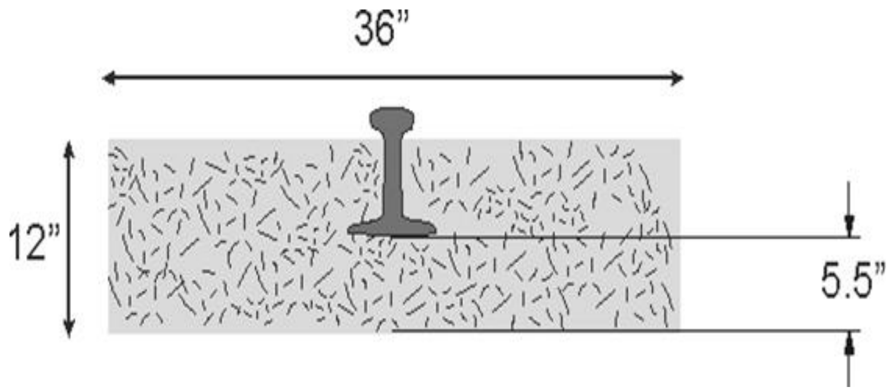
Stray Current Corrosion a Potential Concern

Design Alternatives







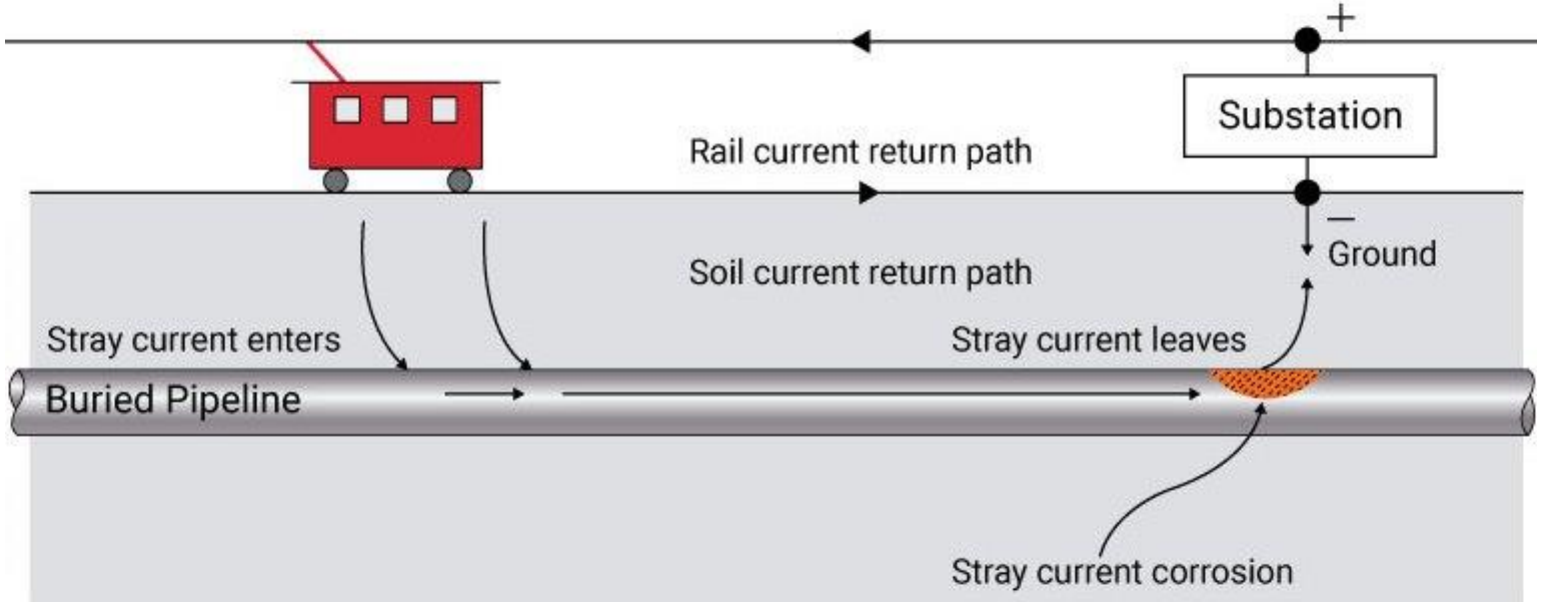
FRC Section

Proposed Testing Plan

- Develop a Testing Plan for the Mockup design and testing
- Size for the mockups : 3x8 ft by 14.5” for reinforced concrete vs 3x8x 12” with FRC only
- Control sample: concrete and rebar cage to meet the reinforcement ratio of the full-size sections
- Two mockups made for each of the three-test series.
- Two standard control sections, and two mockups per modified configuration using steel fibers
- Two suppliers based on their design recommendations are selected.

- Buried pipes, rebars experience Stray current corrosion

- Grounding the rebar is costly

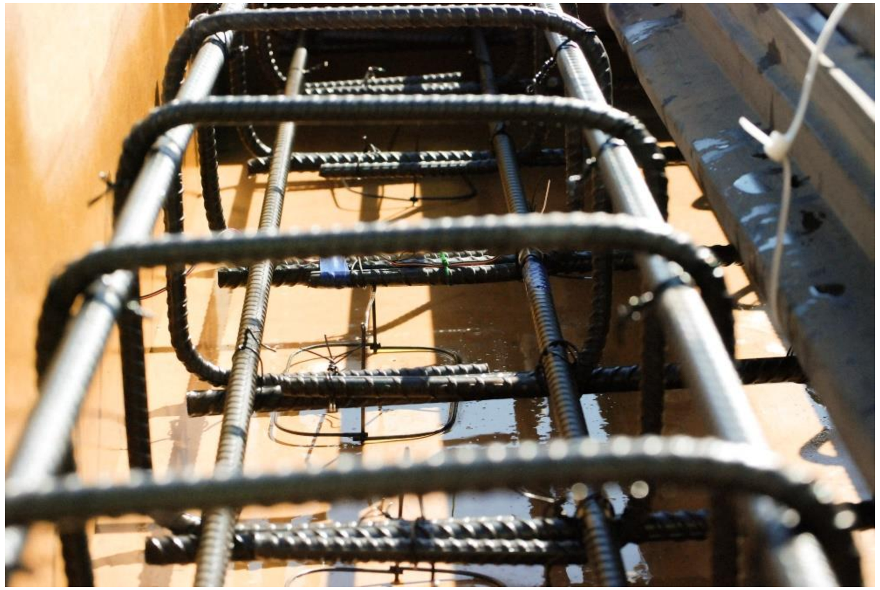


Mock-ups representing RC vs. FRC Design

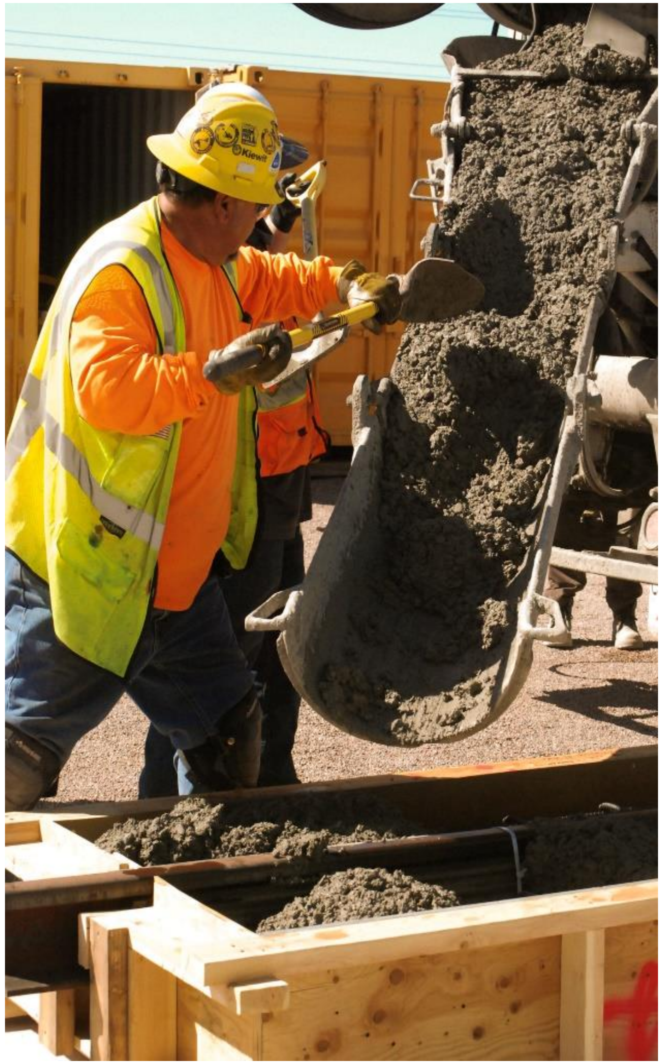
Construction of current Design approach consumes significant time

Proposed design expedites the construction time and cost significantly.

Attachment of Strain Gages



Sample Preparation



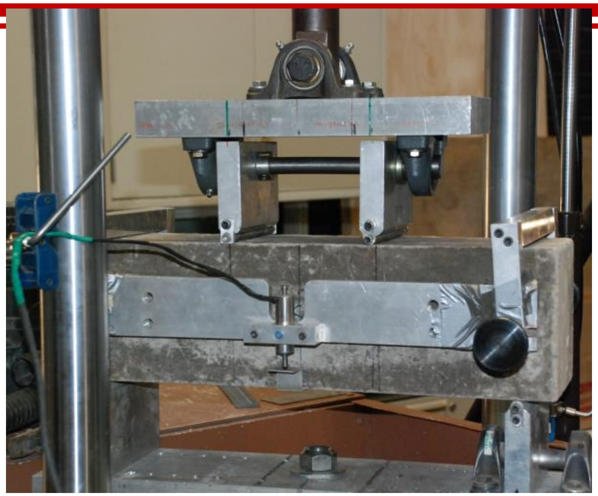
Definition of Serviceability Criteria in terms of Fatigue

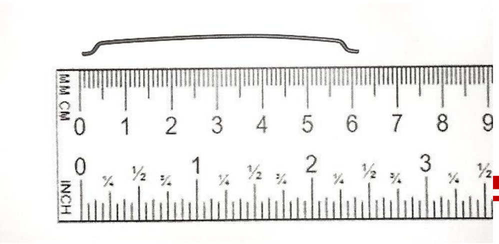
- Simulate the response under fatigue load, a loading history for a service life was considered:
- A service life of 45 years
- Significant ground settlement
  - Ex: water line failure the slab, loss of ground support, 8' long section for the entire width
- Design Wheel loading, fully loaded train with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

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

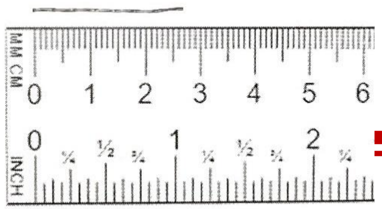
Materials Testing

Material Characterization





Type 1



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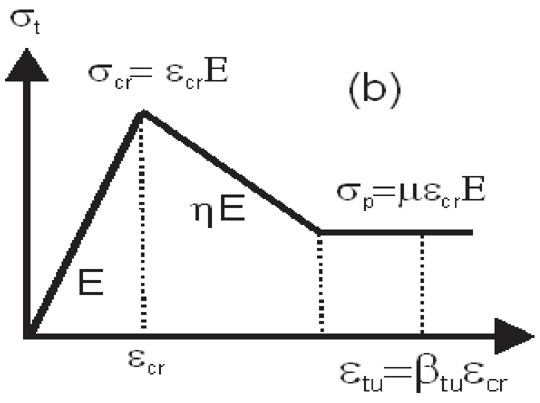
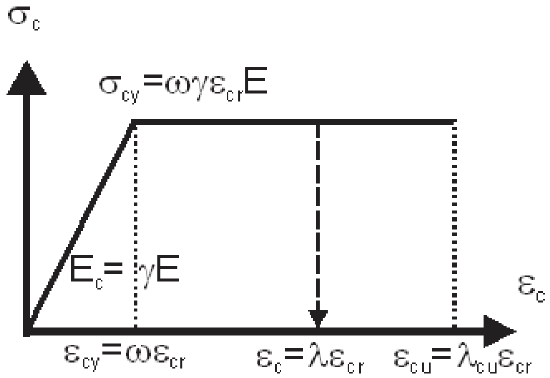
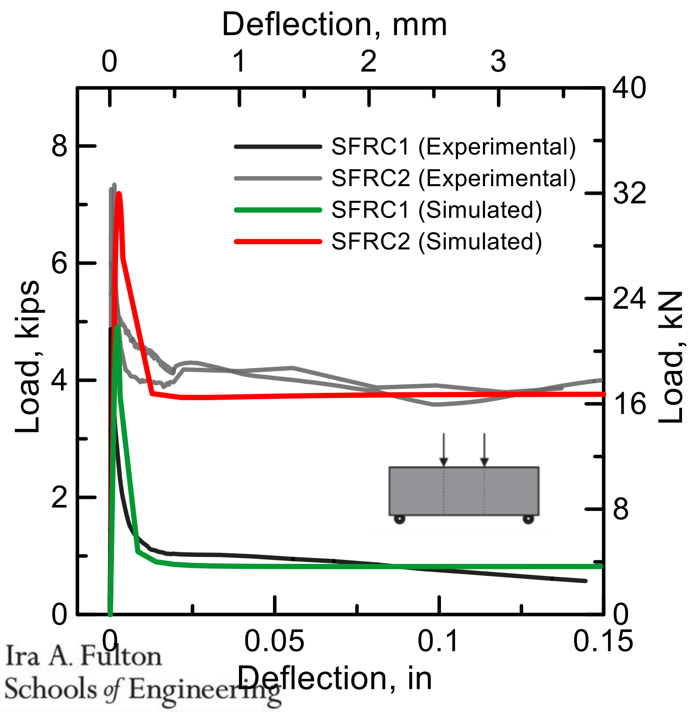
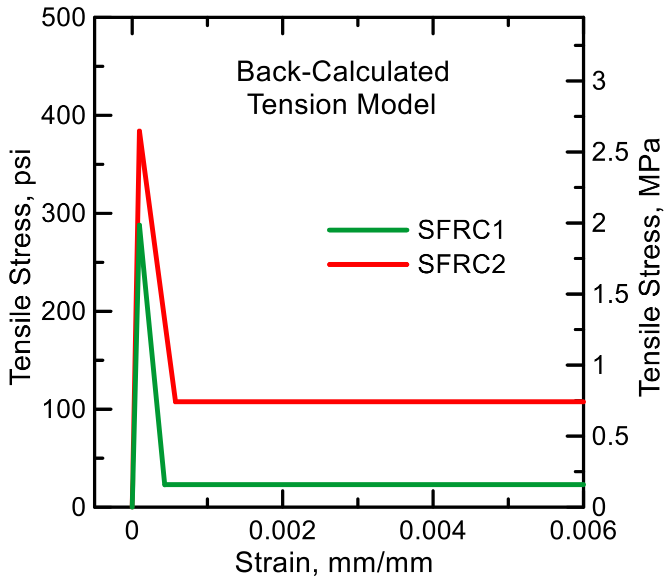


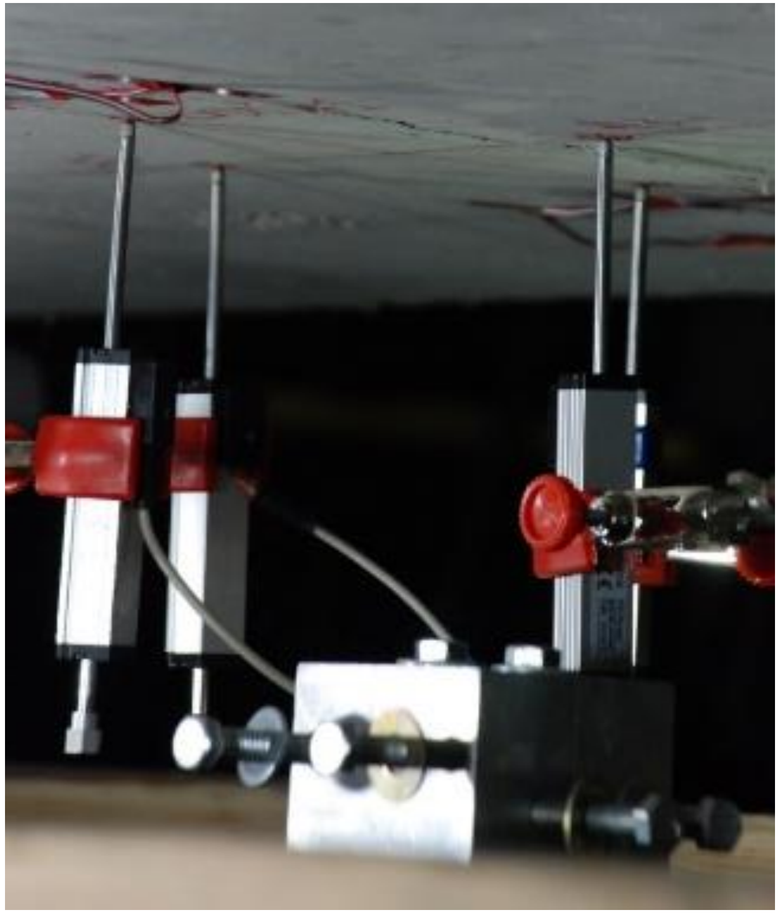






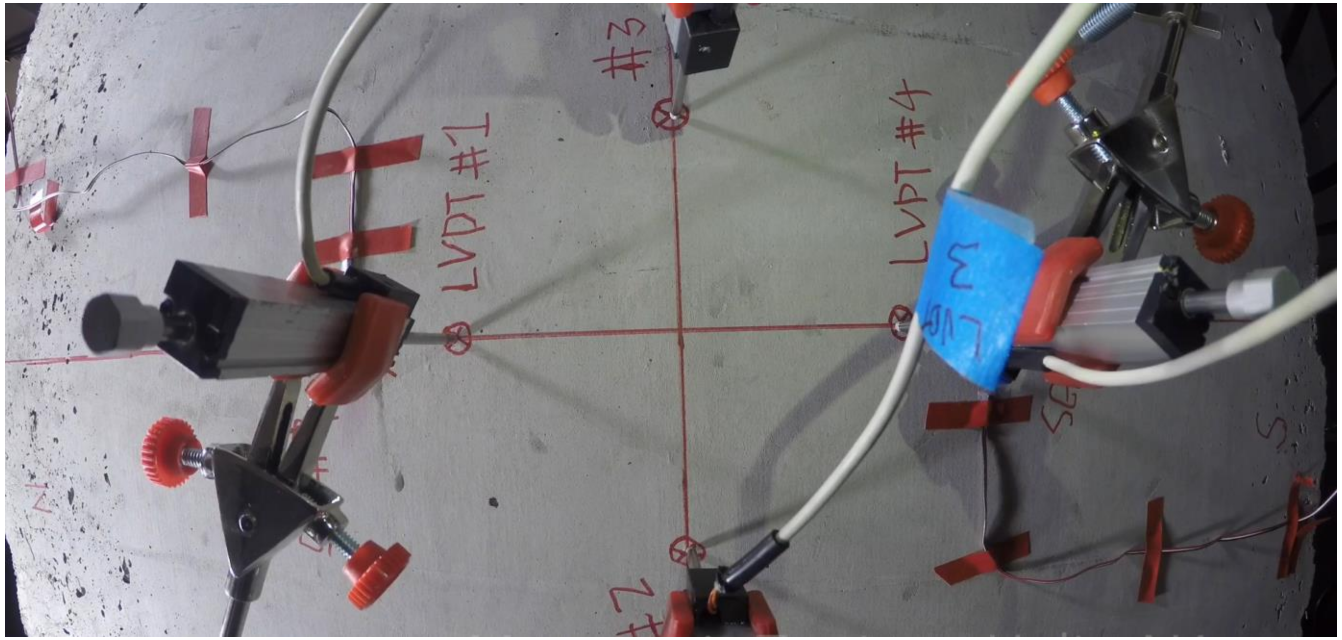
Full Scale Track Slab Testing Arrangement

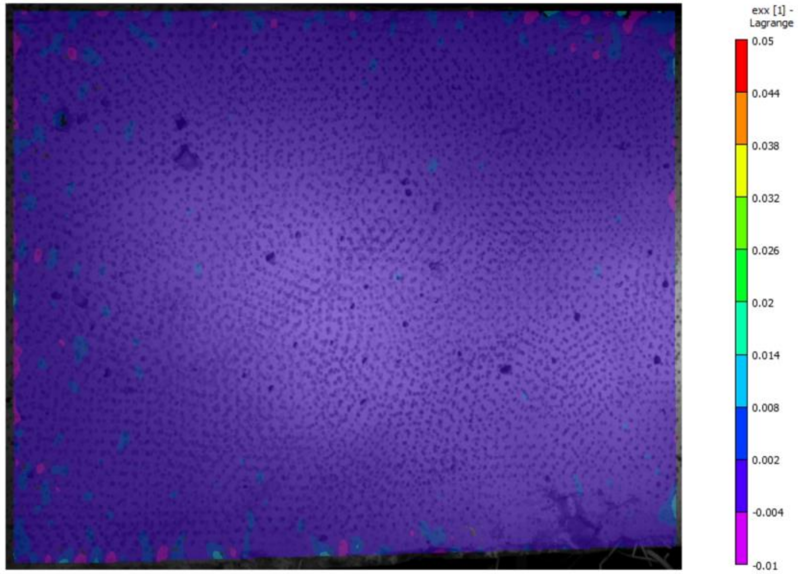
Steel Fiber Reinforced

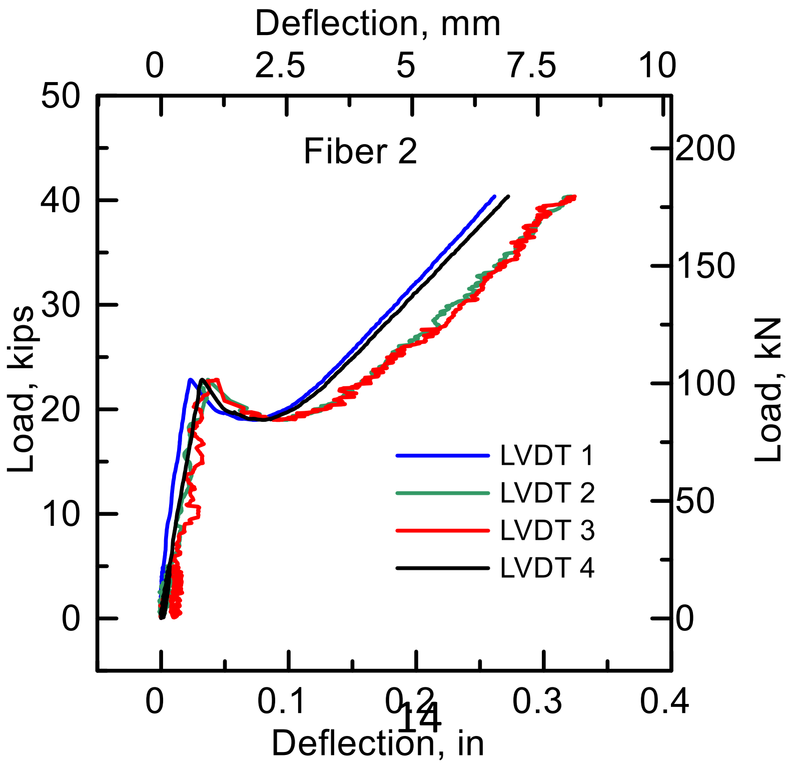


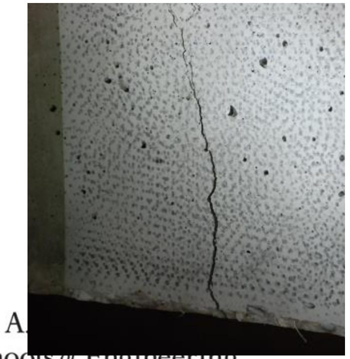
Full scale mockup specimen testing

Monotonic Testing:

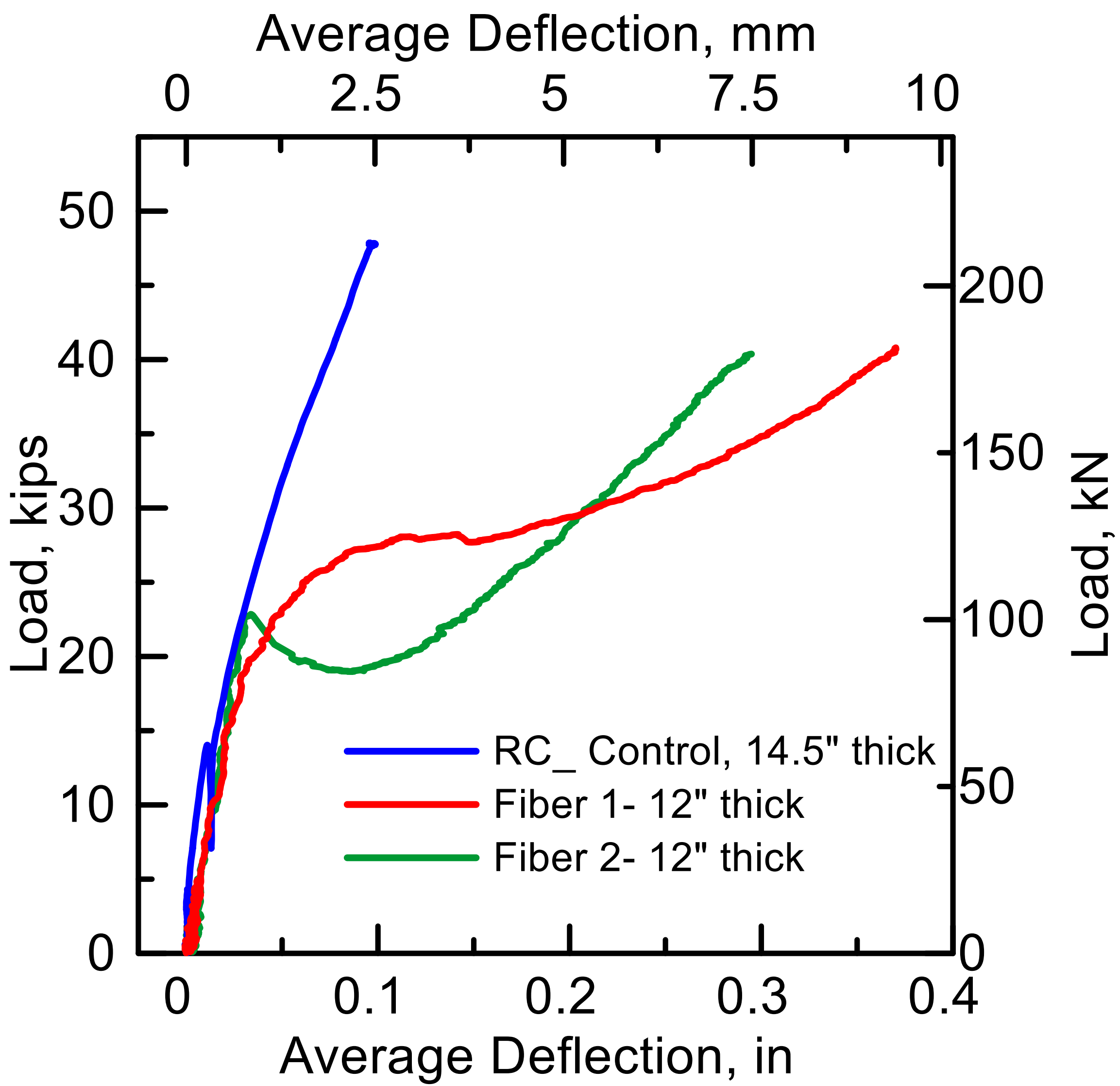






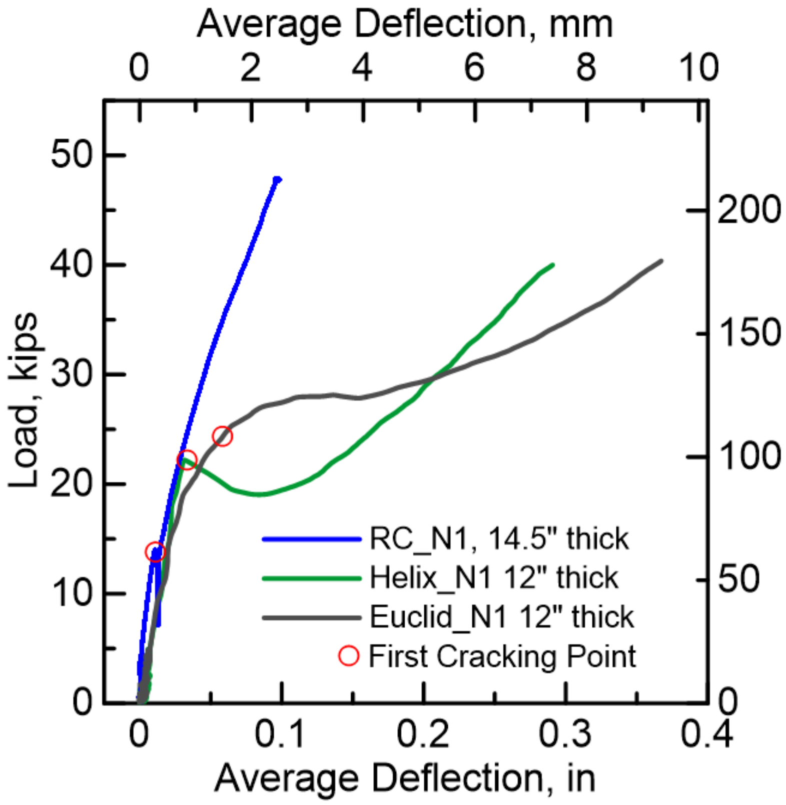


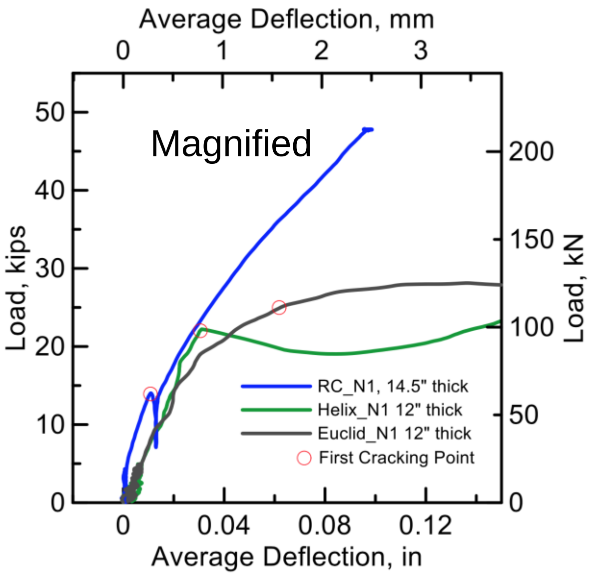
Monotonic Test results comparison

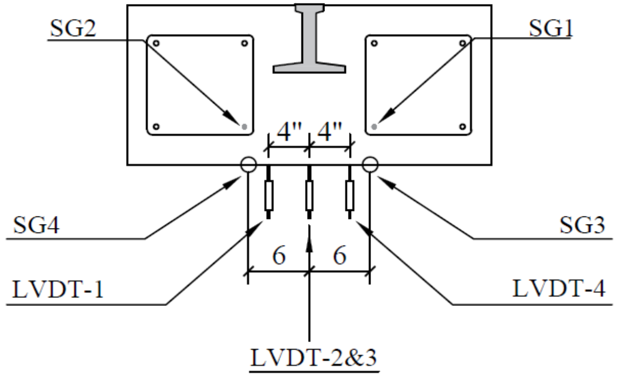


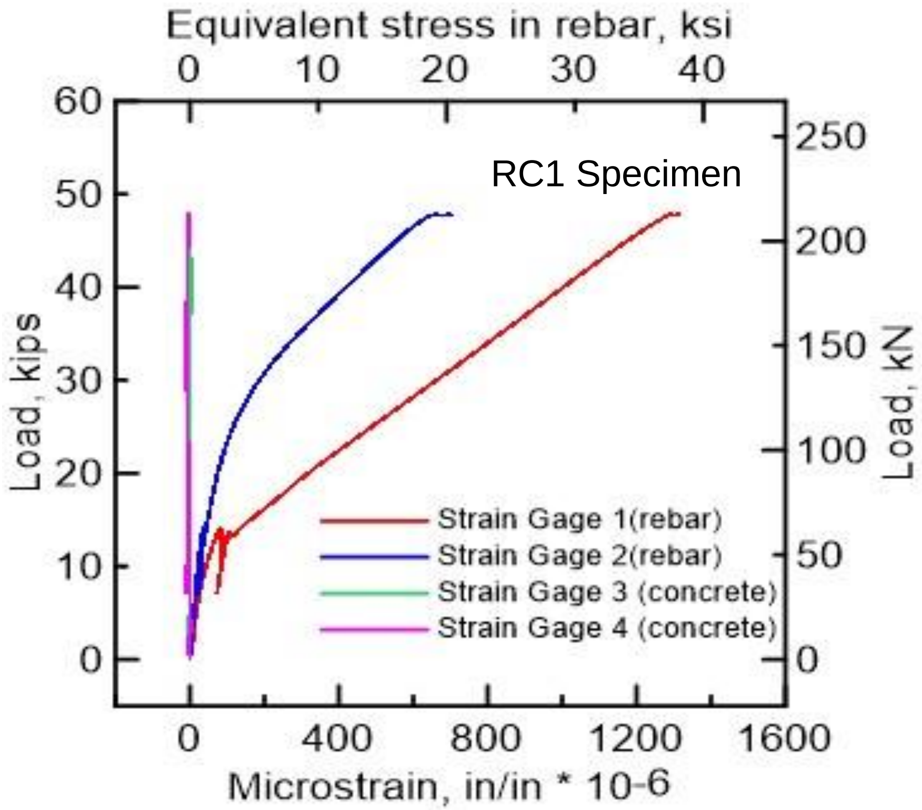
Full scale mockup specimen testing

Monotonic Tests







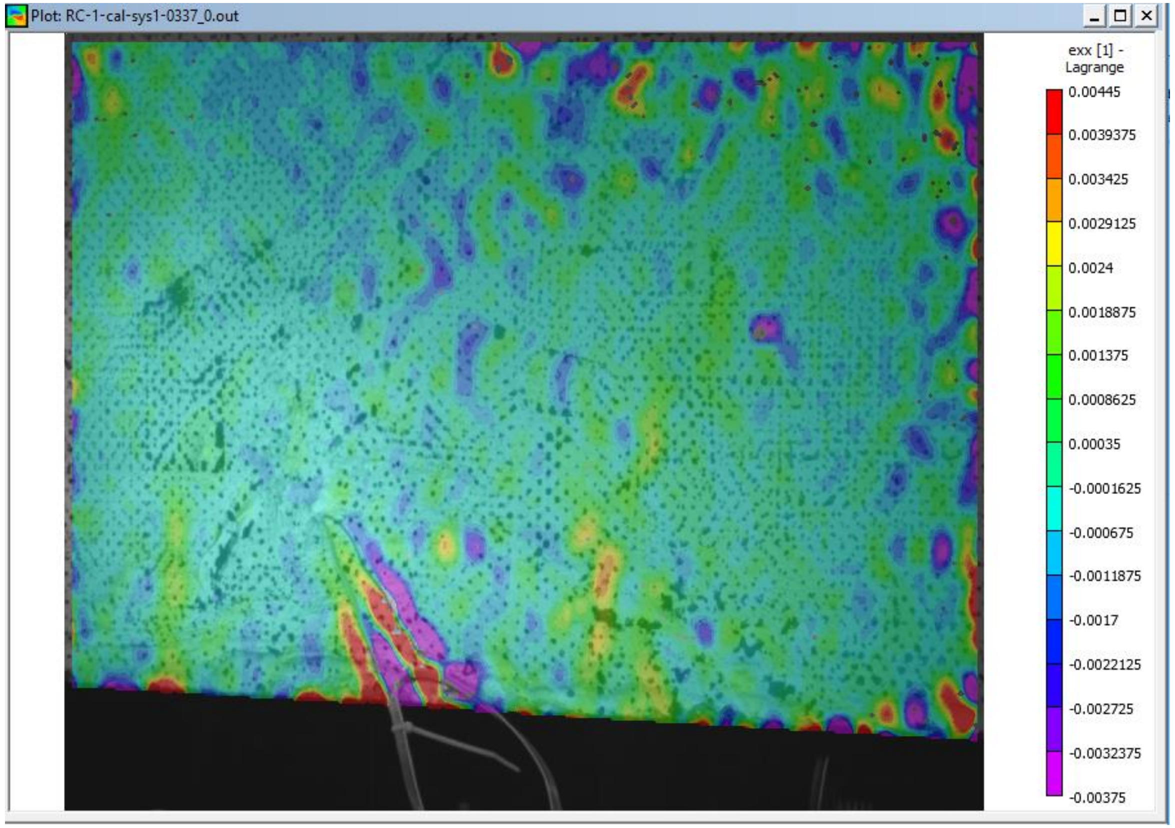


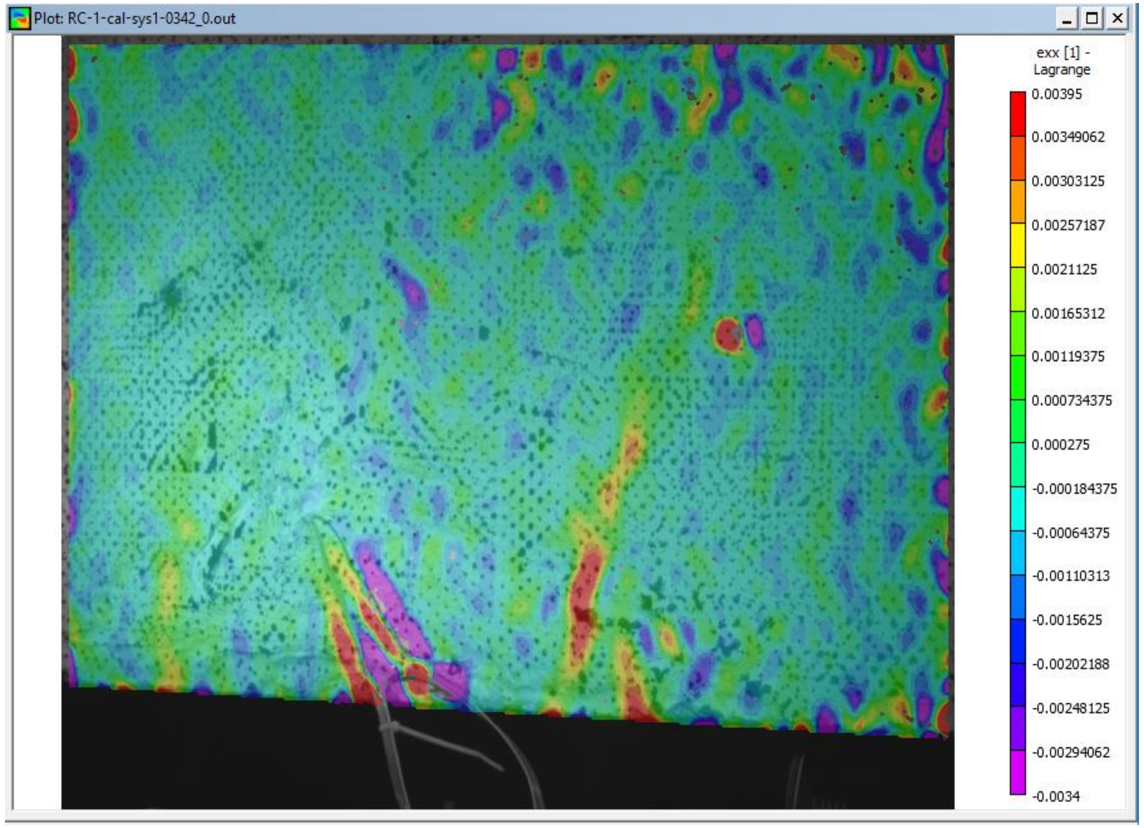
Observations

-Rebars still in elastic phase at 50 kip loading

-Higher first crack load and post crack ductility with fibers

DIC Data collection





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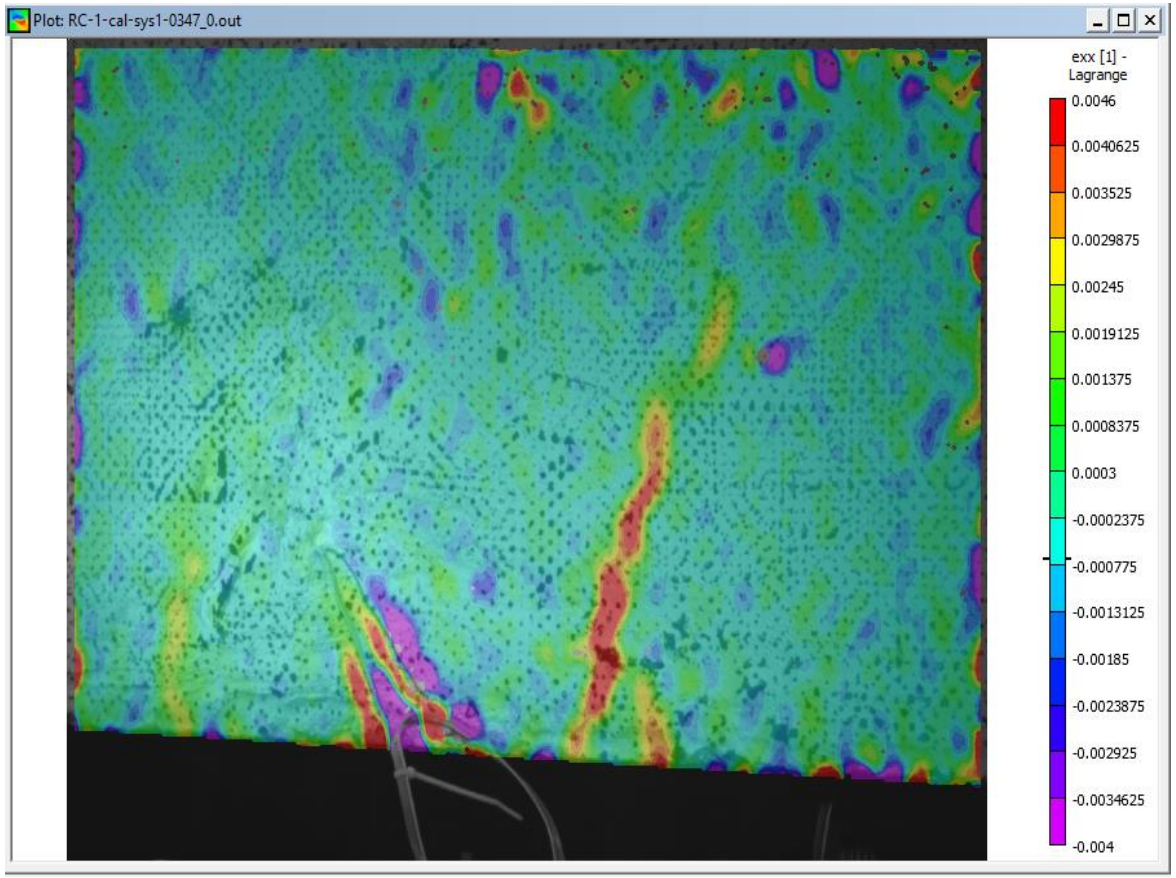
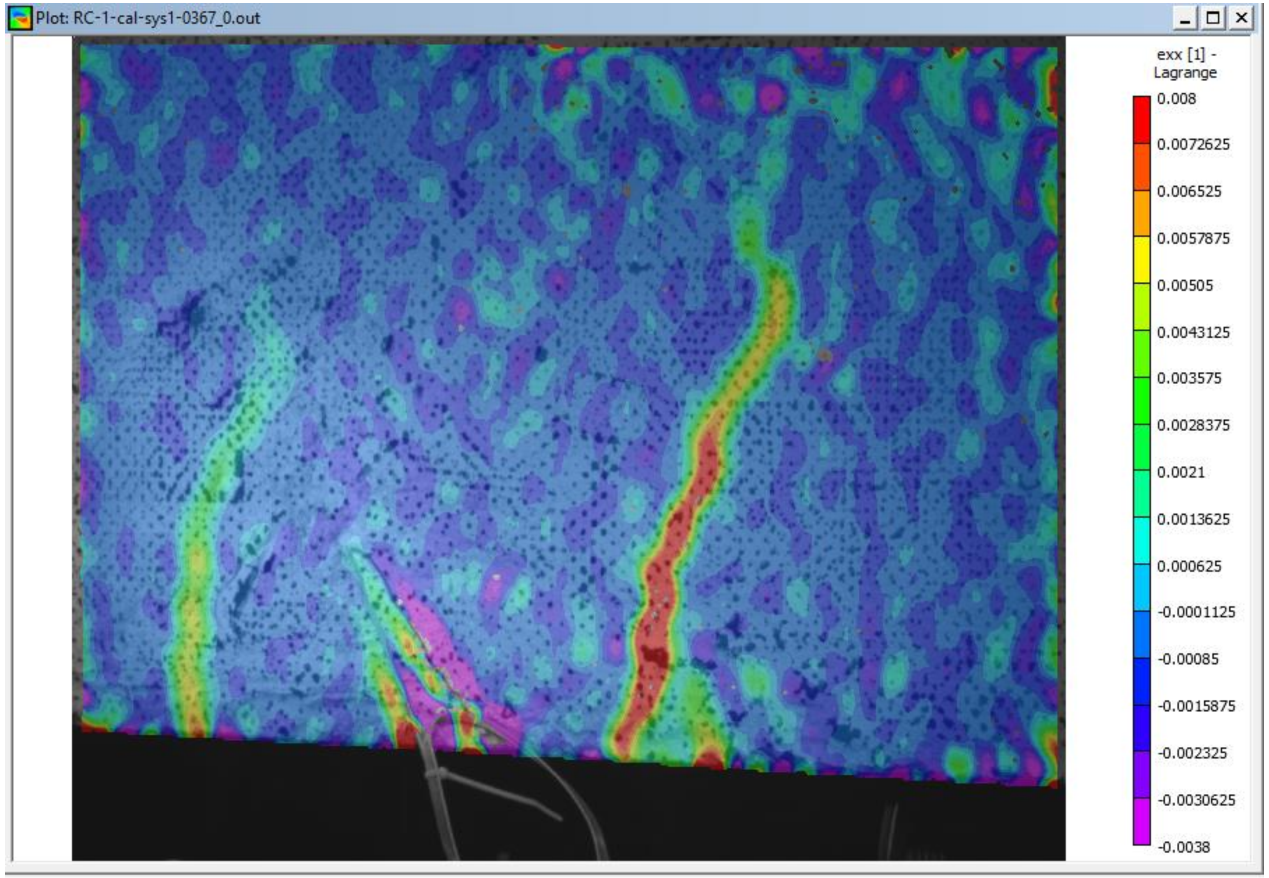
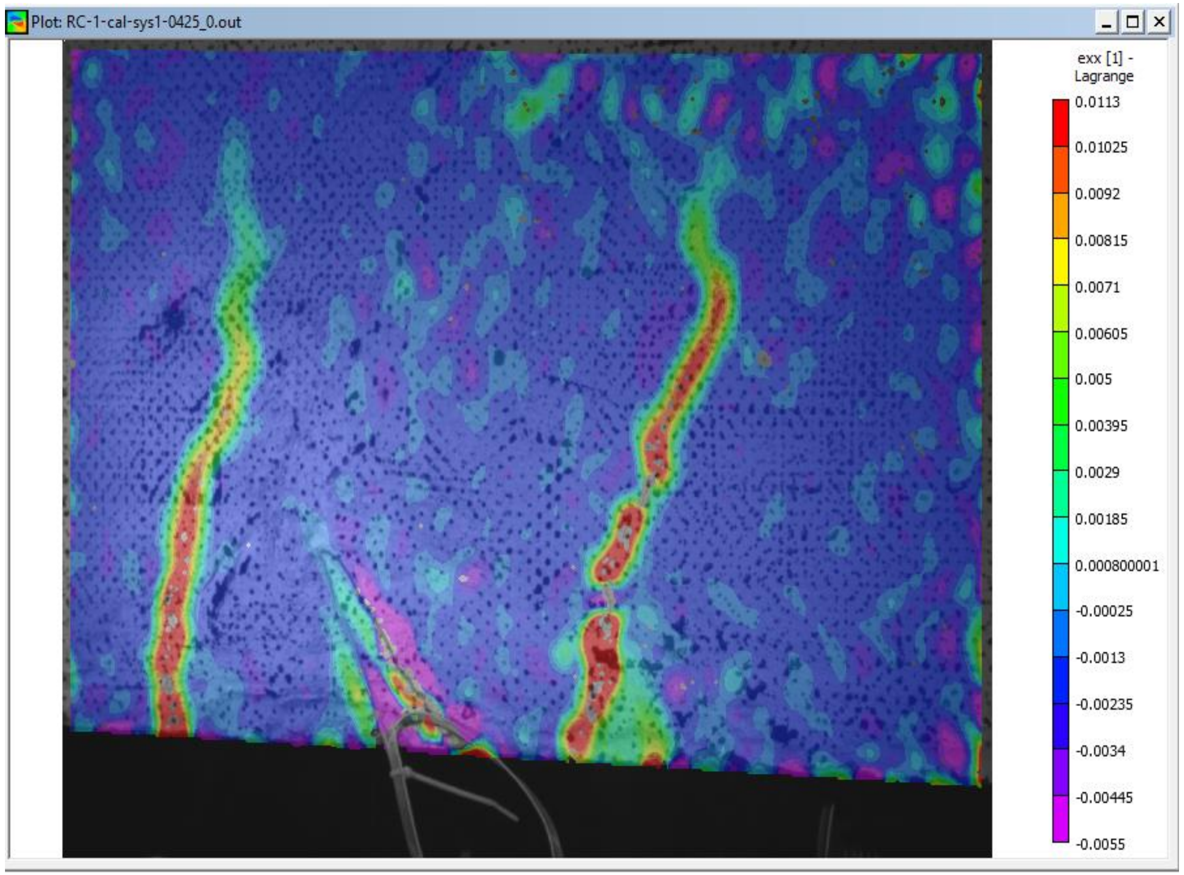
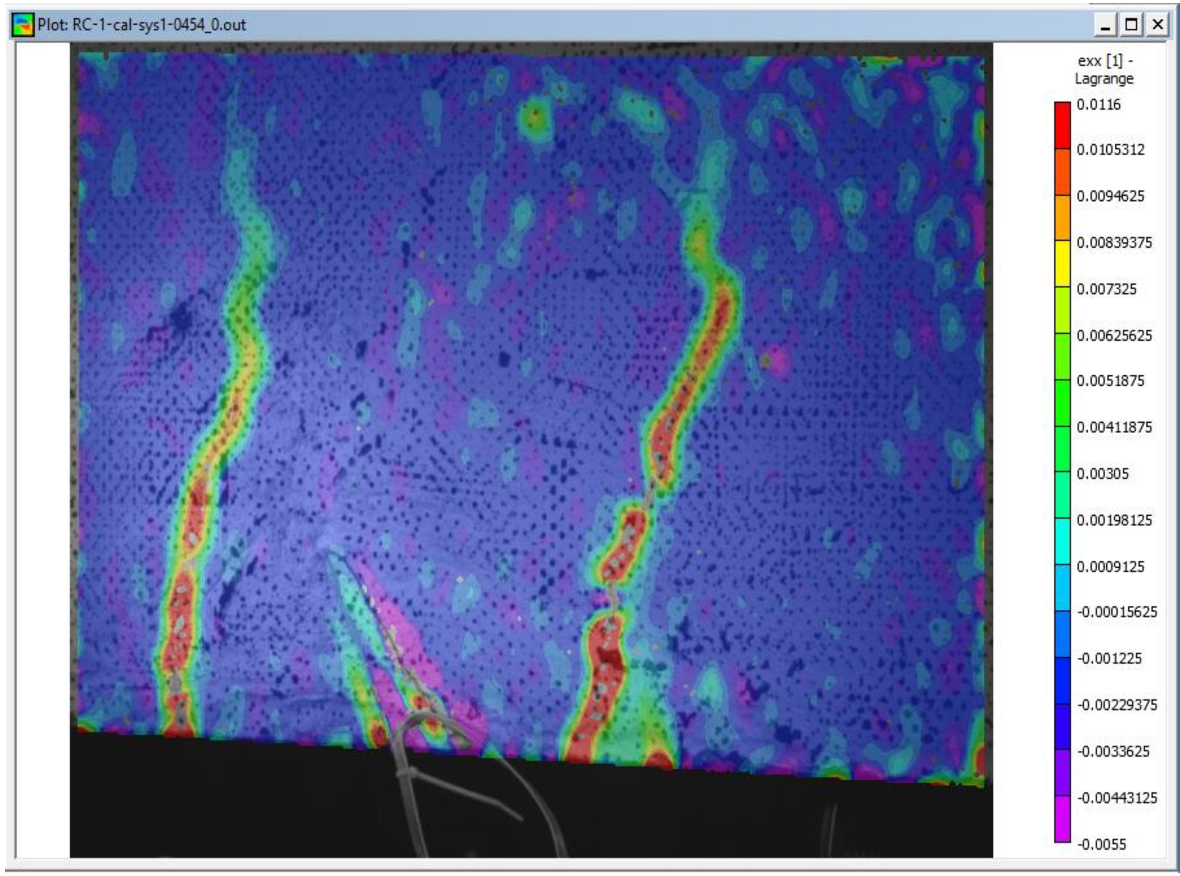
Various stages of cracking



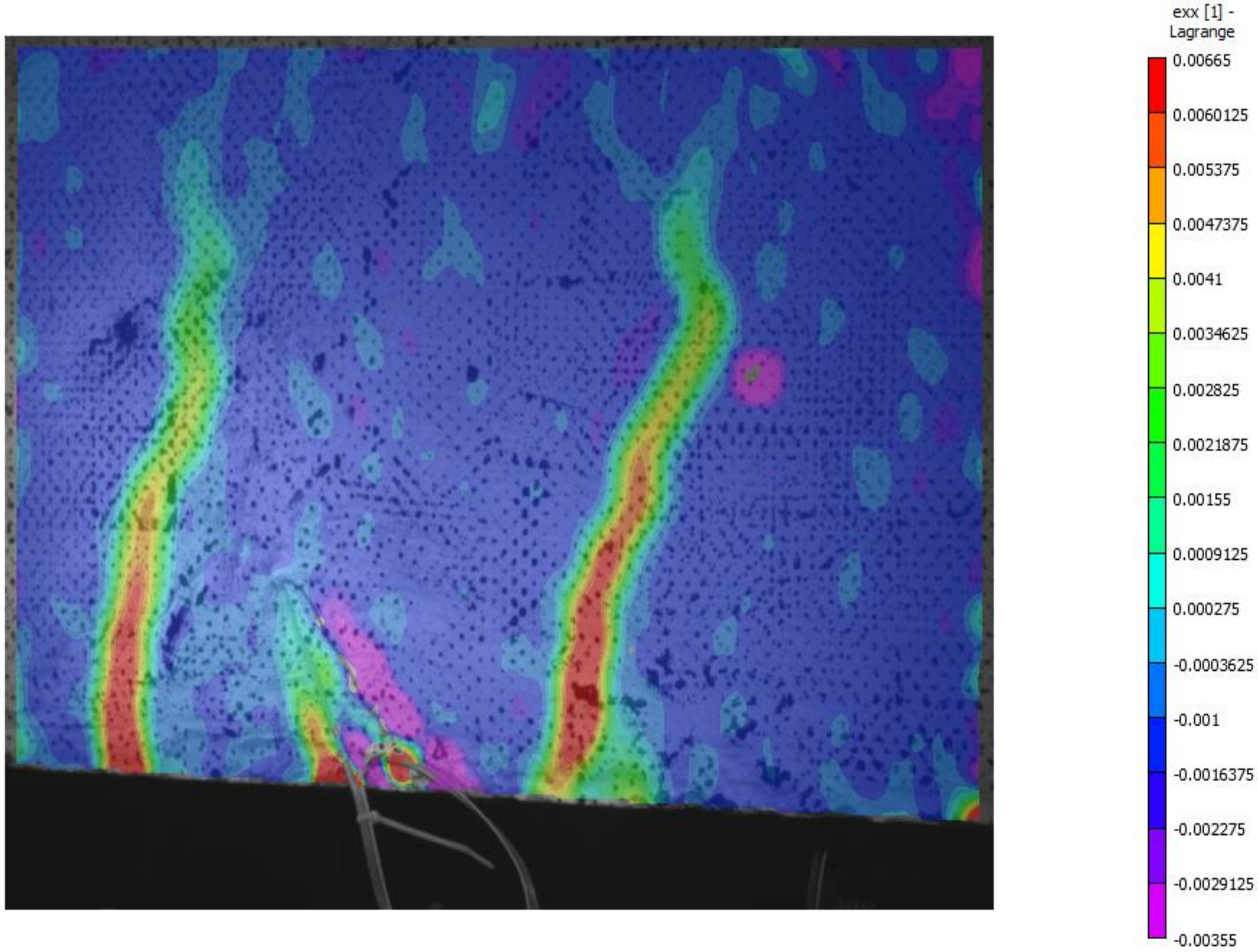


DIC measurements of level of cracking

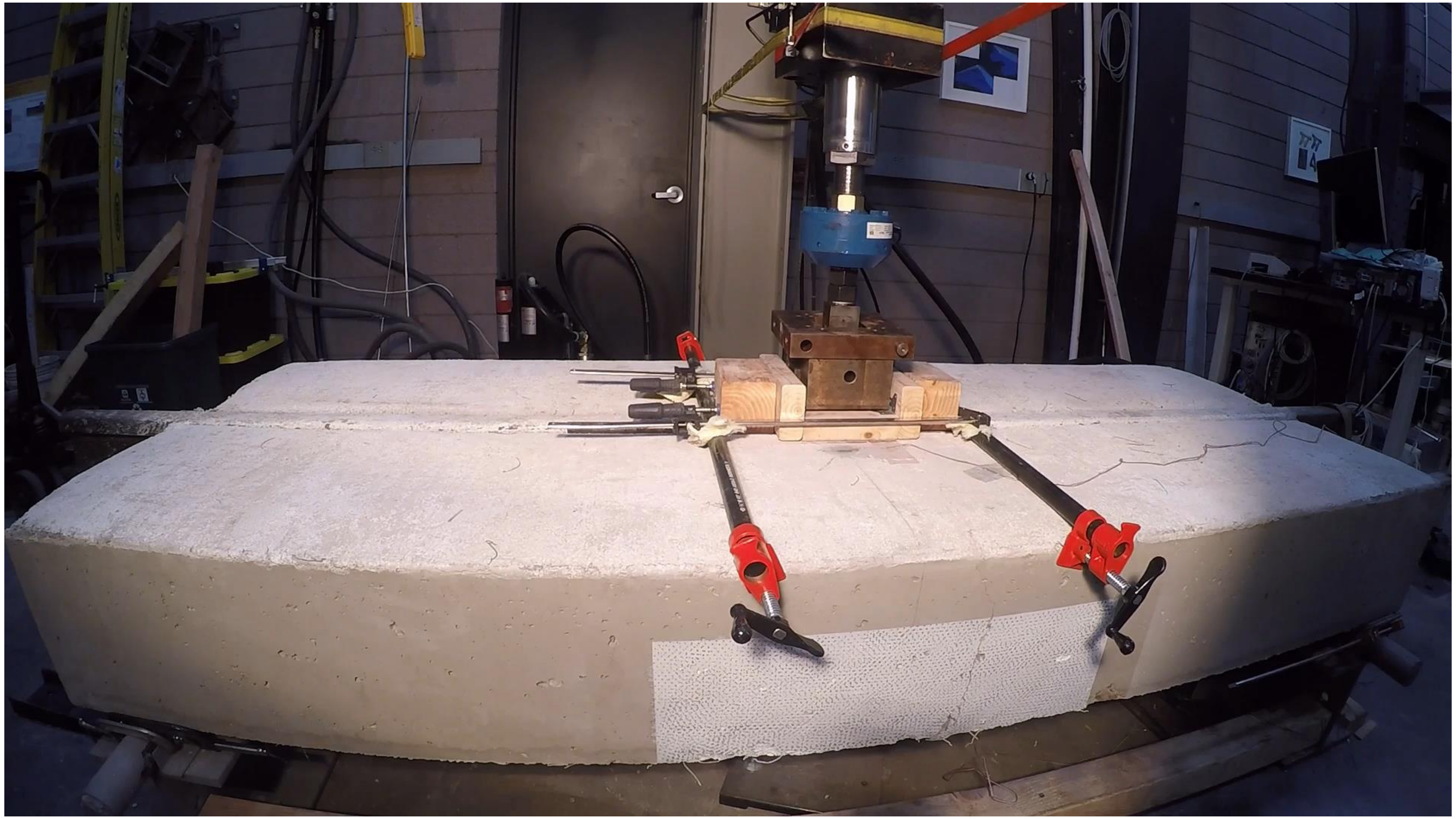


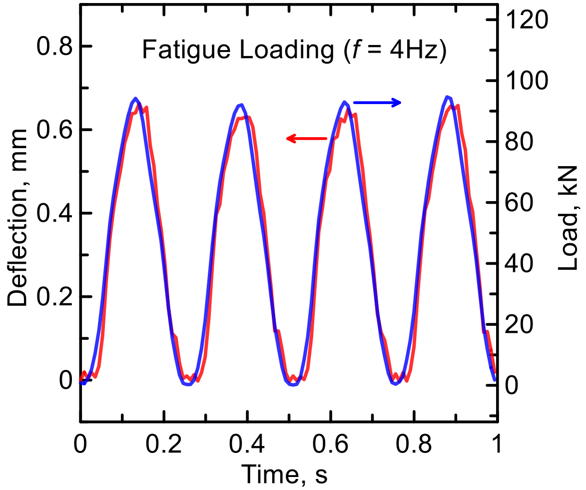


The final state of cracks



Fatigue Testing (2 Million Cycles , 4Hz)





-Loading : 17.5 kips

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

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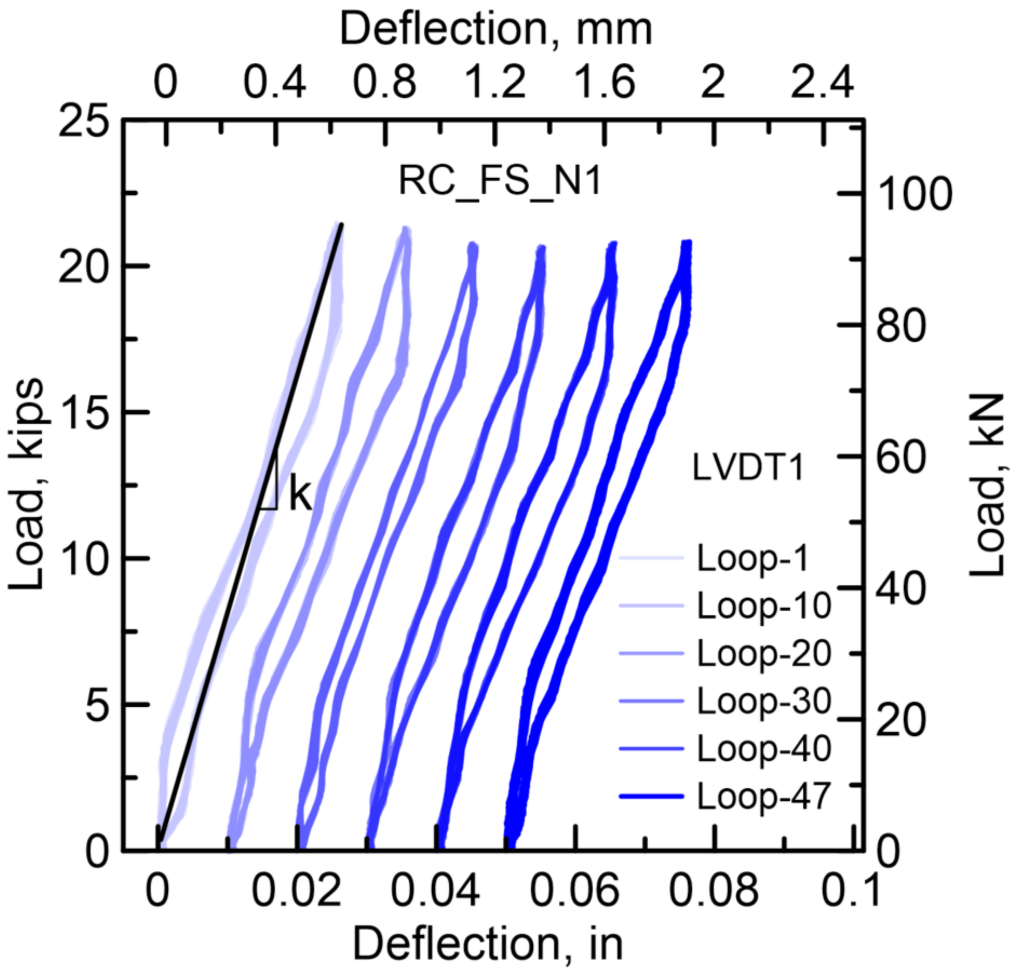
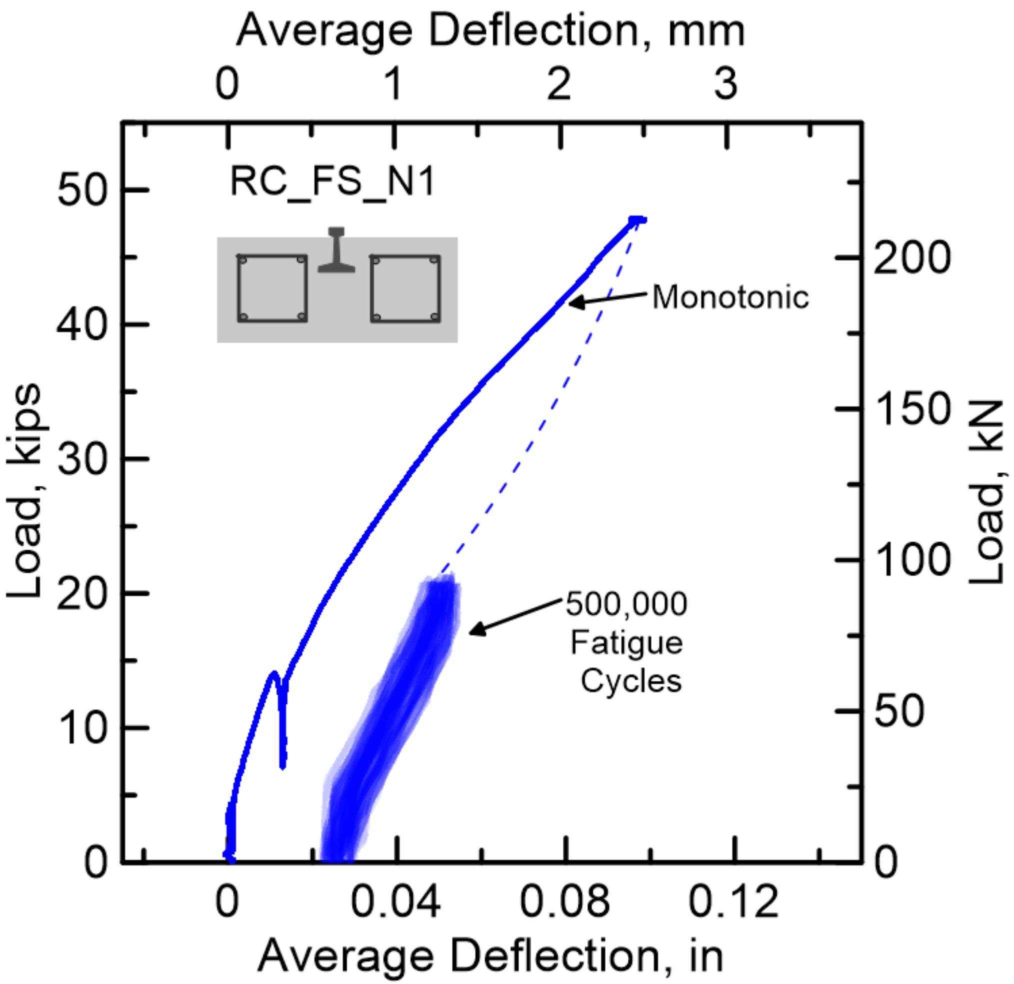
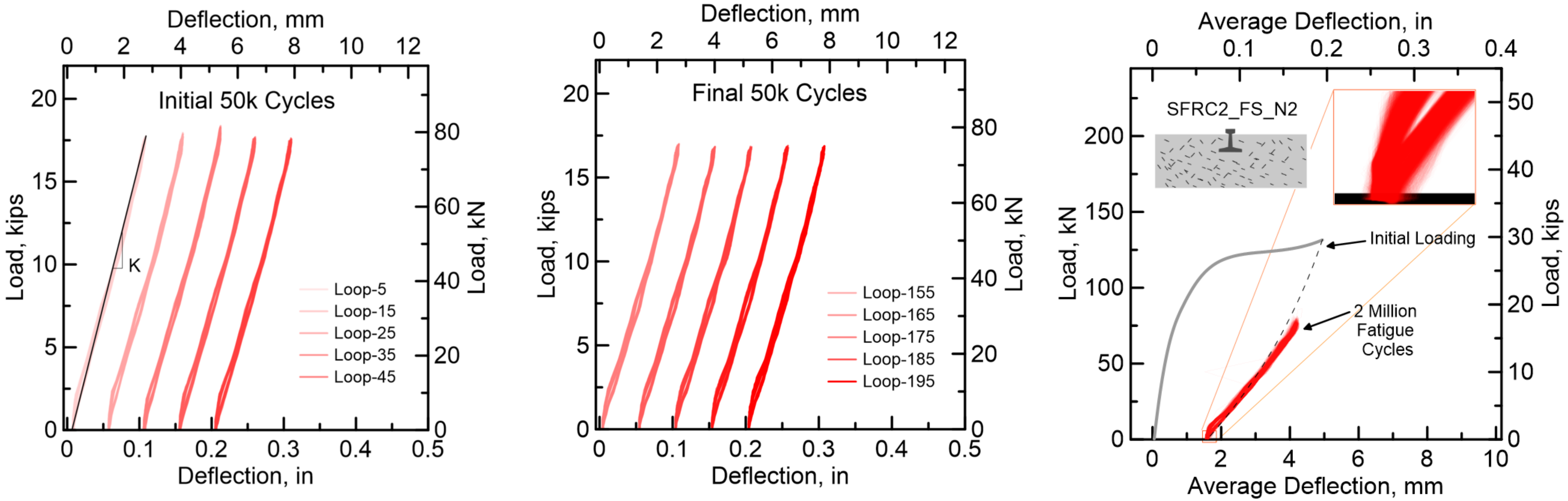
Results (Control Specimen) 500k total Fatigue Cycles



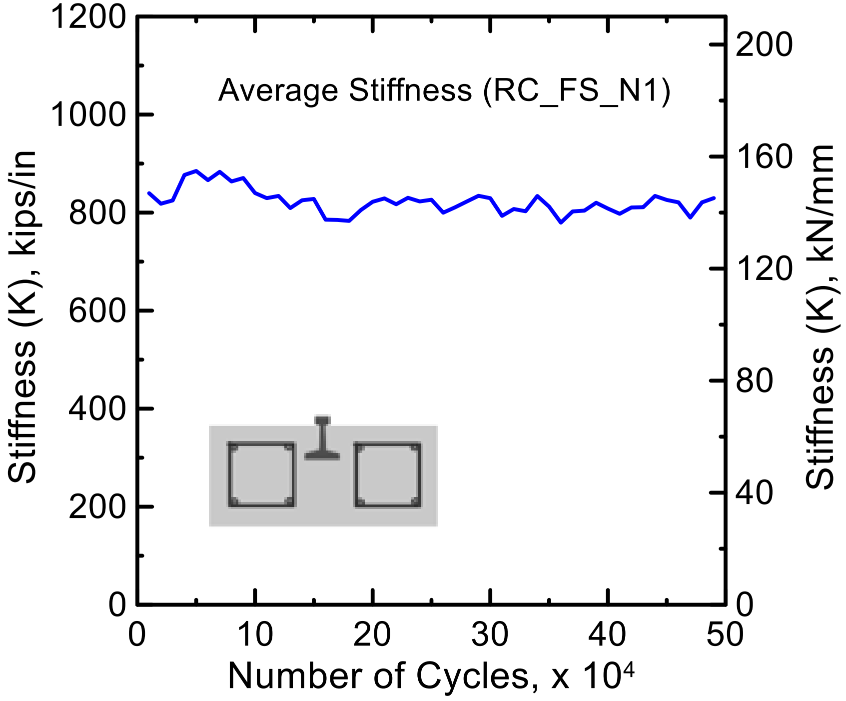


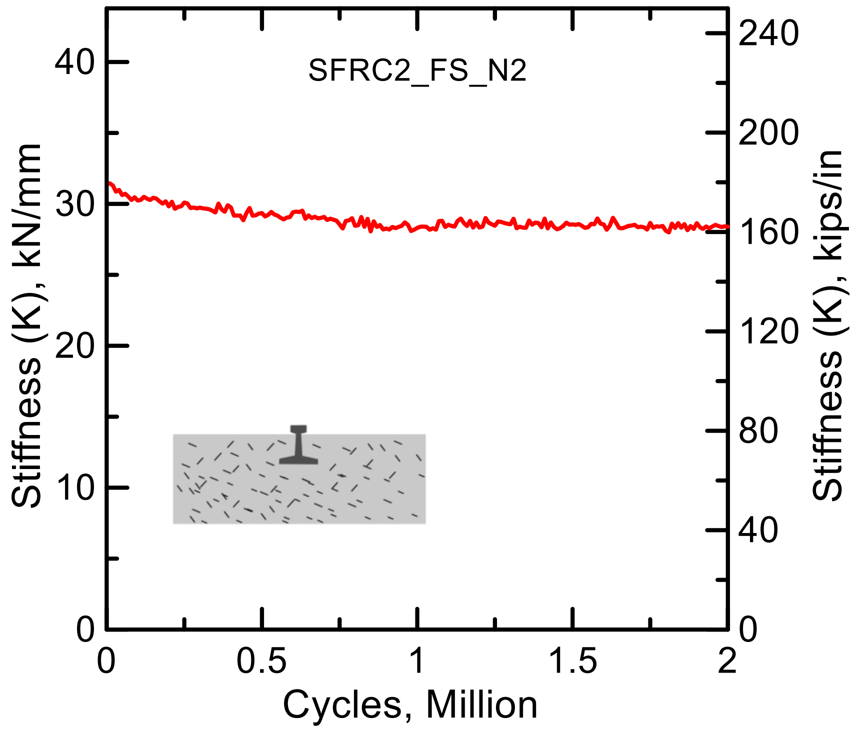
SFRC Specimen



-specimen was subjected to 2 million cycles of fatigue representing 50-year service life under 17.5 kips per cycle loading which is 1.6-1.9 times the service load.

Stiffness Reduction





11% reduction in average stiffness
After 500k cycles

8.6% reduction in average stiffness
After 2M cycles

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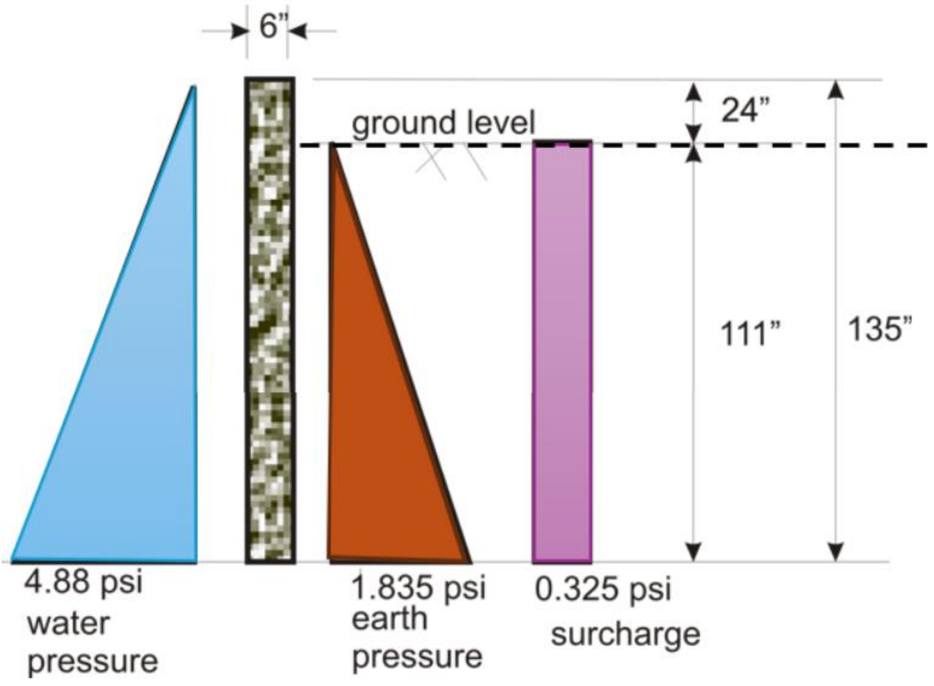
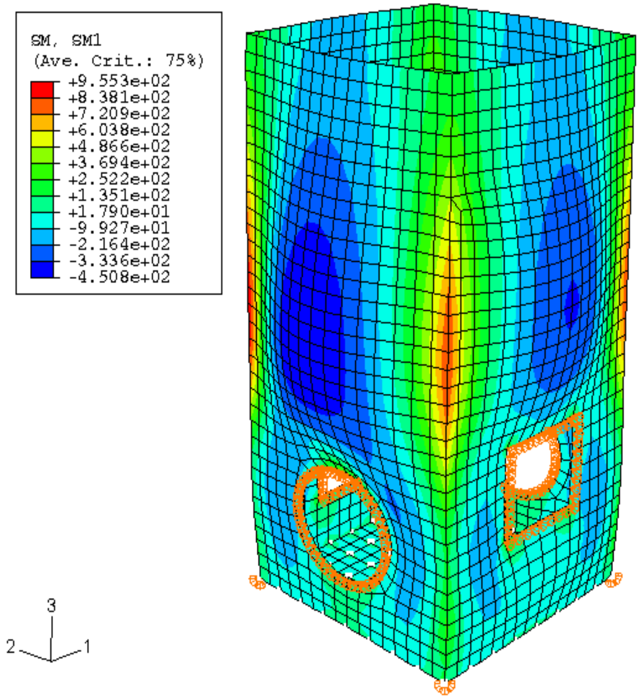
Unit of measure 16’ wide x 1 mile	Original Design approach	Proposed Design Approach
Length, depth	5280’ x 14.5” thick	5280’ x 12” thick
Volume of Concrete used in yd^3	3651 cubic yards	3129 cubic yards
Steel Rebar used	184,000 lbs #4, 298000 lbs #5	
Steel Fiber 60 lbs per cubic yard		203,000 lbs steel fibers, 2”
Costs		
Concrete @ $90 per yard	3651(90)= $328,300	3129($90)= $281,610
Steel cost Rebar vs. Fiber ($90/60 lbs)	#4 $211,600+ #5$342,700= $554,300	3129($90)= $281,610
Inspection	$193,527	$75,400
Materials Testing	$136,000	$53,000
Cost steel rebar	$554,300	
Cost steel fibers		$281,610
Materials only Cost Savings/mile		-$527,193
1 track ft cost in place	$3309	$1013
Total cost per mile	$17,471,000	$5,348,000
Total Cost savings/mile		-$12,122,800
Project Duration for 1 mile		
A 480’ section scheduled (1 labor day is equivalent to 10 workers)	21 days	11 days
Differential per section	-10	
A mile of track	231 days	121 days
Differential per mile	110 days	
Labor Costs	$3309 per track ft labor	$1013 per track ft labor
Total cost per mile	$17,471,520	$5,348,640

Design Verification of Precast water tanks





Load Case1:

1.4 Self weight + 1.4 Water pressure

Load Case2:

1.4 Self weight + 1.7 Earth pressure + 1.7 Uniform pressure due to surcharge

Project Background

- Increase durability, corrosion prevention
- maintain capacity at a certain level (SLS, ULS)
- reduce section size, labor
- reduce the consumption of concrete
- reduce the total cost of the project

Experimental Plan

- Investigate the design, and performance of FRC hybrid design in precast panels.
- 16 panels were cast, tested, analyzed and compared extensively.
- Strength, toughness, crack width control, ductility, and stiffness retention.
- Variables in terms of panel thickness(t), reinforcement ratios(ρ), Hybrid fiber and RC combinations, boundary conditions, and their effects were examined.
- Simplify the design process using sustainability approaches with standard thickness panels, reduced rebar, and reduced labor while improving durability.

Panels setup in casting yard before the pour

Plain FRC Panel Specimen

Conventional Panel specimen

Rebar arrangement for #4@12” and #5@6”

Casting and finishing Process

Bull float finish

Curved float for edging

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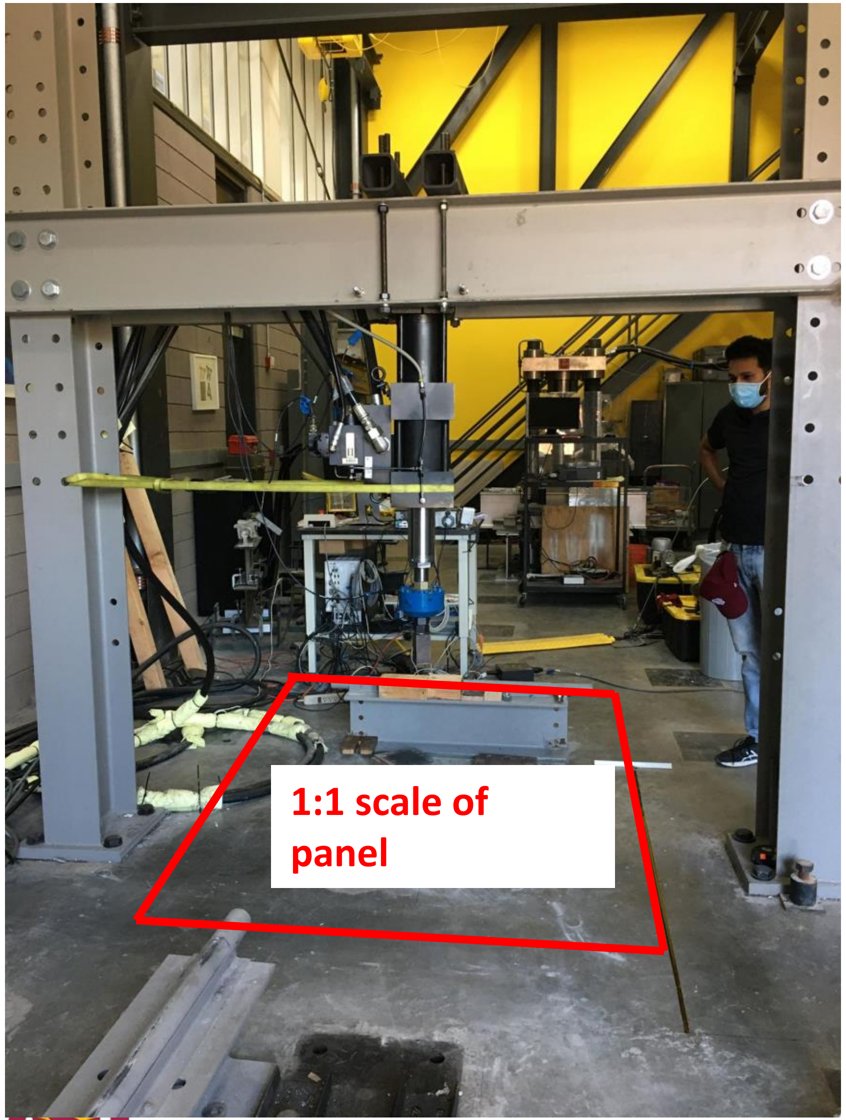
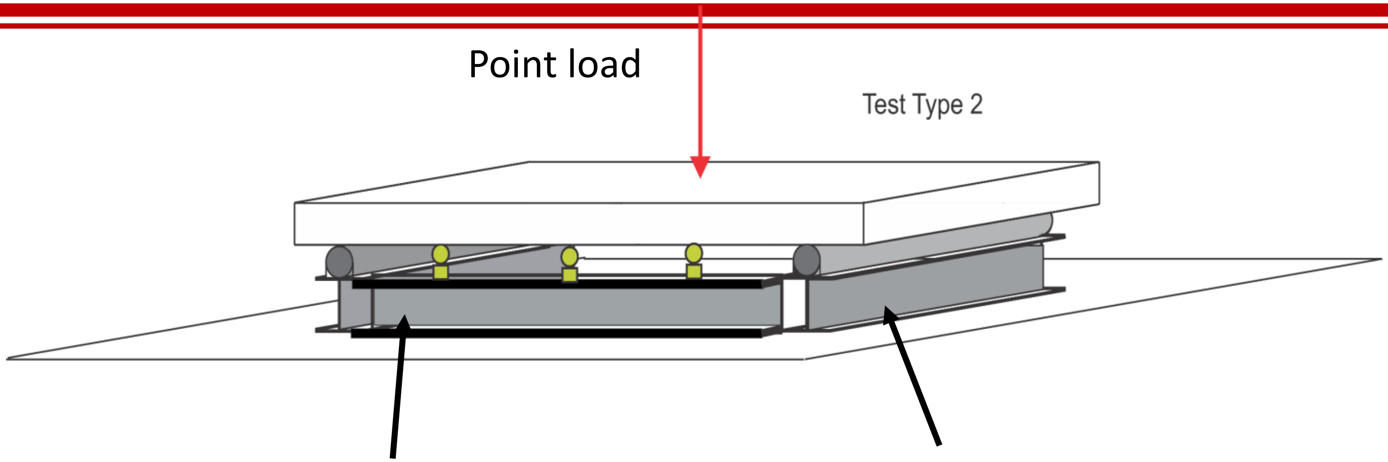
Putting anchors on edge of a panel

Schematic of the Testing-Frame

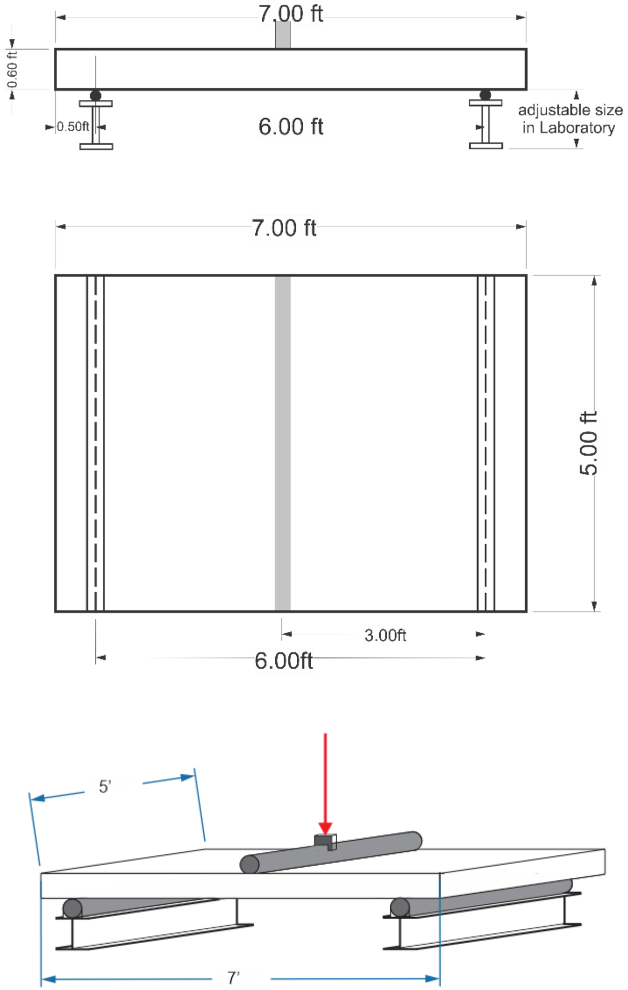




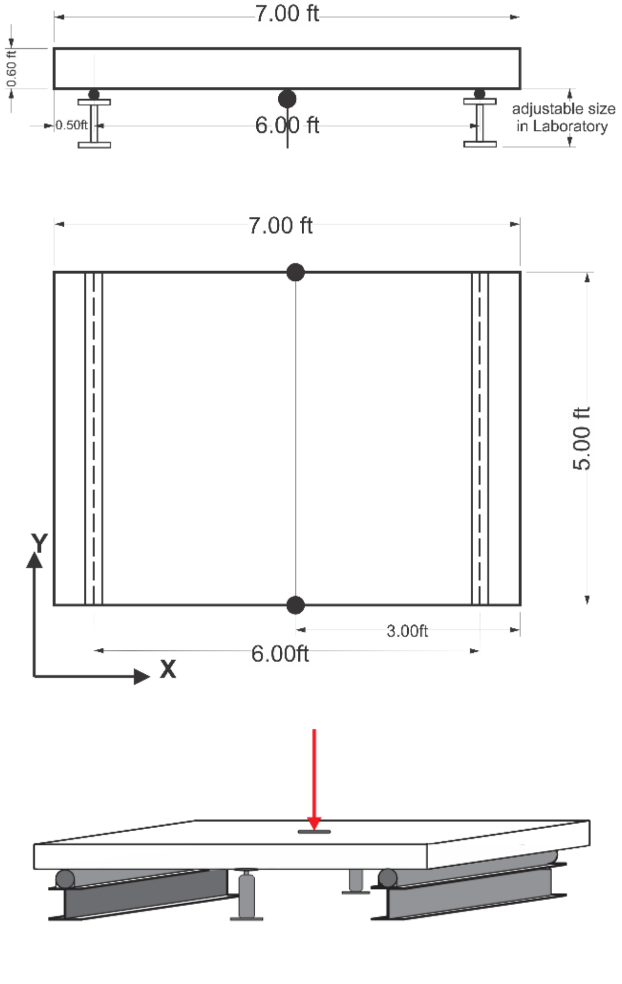
Universal support
Allow to rotate in 3-DOF

W12 x 53 section is support
at 4 edges (h=12.", w=10")

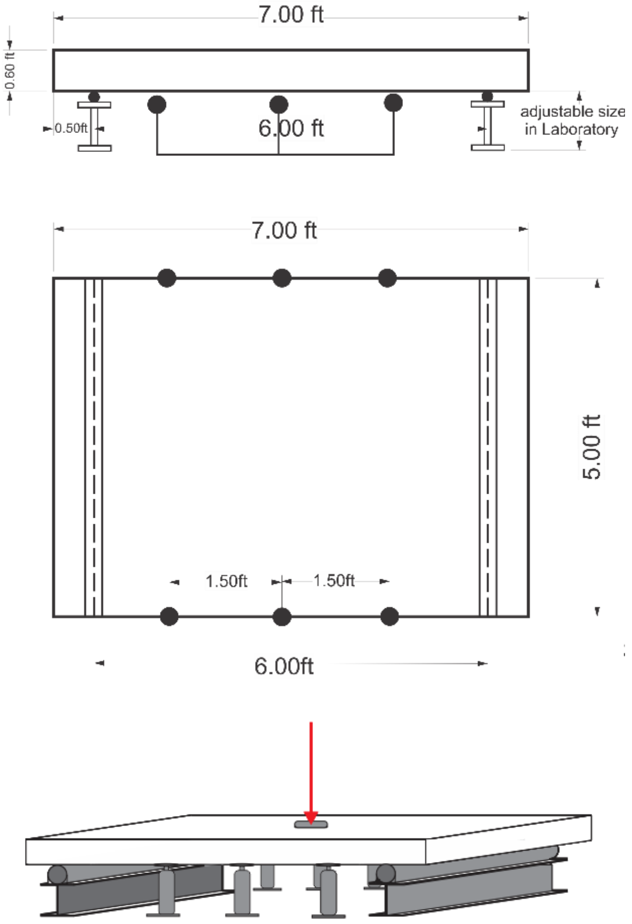
Full-Scale panel testing (3 Different Boundary Conditions)



Test Type 1, 3 Point bend



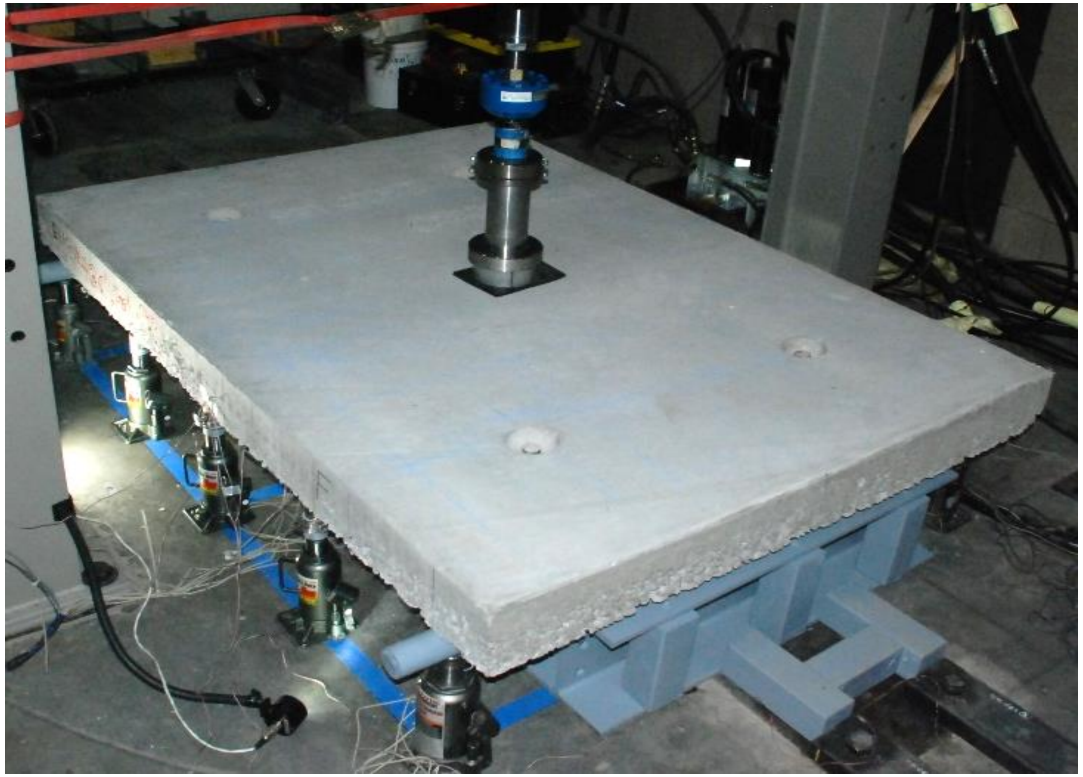
Test Type 2, 2 Line + 2 Point Support

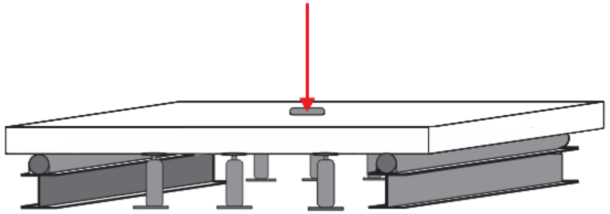


Test Type 3, 2 Line + 6 Point support

Test type 1 is directed at handling, lifting and transportation of panels, Tests type 2 and 3 with 2 point and 6 point supports simulate the connection points to the adjacent orthogonal panels in the structural box under the service conditions

Test Setup for Type-3 Boundary condition

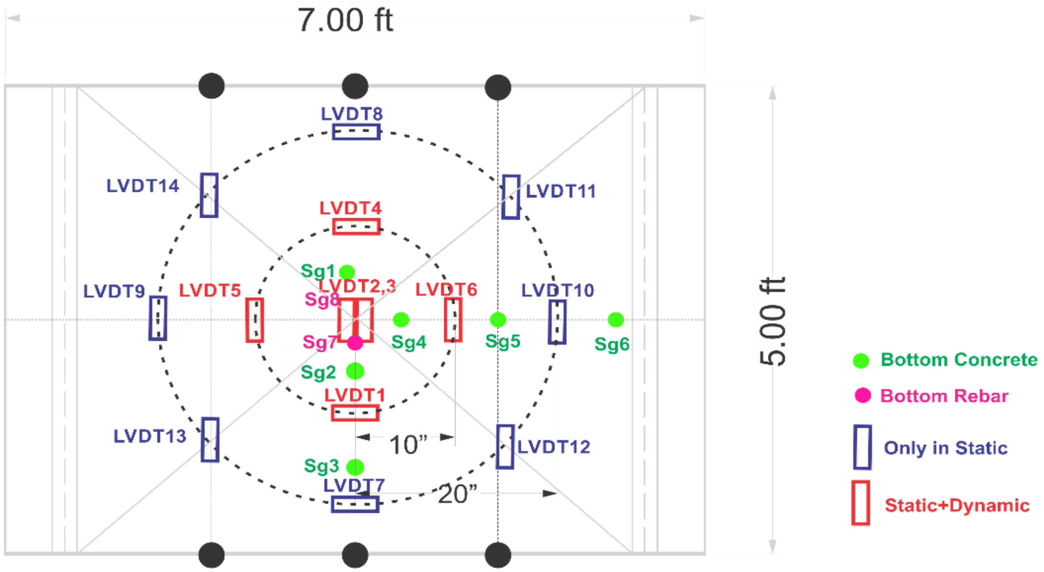




Measuring Method for Full-scale tests

- Vertical displacement LVDT -14
- Bottom Concrete Strain gage- 6
- Rebar Strain gage - 2

- Digital image Correlation(DIC) – Top view, recoding yield line propagation



Plan View

LVDT setup

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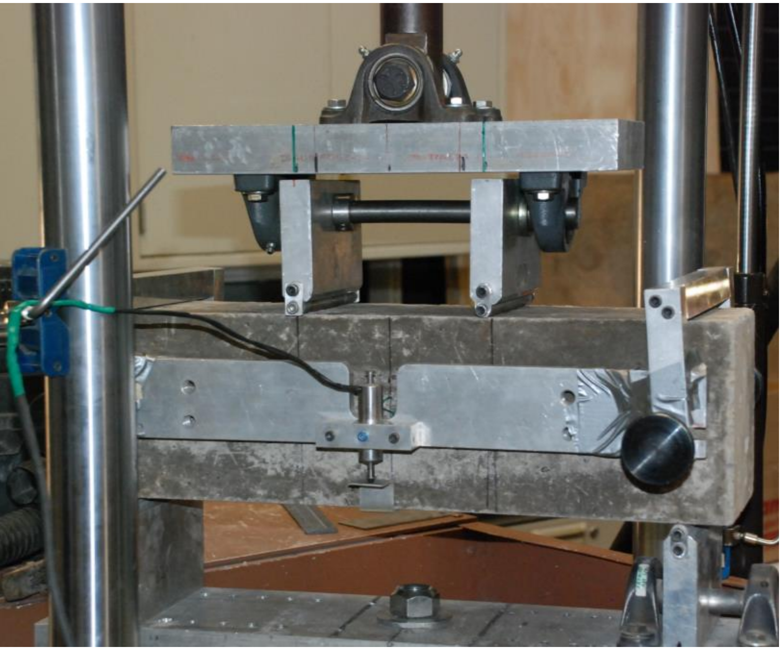
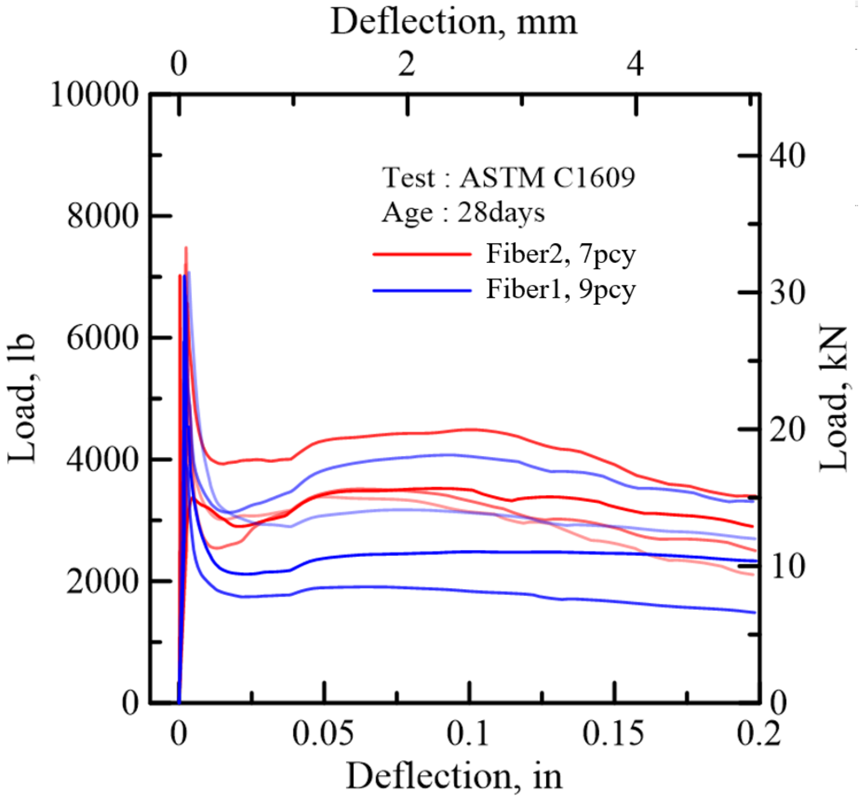
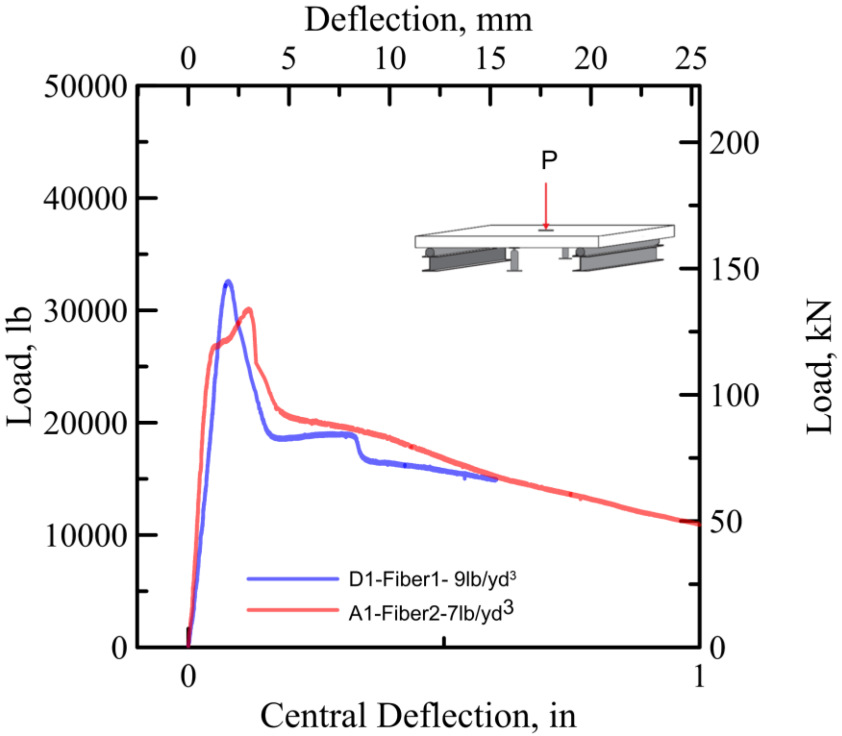
Central Load-Deflection Response in FRC



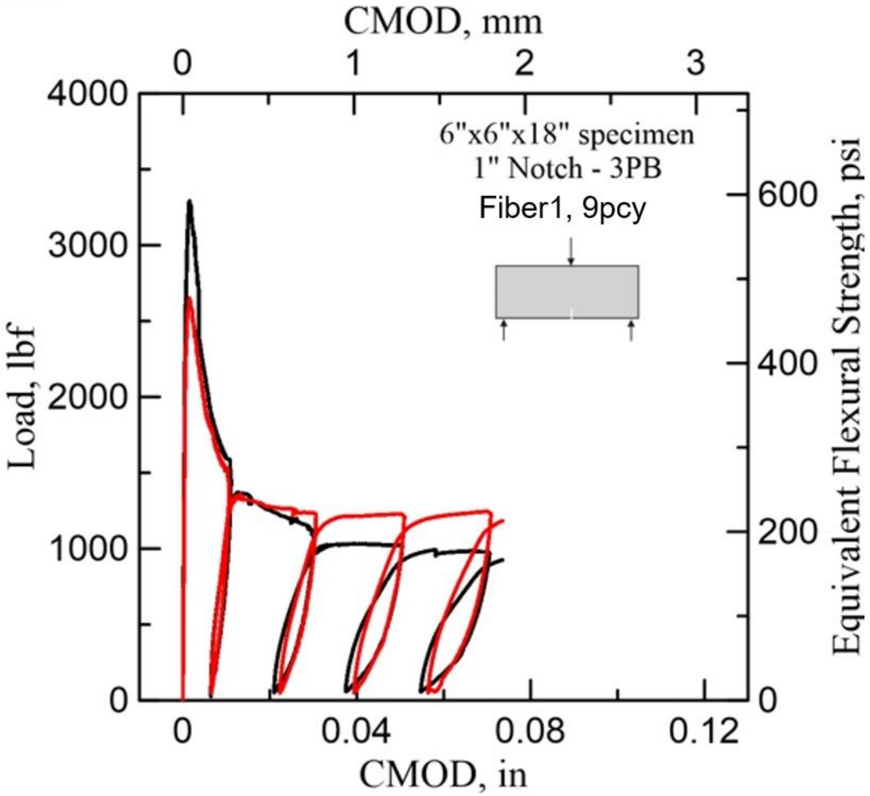


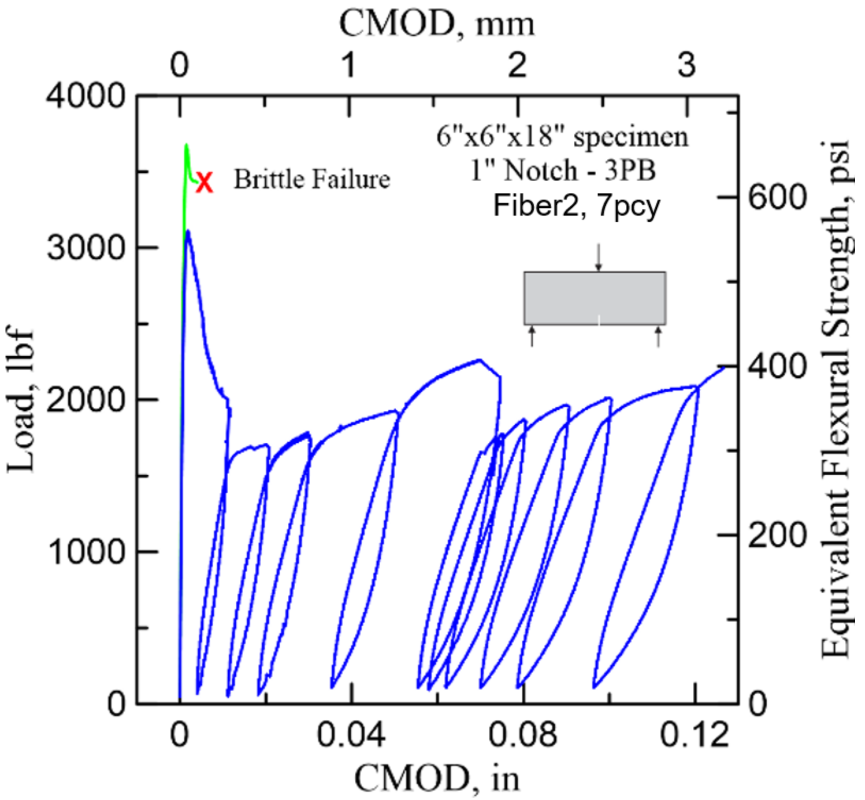


- Both samples show a relatively high flexural strength corresponding to a maximum load of 30,000 lbs, but a continuous decrease in the post-peak response since there are no rebars in these samples.

Cyclic Fracture Tests

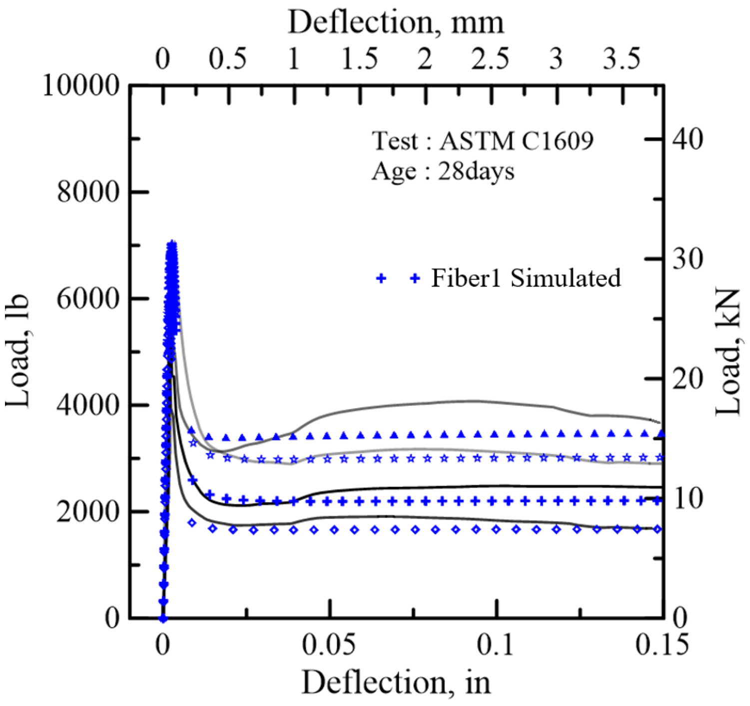
- Fracture tests were also conducted on small beams to study the fatigue resistance properties of fiber reinforced concrete

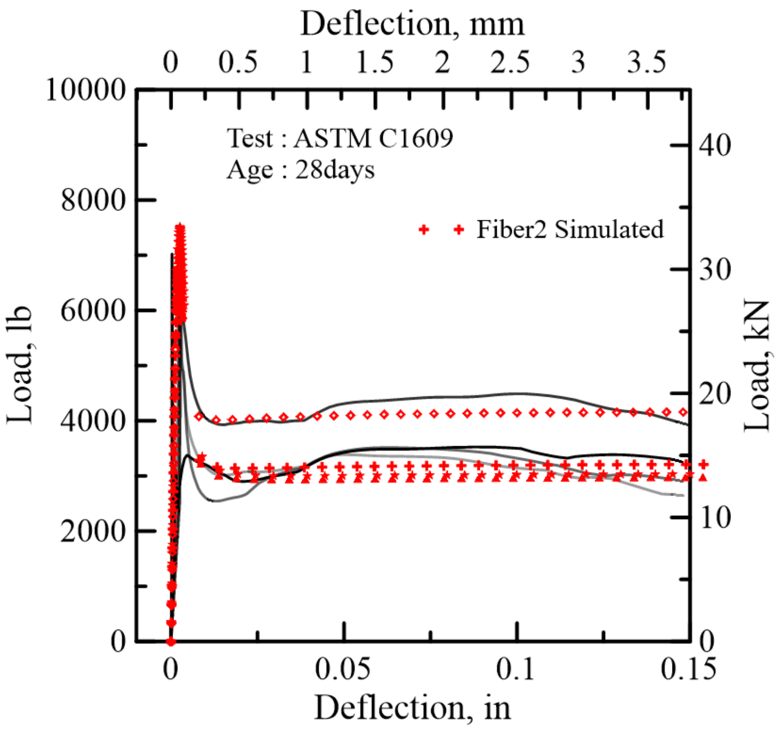


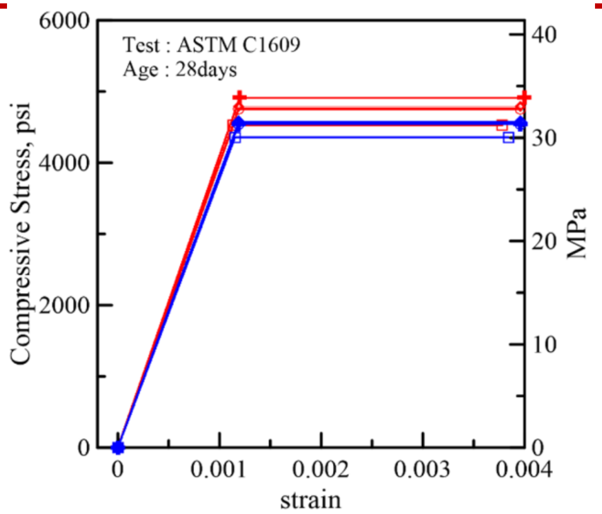


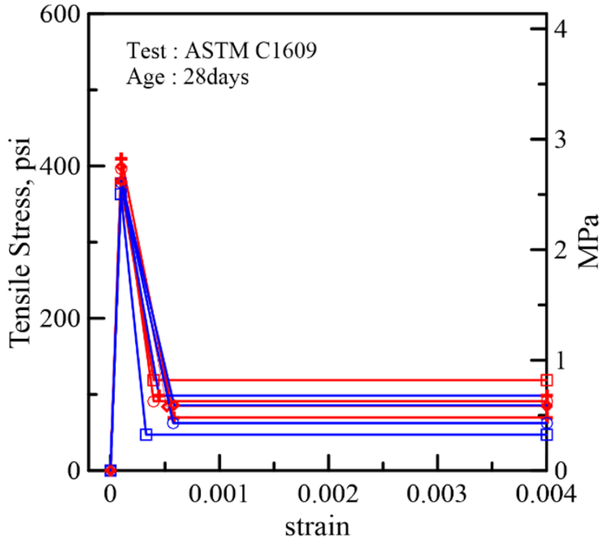
Simulation of Flexural Results

- Back-calculation procedure as per ACI 544.8R was used to extract stress-strain material properties that will be used for designing panels









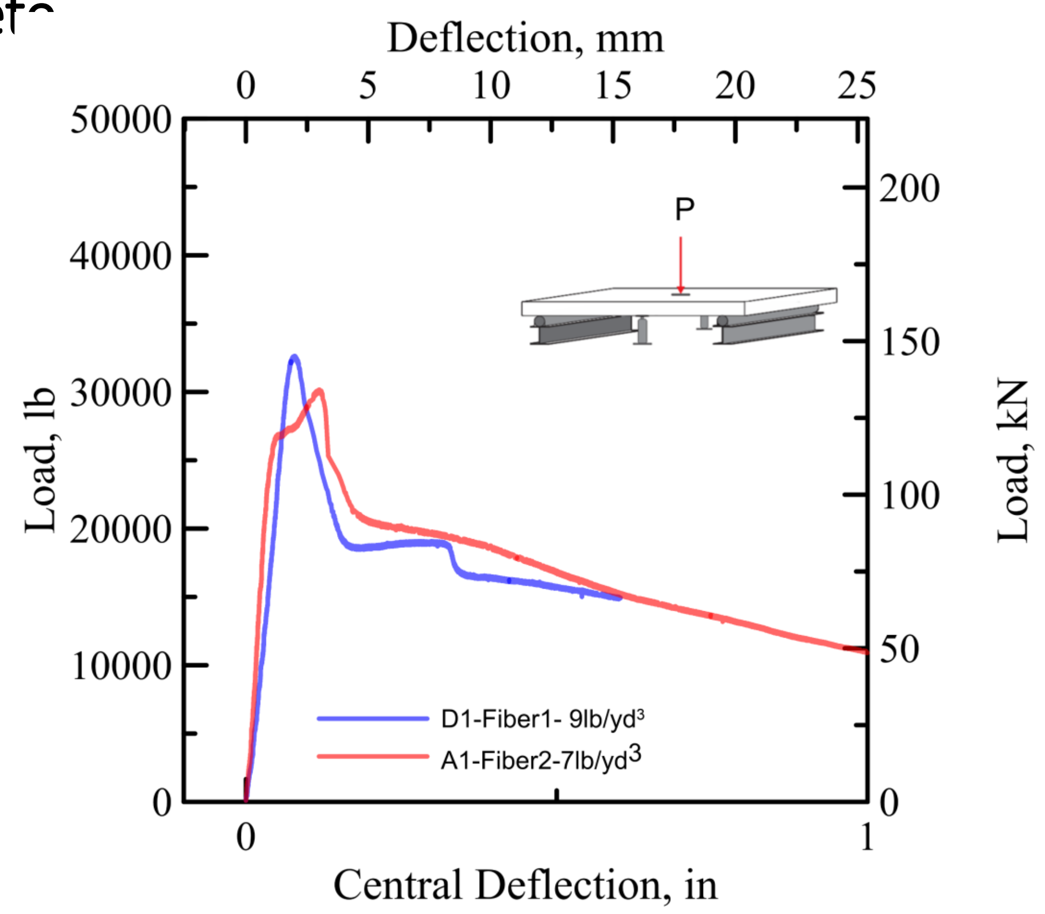
Discussion of Results

Compare Fiber1 vs. Fiber2 plain FRC performance **(id: A vs. D)**

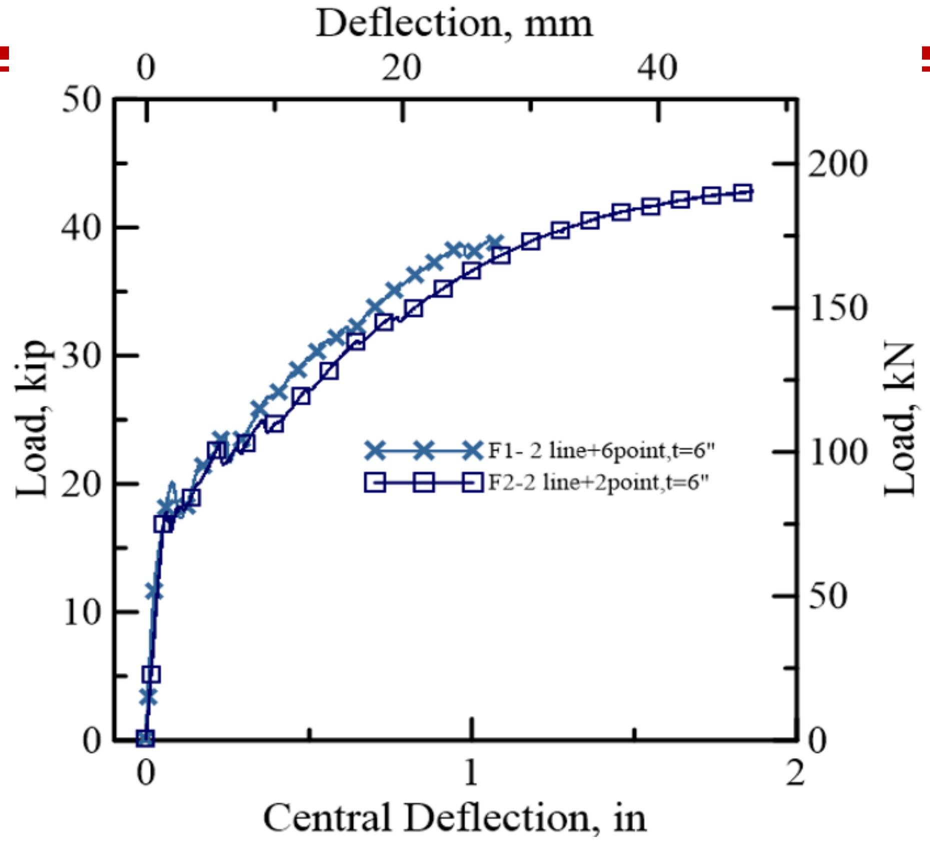
Effect of Fiber Type on Fiber reinforced concrete

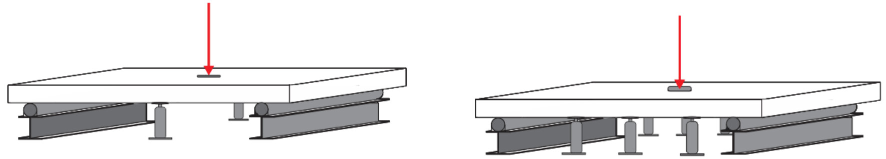
- Both samples show a relatively high flexural strength corresponding to maximum load of 30,000 lbs, but a continuous decrease in the post-peak response since there are no rebars in these samples.

- D1 panel shows higher strength at deflections above 0.75”. However, the performance of both the fiber types are similar as predicted by the flexural test results



Effect of the Boundary Conditions



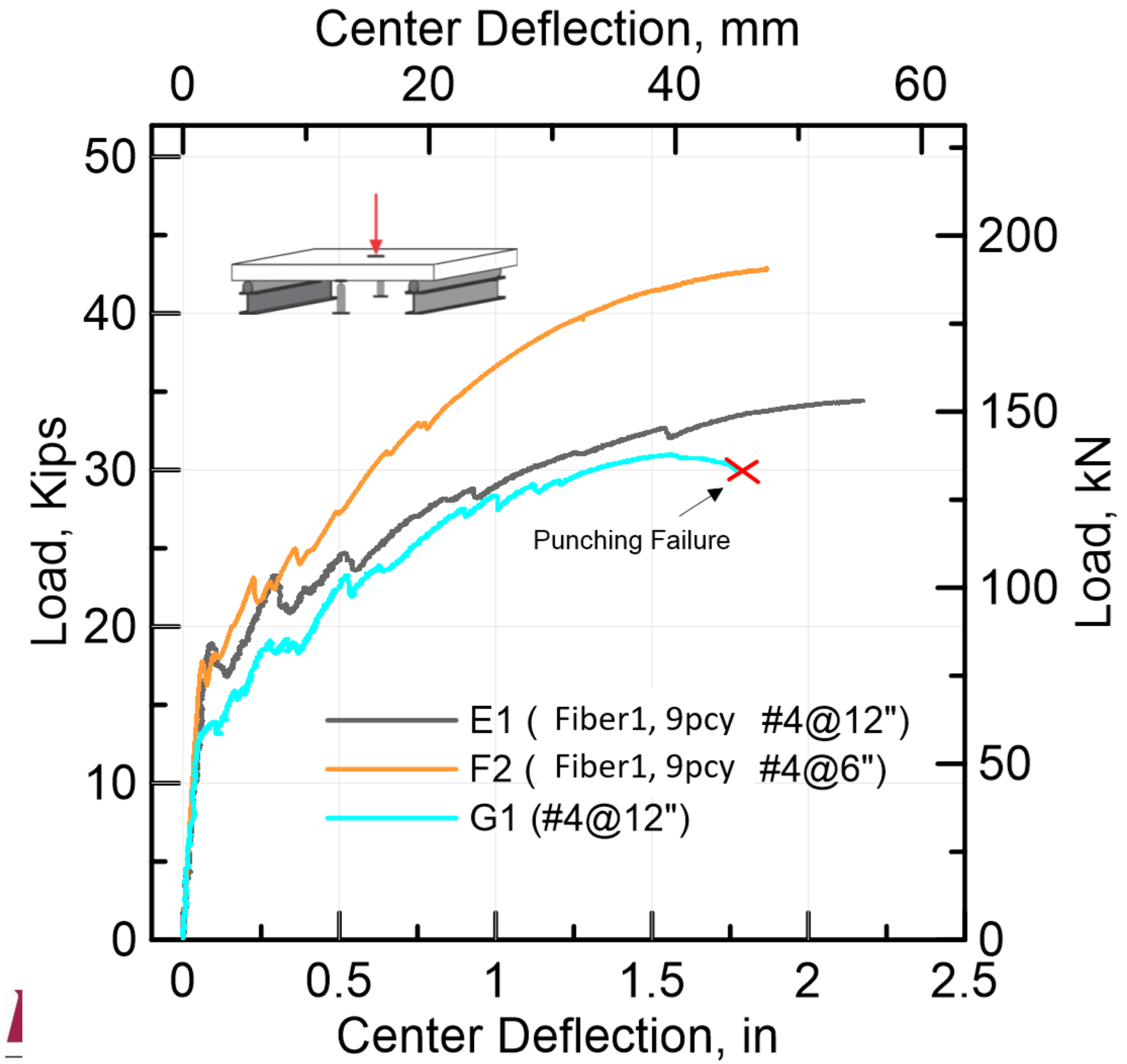


F2

F1 Bottom cracked zone

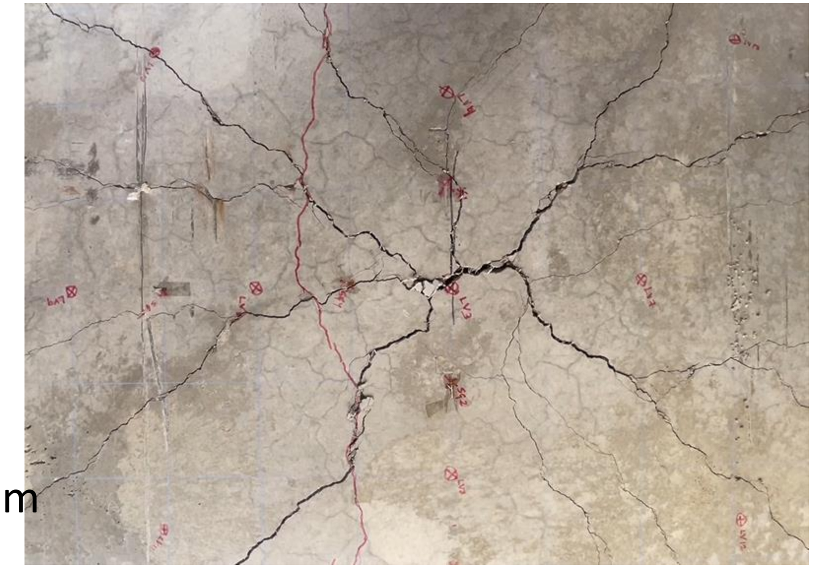
- The addition of 4 more point supports increases the loading capacity by only about 10% with increased number of cracks. The paths to cracking is quite similar

Central Load-Deflection Response in Hybrid RC vs RC

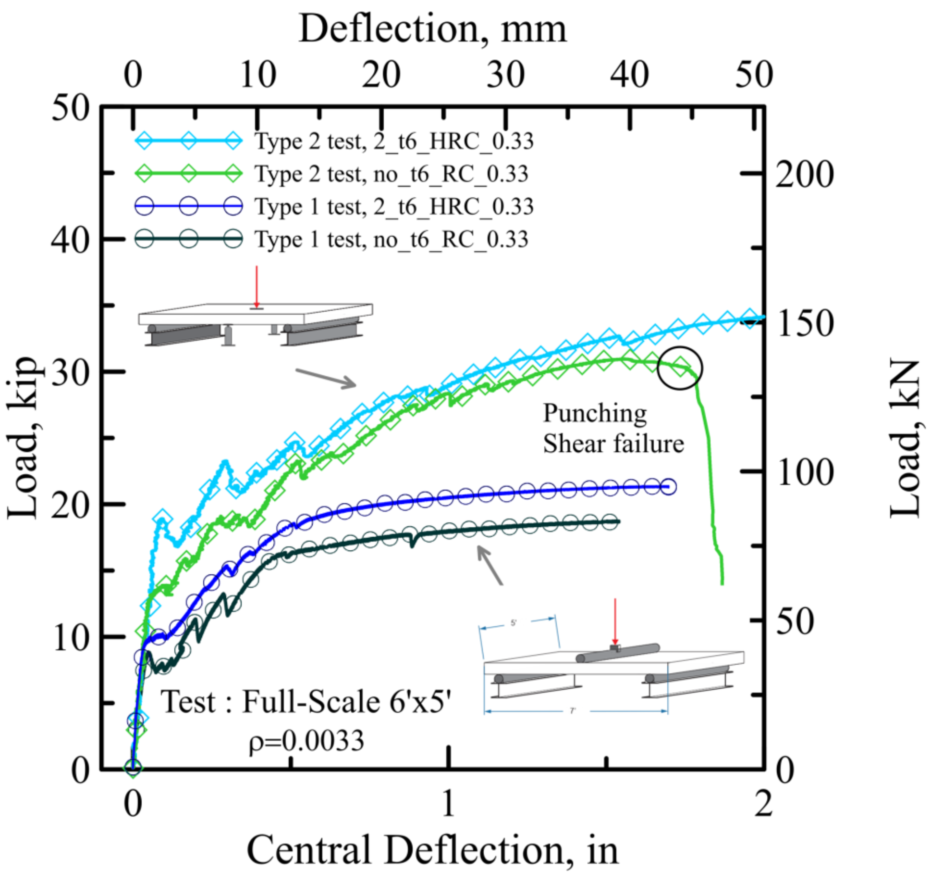


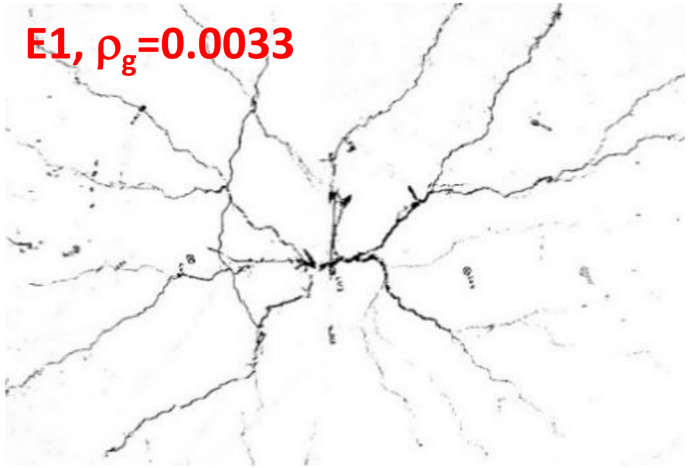
RC
Punching Failure observed in bottom cracks

Hybrid RC
Punching Failure observed in bottom cracks



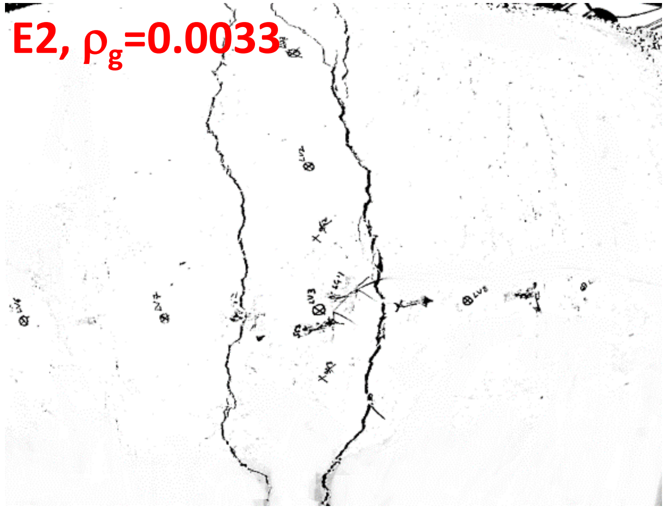
Central Load-Deflection Response in Boundary Conditions





Point load

Fan pattern +Yield Line pattern



3-point bending

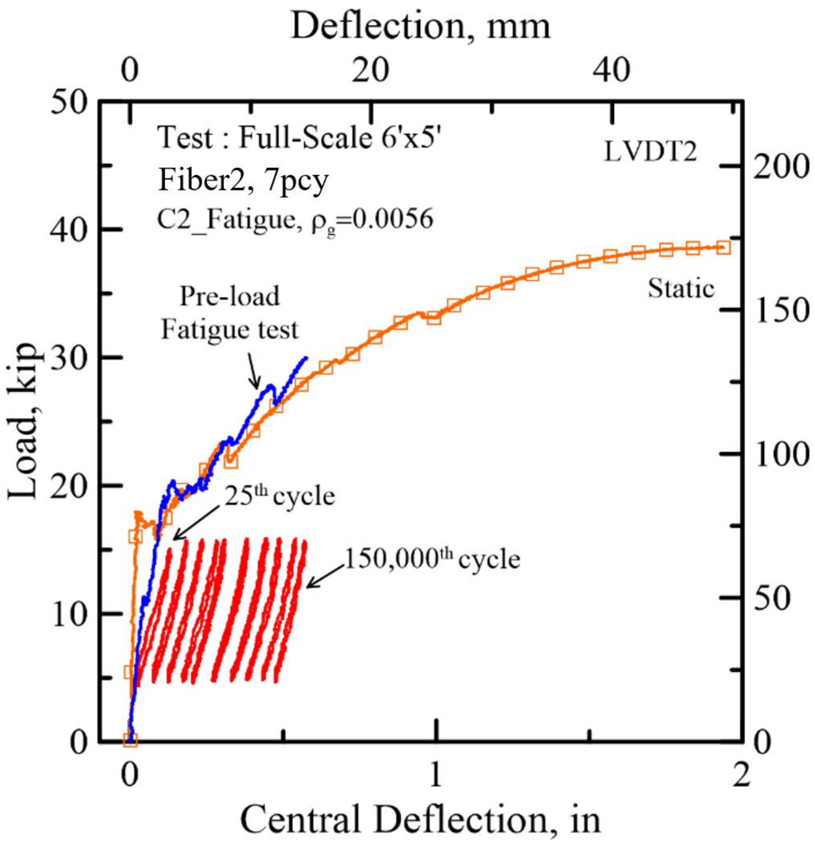
Crack Localization

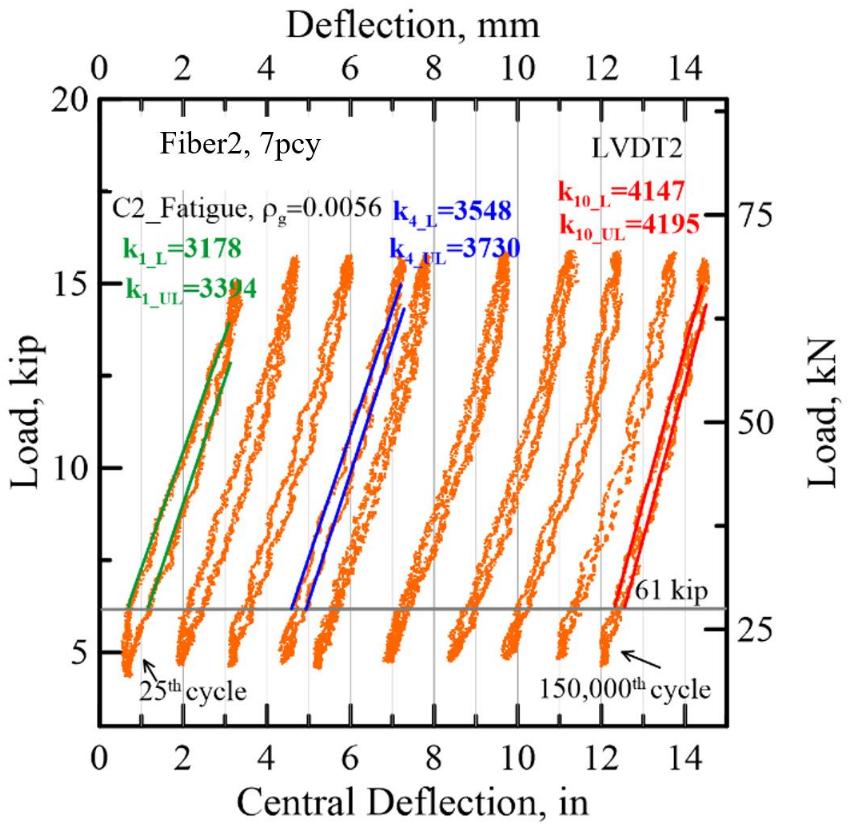
Fatigue tests in Hybrid RC

The panels were loading in a quasi-static condition to initiate cracking after which the panels were subjected to 150000 cycles of fatigue loading at 4Hz frequency.

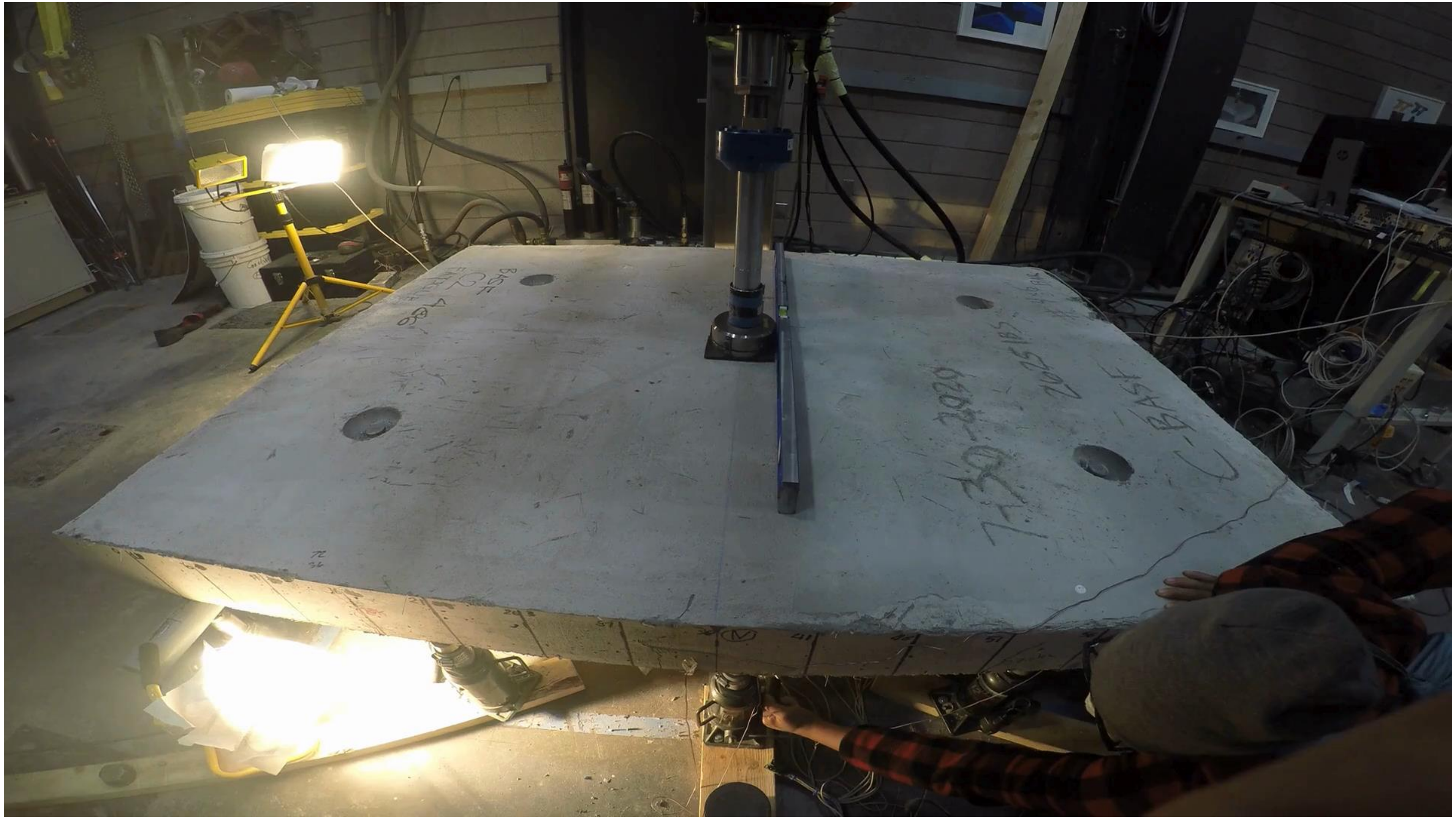
Hybrid RC
ρ =0.0056
Fiber = 7 lb/sq yd
t=15cm

The effect of fiber was pronounced after the fatigue test by increasing stiffness 28%



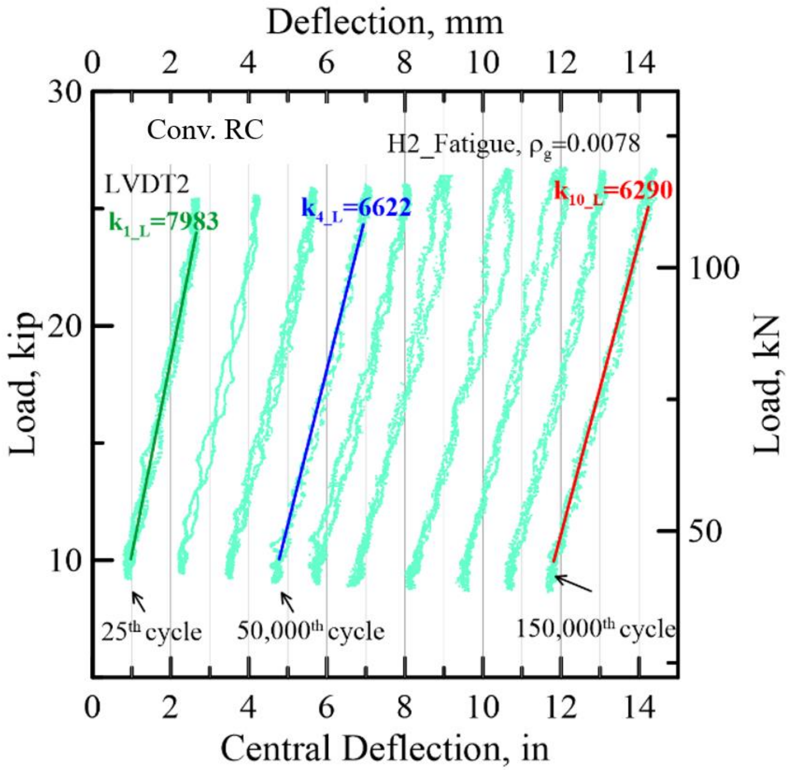


Fatigue test with 150000 cycles loading



Fatigue tests in RC vs FRC

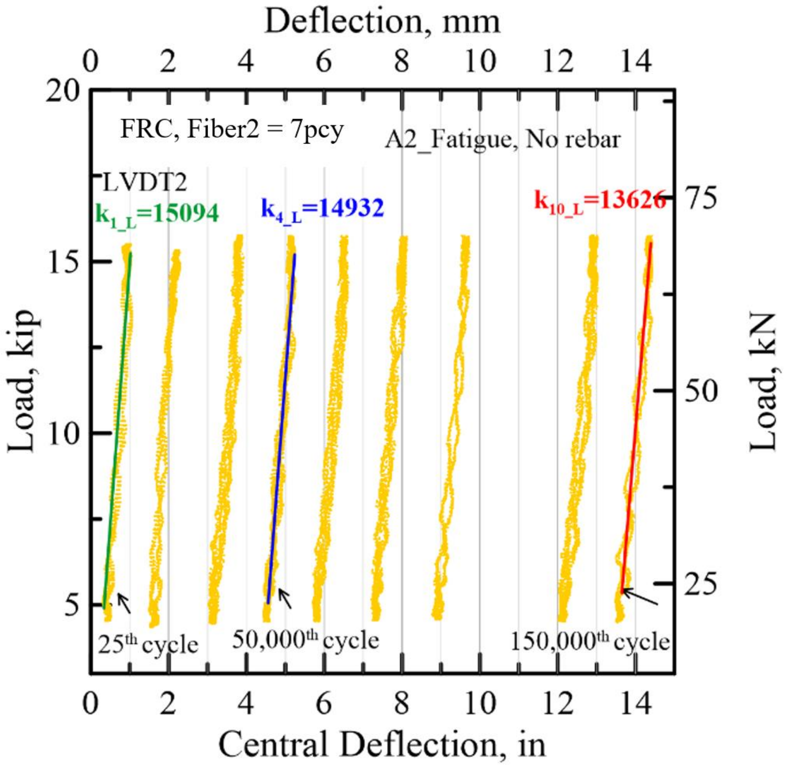
In the study of 150000 cycles of fatigue loading panels with no fibers show 20% reduction in stiffness, and whereas plain FRC panels showed 9.7% reduction in stiffness



RC

ρ =0.0078, t=20 cm

Stiffness
20% reduction ↓



FRC (no rebar)

Fiber = 7lb/sq yd, t =20cm

Stiffness
9.7% reduction ↓

Conclusion

•High Strength & Ductility: FRC and hybrid systems provide a strong case for service load capacity even after cracking.
•Effective Material Modeling: Small-scale tests helped predict full-scale performance using a tri-linear tension model.
•Scalable Model: This approach offers scalable solutions various design application
•Future Potential: Modeling extended to hybrid reinforcement strategies for structural serviceability engineering