High Strength Reduced Modulus Concrete for Railroad Crossties

Dimitris C. Rizos
Director of Advanced Railroad Technology Group
Department of Civil and Environmental Engineering University of South Carolina

William W. Hay Railroad Engineering Seminar

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

January 27, 2017

UNIVERSITY OF SOUTH CAROLINA
College of Engineering and Computing

THE UNIVERSITY OF SOUTH CAROLINA 1801

University of South Carolina - Overview

- **8 Campuses more than 45,000 students**
- **Location:** Columbia, S.C.
- **Organization:** 14 colleges and schools
- **Degree Programs:** more than 324
- **Enrollment:** more than 30,000 (Columbia)
- **Faculty:** approximately 1,560

Environmental Engineering

Transportation Engineering

Geotechnical Engineering

Water Resources Engineering

Structural Engineering & Mechanics

Railroad Engineering

Environmental Engineering

Transportation Engineering

Geotechnical Engineering

Water Resources Engineering

Structural Engineering & Mechanics

Railroad Engineering & the Advanced Railroad Technology Group

OBJECTIVES:

Nationally Recognized Research and Education Program

Nucleus of Excellence within CEE and USC to support industry

Promote Railroads in SC and the USA

The Team

Dimitris C. Rizos
Director
Infrastructure

Juan Caicedo
System Prognosis

Roger Dougal
Power & Controls

Robert Mullen
Reliability& Risk

Michael Sutton
Experimental Mechanics

Dave Clarke
Rail Transportation

Inthuorn Sasanakul
Geotechnical Engineering

Nathan Huynh
Operations & Logistics

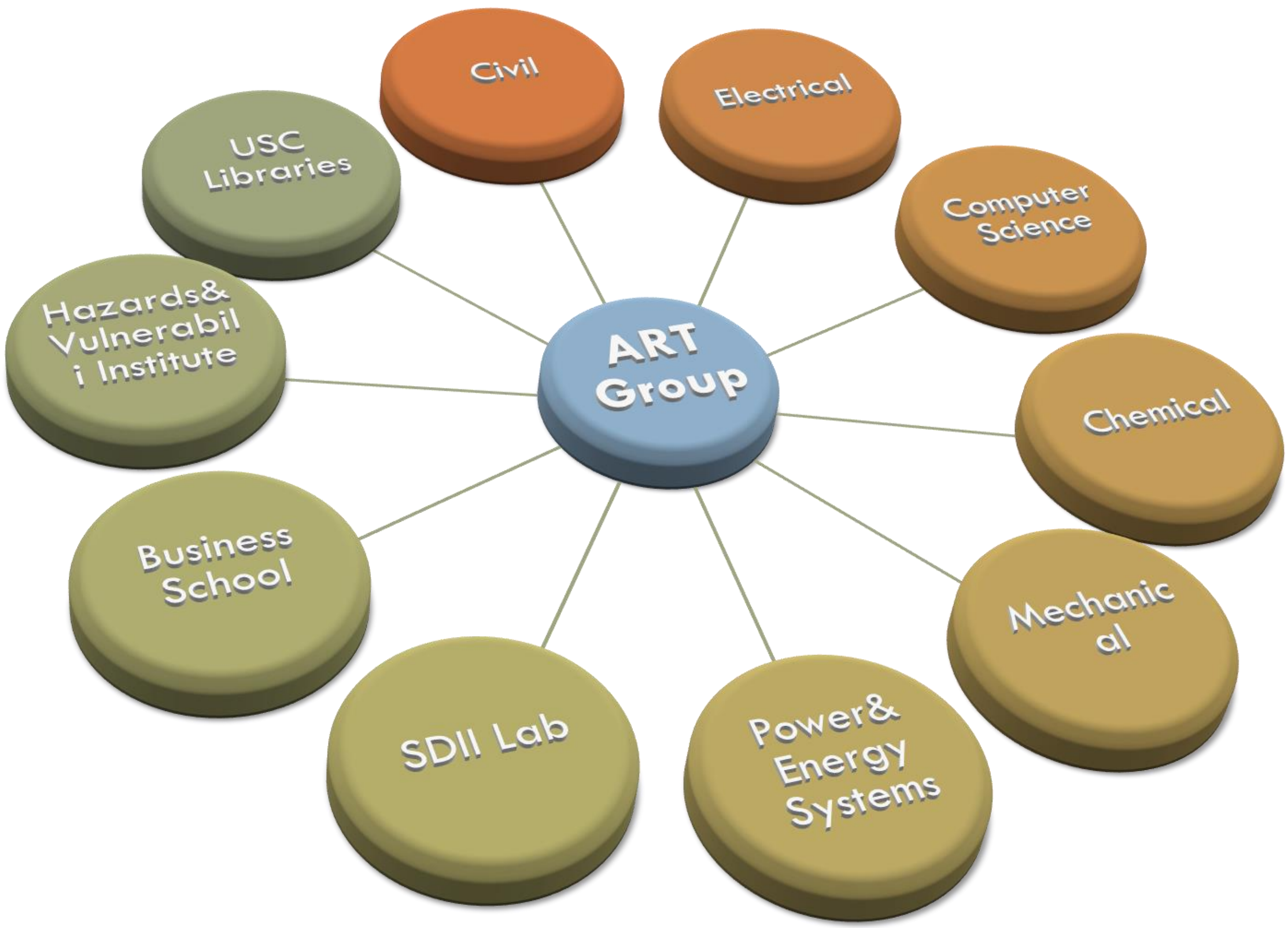
Michael Meadows
Hydraulics & Education

Dallas Richards
Education, Industry Liaison

Organization

- **Program Director** – Dr. Dimitris C. Rizos
  - Program Evaluation Advisory Group
  - **Group I** – Infrastructure
    - New Technologies Risk & Life Cycle Analysis
    - Railroad Track & Structures
    - Health Monitoring & Assessment
    - Geotechnical Engineering
  - **Group II** – Safety & Operations
    - Hazardous Materials Transportation by Railroad
    - Safety Management Systems
    - Operating Practices Passenger &Freight
  - **Group III** – Power, Signals & Communications
    - Railroad Signal Communications & Control
    - Advanced Rail Systems Technology
    - Electric Traction Power Systems
  - **Group IV** – Education & Student Relationships
    - Senior Design Project
    - Infrastructure
    - Operations
    - Multi Modal Networks

Technical Resources within USC



History of Railroad Engineering at USC

- **August 2008** HSR Vibrations (NSF)
- **June 2010** REES Workshop
- **Fall 2010** Course on HSR Dynamics / Railway Dynamics
- **August 2011** **A**dvanced **R**ailway **T**echnology **G**roup

History of Railroad Engineering at USC

Aug. 2011

ART Group

Fall 2011-Spring 2014
Curriculum Development & Student Recruitment

Fall 2012-date
Research Program Development

Industry Liaisons

2015-date
Graduate Certificate, ME, MSc, PhD

Courses Offered At a Glance

Course	Fall	Spr	Smr
ECIV 789: Design Project-Railroad Engineering		●	
ECIV 580: Infrastructure Planning and Design	●		
ECIV 581: Infrastructure Maintenance and Inspections	◌		
ECIV 582: Operations and Logistics		●	
ECIV 588: Analysis & Design of Railroad Bridges	●		
ECIV 784: Dynamics of Railway Systems		●	
ECIV 797: Multimodal Transportation Systems	●		
ECIV 707: Management of Engineering Projects			●
ECIV 708: Risk Analysis of Engineering Applications			●
MGMT 718: Management of Human Resources		●	

Over 250 students attended classes in the last 3 years

Course Delivery

APOGEE

A Program of Graduate Engineering Education

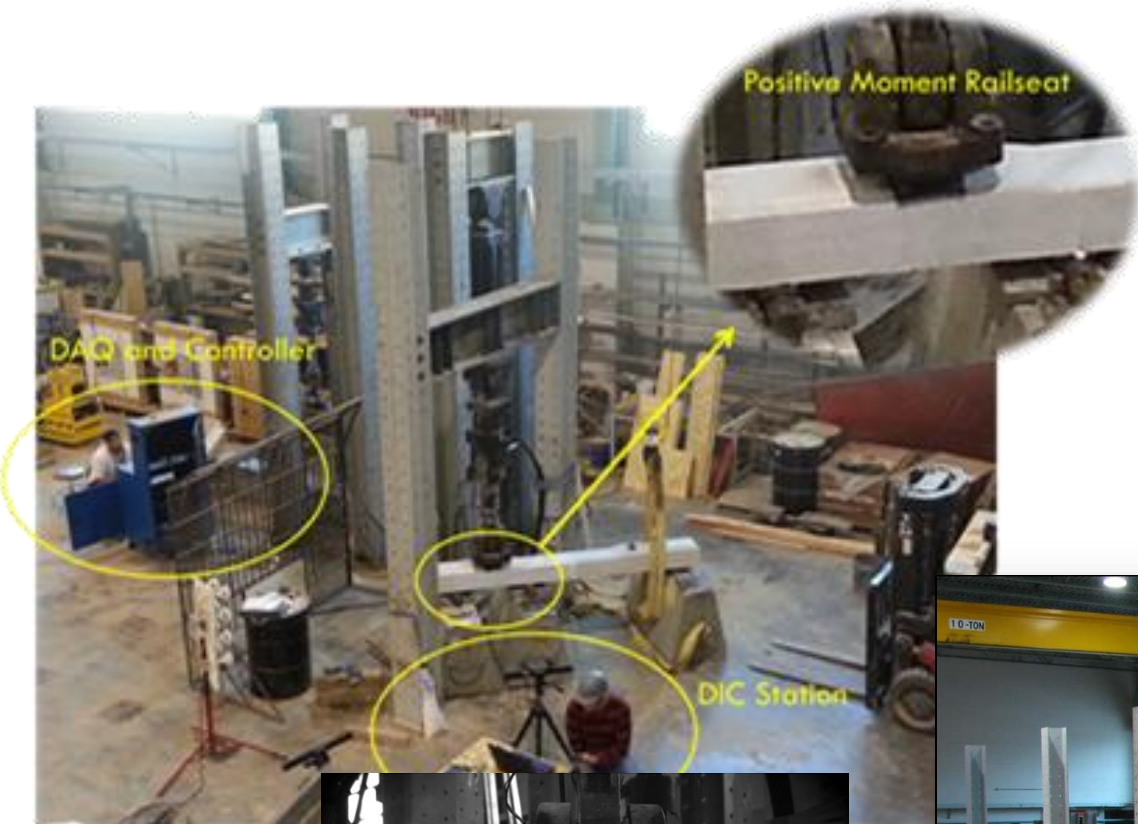
Help engineering professionals earn graduate credit/degree while maintaining full-time employment and without the constraints of on-campus attendance.

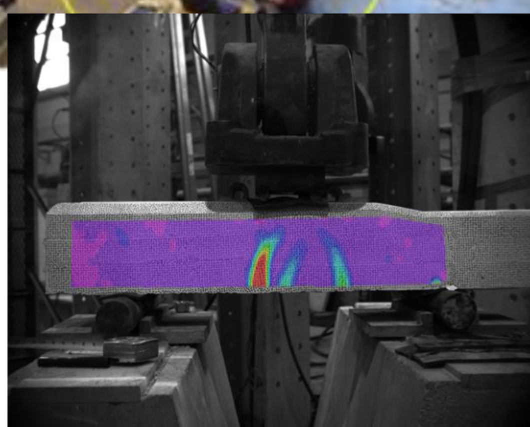
Allows instructors to deliver lectures from anywhere in the world

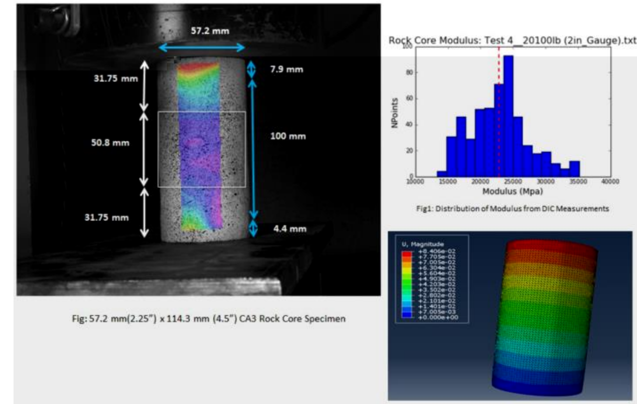
Facilitates the development of shared curricula

US News & World Report has awarded our APOGEE program "Best Online Programs Graduate Education 2013" with a rank of 28 in the nation.

Research Facilities



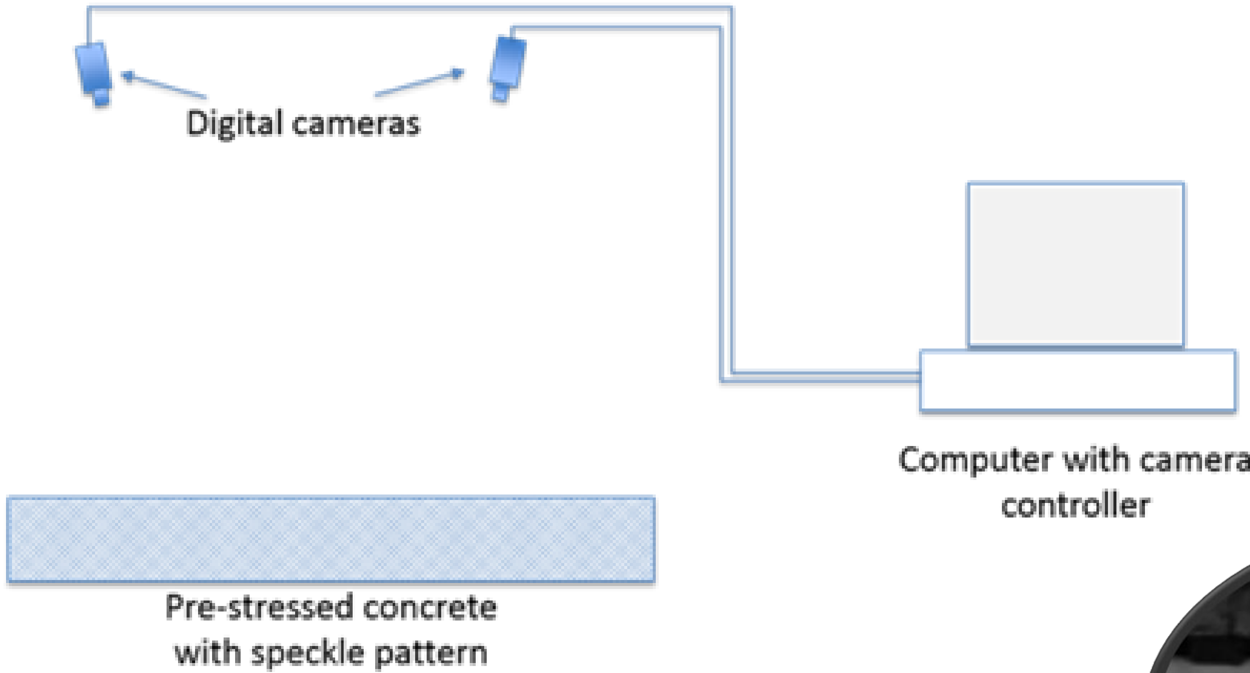


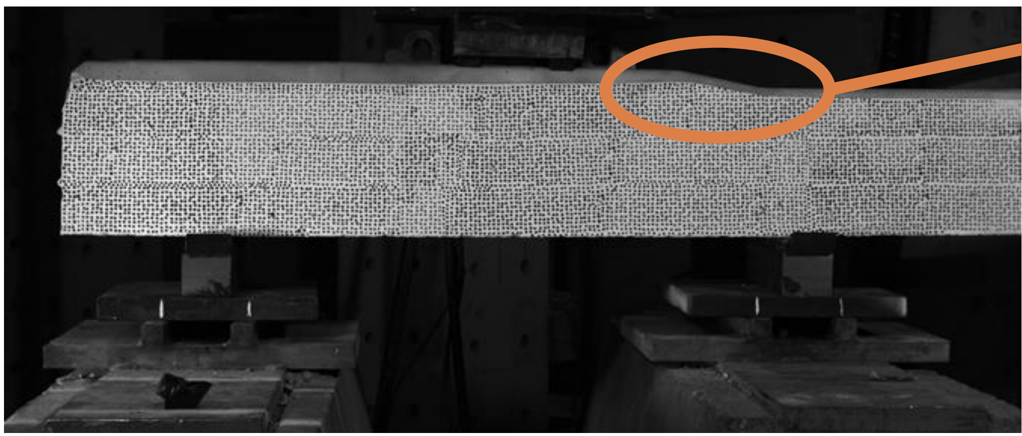


Vision System Development for Full Field Measurements

- 2D and 3D Systems Developed at the University of South Carolina over the last 30+ years
- Proven technology successfully applied to other industries
- Typical 3D System: 2 cameras and a computer setup
  - VIC-3D software by Correlated Solutions is used

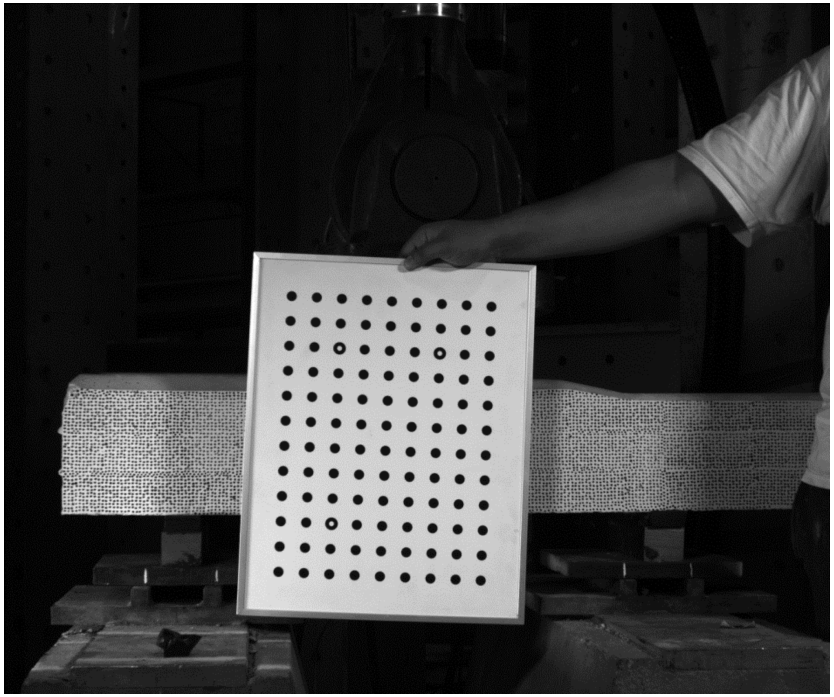
Vision System Development





Vision System Development

- System Calibration (50-100) images



Project

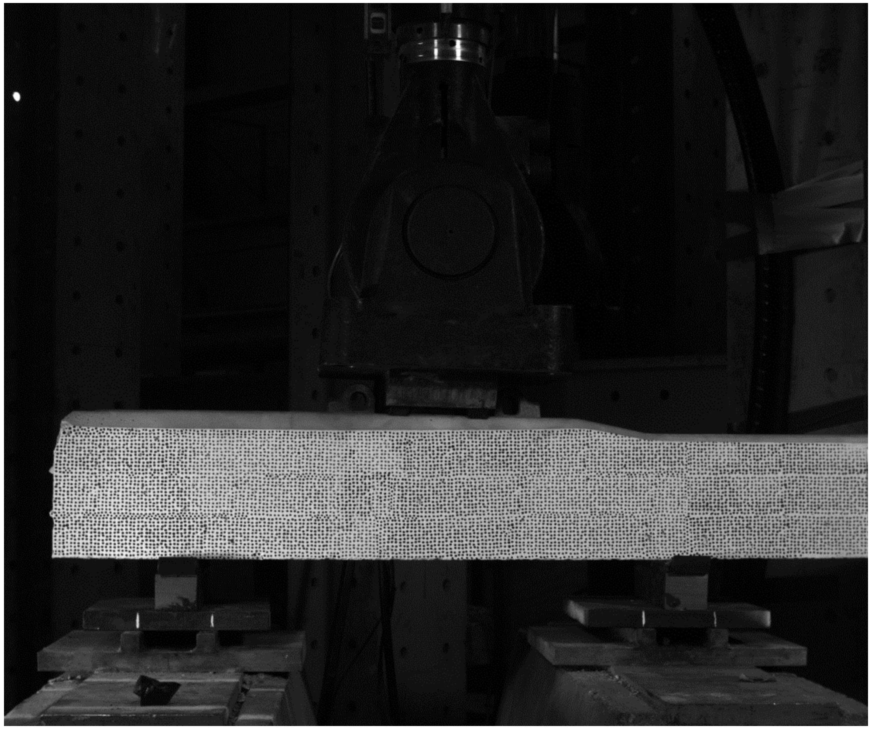
Images | Data | Calibration

- Camera 1
  - Center x: 1686.41 pixel
  - Center y: 1331.03 pixel
  - Focal length x: 4795.94 pixel
  - Focal length y: 4799.28 pixel
  - Skew: -2.19237
  - Kappa 1: -0.16001
  - Kappa 2: 0
  - Kappa 3: 0
- Camera 2
  - Center x: 1682.76 pixel
  - Center y: 1296.27 pixel
  - Focal length x: 4761.49 pixel
  - Focal length y: 4764.16 pixel
  - Skew: -1.57112
  - Kappa 1: -0.16609
  - Kappa 2: 0
  - Kappa 3: 0
- Transformation
  - Alpha: 0.520279 deg
  - Beta: -3.09018 deg
  - Gamma: 0.764269 deg
  - Tx: 110.27 mm
  - Ty: 1.25525 mm
  - Tz: 2.64961 mm
  - Baseline: 110.309 mm

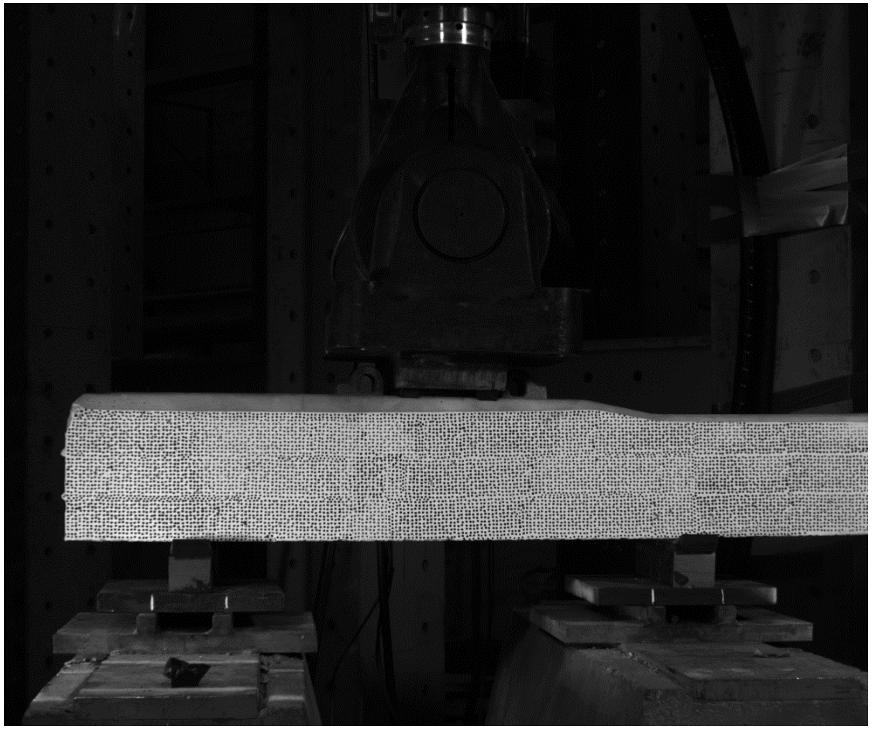
Vision System Development

Take initial set of images before load is introduced SET 0

Left Camera – Set 0

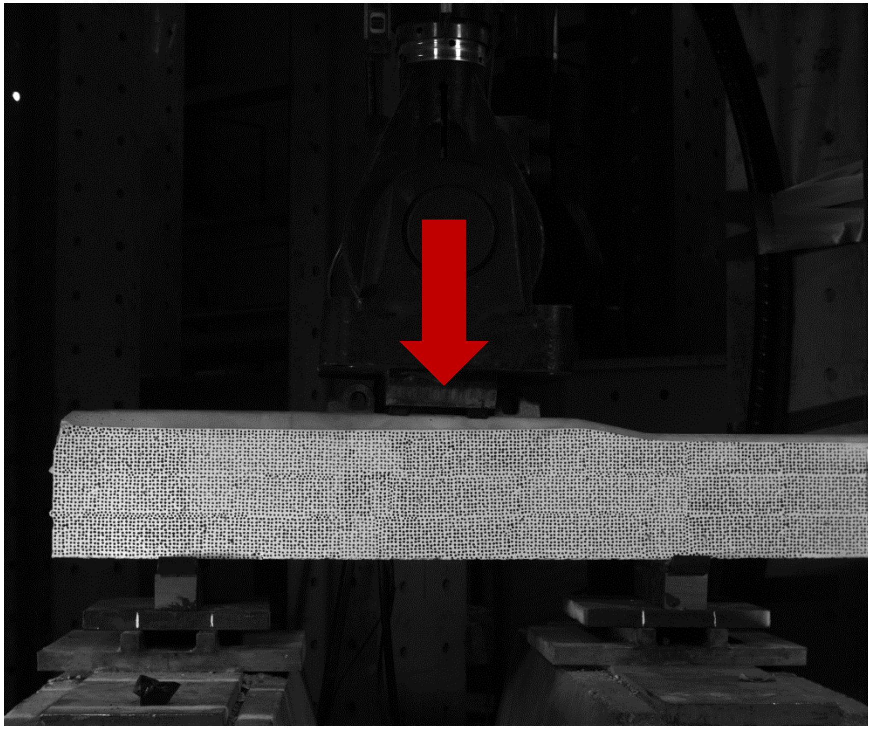


Right Camera – Set 0

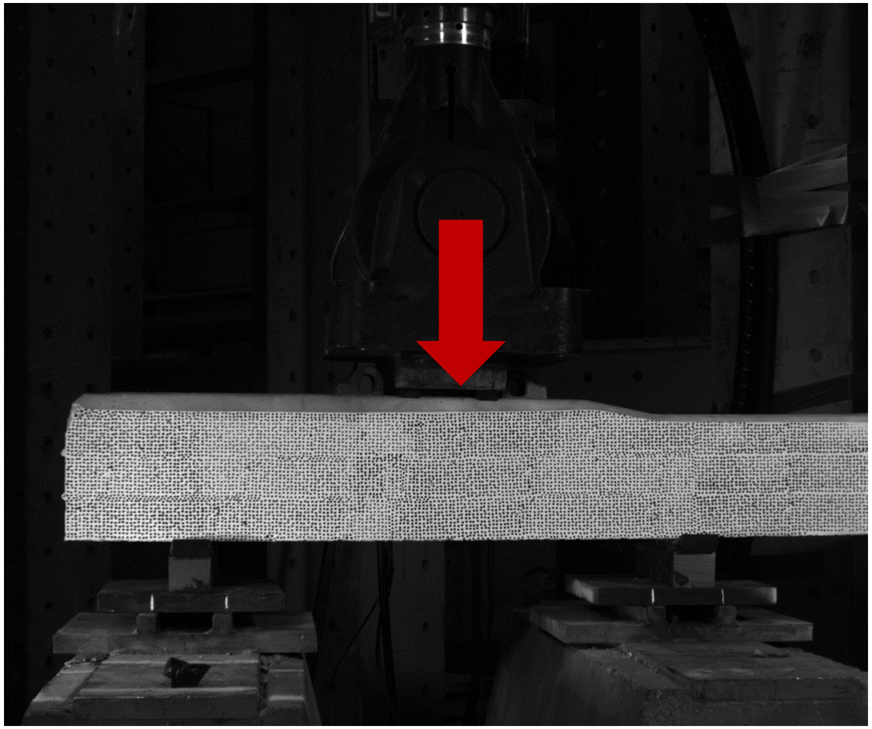


Load specimen

Left Camera



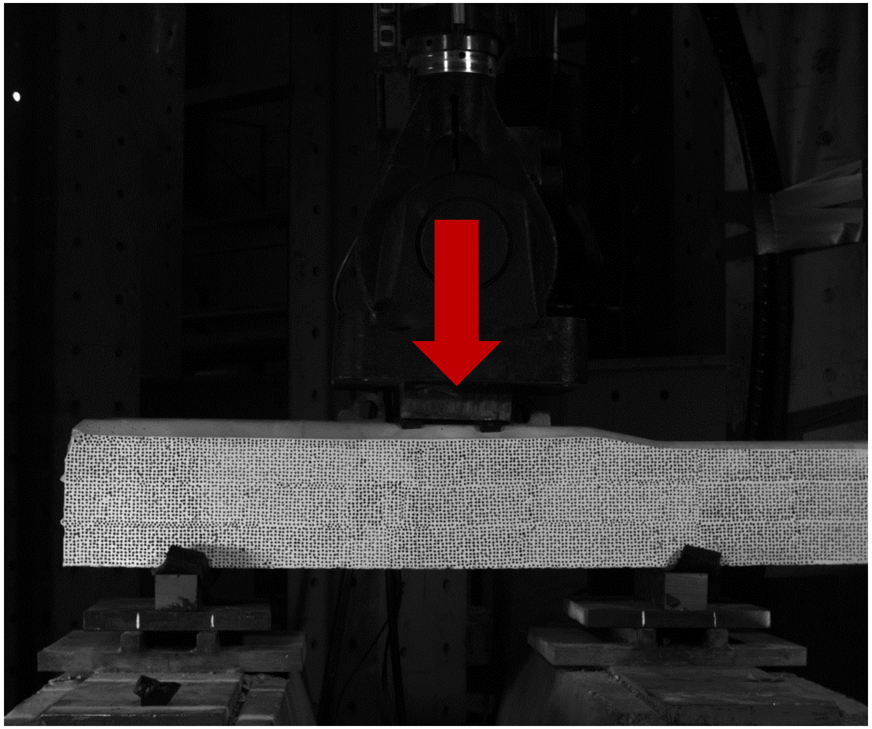
Right Camera



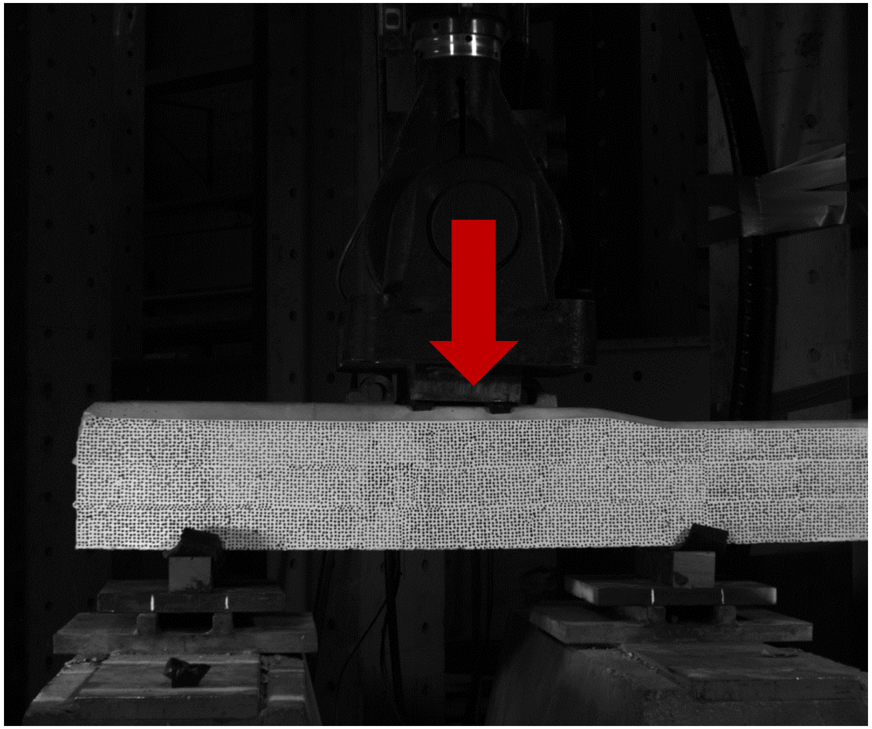
Vision System Development

Take another set of images after load is applied SET 1

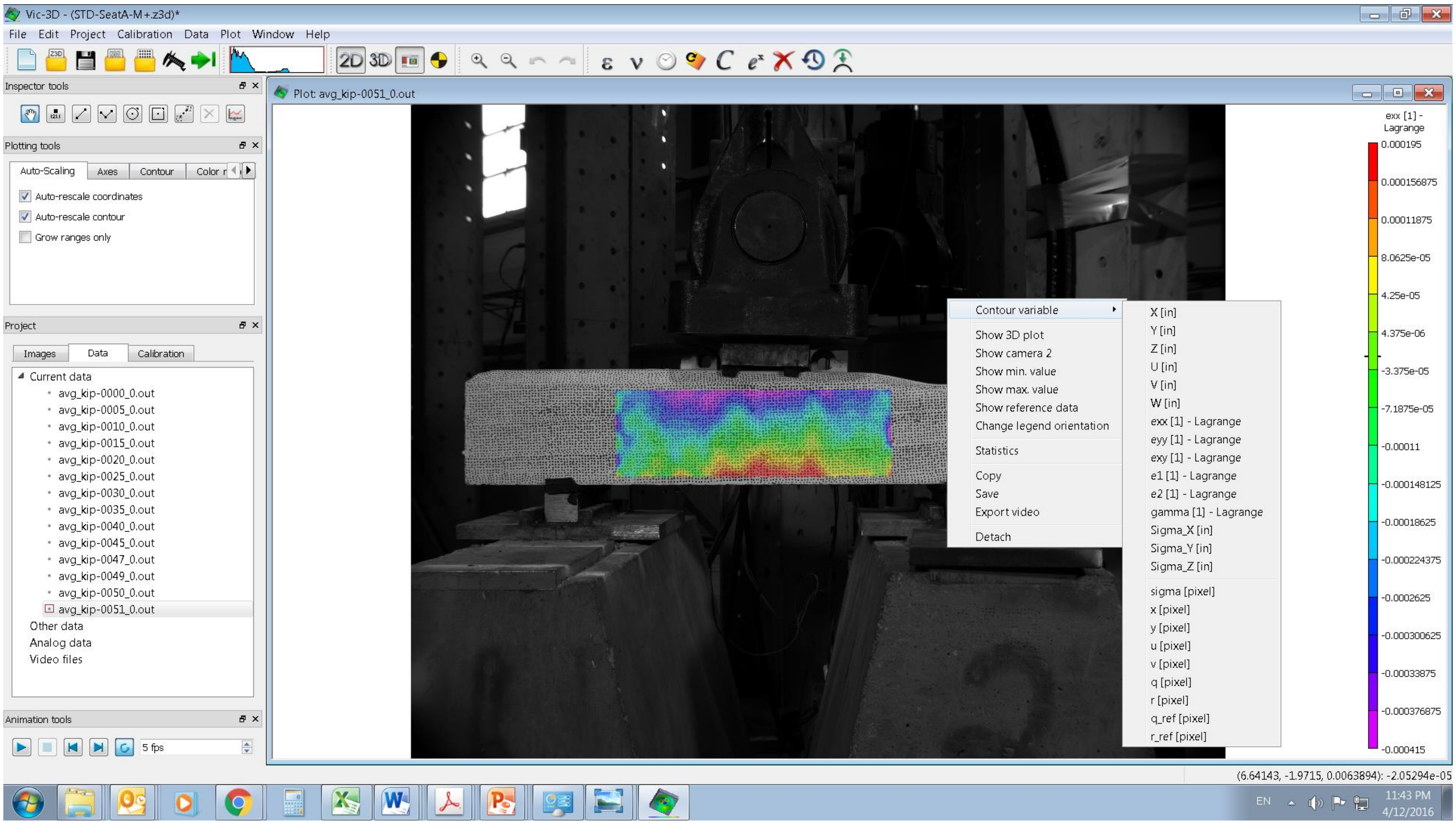
Left Camera – Set 1



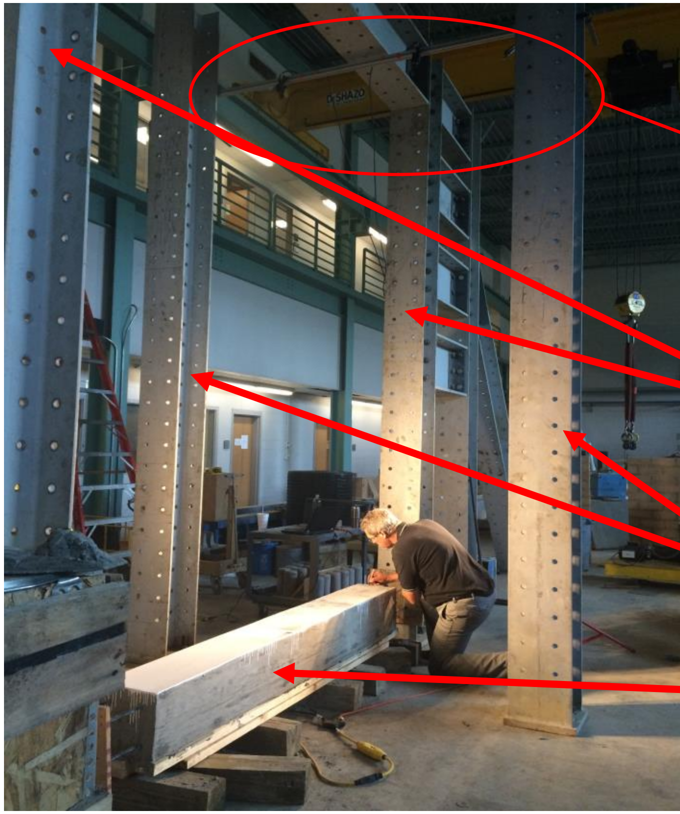
Right Camera – Set 1



Compute 3-D displacement and strain fields through image correlation of two sets



System Verification in Laboratory



Strong-back for pretensioning of cables

Columns of Camera Frame

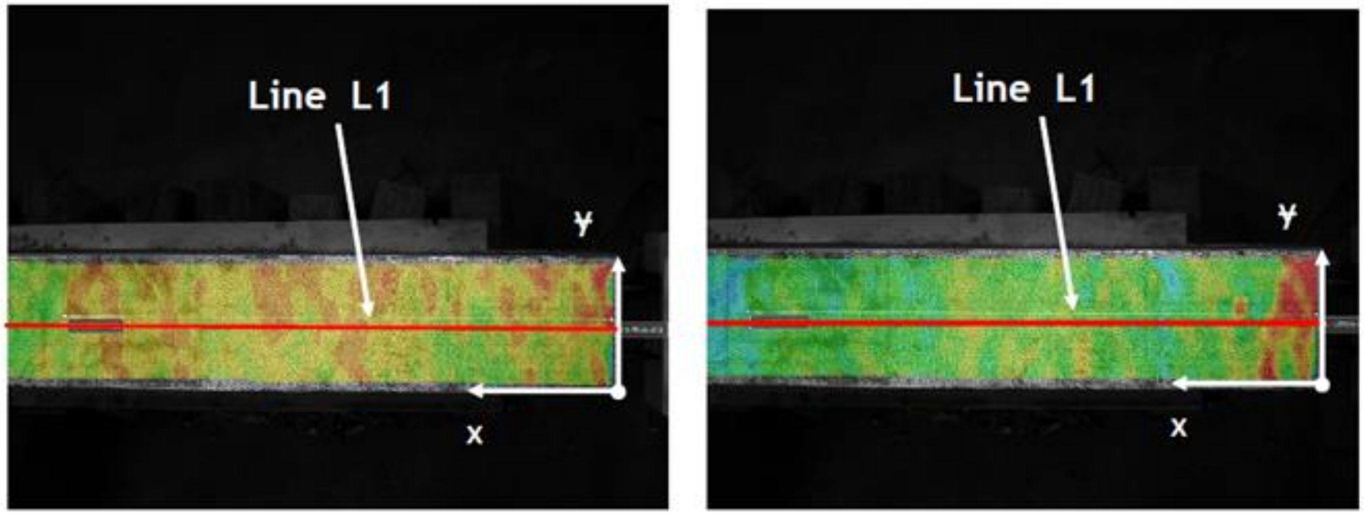
Prestressed Prismatic Beams
2.4m X .3m X .3m

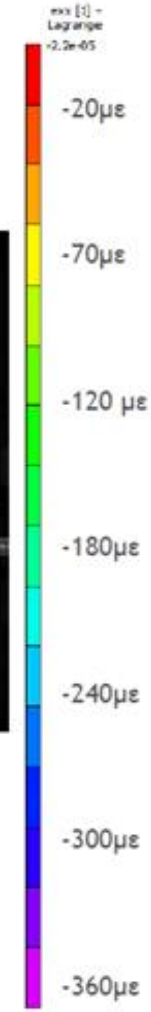
System Verification in Laboratory

Laboratory Specimens

Flame cut

Flame Cut - Axial Strain Results





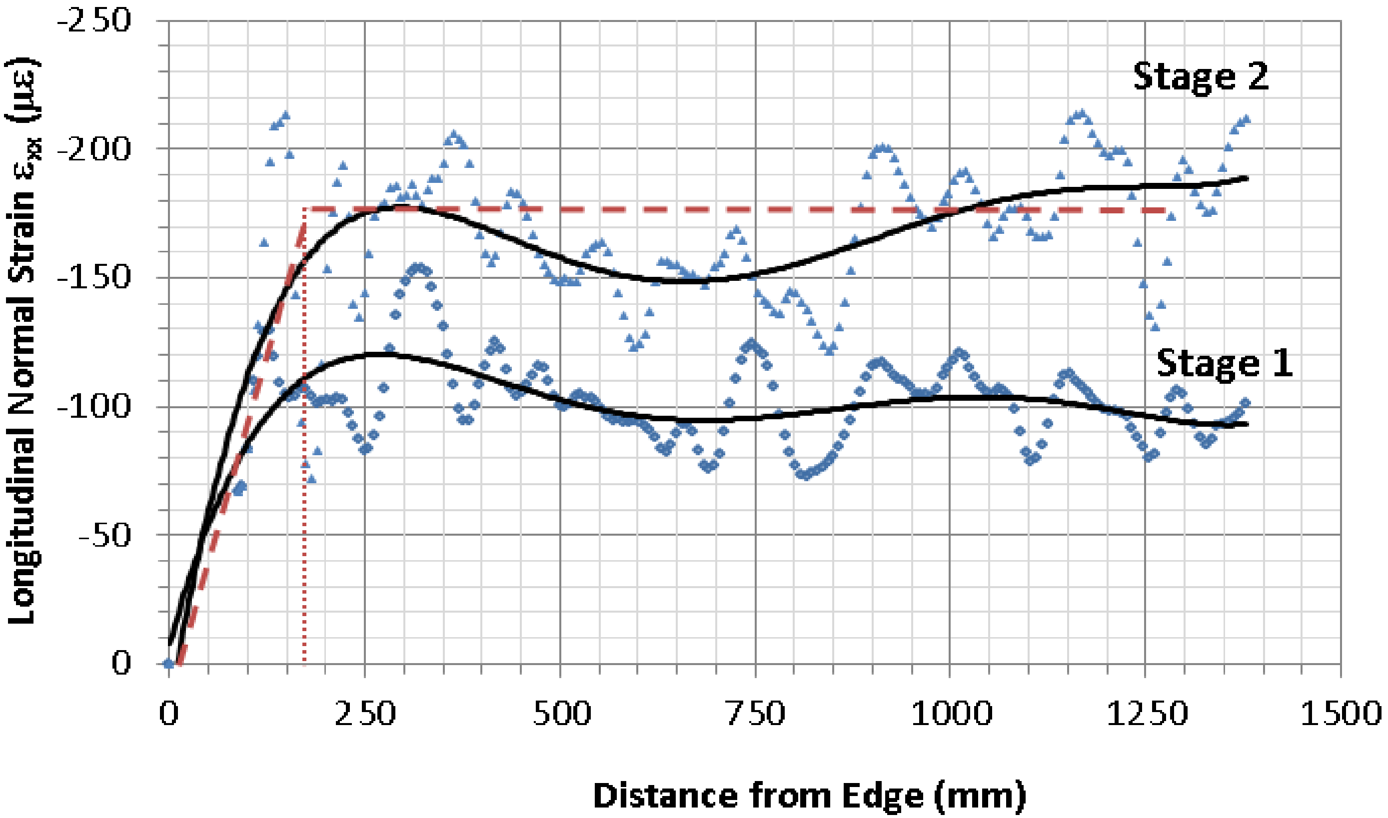
Top Two Cut

Avg strain: -110με

All Four Cut

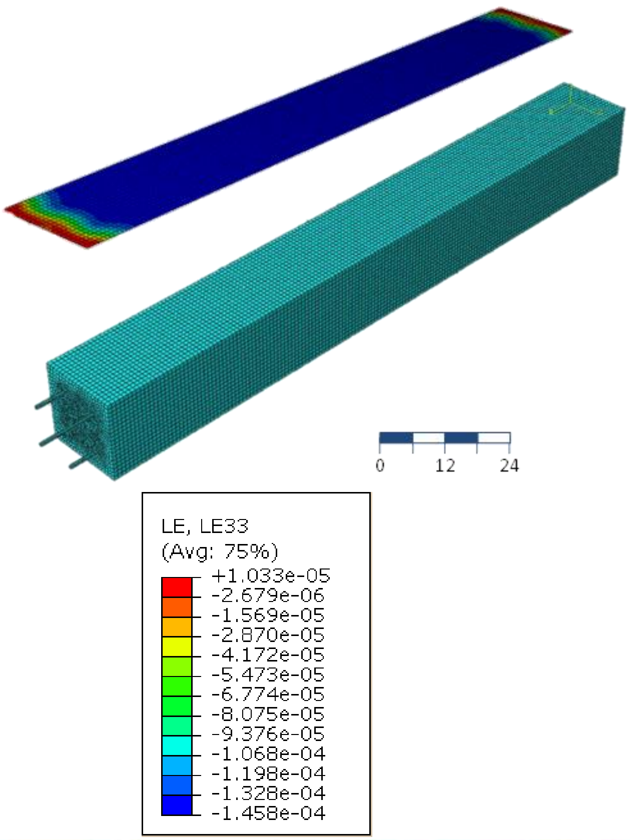
Avg strain: -180με

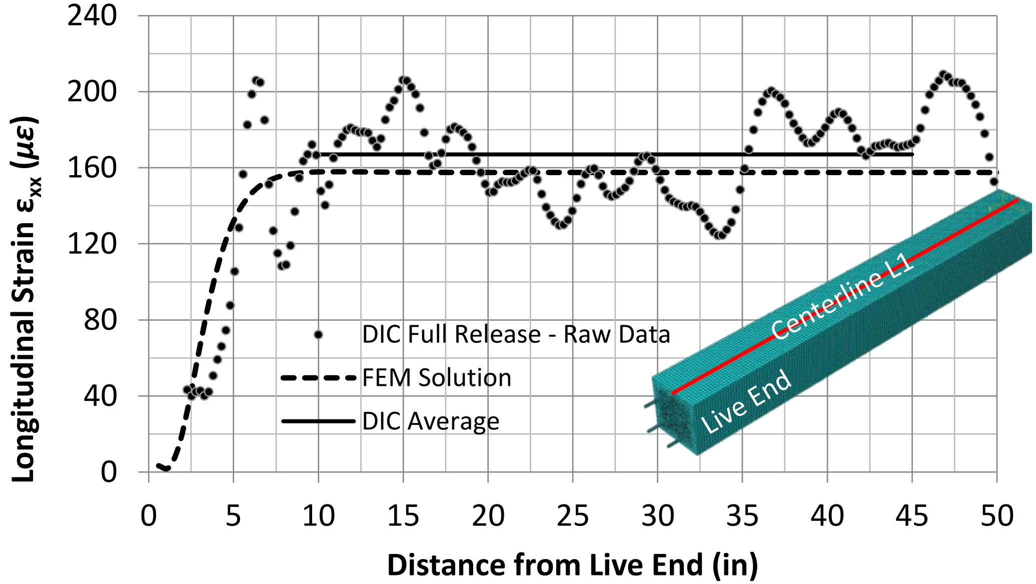
System Verification in the Laboratory

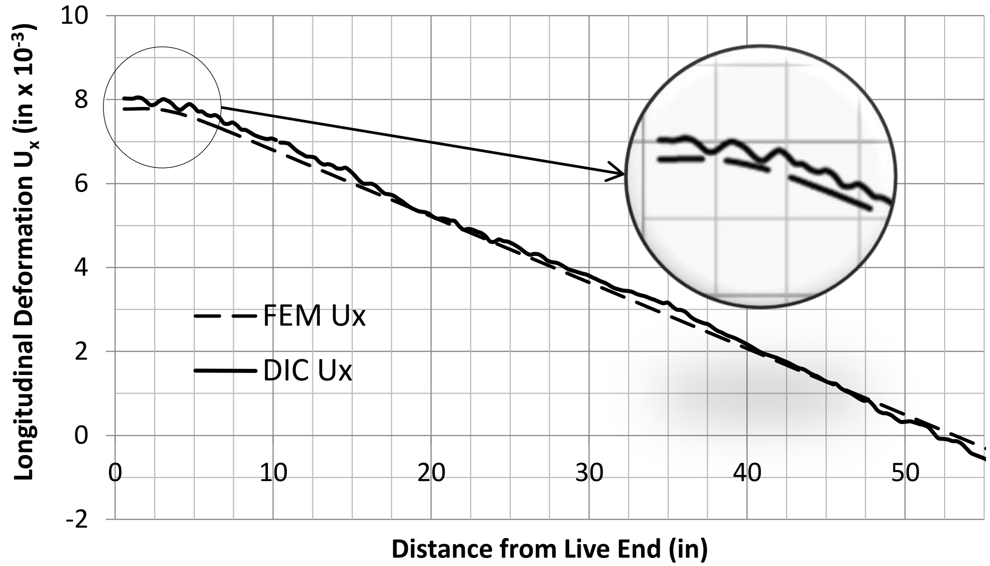


Verification of results with strain gage measurements

System Verification in Laboratory







Design of High Strength Low Modulus Concrete Crossties

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Outline

- Historical Background
- Hypothesis
- Material Development and Characterization
- Prototype Tie Design and Fabrication
- Product Qualification
- Benefits
- Conclusions

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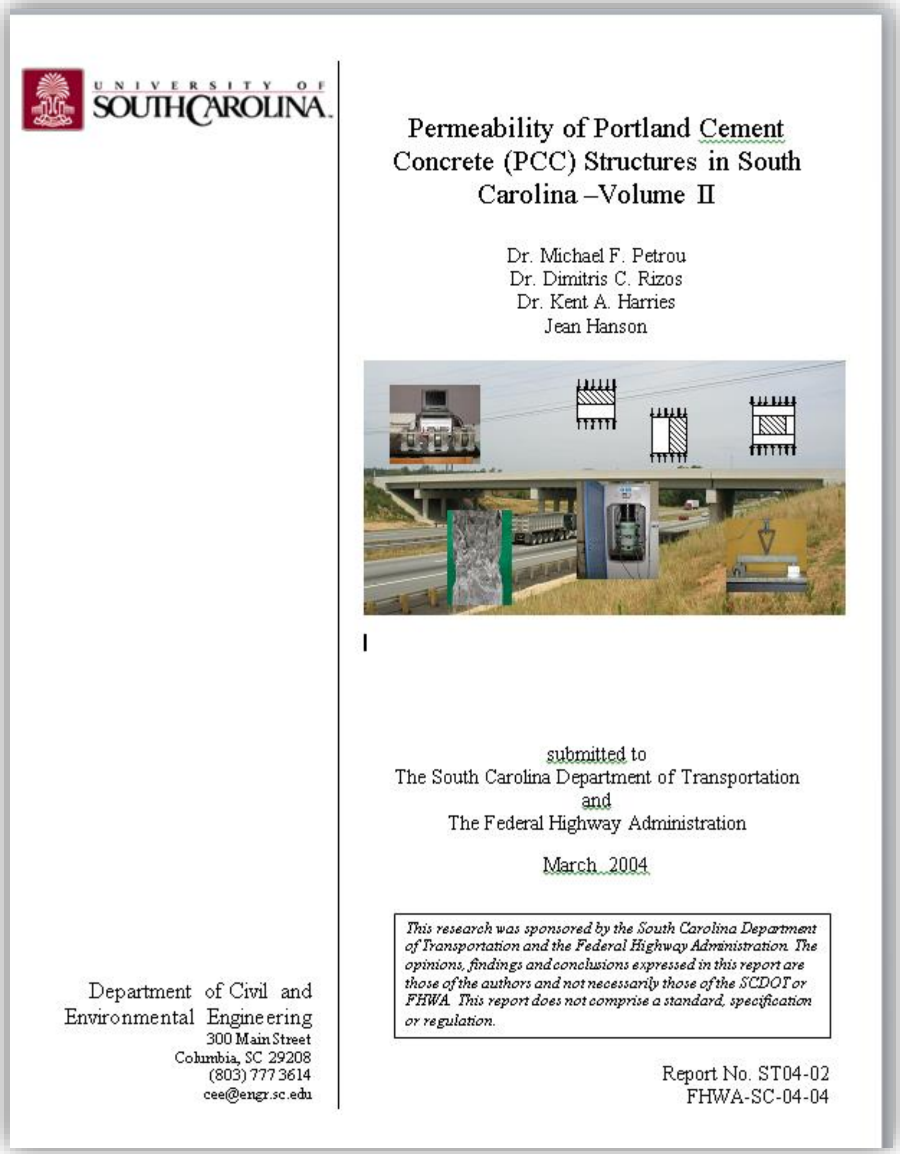
Historical Background



UNIVERSITY OF SOUTH CAROLINA

Permeability of Portland Cement Concrete (PCC) Structures in South Carolina –Volume II

Dr. Michael F. Petrou
Dr. Dimitris C. Rizos
Dr. Kent A. Harries
Jean Hanson

submitted to
The South Carolina Department of Transportation
and
The Federal Highway Administration

March 2004

This research was sponsored by the South Carolina Department of Transportation and the Federal Highway Administration. The opinions, findings and conclusions expressed in this report are those of the authors and not necessarily those of the SCDOT or FHWA. This report does not comprise a standard, specification or regulation.

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Report No. ST04-02
FHWA-SC-04-04

SCDOT Research Project

- HPC for Highway Bridges
- Local Aggregates
- SCDOT Mixture Designs

Table 2.1 Grades of Performance Characteristics for High Performance Structural Concrete (Goodspeed et al., 1996)

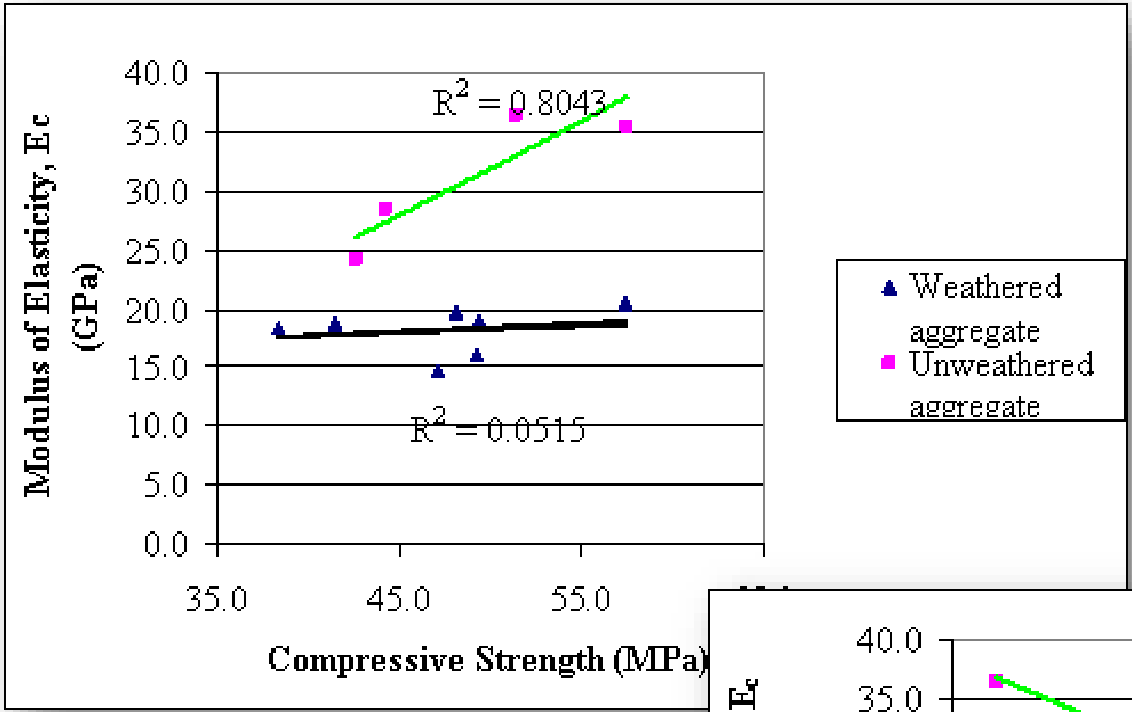
Performance Characteristic	Standard Test Method	FHWA HPC Performance Grade			
		1	2	3	4
Strength (x=compressive strength)	AASHTO T22 ASTM C39	41≤x<55 MPa (6≤x<8 ksi)	55≤x<69 MPa (8≤x<10 ksi)	69≤x<97 MPa (10≤x<14 ksi)	x≥97 MPa (x≥14 ksi)
Elasticity (x=modulus of elasticity)	ASTM C469	28≤x<40 GPa ($4 \leq x < 6 \cdot 10^6$ psi)	40≤x<50 GPa ($6 \leq x < 7.5 \cdot 10^6$ psi)	x≥50 GPa ($x \geq 7.5 \cdot 10^6$ psi)	
Shrinkage (x=microstrain)	ASTM C157	800>x≥600	600>x≥400	400>x	
Creep (x=microstrain/pressure unit)	ASTM C512	75≥x≥60/MPa (0.52≥x≥0.41/psi)	60≥x>45/MPa (0.41≥x>0.31/psi)	45≥x>30/MPa (0.31≥x>0.21/psi)	30/MPa≤x (0.21/psi≤x)
Freeze-thaw durability (x=relative dynamic modulus of elasticity at 300 cycles)	AASHTO T161 ASTM C666 (Procedure A)	60%≤x<80%	80%≤x		
Scaling (x= visual rating of the surface after 50 cycles)	ASTM C672	x=4,5	x=2,3	x=0,1	
Abrasion (x= average depth of wear)	ASTM C944	2.0>x>1.0 mm (0.08>x>0.04 in.)	1.0>x≥0.5 mm (0.04>x>0.02 in.)	x<0.5 mm (x<0.02 in.)	
Chloride Penetration (x=Coulombs)	AASHTO T277 ASTM C1202	3000≥x>2000	2000≥x>800	800≥x	

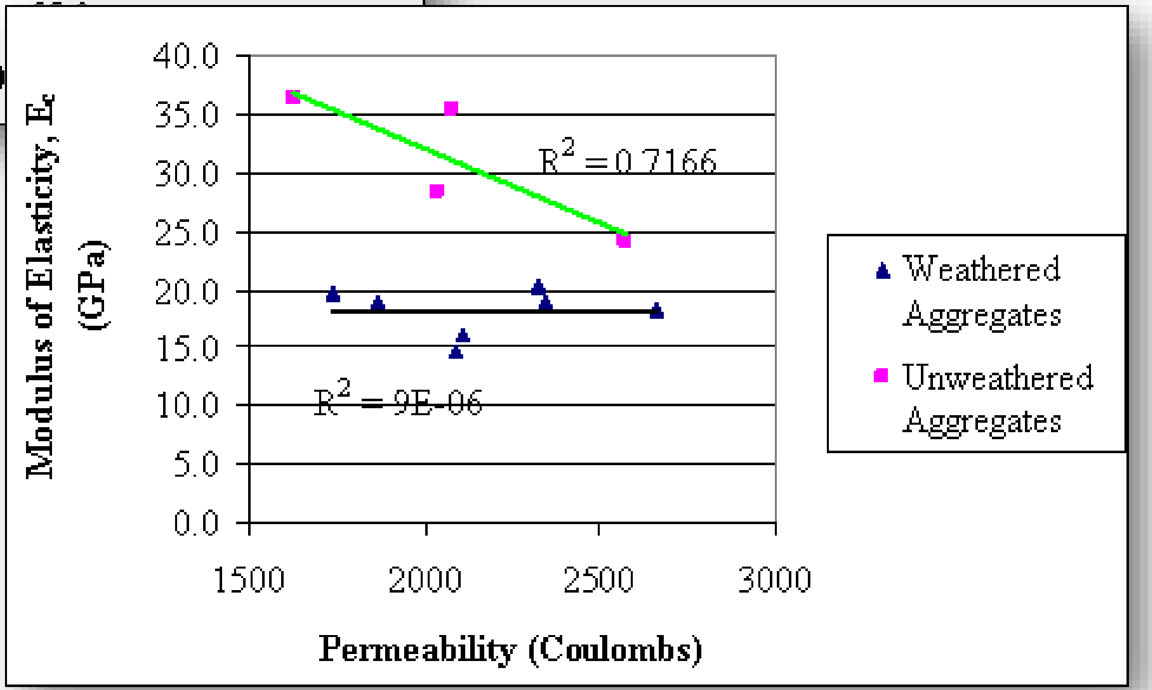
Historical Background

- Aggregates from specific quarries
- HPC Classified as Grade 1 or 2 based on most properties
- Did not meet Grade based on Elastic Modulus
- HPC Rejected

Performance Characteristic	Standard Test Method	Batch No.	Experimental Results	FH… Perfor… Grade
Strength (MPa (psi))	ASTM C39	1	47.5 (6890)	1
		2	51.9 (7525)	1
		3	55.2 (8003)	2
		4	57.6 (8360)	2
Elasticity (GPa (ksi))	ASTM C469	1	21.3 (3089)	< 1
		2	19.4 (2811)	< 1
		3	24.1 (3492)	< 1
		4	24.1 (3501)	< 1
Shrinkage (microstrain)	ASTM C157	Shrinkage tests were not performed		
Creep (microstrain/pressure unit)	ASTM C512	Creep tests were not performed.		
Freeze-thaw durability (relative dynamic modulus of elasticity at 300 cycles, %)	ASTM C666 (Procedure A)	1	---	---
		2	---	---
		3	---	---
		4	>90	2
Scaling (visual rating of the surface after 50 cycles)	ASTM C672	1	4	1
		2	3	2
		3	---	---
		4	---	---
Abrasion (average depth of wear, mm (in.))	ASTM C944	1	1.410 (0.0555)	1
		2	1.711 (0.0674)	1
		3	---	---
		4	---	---
…loride Penetration (…oulombs)	ASTM C1202	1	2144	1
		2	2632	1
		3	2683	1
		4	1065	2

Historical Background





Outline

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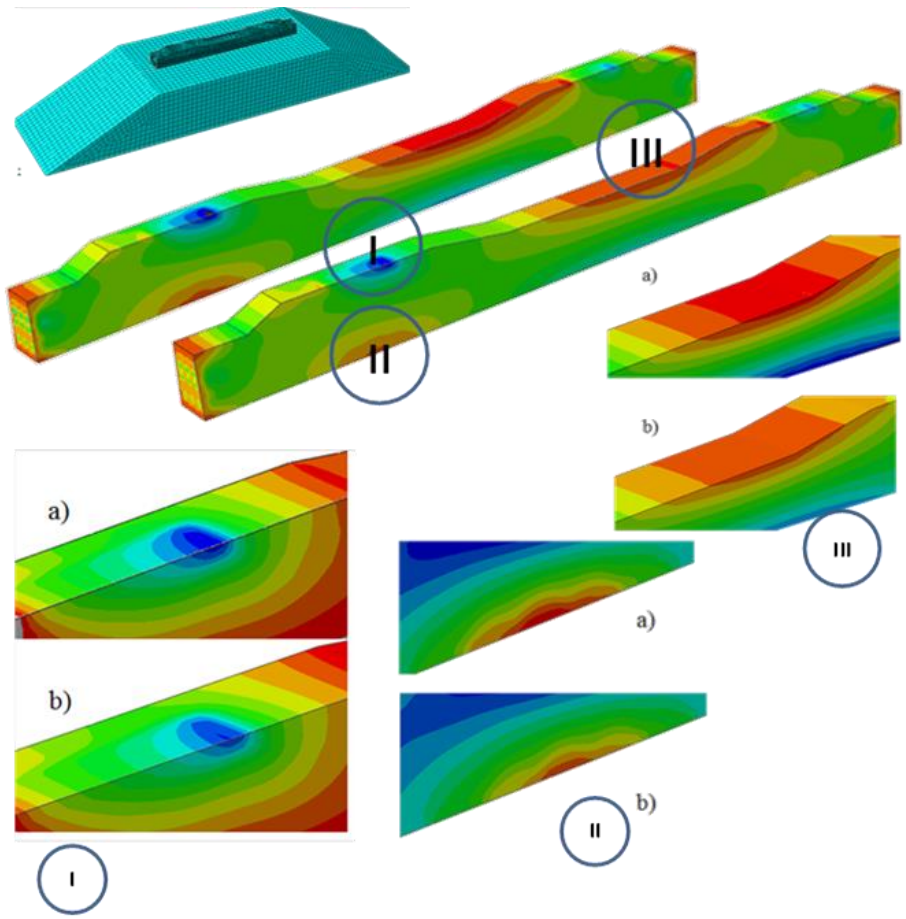
Benefits of Using Higher Resilience Concrete in Prestressed Ties:

- Better load distribution
- Smoother stress gradient
- Lower stress amplitudes
- Delay of onset of damage
- Relative rigidity

Critical Location	Stress Reduction due to HSRM-HPC (%)
I	15%
II	50%
III	48%



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Concrete Mix Designs

- US Major Tie Manufacturer Design
  - Min. 28 Day = 7000psi
  - Min. Transfer Strength = 4000psi
- Direct substitution of aggregates
- 4 Aggregate Sources
  - CA1: Plum Run Stone (Standard)
  - CA2: Weathered Granite Source A
  - CA3: Weathered Granite Source B
  - CA4: Weathered Granite Source C

Material Development and Characterization

Material Development and Characterization

Tests on Rock, Aggregate, Mortar and Concrete

	Test	ASTM
Coarse Ag.	Los Angles Abrasion Test	C131
	Sieve Analysis (Particle Size Distribution)	C136
	Bulk Density and Voids	C29
	Density, Specific Gravity and Absorption	C127
Rock	Compressive Strength	D7012 - 14
	Modulus of Elasticity	D7012 - 14
Concrete	Slump	C143
	Density	C138
	Air Content by pressure method	C231
	Compressive Strength of Concrete	C39
	Flexural Strength of Concrete	C78
	Modulus of Elasticity of Concrete	C469
	Shrinkage	C157
Mortar	Compressive Strength	C 109- 13
	Tensile Strength	C 307-12
	Modulus of Elasticity	C 580-02
	Setting Time (Initial and Final)	C191 - 13

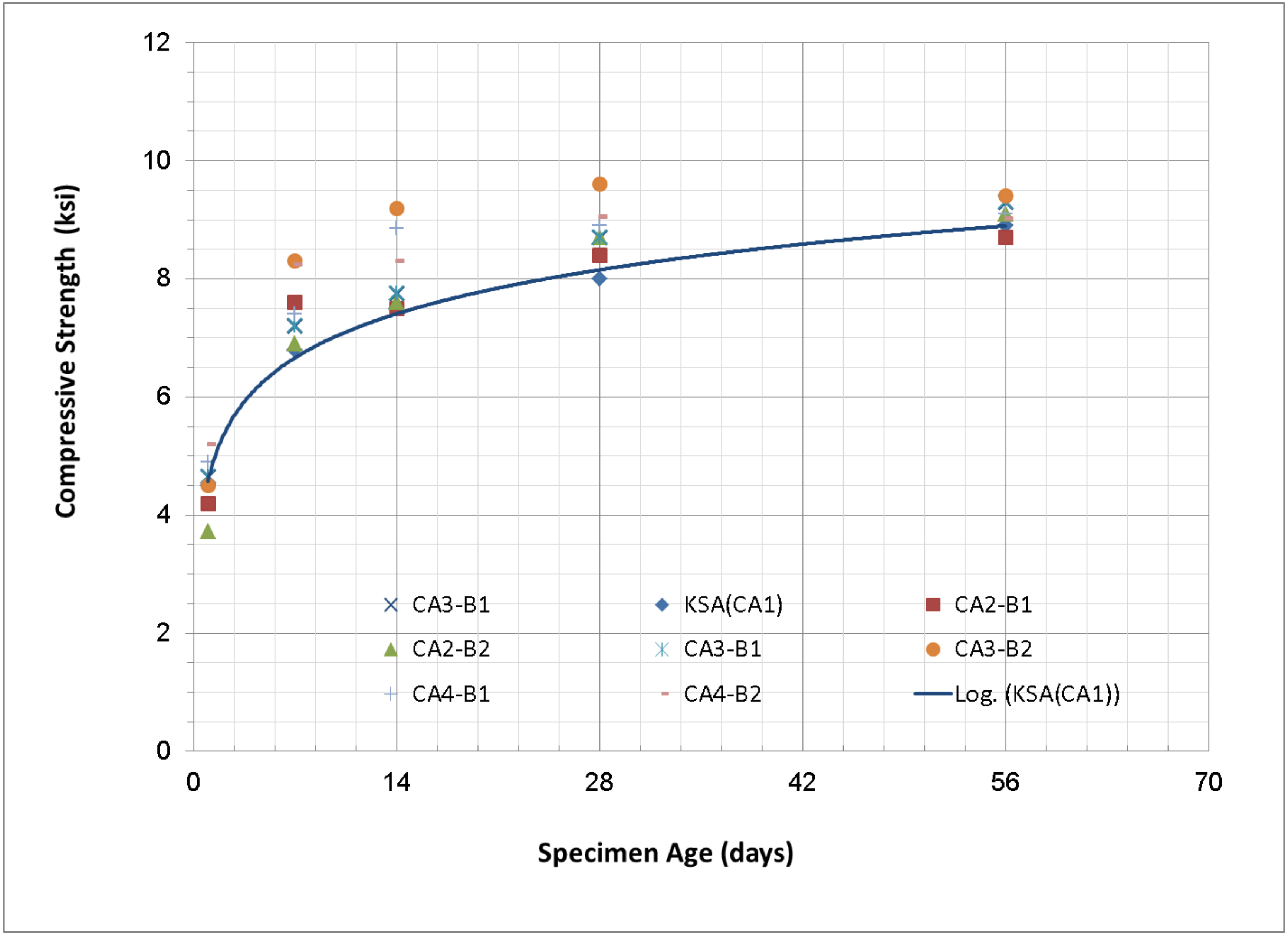
Durability - Abrasion

Procedures and Lapping Machine at UIUC

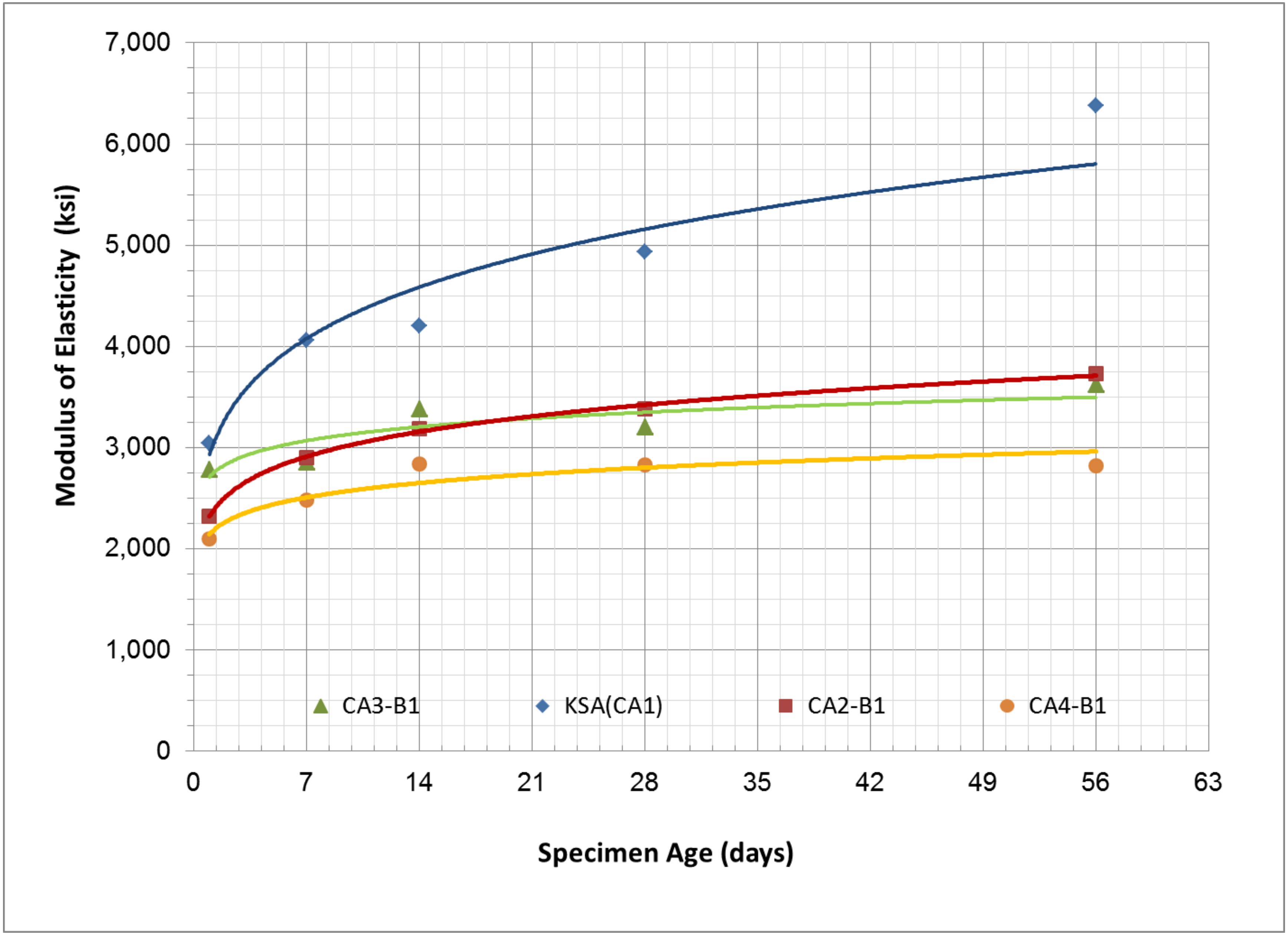
- 12 4x8 specimens from each Mix
- Specimens to UIUC on 6/22 (28 day min)

Abrasion Resistance Testing of Concrete Railway Crossties, E. Van Dam, et al. http://www.purdue.edu/discoverypark/nextrans/assets/pdfs/Van%20Dam

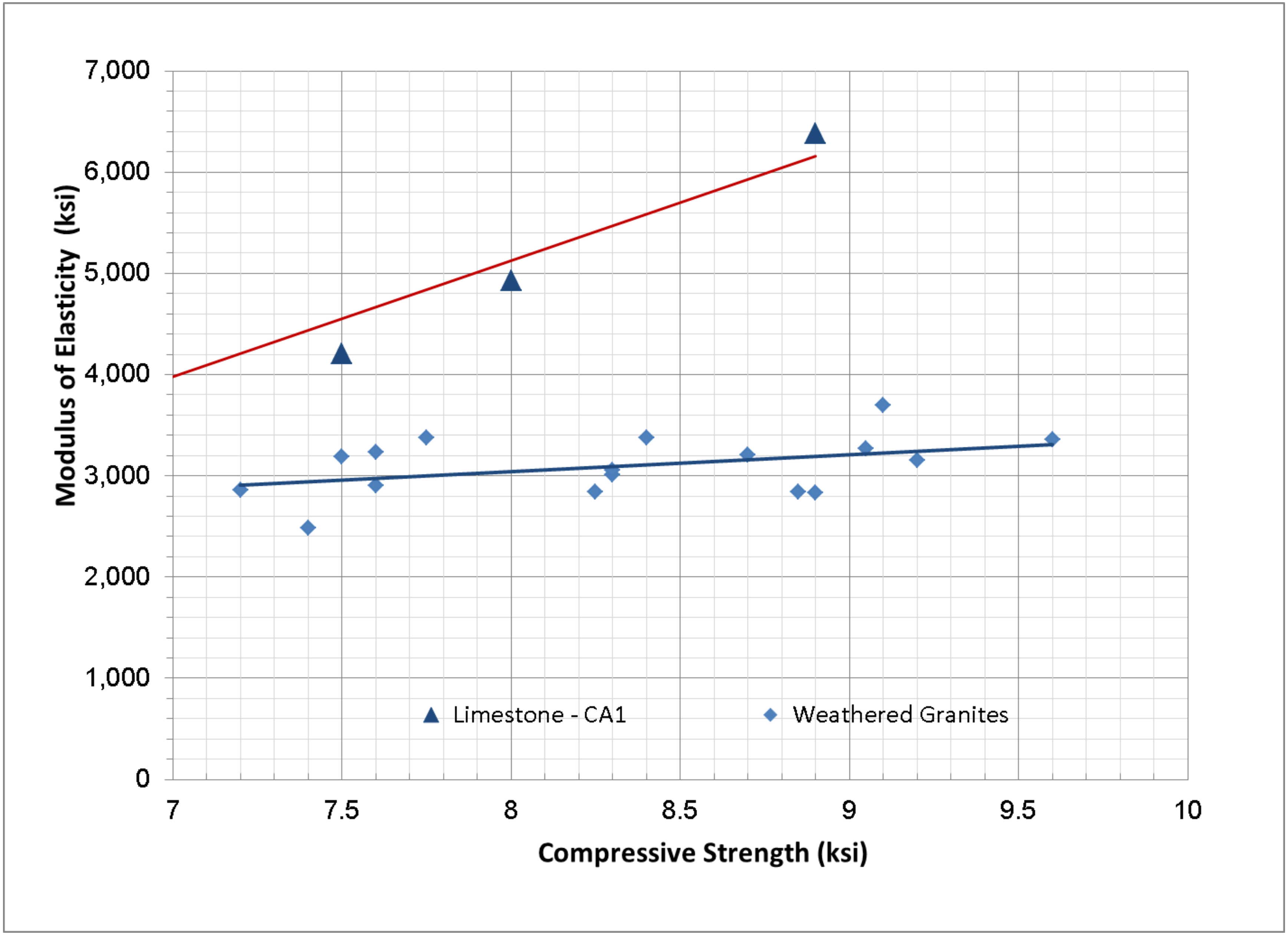
Concrete Strength vs Age



Elastic Modulus of Concrete vs Age



Concrete Modulus vs Strength (fc'>7 ksi)



Properties Comparison

	Property	AGGREGATE			
		KSA (CA1)	CA2	CA3	CA4
Aggreg	Voids	42.73	42.51	39.90	39.10
	Density (lb/ft^3)	161.65	164.50	165.00	167.50
	Relative Density	2.58	2.60	2.65	2.69
	LA Abrasion	27.5%	33.9%	44.3%	46.0%
Fresh Concr	Density (lb/ft^3)	152.90	153.73	154.14	158.55
	Yield (yd^3)	0.15	0.15	0.14	0.14
	Cement Content (lb/yd^3)	618.23	621.53	623.21	632.05
	Slump (in)	7.00	6.50	7.50	4.00
	Air Content (%)	5.0%	5.9%	4.8%	4.0%
Concrete	Compressive Strength (psi)	8.8E+03	8.8E+03	9.2E+03	8.7E+03
	Increase/Reduction %	***0%***	***0%***	***4%***	***-1%***
	Flexural Strength (psi)	0.13fc'	0.125fc'	0.12fc'	-
	Elastic Modulus (psi)	5.6E+06	3.6E+06	3.2+06	2.8E+06
	Elastic Modulus Reduction %	***0%***	***-37%***	***-43%***	***-50%***
	Lapping Test Abrasion Rate (mm/min)	0.042	0.023	0.029	0.039

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  - 9/2015 and 7/2016
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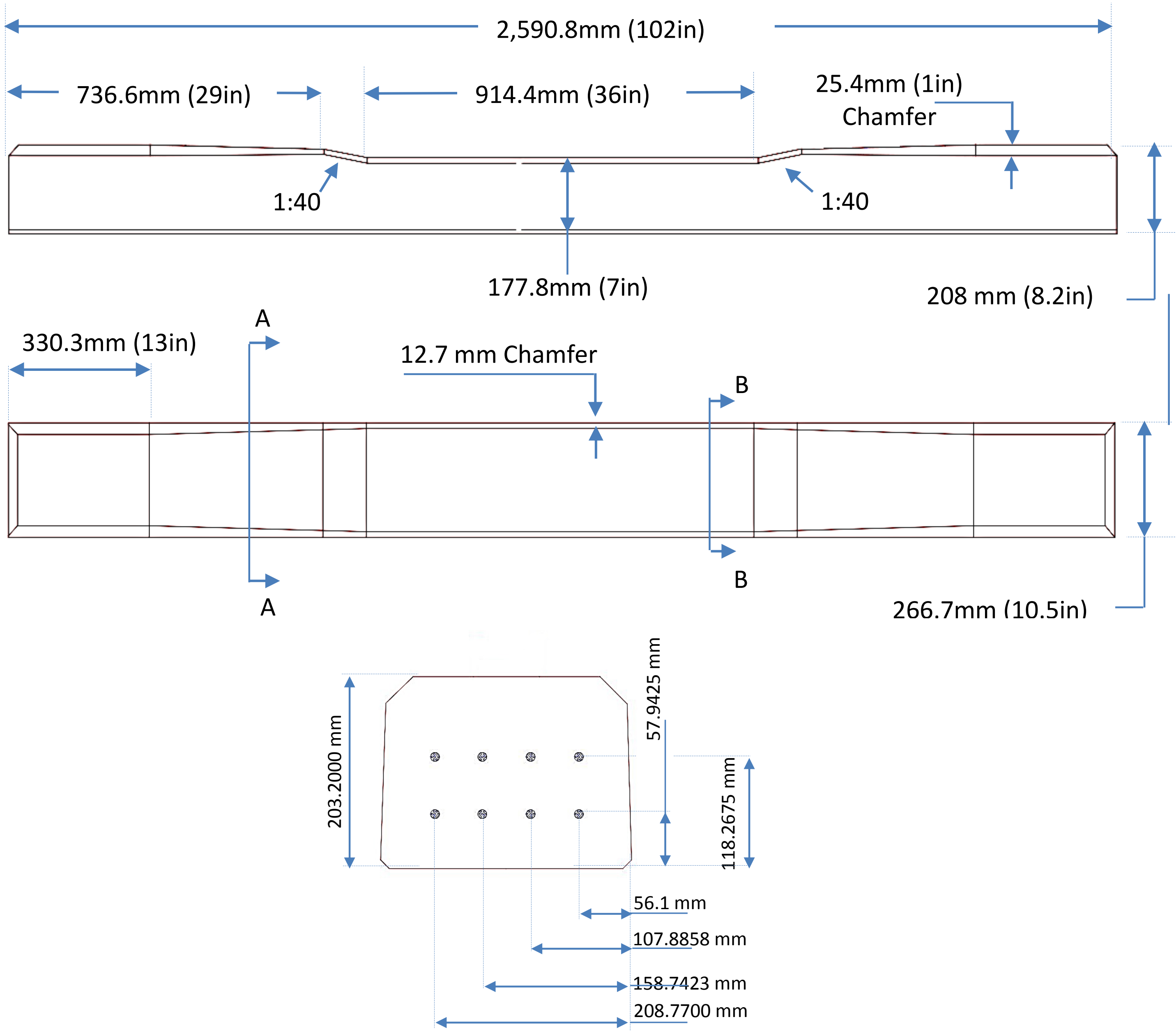
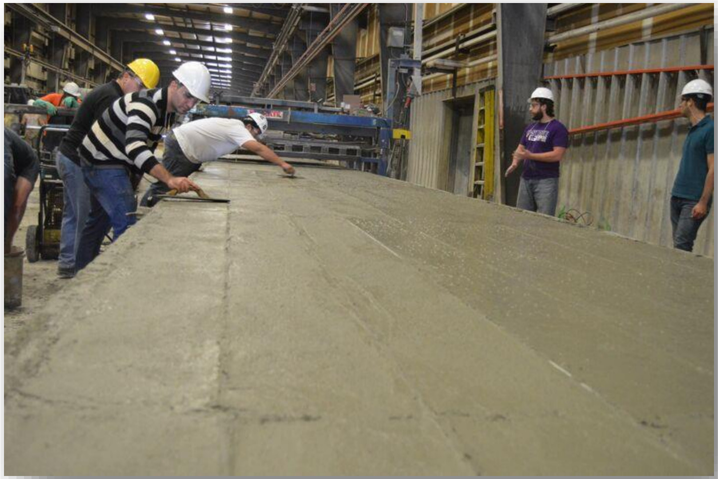
Prototype Tie Geometry



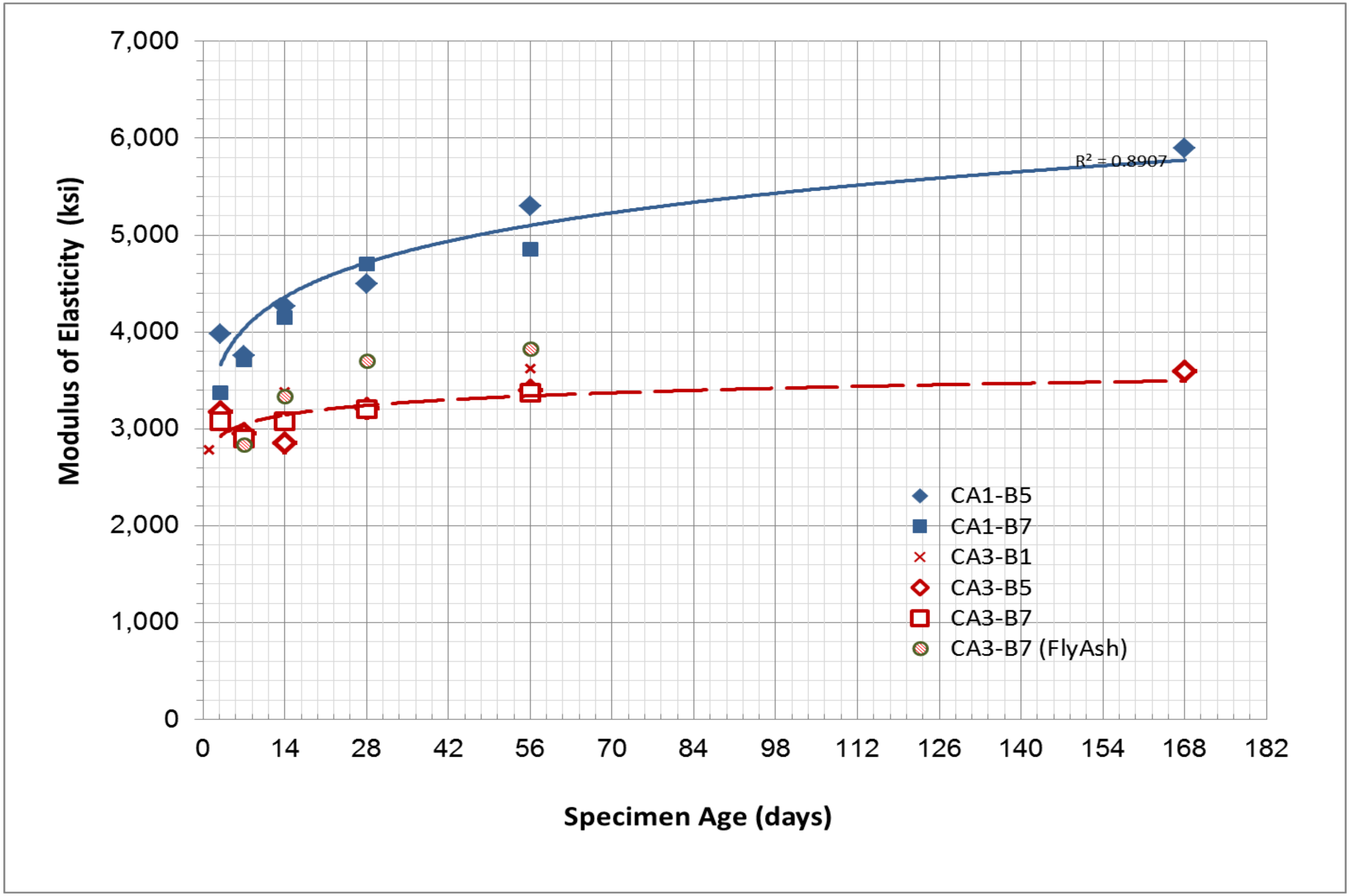
Prototype Fabrication: 9/25/2015

Prototype Fabrication: 9/25/2015

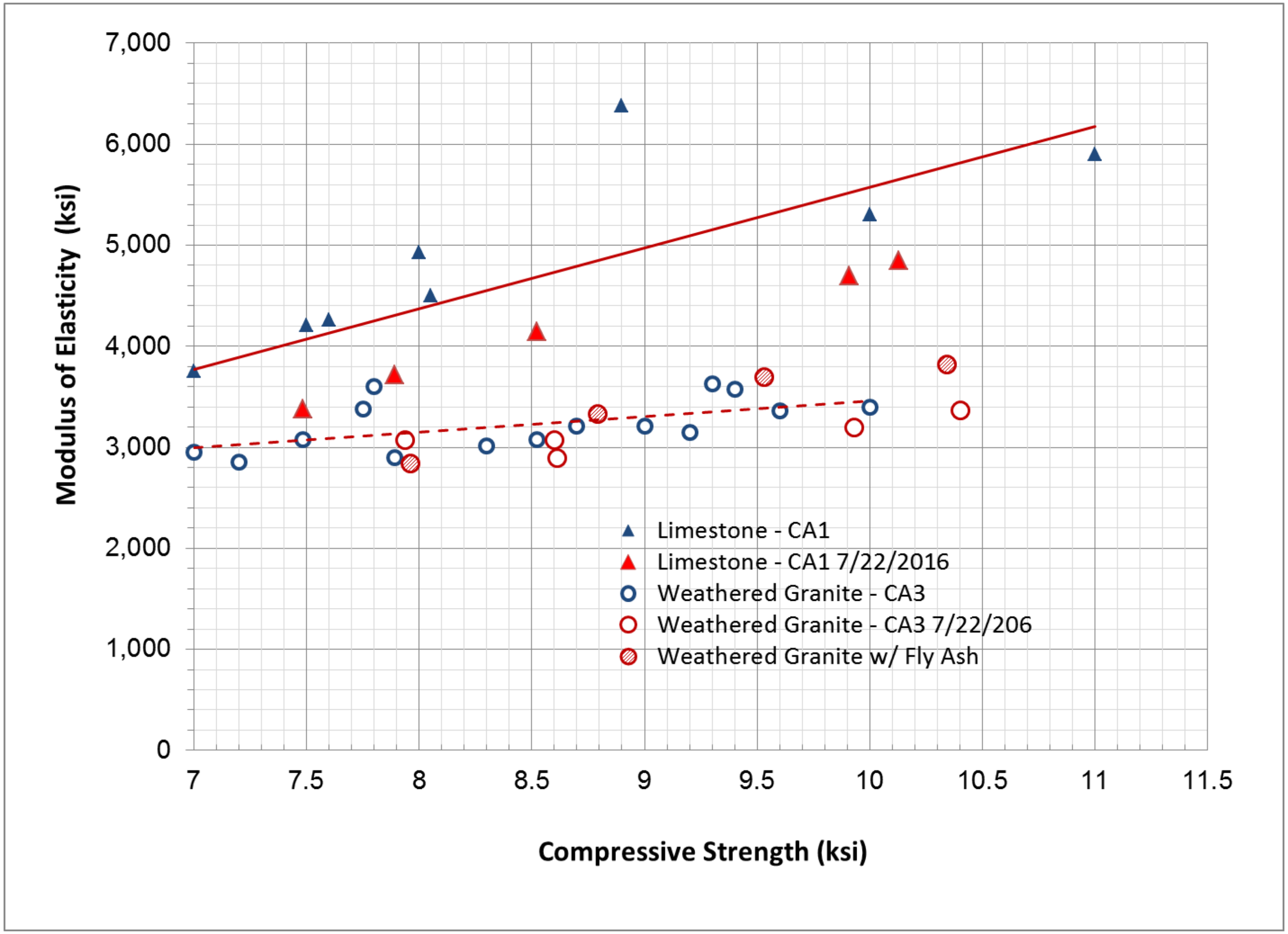


Prototype Fabrication: 9/26/2015

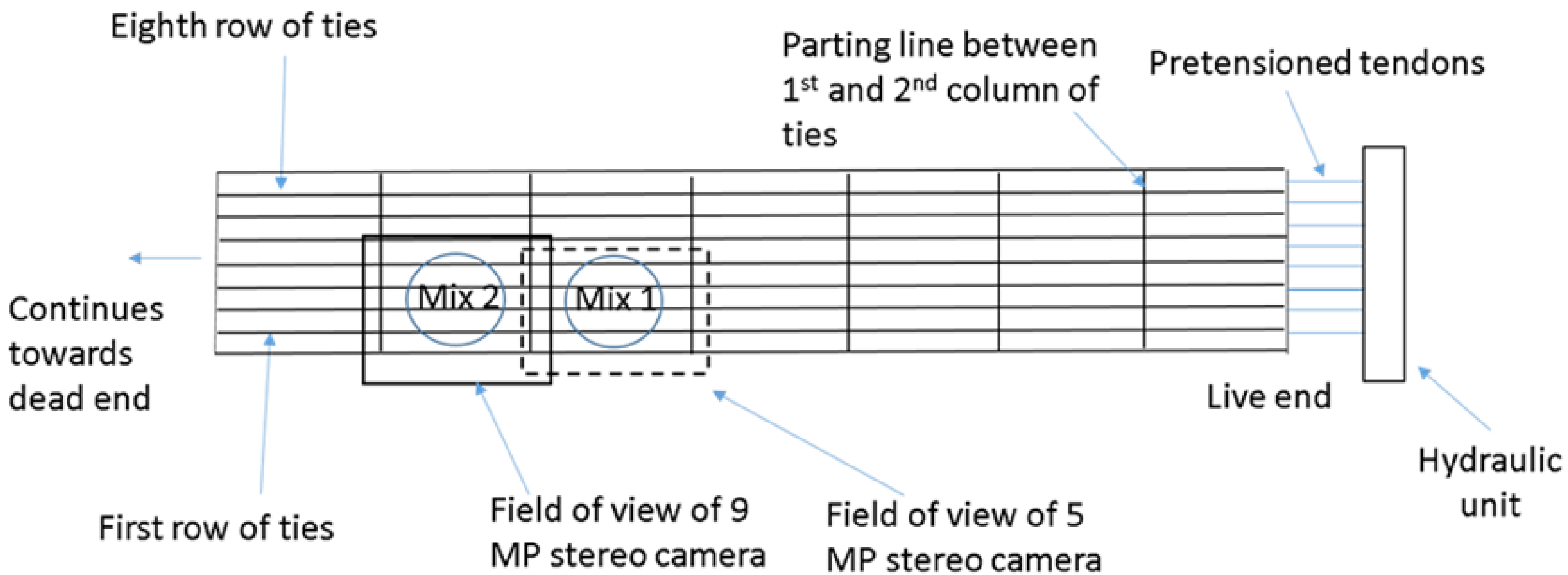
Concrete Elastic Modulus vs. Age



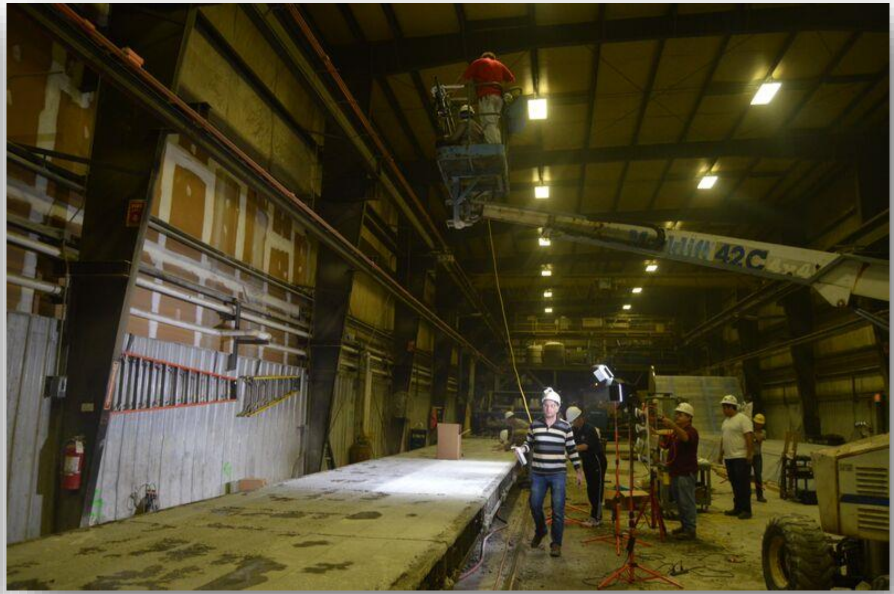
Concrete Modulus vs Strength (f_c'>7 ksi)



Prototype Fabrication – Transfer Length Measurements

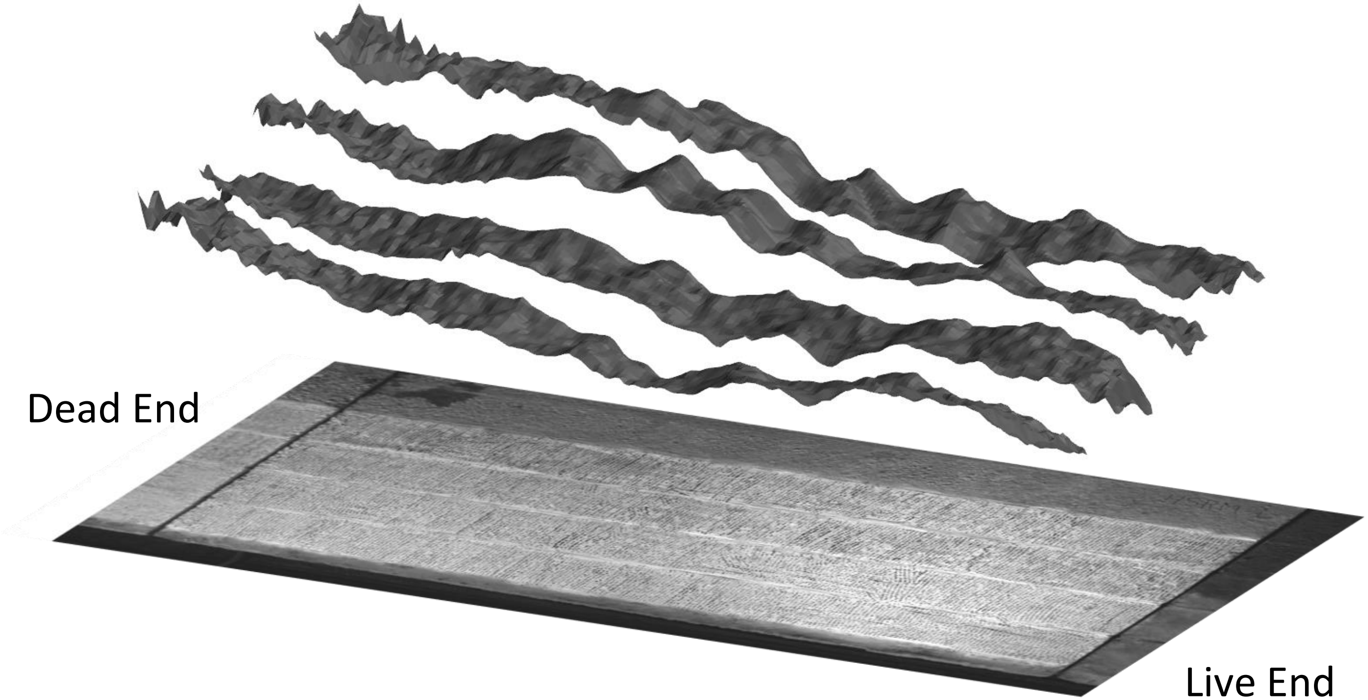


Prototype Fabrication: 9/26/2015

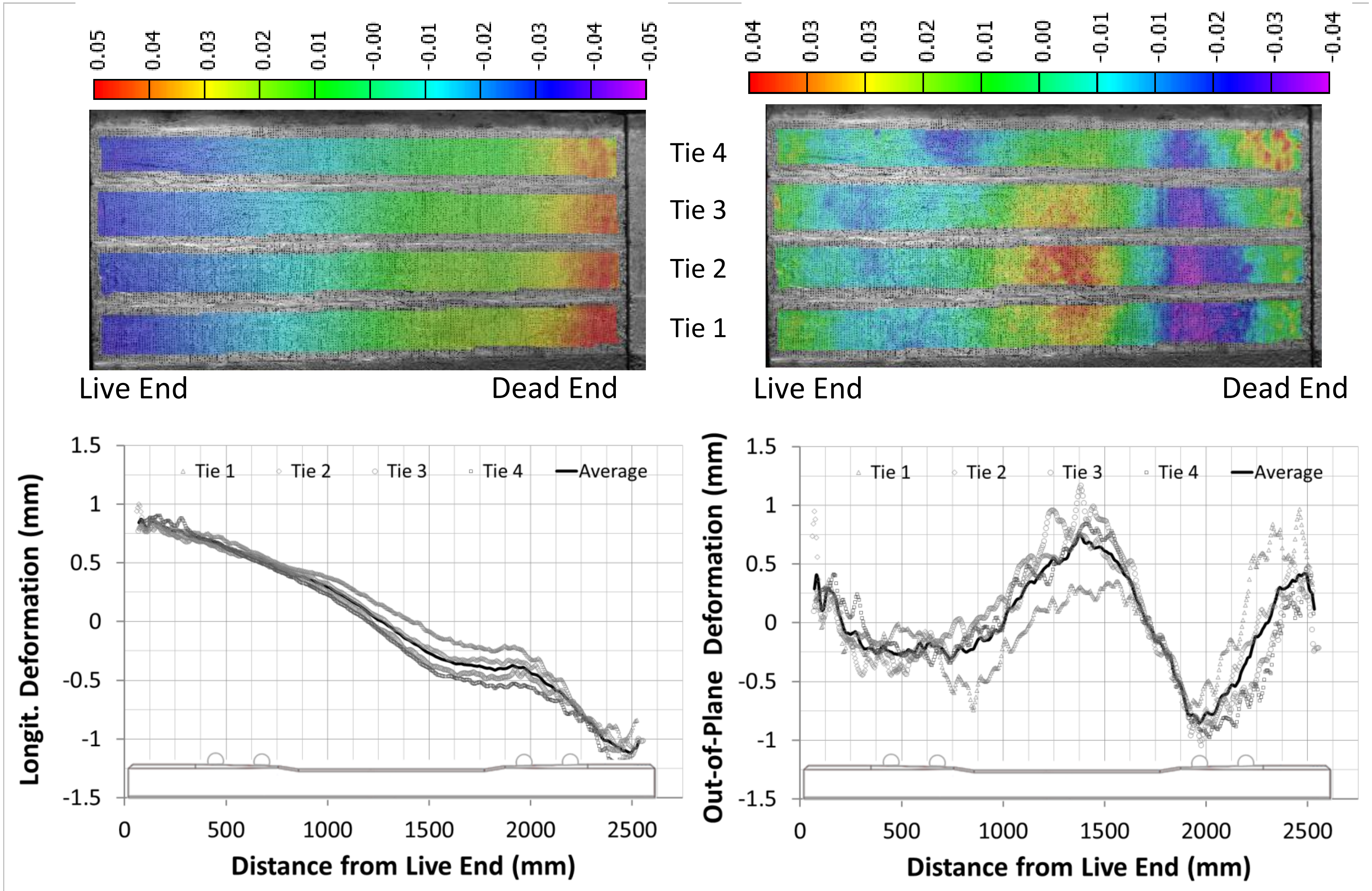


Prototype Fabrication: 9/26/2015

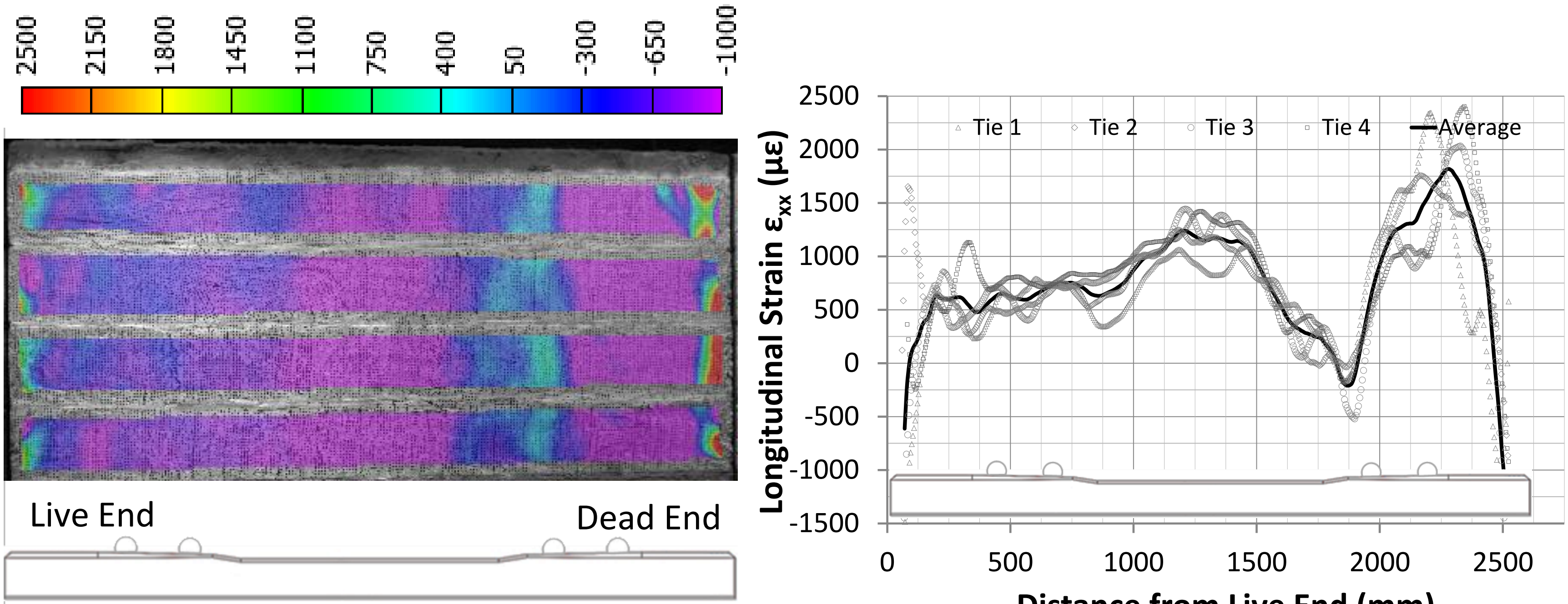
Prototype Fabrication: 9/26/2015



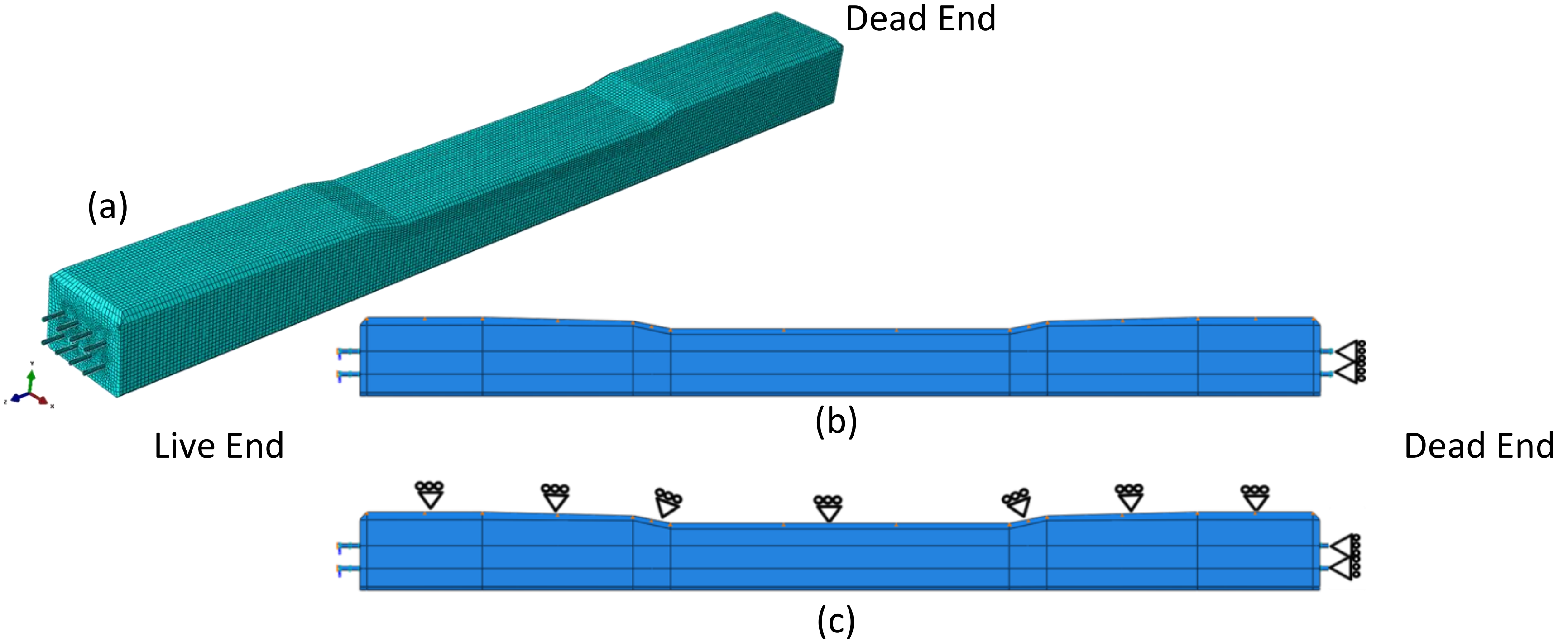
Prototype Fabrication: 9/26/2015



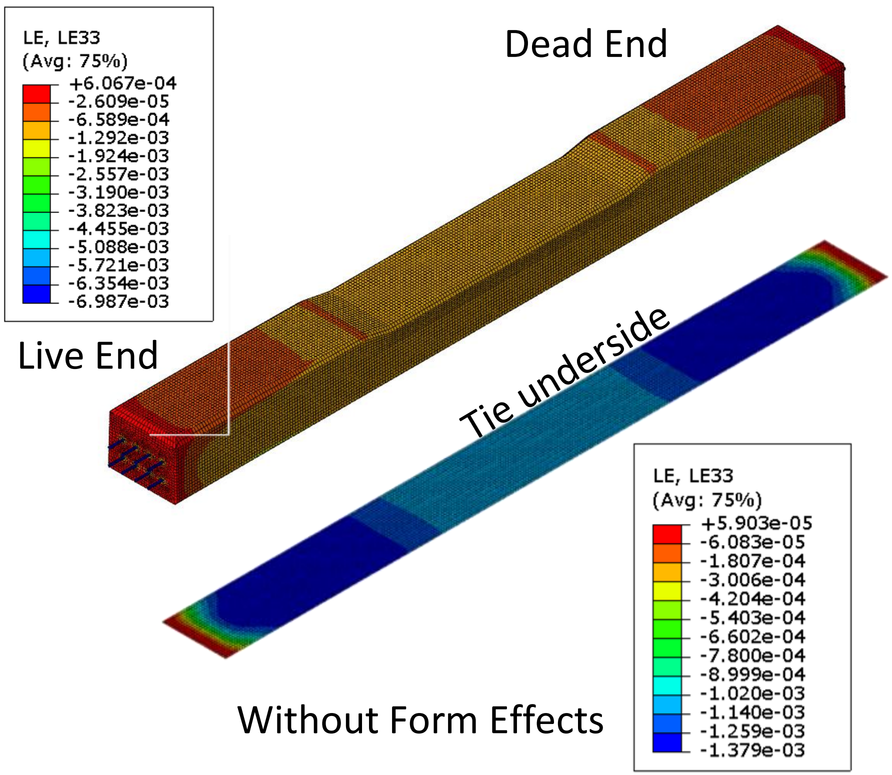
Prototype Fabrication: 9/26/2015

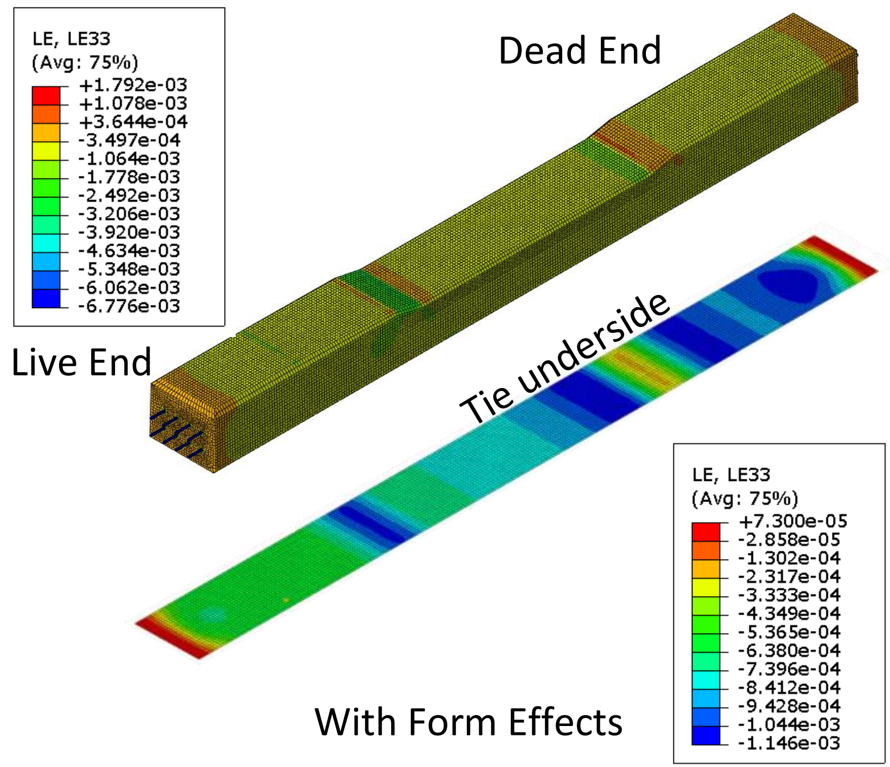


Prototype Fabrication: 9/26/2015

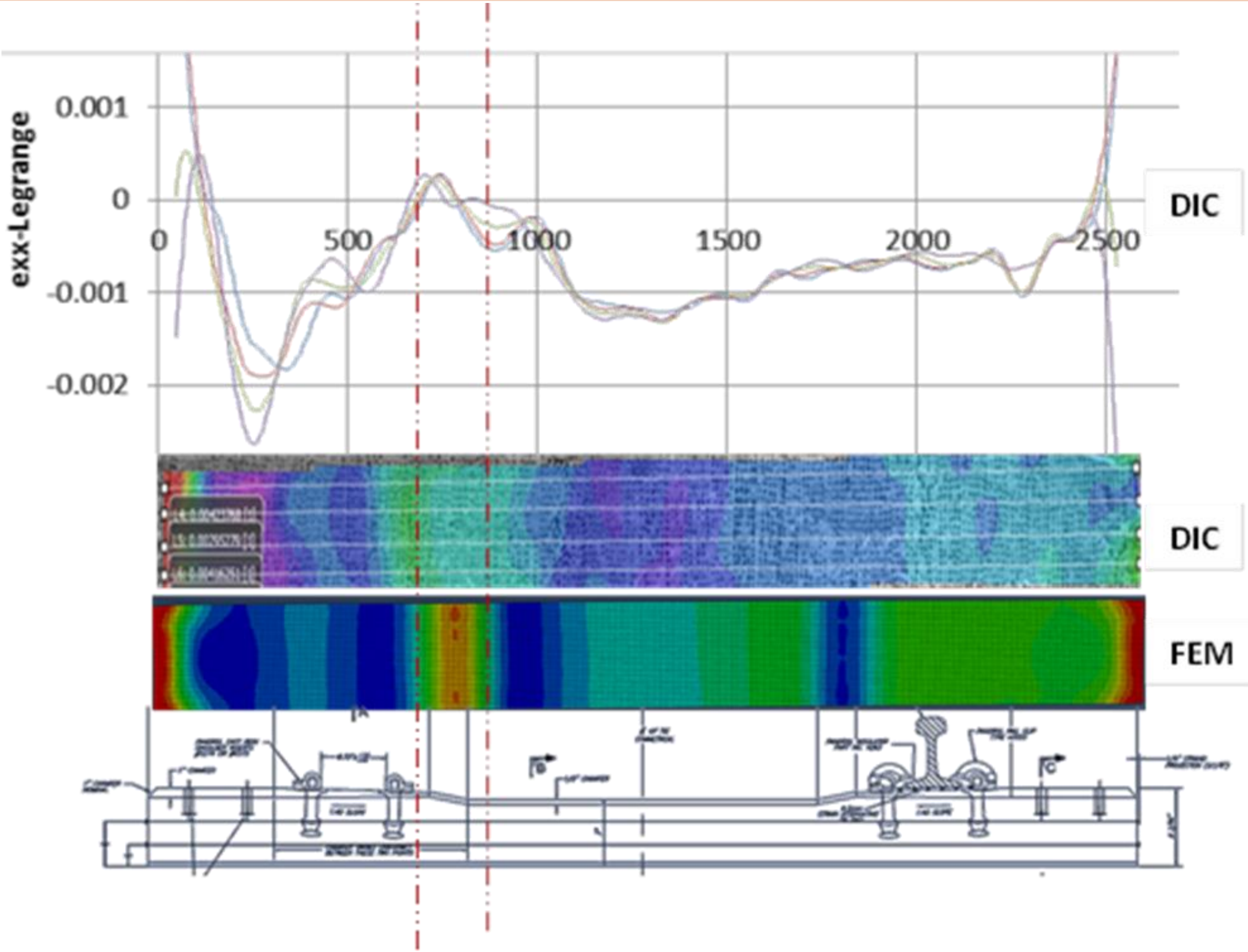


Prototype Fabrication: 9/26/2015





Prototype Fabrication: 9/26/2015



Prototype Fabrication: 9/26/2015 – Transfer Length

Transfer Length	HSRM-HPC	Standard
Average	11.9 in	16.2 in
Std. Deviation	1.0 in	2.5 in
Coeff. Var.	8.4%	15.4%

Outline

- Historical Background
- Hypothesis
- Material Development and Characterization
- Prototype Tie Design and Fabrication
- **Product Qualification**
- Benefits
- Conclusions

4.9.1.1 Sequence of Design Tests (Tie "1")

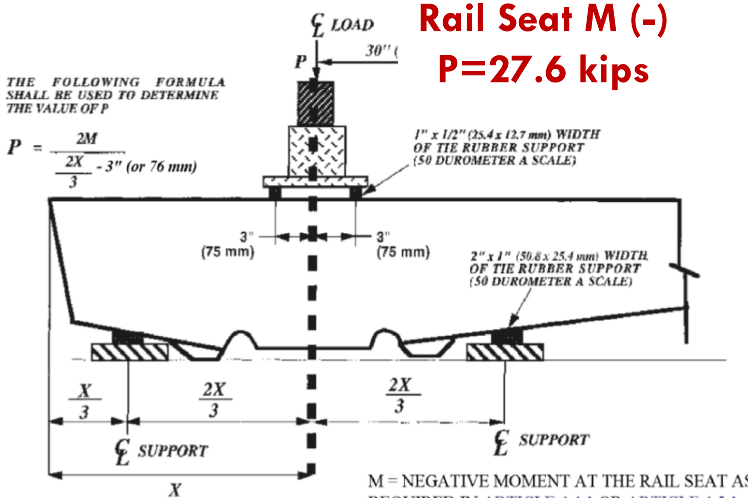
a. Rail Seat Vertical Load Test - Rail seat A (4.9.1.4)
b. Center Negative Bending Moment Test (4.9.1.6)
c. Center Positive Bending Moment Test (4.9.1.7)
d. Rail Seat Vertical Load Test – Rail seat B (4.9.1.4)
e. Bond Development, Tendon Anchorage, and Ultimate Load Test – Rail seat A (4.9.1.8)
f. Rail Seat Repeated Load Test – Rail seat B(4.9.1.5)

4.9.1.2 Sequence of Design Tests (Tie "2")

a. Fastening Insert Test (4.9.1.9)
b. Fastening Uplift Test (4.9.1.10)
c. Electrical Resistance and Impedance Test (4.9.1.14)

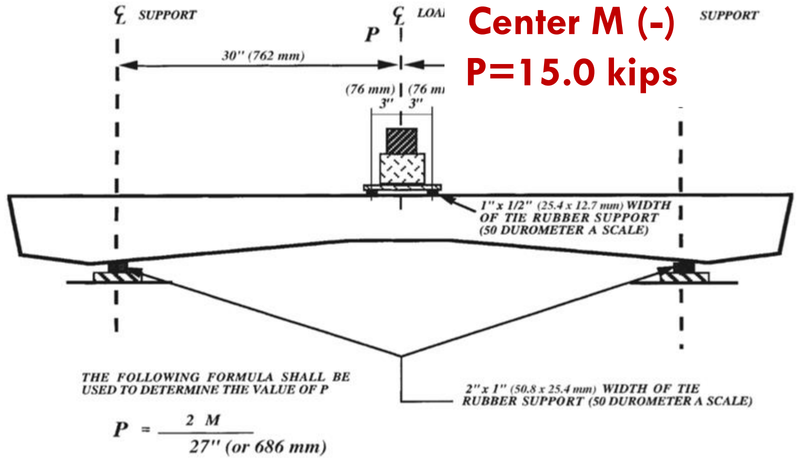
AREMA Sequence of Design Tests (Tie "1")

Rail Seat M (-)
P=27.6 kips



M = NEGATIVE MOMENT AT THE RAIL SEAT AS REQUIRED IN ARTICLE 4.4.1 OR ARTICLE 4.5.1

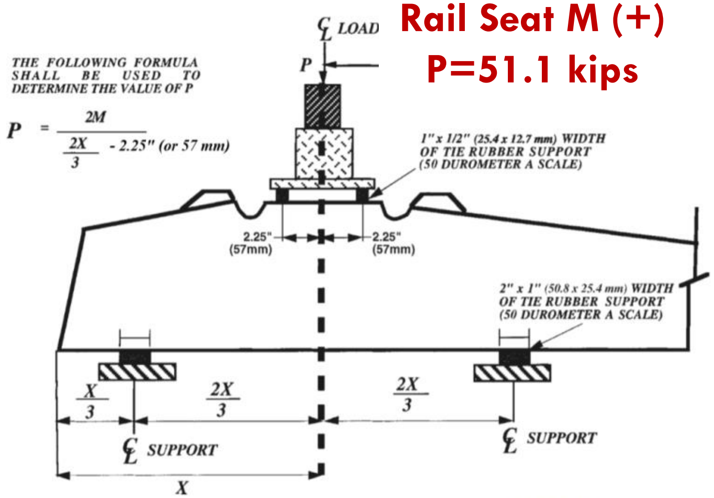
Center M (-)
P=15.0 kips



M = NEGATIVE MOMENT AT THE CENTER OF THE TIE AS REQUIRED IN ARTICLE 4.4.1

Figure 30-4-10. Tie Center Negative Moment Test

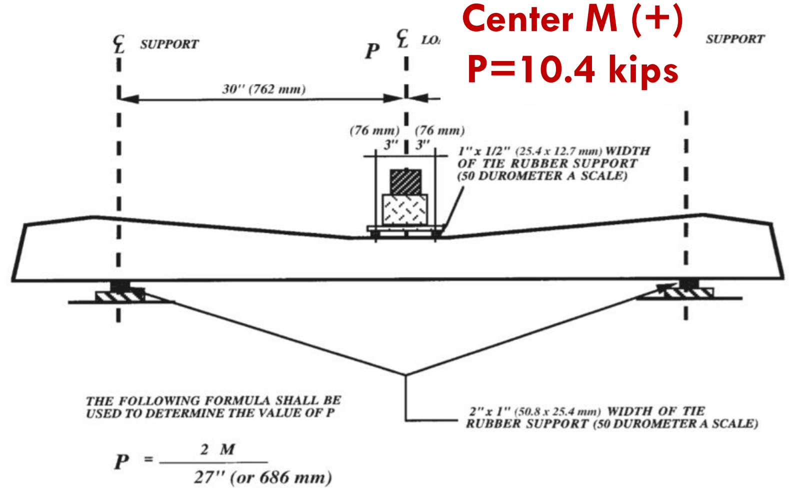
Rail Seat M (+)
P=51.1 kips



M = POSITIVE MOMENT AT THE RAIL SEAT AS REQUIRED IN ARTICLE 4.4.1 FOR PRESTRESSED MONOBLOCK TIES OR ARTICLE 4.5.1 FOR TWO BLOCK TIES

Figure 30-4-8. Rail Seat Positive Moment Test

Center M (+)
P=10.4 kips

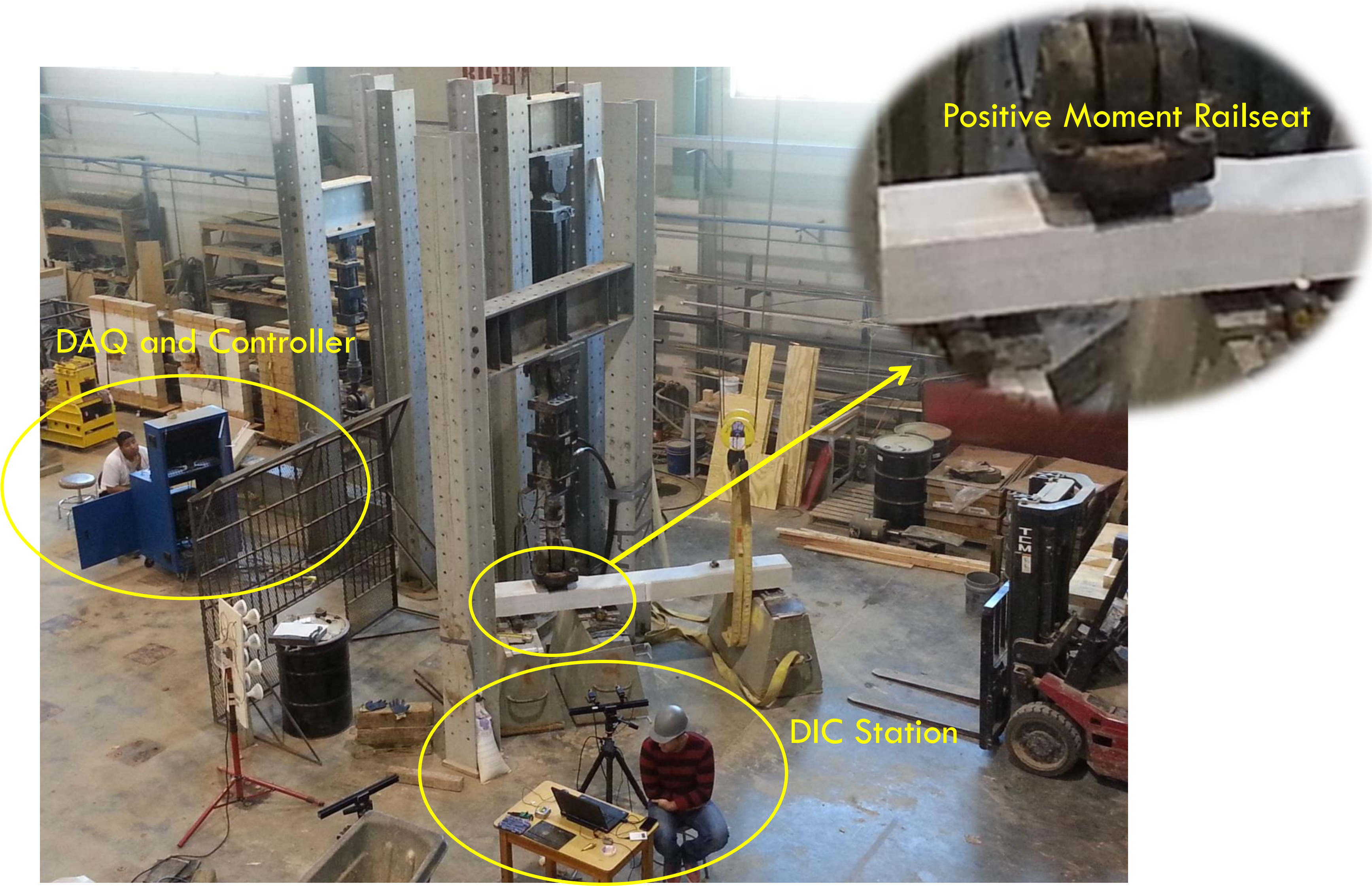


M = POSITIVE MOMENT AT THE CENTER OF THE TIE AS REQUIRED IN ARTICLE 4.4.1

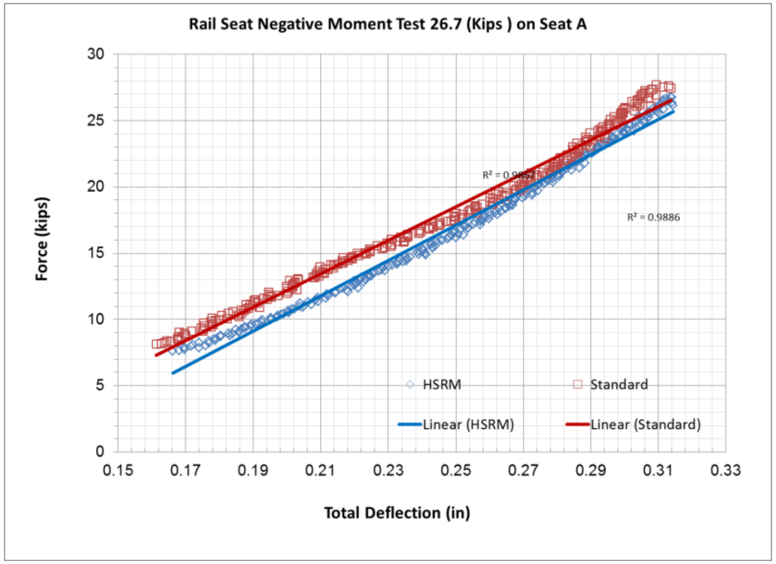
Figure 30-4-11. Tie Center Positive Moment Test

AREMA Sequence of Design Tests (Tie “1”)

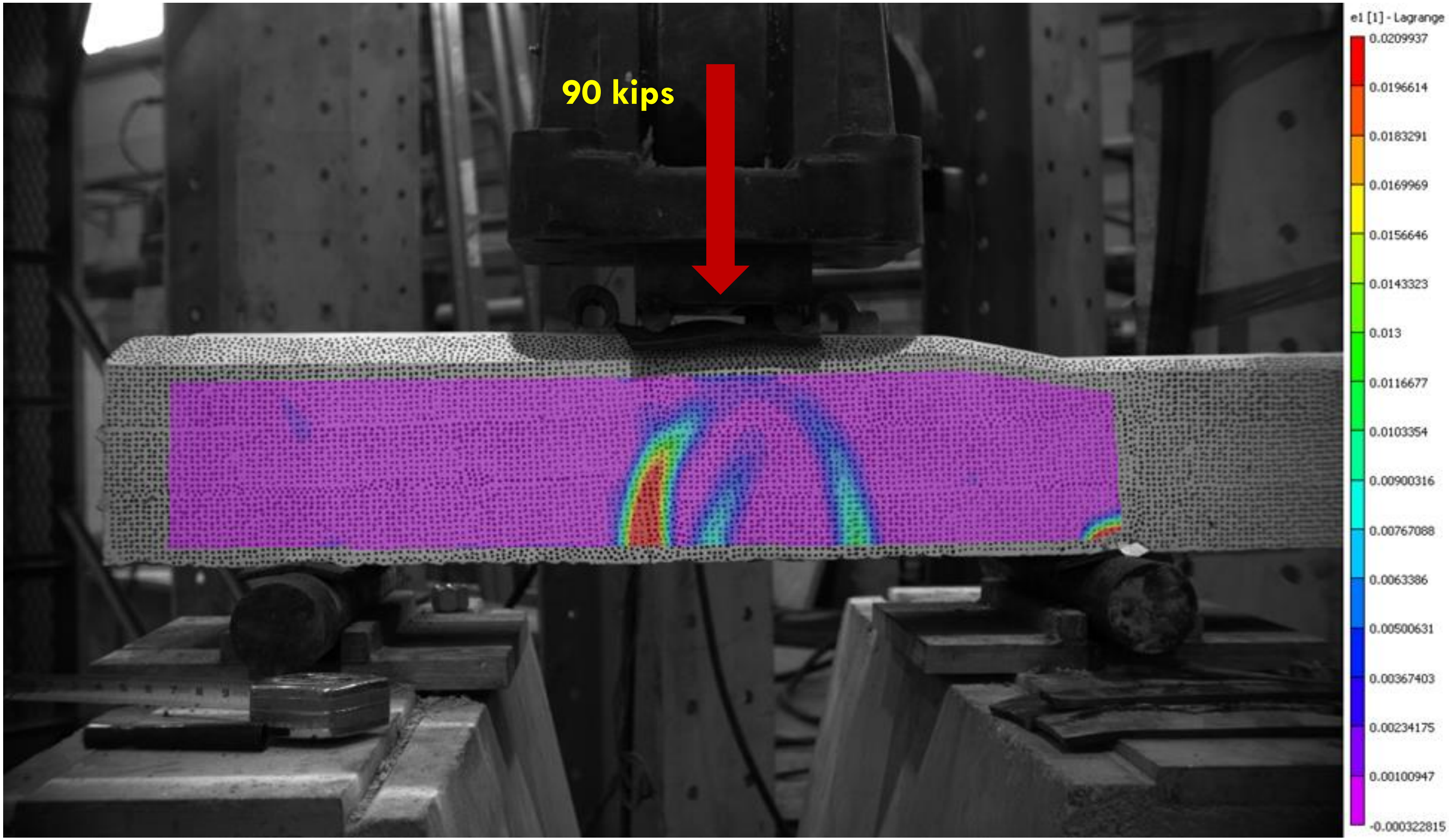
3-D Stereovision System for Strain Field Measurements



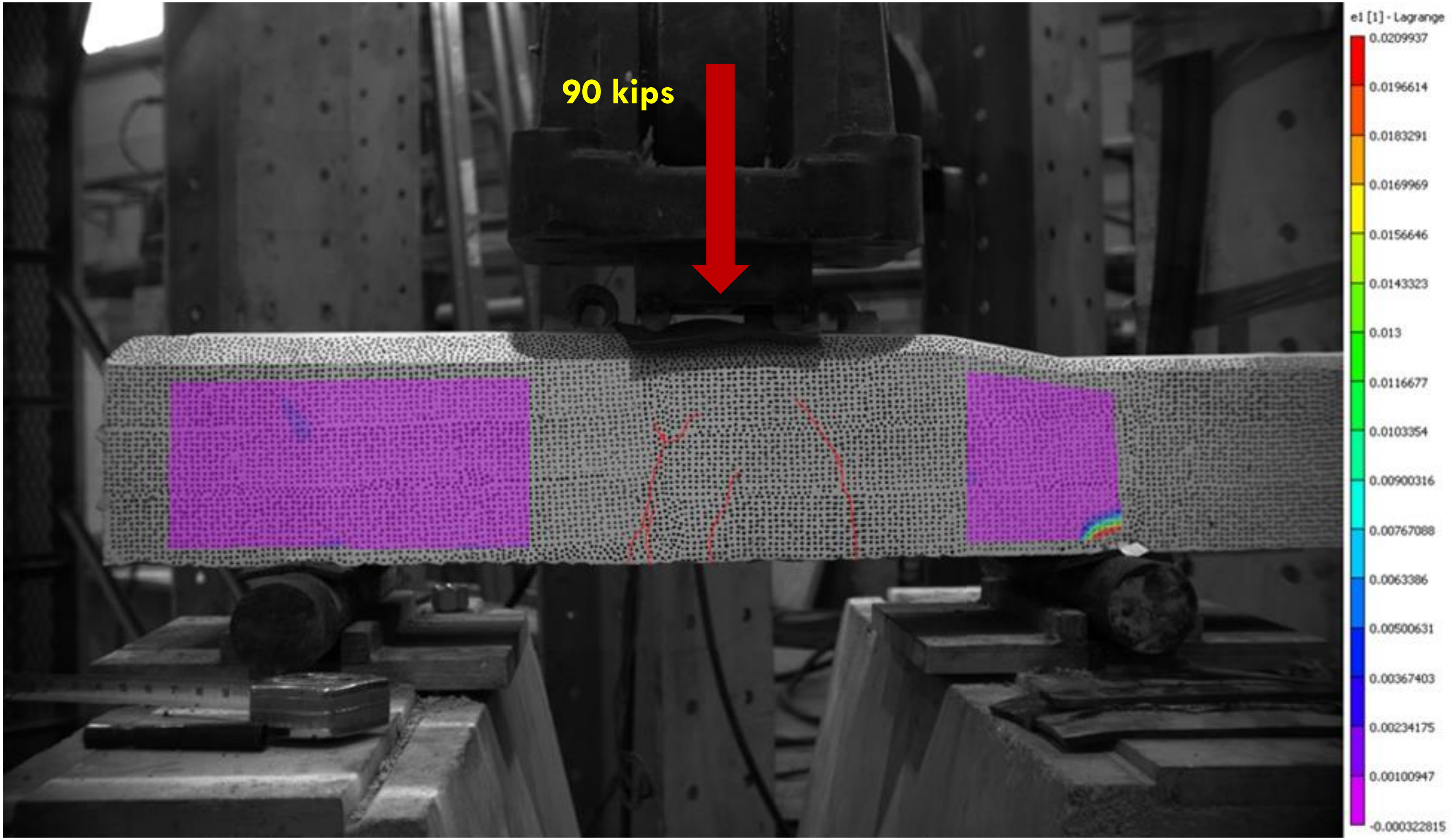
3-D Stereovision System for Strain Field Measurements



Design Performance – AREMA: Ultimate Load Tests



Design Performance – AREMA: Ultimate Load Tests



AREMA Sequence of Design Tests (Tie "1")

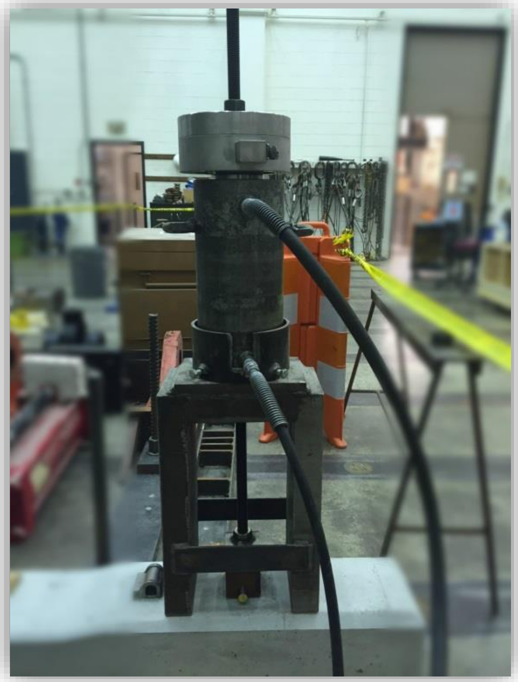
	Tie ID	Rail Seat A		Rail Seat B		Center	
		M +	M -	M +	M -	M +	M -
Prototype	HSRM-Q1	Pass	Pass	Pass	Pass	Pass	Pass
	HSRM-Q2	Pass	Pass	Pass	Pass	Pass	Pass
	HSRM-Q3	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**
	HSRM-Q4	Pass	Pass	Pass	Pass	Pass	Pass
	HSRM-Q5	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**
Baseline	STANDARD-Q1	Pass	Pass	Pass	Pass	Pass	Pass
	STANDARD-Q2	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**
	STANDARD-Q3 (9-1)	Pass	Pass	Pass	Pass	Pass	Pass
	STANDARD-Q4 (11-3)	Pass	Pass	Pass	Pass	Pass	Pass
	STANDARD-Q7	**Pass***	**Pass**	**Pass**	**Pass**	**Pass**	**Pass**
Other	STANDARD-Q5-A	Pass*	Pass	Pass	Pass	Pass	Pass
	STANDARD-Q6-A	Pass	Pass	Pass	Pass	Pass	Pass

*Marginally

Ultimate Load Tests

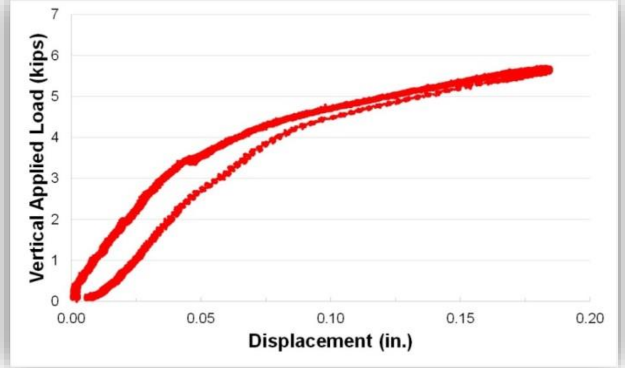
	Tie ID	Rail Seat A					
		$\varepsilon_{prestress}$ (+/- 10%)	ε_{crack}	P_{crack}	1.5P	Pu	Strand Slippage
Prototype	HSRM-Q1	~800 µε	~320µε	56	Pass	>100	No
	HSRM-Q2						
	HSRM-Q3			57	Pass	>100	No
	HSRM-Q4						
	HSRM-Q5			52	Pass	96	No
Baseline	STND-Q1	~500 µε	~220 µε				
	STND-Q2						
	STND-Q3 (9-1)			57.9	Pass	88.9	No
	STND-Q4 (11-3)			52.1	Pass	105.3	No
	STND-Q7			49	Pass	97	No
Other	STND-Q5-A						
	STND-Q6-A						

Fastener Pullout and Torque Tests



Crosstie	Rail Seat	Location	Pull-out (12kips)	Torque (250lb-ft)
Rocla	A	Field	PASS	PASS
		Gauge	PASS	PASS
	B	Field	PASS	PASS
		Gauge	PASS	PASS
USC Prototype	A	Field	PASS	PASS
		Gauge	PASS	PASS
	B	Field	PASS	PASS
		Gauge	PASS	PASS

Fastener Uplift Tests

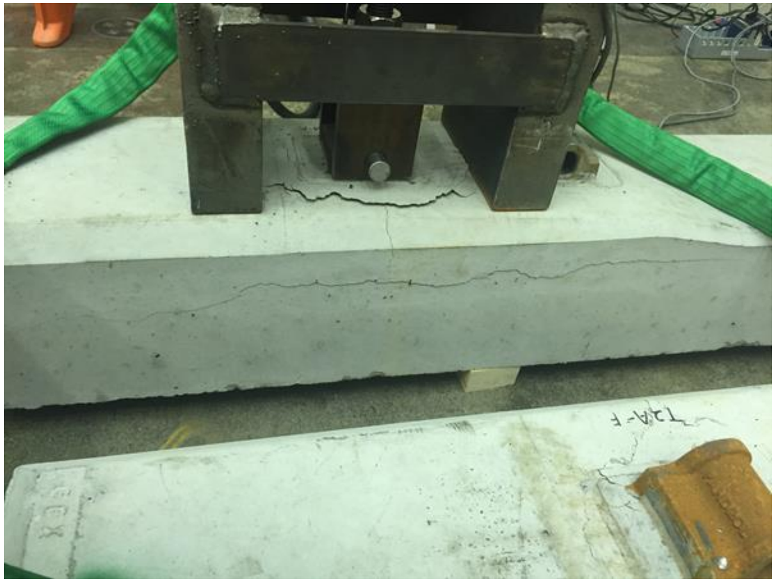


Crosstie	Rail Seat	Result
Standard Crosstie	A	PASS
	B	PASS
USC Prototype Crosstie	A	PASS
	B	PASS

Tie Performance: Fastening Insert Failure Test

Crosstie	Level of Distress	Load (kips)
Standard	Crack Initiation at	31.6
	Insert Pulled out	34.6
HSRM	Crack Initiation	33.2
	Insert Pulled out	35.1

Standard



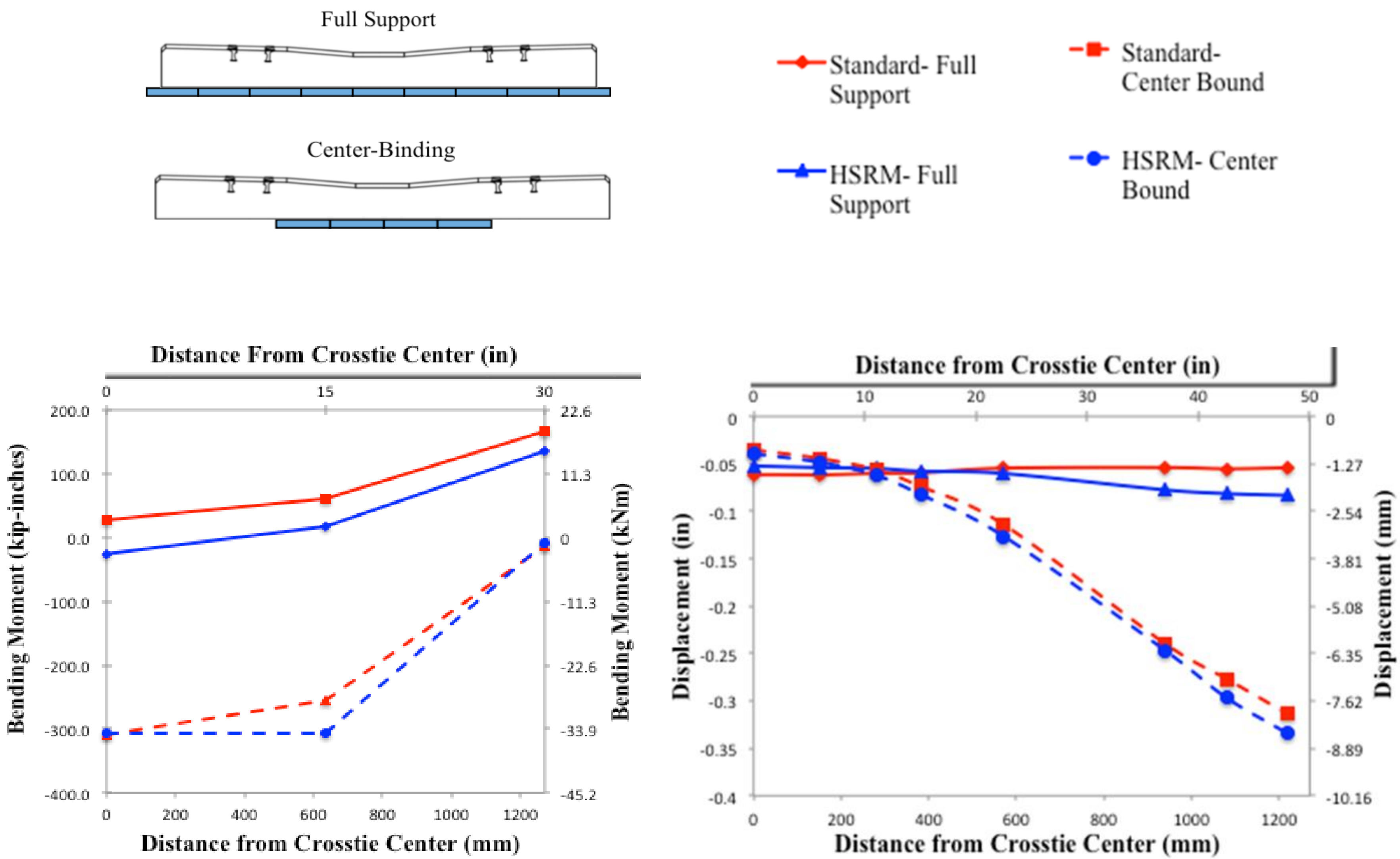
HSRM

Outline

- Historical Background
- Hypothesis
- Material Development and Characterization
- Prototype Tie Design and Fabrication
- Product Qualification
- Benefits / Performance Assessment
- Conclusions

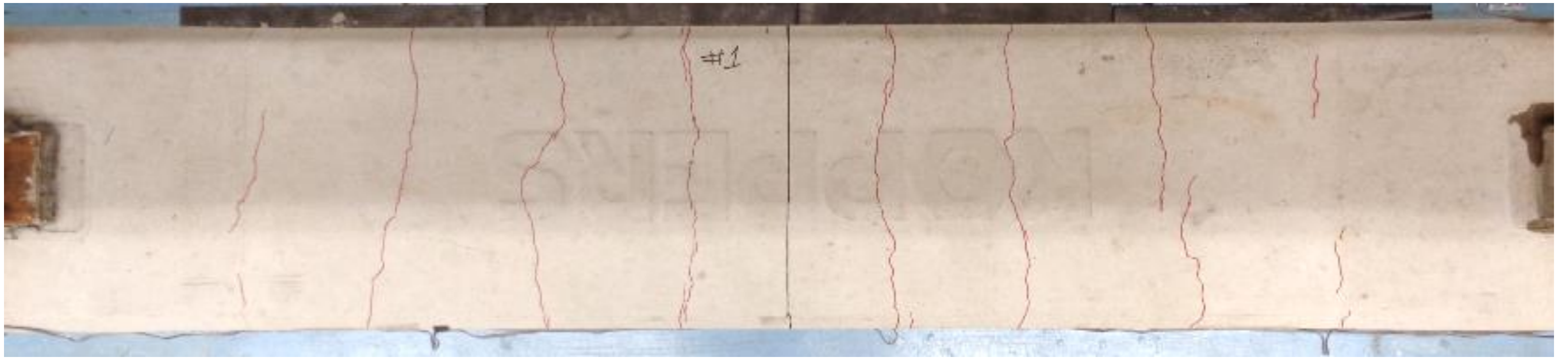
Flexural Tests – Variable Support

Tie Performance – Flexural tests

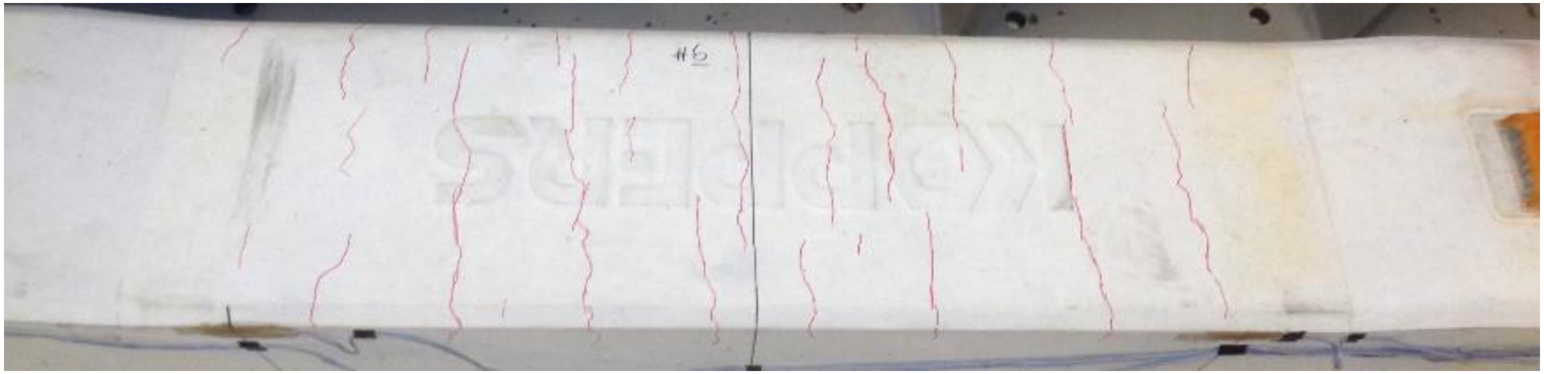


Tie Performance – Flexural tests

Standard Tie



HSRM Tie

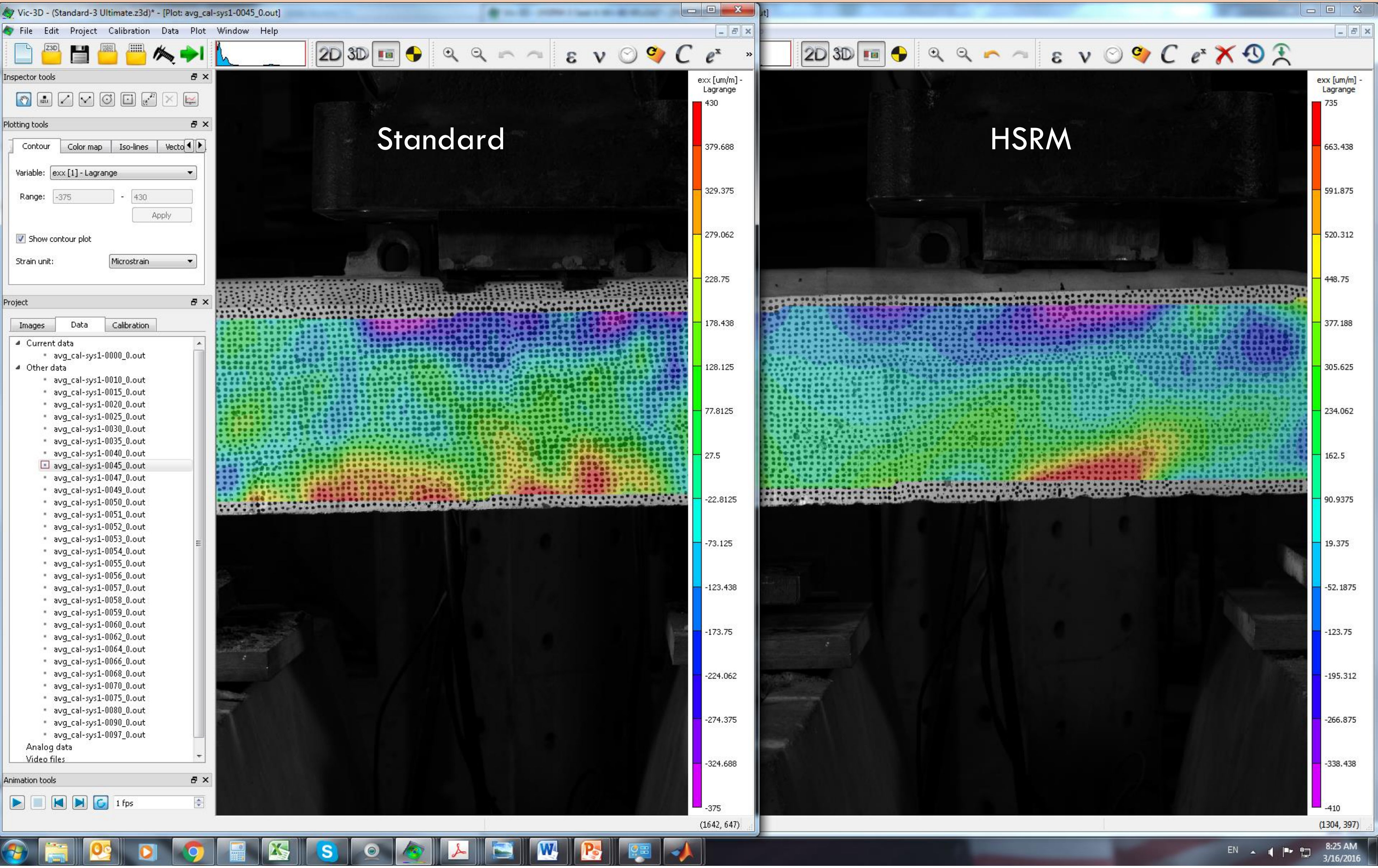


Tie Performance – Flexural tests

(center-binding conditions at 20 kips)	**Standard**		**HSRM**		**CXT505S**	
End Displacement (in/mm)	-0.314	-7.98	-0.334	-8.48	-0.234	-5.94
Expected Gauge-Widening (in/mm)	0.119	3.02	0.114	2.90	0.101	2.57
Center Moment (kip-in/kNm)	-309	-34.8	-306	-34.5	-413	-46.6

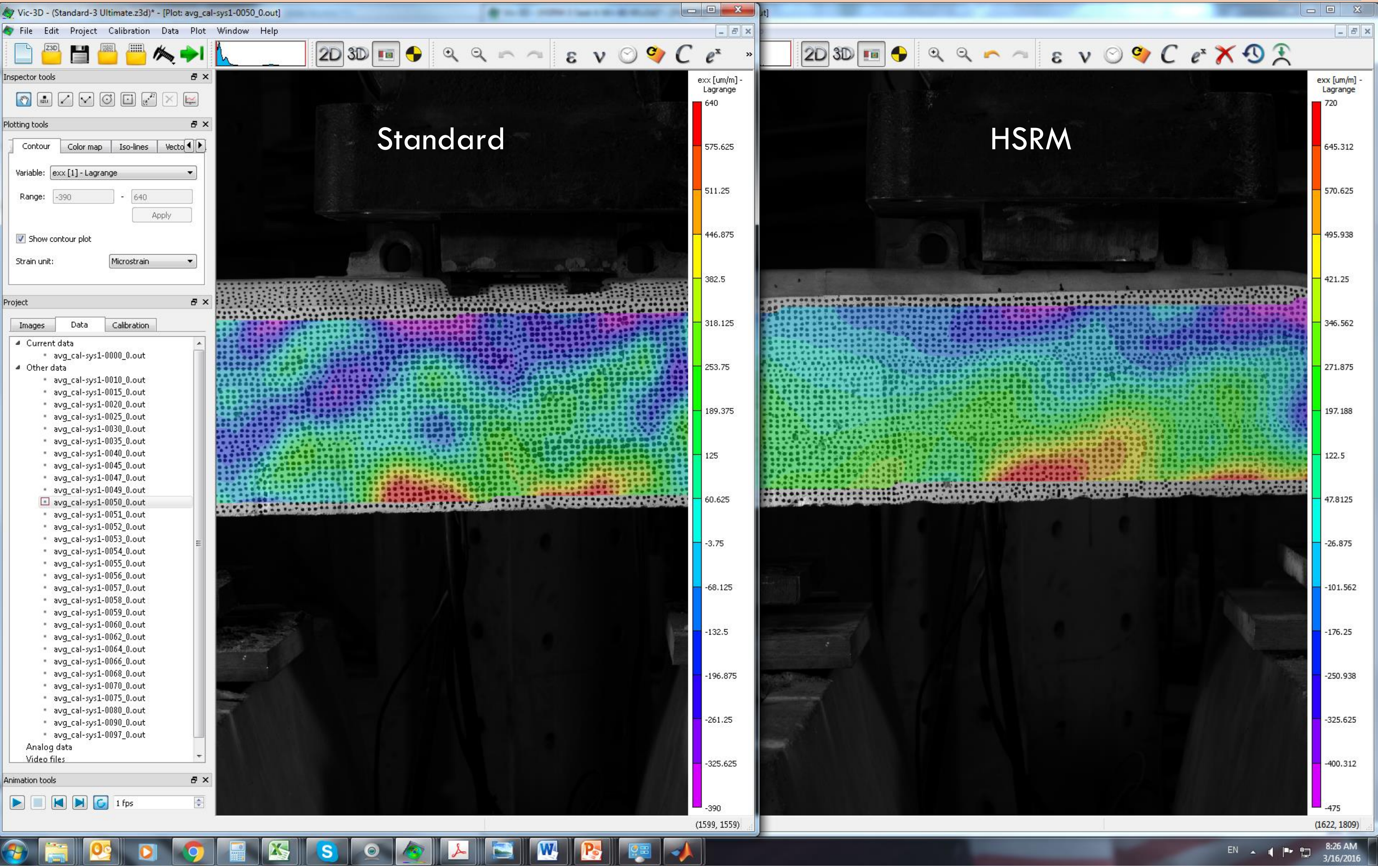
Rail Seat – Ultimate Positive

P=45 kips

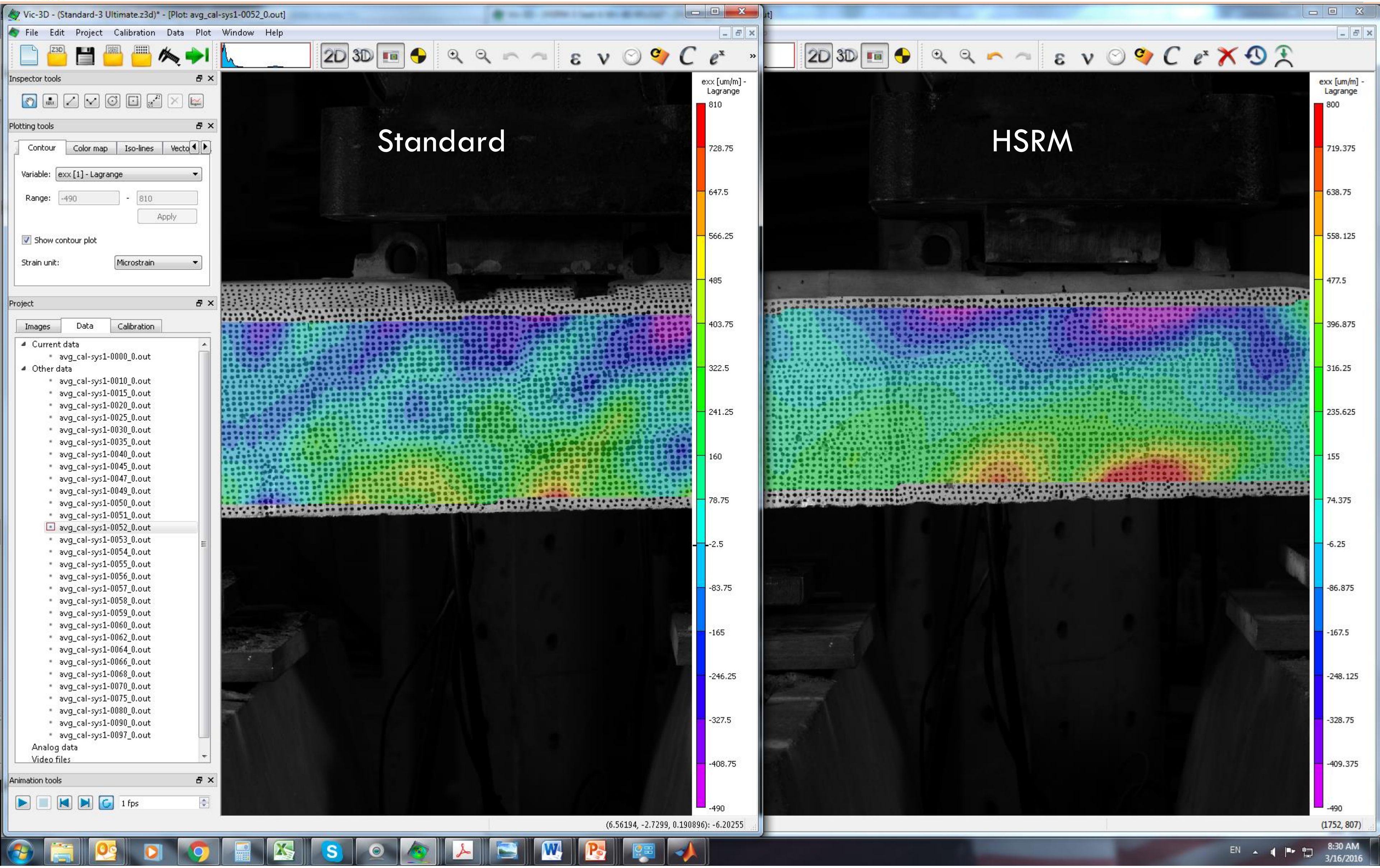


Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0045_0.out]
Standard
HSRM
exx [um/m] - Lagrange
430
379.688
329.375
279.062
228.75
178.438
128.125
77.8125
27.5
-22.8125
-73.125
-123.438
-173.75
-224.062
-274.375
-324.688
-375
exx [um/m] - Lagrange
735
663.438
591.875
520.312
448.75
377.188
305.625
234.062
162.5
90.9375
19.375
-52.1875
-123.75
-195.312
-266.875
-338.438
-410
Variable: exx [1] - Lagrange
Range: -375 - 430
Show contour plot
Strain unit: Microstrain
(1642, 647)
(1304, 397)

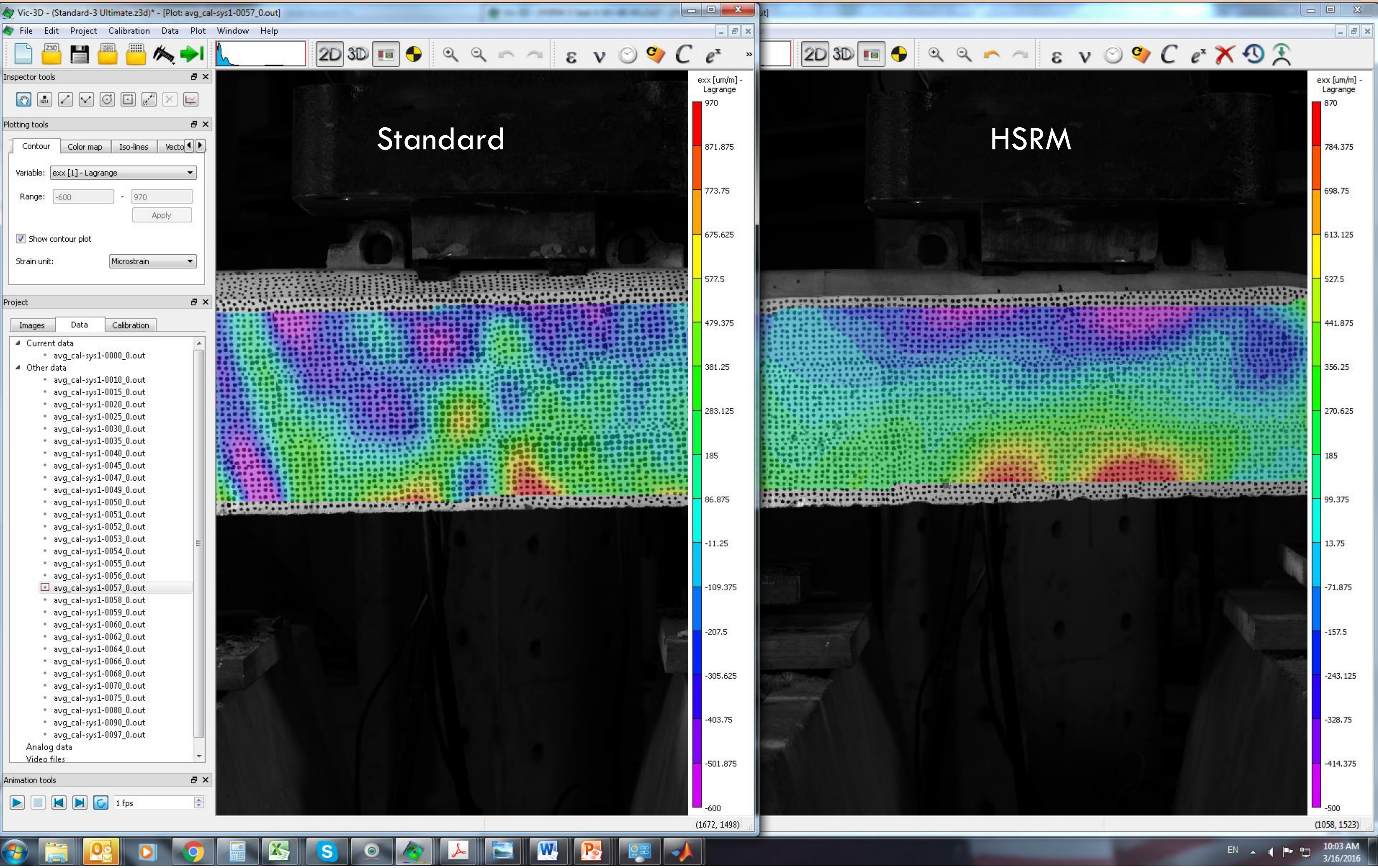
P=50 kips


Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0050_0.out]
Standard
HSRM
exx [um/m] - Lagrange
640
575.625
511.25
446.875
382.5
318.125
253.75
189.375
125
60.625
-3.75
-68.125
-132.5
-196.875
-261.25
-325.625
-390
exx [um/m] - Lagrange
720
645.312
570.625
495.938
421.25
346.562
271.875
197.188
122.5
47.8125
-26.875
-101.562
-176.25
-250.938
-325.625
-400.312
-475
Variable: exx [1] - Lagrange
Range: -390 - 640
Show contour plot
Strain unit: Microstrain
(1599, 1559)
(1622, 1809)

P=52 kips

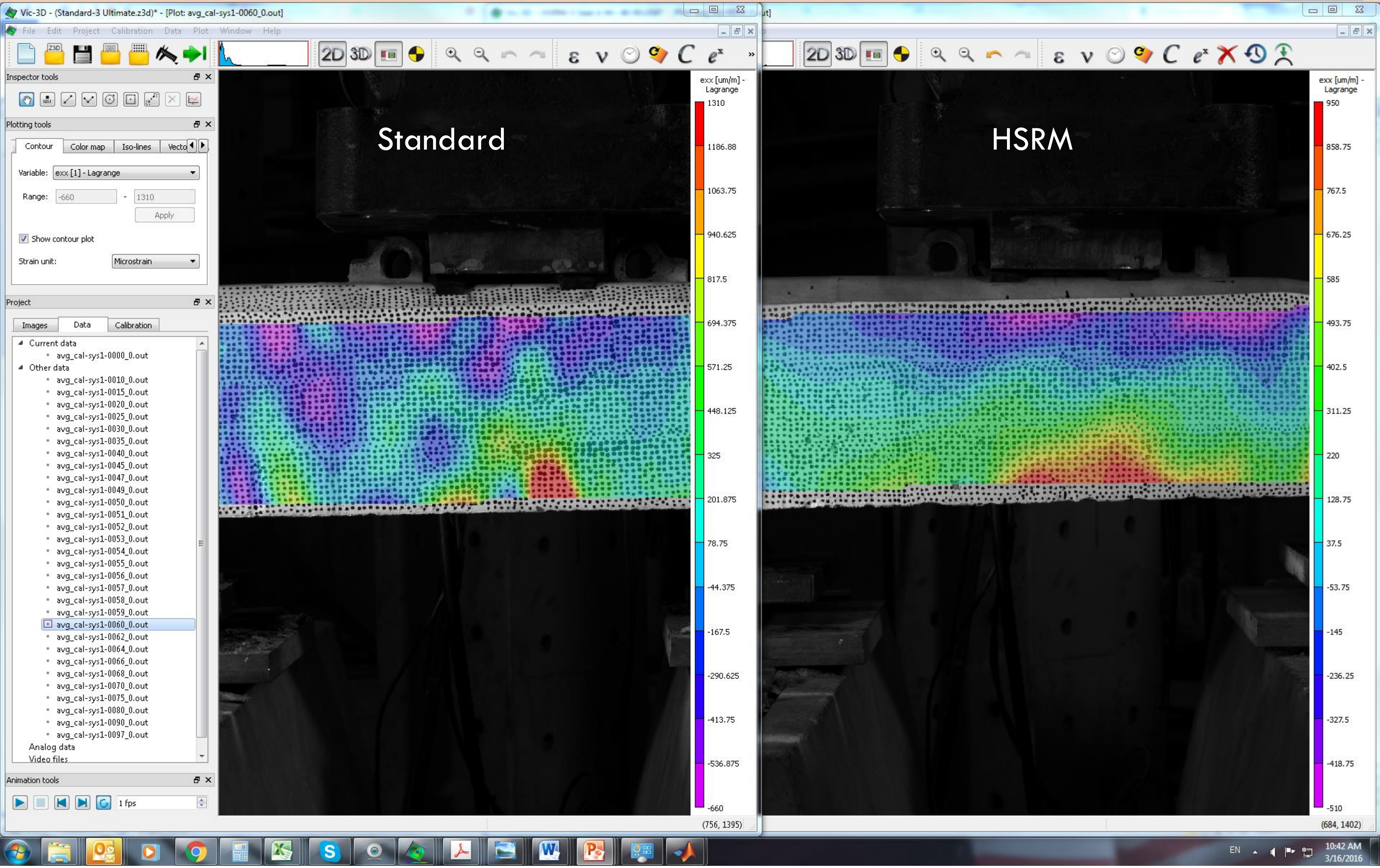

Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0052_0.out]
File Edit Project Calibration Data Plot Window Help
Inspector tools
Plotting tools
Contour Color map Iso-lines
Variable: exx [1] - Lagrange
Range: -490 - 810
Apply
Show contour plot
Strain unit: Microstrain
Project
Images Data Calibration
Current data
avg_cal-sys1-0000_0.out
Other data
avg_cal-sys1-0010_0.out
avg_cal-sys1-0015_0.out
avg_cal-sys1-0020_0.out
avg_cal-sys1-0025_0.out
avg_cal-sys1-0030_0.out
avg_cal-sys1-0035_0.out
avg_cal-sys1-0040_0.out
avg_cal-sys1-0045_0.out
avg_cal-sys1-0047_0.out
avg_cal-sys1-0049_0.out
avg_cal-sys1-0050_0.out
avg_cal-sys1-0051_0.out
avg_cal-sys1-0052_0.out
avg_cal-sys1-0053_0.out
avg_cal-sys1-0054_0.out
avg_cal-sys1-0055_0.out
avg_cal-sys1-0056_0.out
avg_cal-sys1-0057_0.out
avg_cal-sys1-0058_0.out
avg_cal-sys1-0059_0.out
avg_cal-sys1-0060_0.out
avg_cal-sys1-0062_0.out
avg_cal-sys1-0064_0.out
avg_cal-sys1-0066_0.out
avg_cal-sys1-0068_0.out
avg_cal-sys1-0070_0.out
avg_cal-sys1-0075_0.out
avg_cal-sys1-0080_0.out
avg_cal-sys1-0090_0.out
avg_cal-sys1-0097_0.out
Analog data
Video files
Animation tools
1 fps
Standard
exx [um/m] - Lagrange
810
728.75
647.5
566.25
485
403.75
322.5
241.25
160
78.75
-2.5
-83.75
-165
-246.25
-327.5
-408.75
-490
(6.56194, -2.7299, 0.190896): -6.20255
HSRM
exx [um/m] - Lagrange
800
719.375
638.75
558.125
477.5
396.875
316.25
235.625
155
74.375
-6.25
-86.875
-167.5
-248.125
-328.75
-409.375
-490
(1752, 807)
EN
8:30 AM
3/16/2016

P=57 kips

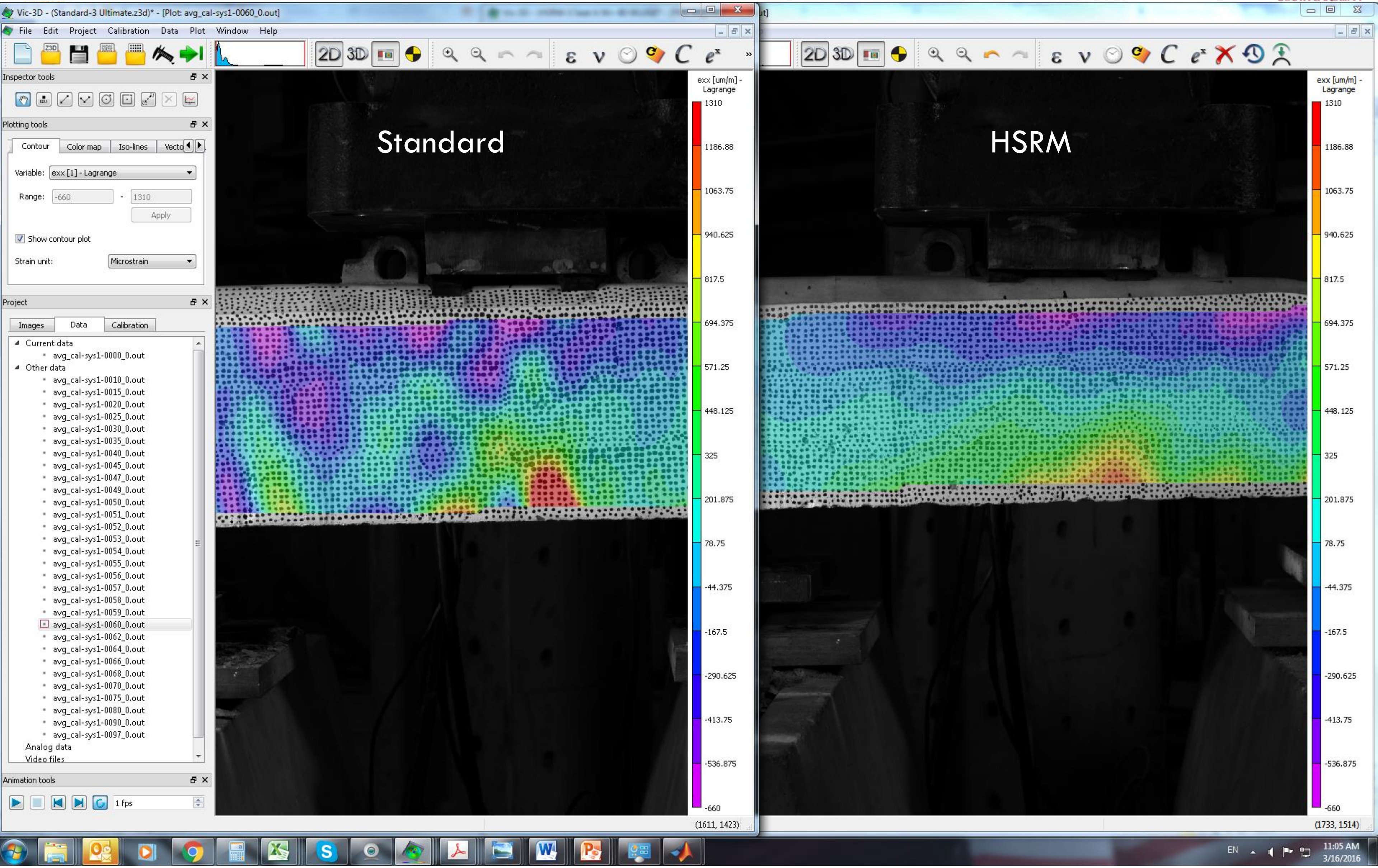


Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0057_0.out]
File Edit Project Calibration Data Plot Window Help
Inspector tools
Plotting tools
Contour
Color map
Iso-lines
Variable: exx [1] - Lagrange
Range: -600 - 970
Apply
Show contour plot
Strain unit: Microstrain
Project
Images
Data
Calibration
Current data
avg_cal-sys1-0000_0.out
Other data
avg_cal-sys1-0057_0.out
Analog data
Video files
Animation tools
1 fps
Standard
HSRM
exx [um/m] - Lagrange
970
871.875
773.75
675.625
577.5
479.375
381.25
283.125
185
86.875
-11.25
-109.375
-207.5
-305.625
-403.75
-501.875
-600
(1672, 1498)
exx [um/m] - Lagrange
870
784.375
698.75
613.125
527.5
441.875
356.25
270.625
185
99.375
13.75
-71.875
-157.5
-243.125
-328.75
-414.375
-500
(1058, 1523)
10:03 AM
3/16/2016

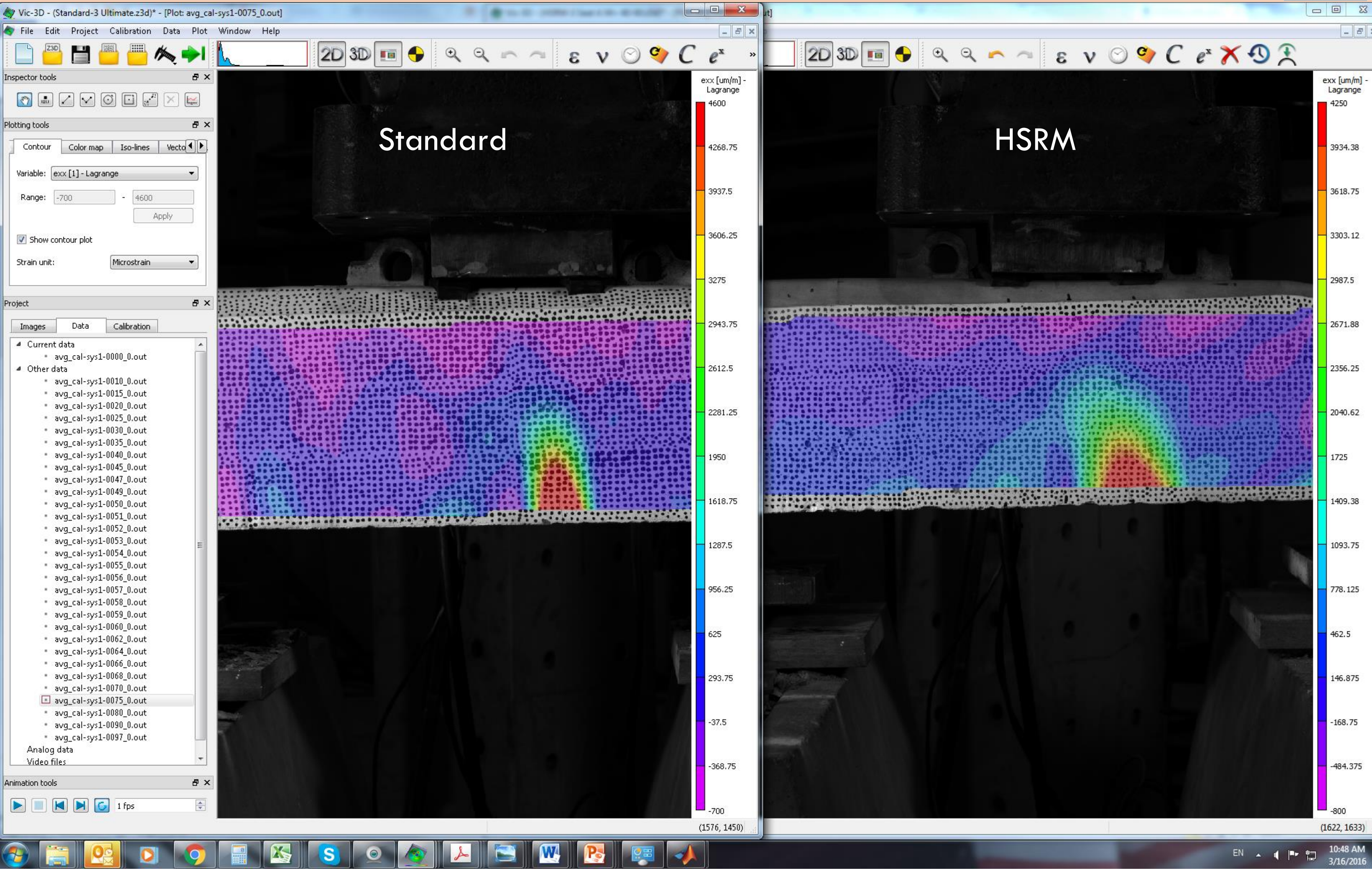
P=60 kips


Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0060_0.out]
File Edit Project Calibration Data Plot Window Help
Inspector tools
Plotting tools
Contour
Color map
Iso-lines
Variable: exx [1] - Lagrange
Range: -660 - 1310
Apply
Show contour plot
Strain unit: Microstrain
Project
Images
Data
Calibration
Current data
avg_cal-sys1-0000_0.out
Other data
avg_cal-sys1-0010_0.out
avg_cal-sys1-0015_0.out
avg_cal-sys1-0020_0.out
avg_cal-sys1-0025_0.out
avg_cal-sys1-0030_0.out
avg_cal-sys1-0035_0.out
avg_cal-sys1-0040_0.out
avg_cal-sys1-0045_0.out
avg_cal-sys1-0047_0.out
avg_cal-sys1-0049_0.out
avg_cal-sys1-0050_0.out
avg_cal-sys1-0051_0.out
avg_cal-sys1-0052_0.out
avg_cal-sys1-0053_0.out
avg_cal-sys1-0054_0.out
avg_cal-sys1-0055_0.out
avg_cal-sys1-0056_0.out
avg_cal-sys1-0057_0.out
avg_cal-sys1-0058_0.out
avg_cal-sys1-0059_0.out
avg_cal-sys1-0060_0.out
avg_cal-sys1-0062_0.out
avg_cal-sys1-0064_0.out
avg_cal-sys1-0066_0.out
avg_cal-sys1-0068_0.out
avg_cal-sys1-0070_0.out
avg_cal-sys1-0075_0.out
avg_cal-sys1-0080_0.out
avg_cal-sys1-0090_0.out
avg_cal-sys1-0097_0.out
Analog data
Video files
Animation tools
1 fps
Standard
exx [um/m] - Lagrange
1310
1186.88
1063.75
940.625
817.5
694.375
571.25
448.125
325
201.875
78.75
-44.375
-167.5
-290.625
-413.75
-536.875
-660
(756, 1395)
HSRM
exx [um/m] - Lagrange
950
858.75
767.5
676.25
585
493.75
402.5
311.25
220
128.75
37.5
-53.75
-145
-236.25
-327.5
-418.75
-510
(684, 1402)
EN
10:42 AM
3/16/2016

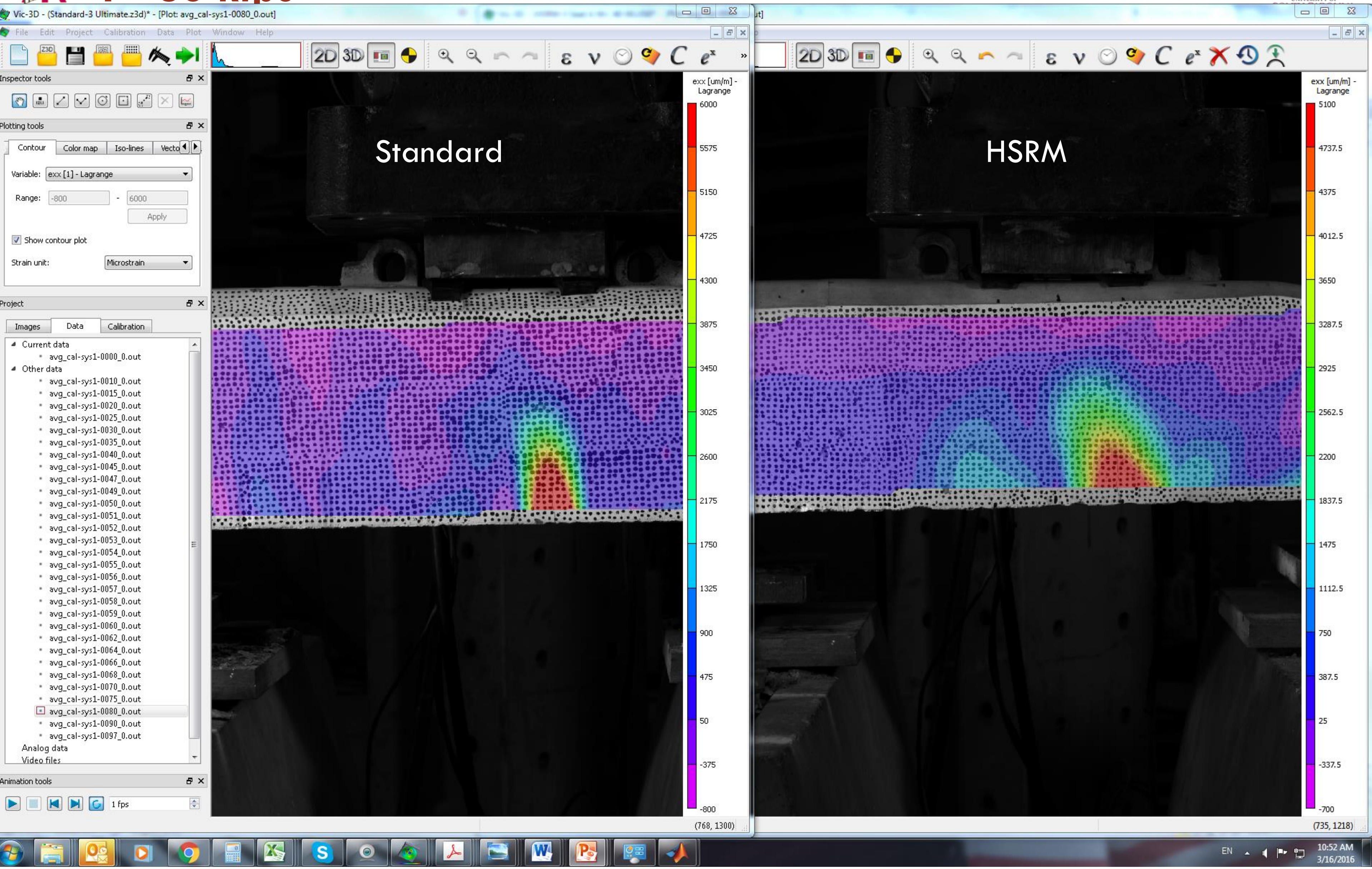
P=60 kips Same Scale



P=75 kips

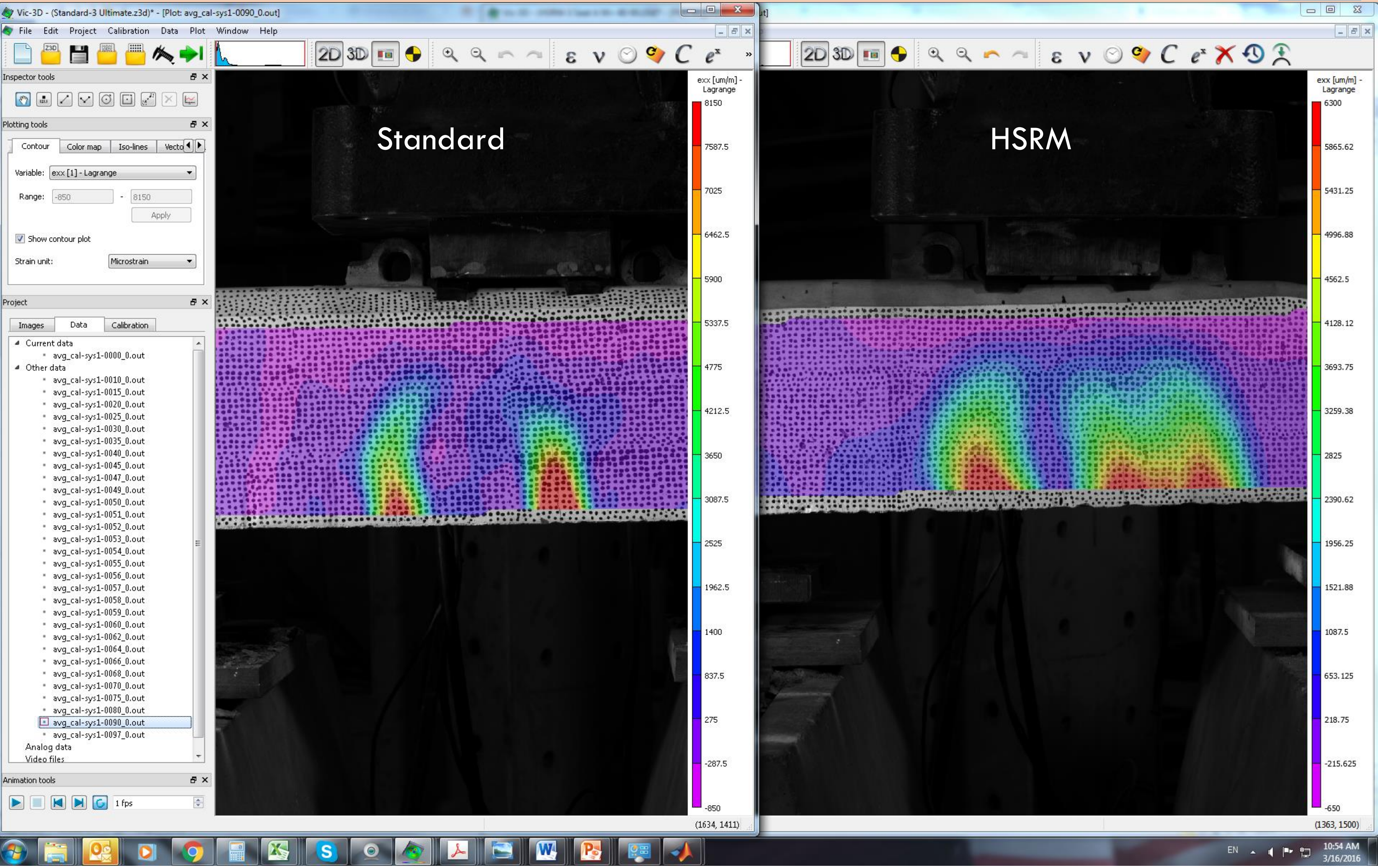

Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0075_0.out]
Standard
HSRM
exx [um/m] - Lagrange
4600
4268.75
3937.5
3606.25
3275
2943.75
2612.5
2281.25
1950
1618.75
1287.5
956.25
625
293.75
-37.5
-368.75
-700
exx [um/m] - Lagrange
4250
3934.38
3618.75
3303.12
2987.5
2671.88
2356.25
2040.62
1725
1409.38
1093.75
778.125
462.5
146.875
-168.75
-484.375
-800
Variable: exx [1] - Lagrange
Range: -700 - 4600
Strain unit: Microstrain

P=80 kips



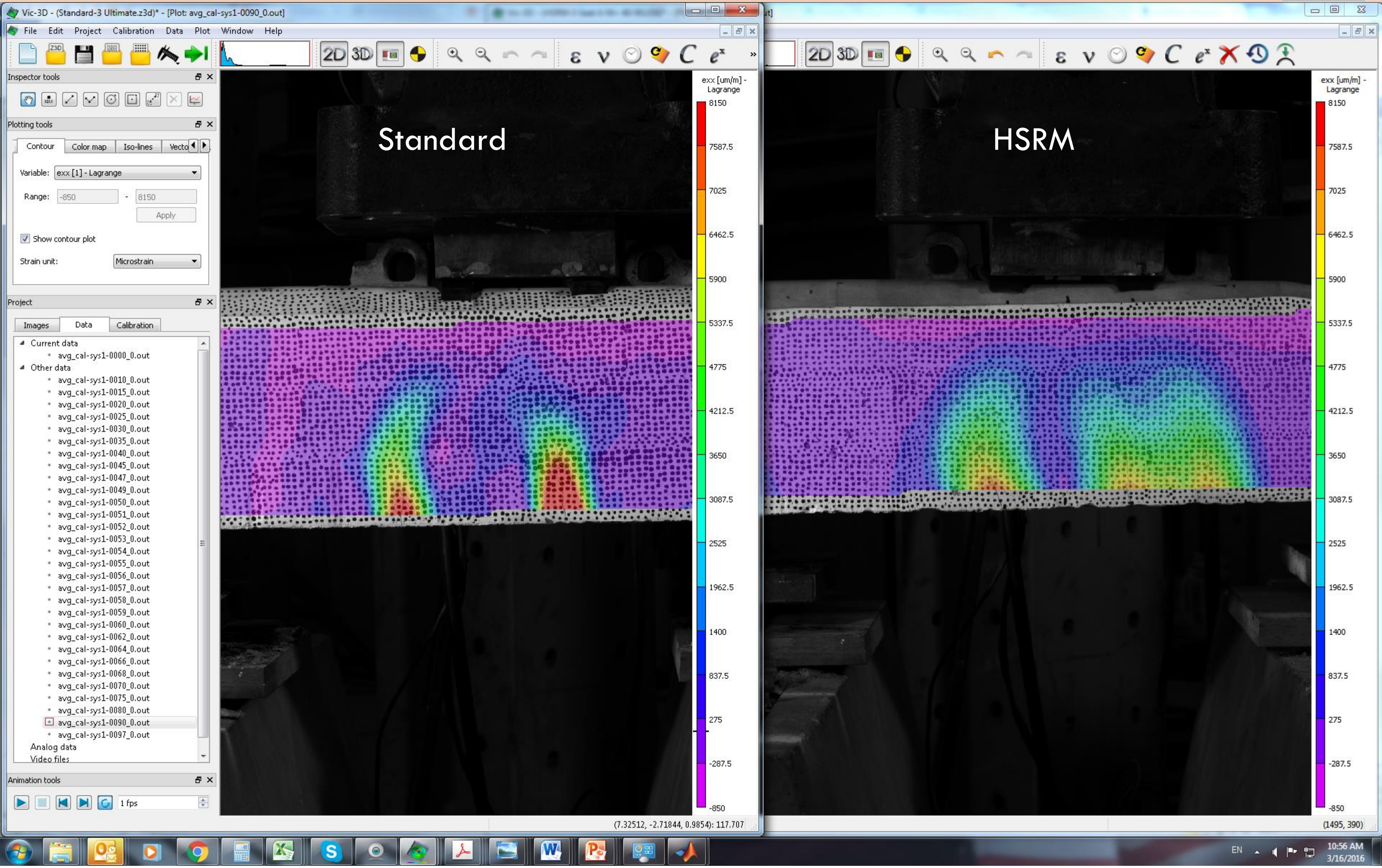
Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0080_0.out]
Standard
HSRM
exx [um/m] - Lagrange
6000
5575
5150
4725
4300
3875
3450
3025
2600
2175
1750
1325
900
475
50
-375
-800
exx [um/m] - Lagrange
5100
4737.5
4375
4012.5
3650
3287.5
2925
2562.5
2200
1837.5
1475
1112.5
750
387.5
25
-337.5
-700

P=90 kips

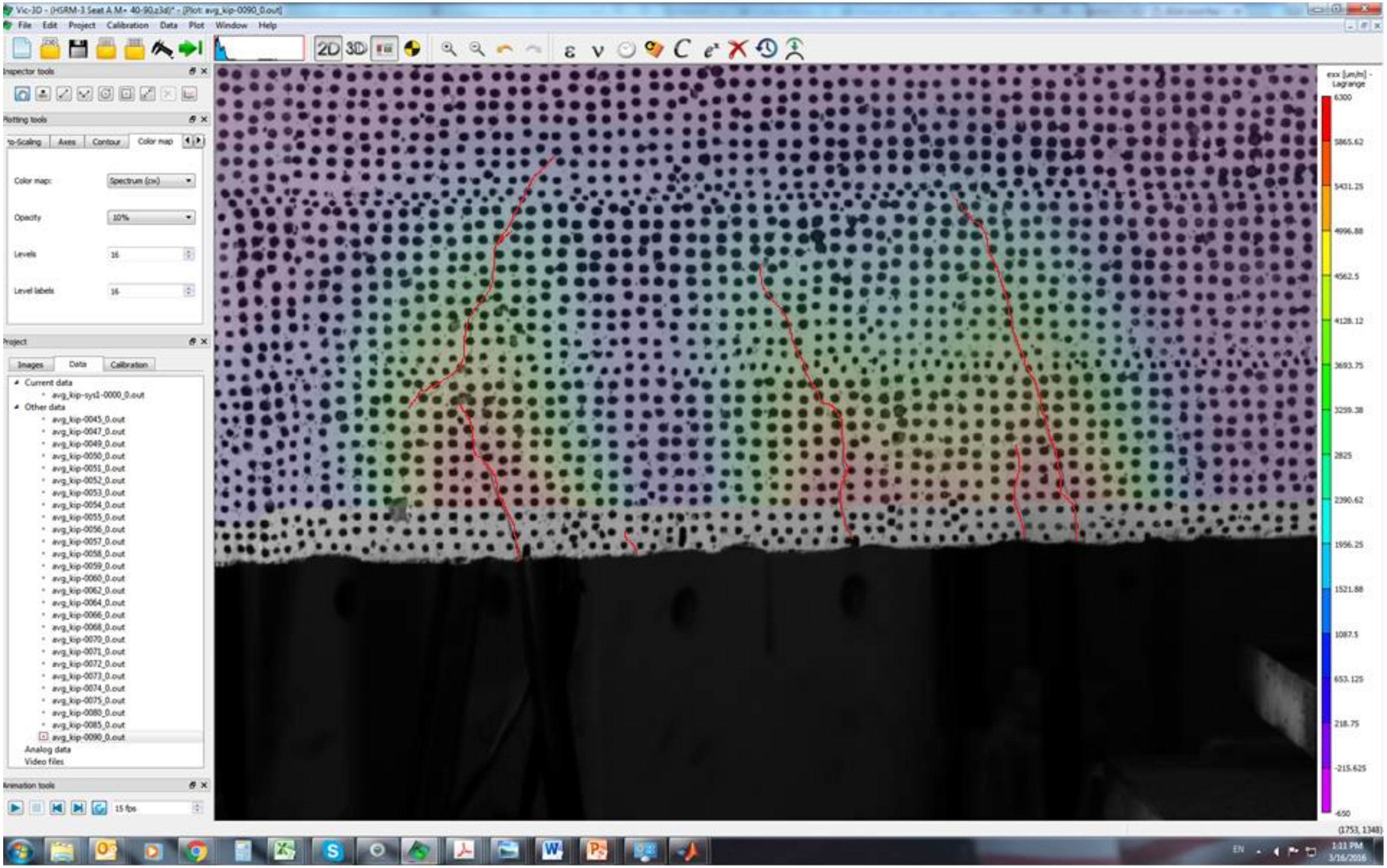


Vic-3D - (Standard-3 Ultimate.z3d)* - [Plot: avg_cal-sys1-0090_0.out]
File Edit Project Calibration Data Plot Window Help
Inspector tools
Plotting tools
Contour
Color map
Iso-lines
Variable: exx [1] - Lagrange
Range: -850 - 8150
Apply
Show contour plot
Strain unit: Microstrain
Project
Images
Data
Calibration
Current data
avg_cal-sys1-0000_0.out
Other data
avg_cal-sys1-0010_0.out
avg_cal-sys1-0015_0.out
avg_cal-sys1-0020_0.out
avg_cal-sys1-0025_0.out
avg_cal-sys1-0030_0.out
avg_cal-sys1-0035_0.out
avg_cal-sys1-0040_0.out
avg_cal-sys1-0045_0.out
avg_cal-sys1-0047_0.out
avg_cal-sys1-0049_0.out
avg_cal-sys1-0050_0.out
avg_cal-sys1-0051_0.out
avg_cal-sys1-0052_0.out
avg_cal-sys1-0053_0.out
avg_cal-sys1-0054_0.out
avg_cal-sys1-0055_0.out
avg_cal-sys1-0056_0.out
avg_cal-sys1-0057_0.out
avg_cal-sys1-0058_0.out
avg_cal-sys1-0059_0.out
avg_cal-sys1-0060_0.out
avg_cal-sys1-0062_0.out
avg_cal-sys1-0064_0.out
avg_cal-sys1-0066_0.out
avg_cal-sys1-0068_0.out
avg_cal-sys1-0070_0.out
avg_cal-sys1-0075_0.out
avg_cal-sys1-0080_0.out
avg_cal-sys1-0090_0.out
avg_cal-sys1-0097_0.out
Analog data
Video files
Animation tools
1 fps
Standard
exx [um/m] - Lagrange
8150
7587.5
7025
6462.5
5900
5337.5
4775
4212.5
3650
3087.5
2525
1962.5
1400
837.5
275
-287.5
-850
(1634, 1411)
HSRM
exx [um/m] - Lagrange
6300
5865.62
5431.25
4996.88
4562.5
4128.12
3693.75
3259.38
2825
2390.62
1956.25
1521.88
1087.5
653.125
218.75
-215.625
-650
(1363, 1500)
EN
10:54 AM
3/16/2016

P=90 kips – Same Scale



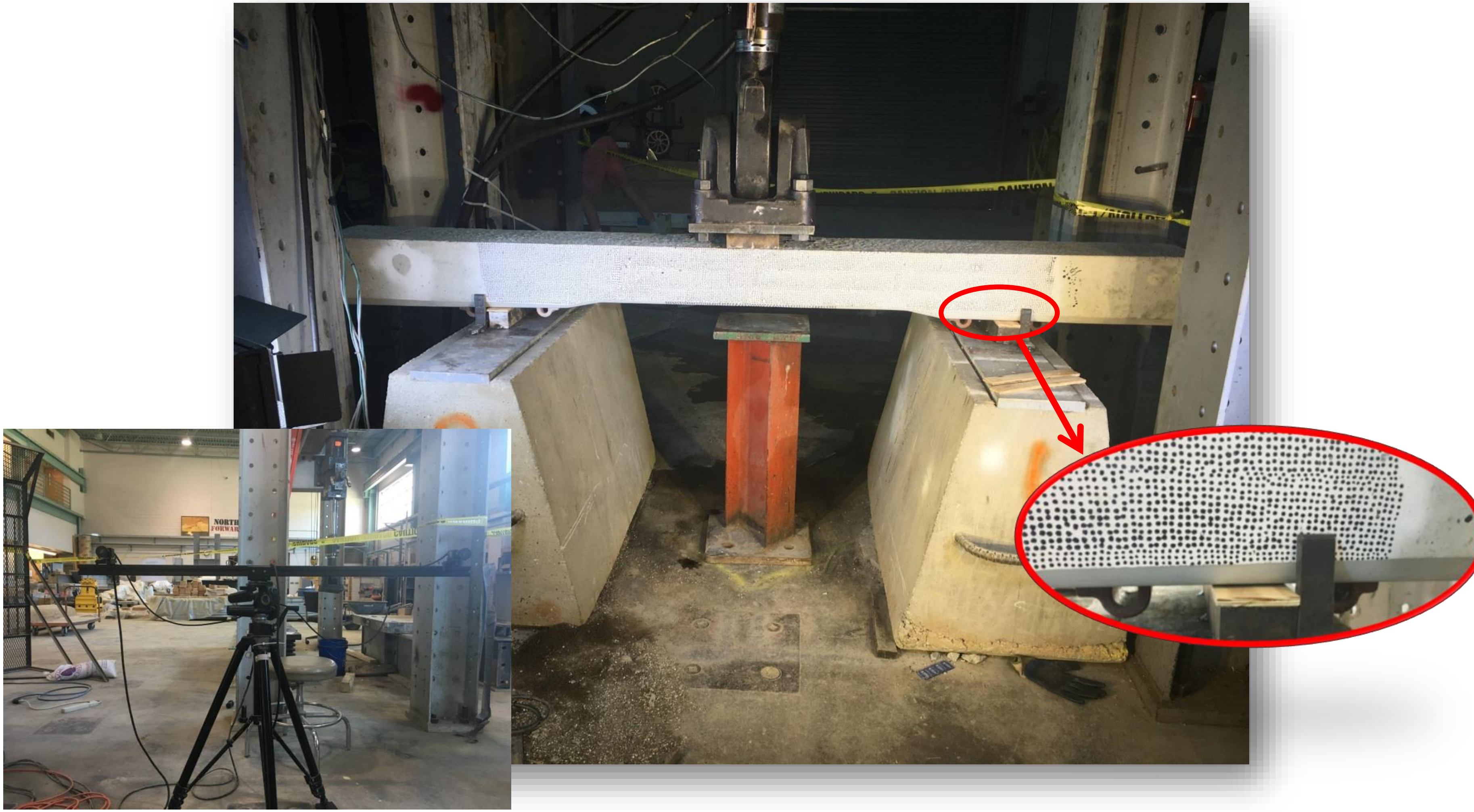
HSRM-Cracking at P=90 kips



Fatigue - Center Negative

Fatigue – Center Negative

Test Setup



Fatigue – Center Negative: Testing Procedure

1. Specimen loaded to 90% of design load (13.5 kips)
   - Strain field captured every 2 kips
2. Cyclic Loading in the range 2-13.5 kips at a rate of 2 load cycles/sec
3. At 500,000 load cycles cyclic loading is paused and the specimen is loaded statically to 90% of design load
   - Strain field captured every 2 kips
4. Cyclic load resumes and continues for ~48 hours (~345,000 additional cycles)
5. Cyclic loading is paused and the specimen is loaded statically to 90% of design load
   - Strain field captured every 2 kips
6. Steps 4-6 are repeated until number of loading cycles exceeds 3 million.

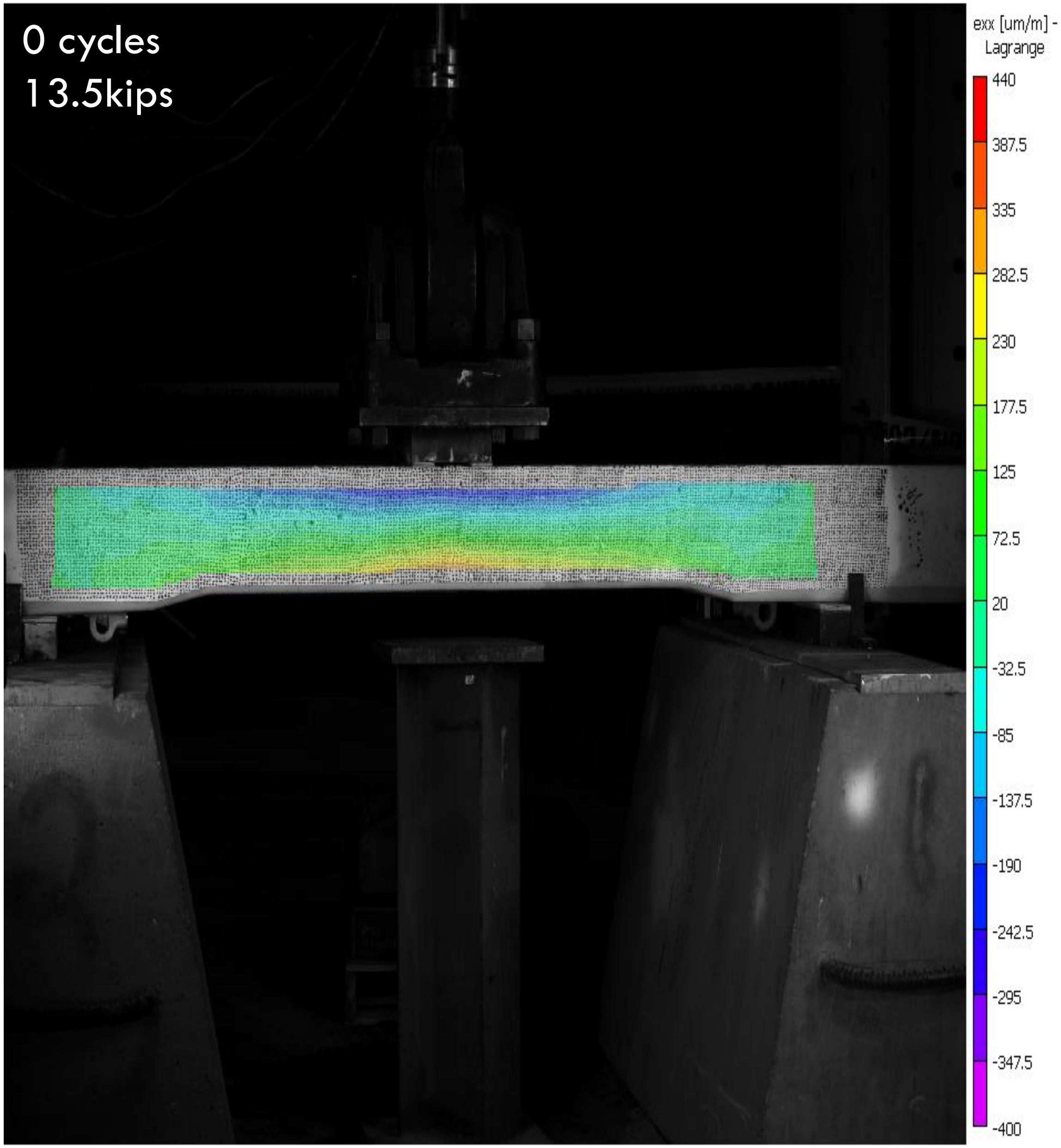
Fatigue – Center Negative: Testing Procedure (cont'd)

7. A crack is induced to the first line of strands and the corresponding load P_{crack} is recorded as 17.5kips (to first strand).
   - Strain field captured every 2 kips
8. Cyclic Loading in the range 2 kips - 110% of design load (2-16.5kips) at a rate of 2 load cycles/sec.
9. At 500,000 load cycles cyclic loading is paused and the specimen is loaded statically to design load.
   - Strain field captured every 2 kips
10. Cyclic load resumes and continues for ~48 hours (~345,000 additional cycles)
11. Cyclic loading is paused and the specimen is loaded statically to 110% design load (16.5kip)
    - Strain field captured every 2 kips
12. Steps 10-12 are repeated until number of loading cycles exceeds 3 million.
13. Specimen is loaded to failure
    - Strain field captured every 2 kips

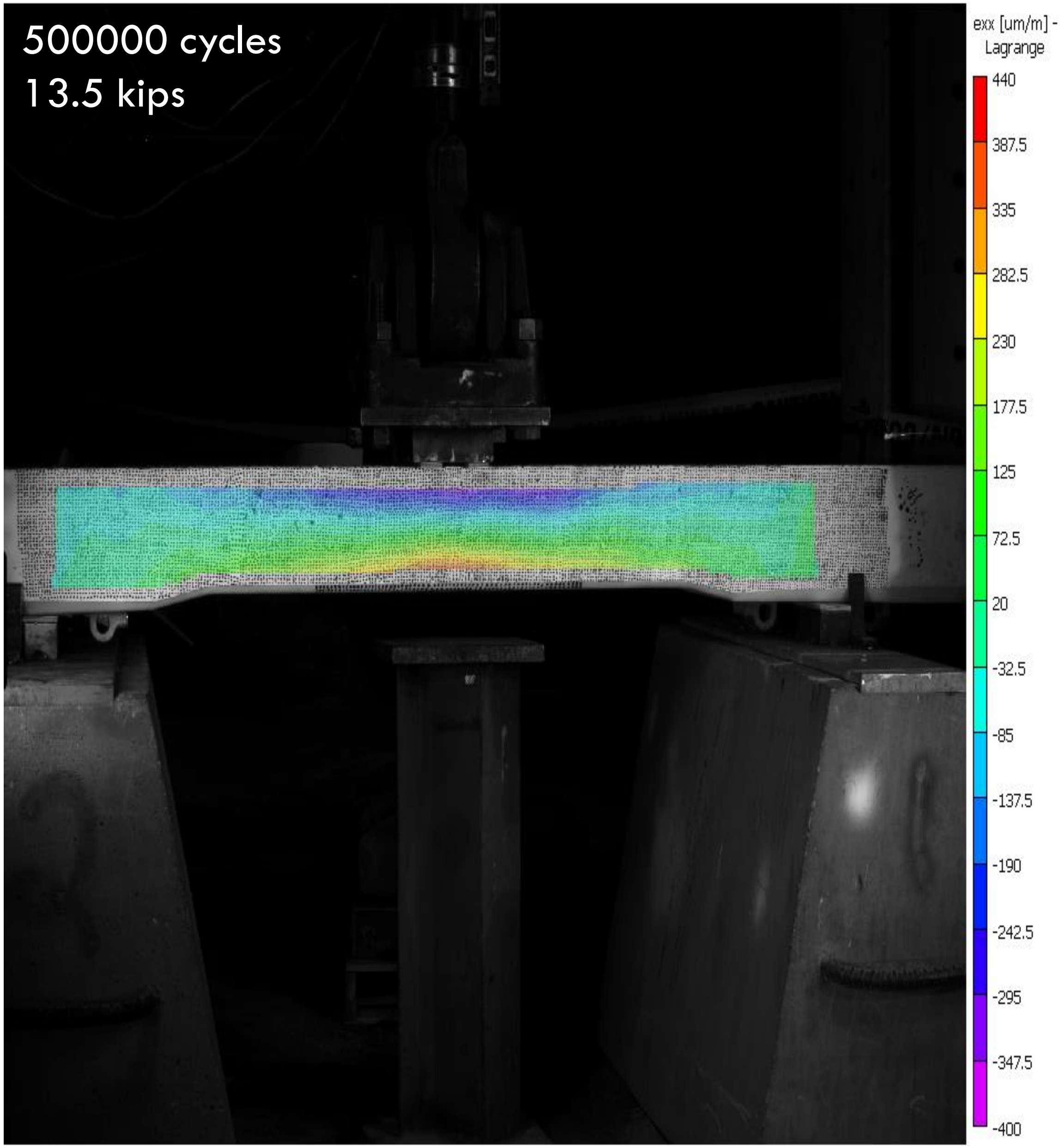
Stage 1 – No Crack

3,000,000 cycles

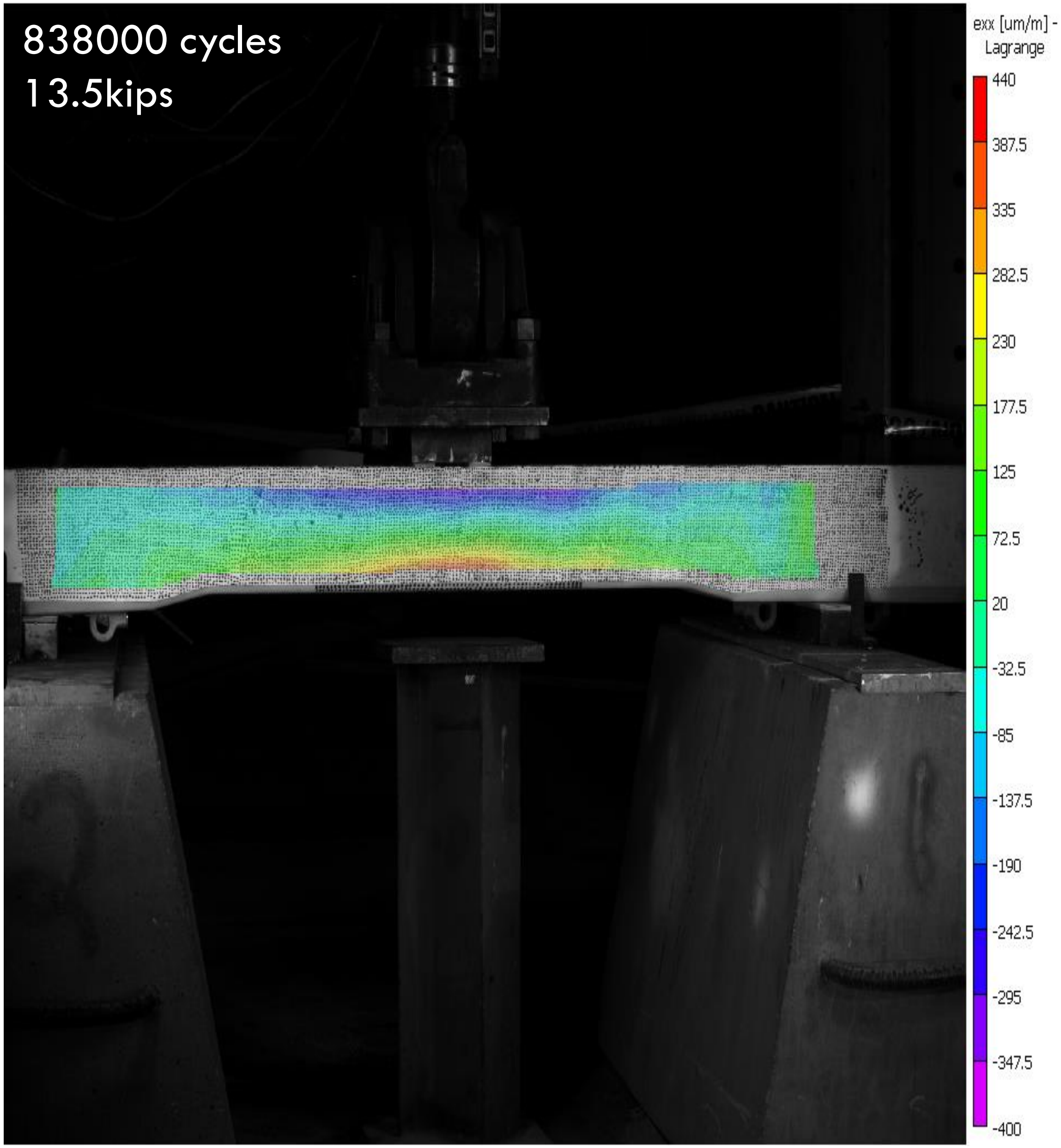
HSRM – Center Negative Moment (Fatigue)



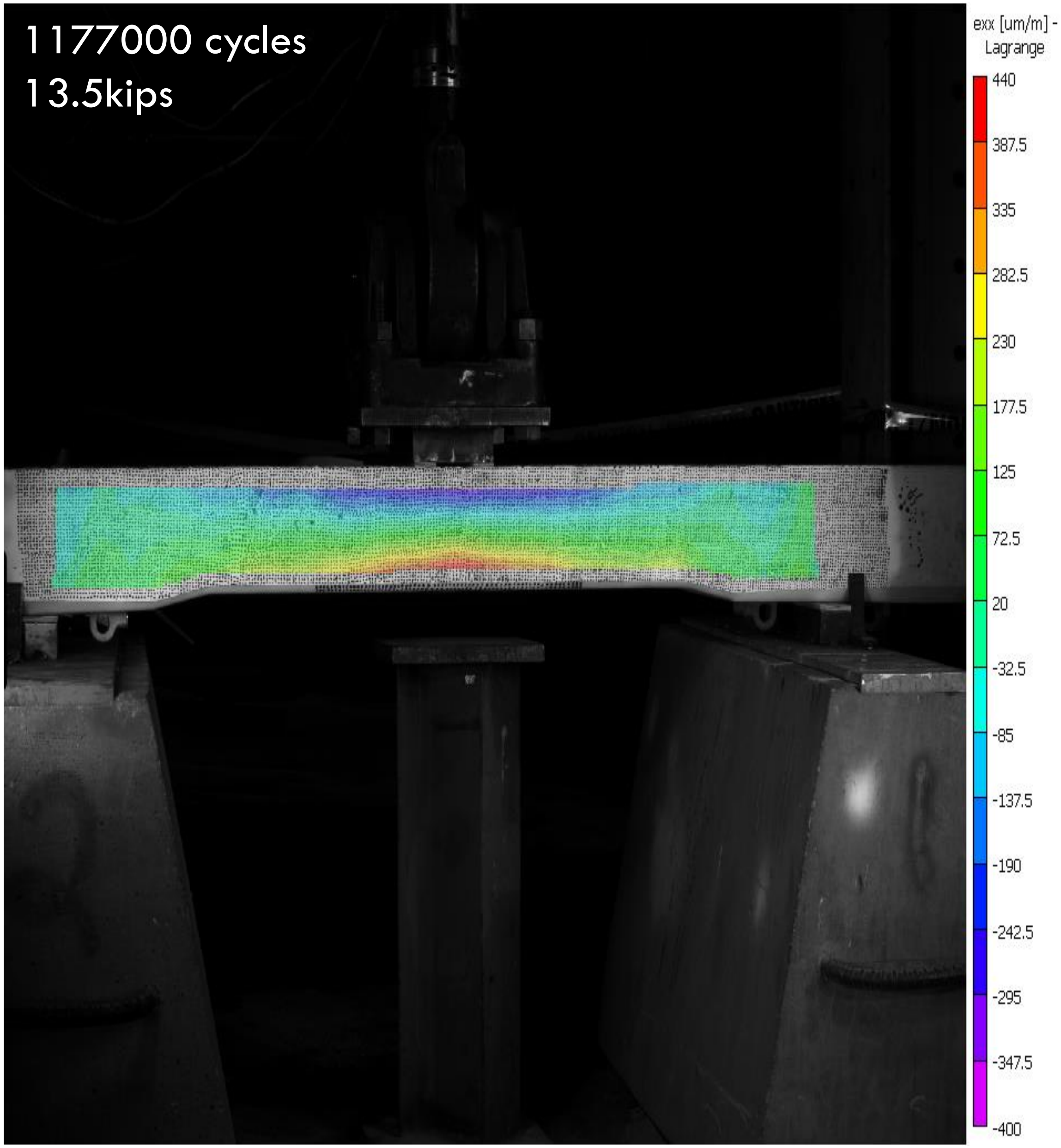
HSRM – Center Negative Moment (Fatigue)



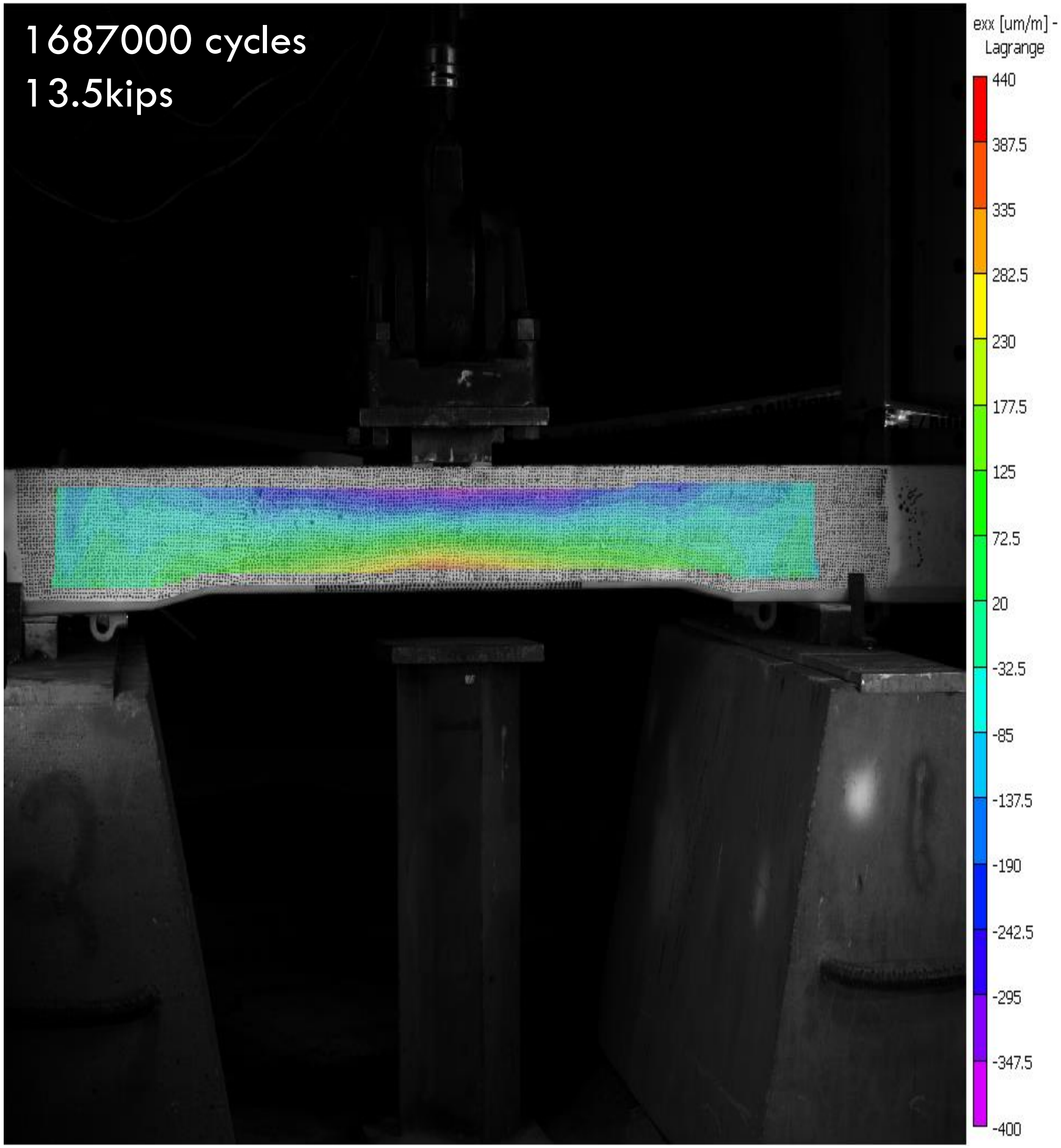
HSRM – Center Negative Moment (Fatigue)



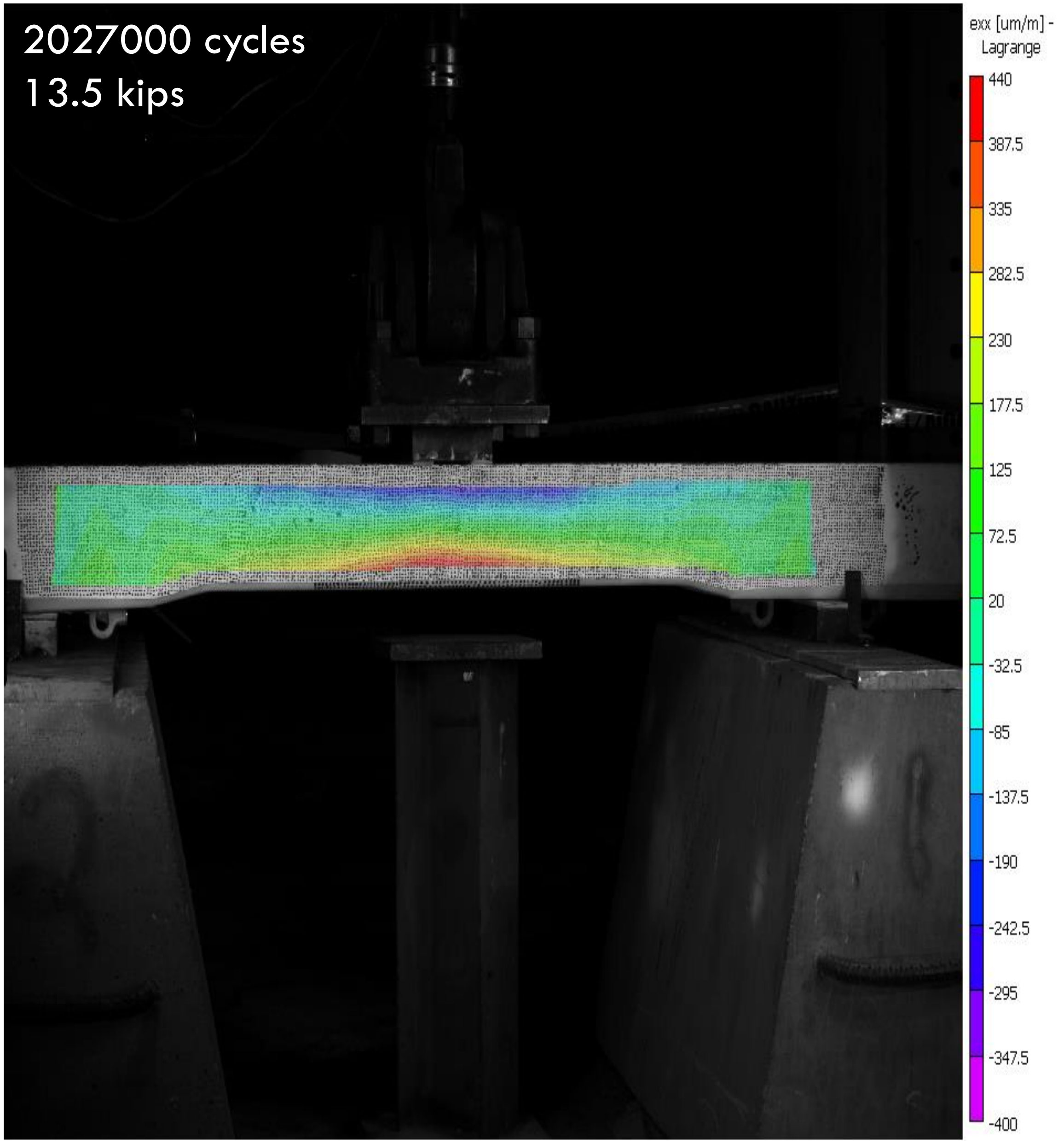
HSRM – Center Negative Moment (Fatigue)



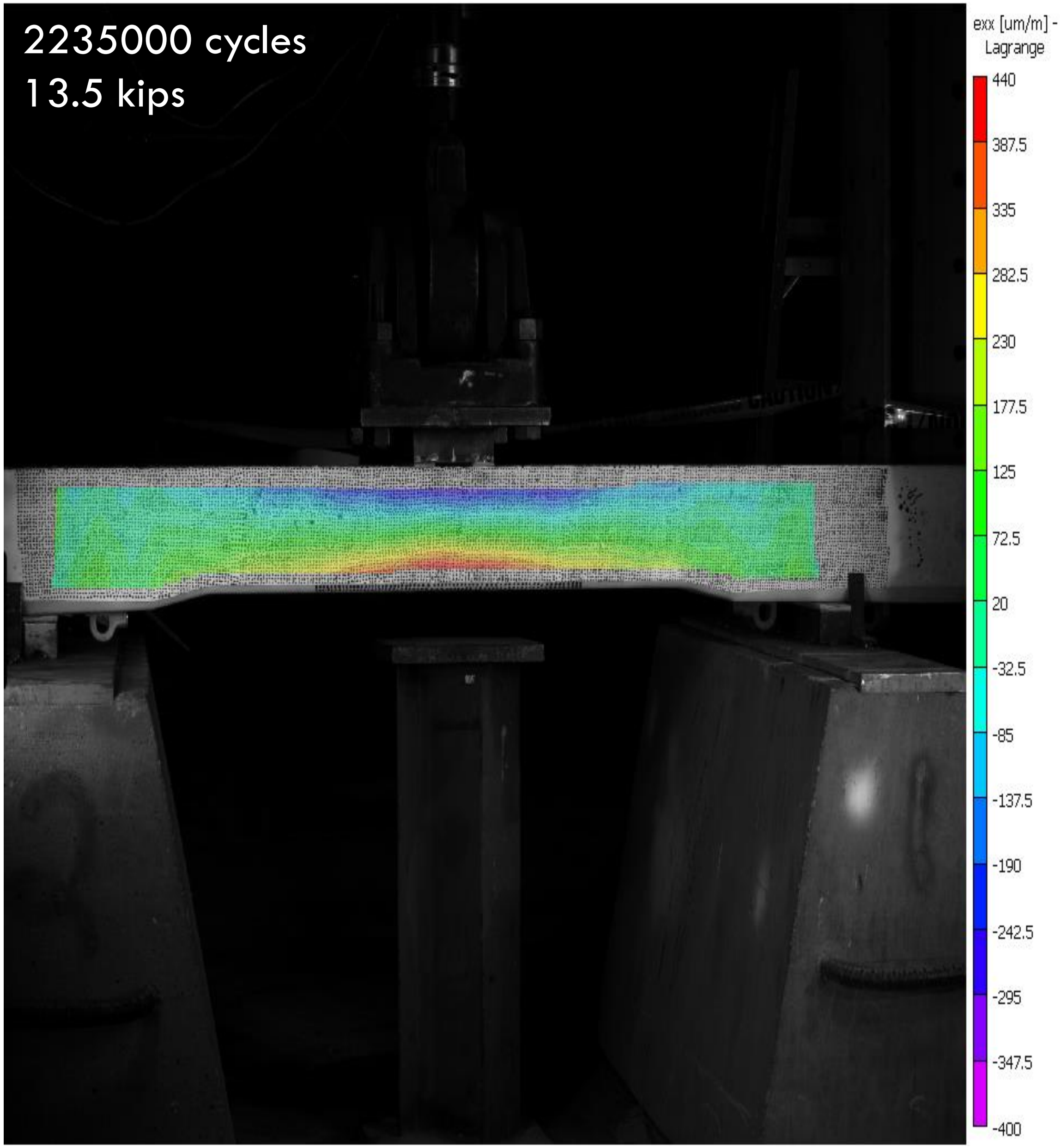
HSRM – Center Negative Moment (Fatigue)



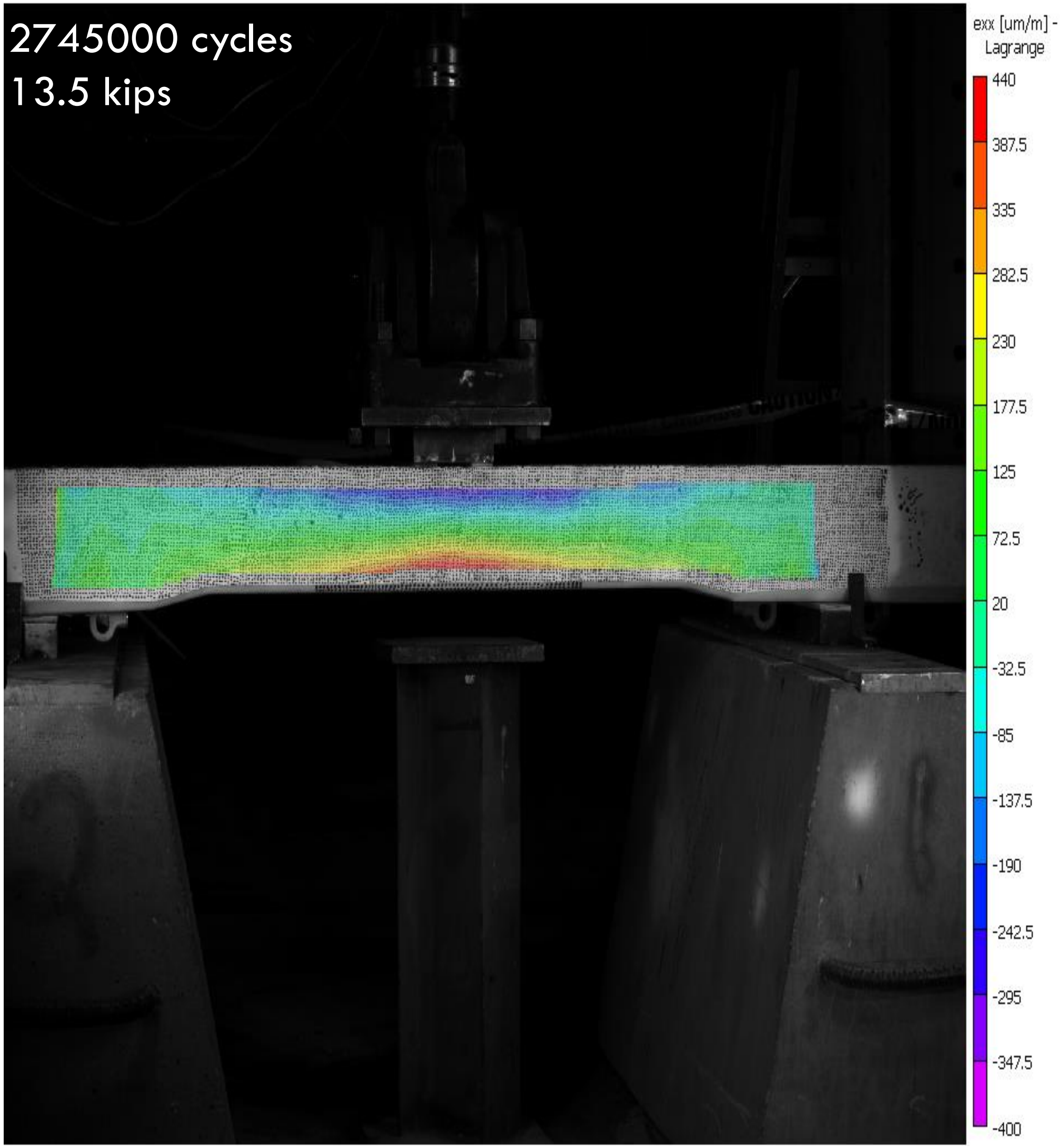
HSRM – Center Negative Moment (Fatigue)



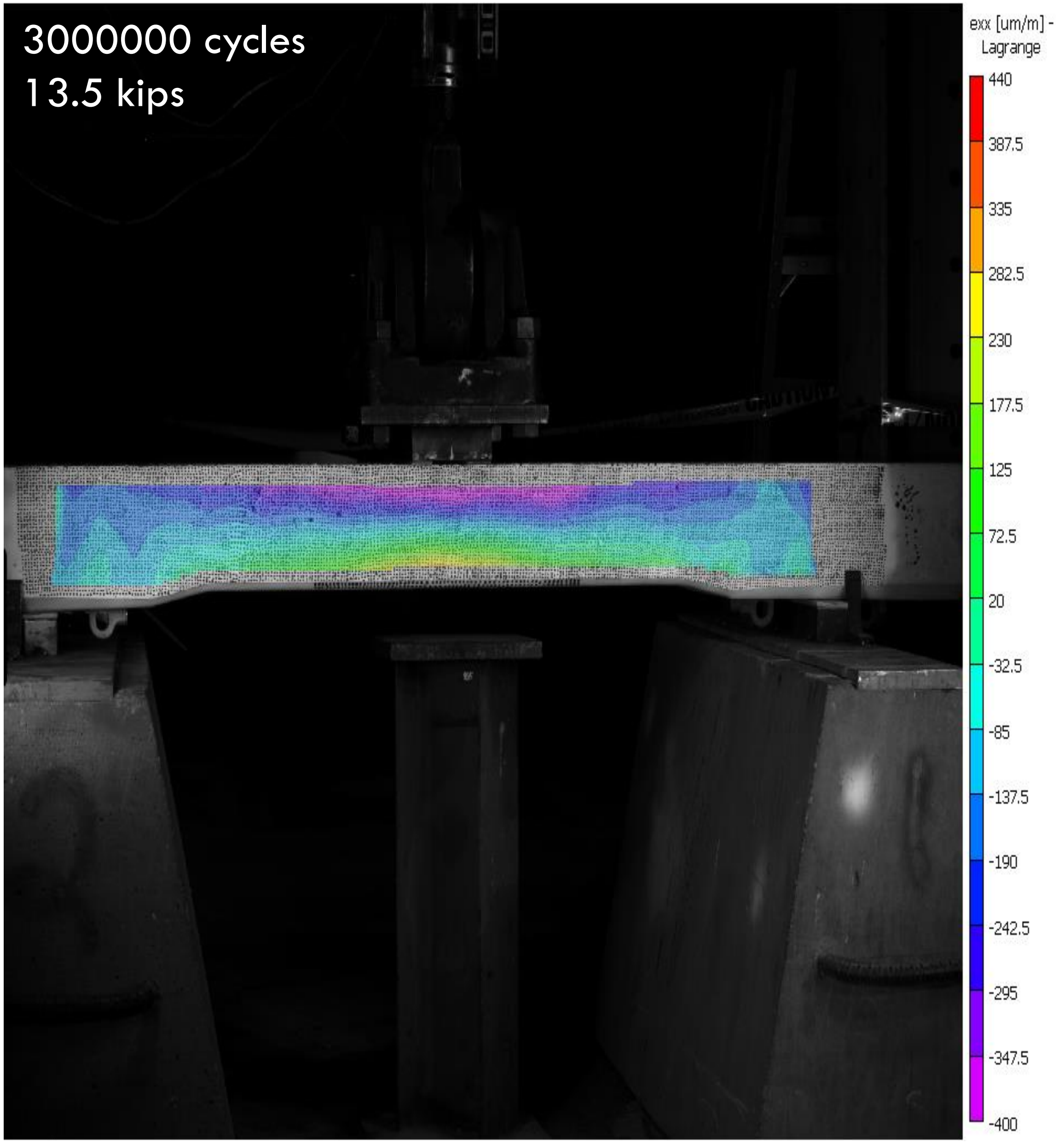
HSRM – Center Negative Moment (Fatigue)



HSRM – Center Negative Moment (Fatigue)



HSRM – Center Negative Moment (Fatigue)



Fatigue – Center Negative: Discussion

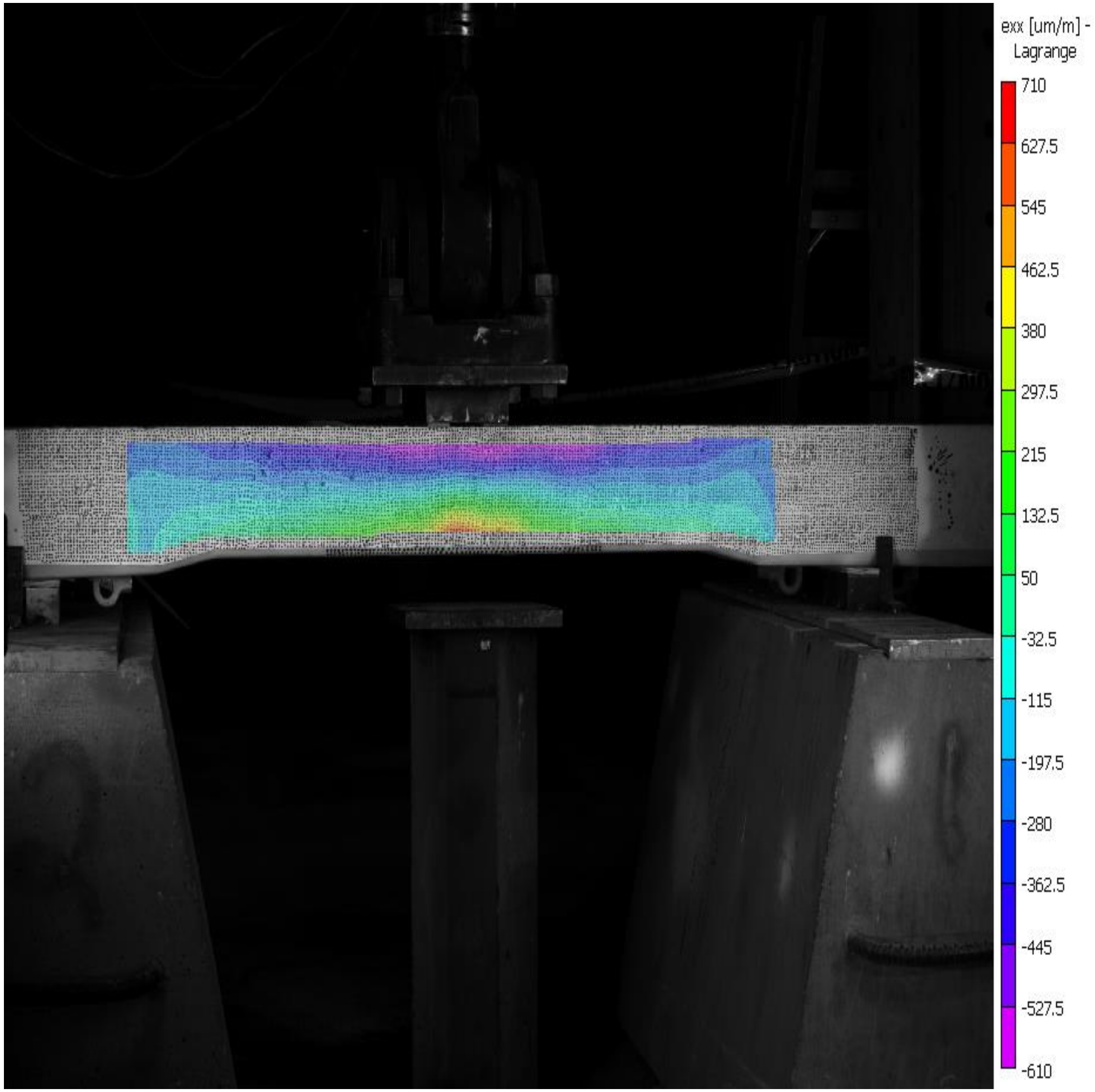
- No significant changes in the strain field as load accumulates
- No cracks observed through visual inspection and DIC measurements

Stage 2 - Cracking induced to first strand

Additional 3,000,000 cycles

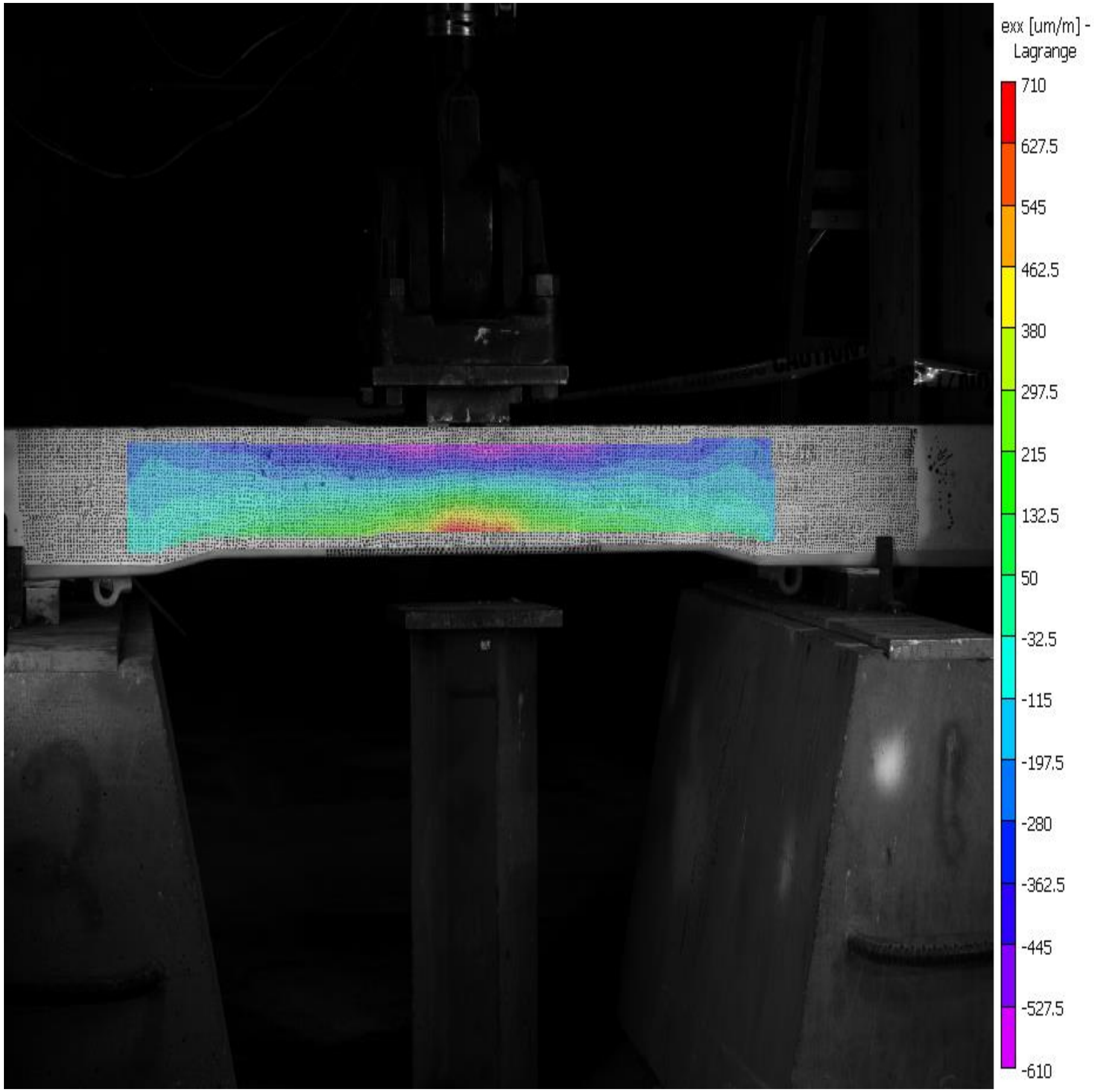
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5 kip , 0 cycles



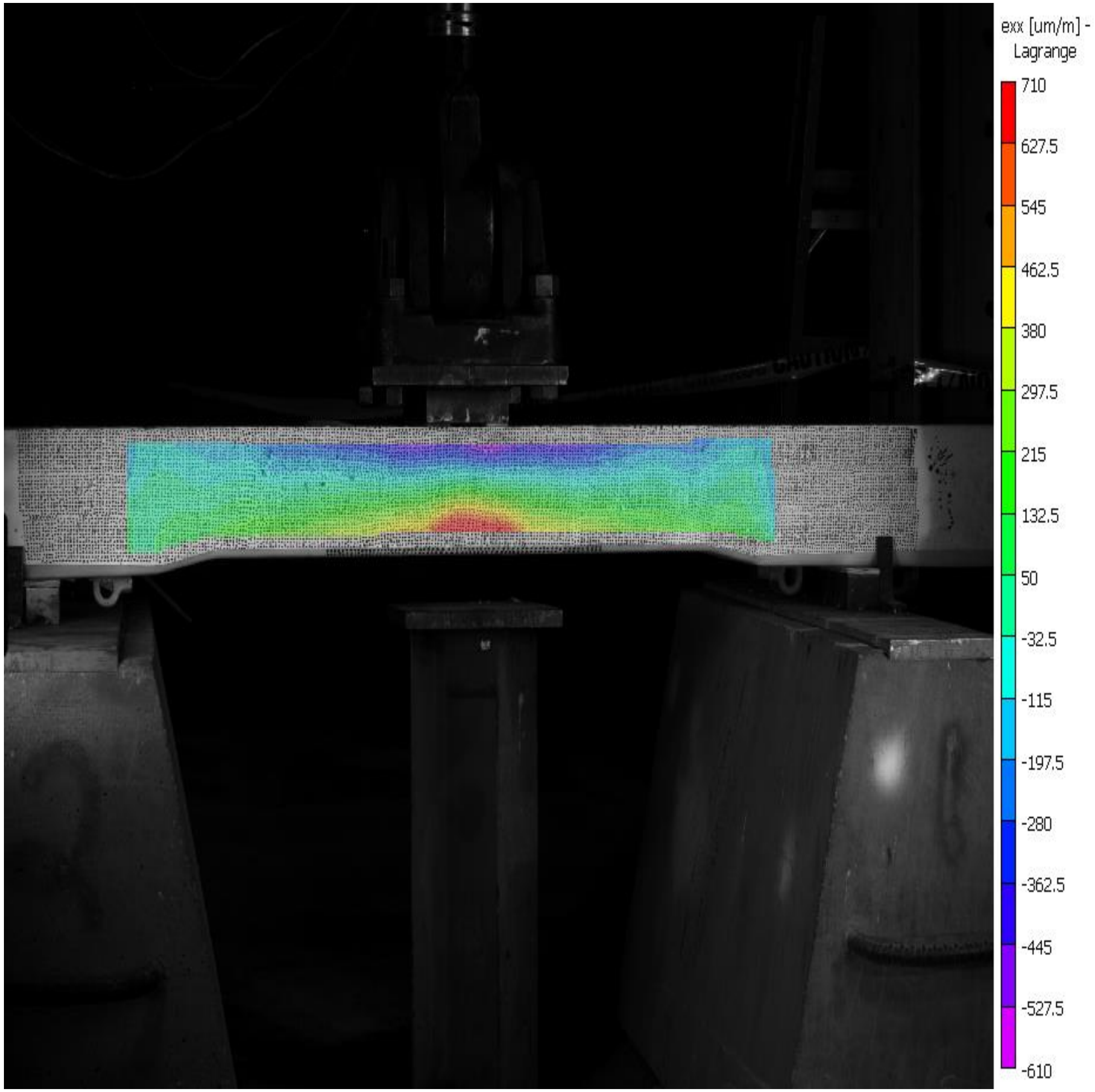
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5 kip, 333250 cycles



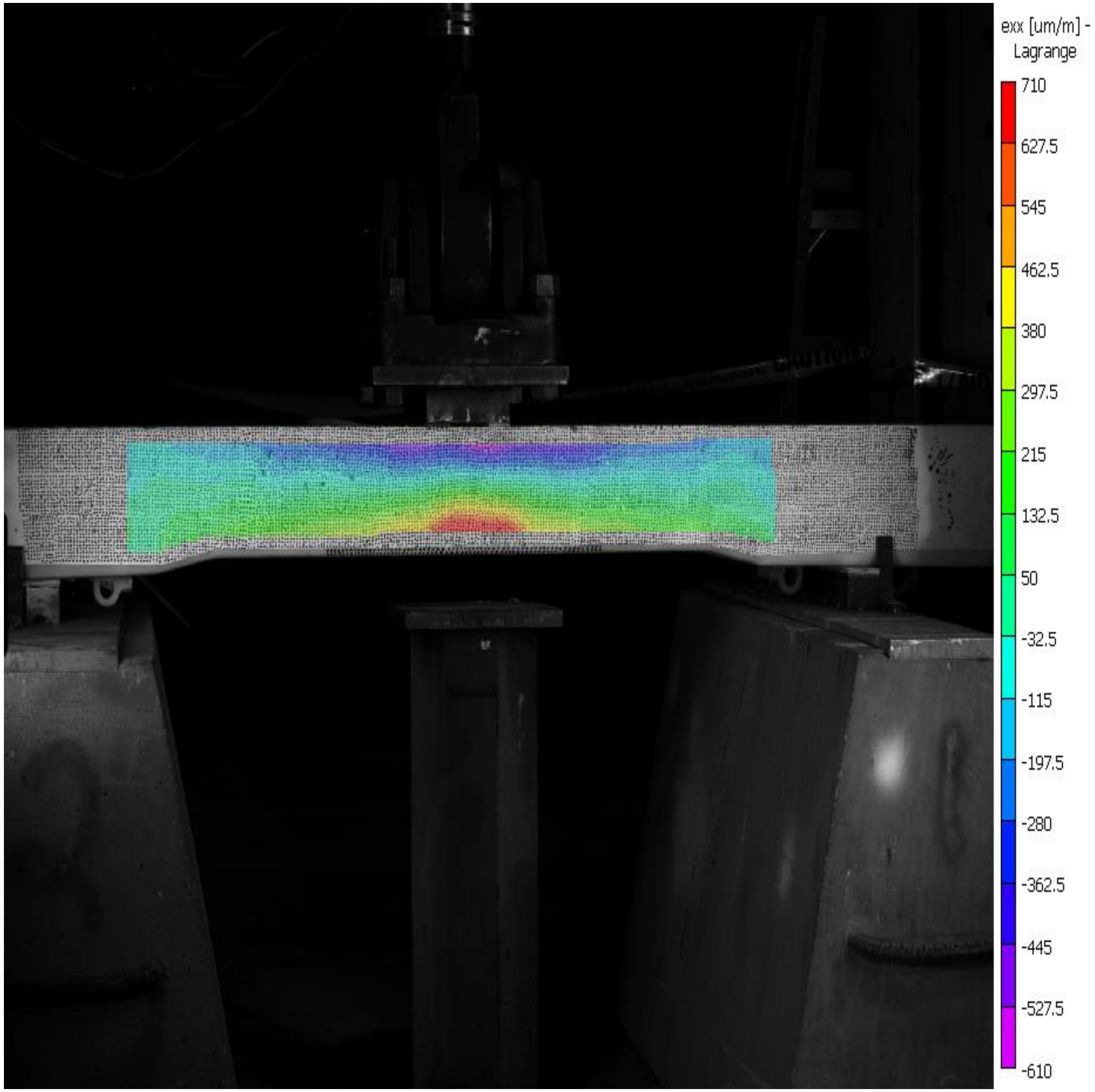
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 848250 cycles



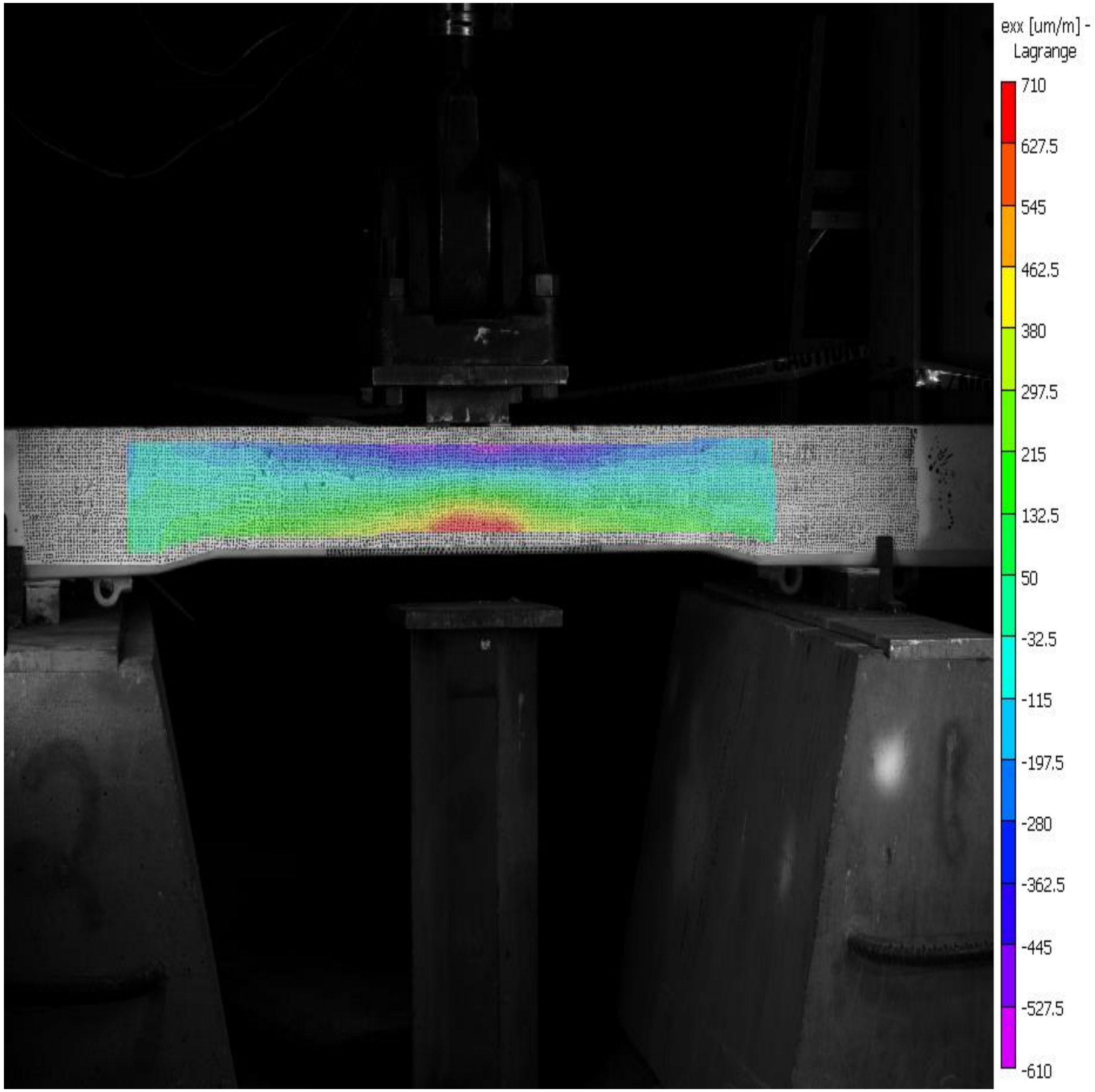
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 1348000 cycles



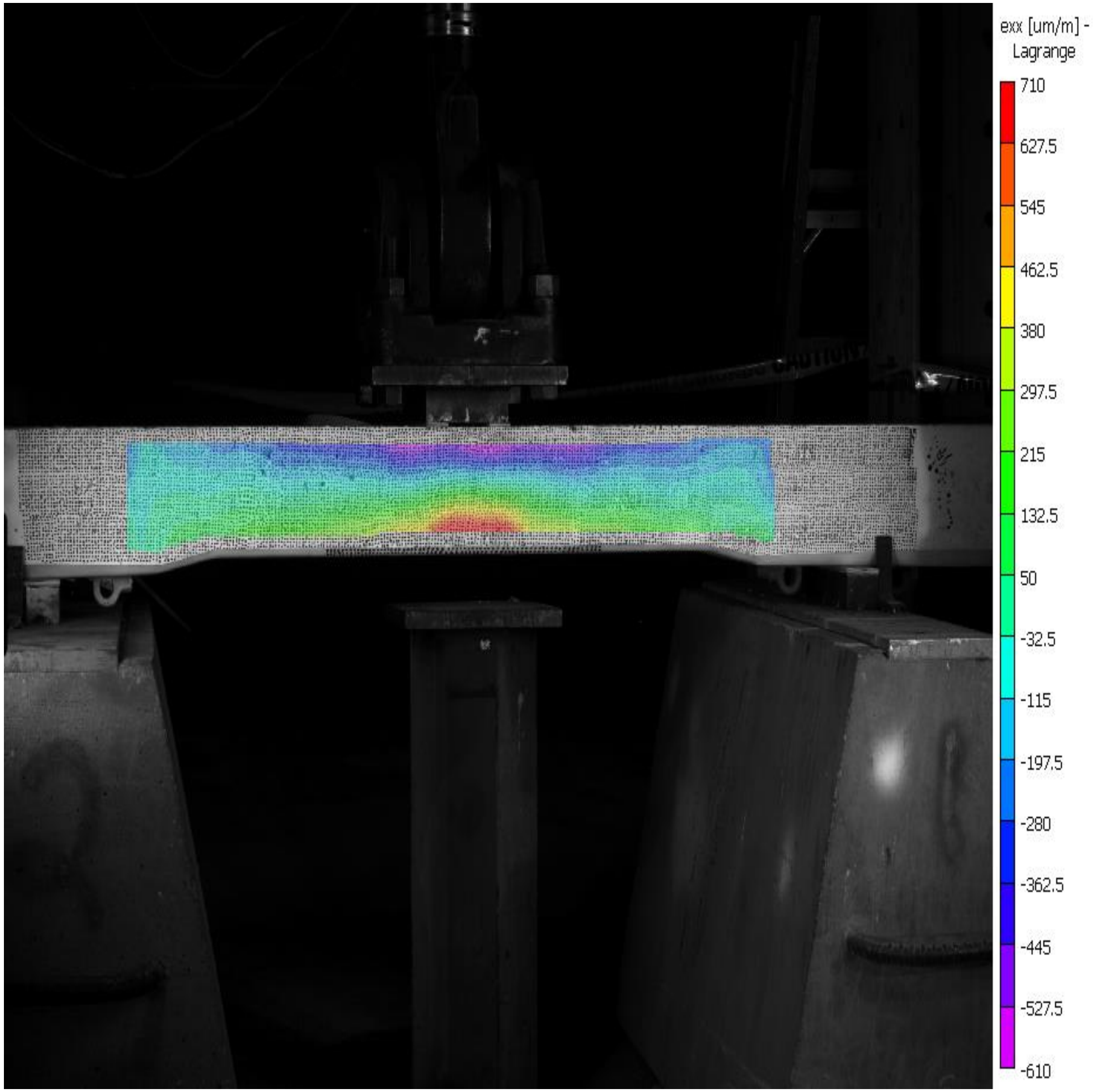
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 1848000 cycles



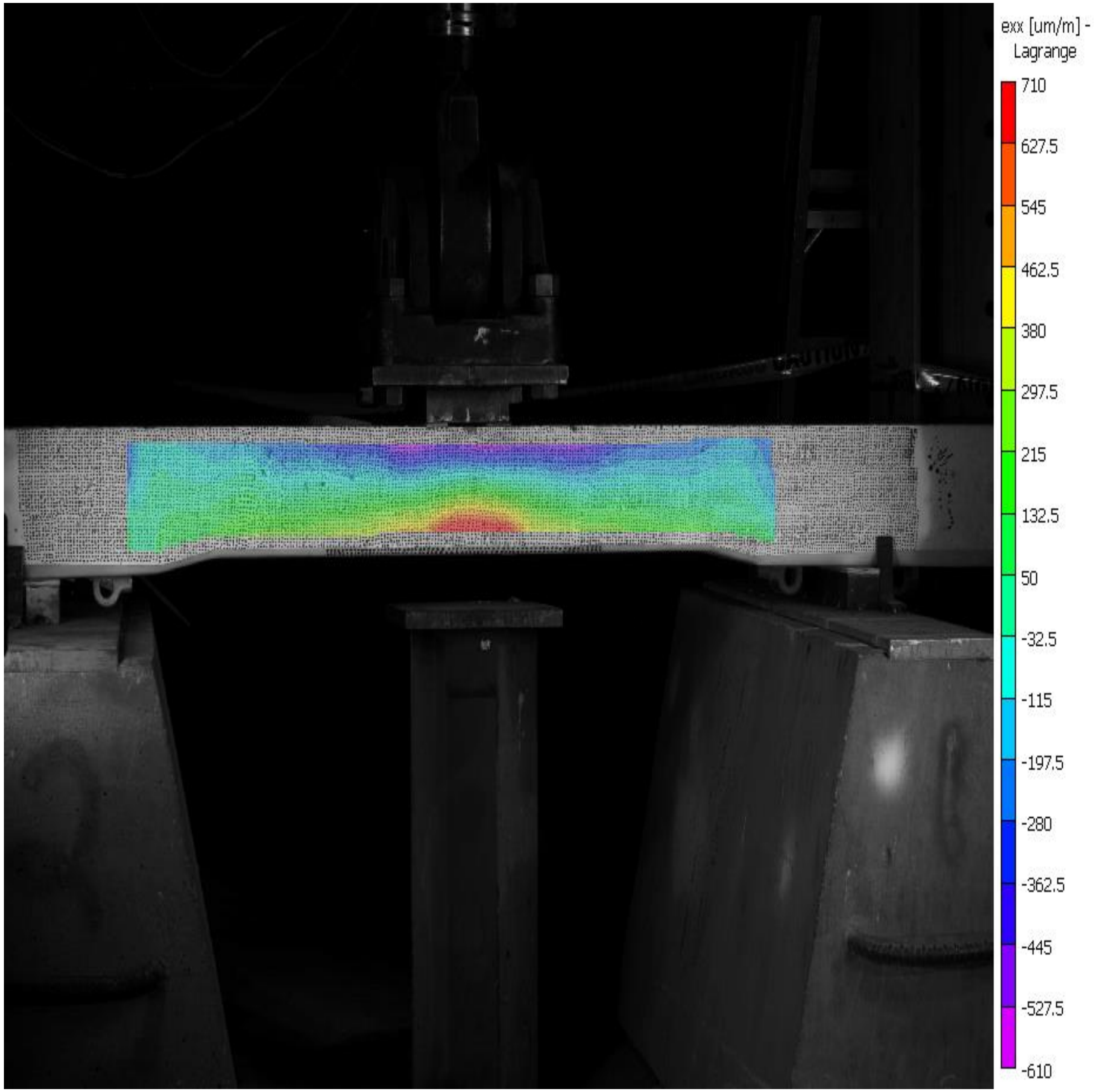
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 2174000 cycles



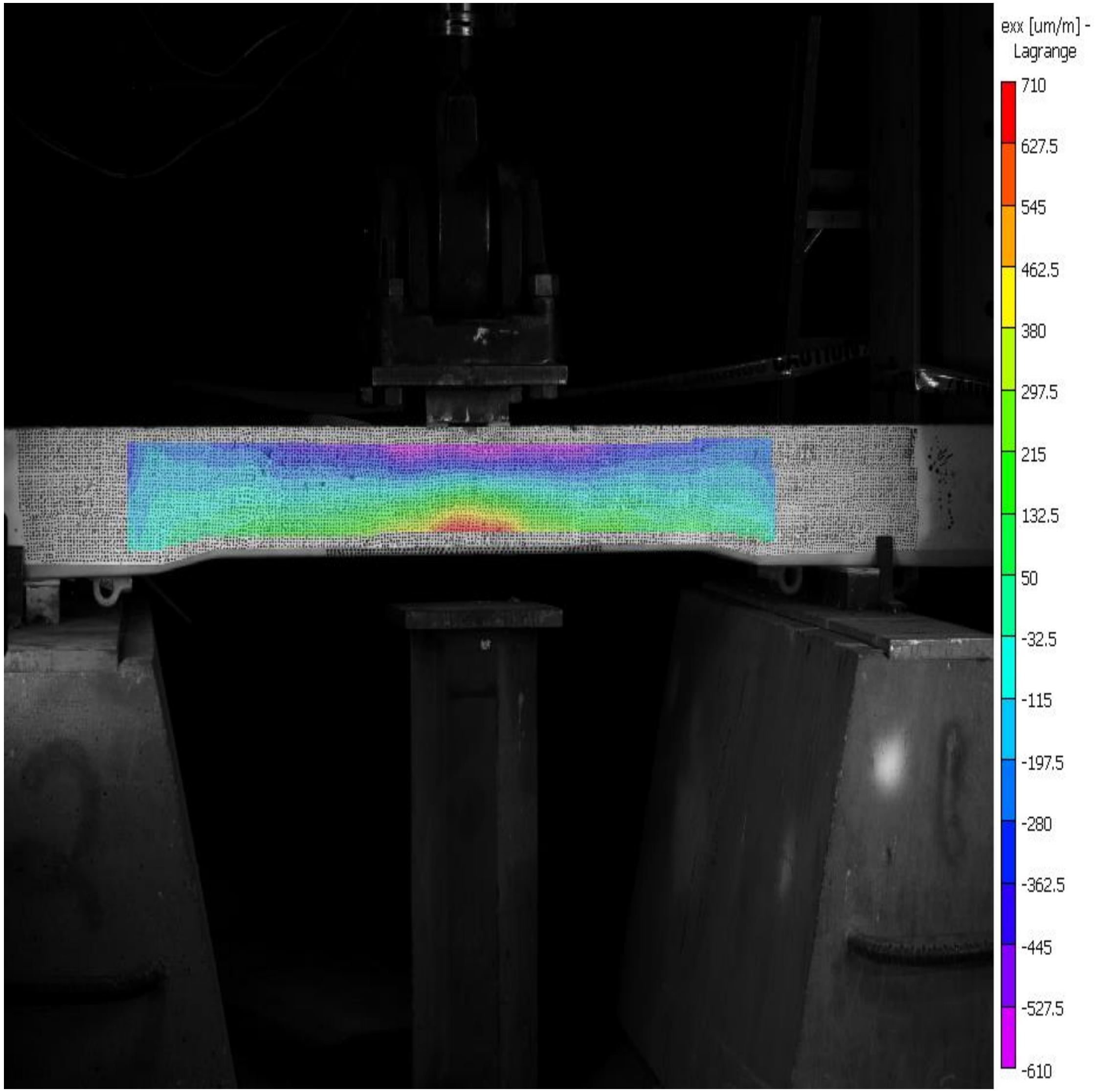
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 2520000 cycles



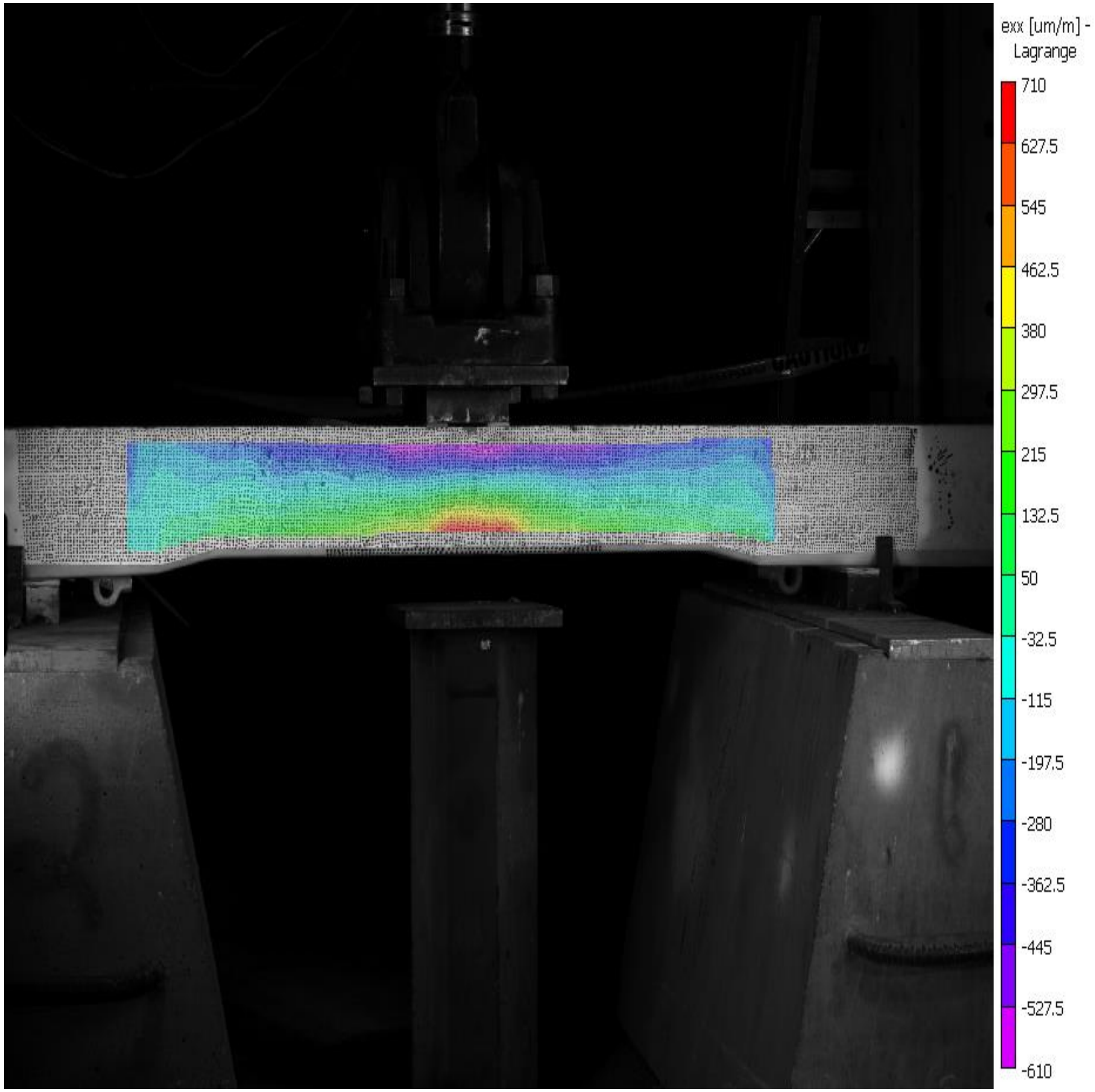
HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 2852000 cycles



HSRM – Center Negative Moment (Fatigue Post Cracking)

16.5kip , 3000000 cycles



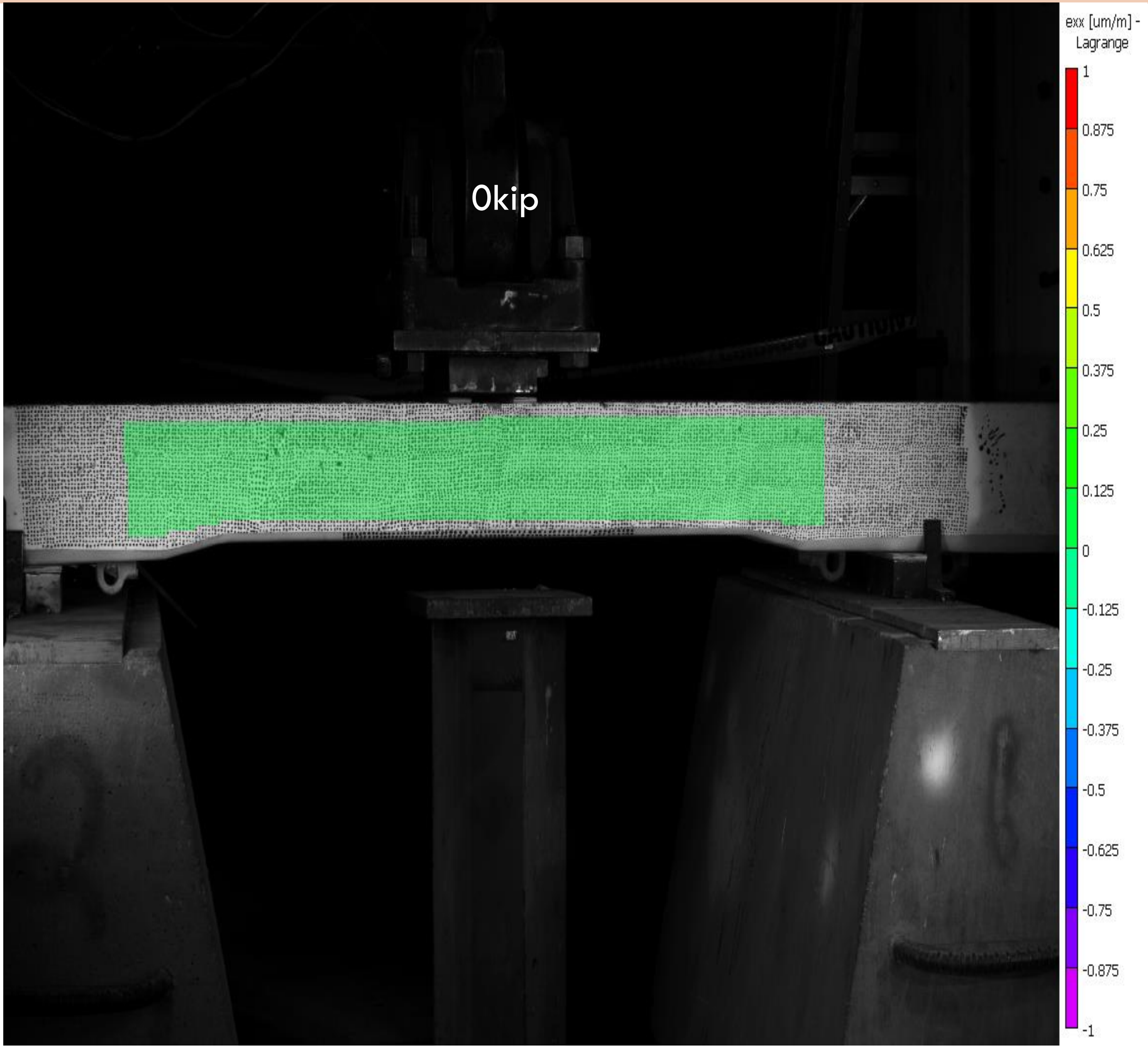
Fatigue – Center Negative : Discussion

- Crack location is evident
- Stress redistribution during first 800,000 cycles
- No additional cracks observed
  - visual inspection and DIC measurements
- Existing crack did not propagate
  - visual inspection and DIC measurements

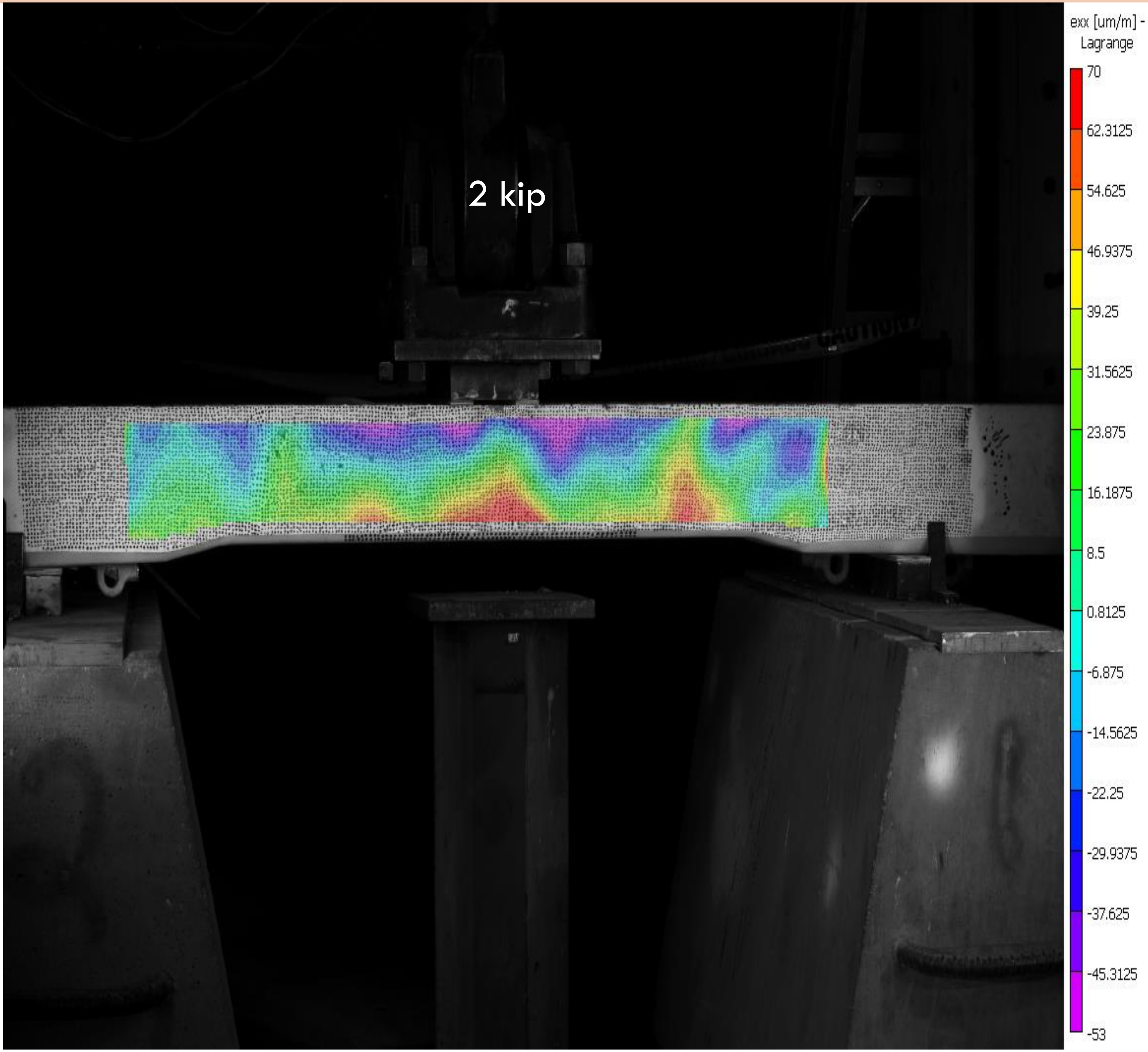
Stage 3 - Loading to Failure

After 6,000,000 total load cycles

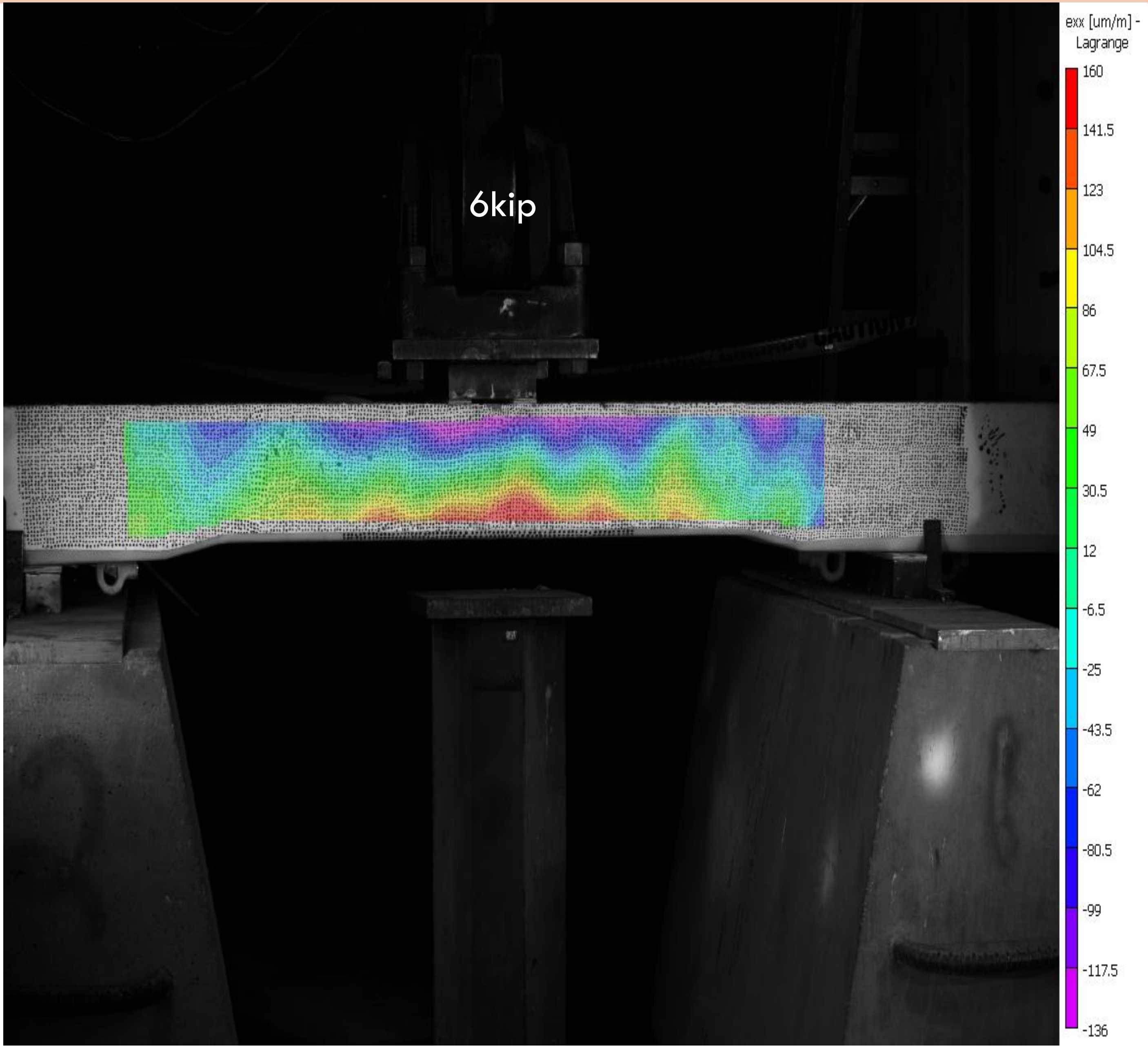
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



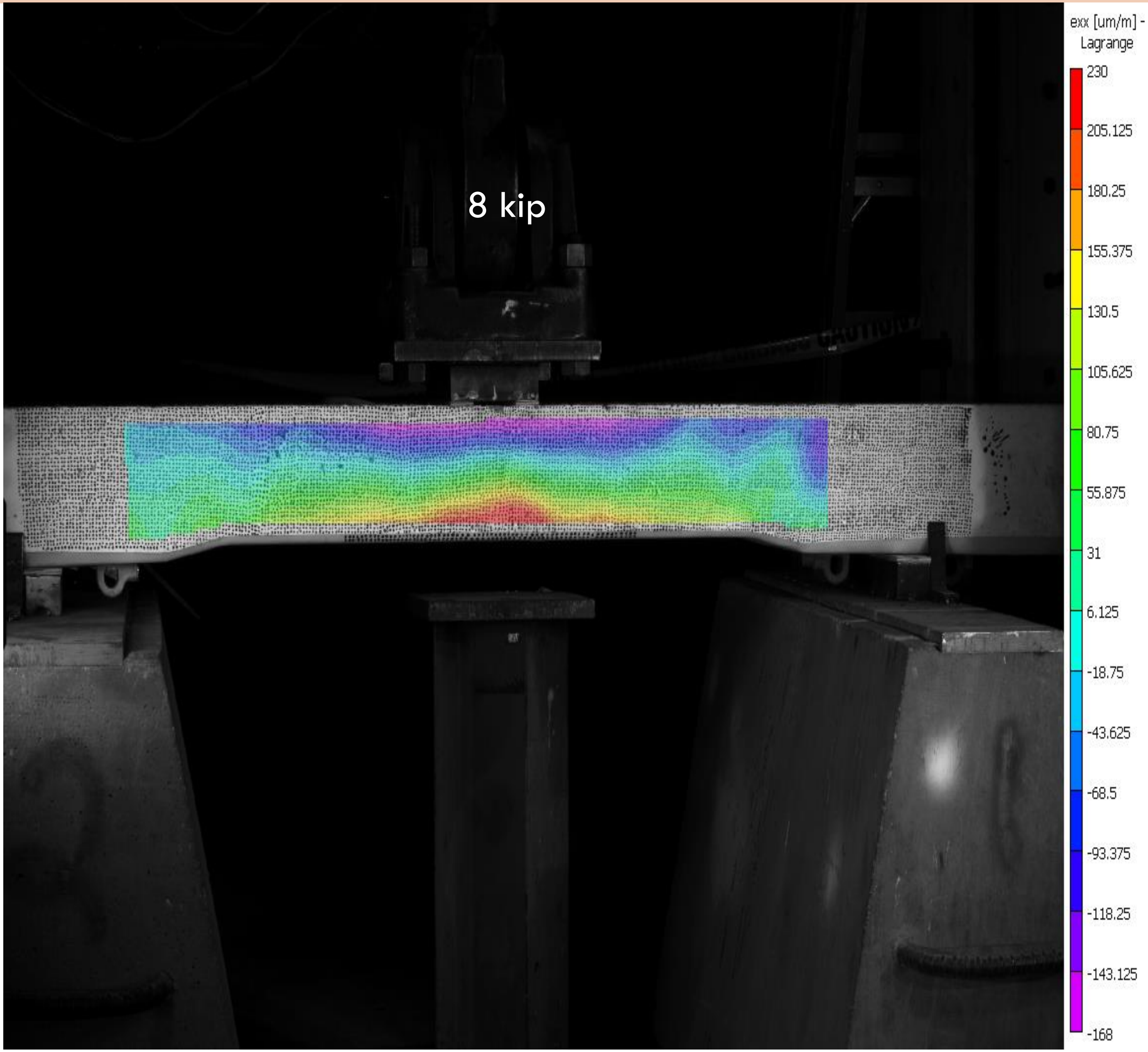
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



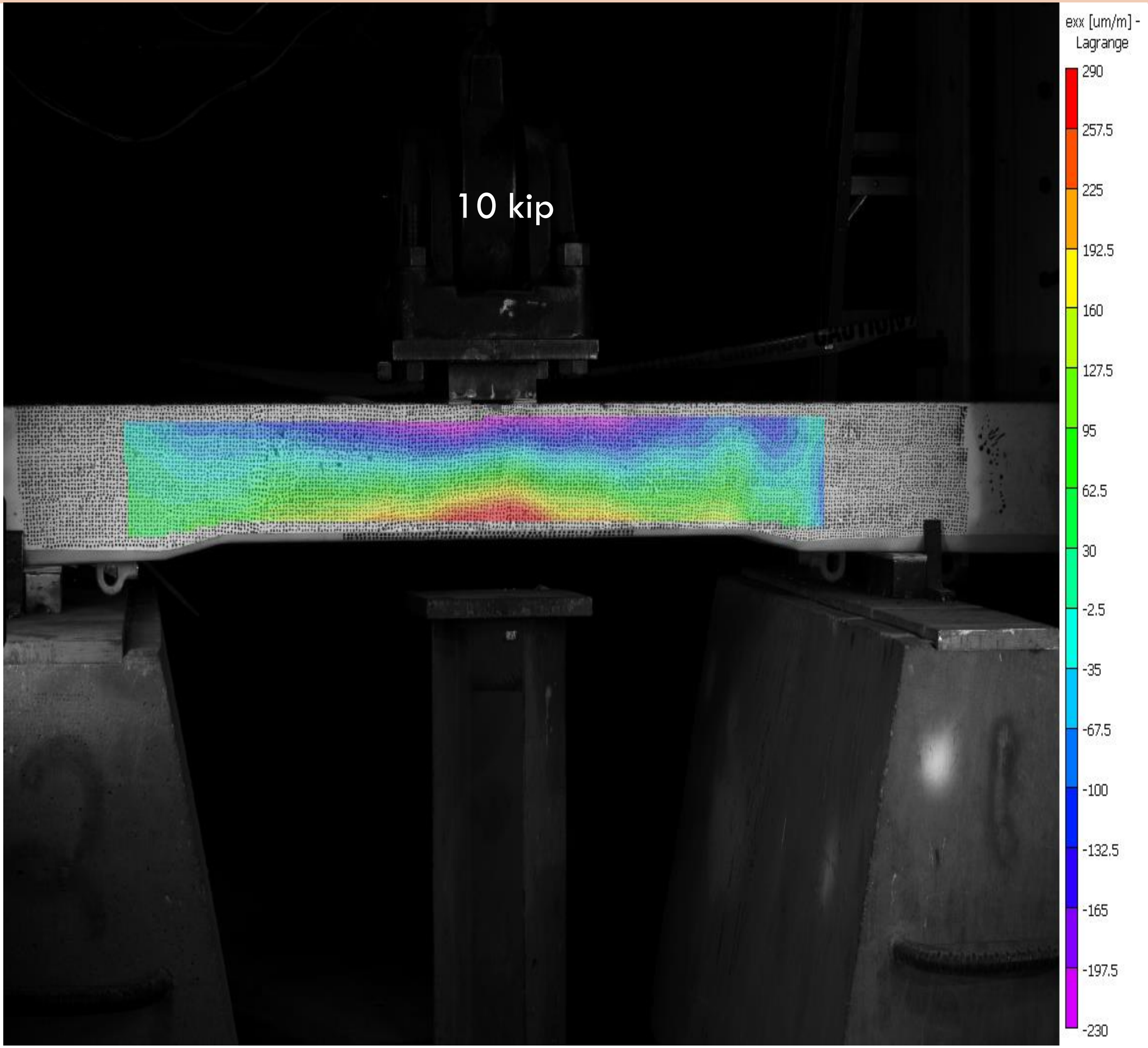
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



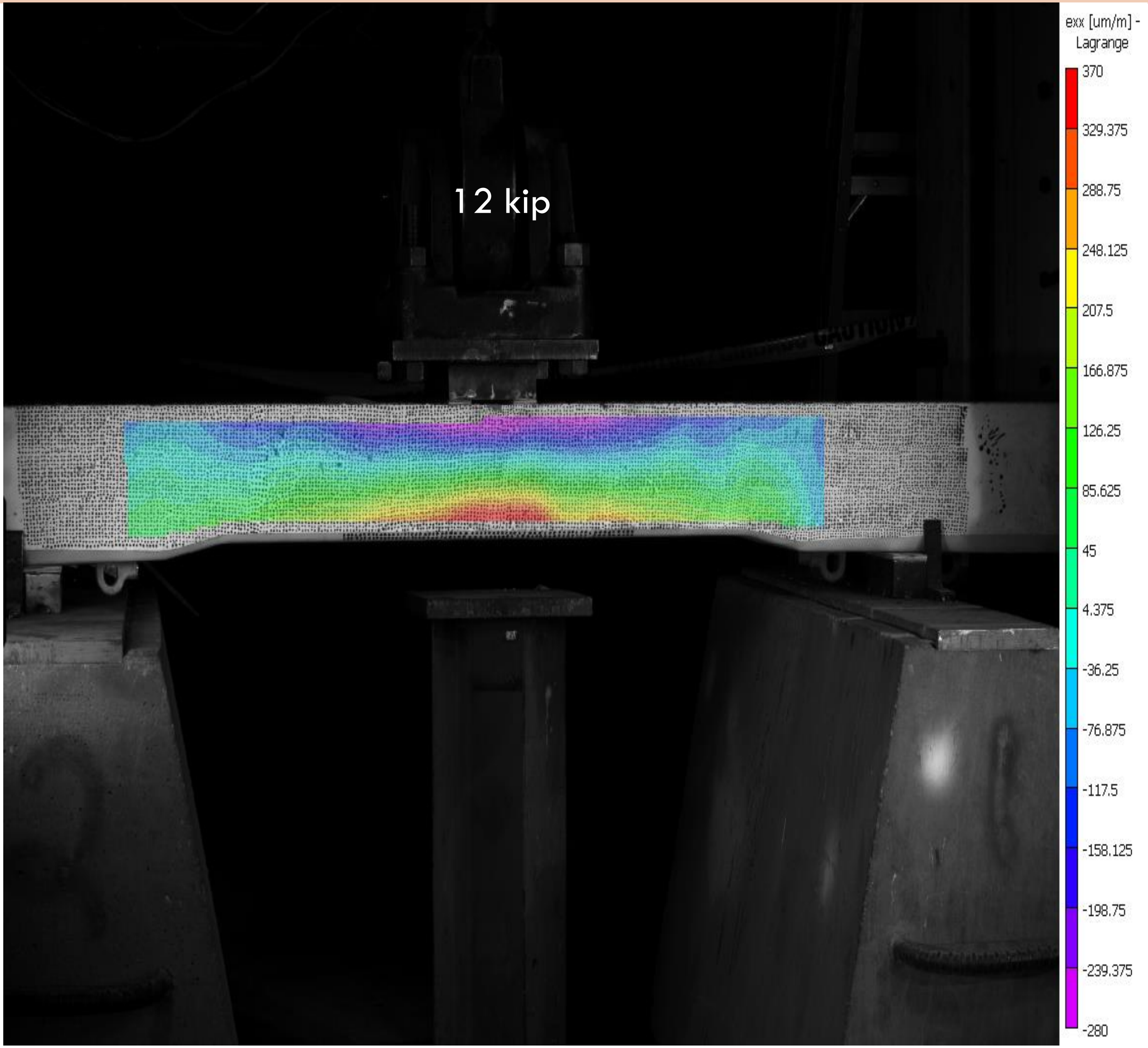
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



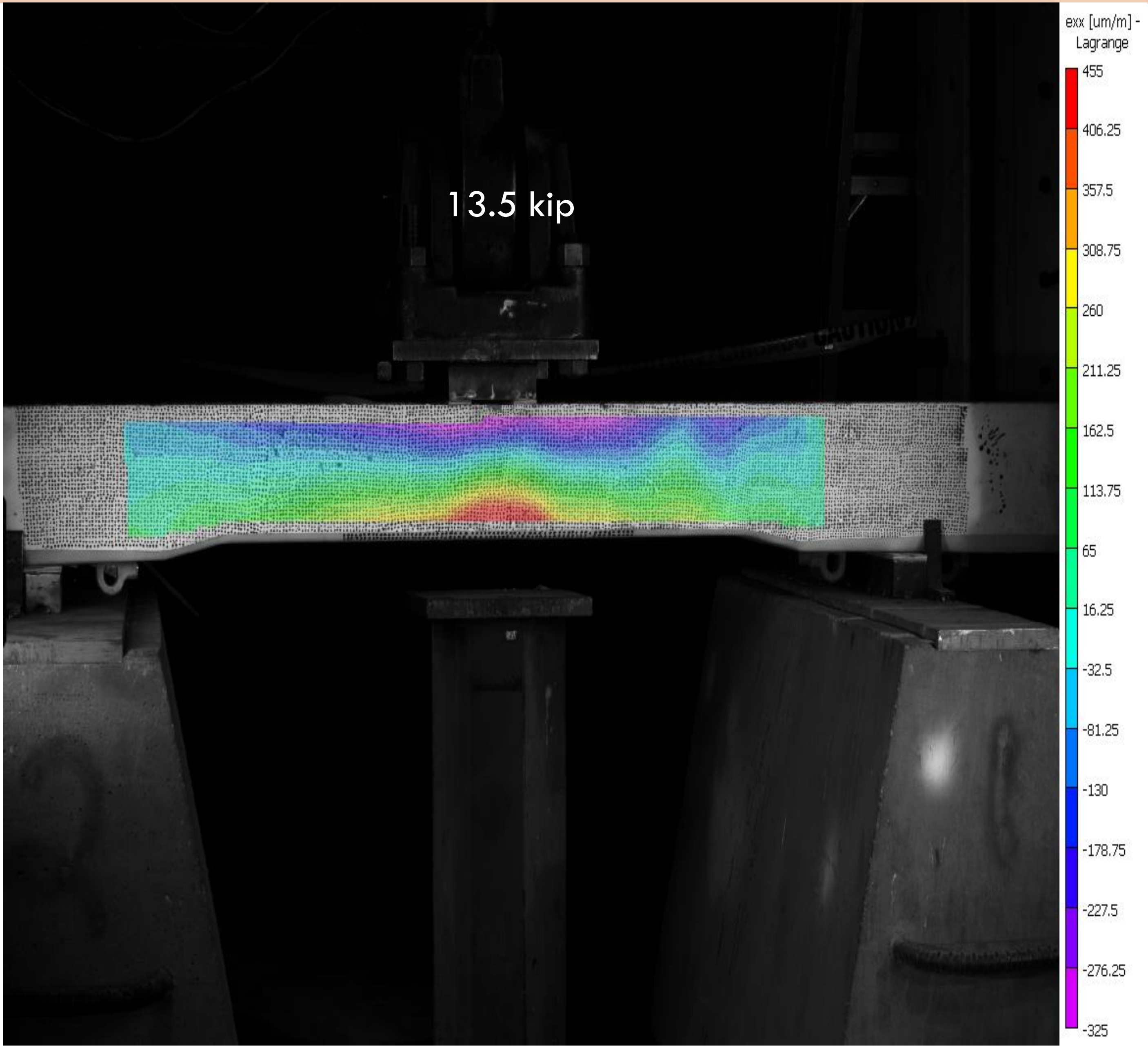
HSRM – Center Negative Moment (Ultimate Post-Fatigue)

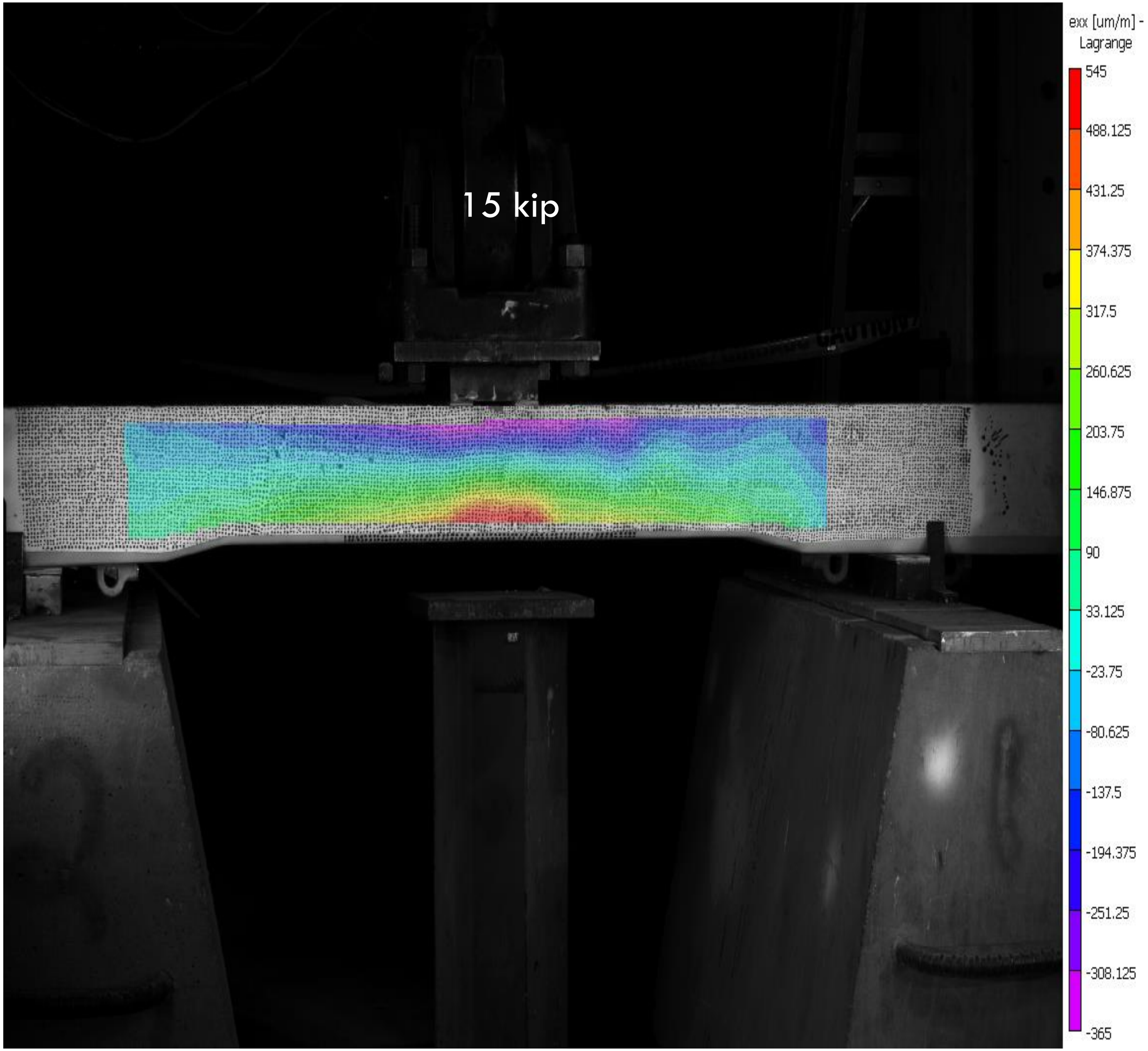


HSRM – Center Negative Moment (Ultimate Post-Fatigue)



HSRM – Center Negative Moment (Ultimate Post-Fatigue)





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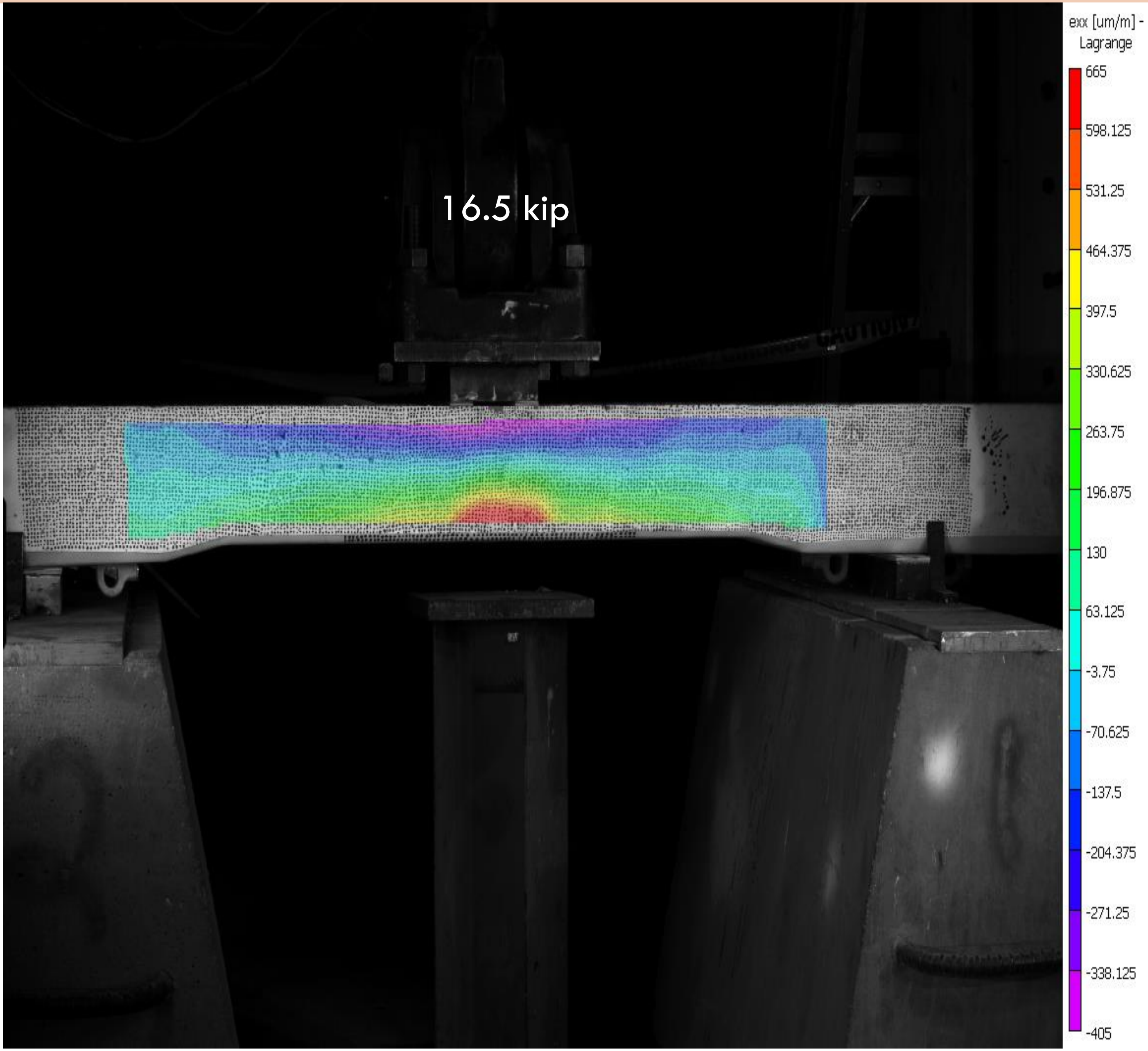
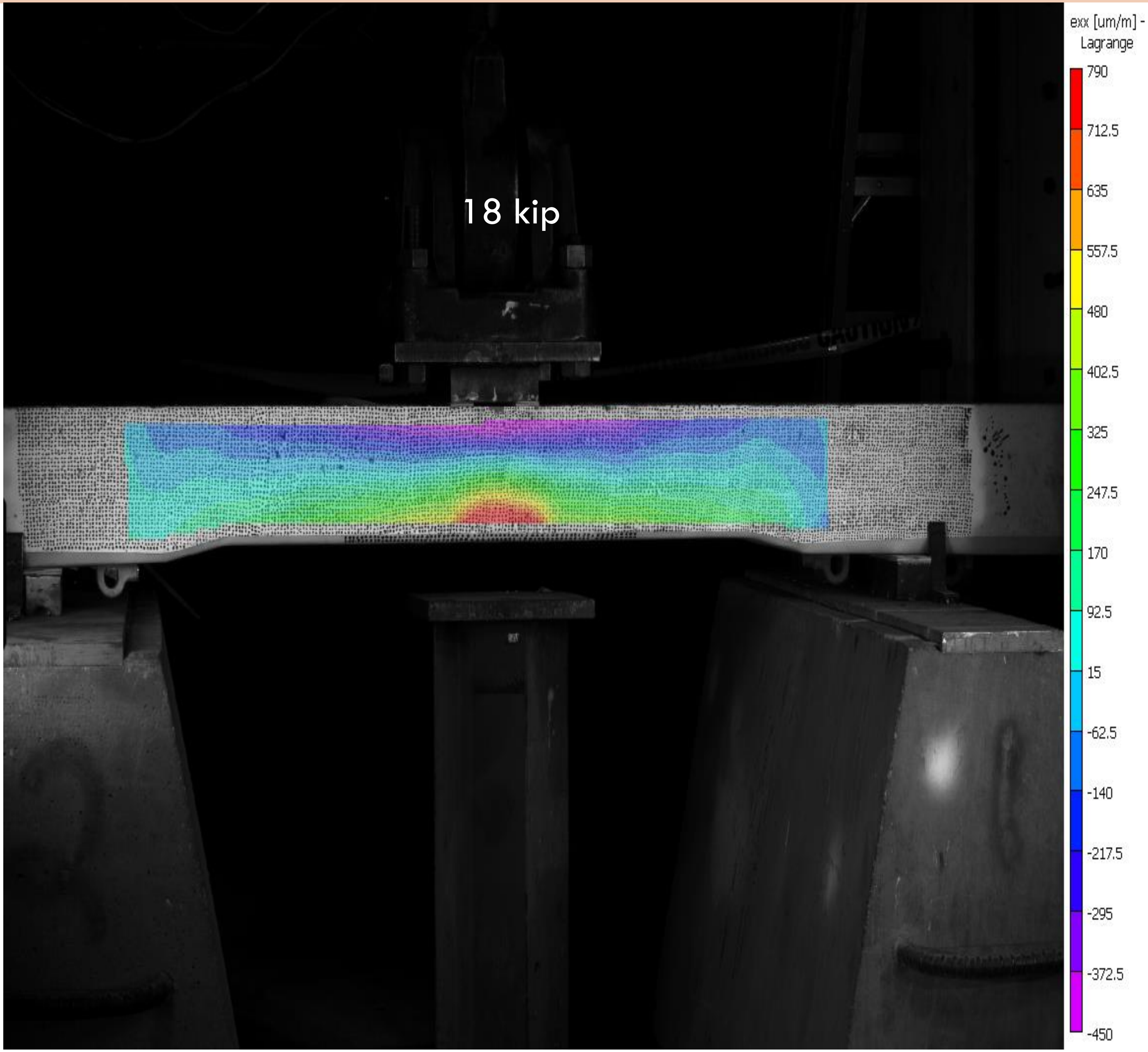
College of Engineering and Computing

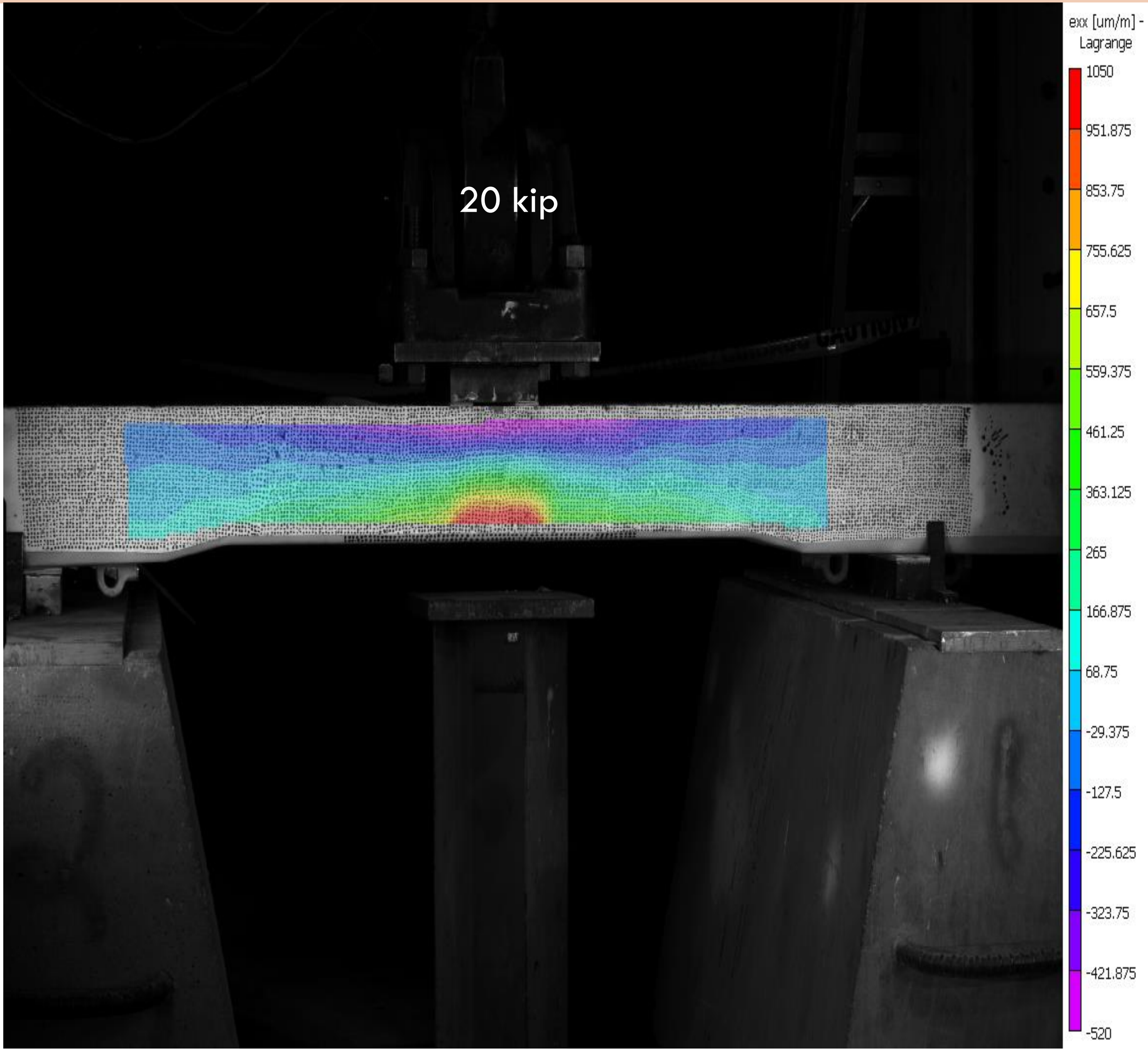
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



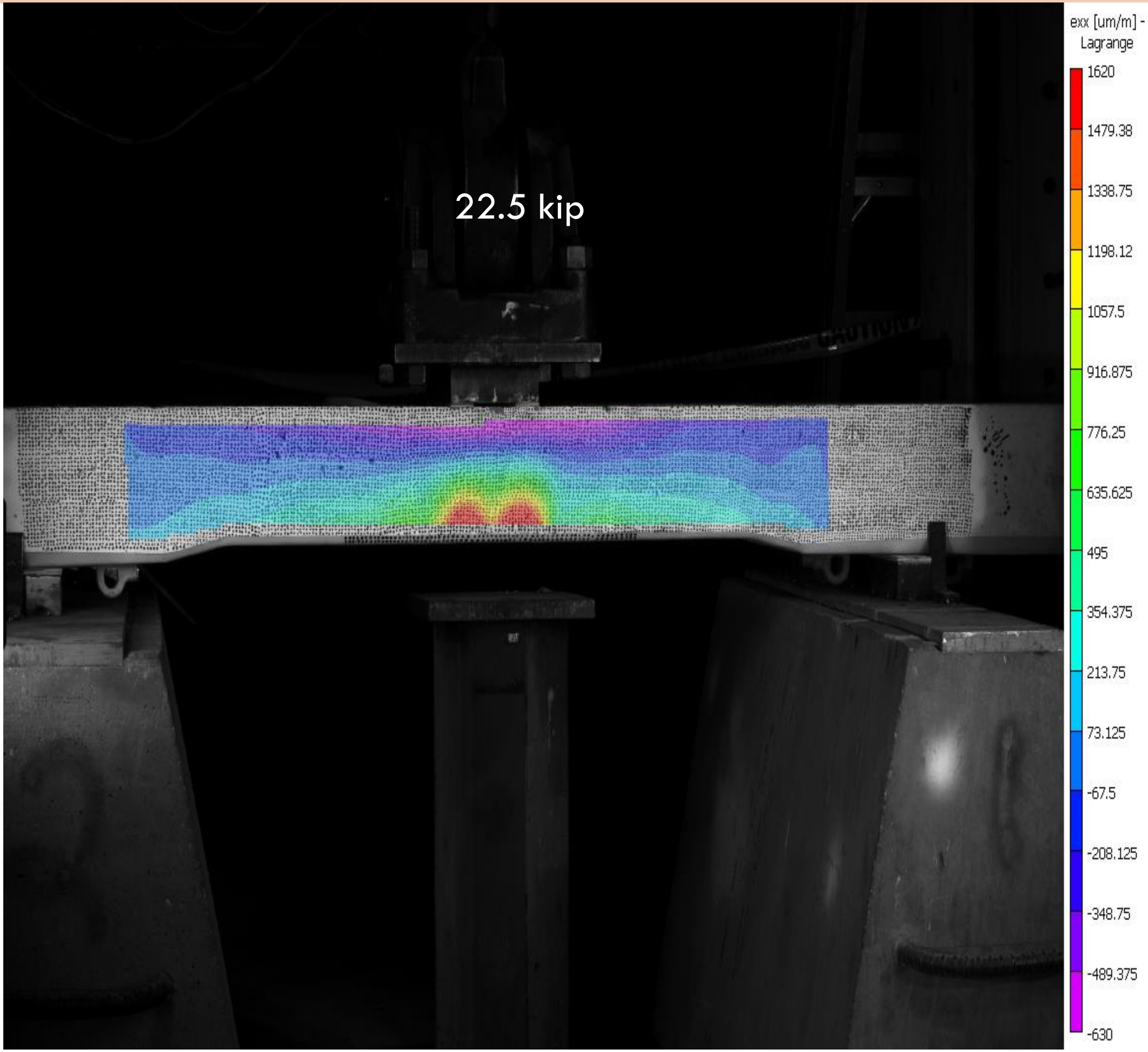
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



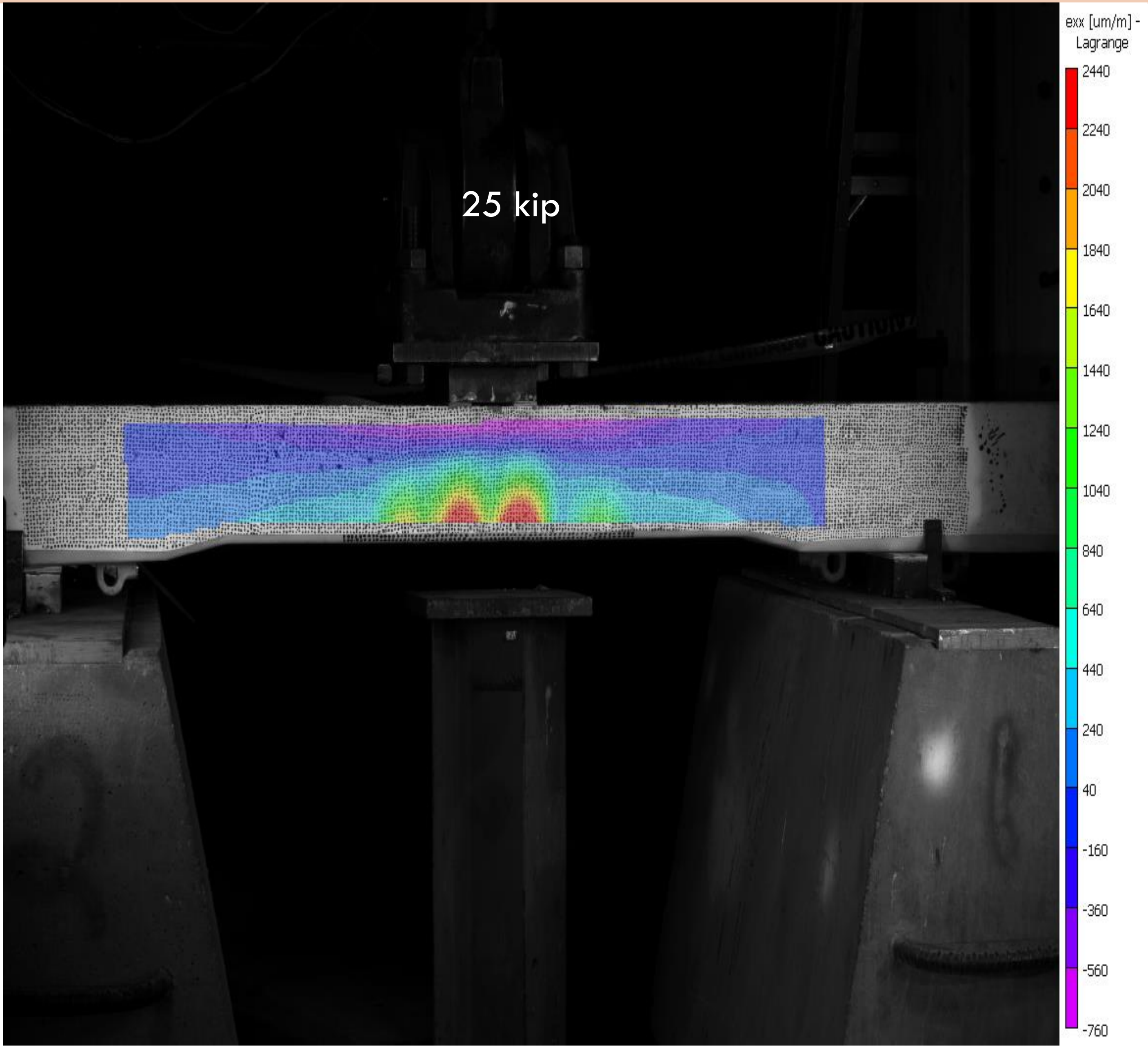
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



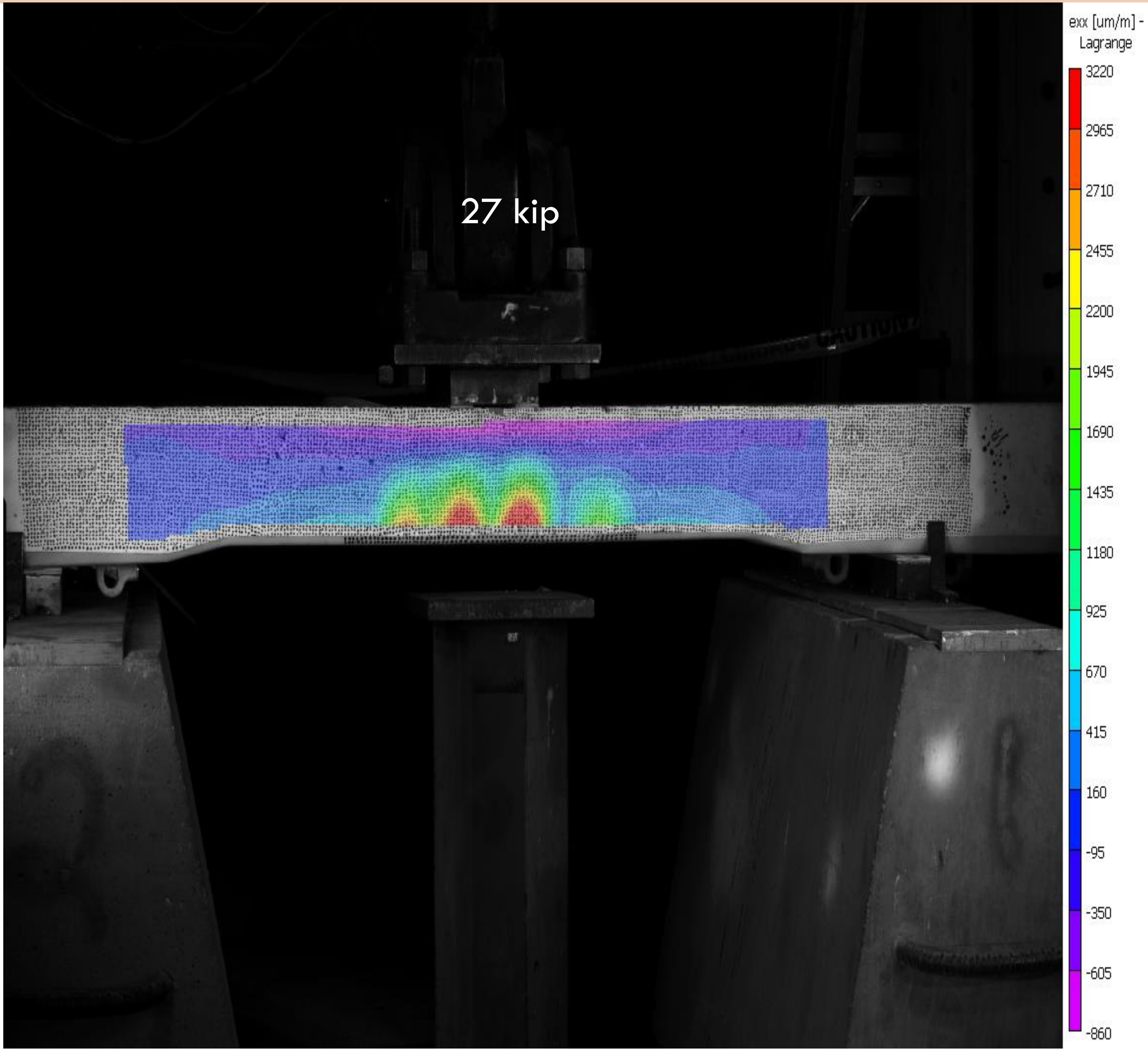
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



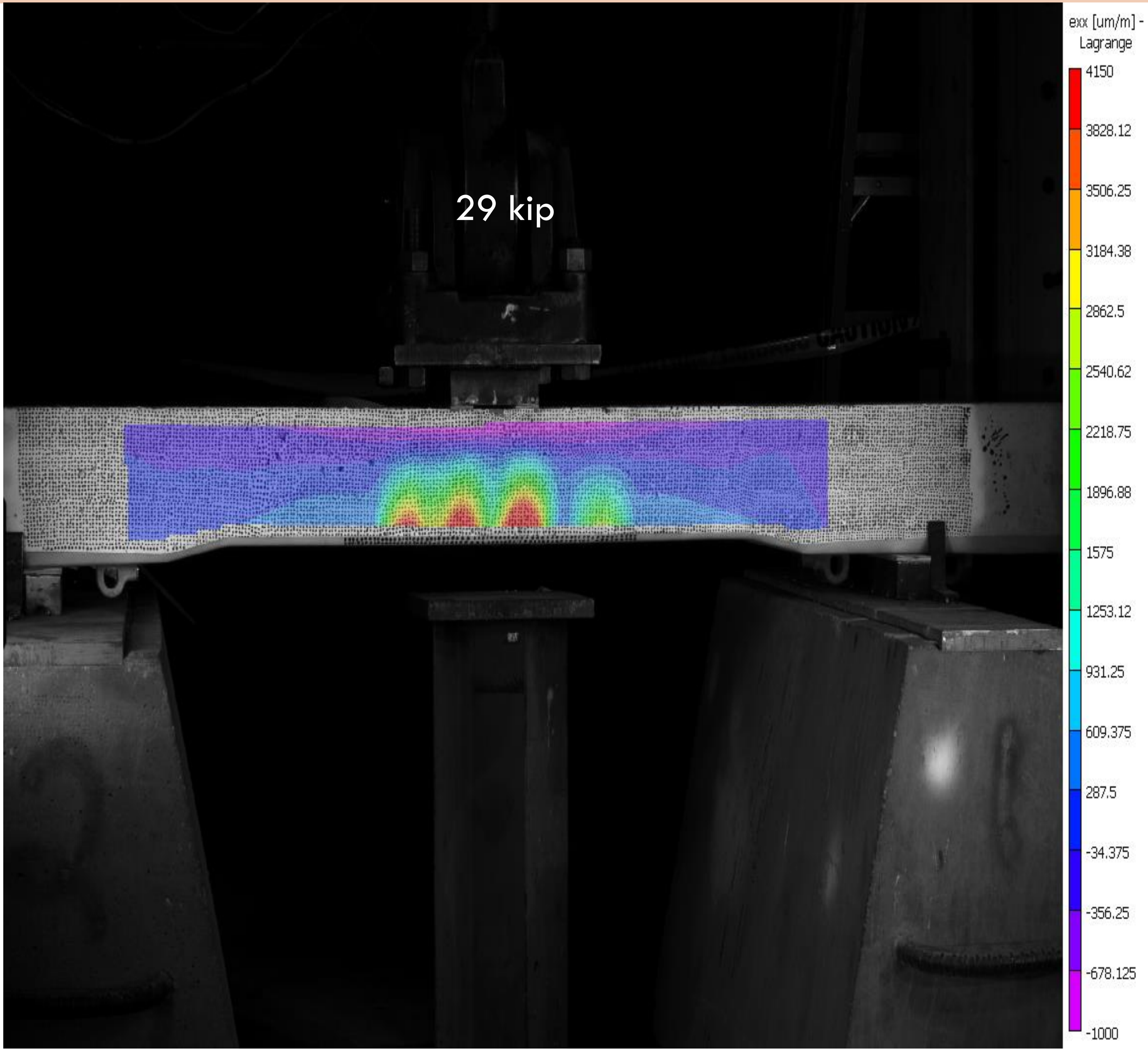
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



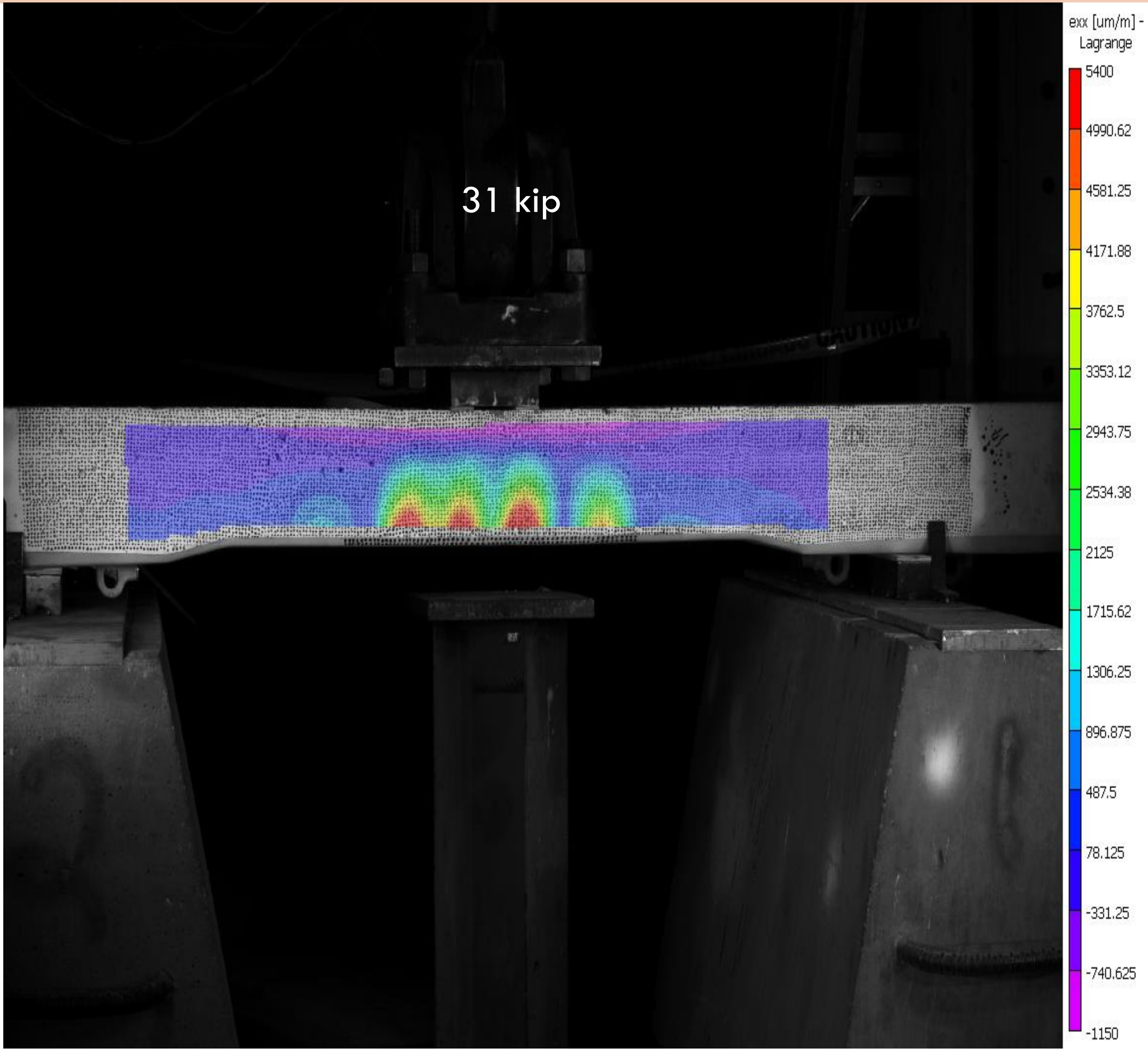
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



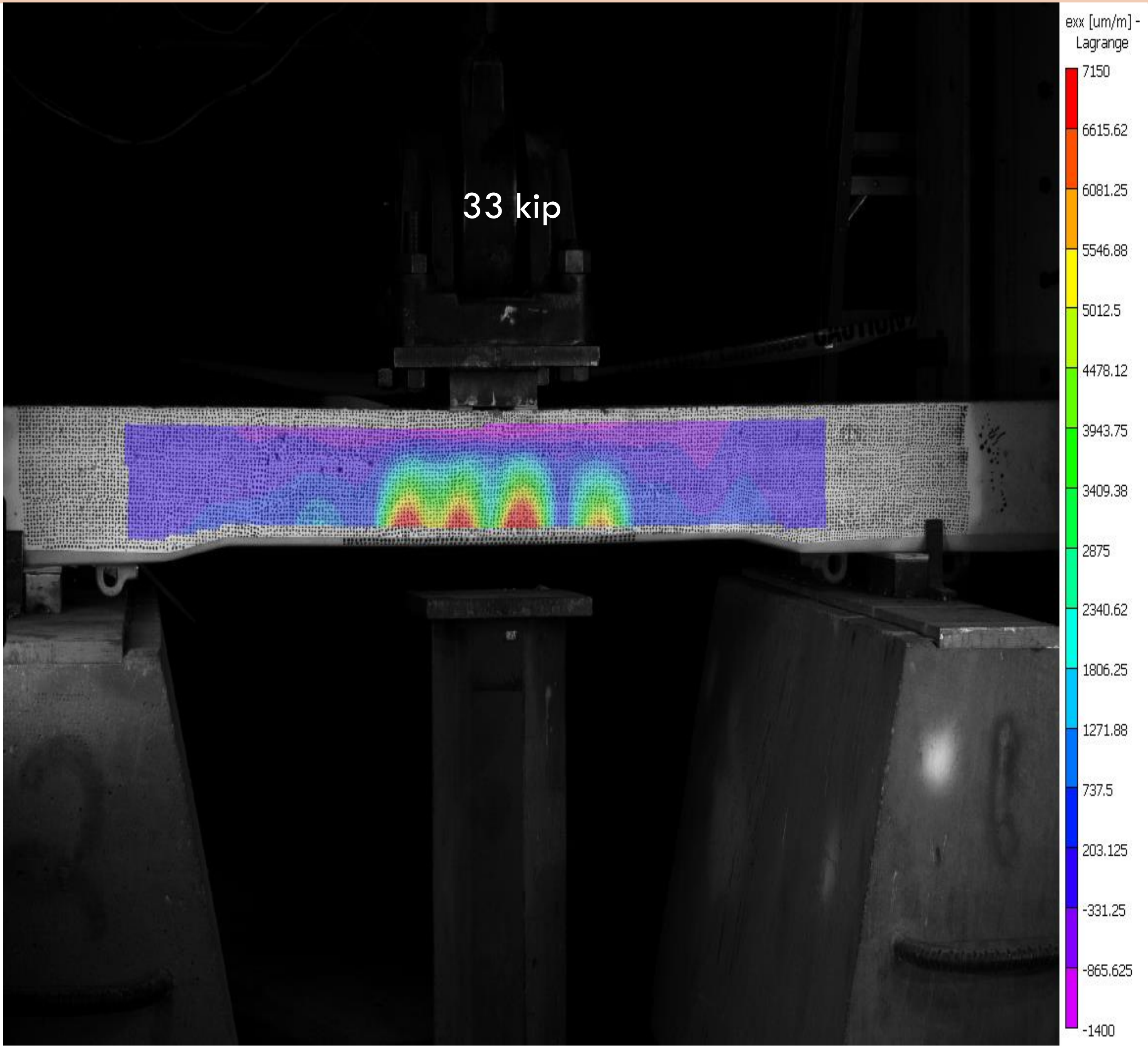
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



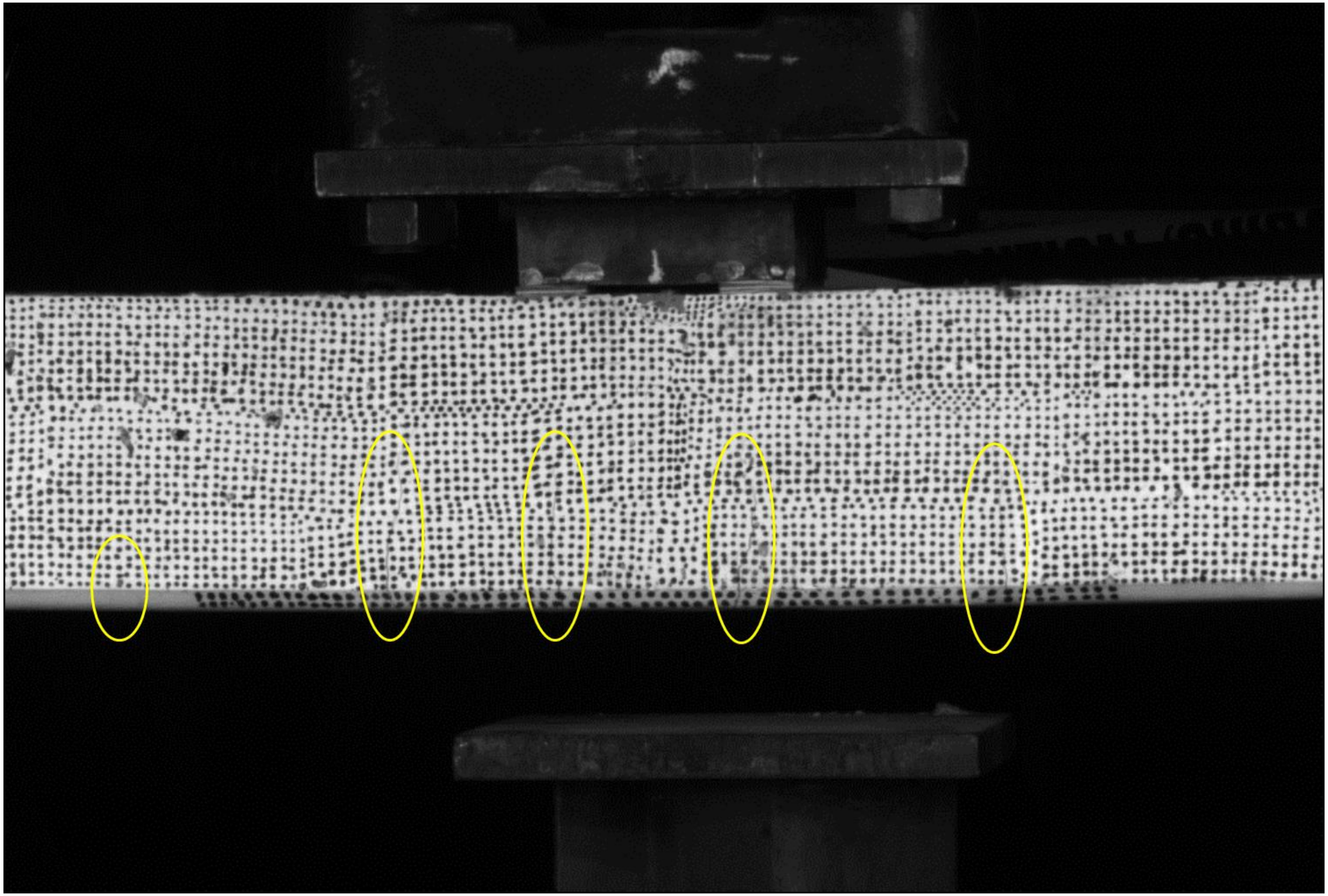
HSRM – Center Negative Moment (Ultimate Post-Fatigue)



HSRM – Center Negative Moment (Ultimate Post-Fatigue)



HSRM – Center Negative Moment (Ultimate Post-Fatigue)

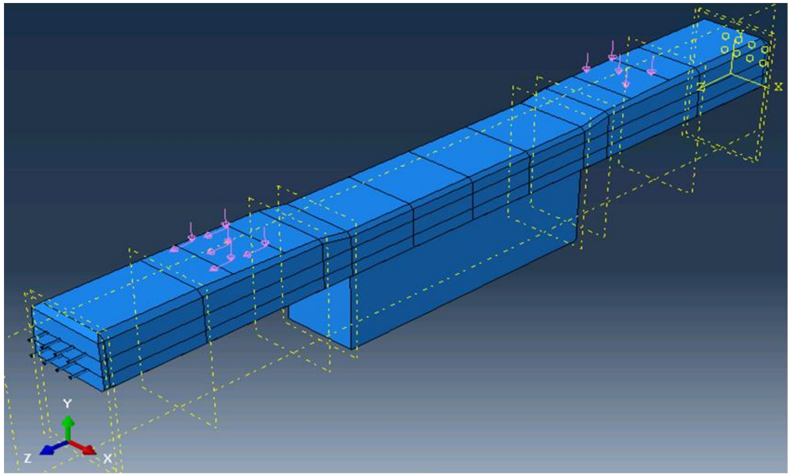


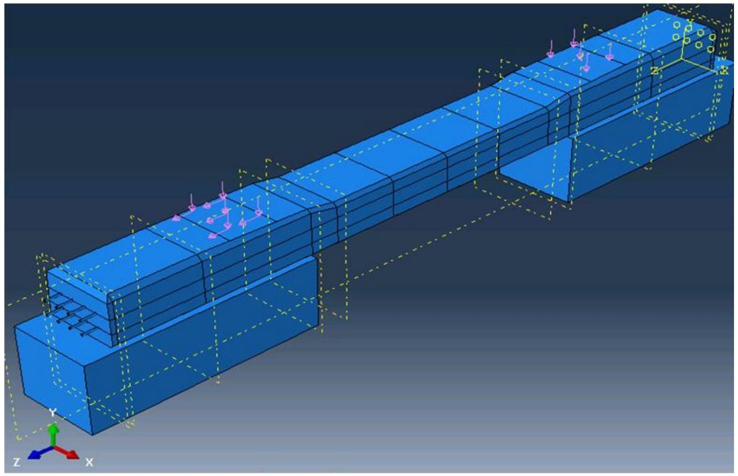
Fatigue – Center Negative : Discussion

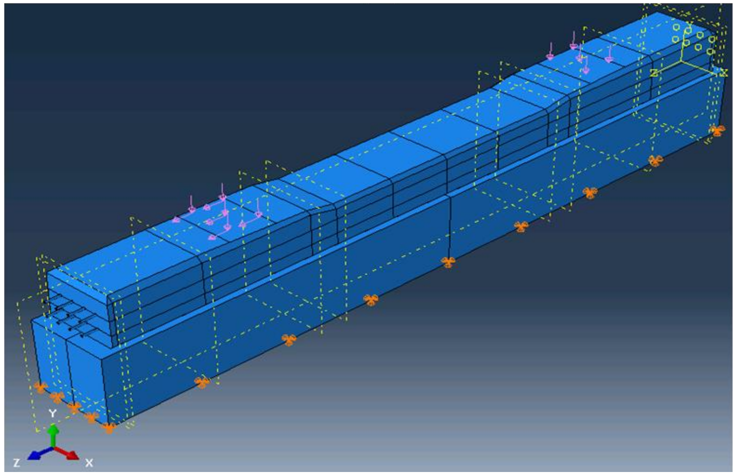
- HSRM Ultimate load 34kips (standard 30kips)
- Multiple shallow cracks indicate load redistribution in HSRM (fewer, deeper cracks in standard)

Parametric Studies– FEM Analysis

FEM Tie Performance: pre-cracking







L/V = 0.0, 0.2, 0.4

Elastic Modulus Values Mpa (ksi)	
Standard	HSRM
31,918 (4,629)	23,018 (3,338)

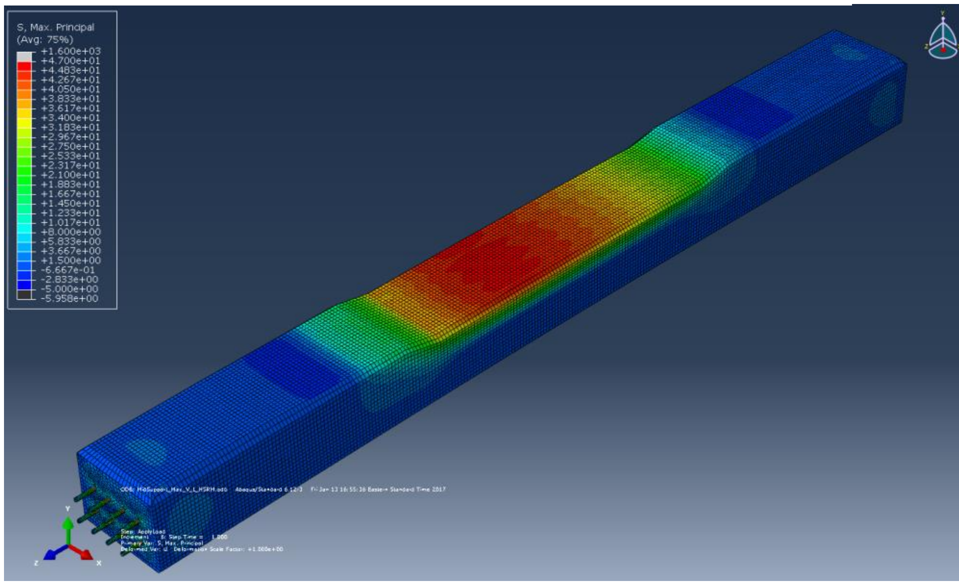
~27% reduction

Ballast: E = 200 (29)

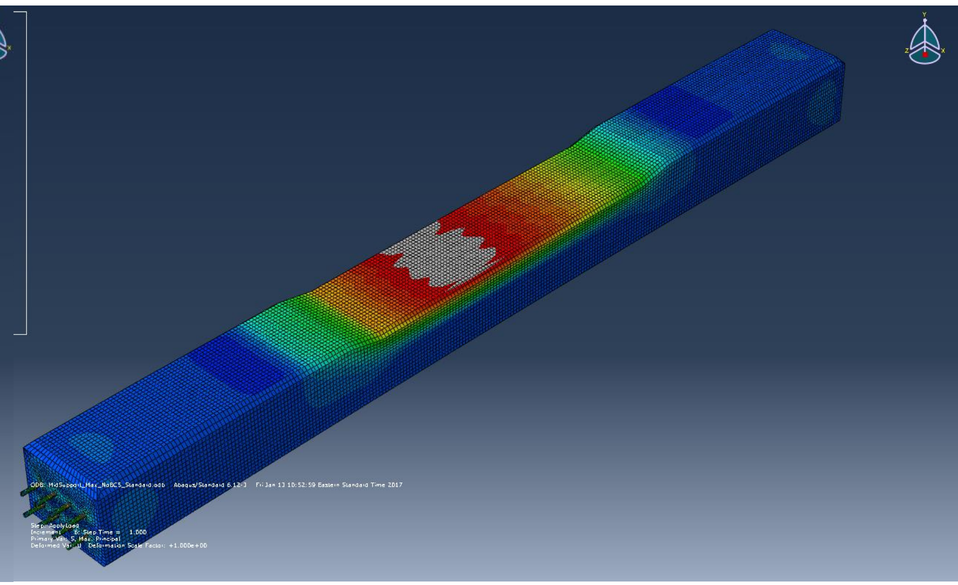
Example: Full Support L/V=0.4 (preliminary)

Max Principle Stress – Example In Progress

HSRM



Standard



3%-12% stress reduction

Benefits - Summary

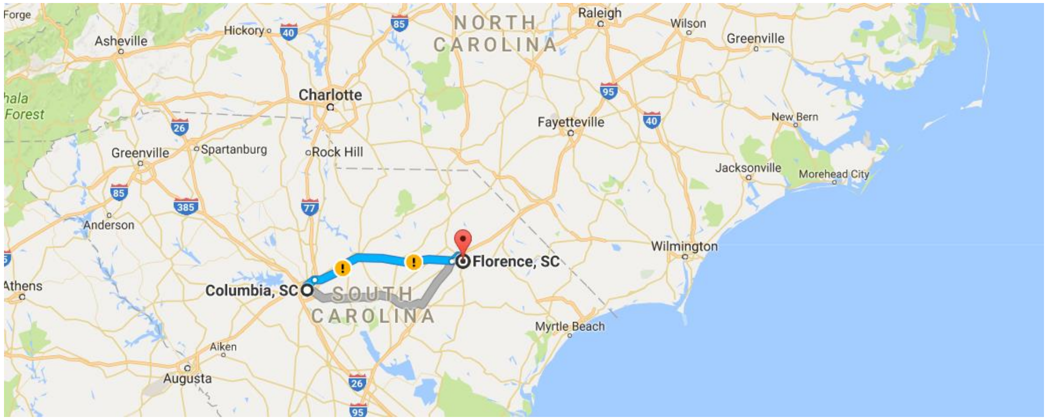
- Maintains high strength
- Smoother stress gradients in tie and stress redistribution after cracking
- Stress amplitude reduction
- Onset of damage delayed
- Better load distribution on track ?

Outline

- Historical Background
- Hypothesis
- Material Development and Characterization
- Prototype Tie Design and Fabrication
- Product Qualification
- Benefits
- **Conclusions & Future Work**

Current Work

- Residual Strength (Post Damage)
- Dynamic DIC measurements
- Effects on load distribution on track
- In situ testing and monitoring



Conclusions

- HSRM-HPC similar properties as Limestone HPC except Elastic Modulus (up to 50% reduction)
- HSRM Ties Passed all AREMA Qualification Tests and meets or exceeds standard tie performance
- A technology based modification in concrete tie technology that improves the safety of rail service and maintenance operations without impacting fabrication cost and process

Acknowledgments

U.S. Department of Transportation
Federal Railroad Administration

Grant Number DTFR53-14-C-00023

CSX

Rocla Concrete Tie, Inc

RAILTEC
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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Sally Bartelmo
Albert Ortiz
Adam Zeitouni
Sreehari Rajan Katil

Kevin Barberena
Spencer Green
Josh Breed
Melissa Brueckner
Brigitte Shumpert

Thank You!

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