Instrumenting, Post-tensioning, Recording and Modeling the Moose Brook Howe Trusses

by

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Wood

Anisotropic – Longitudinal, radial and tangential directions
Inhomogeneous – Mechanical properties vary from point to point
Viscous - Stress-strain behavior is a function of time
Hygroscopic – Ingress/egress of moisture
Flaws – Knots, checks, splits, etc.

Highly variable mechanical properties that are a function of wood moisture content

Atmospheric conditions and truss behavior

Temperature and relative humidity vary continuously in time

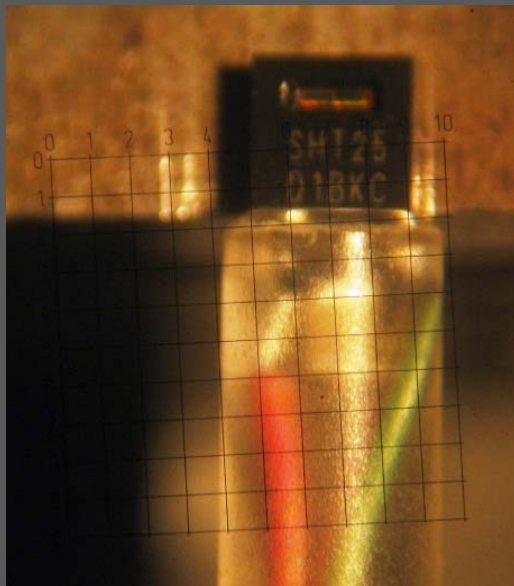
Thermal strains, viscous behavior, and shrinkage/swelling strains from moisture ingress/egress are “concurrent” in structural wood components in an outdoor environment. All three phenomena affect forces in post-tensioned Howe trusses.

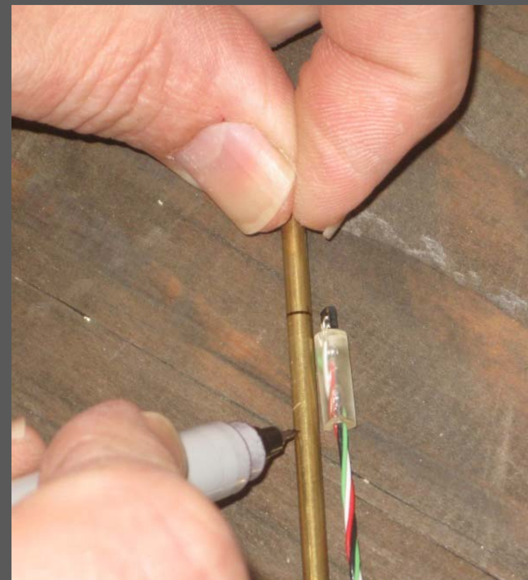
Scope of work and objectives

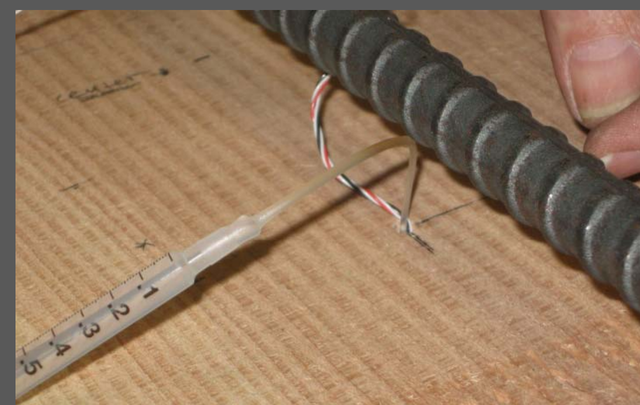
- Instrument Moose Brook Howe trusses with strain, temperature and relative humidity sensors
- Post-tension the trusses and place them outdoors (but protected)
- Acquire and interpret data from truss and atmospheric sensors for a period of at least one year
- Mathematically model the trusses and assess models
- Make judgments on structural significance of viscosity, thermal response and hygroscopic behavior

- Improve understanding of structural behavior of Howe trusses
- Improve rehabilitation technologies for Howe bridges
- Improve designs of new Howe bridges

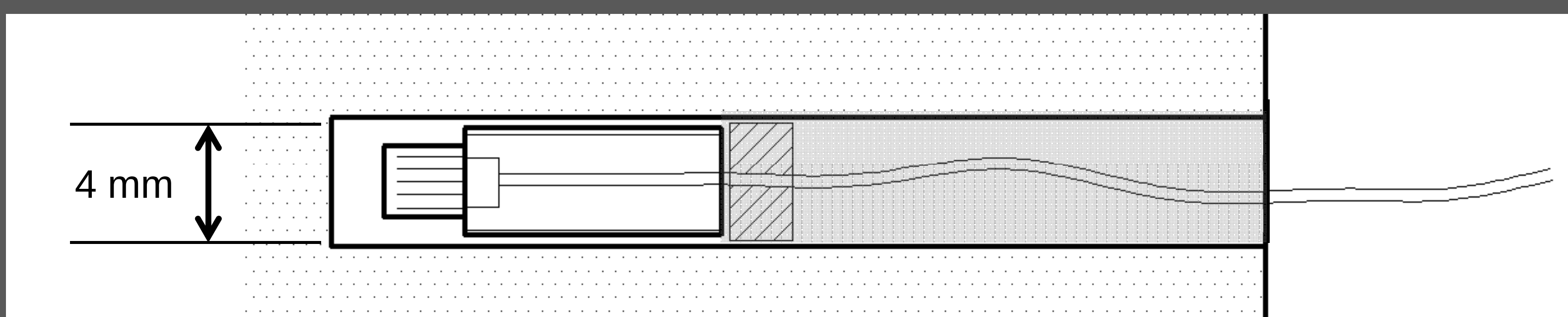
Weldable full bridge strain gauges, HPI model HBWF-35-125-6-10GP-TR-1" PC applied on Diwidag bars







Installation of Sensirion SHT25 semiconductor T/RH sensors



Instrumentation of two Howe trusses

Instrumentation

Single 8x8 post-tensioned specimen
2 Steel stain gauges on two stressed bars
1 Steel strain gauge on unstressed bar section
1 Atmospheric T/RH sensor
1 T/RH sensor in small loose wood block
3 T/RH sensors at three depths within the cross-section

Two Howe trusses
18 Steel strain gauges
1 Steel strain gauge on unstressed bar section
1 Atmospheric T/RH sensor
14 T/RH sensors in various members at various depths

Data acquisition system

Designed, built, and monitored by Jim Berilla.
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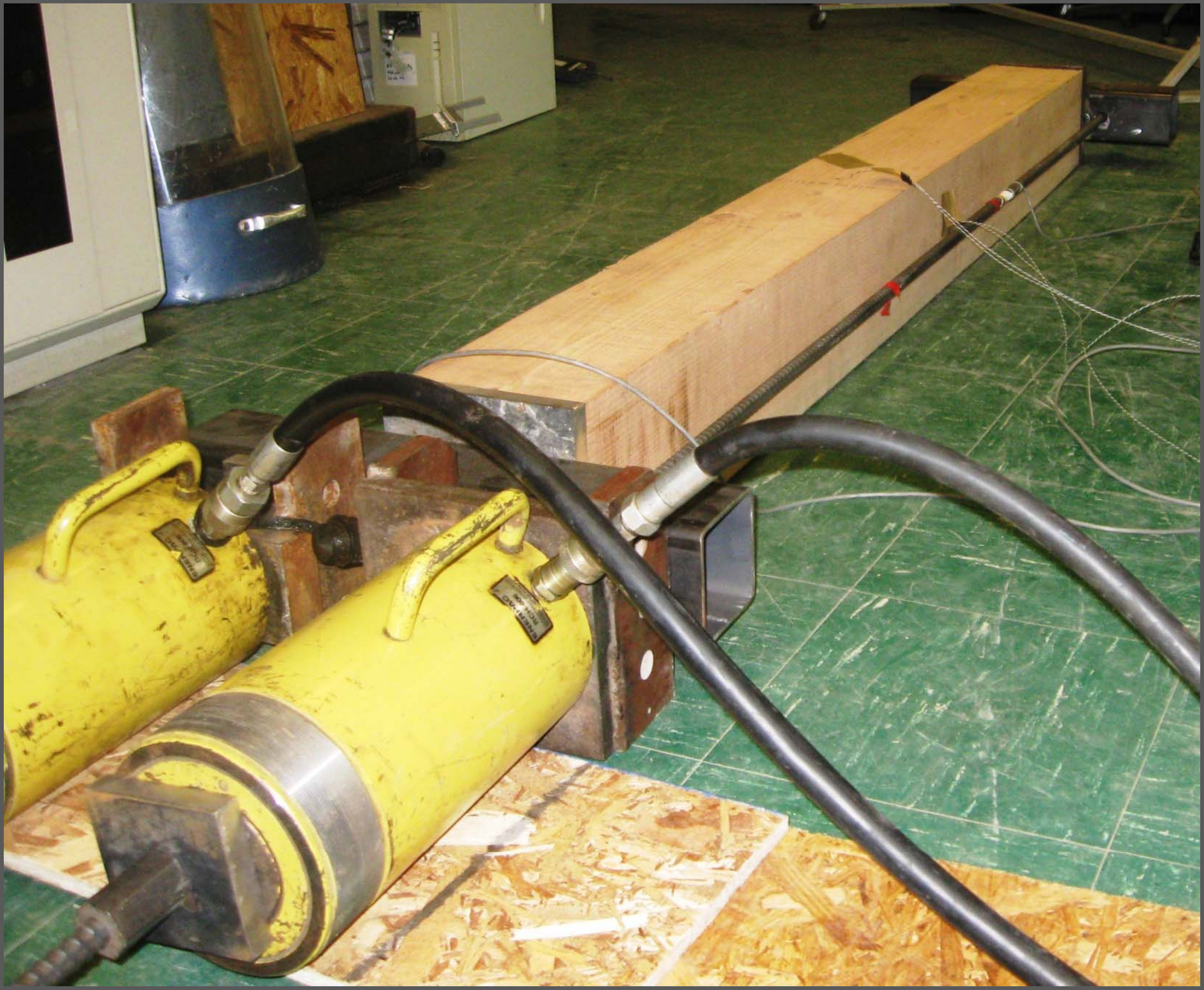
Post-tensioning of single element



Single 8” x 8” Douglas fir post-tensioned specimen

Post-tensioning of two Howe trusses

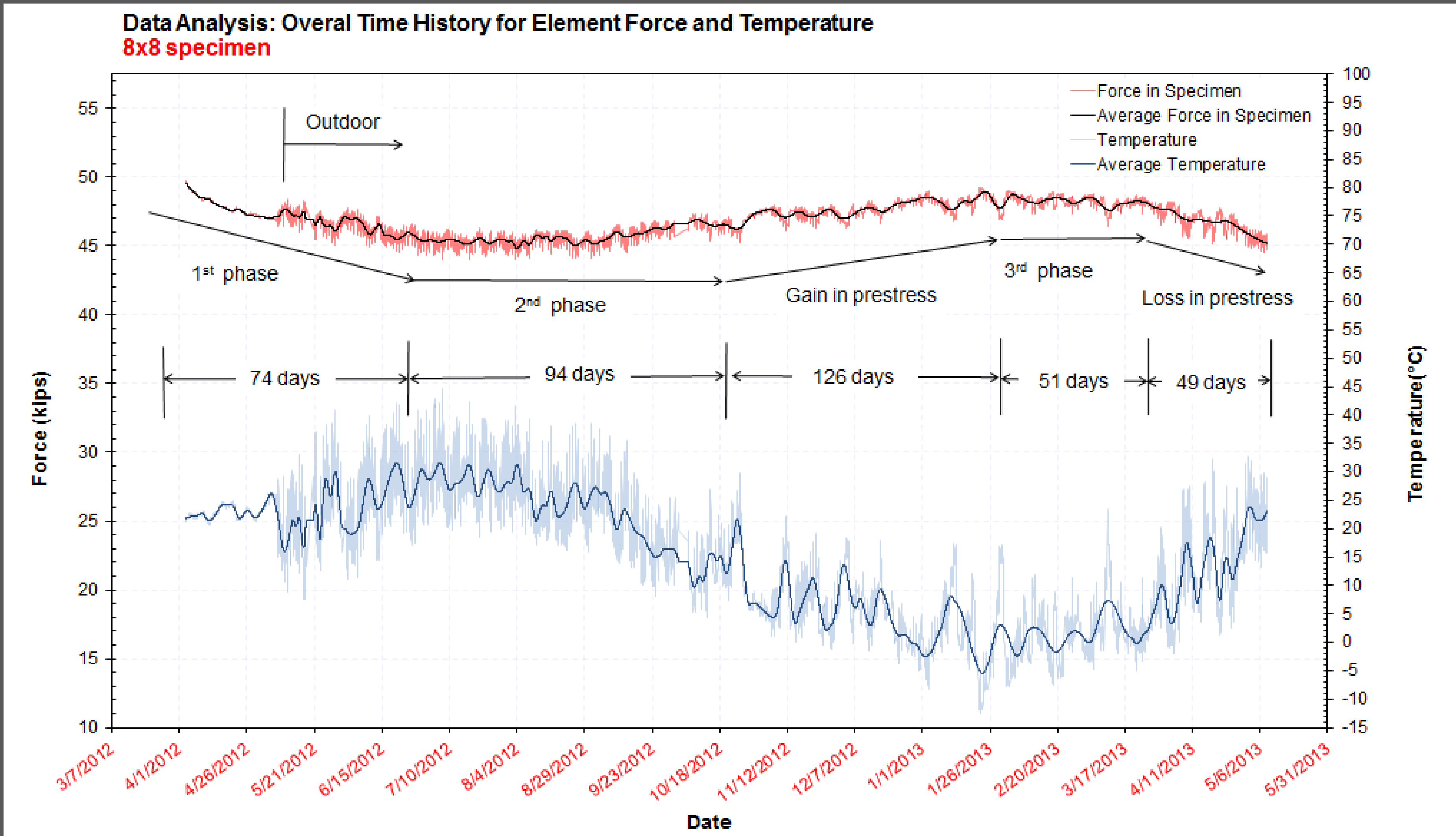
Architectural fabric cover designed, fabricated, and supplied pro-bono by the Seaman Corp. of Wooster, OH

<u>8x8 specimen</u>

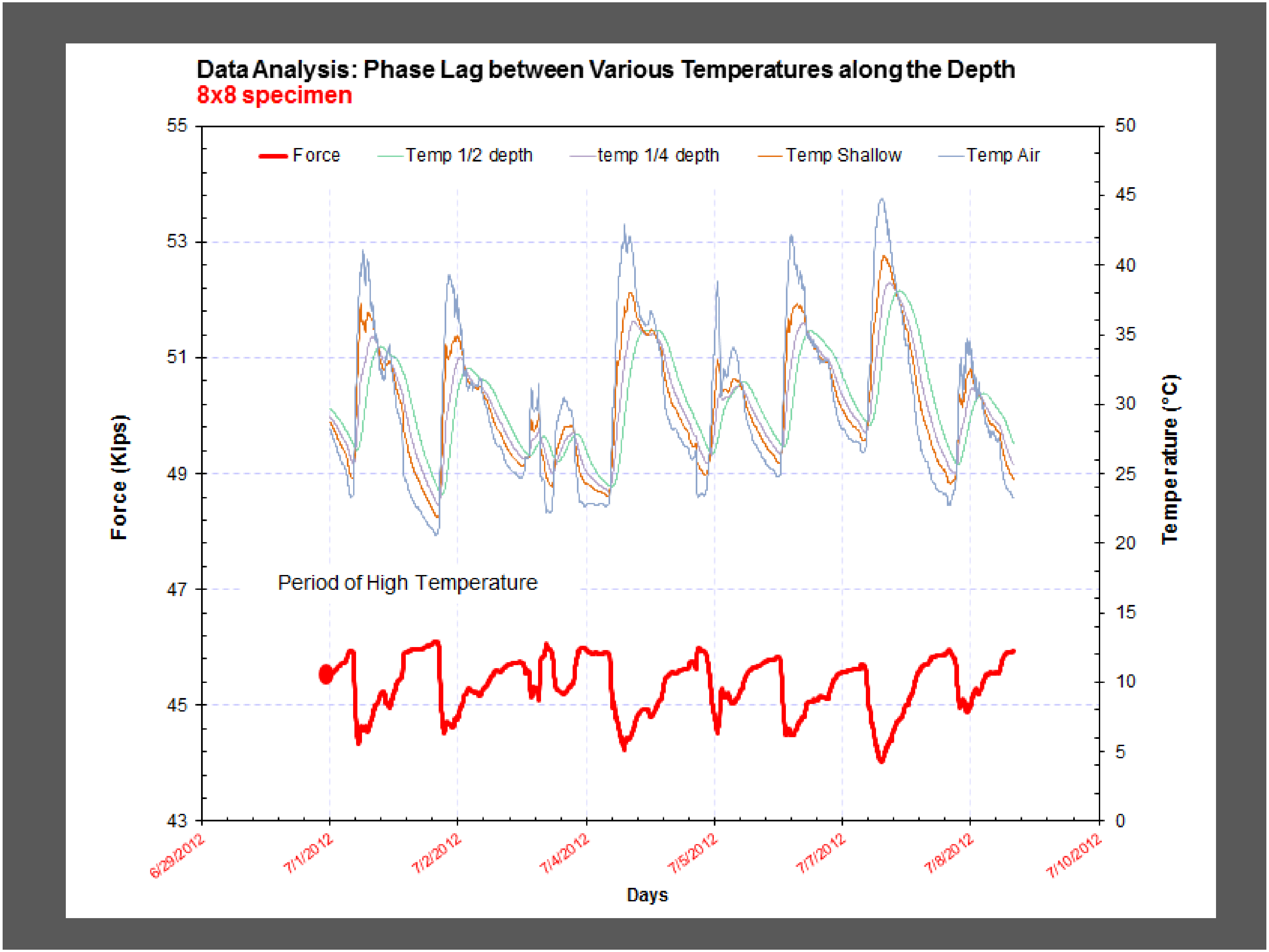
Post-tensioned on 4-3-2012; installed outdoors on 5-8-2012

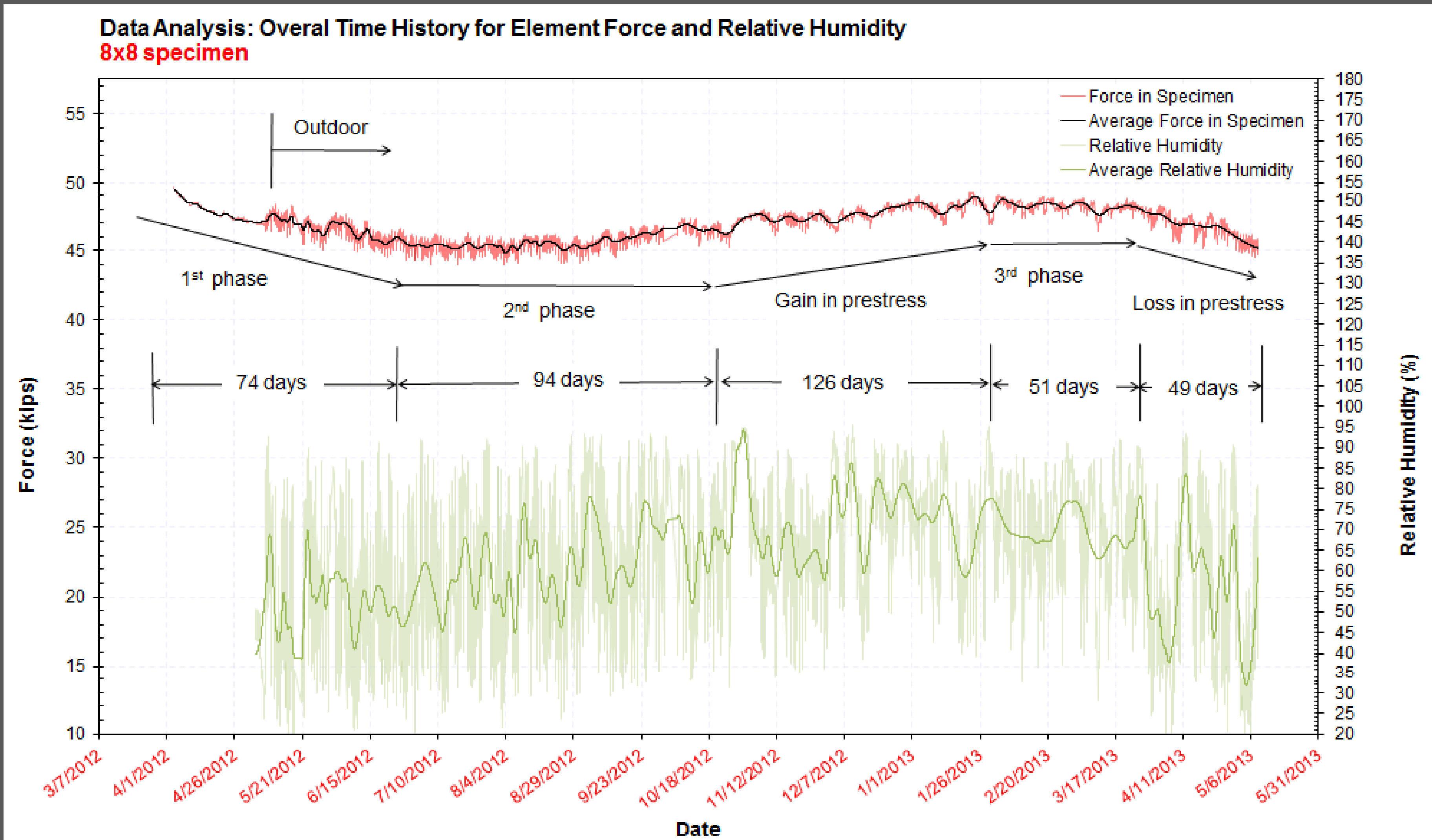
<u>Howe trusses</u>

Post-tensioned on 6-13-2012; installed outdoors on 9-25-2012

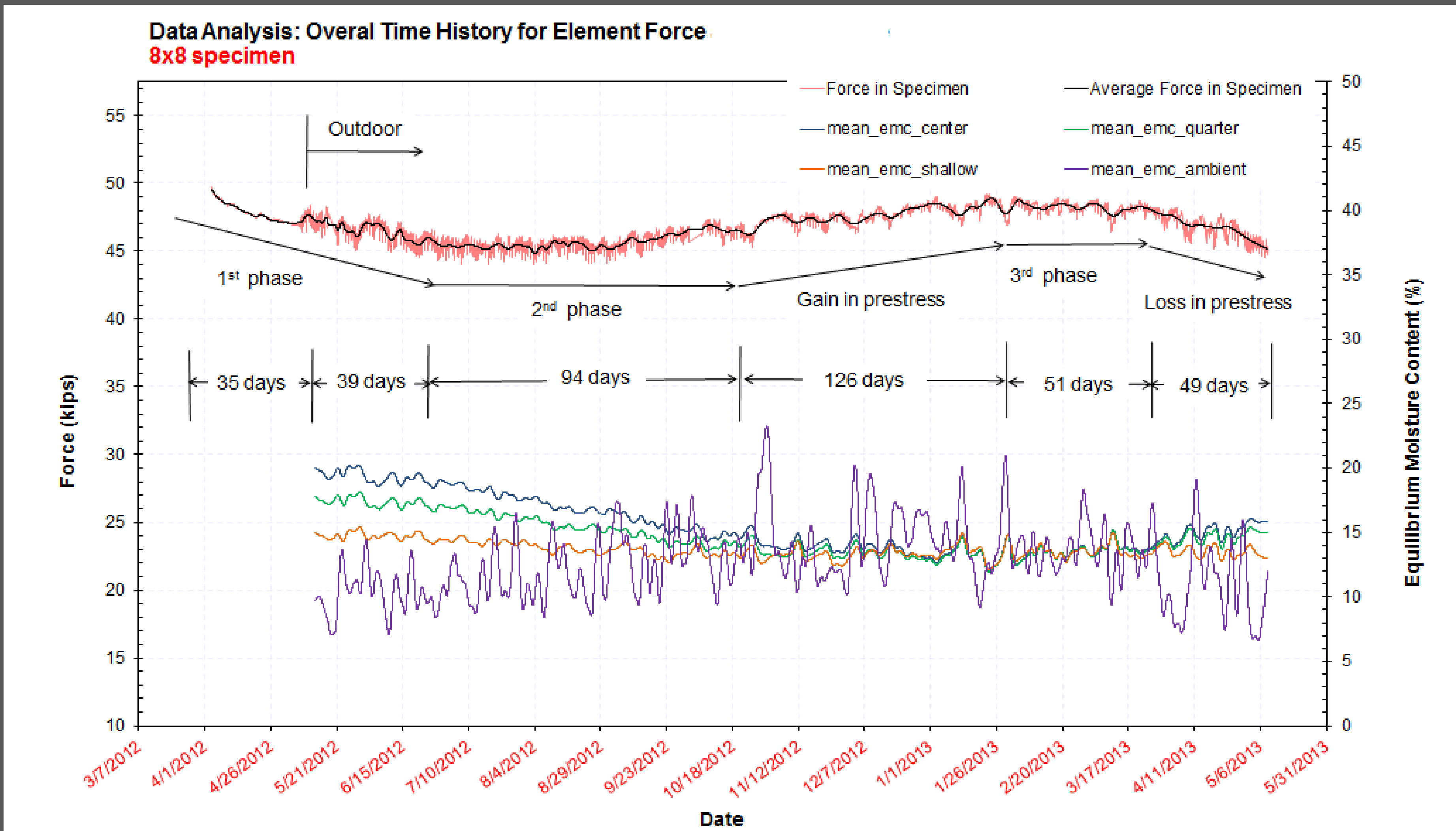


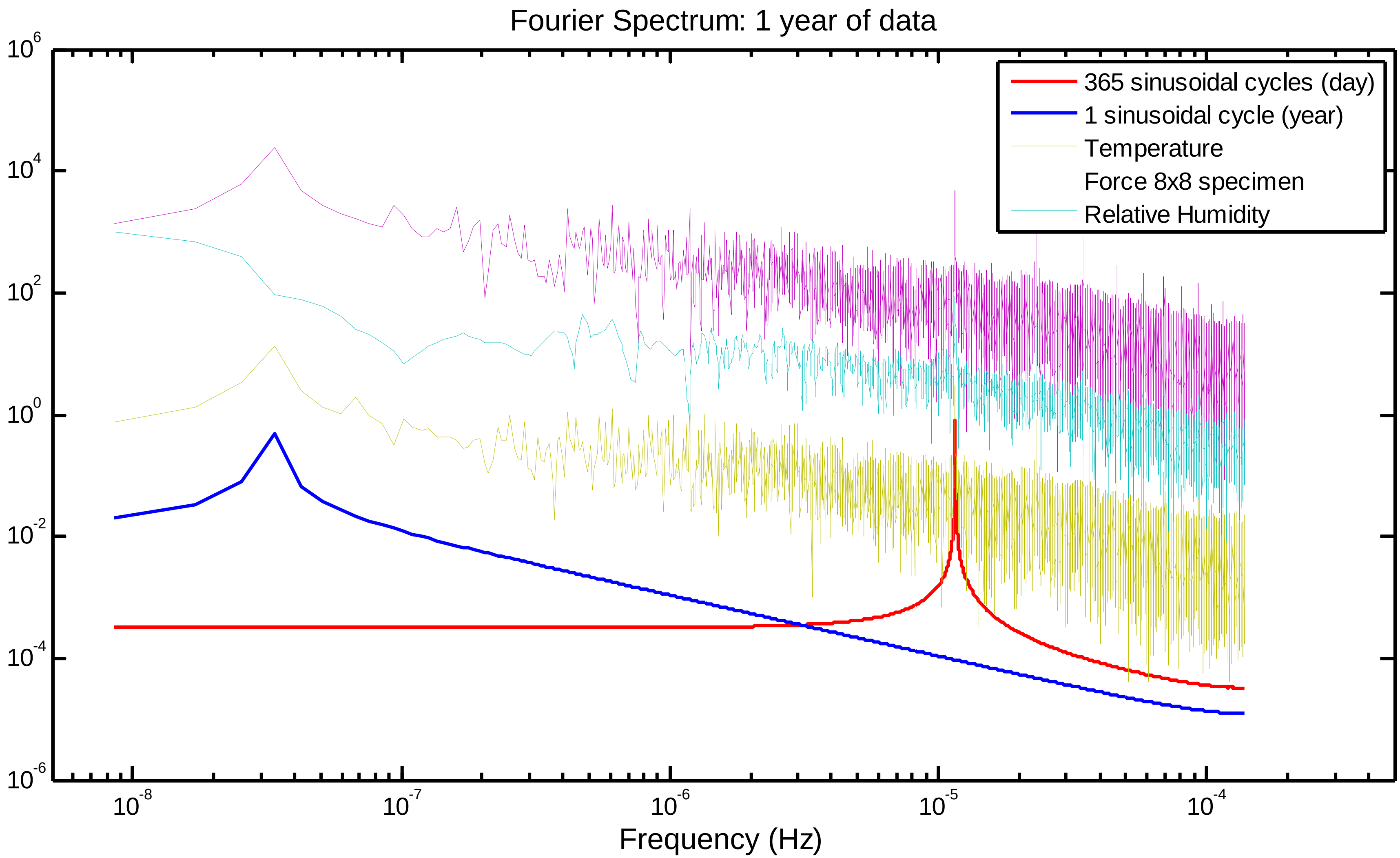
Data Analysis: Overal Time History for Element Force and Temperature
8x8 specimen
Force in Specimen
Average Force in Specimen
Temperature
Average Temperature
Outdoor
1st phase
2nd phase
Gain in prestress
3rd phase
Loss in prestress
74 days
94 days
126 days
51 days
49 days
Force (kips)
Temperature(°C)
Date
3/7/2012
4/1/2012
4/26/2012
5/21/2012
6/15/2012
7/10/2012
8/4/2012
8/29/2012
9/23/2012
10/18/2012
11/12/2012
12/7/2012
1/1/2013
1/26/2013
2/20/2013
3/17/2013
4/11/2013
5/6/2013
5/31/2013


Data Analysis: Phase Lag between Various Temperatures along the Depth
8x8 specimen
Force
Temp 1/2 depth
temp 1/4 depth
Temp Shallow
Temp Air
Period of High Temperature
Force (Kips)
Temperature (°C)
Days
55
53
51
49
47
45
43
50
45
40
35
30
25
20
15
10
5
0
6/29/2012
7/1/2012
7/2/2012
7/4/2012
7/5/2012
7/7/2012
7/8/2012
7/10/2012

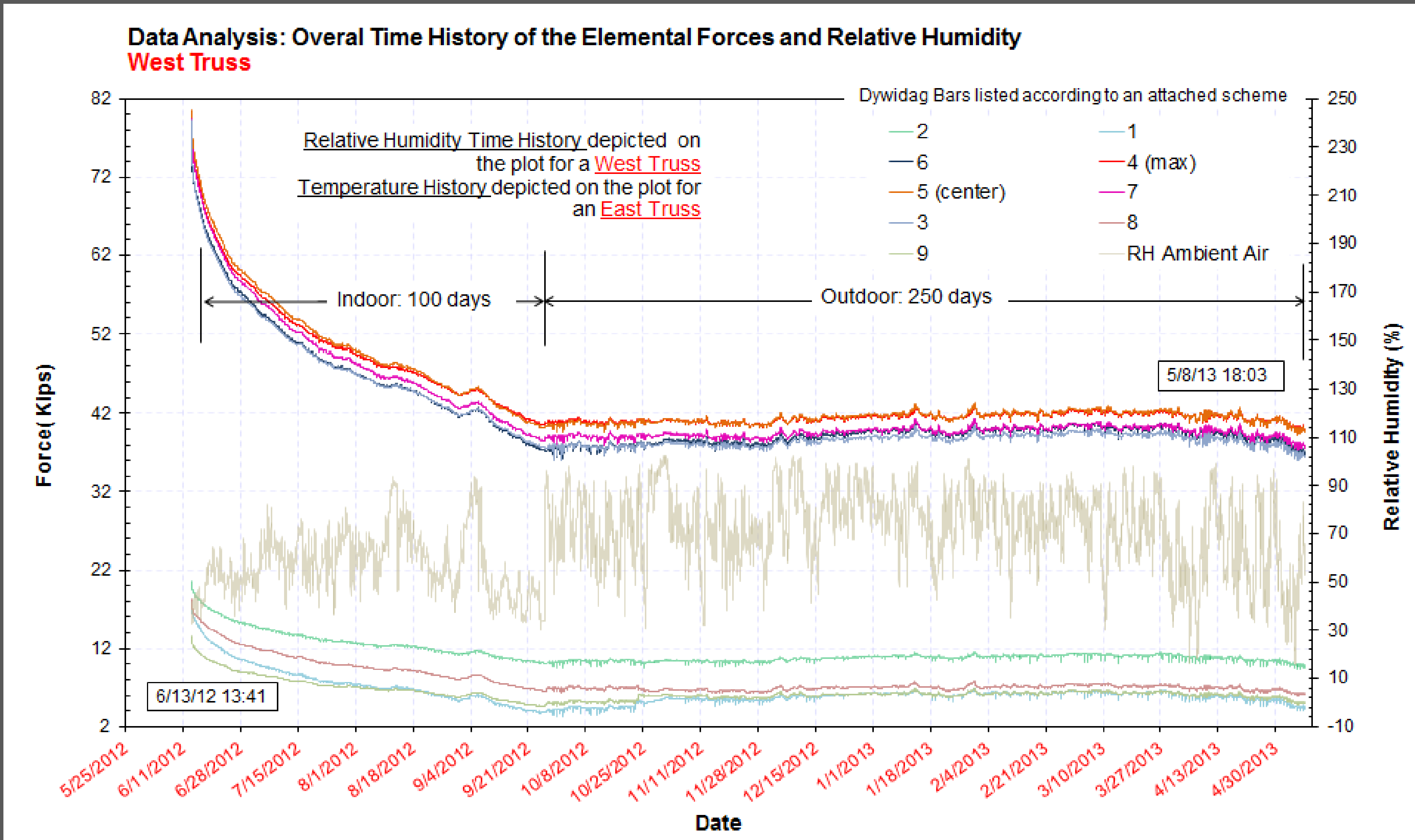


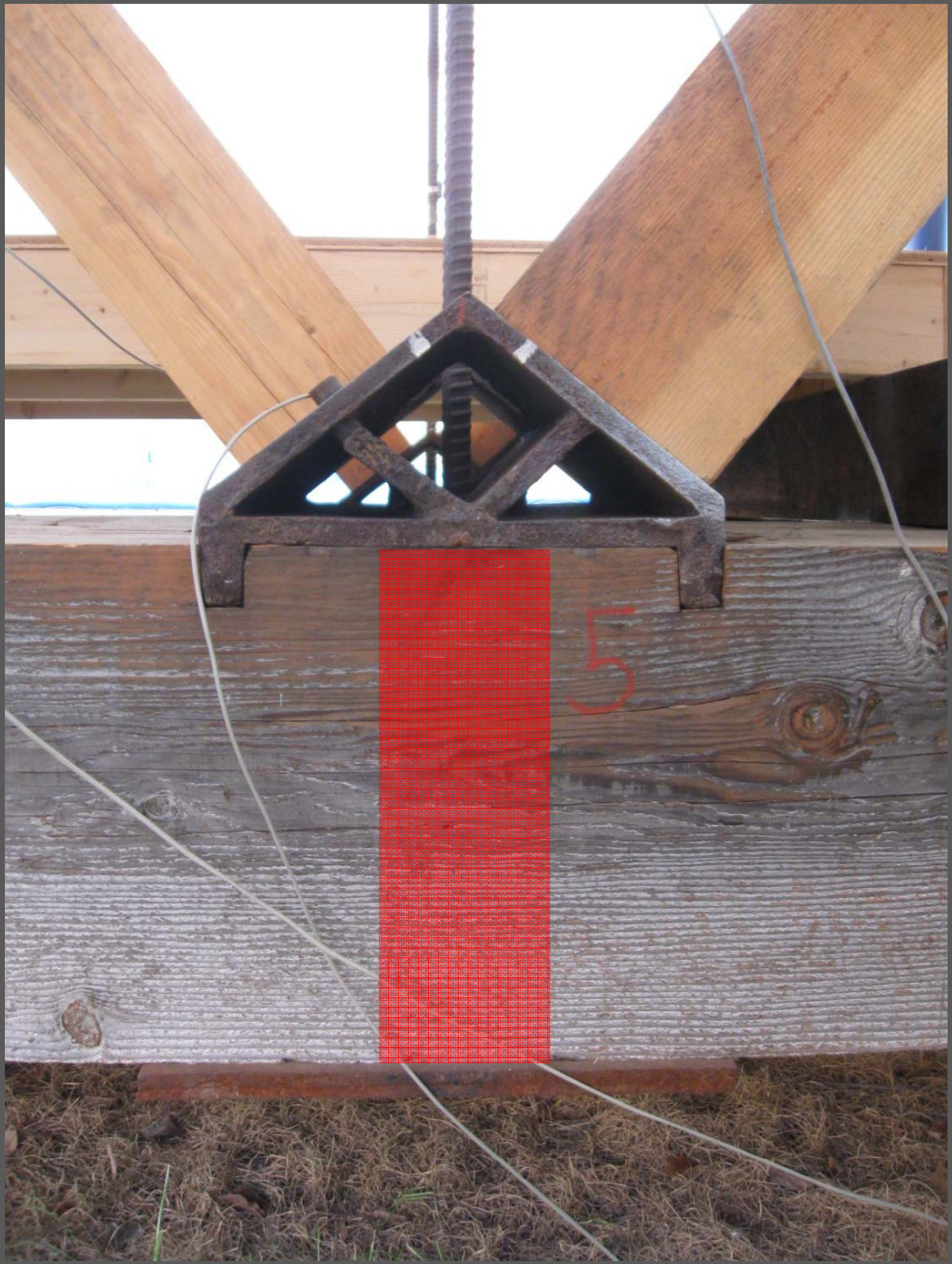
Data Analysis: Overal Time History for Element Force and Relative Humidity
8x8 specimen
Force in Specimen
Average Force in Specimen
Relative Humidity
Average Relative Humidity
Outdoor
1st phase
2nd phase
Gain in prestress
3rd phase
Loss in prestress
74 days
94 days
126 days
51 days
49 days
Force (kips)
Relative Humidity (%)
Date
3/7/2012
4/1/2012
4/26/2012
5/21/2012
6/15/2012
7/10/2012
8/4/2012
8/29/2012
9/23/2012
10/18/2012
11/12/2012
12/7/2012
1/1/2013
1/26/2013
2/20/2013
3/17/2013
4/11/2013
5/6/2013
5/31/2013


Data Analysis: Overal Time History for Element Force
8x8 specimen
Force in Specimen
Average Force in Specimen
mean_emc_center
mean_emc_quarter
mean_emc_shallow
mean_emc_ambient
Outdoor
1st phase
2nd phase
Gain in prestress
3rd phase
Loss in prestress
35 days
39 days
94 days
126 days
51 days
49 days
Force (kips)
Equilibrium Moisture Content (%)
Date
3/7/2012
4/1/2012
4/26/2012
5/21/2012
6/15/2012
7/10/2012
8/4/2012
8/29/2012
9/23/2012
10/18/2012
11/12/2012
12/7/2012
1/1/2013
1/26/2013
2/20/2013
3/17/2013
4/11/2013
5/6/2013
5/31/2013



8x8 specimen – Fourier amplitude spectra of recorded time histories

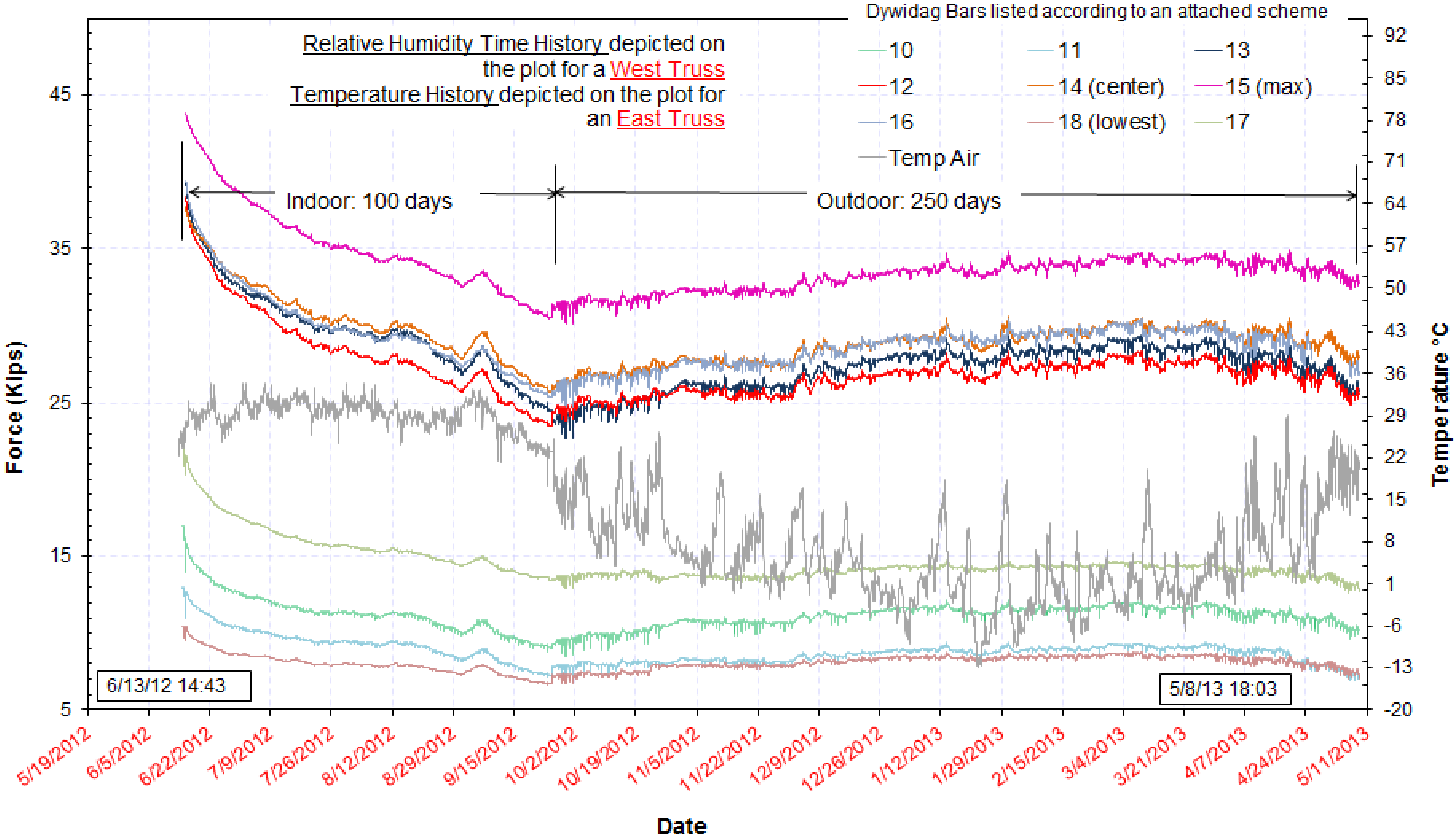

Data Analysis: Overal Time History of the Elemental Forces and Relative Humidity
West Truss
Relative Humidity Time History depicted on the plot for a West Truss
Temperature History depicted on the plot for an East Truss
Dywidag Bars listed according to an attached scheme
2
1
6
4 (max)
5 (center)
7
3
8
9
RH Ambient Air
Indoor: 100 days
Outdoor: 250 days
5/8/13 18:03
6/13/12 13:41
Force(Kips)
Relative Humidity (%)
Date
5/25/2012
6/11/2012
6/28/2012
7/15/2012
8/1/2012
8/18/2012
9/4/2012
9/21/2012
10/8/2012
10/25/2012
11/11/2012
11/28/2012
12/15/2012
1/1/2013
1/18/2013
2/4/2013
2/21/2013
3/10/2013
3/27/2013
4/13/2013
4/30/2013
82
72
62
52
42
32
22
12
2
250
230
210
190
170
150
130
110
90
70
50
30
10
-10



Viscous losses likely from stresses normal to the grain in the chords; minimize by using castings with "sleeves"

Data Analysis: Overall Time History of the Elemental Forces and Temperature

East Truss



Mathematical modeling

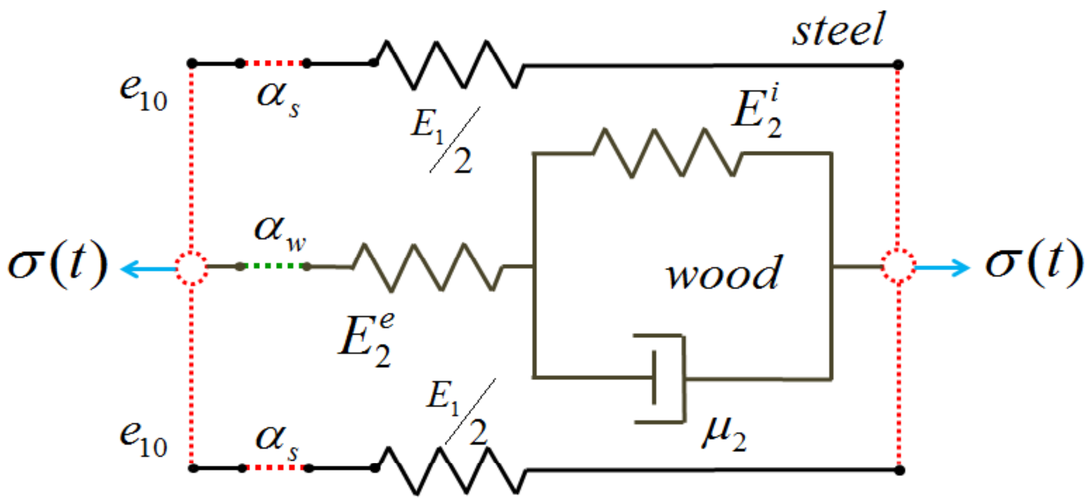
Linear viscoelastic analyses

- **Three parameter solid model**
- **Burger model**

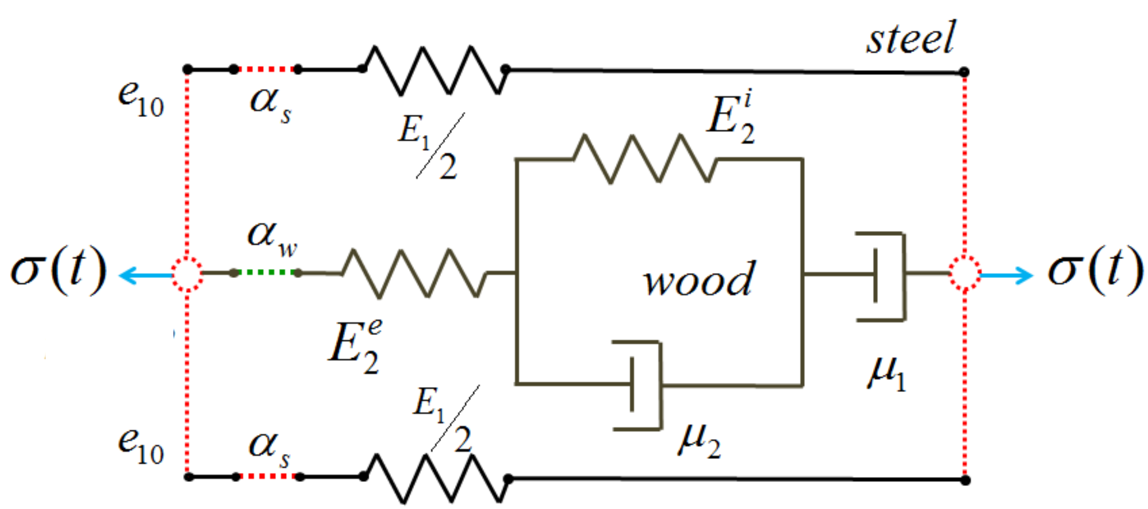
Diffusion analyses

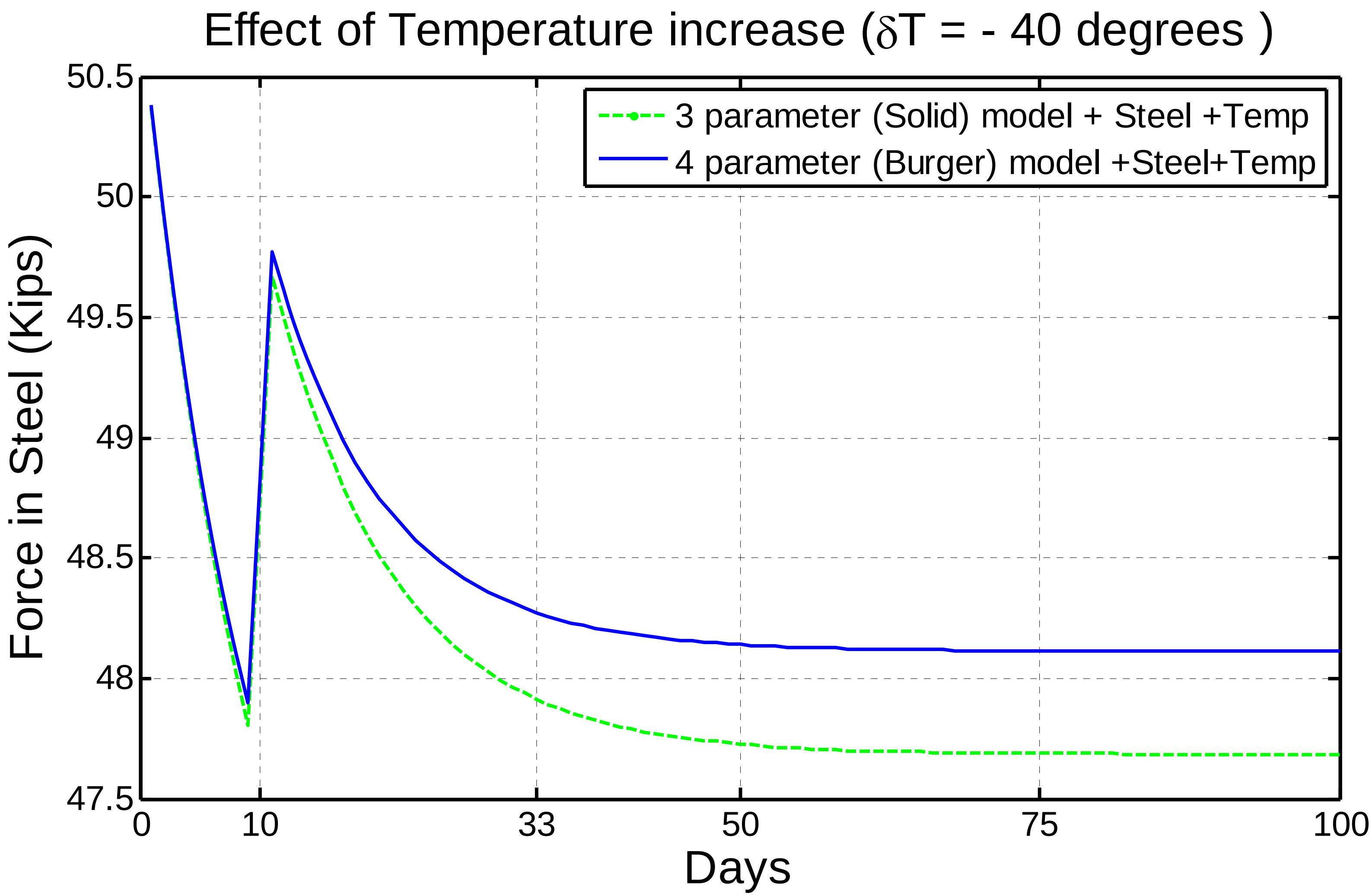
- **Two-dimensional isotropic diffusion model**

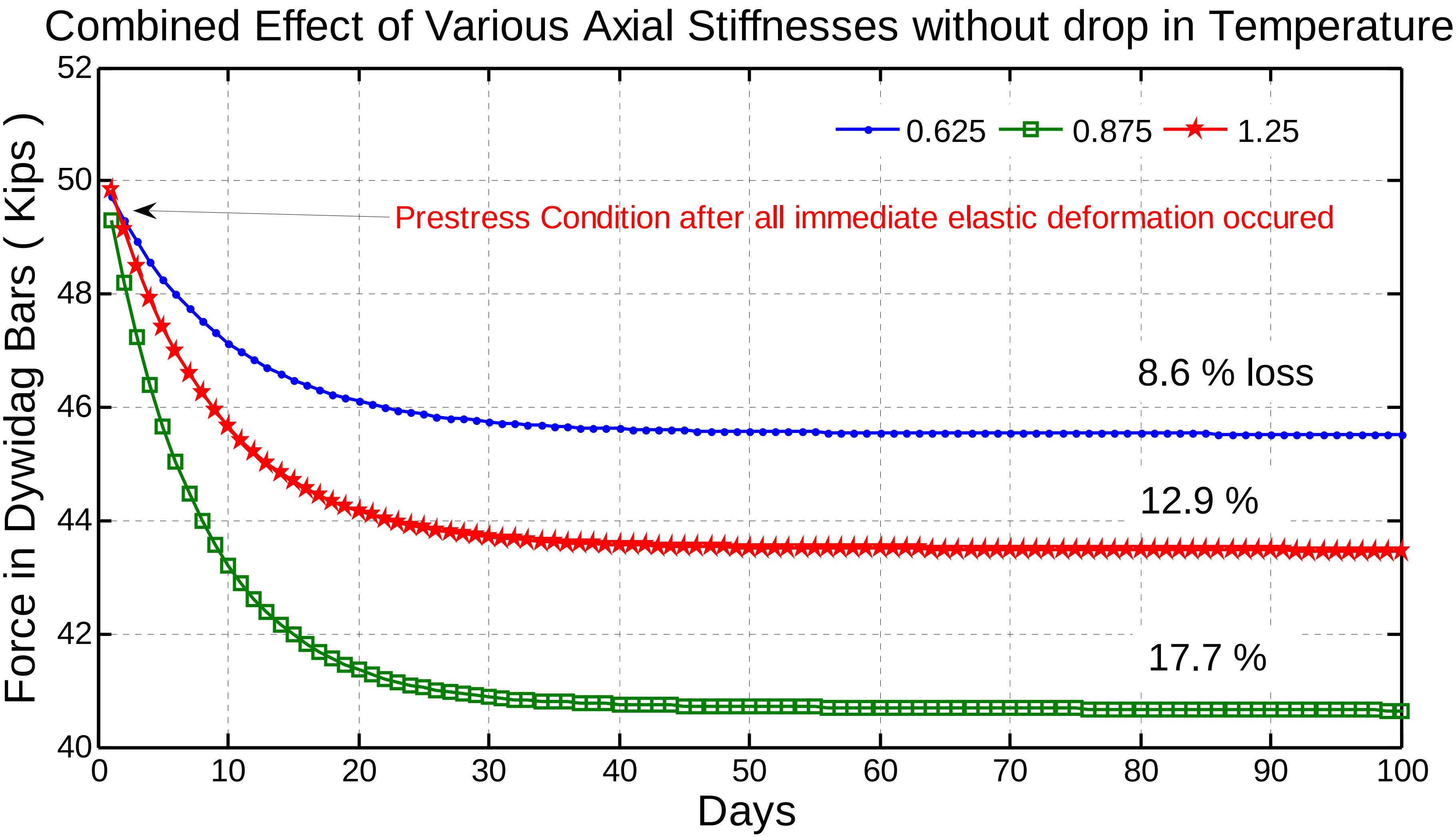
Three-parameter solid model for wood; linear elastic model for steel

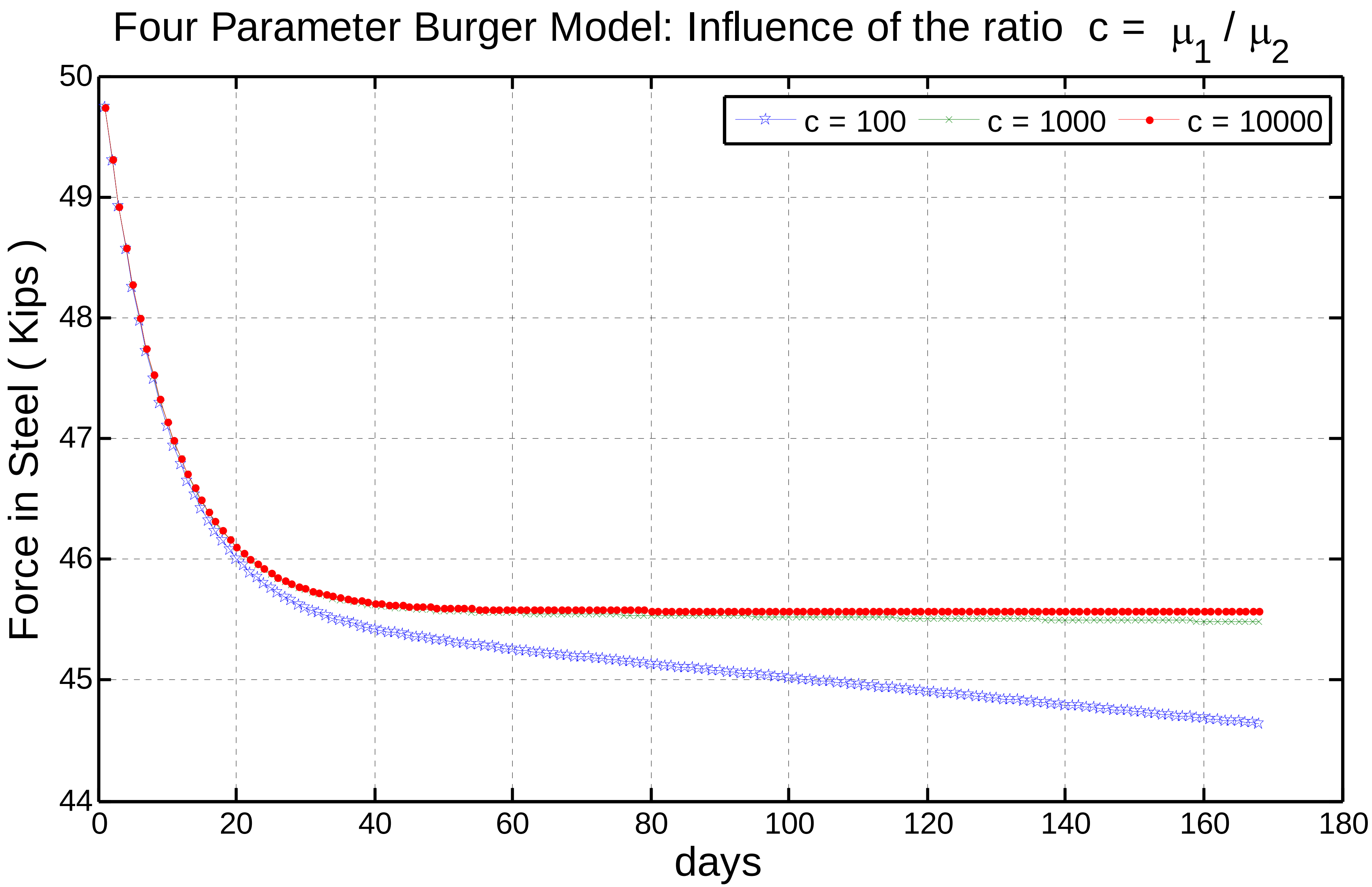


Four-parameter Burger model for wood; linear elastic model for steel




Effect of Temperature increase (δT = - 40 degrees)
3 parameter (Solid) model + Steel +Temp
4 parameter (Burger) model +Steel+Temp
Force in Steel (Kips)
50.5
50
49.5
49
48.5
48
47.5
0
10
33
50
75
100
Days


Combined Effect of Various Axial Stiffnesses without drop in Temperature
0.625
0.875
1.25
Prestress Condition after all immediate elastic deformation occured
8.6 % loss
12.9 %
17.7 %
Force in Dywidag Bars (Kips)
Days
52
50
48
46
44
42
40
0
10
20
30
40
50
60
70
80
90
100


Four Parameter Burger Model: Influence of the ratio c = μ1 / μ2
c = 100
c = 1000
c = 10000
Force in Steel (Kips)
days
50
49
48
47
46
45
44
0
20
40
60
80
100
120
140
160
180

Diffusion model for the egress/ingress of moisture

$$D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)=\frac{\partial C}{\partial t}$$

Two Dimensional Isotropic Fickian Diffusion Model

$D -$ *Diffusion coefficient*

$C -$ *Concentration*

$$D\frac{\partial C}{\partial x}=S(C_b - C_e(t))$$

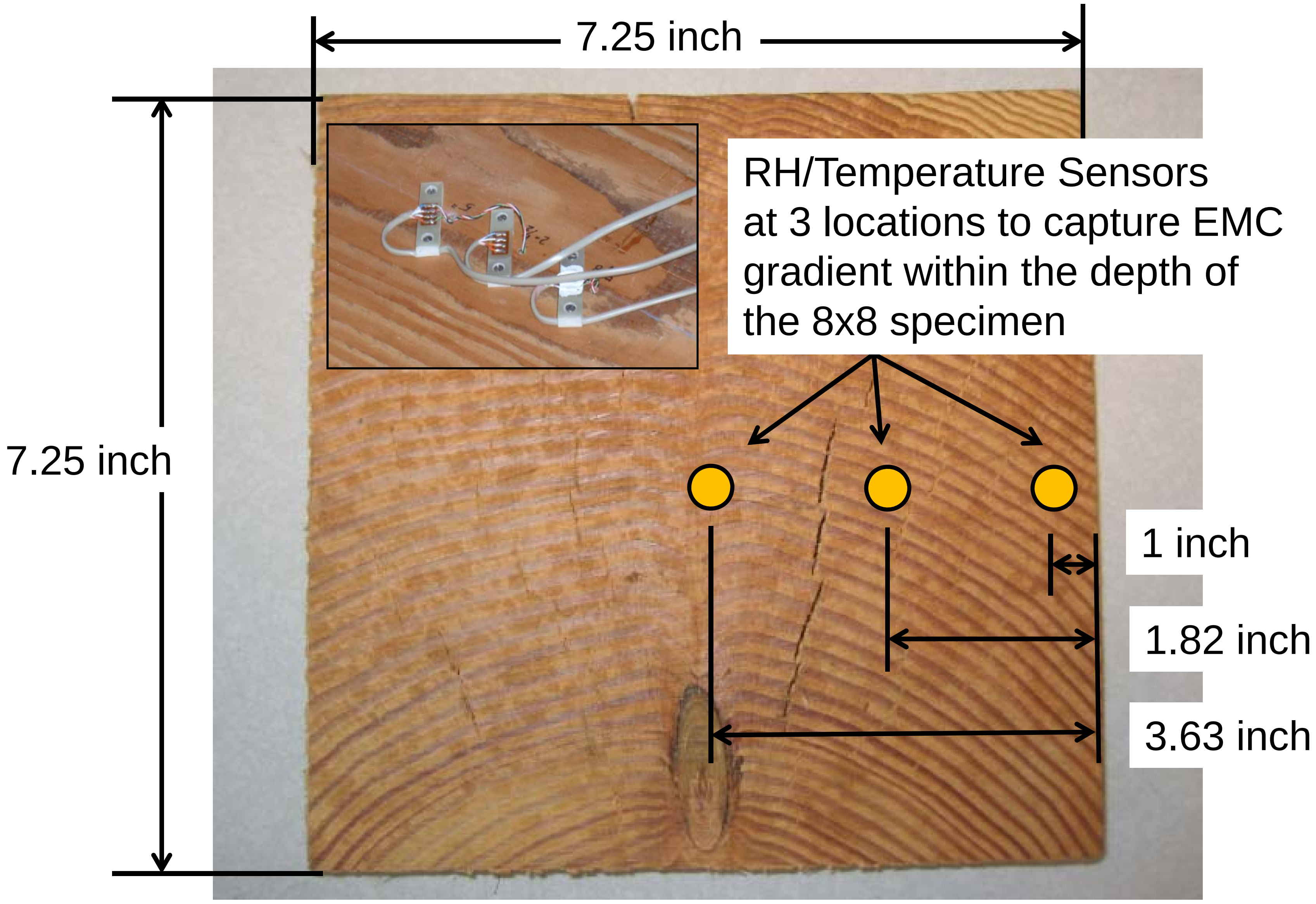
Emission / Admission Model at boundary

$S -$ *Surface emission coefficient*

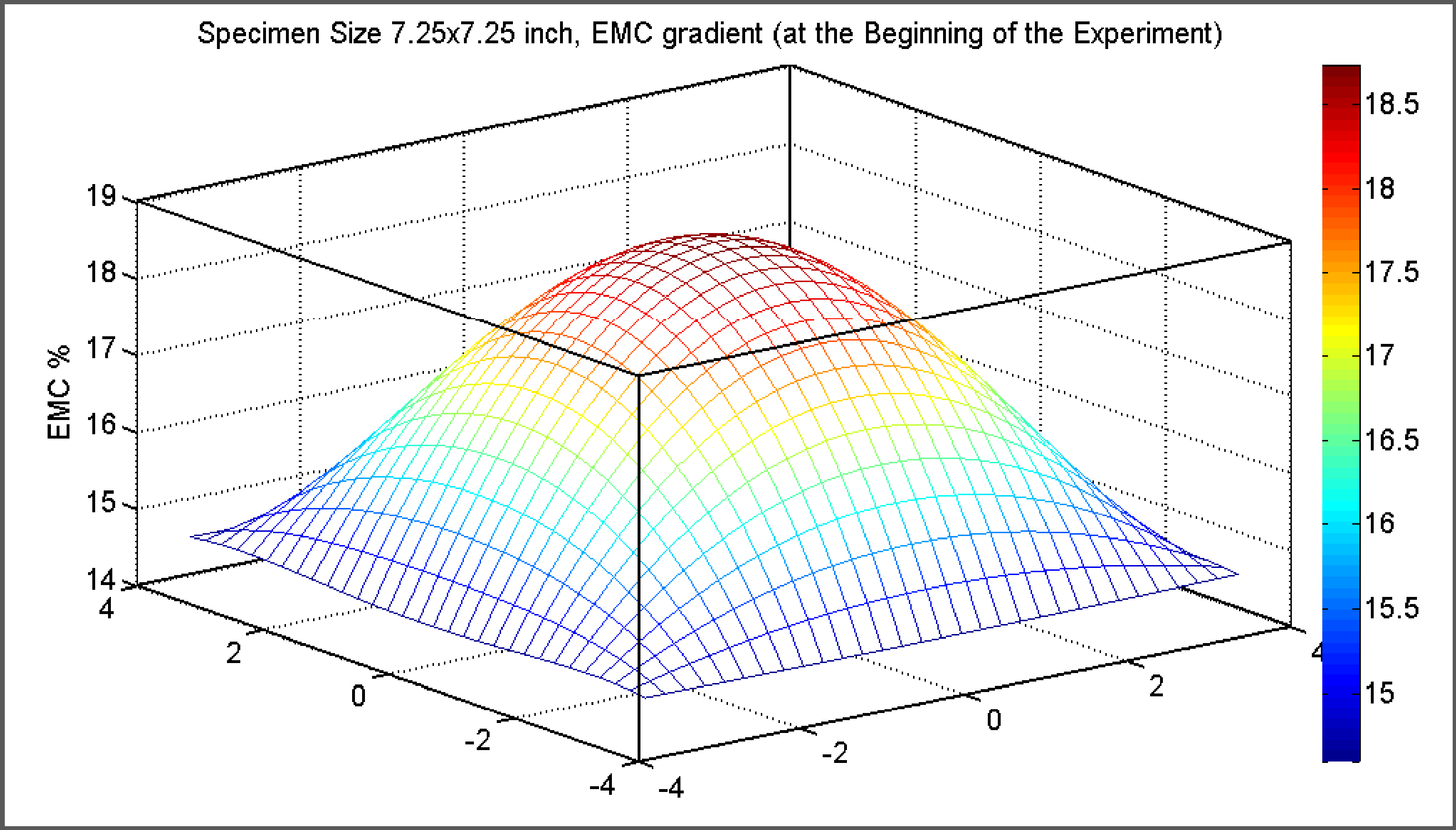
$C_e(t) -$ *Concentration in equilibrium with atmospheric conditions*

$C_b -$ *Concentration at boundary*

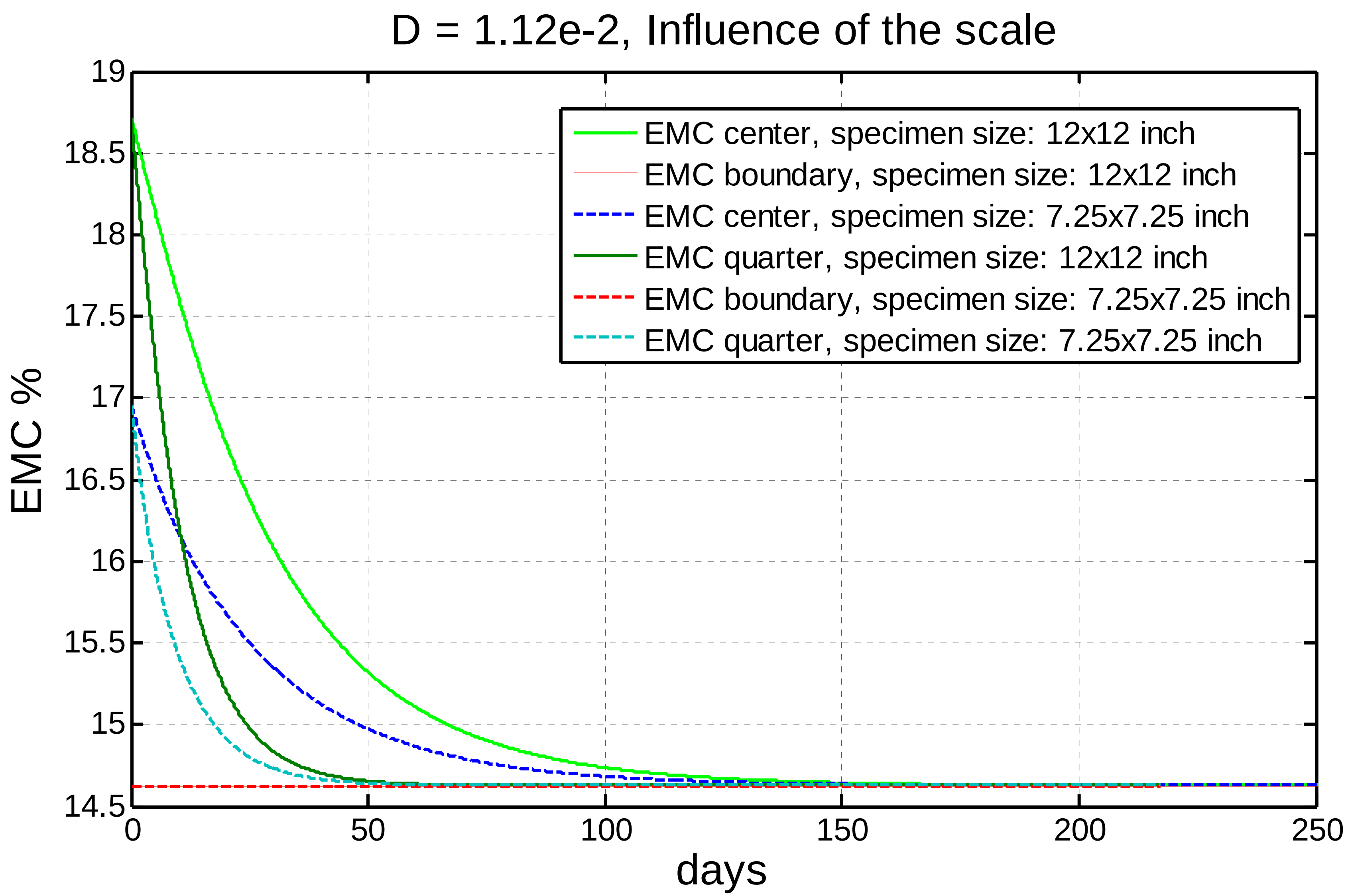
Initial conditions and boundary conditions

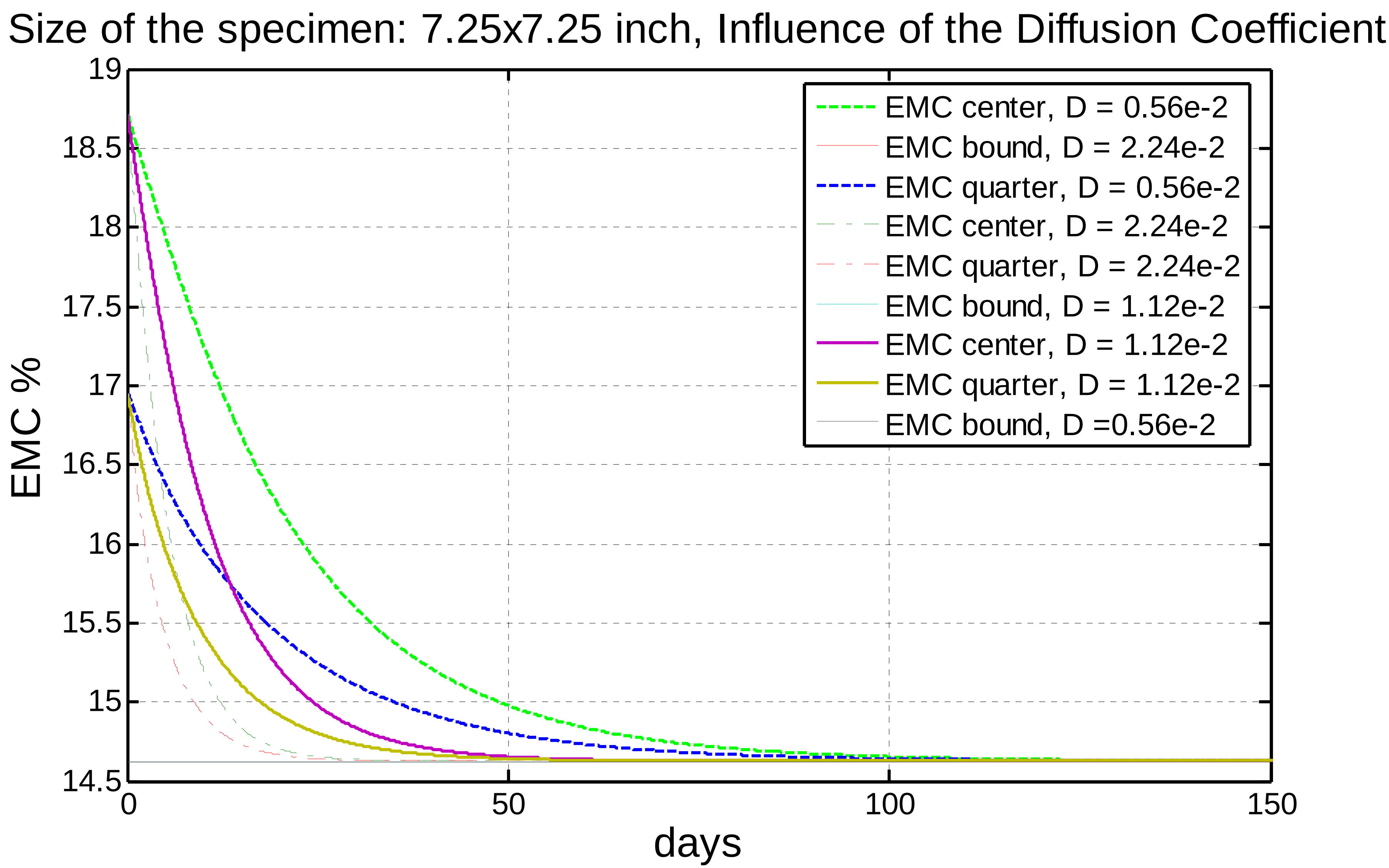


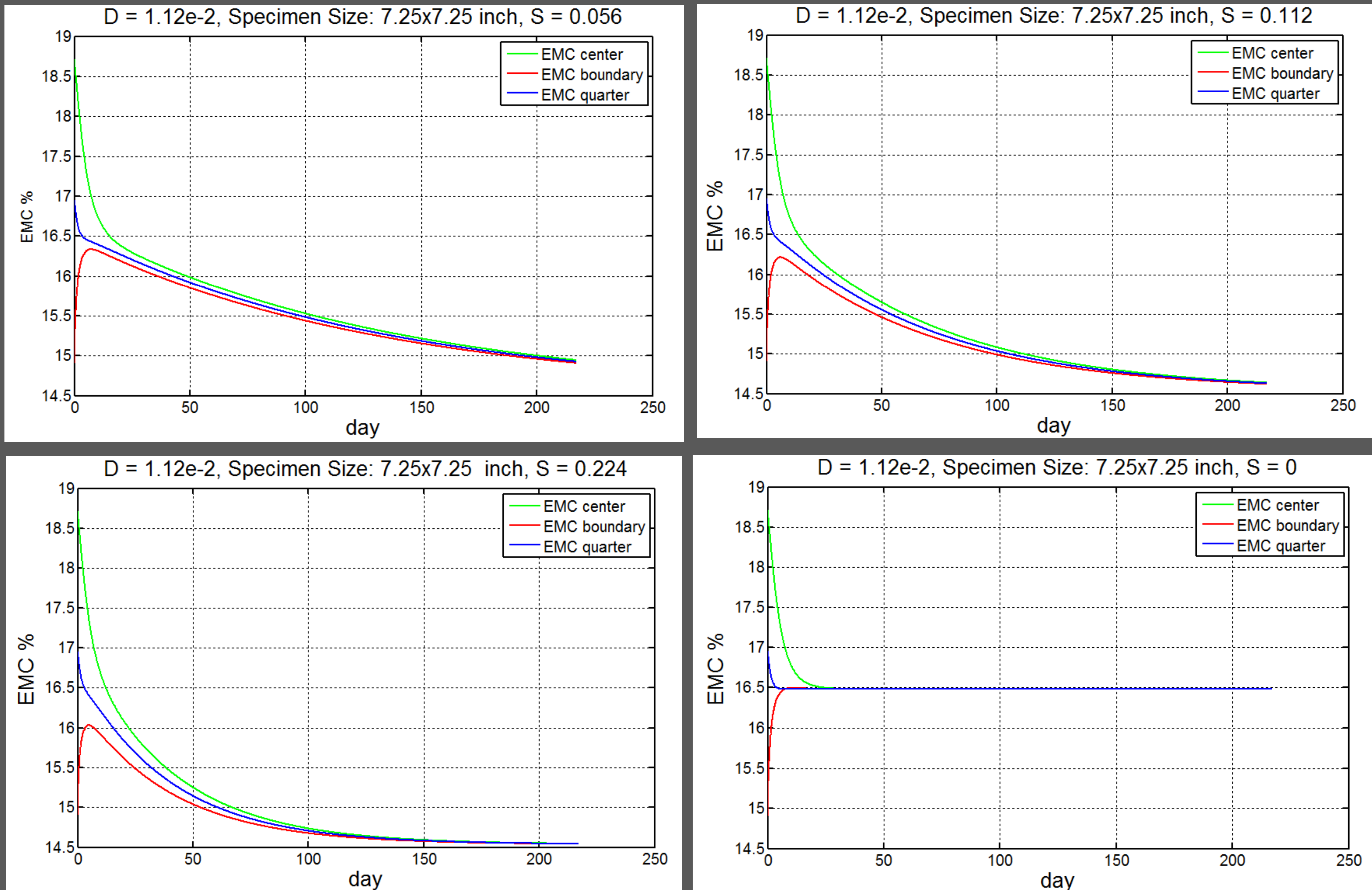
7.25 inch
7.25 inch
RH/Temperature Sensors
at 3 locations to capture EMC
gradient within the depth of
the 8x8 specimen
1 inch
1.82 inch
3.63 inch



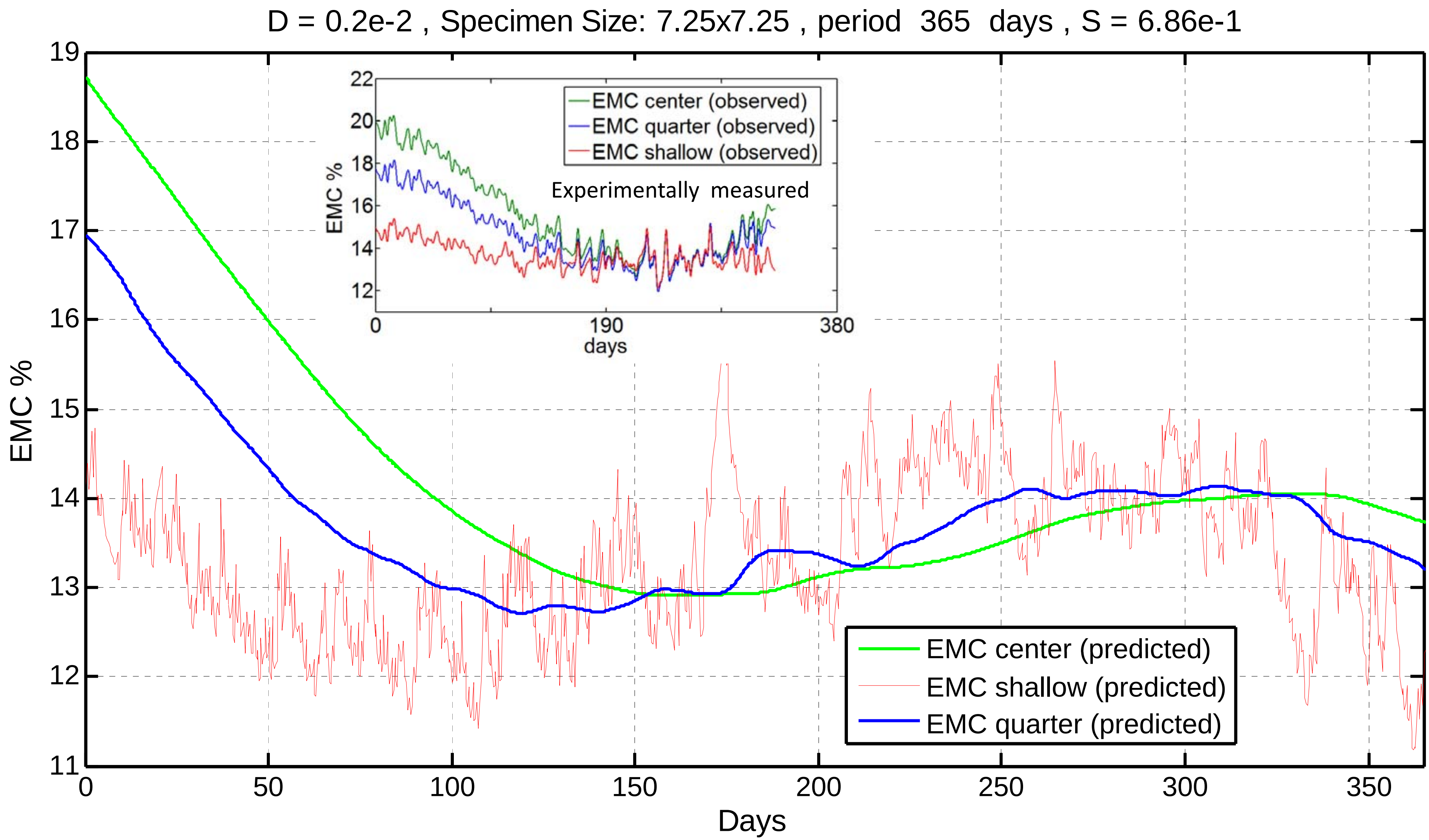
Assumed initial moisture content distribution within cross-section


D = 1.12e-2, Influence of the scale
EMC %
days
EMC center, specimen size: 12x12 inch
EMC boundary, specimen size: 12x12 inch
EMC center, specimen size: 7.25x7.25 inch
EMC quarter, specimen size: 12x12 inch
EMC boundary, specimen size: 7.25x7.25 inch
EMC quarter, specimen size: 7.25x7.25 inch
19
18.5
18
17.5
17
16.5
16
15.5
15
14.5
0
50
100
150
200
250


Size of the specimen: 7.25x7.25 inch, Influence of the Diffusion Coefficient
EMC %
days
19
18.5
18
17.5
17
16.5
16
15.5
15
14.5
0
50
100
150
EMC center, D = 0.56e-2
EMC bound, D = 2.24e-2
EMC quarter, D = 0.56e-2
EMC center, D = 2.24e-2
EMC quarter, D = 2.24e-2
EMC bound, D = 1.12e-2
EMC center, D = 1.12e-2
EMC quarter, D = 1.12e-2
EMC bound, D =0.56e-2



Influence of the surface emission coefficient on moisture content within cross-section



Predicted vs. measured moisture content time histories with the observed actual atmospheric temperature and relative humidity fluctuations as boundary conditions

Observations

•The 8x8 specimen lost approximately 8% of its prestress over one year due to wood viscosity; the present loss rate is extremely small.

• The prestress losses in the Howe trusses are approximately 30% and 50%, but these could be minimized by use of “sleeved” nodal castings.

• It’s almost certain that with current prestressing processes a permanent state of pre-stress can be achieved in Howe trusses.

• Atmospheric T and RH fluctuations do affect forces in Howe trusses, but the stress ranges in the wood and steel are small.

Observations

- Effects of temperature variations are predicted well by linear elastic models

- Diffusion models can be calibrated to predict wood moisture content variations that match observed values well.

Additional work

• Continue acquiring data through the end of 2013

• One of the Howe trusses will be re-tightened to observe changes in subsequent viscous behavior in wood

• A coupled "mechanosorptive" model is required to predict stresses from wood strain caused by moisture content variation; the diffusion model predictions may be helpful in defining an effective axial strain from moisture ingress/egress.

Suggestions……

If a *new* covered bridge is commissioned,

- **Select a Howe truss in its original form**
- **Use nodal castings with “sleeves”**
- **Use low moisture content wood**
- **No need for bolts, gusset plates, adhesives, fiber-reinforced wraps, trunnels, complex wood joinery, etc.**
- **Maximize shop fabrication and pre-assemble trusses**
- **Use current post-tensioning technologies**
- **Post-tension in summer**
- **Achieve a permanently post-tensioned wood Howe bridge!**

If a Howe bridge is to be rehabilitated,

- **Don’t allow/assume slack counter-diagonals**
- **Control initial tightening and prescribe re-tightening**

Acknowledgments

FHWA/NHCBP – Sheila Duwadi
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