Status Report
on
MDTA Link Slab Study

by

By Dr. Chung C. Fu, P.E., Director and Research Professor
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I. PHASE I RESEARCH PLAN AND REPORT

Following tasks were proposed for Phase I study:

Task 1 – Conduct literature review from the federal and other state agencies

Task 2 – Perform laboratory testing

Task 3 – Select and analyze a bridge for pilot study

Task 4 - Provide recommendation of standard practice

Task 5 - Summary and Report

Following missions are completed in this study. (Details are covered in **Attachment A** – "A Pilot Application of Link Slab with Selected material for MDTA Steel Bridges".)

- Task 1: Kick-off meeting to present the study plan was performed on June 14, 2017.
- Task 1: literature search and information collection were performed; meeting with Lafarge, the sole UHPC producer in the US, and tele-con with NYDOT engineers on their experience using UHPC were set on November 29, 2017,
- Task 2: ECC mixing and testing were performed in the summer of 2017; the best performed ECC mix from a collected three candidates for the pilot project was selected.
- Task 2: presentation on ECC mixes and testing results was made to the MDTA on September 28, 2017,
- Task 3: several bridges from MDTA inventory for the pilot bridge implementation and modeling were investigated for possible pilot study candidate.
- Task 3: a pilot bridge was selected and a site visit was conducted with MDTA and Lafarge representatives on November 29, 2017.
- Tasks 3 and 4: studies of the feasibility of implementing ECC as well as UHPC without modifying bearings were performed.
- Tasks 3 and 4: studies of a side-by-side ECC and UHPC implementations on the same bridge were concluded with suggestions,
- Task 5: Report of the study was drafted and delivered here.

II. PHASE II RESEARCH PLAN AND REPORT

Following tasks were proposed for Phase II study:

Task 1 –Boundary Condition Investigation

Task 2 - Link slab design procedure

Task 3 - Link slab special provision

Task 4 - Link slab typical details and specifications

Task 5 - Summary and Report

Task 6 – Pilot Implementation (with monitoring plus additional task on sensor testing)

II.1 - Progress report in Attachment B Progress Report #1 reports the status to 08/31/2018, on all Tasks.

Activities in chronical order are list here:

1. 12/19/2017 – Submitted Phase 1 final report to conclude Phase 1;
2. 03/02/2018 – Received executed MOU dated 02/27/2018 and started Phase 2 officially.
3. 03/06/2018 – Finalized and delivered the specifications of Category 400 for Structures and Category 900 for Material for link slab field applications.
4. 03/23/2018 – Prepared and delivered a zip file containing specifications (2), design calculation in excel files (2), design drawings (4).
5. 05/20/2018 – conducted meeting and discussed with sensor provider, Resensys, on concrete embedment; formed strategic partner with Resensys on sensing capability embedded in concrete; conducted lab test with sensors embedded in ECC and UHPC during May-September 2018.
6. 06/29/2018 – Conducted meeting with MDTA and site visit to both CEXA27001 and CEX95200 bridges.
7. 07/16/2018 – During March-July 2018 studied and proposed link slab design on grid deck.
8. 07-18/2018 – Visited FHWA TFHRC and witnessed UHPC mixing; Obtained UHPC material and admixtures.
9. Ongoing (expected done by 09/09/18) – During May-September 2018 studied, obtained, lab tested on UHPC specimens (update: This task has been completed in 2018 after release of the report)

II.2 - Progress report in Attachment C Progress Report #2 reports the status to 03/31/2019, mainly on Tasks 2 and 6 of Phase II.

- Subject 1– Link slab material mixing and testing: Fourteen three-point bending tests were conducted. Due to material variance, ECC mixture is updated as Table 1. Results of specimens, including ECC and UHPC, are listed in Tables 2&3.
- Subject 2– ECC material properties: To verify ECC material properties and determine their reasonable ranges for quality control, elasticity modulus, ductile performances and fine crack identifications were conducted in following cases.
- Subject 3– Sensor test & recommendation: Report on sensor placement and survival rate, feasibility of strain gauge with steel plate in the field, and recommendation

II.3 - Progress report in Attachment D Progress Report #3 reports the status to 09/30/2019, mainly on Tasks 2, 4, 5 and 6.

Activities and Tasks Order Releases are highlighted here:

- Jointly with WMA prepare the release of TO_1533 DRAFT_0529 on June 1, 2018 and then TO_1533_Optimized_1015changed to CEX952001 on Oct. 20, 2018; TO_1533_1031 on Nov. 23, 2018; TO_1533_FINAL_0208 with updated detour plan on Feb. 12, 2019
- Jointly with WMA revise TO 1533 Redline bearing revised on Apr. 30, 2019; TO 1533 Redline_Revised Page 1 and 3_removal revised & TO_1533_FINAL_page6_ECC width revised on Jun. 28, 2019; TO 1533 Redline 2_Optimized_REPLACE COMPRESSION SEAL JOINTS AND MODIFY BEARINGS on Jul 2, 2019; Task Order 1533R2_Final_0813 on Aug. 13, 2019; Link Slab specs_ECC revised on Aug. 15, 2019; Task Order 1533 Redline 2_0816 on Aug. 16, 2019.
- Jointly with WMA select the best candidate for the pilot bridge CEXA27001 and hold a link slab pilot meeting at bridge site on April 10, 2019
- Submit Sequence of Construction_rev.pdf (related to UM's work) on June 14, 2019.
- Hold link slab follow up meeting at 2400 Broening Highway large conference room w/MDTA, UM, and contractors/consultants on June 19. 2019
- Experiment by UM team on new ECC material from EA DOT and revise design for ECC link slab on June 27, 2019
- Coordinate by the UM research team with new EA DOT supplier on their testing (7/1/2019), conference calls (7/1-7/3/2019)
- Jointly conduct meeting with MDTA (and consultants) and Elephant Armor regarding materials at NRMCA lab, Greenbelt, MD on July 12, 2019 demonstrated by EA DOT supplier and July 12 – August 28. 2019 tested by the UM research team. Submit memo on EA DOT Material 7-Day Test by the UM research team on July 31, 2019. Receive and review by the UM research team on Aug. 7, 2019 about Curtis 1day Cube Results.pdf from EA DOT contracted laboratory
- Conduct sensor arrangement and installation upgrading by the UM research team [Resensys- sensor vendor] July 12 – Sep, 26, 2019

- Revise SECTION 400.03 ECC LINK SLAB & SECTION 902.19 Link Slab Material by the UM research team on Aug. 15, 2019
- Jointly hold Task 1533 pre-construction meeting at 9114 Philadelphia Road. Suite #104. Rosedale, MD on Sep. 13, 2019
- Start construction on Sep. 23, 2019; Field visit by the UM research team on Sep. 27, 2019 for installing accelerometers, Senimax (Gateway) with the solar panel, displacement sensor installation had been postponed until the bearing modification complete. Field visit by the UM research team on Oct. 2, 3, 4 & 9 2019 for scheduled sensor installation

In summary, the works performed during 07/01/2019-09/30/2019) are summarized are:

- Adopted EADOT as the new ECC material and performed lab material test
- Redesigned link slab details for ECC and UHPC by using the same link slab dimensions
- Revised TO for construction accordingly
- Prepared for construction and ready for sensor installation
- Corresponded and coordinated with MDTA and its consultants/contractors

Attachment C shows the link slab activities during the period of 04/01/2019 to 09/30/2019. Also, attachments show the TOs released during this period.

III. PHASE II REMAINING WORK

Remaining work involves Tasks 5 and 6. Sensors have been placed (except displacement sensors' placement, pending on contractor's bearing modification work) and preliminary calibration has been done. Next two trips involve:

1. Final calibration and test installed sensors;
2. Live load test onsite
3. Collect and analyze data offsite
4. Compare with numerical results

Final report as stated in Tasks 5 and 6 will be provided in the next progress report for the project.

Attachment A

A Pilot Application of Link Slab with Selected material for MDTA Steel Bridges

Final version 01/16/2018

ATTAACHMENT A

Report to the MDTA

MDTA
Maryland
Transportation
Authority

For

A Pilot Application of Link Slab with Selected material for MDTA Steel Bridges

By Dr. Chung C. Fu, P.E., Director/Research Professor and Yifan Zhu, Research Assistant

The Bridge Engineering Software and Technology (BEST) Center

Department of Civil and Environmental Engineering, University of Maryland

I. Introduction

Many MDTA bridges are multiple simple span structures, either in steel or prestressed concrete girders. The first phase of this study found that link slab can be used to eliminate these desk joints by making the deck continuous while keeping the girders as simple spans. Applications have been found in different states, such as MI, NY and VA. In modern design, various types of material can be used for constructing the link slab, which are listed in Table 1.

Table 1 – Materials for link slab

Candidate	Note
RC Slab	Common reinforced concrete link slabs (Since 1989)
LMC with Rapid Set Cement	High early strength
FRP	Fiberglass-reinforced plastic (Not many applications)
Ductile ECC	Better structural performance (Lower reinforcement ratio but better cracks control)
FRC with Polypropylene or Steel Fibers	VDOT/ VTRC Tested
UHPC	Applied in NY states since 2008

Our phase I study shows the best candidates for the link slab application are ECC and UHPC. The research team has conducted an extensive study in the Phase I of this study and selected the best performed ECC mix for the link slab application.

This research team has contacted FHWA and Lafarge on the UHPC application. Due to the high cost of UHPC, it may be considered using in special cases, like grid decks. The research team has also invited UHPC representatives from Lafarge and NYSDOT to present their applications and share their experiences. The NYSDOT Office of Structures developed a link slab design utilizing Ultra High Performance Concrete (UHPC) to eliminate transverse deck joints wherever feasible. UHPC link slabs provide an excellent way to eliminate joints in existing bridges. Based on NYSDOT's experience to date, link slabs are performing well with no visible cracks within the UHPC slab. As reported by NYSDOT, these bridges with UHPC link slabs overall are performing as designed.

The study of different boundary conditions was also evaluated in this study. Conclusion for the pilot bridge is made on varied boundary conditions for their limitation on the link slab application.

II. RESEARCH PLAN

The study involves the execution of the following tasks:

1. Task 1 – Conduct literature review from the federal and other state agencies

The focus of this phase is to locate, collect and list all the available current state-of-the-practice methods for (1) FHWA's regulations, (2) Other states' practices, and (3) Research and testing findings. Contact and then visit were made to FHWA/TFHRC on June 7th 2017 meeting with the group of concrete experts experienced in UHPC and ECC mixes led by

Ben Graybeal, Ph.D., P.E.
Team Leader - Bridge Engineering Research
FHWA-TFHRC in McLean, Virginia
202-493-3122 or benjamin.graybeal@dot.gov

Also contacted were made to Lafarge, UHPC producer and NYSDOT design engineers. Meeting at MDTA headquarters was made at 1:30-3:30pm on November 29, 2017 and tele-con with NYSDOT on their experience with UHPC.

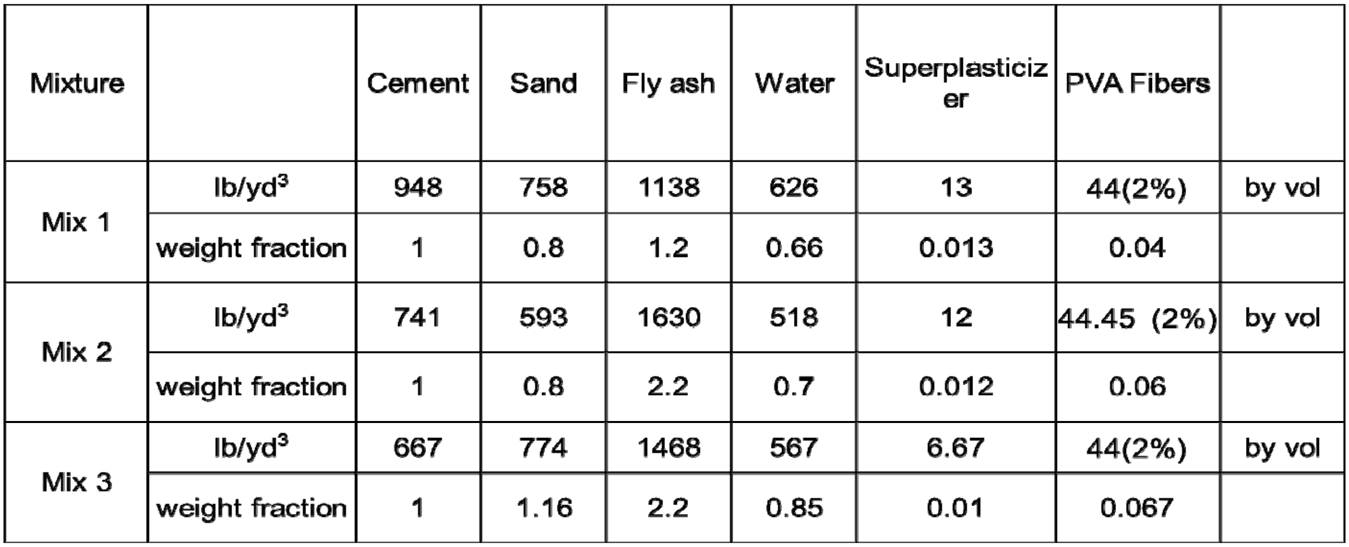
Gregory Nault, PE, SE | Project Manager
Ductal® UHPC Bridge Engineering |
LafargeHolcim | 8700 W Bryn Mawr Ave, Ste 300, Chicago, IL 60631
O 773-372-1027 M 773-230-3069 E gregory.nault@lafargeholcim.com

Mathew Royce and Jim Scarlata
Structures Design Bureau
New York Department of Transportation

2. Task 2 – Perform laboratory testing

Two of the six types of materials listed above, ECC and UHPC, were selected. UHPC is produced by Lafarge and standard tests were made with published test results. Laboratory tests of ECC were performed by the research group to determine the compression strength, flexural strength, and shrinkage for these ECC mixes. Three types of ECC material were selected. Summary is made below in Table 2.

Table 2 – Three selected ECC mixes



Mixture		Cement	Sand	Fly ash	Water	Superplasticizer	PVA Fibers	
Mix 1	lb/yd^3	948	758	1138	626	13	44(2%)	by vol
	weight fraction	1	0.8	1.2	0.66	0.013	0.04	
Mix 2	lb/yd^3	741	593	1630	518	12	44.45 (2%)	by vol
	weight fraction	1	0.8	2.2	0.7	0.012	0.06	
Mix 3	lb/yd^3	667	774	1468	567	6.67	44(2%)	by vol
	weight fraction	1	1.16	2.2	0.85	0.01	0.067	

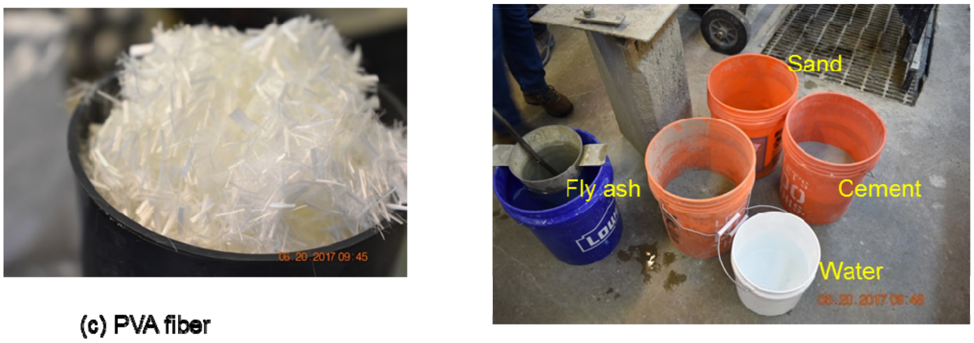
In our selection, Mix 1 is based on VTRC/ Victor Li' s research and similar to ECC M45, Mix 2 is based on UCLA's lab mixture design and Mix 3 is based on Victor Li's most recent publication that focused on ECC crack control.

Originally, three (3) mixes were selected. For the test part, four (4) cylinders and four (4) prisms per mix were planned for a total of 24 specimens. However, due to variety and mixing, final summary of the test is shown below:

- Total Batches: 27; total 150 specimens
- Success: 23 batches; total made 134 specimens
- Small Mixer : 9 batches (1 failed); 29 specimens
- Large Mixer: 18 batches (3 failed); 121 specimens
- Time Duration:
  - Mixing: June 17th. to August 2nd, 2017.
  - Testing: June 24th to September 5th, 2017.

(a) Small Mixer

(b) Large Mixer



(c) PVA fiber

(d) Mixing Material
- Fiber, Cement. Sand, Fly ash, Water reducer (not shown), and Water

Figure 1 – ECC lab mixes at Ready Mix Concrete Lab in Greenbelt, MD

Small and large mixers are following different sequences in the lab mix as listed below:

<u>Small Mixer (Shear Mixer)</u>

- Charge all solid material (2 min)
- Charge 80-90% water and all HRWR
- Mix for 3-5 min so that a dough-like consistency was reached.
- Fibers were added and mixed for 8-10 minutes.
- The remaining water was added (if needed)
- Mixed for 5-10 min until material is homogeneous.

<u>Large Mixer</u>

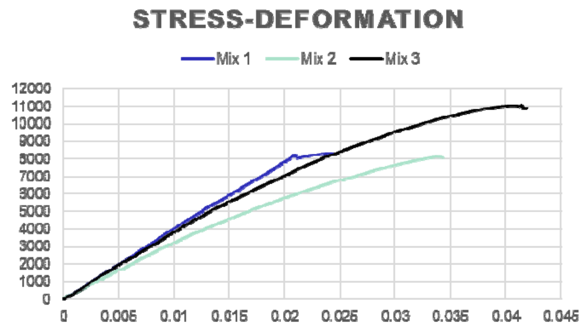
- Charge all sand (2 min)
- Charge approximately 90-95% Water, all HRWR, all hydration stabilizer (2 min)
- Charge all fly ash (2 min)
- Charge all cement (2 min)
- Charge remaining mixing water
- Mix for 5-10 min until material is homogenous
- Charge fibers
- Mix for 5-10 min until material is homogenous

Primary Test Standards and Reference listed below are followed:

- Cast, Curing and Fresh Concrete Test
    - <u>ASTM C192/C192M</u> Practice for Making and Curing Concrete Test Specimens in the

Laboratory

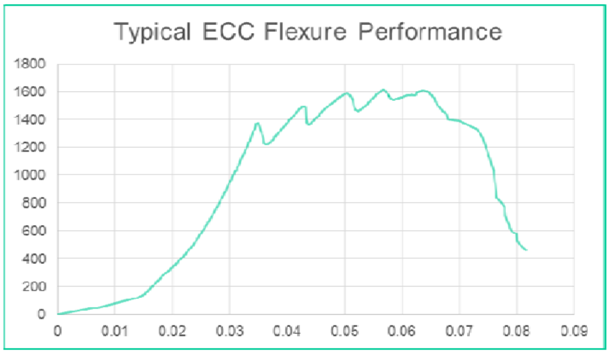
  - ASTM C138 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
  - VTRC Evaluation of High-Performance Fiber-Reinforced Concrete for Bridge Deck Connections, Closure Pours, and Joints
  - Victor Li, Concrete Construction Handbook, Second Edition, Chapter 24
- Compression
  - ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
- Flexure
  - ASTM C78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
  - ASTM C1609 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)
- Shrinkage
  - ASTM C157 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete



	7 Days Result (Psi)	28 Days Result (Psi)
Mix 1	7757	7940
Mix 2	6156	8092
Mix 3	9038	11214

Specimen dimensions: 4×8 (in) and 3×6 (in) (trial)

Figure 2 - Result of lab compression test



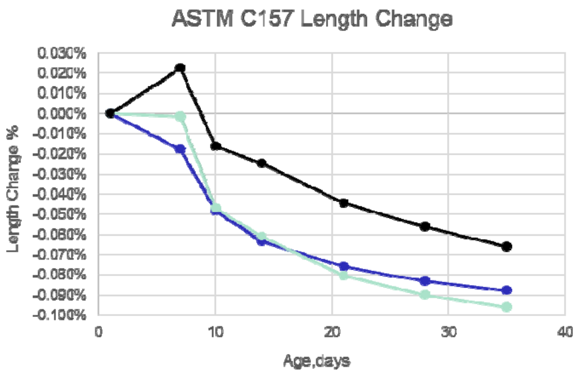
	7 Days Result (Psi)	28 Days Result (Psi)
Mix 1	1249	1508
Mix 2	1196	1089
Mix 3	1125	1404

Specimen dimensions:

Third points test: 4×4×14 (in)

Three points test: 3×3×12 (in) (trial)

Figure 3 - Result of lab flexural test



	Mix 1	Mix 2	Mix 3
7 Days	-0.018%	-0.002%	0.022%
7+7 Days	-0.063%	-0.061%	-0.025%
7+28 Days	-0.088%	-0.096%	-0.066%

Specimens dimension: 3×3×10 (in.)

Figure 4 - Result of lab shrinkage test

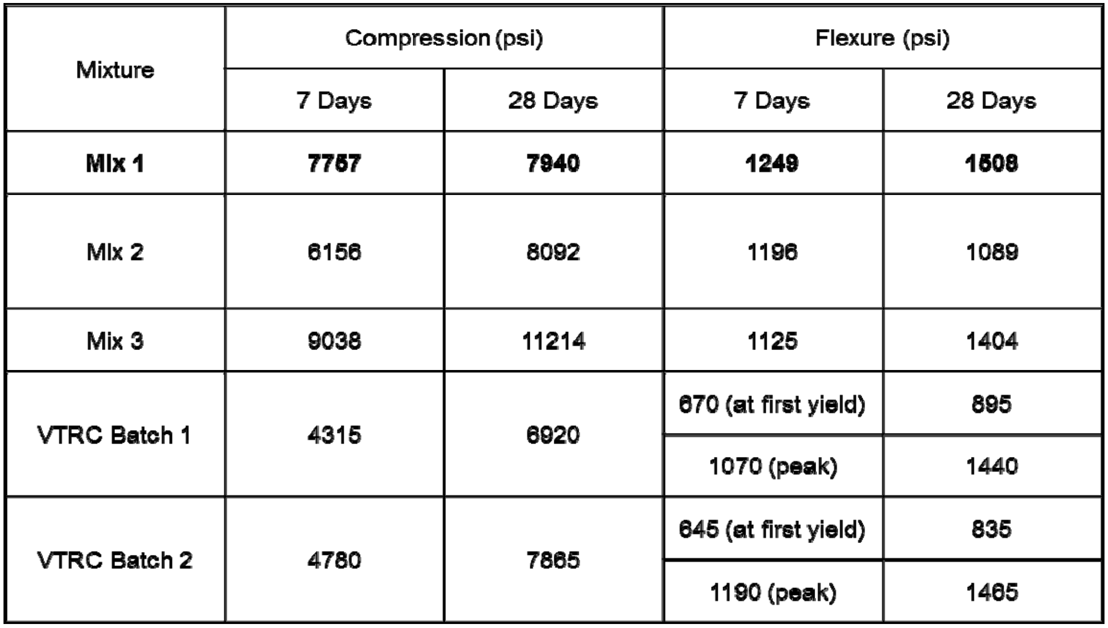
Selection criteria of the optimal ECC are set as follows:

- Choose average value from results
- Compression strength:

    - Small Mixer: Mix 1> Mix 2> Mix 3
    - Large Mixer: Similar
- Flexure strength:
    - Small Mixer: Similar
    - Large Mixer: Mix 1> Mix 3> Mix 2
- Shrinkage variation:
    - Mix 3< Mix 1 <Mix 2

Based on the mixture data from the last Full-batch mixes, selection was made and results were compared with VTRC's results.

Table 3 – Final selection compared with VTRC's results



Mixture	Compression (psi)		Flexure (psi)	
	7 Days	28 Days	7 Days	28 Days
Mix 1	**7757**	**7940**	**1249**	**1508**
Mix 2	6156	8092	1196	1089
Mix 3	9038	11214	1125	1404
VTRC Batch 1	4315	6920	670 (at first yield)	895
			1070 (peak)	1440
VTRC Batch 2	4780	7865	645 (at first yield)	835
			1190 (peak)	1465

ECC selection Notes and Recommendations are listed below:

- Mixture design will be modified by material and field environment
- There will be a 25%-30% deduction of compression and flexure in field due to the change of curing conditions (Reference: ACI magazine Q&A: Field- versus Standard-Cured Cylinders Made from High Strength Concrete)
- The result of ECC mixes has a high variation that is affected by material, procedure etc.
- Construction sequence and ECC mixing procedure will be set when applied.

3. Task 3 – Select and analyze a bridge for pilot study

As mentioned, two (or three, if required) types of practices will be studied. Cost and practicality will be consulted and collaborated with designers and contractors. As such, an economical and practical design will be recommended. Flow chart of this task is shown in Figure 5. Further, Figure 6 shows collection of States' practices on link slab.

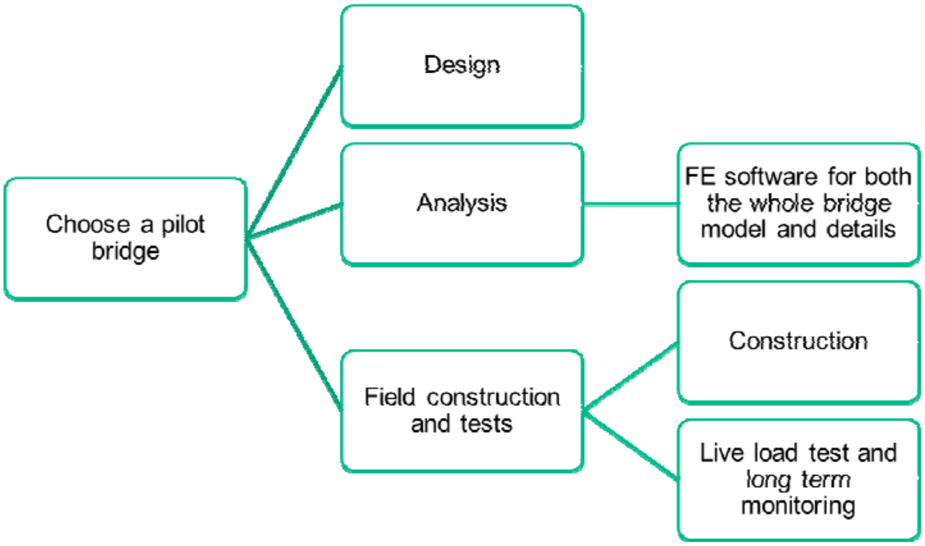
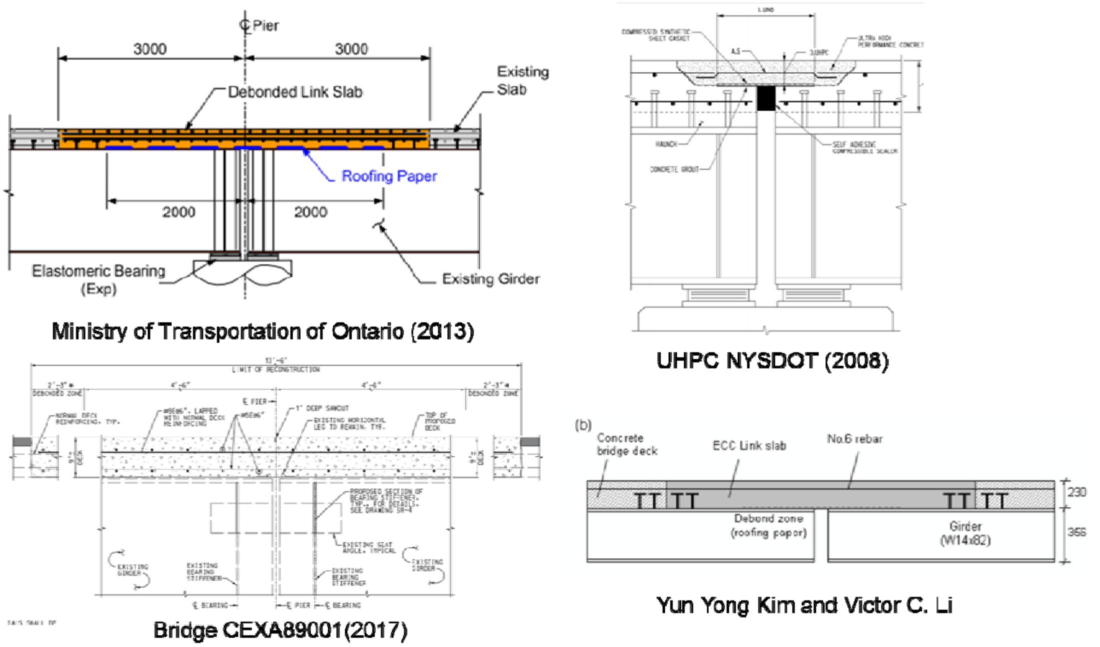


Figure 5 – Flow chart of pilot bridge demonstration



Ministry of Transportation of Ontario (2013)

UHPC NYSDOT (2008)

Bridge CEXA89001(2017)

Yun Yong Kim and Victor C. Li

Figure 6 – Collection of states’ practices on link slab

We have received three sets of drawings from MDTA, which are CEXA89 (skewed and wide straight bridge), CEXA27001 (normal straight, we visited last time) and CEXA83001 (mild curved bridge). All are in a pattern of two short side spans under 50' and two middle spans over 50' with two fixed bearing at the middle pier and at the end abutments. We have modeled existing CEXA27001 bridge and alternating parameters to check different cases, such as altering bearings, adding link slab with Regular concrete/ECC/UHPC, changing length of debonded zone (only in ECC link slab)..., etc. Table A1 in the Appendix lists all candidates considered for link slab pilot demonstration. Figure A1 displays the selected MDTA Bridge CEXA27001 GPE & framing plan.

Trip was made with MDTA engineer, Lafarge engineer and BEST Center researchers. Photos were taken and some relevant photos are shown in Appendix A.

3.1 Approach of prototype bridge analysis

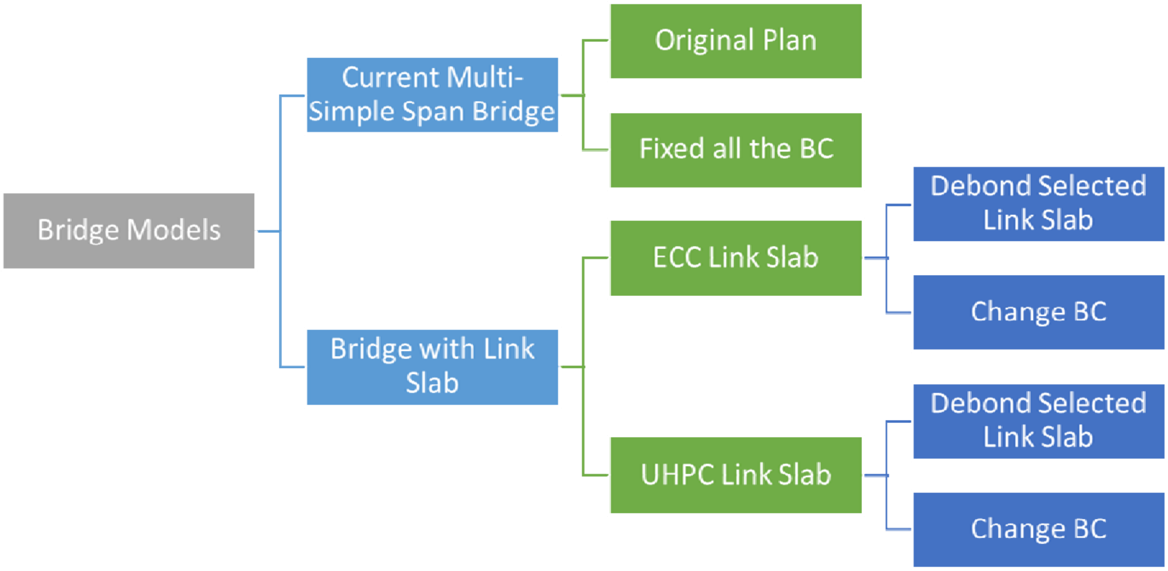
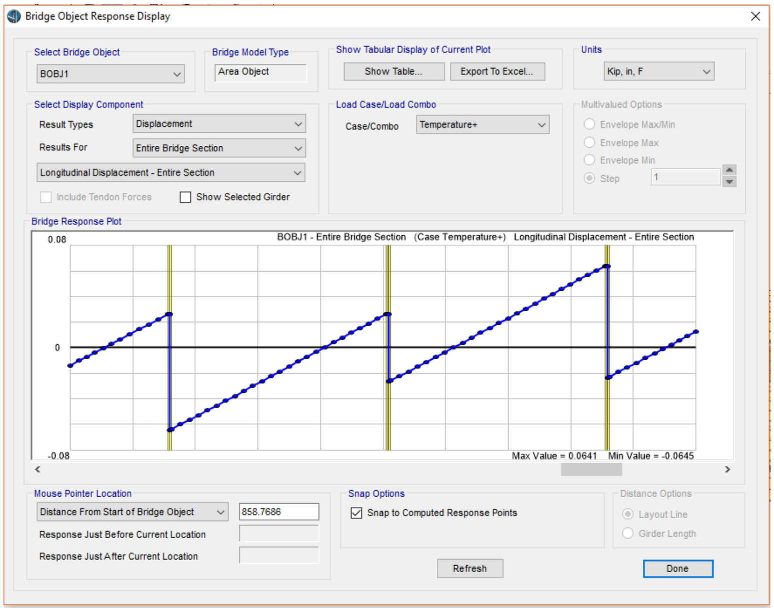


Figure 7 – Feasibility analysis of the prototype bridge

Based on previous literature reviews and meetings, link slab behaviors would be influenced mostly under Live Load and thermal movement. Results and findings are based on comparisons under these loading conditions.

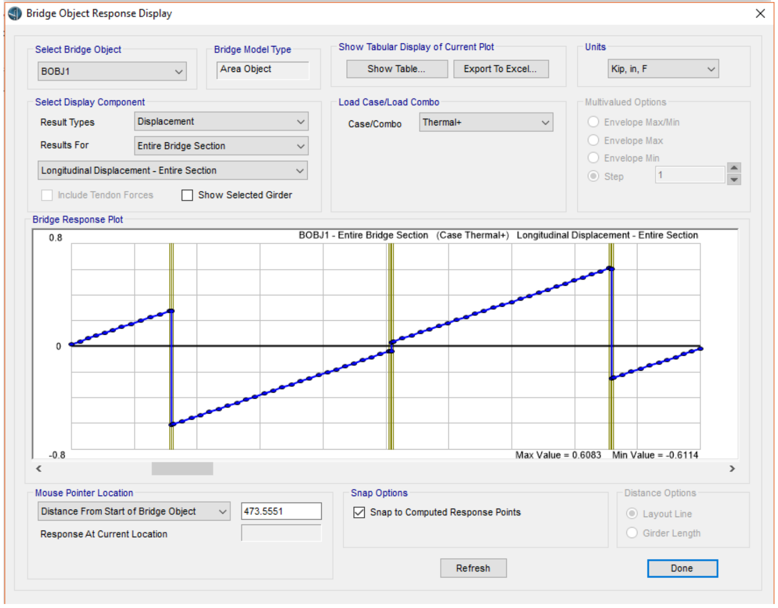
In order to get a full understanding of the thermal behavior of this prototype bridge, six models were made with two types of thermal analyses: (1) Temperature Gradient (based on AASHTO, Zone 2); (2) Thermal Expansion (based on temperature increase or decrease within 110°F, which for the extreme case). The results shown are longitudinal displacements for the entire bridge and stresses on the top of the slab under the extreme case.

3.2 Model with current multi-simple span bridge



Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Displacement
Results For: Entire Bridge Section
Longitudinal Displacement - Entire Section
Case/Combo: Temperature+
Step: 1
BOBJ1 - Entire Bridge Section (Case Temperature+) Longitudinal Displacement - Entire Section
Max Value = 0.0641 Min Value = -0.0645
Distance From Start of Bridge Object: 858.7686
Response Just Before Current Location:
Response Just After Current Location:
☑ Snap to Computed Response Points

(a) Positive temperature gradient



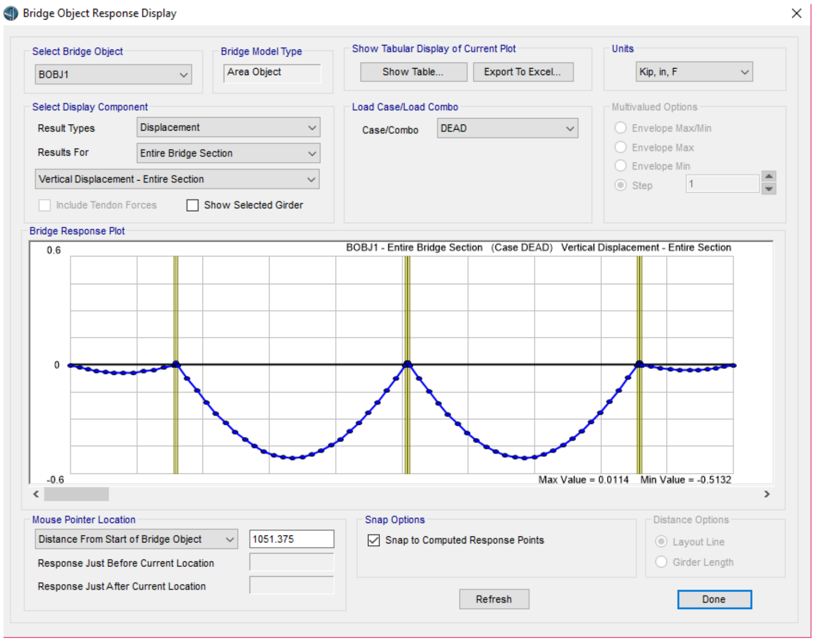
Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Displacement
Results For: Entire Bridge Section
Longitudinal Displacement - Entire Section
Case/Combo: Thermal+
Step: 1
BOBJ1 - Entire Bridge Section (Case Thermal+) Longitudinal Displacement - Entire Section
Max Value = 0.6083 Min Value = -0.6114
Distance From Start of Bridge Object: 473.5551
Response At Current Location:
☑ Snap to Computed Response Points

(b) Thermal expansion, extreme case, increasing 110°F

Figure 8 – Longitudinal thermal movement of the bridge

Summary of analysis:

- Compared with temperature gradients (Figure 8(a)), the displacement due to thermal expansion/ contraction in the longitudinal direction (Figure 8(b)) is relatively large so the thermal expansion/contraction is considered in this study.
- The maximum displacement (with the 110°F variation or ±55°F) in longitudinal direction due to thermal expansion/contraction between two spans in this pilot bridge is no more than 0.9 in. i.e., if the temperature increased 55°F, the two sides of the expansion joint will be 0.45 in. closer due to the expansion form the spans, and when temperature decreased 55°F, the gap of the joint will grow 0.45 in.



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Show Tabular Display of Current Plot: Show Table... Export To Excel...

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 0.0114 Min Value = -0.5132

Mouse Pointer Location

Distance From Start of Bridge Object: 1051.375

Response Just Before Current Location

Response Just After Current Location

Snap Options

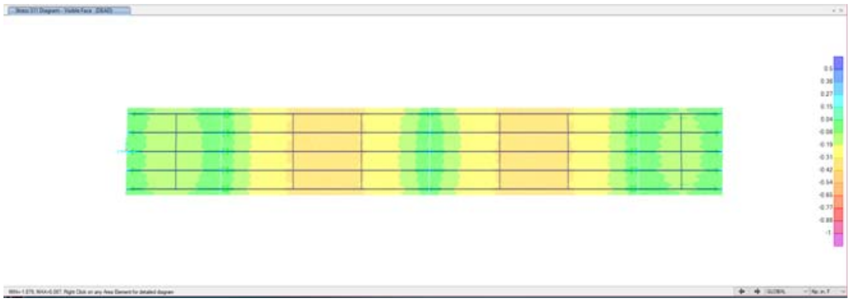
☑ Snap to Computed Response Points

Distance Options

● Layout Line

○ Girder Length

(a) Vertical displacement

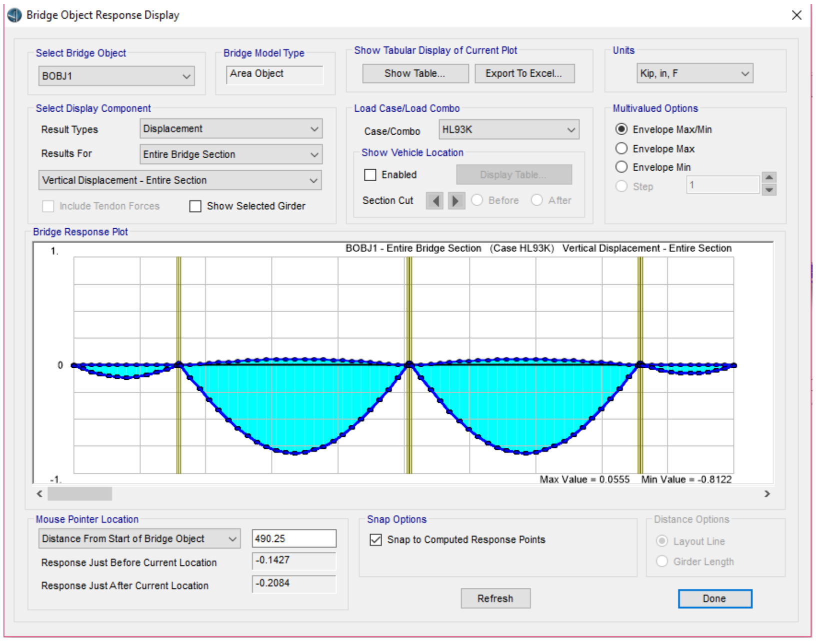


(b) Stress contour at the top of the slab

Figure 9 – Bridge behavior under dead load (structural component only)

Summary of analysis:

- As expected, compared with vertical displacement (maximum 0.5132 in. at the middle of 2 and 3 spans), longitudinal displacement (maximum 0.0658 in. at the center bearing), is relatively small under dead load.



Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component
Result Types: Displacement
Results For: Entire Bridge Section
Vertical Displacement - Entire Section
☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo
Case/Combo: HL93K
Show Vehicle Location
☐ Enabled
Section Cut ○ Before ○ After

Multivalued Options
● Envelope Max/Min
○ Envelope Max
○ Envelope Min
○ Step 1

Bridge Response Plot
BOBJ1 - Entire Bridge Section (Case HL93K) Vertical Displacement - Entire Section

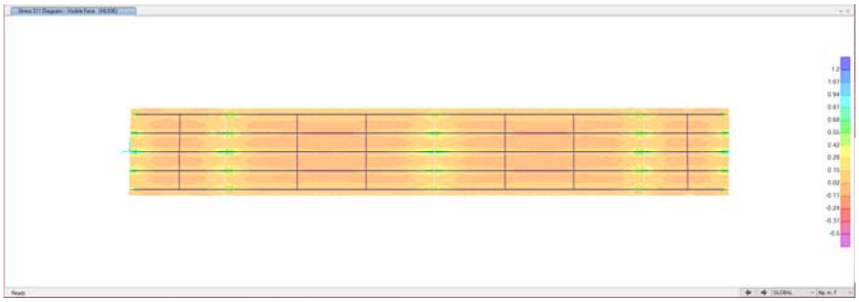
Max Value = 0.0555 Min Value = -0.8122

Mouse Pointer Location
Distance From Start of Bridge Object: 490.25
Response Just Before Current Location: -0.1427
Response Just After Current Location: -0.2084

Snap Options
☑ Snap to Computed Response Points

Distance Options
○ Layout Line
○ Girder Length

(a) Vertical displacement



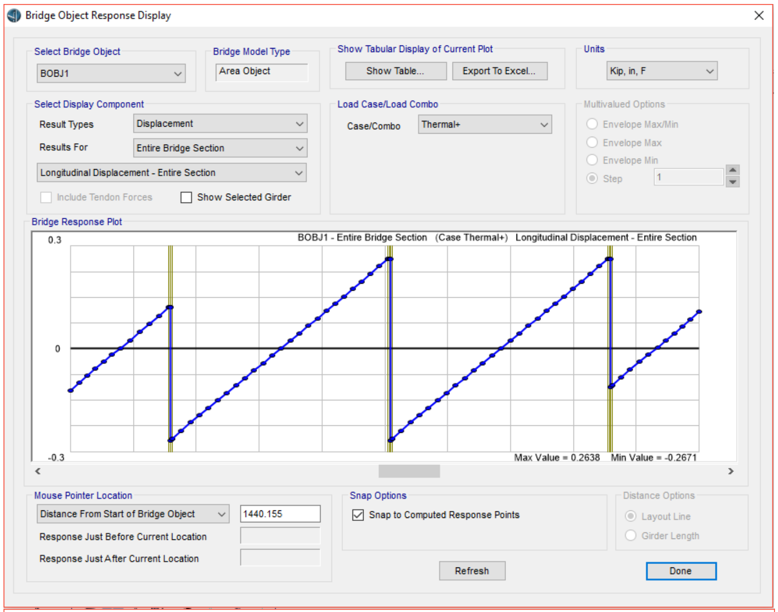
(b) Stress contour at the top of the slab

Figure 10 – Bridge behavior under live load

Summary of analysis:

- Results of this bridge under dead load, live load and thermal movement are used to compare with other corresponding cases with changing boundary conditions and/or adding link slabs. The maximum stress and displacement are in the middle of spans, which are, however, not the focus in the analysis.

3.3 Model with current multi-simple span bridge with all FIXED bearings


Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F

Select Display Component
Result Types: Displacement
Results For: Entire Bridge Section
Longitudinal Displacement - Entire Section
☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo
Case/Combo: Thermal+

Multivalued Options
○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

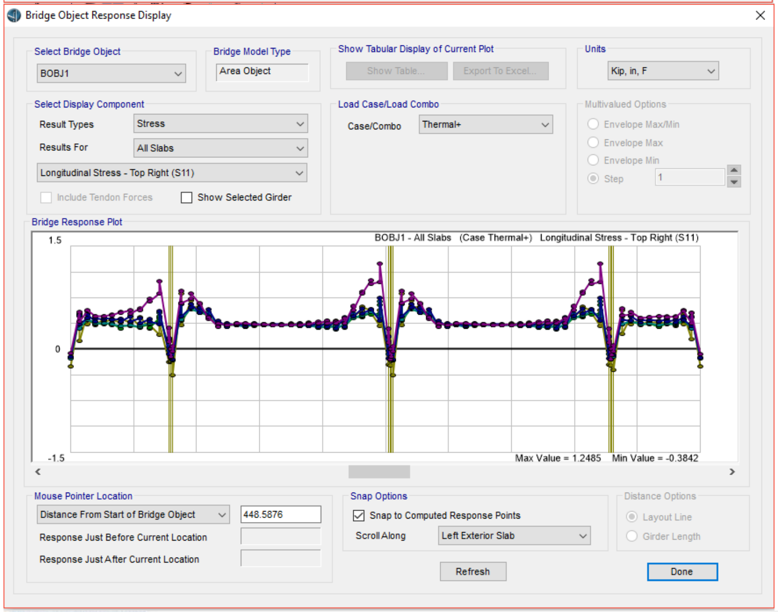
Bridge Response Plot
BOBJ1 - Entire Bridge Section (Case Thermal+) Longitudinal Displacement - Entire Section
Max Value = 0.2638 Min Value = -0.2671

Mouse Pointer Location
Distance From Start of Bridge Object: 1440.155
Response Just Before Current Location
Response Just After Current Location

Snap Options
☑ Snap to Computed Response Points

Distance Options
● Layout Line
○ Girder Length

(a) Longitudinal displacement


Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F

Select Display Component
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Top Right (S11)
☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo
Case/Combo: Thermal+

Multivalued Options
○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

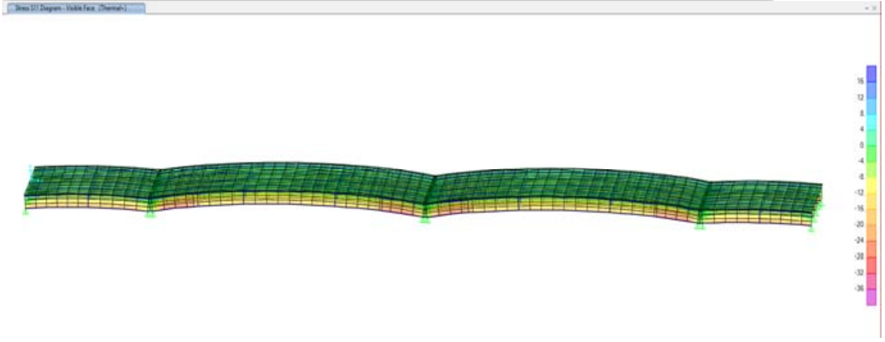
Bridge Response Plot
BOBJ1 - All Slabs (Case Thermal+) Longitudinal Stress - Top Right (S11)
Max Value = 1.2485 Min Value = -0.3842

Mouse Pointer Location
Distance From Start of Bridge Object: 448.5876
Response Just Before Current Location
Response Just After Current Location

Snap Options
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab

Distance Options
● Layout Line
○ Girder Length

(b) Longitudinal stress

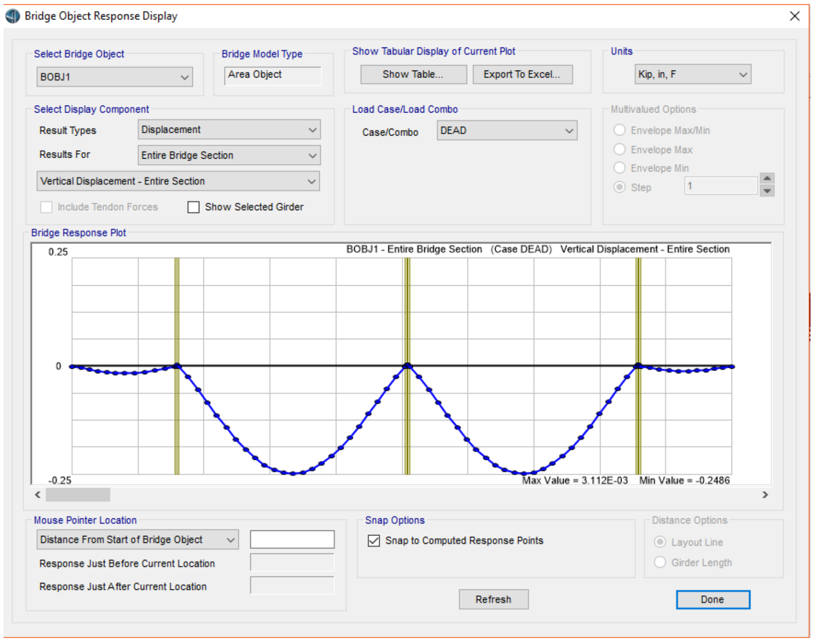


(c) Stress contour of the all-fixed bearing bridge

Figure 11 – Thermal expansions with 110°F increase for bridge with all FIXED bearings

Summary of analysis:

- Compared with current bridge model, if fixed at all bearings (assuming the sliding plate or rockers are not functioning in the current bridges and all the bearings are under fixed condition), the displacement at expansion joints of the entire bridge due to temperature change of 110°F (the most extreme case) would decrease from 0.9 in to 0.3 in. at joints of span 1-2 and span 3-4, but increased from 0.1 in. to 0.5 in. at joint of span 2-3.
- The maximum stress in slabs without averaging the stress in joints at each element, using thermal expansion for example, will increase more than 4 times (0.24 kip/in^2 to 1.1 kip/in^2, in the extreme case 110°F increasing.).



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces

☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 3.112E-03 Min Value = -0.2486

Mouse Pointer Location: Distance From Start of Bridge Object

Response Just Before Current Location

Response Just After Current Location

Snap Options

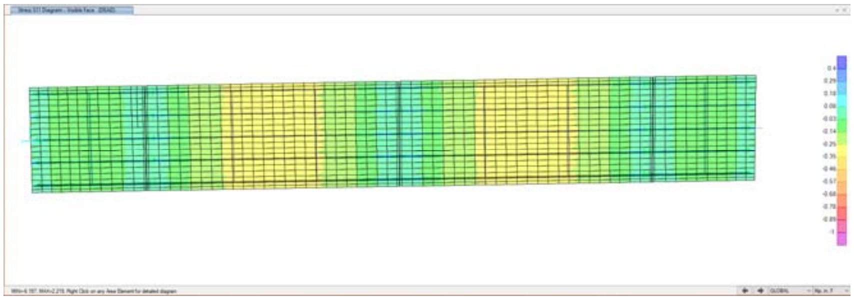
☑ Snap to Computed Response Points

Distance Options

● Layout Line

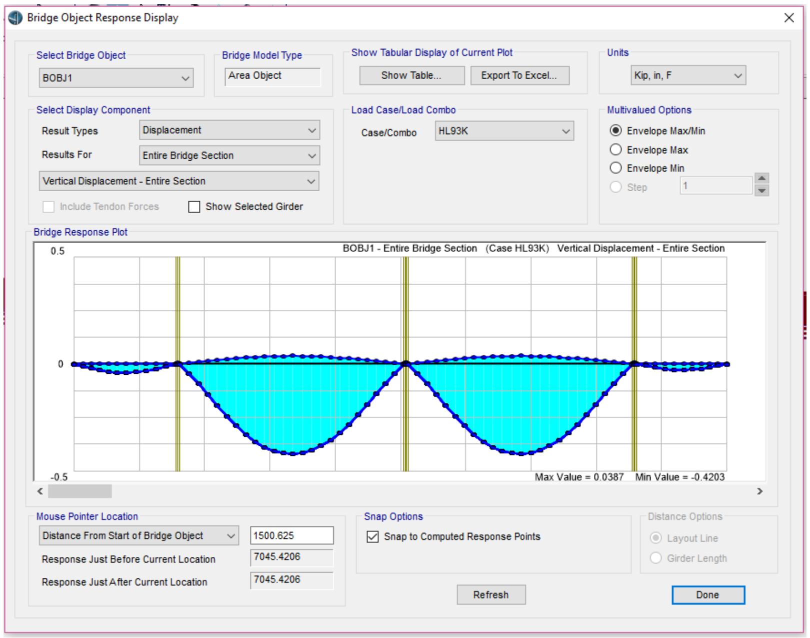
○ Girder Length

(a) Vertical displacement



(b) Stress contour at the top of the slab

Figure 12 – Bridge behavior under dead load (structural component only)



Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: HL93K

Multivalued Options

● Envelope Max/Min

○ Envelope Max

○ Envelope Min

○ Step 1

BOBJ1 - Entire Bridge Section (Case HL93K) Vertical Displacement - Entire Section

Max Value = 0.0387 Min Value = -0.4203

Mouse Pointer Location

Distance From Start of Bridge Object: 1500.625

Response Just Before Current Location: 7045.4206

Response Just After Current Location: 7045.4206

Snap Options

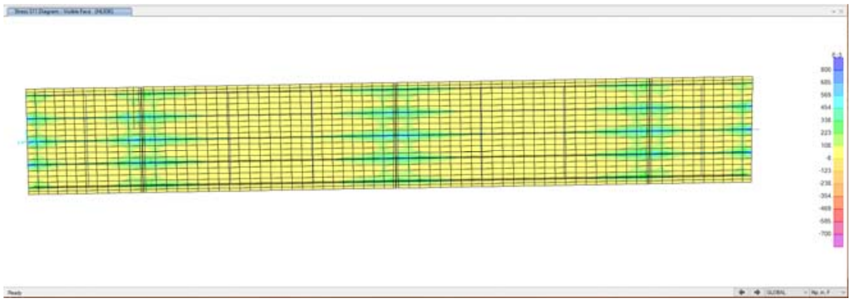
☑ Snap to Computed Response Points

Distance Options

○ Layout Line

○ Girder Length

(a) Vertical displacement



(b) Stress contour at the view on the top of the slab

Figure 13 – Bridge behavior under live load

Summary of analysis:

- Compared with vertical displacement (maximum 0.5132 in. at the middle of 2 and 3 spans), longitudinal displacement (maximum 0.0658 in. at the center bearing) is relatively small under dead load.
- This bridge has a displacement decrease if fixed at all boundaries under both dead and live loads. For bridge decks, the stress in the longitudinal direction is also decreased.
- The maximum stresses in the deck due to thermal movement are located near the bearings.

3.4 General case of model with link slab

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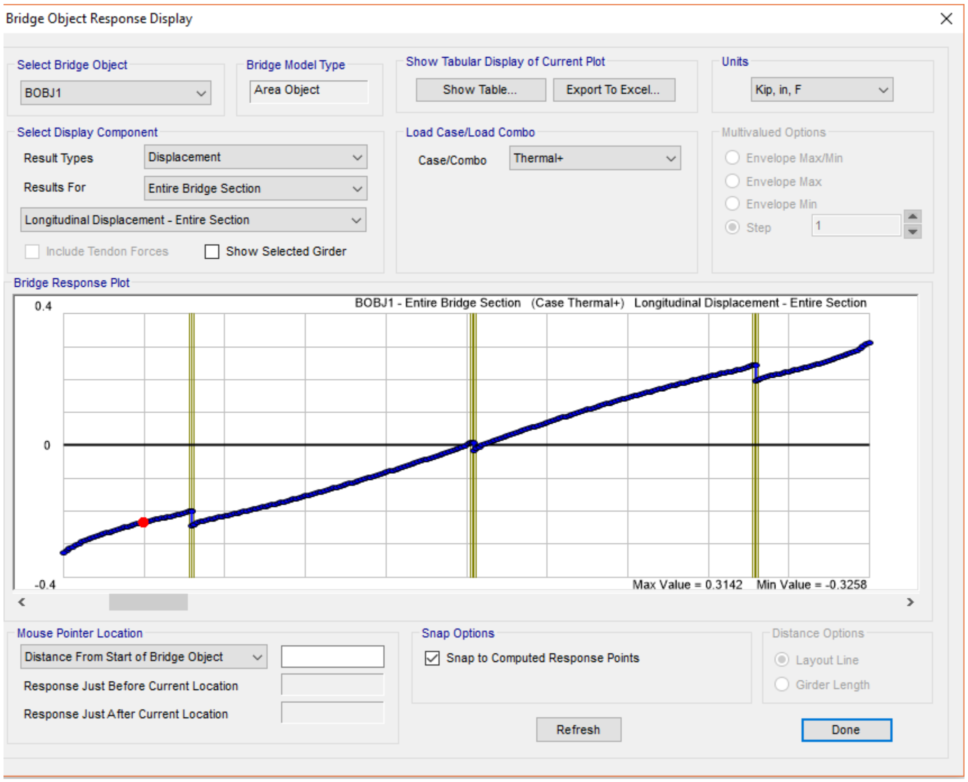

Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Result Types: Displacement

Results For: Entire Bridge Section

Longitudinal Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Case/Combo: Thermal+

○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1

BOBJ1 - Entire Bridge Section (Case Thermal+) Longitudinal Displacement - Entire Section

Max Value = 0.3142 Min Value = -0.3258

Distance From Start of Bridge Object

☑ Snap to Computed Response Points

● Layout Line ○ Girder Length

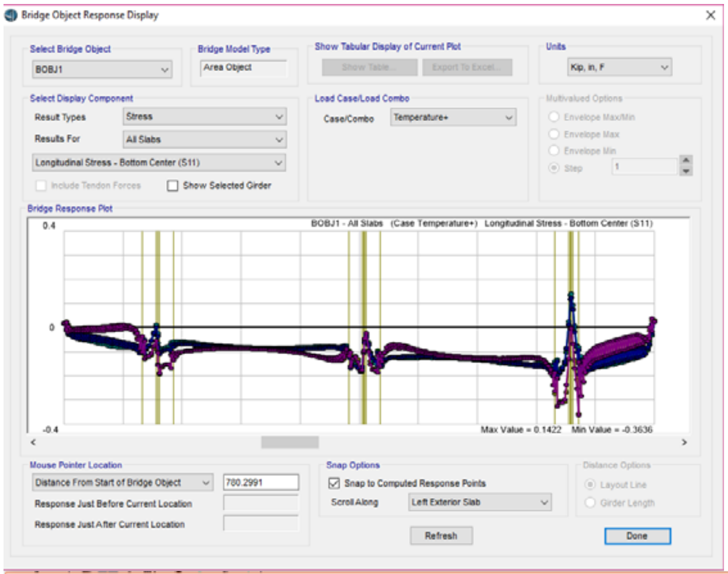
Figure 14 – Typical thermal movement at bearings for bridges with link slab (bridge with UHPC link slab for example)

Summary of analysis:

- The displacement distribution would change and the values between 2 spans are small compared with current multi-simple span bridges.
- The stress distribution changes a lot.

Thus, results and comparisons are focused on stress distribution at bridge deck due to thermal movement, dead load, and live load.

3.5 Model with current boundary conditions and ECC/RC link slab

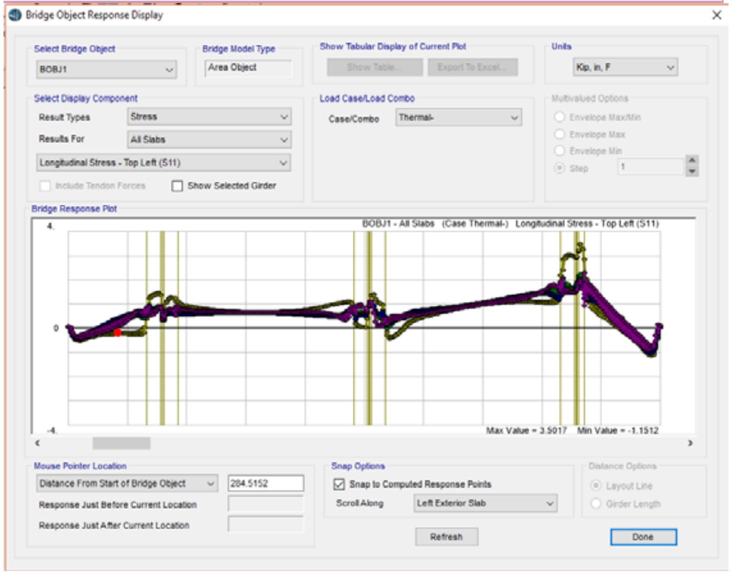

Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Bottom Center (S11)
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: Temperature+
Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1

Max Value = 0.1422 Min Value = -0.3636

Distance From Start of Bridge Object: 780.2991
Response Just Before Current Location:
Response Just After Current Location:
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab
Distance Options: ● Layout Line ○ Girder Length

(a) Stress at the bottom of slabs due to Positive Temperature Gradients

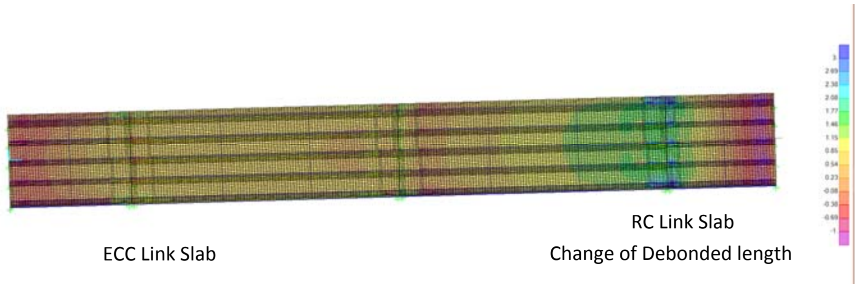

Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Top Left (S11)
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: Thermal-
Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1

Max Value = 3.5017 Min Value = -1.1512

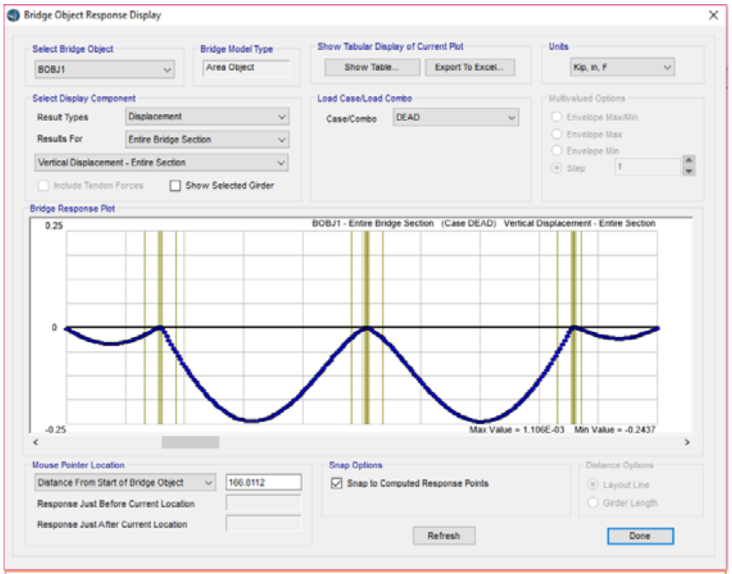
Distance From Start of Bridge Object: 284.5152
Response Just Before Current Location:
Response Just After Current Location:
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab
Distance Options: ● Layout Line ○ Girder Length

(b) Stresses at top of the slab for temperature decrease of 110F°



(c) Stress contour at top of the slab for temperature decrease

Figure 15 –Thermal behaviors of bridges with ECC link slab (left and middle joints) and RC link slab (right joint, change of debonded zone at the right span)



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 1.106E-03 Min Value = -0.2437

Mouse Pointer Location

Distance From Start of Bridge Object: 166.8112

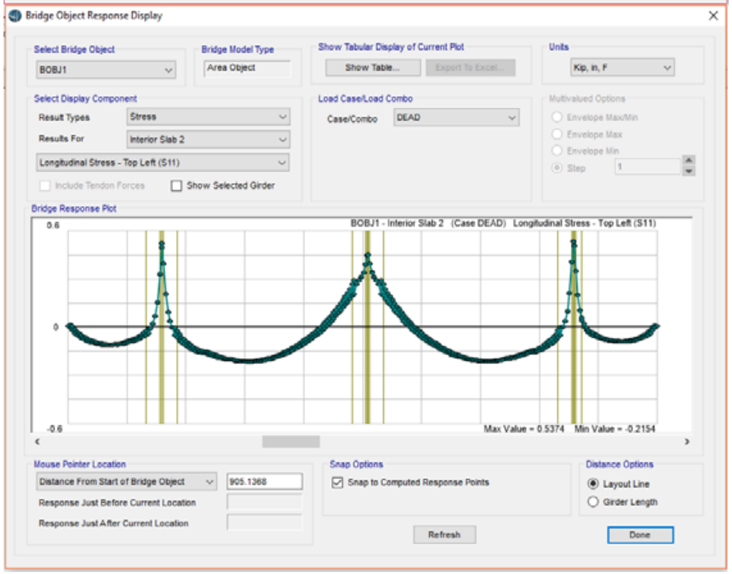
Response Just Before Current Location

Response Just After Current Location

Snap Options: ☑ Snap to Computed Response Points

Distance Options: ● Layout Line ○ Girder Length

(a) Vertical displacement



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: Interior Slab 2

Longitudinal Stress - Top Left (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1

Bridge Response Plot

BOBJ1 - Interior Slab 2 (Case DEAD) Longitudinal Stress - Top Left (S11)

Max Value = 0.5374 Min Value = -0.2154

Mouse Pointer Location

Distance From Start of Bridge Object: 905.1368

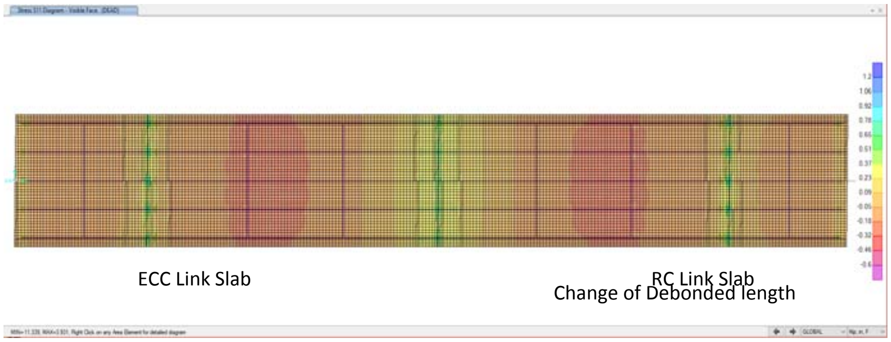
Response Just Before Current Location

Response Just After Current Location

Snap Options: ☑ Snap to Computed Response Points

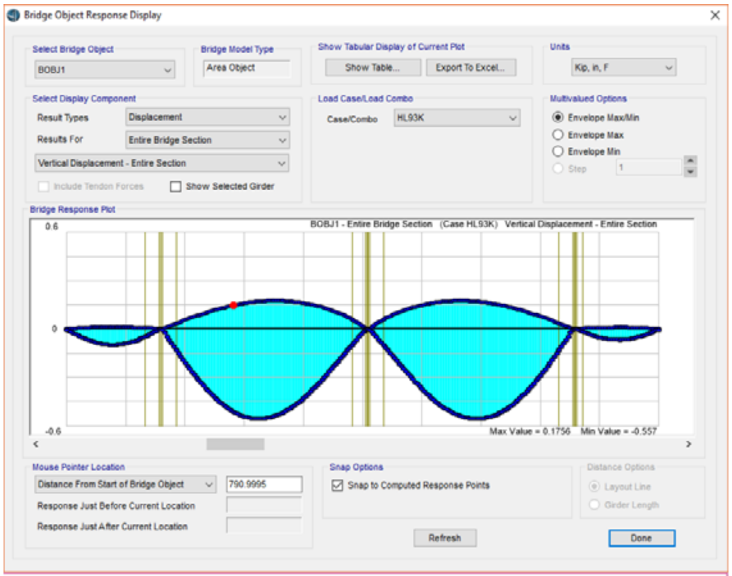
Distance Options: ● Layout Line ○ Girder Length

(b) Stresses at the top of the slab



(c) Stress contour view from top of the slab

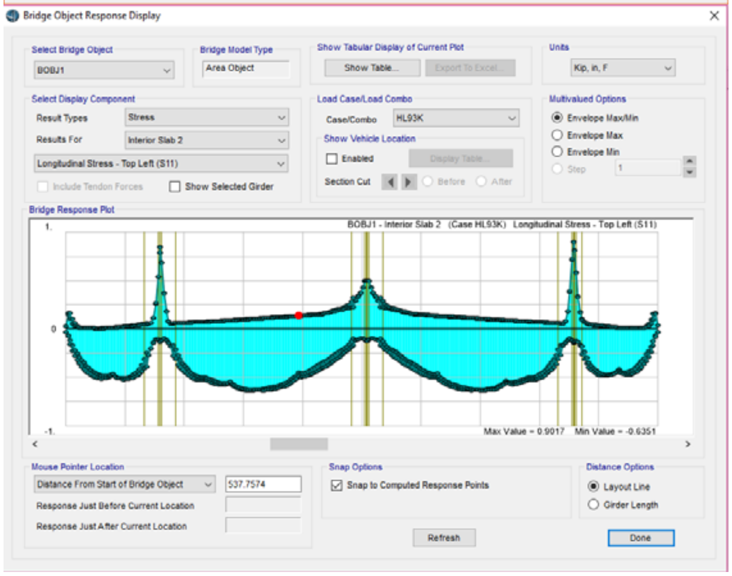
Figure 16 –Behaviors of bridges with ECC link slab (left and middle) and RC Link Slab (right, change of debonded zone at the right span) under Dead Load



Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Displacement
Results For: Entire Bridge Section
Vertical Displacement - Entire Section
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: HL93K
Multivalued Options: ● Envelope Max/Min ○ Envelope Max ○ Envelope Min ○ Step 1
BOBJ1 - Entire Bridge Section (Case HL93K) Vertical Displacement - Entire Section
Max Value = 0.1756 Min Value = -0.557
Mouse Pointer Location: Distance From Start of Bridge Object 790.9995
☑ Snap to Computed Response Points
Distance Options: ● Layout Line ○ Girder Length

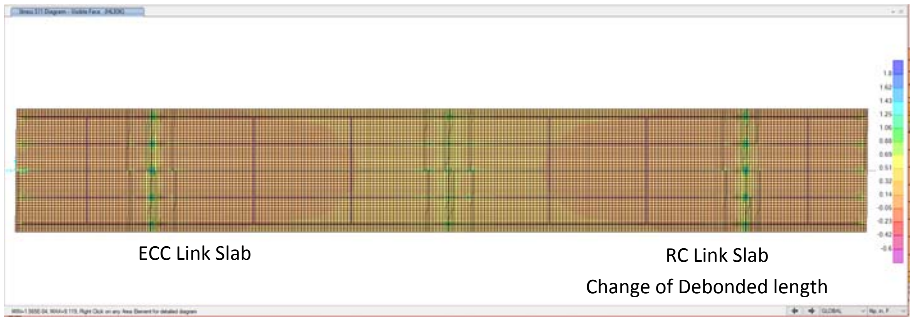
(a) Vertical displacement



Bridge Object Response Display

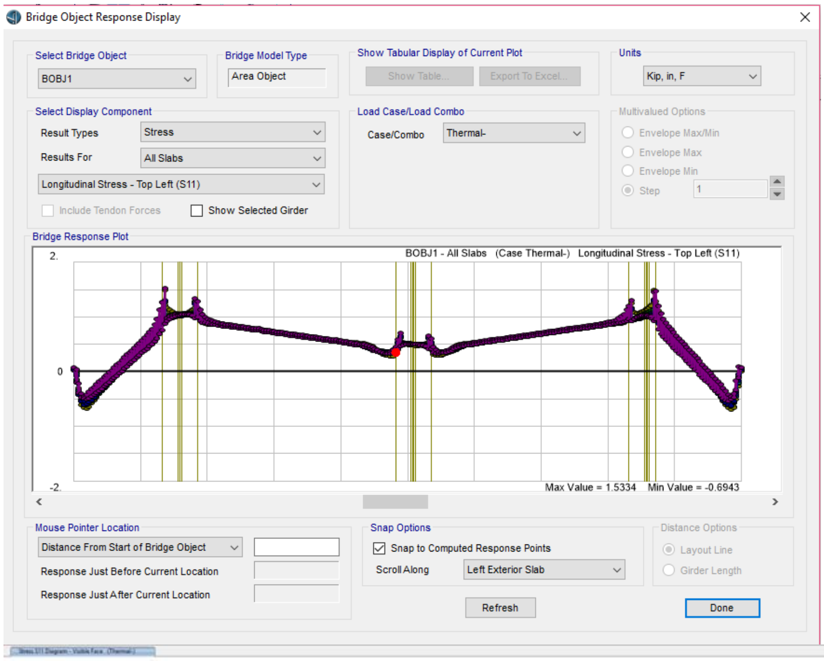
Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: Interior Slab 2
Longitudinal Stress - Top Left (S11)
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: HL93K
Show Vehicle Location: ☐ Enabled
Section Cut ○ Before ○ After
Multivalued Options: ● Envelope Max/Min ○ Envelope Max ○ Envelope Min ○ Step 1
BOBJ1 - Interior Slab 2 (Case HL93K) Longitudinal Stress - Top Left (S11)
Max Value = 0.9017 Min Value = -0.6351
Mouse Pointer Location: Distance From Start of Bridge Object 537.7574
☑ Snap to Computed Response Points
Distance Options: ● Layout Line ○ Girder Length

(b) Longitudinal stress of slab



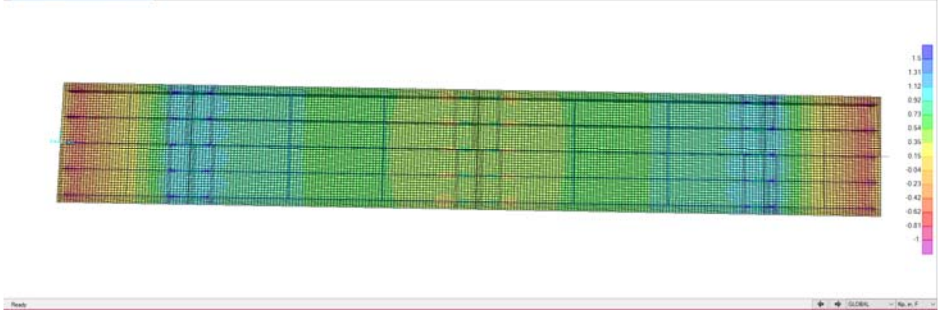
(c) Stress contour view from top of the slab

Figure 17 –Behaviors of bridges with ECC link slab (left and middle) and RC Link Slab (right, change of debonded zone at the right span) under Live Load



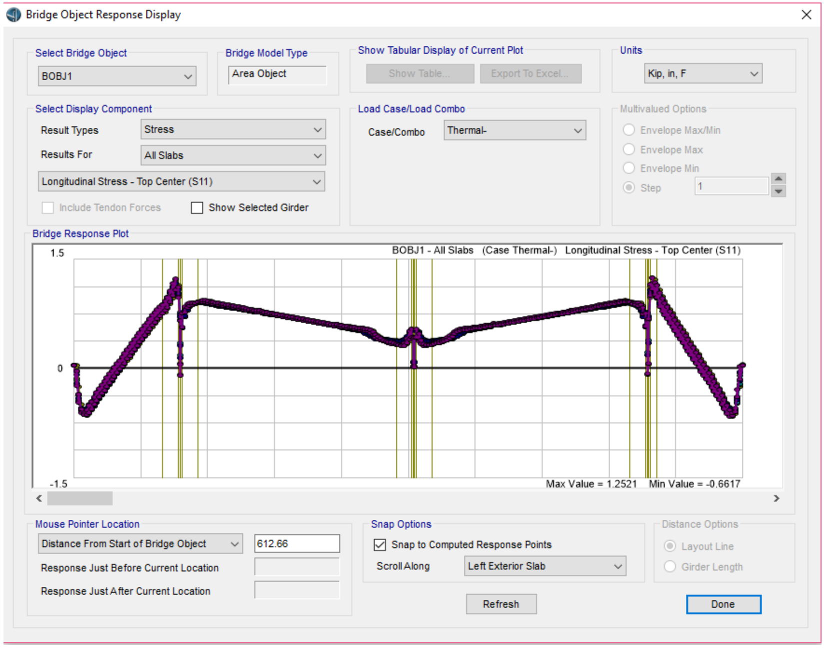
Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Top Left (S11)
☐ Include Tendon Forces
☐ Show Selected Girder
Load Case/Load Combo – Case/Combo: Thermal-
Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1
Bridge Response Plot: BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Top Left (S11)
Max Value = 1.5334 Min Value = -0.6943
Mouse Pointer Location: Distance From Start of Bridge Object
Response Just Before Current Location
Response Just After Current Location
Snap Options: ☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab
Distance Options: ● Layout Line ○ Girder Length

(a) Stresses at top of the slab for temperature decrease of 55F°



(b) Stress contour view from top of the slab

Figure 18 –Thermal behaviors of bridges with ECC link slab



Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Top Center (S11)
☐ Include Tendon Forces
☐ Show Selected Girder
Load Case/Load Combo – Case/Combo: Thermal-
Multivalued Options: ○ Envelope Max/Min ○ Envelope Max ○ Envelope Min ● Step 1
Bridge Response Plot: BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Top Center (S11)
Max Value = 1.2521 Min Value = -0.6617
Mouse Pointer Location: Distance From Start of Bridge Object 612.66
Response Just Before Current Location
Response Just After Current Location
Snap Options: ☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab
Distance Options: ● Layout Line ○ Girder Length

(a) Stresses at top of the slab for temperature decrease of 55F°

Figure 19 –Thermal behaviors of bridges with ECC link slab without debonded zone

Details of analysis:

- For comparison, change debonded zone of link slabs in the left and right span
- Link slab in span 4 is using RC slab with small debonded zone
- In the analysis, the parameter of thermal expansion for ECC is assumed

Summary of analysis:

The maximum tensile stress due to thermal movement will occur when temperature decreases. So the results show the most extreme case, which is, the temperature decrease 110°F

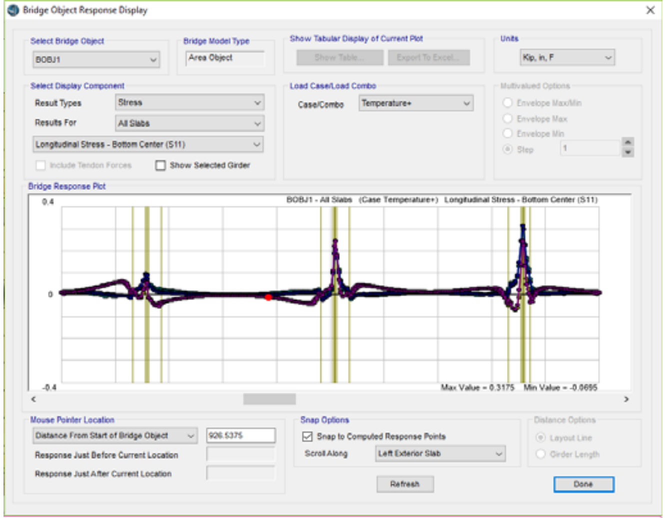
1) Compared with the current multi-simple span model:
   - Displacement due to dead load, live load and thermal movement in the longitudinal direction are all decreased.
   - Stress due to thermal movement (in the extreme case 110°F decrease which would not happen in the real situation) are less than 3.5 kip/in^2 for maximum calculated stress and 2.6 kip/in^2 when averaging stresses in joints (if in a ±55 F° range, the results would be 1.7 kip/in^2 and 1.3 kip/in^2).

2) Compared with ECC and RC link slabs in different debonded zones
   - RC link slab with short debonded zone has a worse performance under thermal movement. Since the regular reinforce concrete is assumed not to take any tension, RC link slab is not recommended.
   - Exterior span slabs will take more stresses under thermal movement with RC link slabs.

3) Compared with ECC link slab case:
   - Deboned length would not affect much on stress distribution due to thermal movement.
   - If using all ECC link slabs rather than ECC and RC link slabs, the maximum tensile stress would slightly decrease in the link slab zones.

3.6 Model with changed boundary conditions and ECC/RC link slab

This case is to modify the model shown in Section 3.5 with current boundary conditions to changed boundary conditions with one fixed bearing in the middle and extension bearings at other locations.

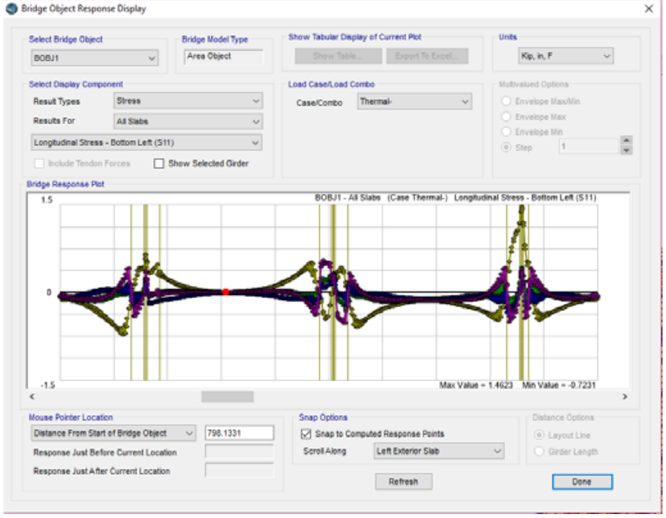

Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Bottom Center (S11)
Case/Combo: Temperature+
☐ Include Tendon Forces ☐ Show Selected Girder
Step: 1

BOBJ1 - All Slabs (Case Temperature+) Longitudinal Stress - Bottom Center (S11)
Max Value = 0.3175 Min Value = -0.0695

Distance From Start of Bridge Object: 926.5375
Response Just Before Current Location
Response Just After Current Location
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab

(a) Stress at the bottom of the slab due to positive temperature gradients

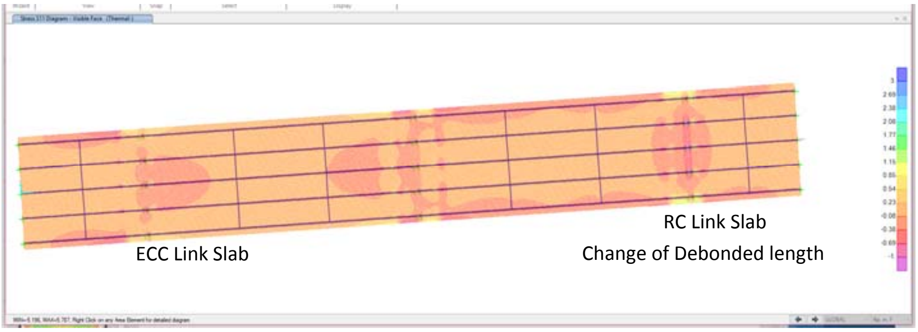

Bridge Object Response Display

Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Bottom Left (S11)
Case/Combo: Thermal-
☐ Include Tendon Forces ☐ Show Selected Girder
Step: 1

BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Bottom Left (S11)
Max Value = 1.4623 Min Value = -0.7231

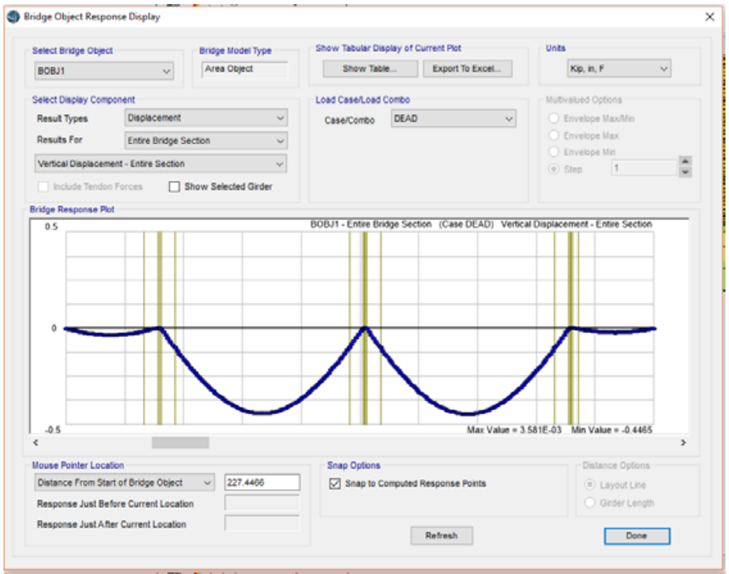
Distance From Start of Bridge Object: 798.1331
Response Just Before Current Location
Response Just After Current Location
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab

(b) Stresses at top of the slab for temperature decrease of 110F°



(c) Stress contour at top of the slab for temperature decrease

Figure 20 –Thermal behaviors of bridges with ECC link slab and RC Link Slab



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Case/Combo: DEAD

Step: 1

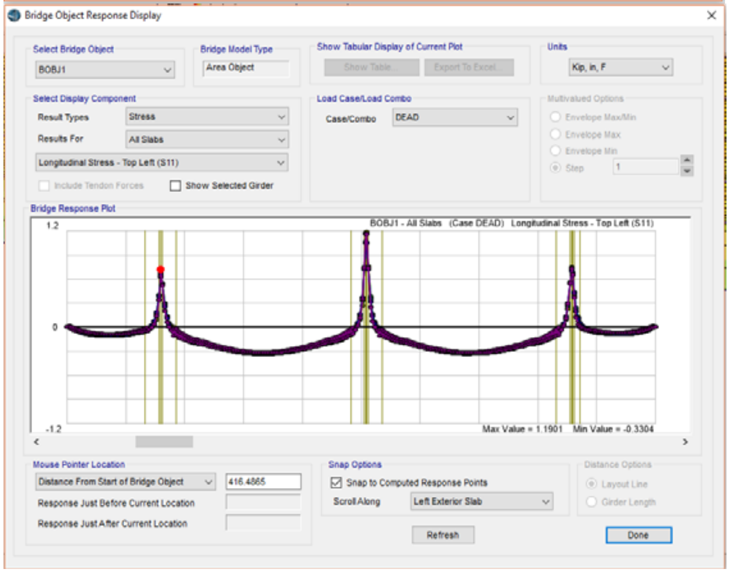
BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 3.581E-03 Min Value = -0.4465

Distance From Start of Bridge Object: 227.4466

☑ Snap to Computed Response Points

(a) Vertical displacement



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Top Left (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Case/Combo: DEAD

Step: 1

BOBJ1 - All Slabs (Case DEAD) Longitudinal Stress - Top Left (S11)

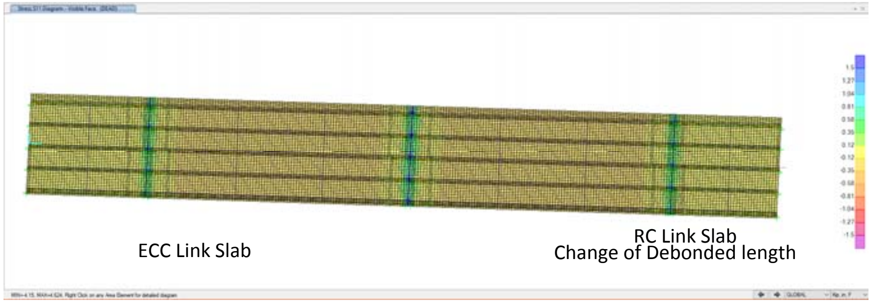
Max Value = 1.1901 Min Value = -0.3304

Distance From Start of Bridge Object: 416.4865

☑ Snap to Computed Response Points

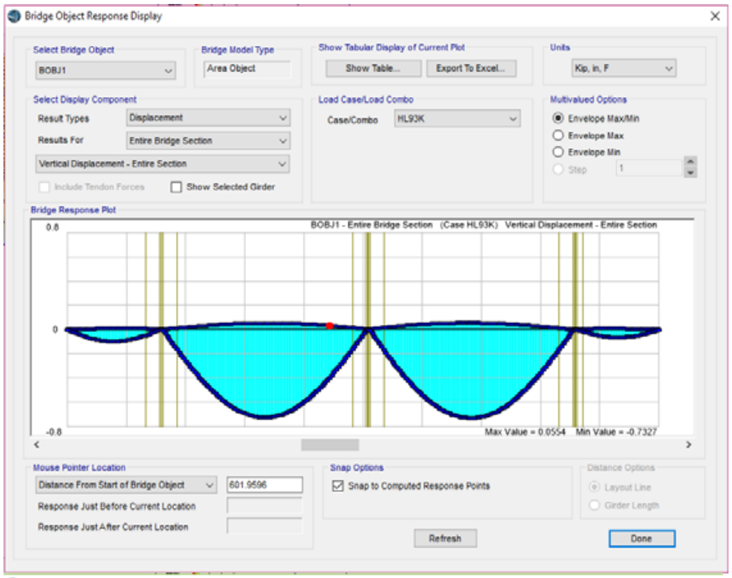
Scroll Along: Left Exterior Slab

(b) Stresses at top of the slab



(c) Stress contour view from top of the slab

Figure 21 –Behaviors of bridges with ECC link slab (left and middle) and RC Link Slab (right, change of debonded zone at the right span) under Dead Load



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: HL93K

Multivalued Options

● Envelope Max/Min

○ Envelope Max

○ Envelope Min

○ Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case HL93K) Vertical Displacement - Entire Section

Max Value = 0.0554 Min Value = -0.7327

Mouse Pointer Location

Distance From Start of Bridge Object: 601.9596

Response Just Before Current Location

Response Just After Current Location

Snap Options

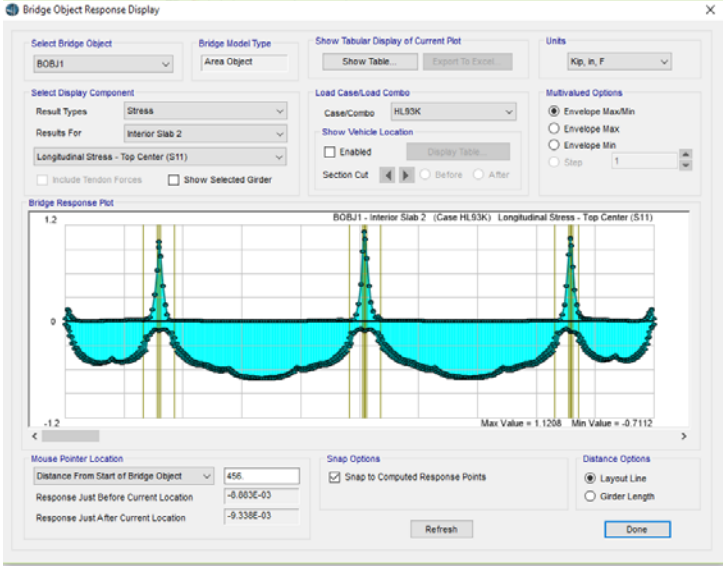
☑ Snap to Computed Response Points

Distance Options

○ Layout Line

○ Girder Length

(a) Vertical displacement



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: Interior Slab 2

Longitudinal Stress - Top Center (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: HL93K

Show Vehicle Location

☐ Enabled

Section Cut ○ Before ○ After

Multivalued Options

● Envelope Max/Min

○ Envelope Max

○ Envelope Min

○ Step 1

Bridge Response Plot

BOBJ1 - Interior Slab 2 (Case HL93K) Longitudinal Stress - Top Center (S11)

Max Value = 1.1208 Min Value = -0.7112

Mouse Pointer Location

Distance From Start of Bridge Object: 456.

Response Just Before Current Location: -8.883E-03

Response Just After Current Location: -9.338E-03

Snap Options

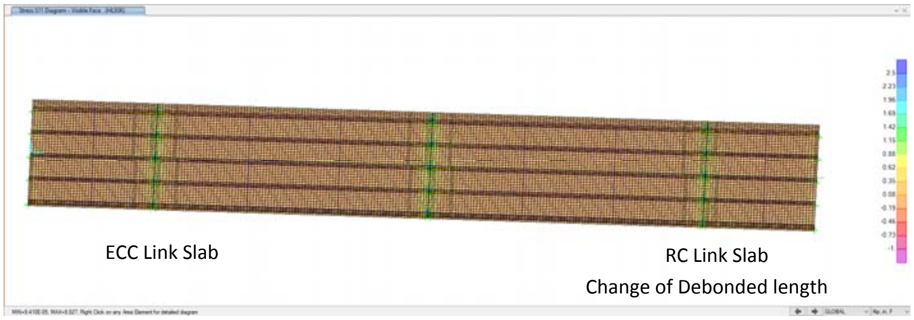
☑ Snap to Computed Response Points

Distance Options

● Layout Line

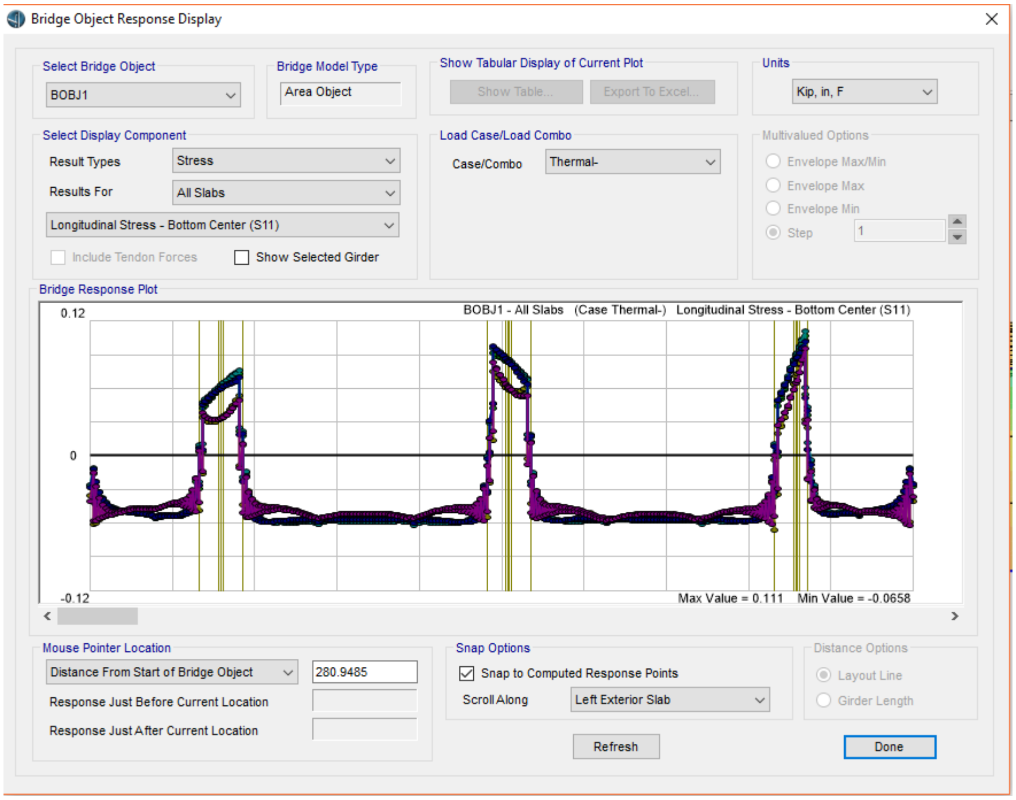
○ Girder Length

(b) Longitudinal stress of slab



(c) Stress contour at the top of the slab

Figure 22 –Behaviors of bridges with ECC link slab (left and middle) and RC link slab (right, change of debonded zone at the right span) under Live Load


Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Bottom Center (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: Thermal-

Multivalued Options

○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Bottom Center (S11)

Max Value = 0.111 Min Value = -0.0658

Mouse Pointer Location

Distance From Start of Bridge Object: 280.9485

Response Just Before Current Location

Response Just After Current Location

Snap Options

☑ Snap to Computed Response Points

Scroll Along: Left Exterior Slab

Distance Options

● Layout Line
○ Girder Length

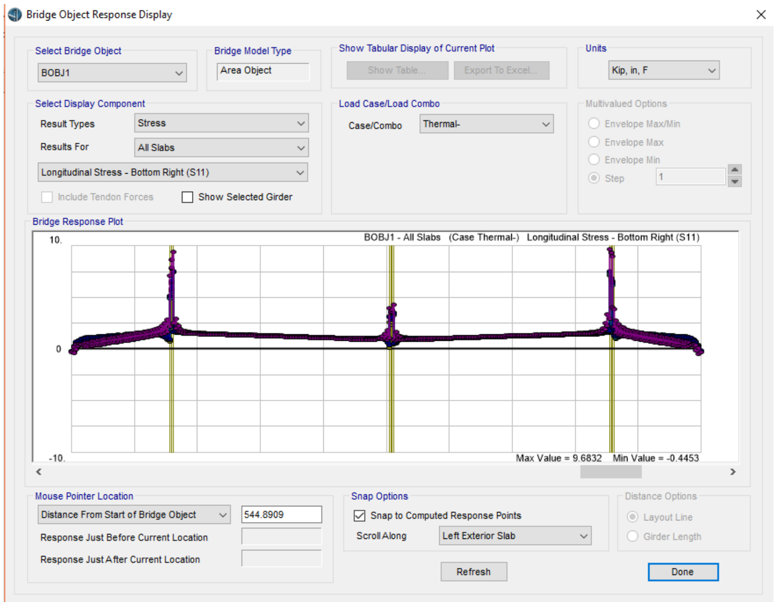
Figure 23 – Stress distribution on decks due to thermal behaviors of bridges with ECC link slab

Summary of analysis:

Compared with results shown in Section 3.5, i.e., the bridge using current bearing conditions with ECC/ RC link slab:

- For thermal movement, there are significant changes for maximum stresses occurring at link slabs. Also, the stresses on bridge decks are tending to close to zero, which means the deck will take less stress than the case of current boundary conditions.
- The maximum tensile stress on the RC link slab significantly increased.
- If using ECC for all link slabs and changing the boundary conditions, the stress due to thermal movement will decrease to a negligible level.
- For the model under dead load and live load, both maximum displacement and maximum stress are increased.

3.7 Model with current boundary conditions and UHPC link slab



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Bottom Right (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: Thermal-

Multivalued Options

○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Bottom Right (S11)

Max Value = 9.6832 Min Value = -0.4453

Mouse Pointer Location

Distance From Start of Bridge Object: 544.8909

Response Just Before Current Location

Response Just After Current Location

Snap Options

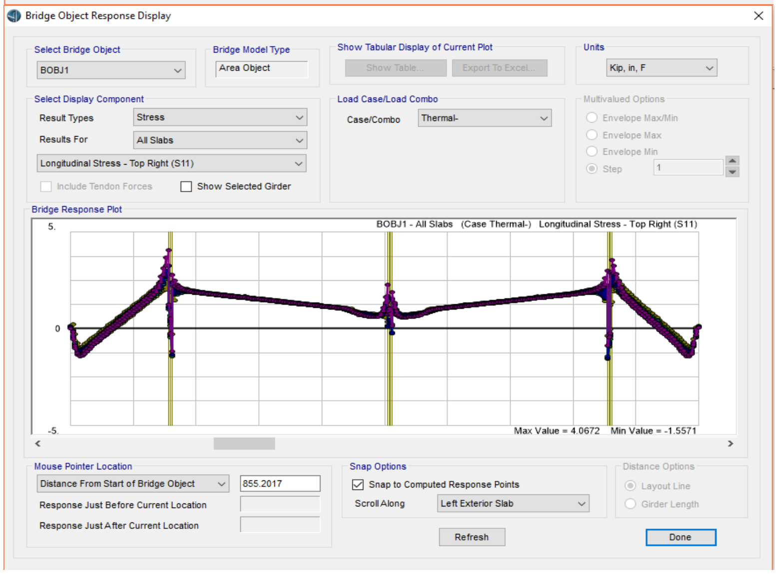
☑ Snap to Computed Response Points

Scroll Along: Left Exterior Slab

Distance Options

● Layout Line
○ Girder Length

(a) Longitudinal stress at the top of the slab under temperature decrease of 110F°



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Top Right (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: Thermal-

Multivalued Options

○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Top Right (S11)

Max Value = 4.0672 Min Value = -1.5571

Mouse Pointer Location

Distance From Start of Bridge Object: 855.2017

Response Just Before Current Location

Response Just After Current Location

Snap Options

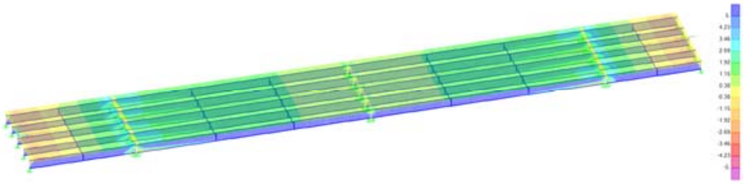
☑ Snap to Computed Response Points

Scroll Along: Left Exterior Slab

Distance Options

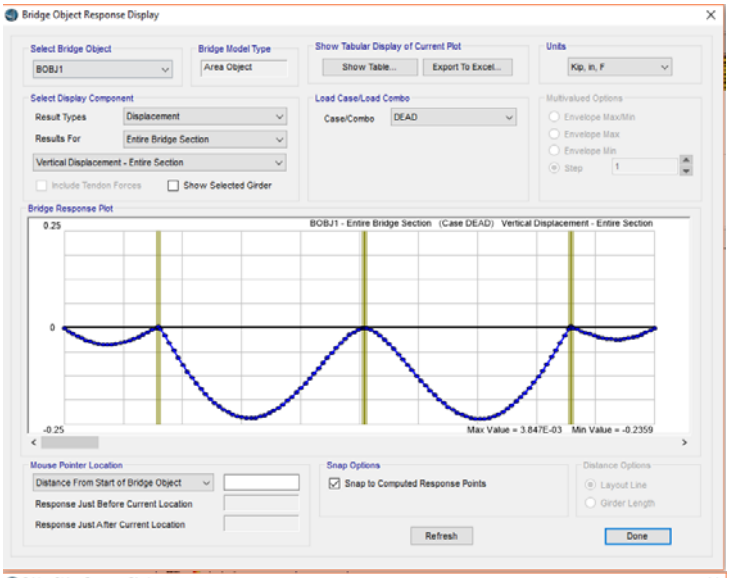
● Layout Line
○ Girder Length

(b) Longitudinal Stress at the bottom of the slab under temperature decrease of 110F°



(b) Stress contour for temperature decrease of 110F°

Figure 24 – Thermal movement at bearings and stress/stress contour at the top of the slab


Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 3.847E-03 Min Value = -0.2359

Mouse Pointer Location

Distance From Start of Bridge Object

Response Just Before Current Location

Response Just After Current Location

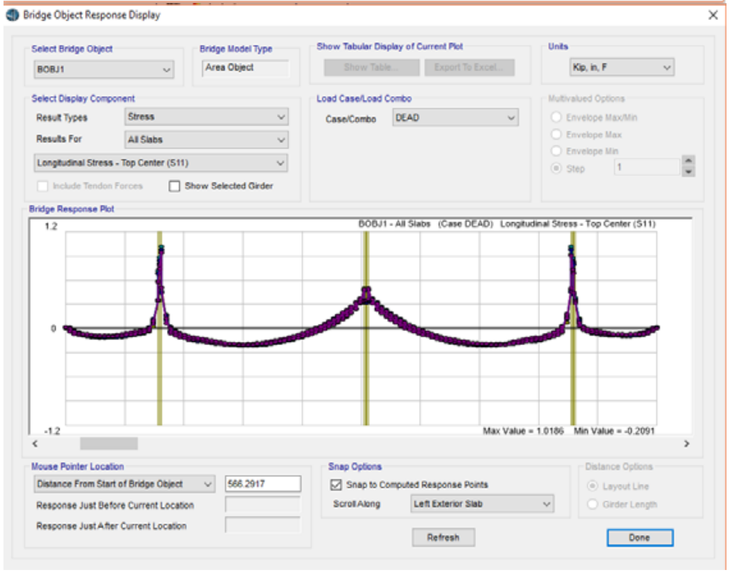
Snap Options

☑ Snap to Computed Response Points

Distance Options

● Layout Line
○ Girder Length

(a) Vertical displacement


Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Top Center (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min
○ Envelope Max
○ Envelope Min
● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case DEAD) Longitudinal Stress - Top Center (S11)

Max Value = 1.0186 Min Value = -0.2091

Mouse Pointer Location

Distance From Start of Bridge Object: 566.2917

Response Just Before Current Location

Response Just After Current Location

Snap Options

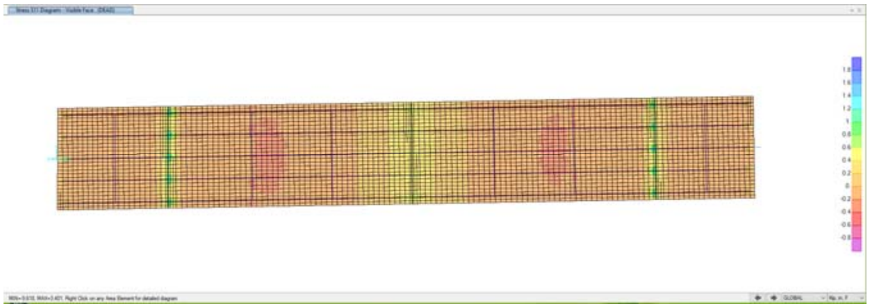
☑ Snap to Computed Response Points

Scroll Along: Left Exterior Slab

Distance Options

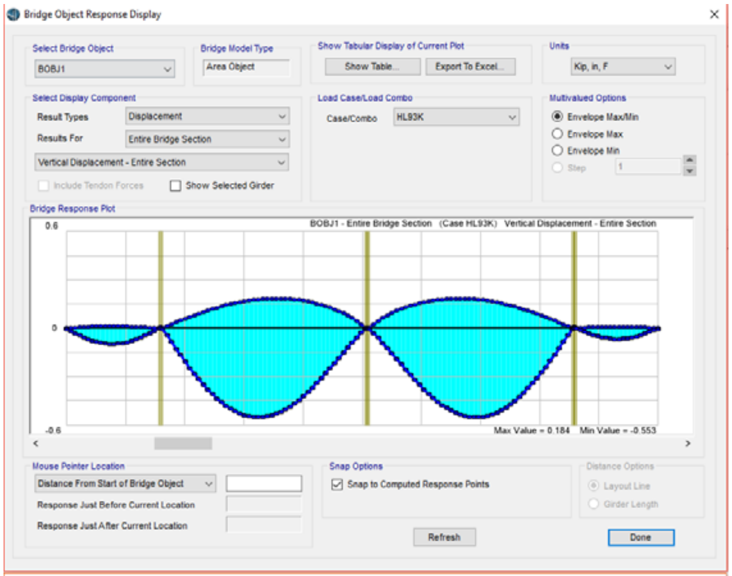
● Layout Line
○ Girder Length

(b) Stresses at the top of the slab



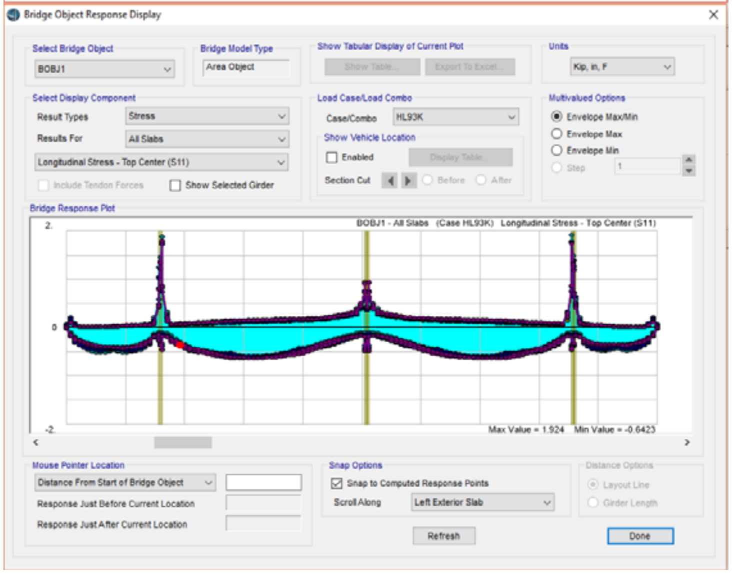
(c) Stress contour view from top of the slab

Figure 25 –Behaviors of bridges with UHPC link slab under dead load



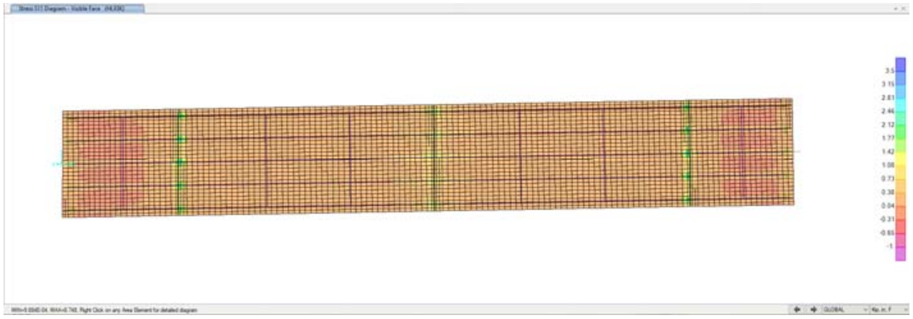
Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Displacement
Results For: Entire Bridge Section
Vertical Displacement - Entire Section
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: HL93K
Multivalued Options: ● Envelope Max/Min ○ Envelope Max ○ Envelope Min ○ Step 1
BOBJ1 - Entire Bridge Section (Case HL93K) Vertical Displacement - Entire Section
Max Value = 0.184 Min Value = -0.553
Distance From Start of Bridge Object
Response Just Before Current Location
Response Just After Current Location
☑ Snap to Computed Response Points

(a) Vertical Displacement



Select Bridge Object: BOBJ1
Bridge Model Type: Area Object
Units: Kip, in, F
Result Types: Stress
Results For: All Slabs
Longitudinal Stress - Top Center (S11)
☐ Include Tendon Forces ☐ Show Selected Girder
Case/Combo: HL93K
Show Vehicle Location: ☐ Enabled
Section Cut ○ Before ○ After
Multivalued Options: ● Envelope Max/Min ○ Envelope Max ○ Envelope Min ○ Step 1
BOBJ1 - All Slabs (Case HL93K) Longitudinal Stress - Top Center (S11)
Max Value = 1.924 Min Value = -0.6423
Distance From Start of Bridge Object
Response Just Before Current Location
Response Just After Current Location
☑ Snap to Computed Response Points
Scroll Along: Left Exterior Slab

(b) Longitudinal Stress of slab



(c) Stress contour view from top of the slab

Figure 26 –Behaviors of bridges with UHPC link slab under Live Load

Details of analysis:

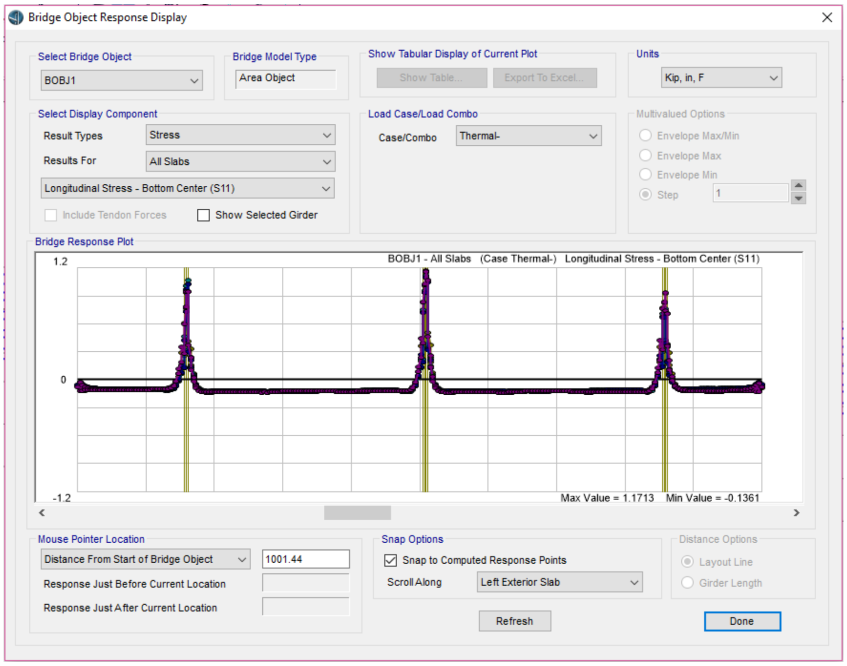
- Debonded zones for UHPC link slabs are relatively small than in ECC link slabs
- No obvious deformation in the link slab zone
- All the parameters are adopted from Lafarge and NYDOT design example

Summary of analysis:

- The maximum stress occurs at the location above bearing (also above girders) in the model.
- The entire slab will be under tension where maximum tensile stress values could reach 5 kips/in^2 when there is a 110°F temperature decrease for the extreme case, and in the common ±55°F range, the maximum tensile stress could reach up to 2.5 kip/in^2.
- Tension/Compression phase changes comparing with current bridge.
- Compared with the current bridge model with or without ECC link slabs, stresses in the UHPC link slabs will increase significantly.
- Compared with bridge model with ECC link slab, the maximum stresses in UHPC link slab are larger but with similar deformation under dead load and live load cases.
- The material properties for UHPC, mentioned by Lafarge engineer, are designed for strain control.

3.8 Model with changed boundary conditions and UHPC link slab

This case is to modify the model shown in Section 3.7 with current boundary conditions to changed boundary conditions with fixed bearings in the middle and extension bearings at other locations.



Bridge Object Response Display

Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Bottom Center (S11)

☐ Include Tendon Forces

☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: Thermal-

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case Thermal-) Longitudinal Stress - Bottom Center (S11)

Max Value = 1.1713 Min Value = -0.1361

Mouse Pointer Location

Distance From Start of Bridge Object: 1001.44

Response Just Before Current Location

Response Just After Current Location

Snap Options

☑ Snap to Computed Response Points

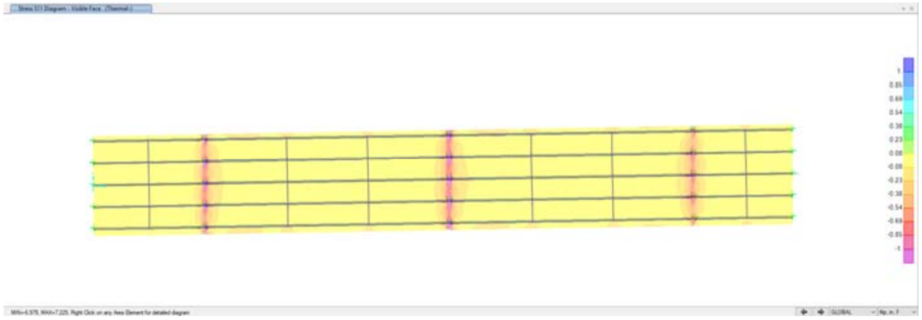
Scroll Along: Left Exterior Slab

Distance Options

● Layout Line

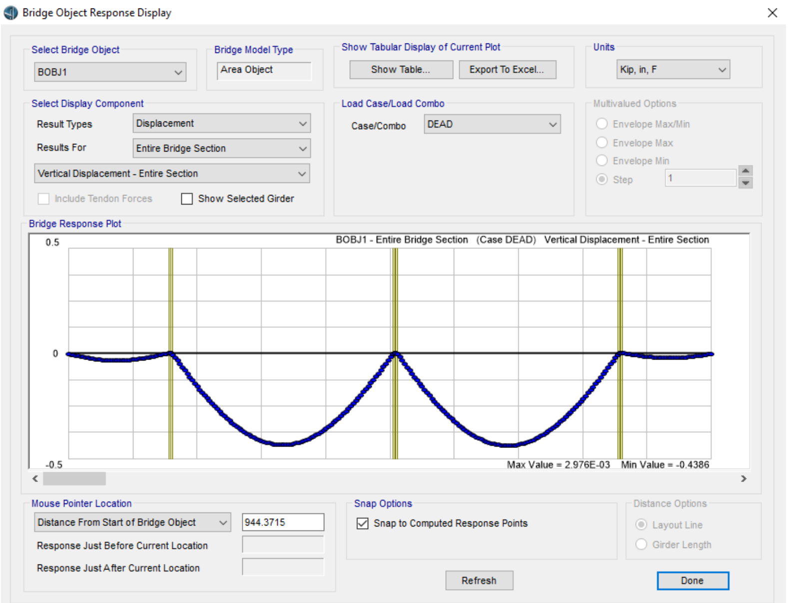
○ Girder Length

(a) Longitudinal Stress at the bottom of the slab under temperature decrease of 110F°



(b) Stress contour at the top of the slab for temperature decrease

Figure 27 –Thermal behaviors of bridges with UHPC link slab



Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Displacement

Results For: Entire Bridge Section

Vertical Displacement - Entire Section

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - Entire Bridge Section (Case DEAD) Vertical Displacement - Entire Section

Max Value = 2.976E-03 Min Value = -0.4386

Mouse Pointer Location

Distance From Start of Bridge Object: 944.3715

Response Just Before Current Location

Response Just After Current Location

Snap Options

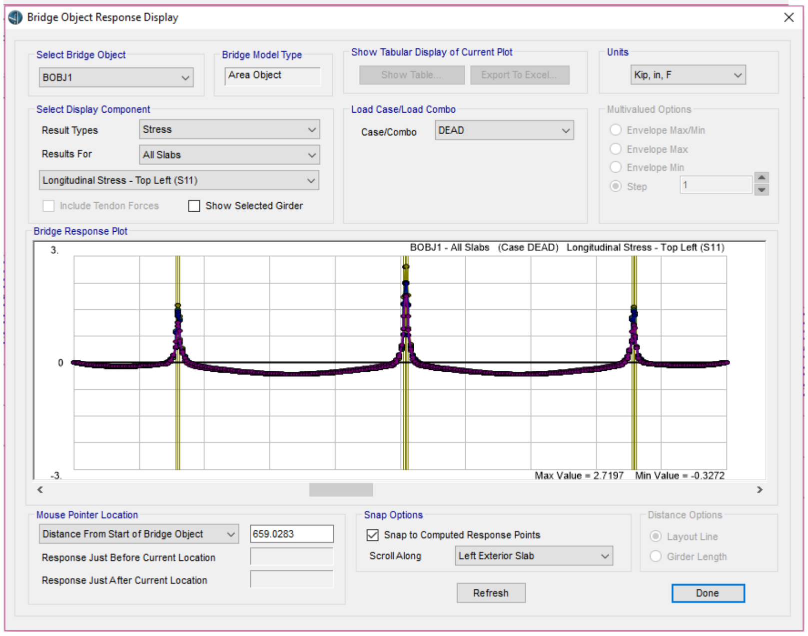
☑ Snap to Computed Response Points

Distance Options

● Layout Line

○ Girder Length

(a) Vertical displacement



Select Bridge Object: BOBJ1

Bridge Model Type: Area Object

Units: Kip, in, F

Select Display Component

Result Types: Stress

Results For: All Slabs

Longitudinal Stress - Top Left (S11)

☐ Include Tendon Forces ☐ Show Selected Girder

Load Case/Load Combo

Case/Combo: DEAD

Multivalued Options

○ Envelope Max/Min

○ Envelope Max

○ Envelope Min

● Step 1

Bridge Response Plot

BOBJ1 - All Slabs (Case DEAD) Longitudinal Stress - Top Left (S11)

Max Value = 2.7197 Min Value = -0.3272

Mouse Pointer Location

Distance From Start of Bridge Object: 659.0283

Response Just Before Current Location

Response Just After Current Location

Snap Options

☑ Snap to Computed Response Points

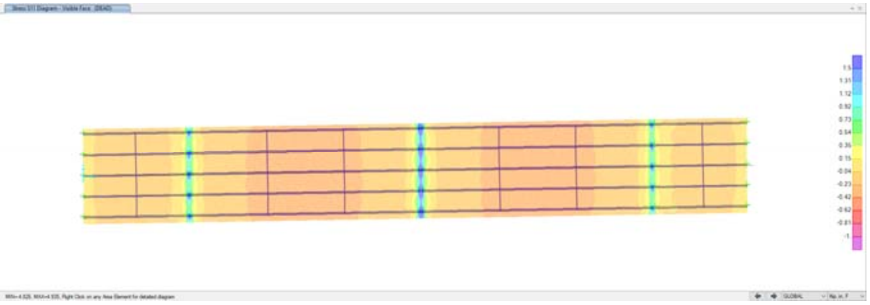
Scroll Along: Left Exterior Slab

Distance Options

○ Layout Line

○ Girder Length

(b) Stresses at the top of the slab



(c) Stress contour view from top of the slab

Figure 28 – Behaviors of the bridge with UHPC link slab under dead load

Summary of analysis:

- Compared with the result of section 3.7, stresses due to thermal movement in slabs and girders decreased significantly
- The maximum stress due to thermal movement (110F° decreased, known as the extreme case but should not happened) are decreased from 4.5 to 1.5 kip/in^2 in average solution for the extreme case, but for the common ±55F° range, the result of maximum stress should decrease from 2.3 kip/in^2 to 0.7 kip/in^2 in this case.
- The maximum displacement and stress caused by dead load are increasing when changing the boundary conditions.
- When the maximum tensile stress due to thermal movement happens in UHPC link slab, other parts of the bridge deck are mostly under compression when changing the bearing conditions.

4. Task 4 - Provide recommendation of standard practice

Based on previous computer runs, we have the following findings and have them listed here for discussion:

- For the current bearing arrangement, the pilot bridge (CEXA27001) with link slab is tolerable with the thermal movement, but thermal stress would increase.

- At abutments fixed bearings are specified for current bridge bearing arrangement. MDOT (SHA Standards) specifies the same details for the expansion and fixed bearings for spans under 50', but the former one with slotted holes and the latter one without. If slotted holes are introduced for the fixed bearings at abutments, we may treat them as expansion ends and thermal stresses could be released. The question is whether it is feasible or not in real situations. If feasible, the boundary conditions of this 4-span case can be treated as RRHRR and the link slab option is feasible numerically (, which is recommended to be validated physically.) In NYSDOT bearings are all replaced by elastomeric bearings and the 3-span case are treated as RHRR.

- Most of the MDTA overpass bridges are in the same pattern so we may consider them as a group and find the feasible range for link slab application.

5. Task 5 - Summary and Report

Following missions are completed in this study:

- Task 1: Kick-off meeting to present the study plan was performed on June 14, 2017.
- Task 1: literature search and information collection were performed; meeting with Lafarge, the sole UHPC producer in the US, and tele-con with NYDOT engineers on their experience using UHPC were set on November 29, 2017,
- Task 2: ECC mixing and testing were performed in the summer of 2017; the best performed ECC mix from a collected three candidates for the pilot project was selected.
- Task 2: presentation on ECC mixes and testing results was made to the MDTA on September 28, 2017,
- Task 3: several bridges from MDTA inventory for the pilot bridge implementation and modeling were investigated for possible pilot study candidate.
- Task 3: a pilot bridge was selected and a site visit was conducted with MDTA and Lafarge representatives on November 29, 2017.
- Tasks 3 and 4: studies of the feasibility of implementing ECC as well as UHPC without modifying bearings were performed.
- Tasks 3 and 4: studies of a side-by-side ECC and UHPC implementations on the same bridge were concluded with suggestions,
- Task 5: Report of the study was drafted and delivered here.

APPENDIX A

Table A1 – Candidate considered for Link Slab Pilot Demonstration

Bridge Number	Bridge Name	Facility	Year Built	Structure Type	Span Lengths						Total Length	Width	# Spans	2016 ADT
H-X894001	Lapidum Rd over I-95	JFK	1963, 1974	Steel Beam	33'	40'	76'	76'			225'	26'	4	100
CEXA27001	Union Church Rd over I-95	JFK	1963	Steel Beam	34'	31'	76'	76'			217'	26'	4	375
CEX952001	Winch Rd over I-95	JFK	1963, 1974	Steel Beam	34'	29'	76'	76'			215'	26'	4	1,000
CEXA11001	Bouchelle Rd over I-95	JFK	1963	Steel Beam	31'	40'	76'	76'			223'	26'	4	1,000
CEXA38001	Deaver Rd over I-95	JFK	1963	Steel Beam	39'	30'	77'	77'			223'	26'	4	1,000
H-X881001	Earlton Rd over I-95	JFK	1963, 1974	Steel Beam	36'	34'	83'	83'			236'	26'	4	1,095
HOY012001	I-895 SBR Ramp over US 1, Patapsco River	BHT	1957	Steel Beam	76'	74'	36'	60'	135'	57'	438'	26'	6	1,190
H-X837001	Stepney Rd over I-95	JFK	1963	Steel Beam & Girder	53'	34'	100'	100'			287'	30'	4	1,210
HOY013001	I-895 NBR Ramp over Patapsco River	BHT	1957	Steel Beam	38'	107'	107'	40'	42'	30'	364'	26'	6	1,350
BCWT34001	I-395 Ramp EE over Warner St	FMT	1980	Steel Box Girder	116'	135'					251'	22'	2	1,596
H-X878001	Chapel Rd over I-95	JFK	1963, 1974	Steel Beam	33'	33'	78'	78'			222'	26'	4	1,765
CEX960001	Belvedere Rd over I-95	JFK	1963	Steel Beam	41'	33'	81'	81'			236'	26'	4	1,800
CEXA83001	MD 316 (Appleton Rd) over I-95	JFK	1963, 1987	Steel Beam	43'	76'	76'	30'			225'	32'	4	4,300
H-X859001	Maxa Rd over I-95	JFK	1963, 1987	Steel Beam	45'	86'	86'	32'			249'	28'	4	5,000
H-X796001	MD 136 (Calvary Rd) over I-95	JFK	1963, 1974	Steel Beam	39'	29'	77'	77'			222'	30'	4	6,760
CEXA62001	MD 213 (Singerly Rd) over I-95	JFK	1963	Steel Beam	30'	42'	79'	79'			230'	30'	4	9,700
CEX934001	MD 222 (Perrylawn Dr) over I-95	JFK	1963	Steel Beam	35'	46'	89'	89'			259'	30'	4	14,800

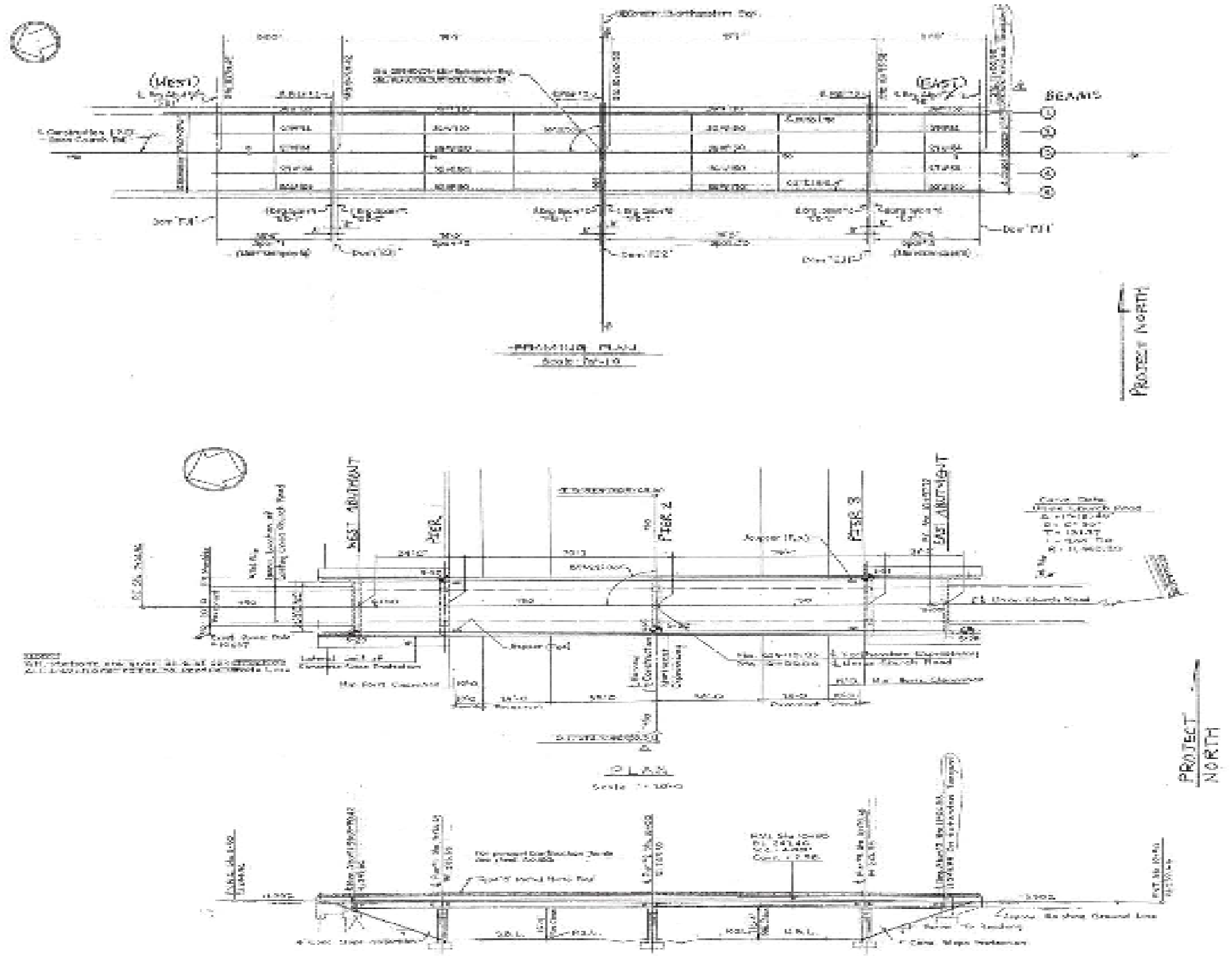


Figure A1 - MDTA Bridge
CEXA27001 GPE & Framing Plan

Figure A2 - Bridge CEXA27001

Figure A3 – Exterior pier top deck expansion joint

Figure A4 – Interior pier top deck expansion joint

Figure A5 – Exterior pier bearings

Figure A6 – Abutment fixed bearing

Figure A7 – Exterior pier extension bearings

Attachment B

Progress Report #1 for Phase 2 - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

Report dated 08/31/2018

ATTACHMENT B

Progress Report 1 to the MDTA

For

Phase II - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

By Dr. Chung C. Fu, P.E., Director/Research Professor
and Yifan Zhu & Kuangyuan Hou, Research Assistants
The Bridge Engineering Software and Technology (BEST) Center
Department of Civil and Environmental Engineering, University of Maryland

August 31, 2018

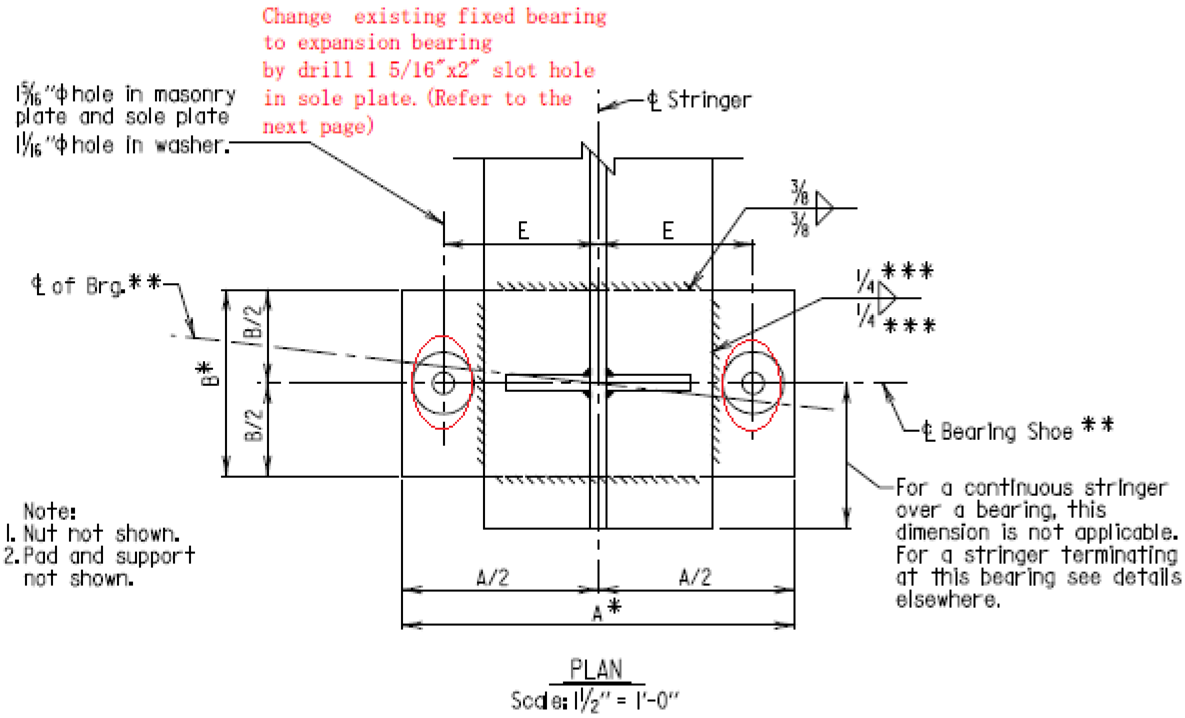
i. Status Report

The Phase II study involves the execution of the following tasks and their current status is listed herein:

Task 1 –Boundary Condition Investigation

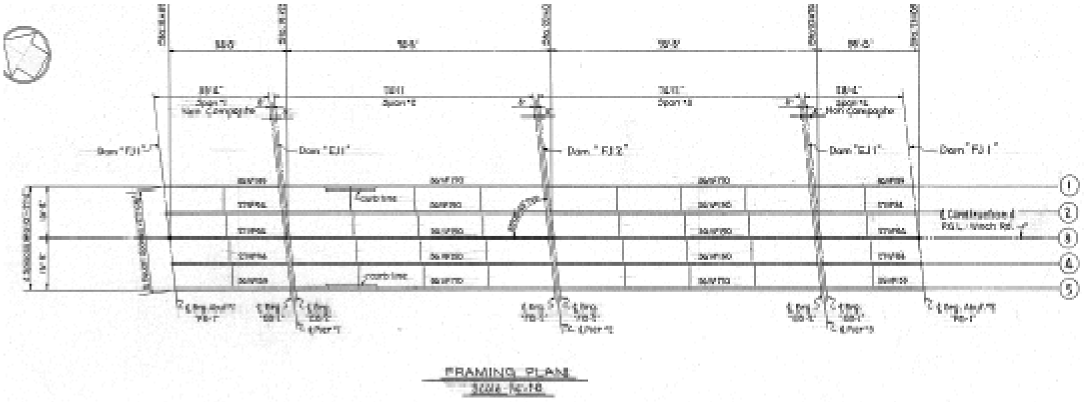
Preliminary study for the bridge boundary conditions has been made in Phase I and is carried on during Phase II. Study and then suggestions for bearing have been made on the pilot bridge CEX95200 (used to be CEXA27001). Even with the change of the pilot bridge, based on preliminary computer runs, same findings are made here:

1. For current bearing arrangement, the bridge is tolerable with the thermal movement, but thermal stress increased, which is not desirable.
2. Abutments fixed bearings are specified for the pilot bridge. MDOT (SHA Standards) specifies the same details for the expansion and fixed bearings, but one with slotted holes and one without. If slotted holes are introduced for the fixed bearing at abutmenta, we may treat them as expansion ends and thermal stresses can be released. The reconstruction to expansion ends have been discussed with MDTA and consultants. It is considered feasible.
3. Most of the MDTA overpass bridges are in the same pattern so we may consider them as a group and find the feasible range for link slab application.



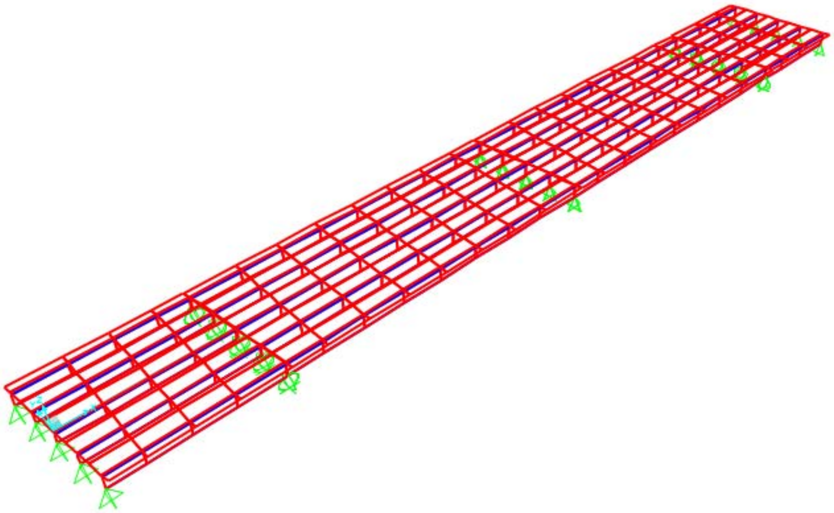
The study of different boundary conditions of different configurations is going to be evaluated in this Phase II study. The purpose is to find the feasible span ranges without changing the boundary conditions. Conclusion of more general cases will be made on various boundary conditions for their limitation on the application.

Due to traffic concerns based on the joint site visit made on June 29. 2018, the pilot bridge was decided switching from a straight bridge CEXA27001 to a slightly skew bridge CEX95200 nearby. Sketch, photos and FEM model of the new pilot bridge are shown here:



CEX95200 Bridge

Photos of CEX95200 taken by the BEST Center during field visit (Girders, bearing condition and substructures cannot reach)



Finite Element model of CEX95200

In order to get a full understanding of the thermal behavior of this prototype bridge, six models were made with two types of thermal analyses: (1) Temperature Gradient (based on AASHTO, Zone 2); (2) Thermal Expansion (based on temperature increase or decrease within 100°F, which is for the extreme case).

These models are: (1) Current bridge model; (2) Bridge with 3 ECC link slabs; (3) Bridge with 3 ECC link slabs and change of boundary conditions (bearings); (4) Bridge with 3 UHPC link Slabs; (5) Bridge with 3 UHPC link slabs and change of boundary condition; (6) Bridge with 2 ECC link slabs and 1 UHPC link slabs with the change of bearings.

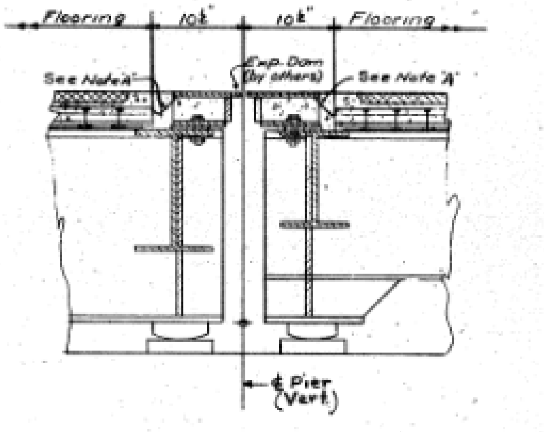
The results for the completed study will be based on longitudinal displacements for the entire bridge and stresses on the top of the slab under the extreme case.

Task 2 - Link slab design procedure

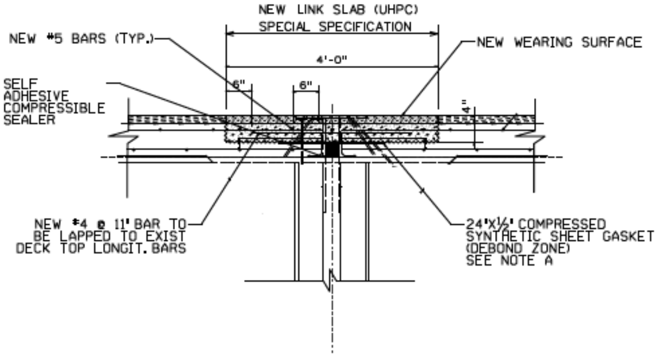
Full slab depth (usually 8" deep) with full two-layer reinforcement for ECC link slab and 4" thickness with light one-layer reinforcement for UHPC link slab have been analyzed and then designed. Final designs have been delivered on March 23, 2018, with all limit states considered.

Task 3 - Link slab special provision

Steel gird deck with link slab implementation on B-Y0118 Bridge has been studied. As mentioned, due to the high cost of UHPC, special cases, such as grid slab, can be considered an ideal candidate for application. Structural details on B-Y0118 Bridge have been collected and it was determined the details for grid deck will be similar to UHPC details on regular concrete deck.



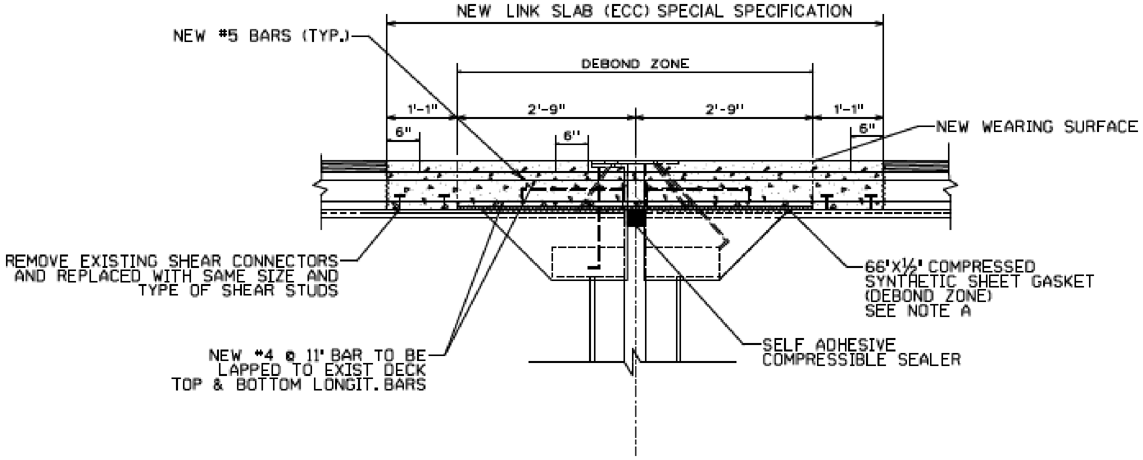
EXISTING



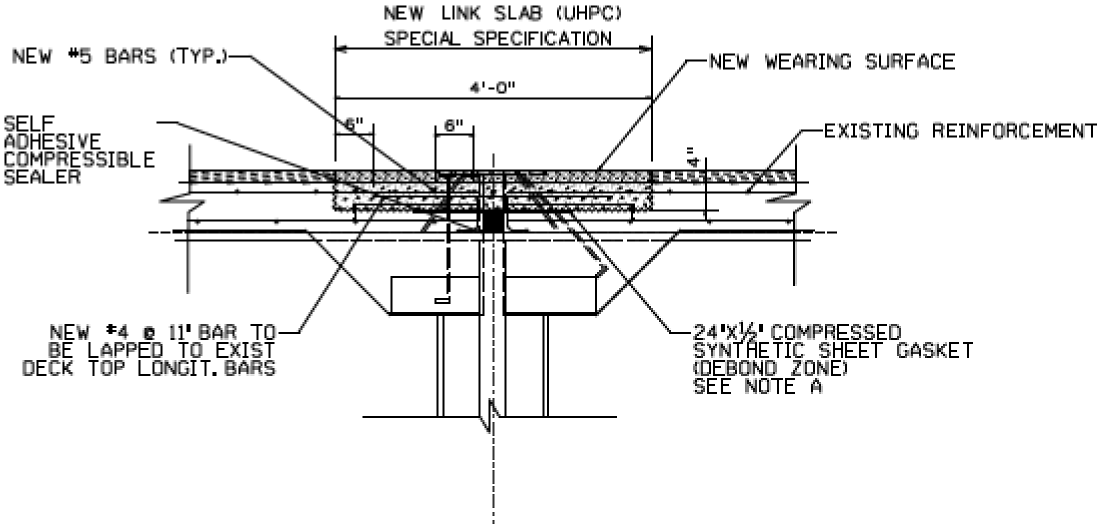
PROPOSED

Task 4 - Link slab typical details and specifications

Details based on the design procedure and special provisions for both ECC and UHPC link slabs were delivered on March 23, 2018 and the proposed sections are summarized here for demonstration purpose. The specifications of Category 400 for Structures and Category 900 for Material for link slab field applications were first delivered on March 6, 2018 and then combined with calculation sheets and design drawings delivered on March 23, 2018.



PROPOSED ECC LINK SLAB



PROPOSED UHPC LINK SLAB

Task 5 - Summary and Report

Pending (This progress report will serve as report 1 of this phase.)

Task 6 – Pilot Implementation with monitoring

Based on pending schedule, load test and relatively long-term monitoring will be performed. Thermal movement plus the strain (stress) measurement will be field monitored.

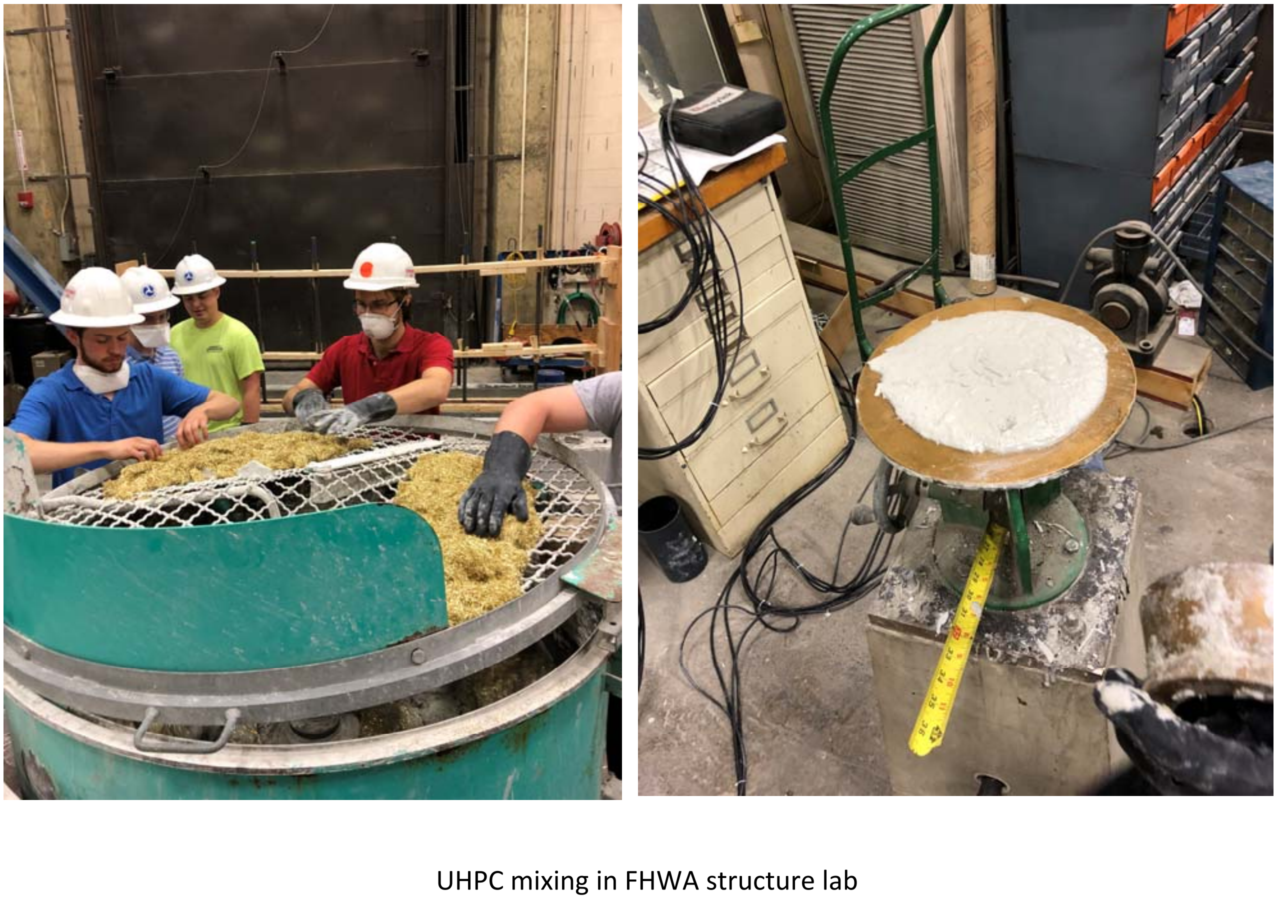
Before conducting load test, sensor placement has to be made. The research team has added two more subtasks under Task 6, which are

1. Subtask 1 – Pure compression test and bending test in the lab with various sensor embedment arrangements for ECC specimens.

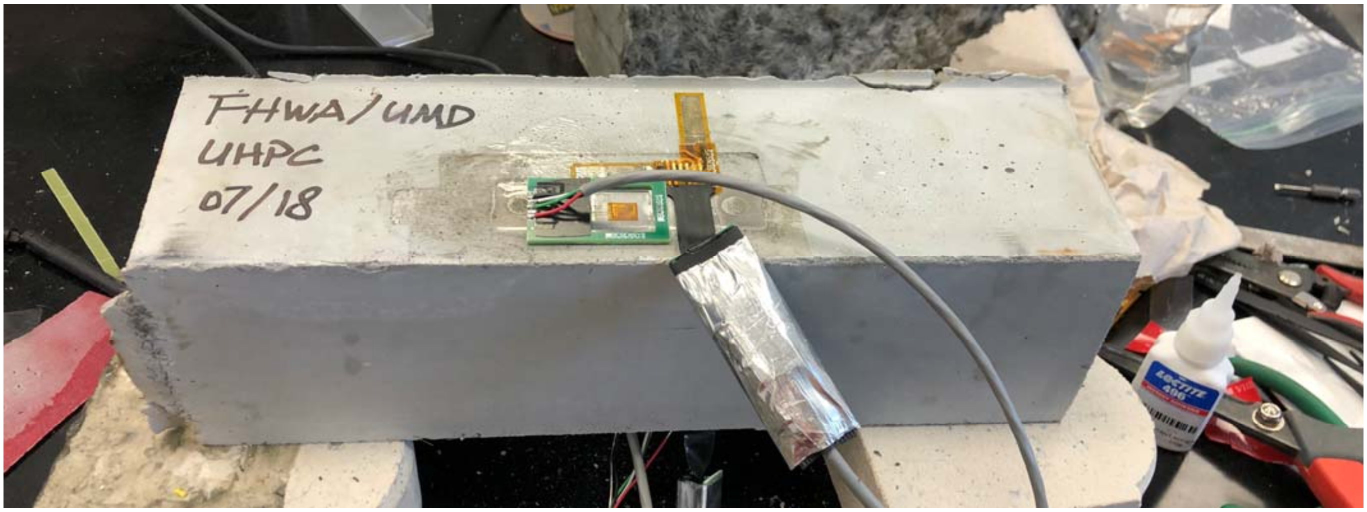
2. Subtask 2 – Pure compression test and bending test in the lab with various sensor embedment arrangements for UHPC specimens.

ECC mixing for subtask 1 is made in-house with admixtures supplied by NRMCA lab. In order to get the UHPC material for subtask 2, contact was first made to Greg Nault of LafargeHocim on Jan. 24, 2018 and followed in June and July 2018. Due to small amount (50 pounds in total) of UHPC required for our testing, the research team was referred to FHWA Turner-Fairbank Highway Research Center (TFHRC) where our first meeting was conducted last year.

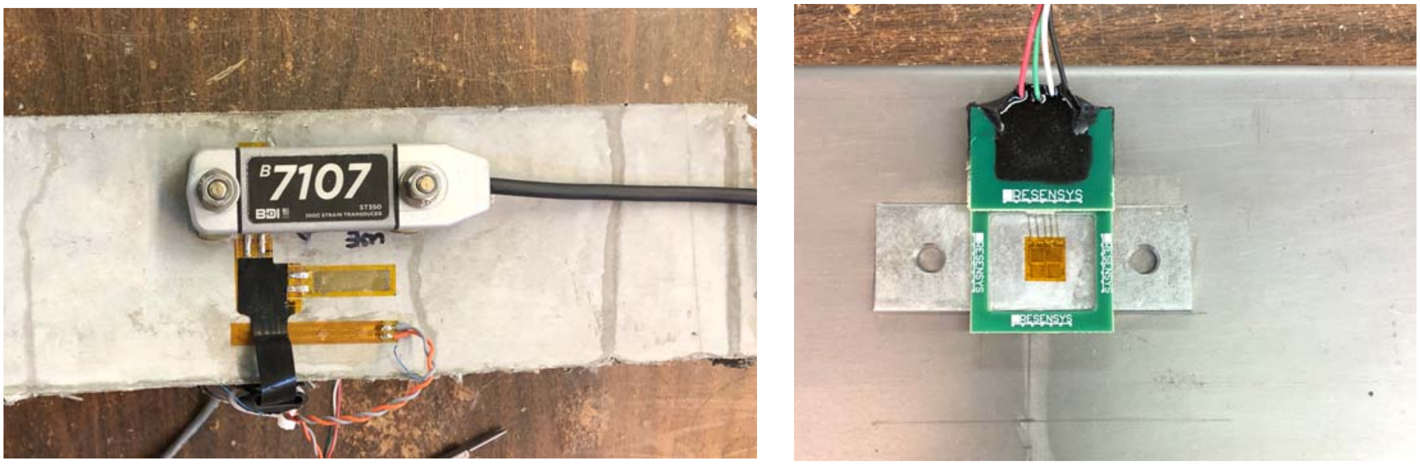
Finally, FHWA and Larfarge have stricken a deal on July 2018 that we may obtain the 50-lb premix UHPC free of charge from the large quantity FHWA ordered. Visit 2018 to FHWA/TFHRC was made on July 18, 2018 to witness the UHPC mixing and carried back 50-lb premix and admixtures for our own test. Photos for the FHWA mixing demonstration and the research team own mixing practices are shown below.



UHPC mixing in FHWA structure lab

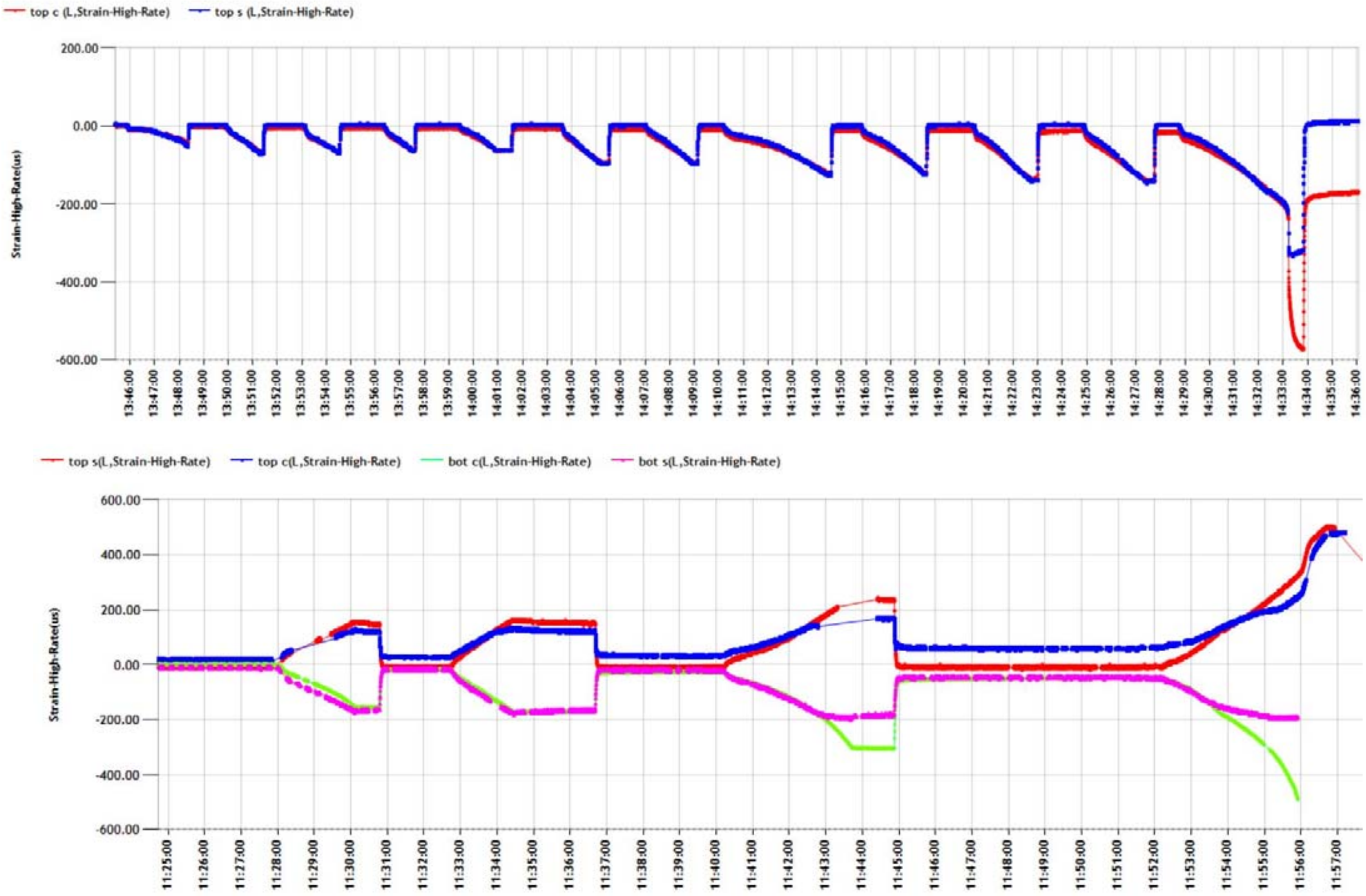


UHPC prism with embedded and surface strain gauges



ECC prism with embedded strain gauges and BDI Strain Transducer

Four-point bending test with embedded wireless strain gauges



Compression and tension zone strain variation with cycle loading from surface and embedded strain gauges

ii. Activities in Chronical order

1. 12/19/2017 – Submitted Phase 1 final report to conclude Phase 1;
2. 03/02/2018 – Received executed MOU dated 02/27/2018 and started Phase 2 officially.
3. 03/06/2018 – Finalized and delivered the specifications of Category 400 for Structures and Category 900 for Material for link slab field applications.
4. 03/23/2018 – Prepared and delivered a zip file containing specifications (2), design calculation in excel files (2), design drawings (4).
5. 05/20/2018 – conducted meeting and discussed with sensor provider, Resensys, on concrete embedment; formed strategic partner with Resensys on sensing capability embedded in concrete; conducted lab test with sensors embedded in ECC and UHPC during May-September 2018.
6. 06/29/2018 – Conducted meeting with MDTA and site visit to both CEXA27001 and CEX95200 bridges.
7. 07/16/2018 – During March-July 2018 studied and proposed link slab design on grid deck.
8. 07-18/2018 – Visited FHWA TFHRC and witnessed UHPC mixing; Obtained UHPC material and admixtures.
9. Ongoing (expected done by 09/09/18) – During May-September 2018 studied, obtained, lab tested on UHPC specimens.

iii. Upcoming Activities

1. Complete lab tests of ECC and UHPC specimens with embedded sensors.
2. Complete numerical simulation of the new pilot bridge CEX95200
3. Get sensors with wireless remote communication ready for long-term monitoring.
4. Conduct field construction of link slabs and sensor placement.
5. Conduct on-site load test with designated trucks
6. Conduct long-term remote-sensing monitoring for link slab movement and behavior.
7. Produce summary and conclusion of the project.

Attachment C

Progress Report #2 for Phase 2 - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

Report dated 03/31/2019

ATTACHMENT C

The Bridge Engineering Software and Technology (BEST) Center
Department of Civil and Environmental Engineering, University of Maryland

Invoice Progress Report
Contract #AD30310000, KFS#4300062

Progress Report #2 for Phase 2 - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

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From: C. C. Fu, Director, Ph.D., P.E. BEST Center, CEE Department University of Maryland Address: 4116 Technology Ventures Building 5000 College Ave College Park, MD 20740	Invoice No: KFS#4300062 Invoice Period: 01/01/2019-03/31/2019

Project Manager: Ruel Sabellano, P.E

Work Performed During Report Period:

The Phase II study involves the execution of the following tasks and their current status is listed herein:

Task 1– Link slab material mixing and testing

Task 2– ECC material properties

Task 3– Sensor test & recommendation

Progressive Report

of

Phase 2 - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

Revision 1

2/12/2019

By Dr. Chung C. Fu, P.E., Yifan Zhu, Kuangyuan Hou and Naiyi Li
The Bridge Engineering Software and Technology (BEST) Center
Department of Civil and Environmental Engineering, University of Maryland

The Phase II study involves the execution of the following tasks and their current status is listed herein:

Task 1– Link slab material mixing and testing

Fourteen three-point bending tests were conducted. Due to material variance, ECC mixture is updated as Table 1. Results of specimens, including ECC and UHPC, are listed in Tables 2&3.

Table 1 - Updated ECC mixture

Material	By weight
Cement	1
Fly ash (Class F)	1.2
Silica Sand (20-30 or finer)	0.8
Water	0.53
HRWR (Types A&F)	0.013
PVA Fiber	2% (by volume)

Table 2 - ECC test result

No	Compression Strength (psi)	Concrete Tensile Failure Strain	No. of Sensors
1	9,497	$500*10^{-6}$	4
2	9,497	$1200*10^{-6}$	4
3	11,597.8	N/A	1
4	11,597.8	N/A	1
5	10,927.2	$500*10^{-6}$	4
6	11,927.4	N/A	2
7	11,198.9	$700*10^{-6}$	3
8	11,927.4	$1600*10^{-6}$	2
9	11,927.4	$3100*10^{-6}$	4
10	11,198.9	$210*10^{-6}$	2
11	11,198.9	$220*10^{-6}$	4

Table 3 - UHPC test result

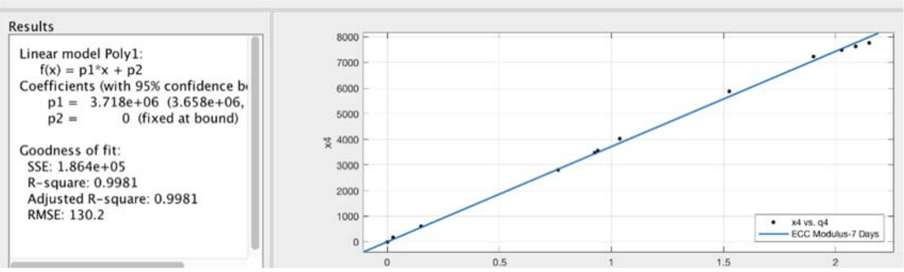
No	Compression Strength (psi)	Concrete Tensile Failure Strain	No. of Sensors
1	N/A	N/A	4
2	N/A	$1200*10^{-6}$	4
3	N/A	$250*10^{-6}$	4

Task 2– ECC material properties

To verify ECC material properties and determine their reasonable ranges for quality control, elasticity modulus, ductile performances and fine crack identifications were conducted in following cases.

2.1 ECC modulus of elasticity

This test follows ASTM C469/C469M—14 Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression to determine the modulus of elasticity (Young's) of one ECC specimen. The specimen is a 3×6 cylinder using bonded strain gauge and unbonded compressometer. The deformation and the corresponding load are recorded. The modulus of elasticity of this specimen at 7 days was calculated as approximate 3,718 ksi by curve fitting (Figure 1). Based on ECC major physical properties, the range of Young's modulus is around 2,500 ksi – 5,000 ksi (ECC Material, Structural, and Durability Performance, Victor Li, 2007).



```
Results
Linear model Poly1:
    f(x) = p1*x + p2
Coefficients (with 95% confidence b
      p1 =   3.718e+06  (3.658e+06,
      p2 =           0  (fixed at bound)

Goodness of fit:
  SSE: 1.864e+05
  R-square: 0.9981
  Adjusted R-square: 0.9981
  RMSE: 130.2
```

Figure 1 - Curve fitting method for Young’s modulus

2.2 Fine crack identification

During three-point bending test, fine cracks might form but invisible. Fine cracks are assumed as main contribution for ductile performance in ECC material. After tests, colorful pigment could be used to indicate fine cracks and crack propagation. The following pictures (Figures 2 and 3) identified fine cracks successfully.

Figure 2 - Fine cracks identification

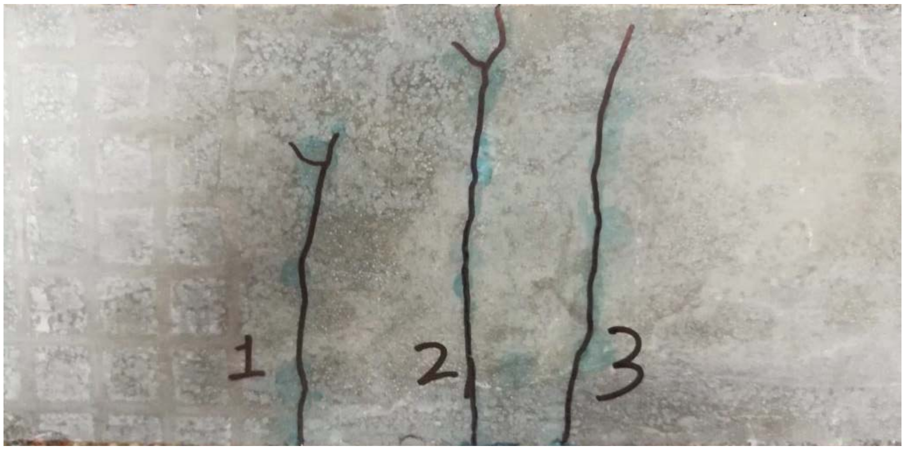


Figure 3 - Cracks propagation and distribution

2.3 ECC ductility performance

To simulate cycle loading in the field, three-point bending tests were conducted repeatedly with increasing loads. Figure 4 demonstrates the stress and strain data recorded in the test. The specimen was loaded cyclically until failure. The wave shapes of the plots correspond to five loading cycles; namely, from left to right, each peak on the graph represents the first, second, third, fourth and final loading cycle, respectively.

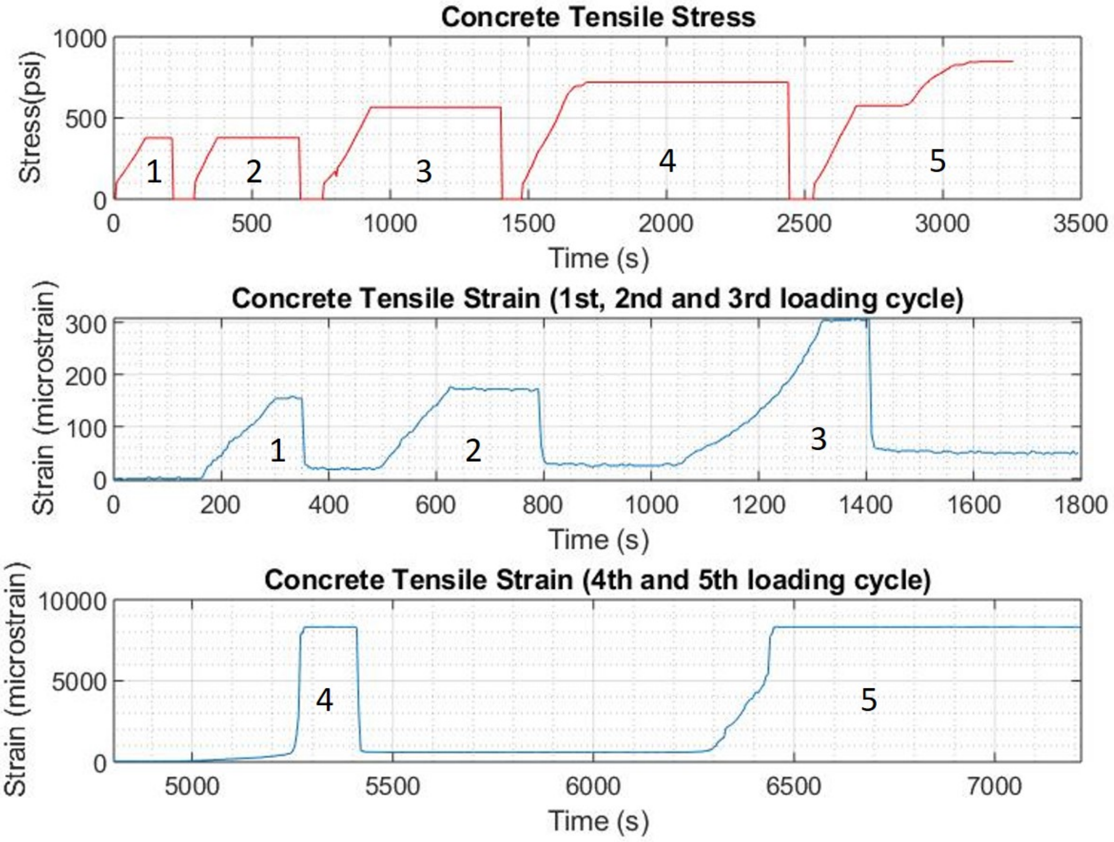
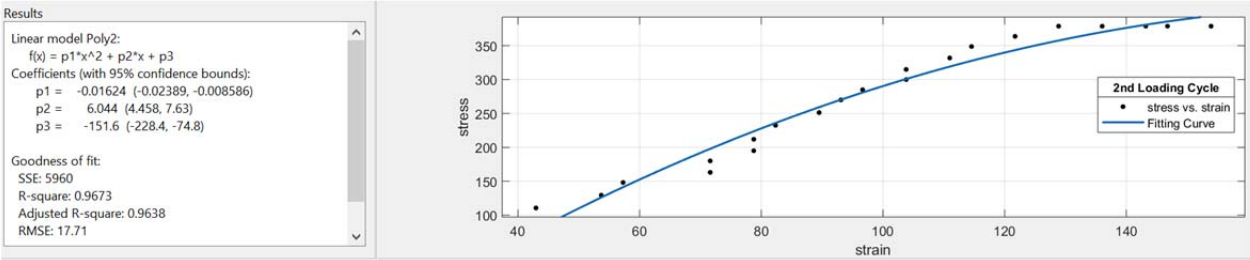


Figure 4 - Stress and strain by cyclic loading

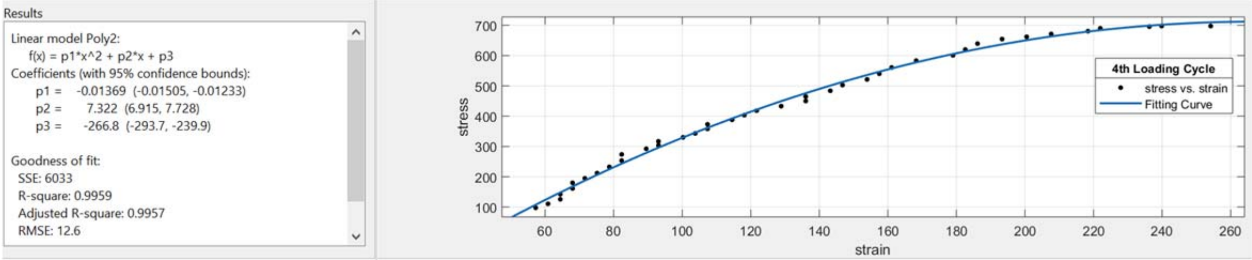
Based on experimental data, two-stage plots representing stress-strain relationship were generated by curve fitting method in Figures 5 and 6. Specifically, Figure 5 represents the stress-strain curve during which the specimen was undergoing the second loading cycle. Figure 6 shows the stress-strain relationship when the specimen was experiencing the fourth loading cycle, approaching to failure state. Comparison of the two graphs indicates that the slope of the stress-strain curve remains relatively constant in early stages (lower loading) and decreases as the specimen was approaching its failure state. Hence, it can be concluded that the ECC material was within its ductile region.



```
Linear model Poly2:
    f(x) = p1*x^2 + p2*x + p3
Coefficients (with 95% confidence bounds):
      p1 =   -0.01624  (-0.02389, -0.008586)
      p2 =      6.044  (4.458, 7.63)
      p3 =     -151.6  (-228.4, -74.8)

Goodness of fit:
  SSE: 5960
  R-square: 0.9673
  Adjusted R-square: 0.9638
  RMSE: 17.71
```

Figure 5 - Curve fitting for the 2nd loading cycle



```
Linear model Poly2:
    f(x) = p1*x^2 + p2*x + p3
Coefficients (with 95% confidence bounds):
      p1 =   -0.01369  (-0.01505, -0.01233)
      p2 =      7.322  (6.915, 7.728)
      p3 =     -266.8  (-293.7, -239.9)

Goodness of fit:
  SSE: 6033
  R-square: 0.9959
  Adjusted R-square: 0.9957
  RMSE: 12.6
```

Figure 6 - Curve fitting for the 4th loading cycle

Task 3– Sensor test & recommendation

3.1 Sensor placement and survival rate

Among 14 three-point bending tests, 35 strain gauge sensor systems were used, and 10 sensor systems failed. The survival rate of overall sensors is about 71%. To simulate field condition, strain gauges were pre-installed on a small steel plate as a sensor system shown in Figure 7 below and then the sensor system was buried during concrete pouring (Figure 8). 83% of steel plate sensor system functioned during the three-point bending test process.

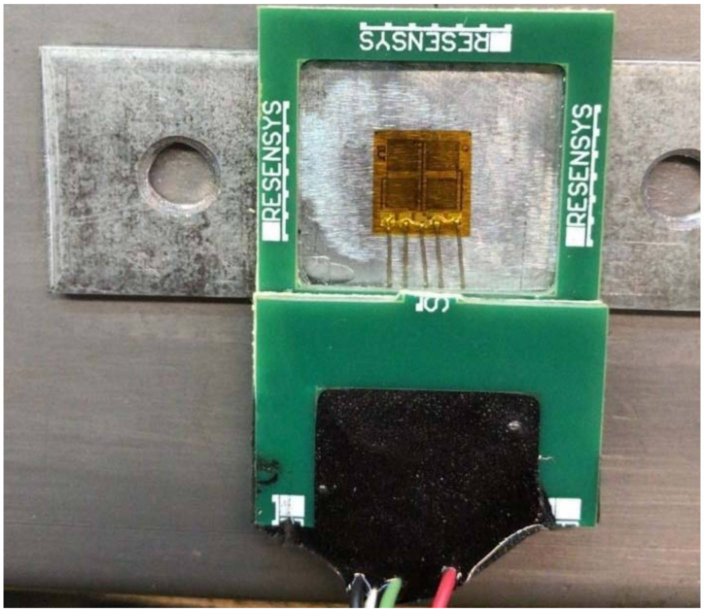


Figure 7 - Strain gauge installed on steel plate

Figure 8 - Buried sensor system after concrete pouring

3.2 Feasibility of strain gauge with steel plate in the field

Considering field construction, it is proposed here that a strain gauge could be installed on a small steel plate as a sensor system to measure concrete strain. To verify measurement from steel plate, another strain gauge is placed on concrete surface side-by-side during the three-point bending test. According to output data, measurement of compressive strain is consistent between strain gauge on concrete and installed on steel plate within the feasible measurement range.

3.3 Recommendation

The feasible measurement range mentioned above is a linear calibration relationship between concrete strain and steel plate sensor system. For compressive strain measurement, the feasible ranges of steel plate sensor system are up to $890*10^{-6}$ (UHPC) and $340*10^{-6}$ (ECC). For tensile strain measurement, the feasible ranges of steel plate sensor system are $304*10^{-6}$ (UHPC) and $200*10^{-6}$ (ECC). When concrete strain exceeds these feasible ranges, measurements from concrete surface and sensor system become diverse as shown in Figure 9. Based on strain design calculation, ultimate factored compressive strain could be covered by feasible measurement range in either UHPC or ECC. However, the ultimate factored design tensile strain of UHPC and ECC are higher than feasible measurement ranges. Regarding tensile strain above feasible measurement range, further nonlinear or multistep calibrations are needed for steel plate sensor system in order to measure higher concrete tensile strain.

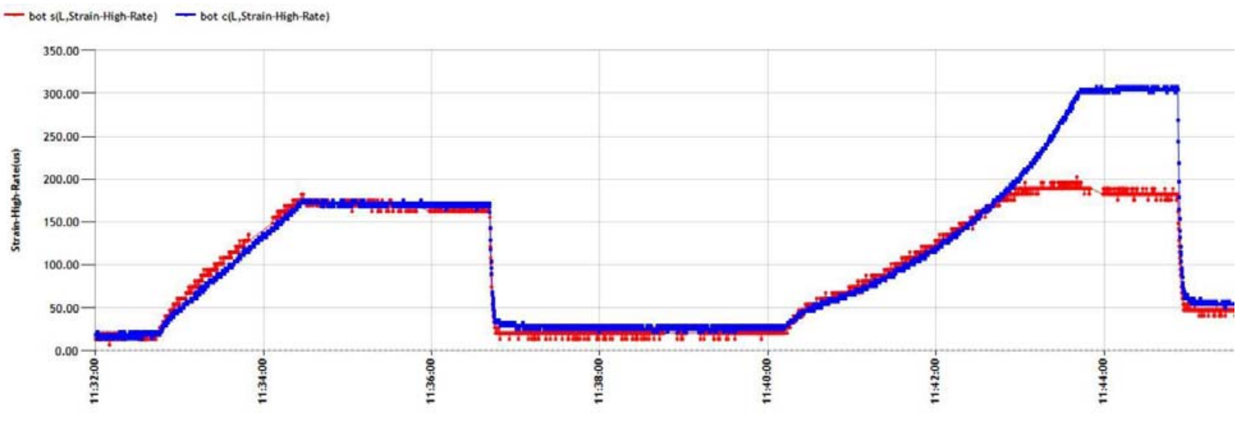


Figure 9 - Strain measurement from concrete surface vs steel plate

Attachment D

Work performed during the period of 04/01/2019 to 09/30/2019.

1. Link slab activities
2. TOs released

Report dated 10/14/2018

ATTACHMENT D

The Bridge Engineering Software and Technology (BEST) Center
Department of Civil and Environmental Engineering, University of Maryland

Invoice Progress Report
Contract #AD30310000, KFS#4300062

Progress Report #3 for Phase 2 - Field Application of Link Slab with ECC and UHPC for MDTA Steel Bridges

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From: C. C. Fu, Director, Ph.D., P.E.
BEST Center, CEE Department
University of Maryland
Address: 4116 Technology Ventures Building
5000 College Ave College Park, MD 20740

Invoice No: KFS#4300062-10

Invoice Period: 07/01/2019-09/30/2019

Project Manager: Ruel Sabellano, P.E

Work Performed During Report Period:

The Phase II study involves the execution of the tasks listed in Table 1 and TOs produced in Table 2:

Task 1– Link slab activities

Task 2– TO Releases

Attachment 1 – Test Results submitted by EA DOT (ASTMC 1202 RCP.pdf in Testing Results EA DOT.zip)

Attachment 2 - EA DOT Material 7-Day Test by UMD (MDTA_LinkslabECC_073119.mem)

Attachment 3 – 1-Day Test Results by EA DOT contracted laboratory ECS Mid-Atlantic (Curtis 1day Cube Results.pdf)

Attachment 4 –UMD updated Sensor System EA DOT Material Property Summary by UMD (MDTA_LinkslabECC_083019.mem)

Table 1 - Activities from April 1st – September 31st , 2019
(w/October activity numbers 24-30 as a continuation of the field construction started at the end of September 2019)

No.	Date	Activity
1	4/9/2019	Reply to MDTA questions on debonding membrane/gasket and ASTM-F104
2	4/10/2019	Hold link slab pilot meeting at bridge site [Field Visit]
3	4/19/2019	Submit ProgReport Linkslab_033119_revised.pdf for 01/01/2019-03/31/2019
4	4/26/2019	Submit comments on LINK SLAB_rev.pdf (as part of TO revision)
5	4/26/2019	Conference call with Dave & Les of Wallace Montgomery on deck core drill results and adjusted link slab dimensions
6	6/7/2019	Conference call w/Ruel of MDTA and consultants/contractors
7	6/14/2019	Submit Sequence of Construction_rev.pdf (related to UM's work)
8	6/19/2019	Link slab follow up meeting at 2400 Broening Highway large conference room w/Ruel of MDTA and contractors/consultants
9	06/24/2019-07/07/2019	Request several times by emails and telephone calls for EA DOT results
10	6/27/2019	Revising design for ECC link slab due to new materials form EA DOT
11	7/1/2019	Received partial testing results EA DOT.zip from EA (<u>Attachment 1</u>)
12	7/3/2019	Hold link slab conference call meeting on EA DOT w/Ruel of MDTA and consultants/contractors
13	7/12/2019	Conduct meeting with MDTA (and consultants/contractors) and Elephant Armor regarding materials at NRMCA lab, Greenbelt, MD
14	07/12/2019-08/28/2019	Conduct ECC material/sensor testing in NRMCA's lab
15	07/12/2019-09/26/2019	Conduct sensor arrangement and installation upgrading [Resensys- sensor vendor]
16	07/31/2019	Submit MDTA_LinkslabECC_073119.mem on EA DOT Material 7-Day Test conducted before 7/30/2019 (<u>Attachment 2</u>)
17	08/07/2019	Received Curtis 1day Cube Results.pdf from EA DOT contracted laboratory after error report by their previous lab in Oakland reported 7/26/2019 (<u>Attachment 3</u>)
18	08/15/2019	Revise SECTION 400.03 ECC LINK SLAB & SECTION 902.19 Link Slab Material

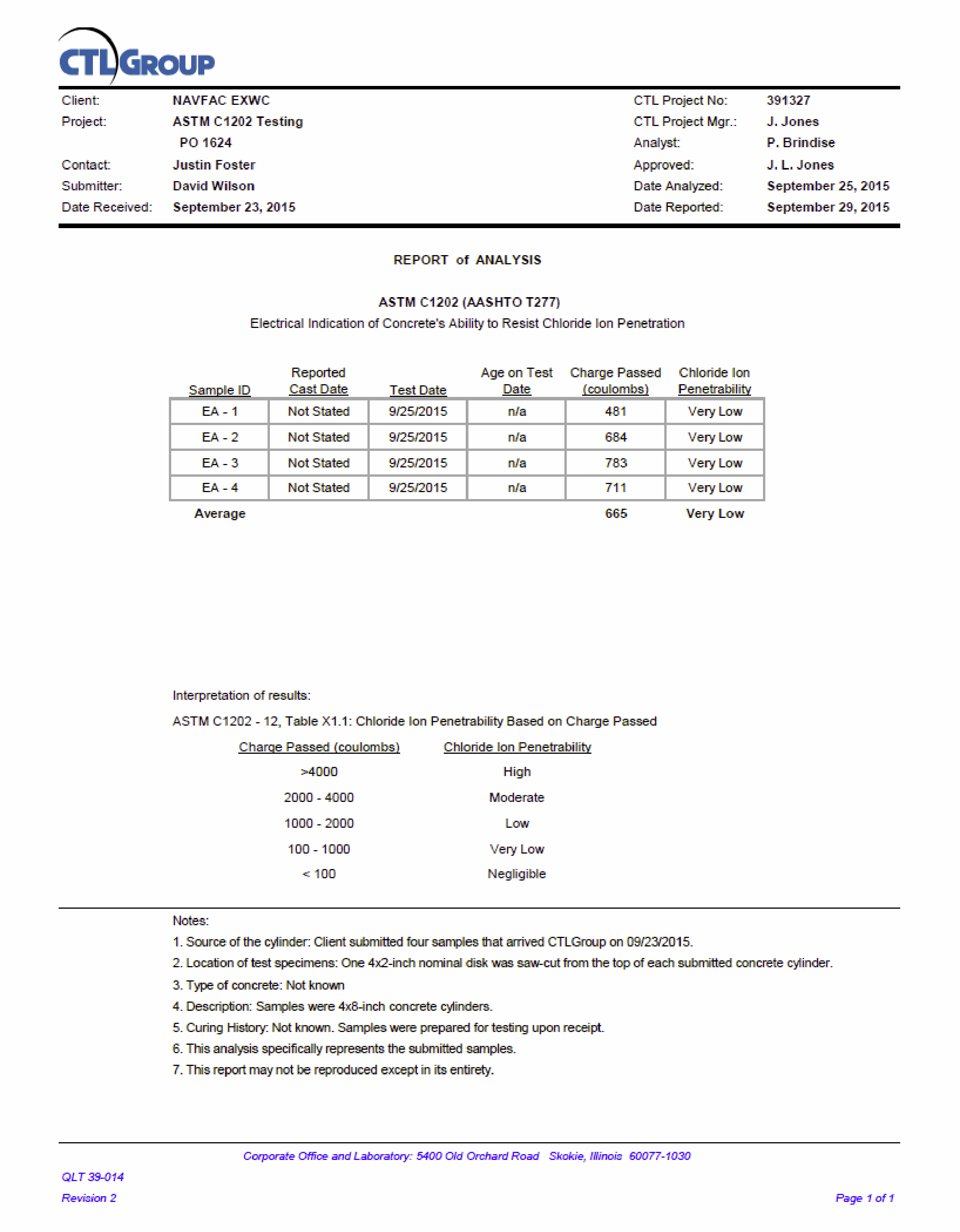
No.	Date	Activity
19	08/30/2019	Submit MDTA_LinkslabECC_083019.mem on UMD updated Sensor System EA DOT Material Property Summary (Attachment 4)
20	09/13/2019	Hold Task 1533 pre-construction meeting at 9114 Philadelphia Road. Suite #104. Rosedale, MD
21	09/26/2019	Hold sensor installation training [Resensys-sensor vendor]
22	09/27/2019	Field visit for installing accelerometers, Senimax (Gateway) with the solar panel, displacement sensor installation had been postponed until the bearing modification complete
23	09/30/2019	Start construction (previous set 09/23/2019)
24	10/02/2019	Field visit for scheduled sensor installation. Witness the construction of concrete removal for link slab. Contacted with Maurice and construction workers for leveling the remaining deck that is underneath sheet gasket
25	10/03/2019	Receive UHPC SOP_2019.pdf, UHPC QC_2019.pdf & JS1000-E.pdf from Ductal/Lafarge
26	10/03/2019	Second visit for strain gauges' installation, not complete due to construction schedule has delayed. back at 1:00pm
27	10/04/2019	Conduct strain gauges' installation for Pier 3 (UHPC), collect samples for material testing and sensor verification. Witness the UHPC pouring for Pier 3
28	10/08/2019	Release form for UHPC samples and sent to Resensys for strain gauges' installation
29	10/09/2019	Conduct strain gauges' installation for Pier 1 (ECC), collect samples for material testing and sensor verification. Witness the ECC pouring for Pier 1 and 2
30	10/09/2019 (afternoon)	Carry ECC samples sent to NRMCA's lab

Table 2 – TO Releases (from 06/01/2018-08/16/2019 where items 1-4E for the early period)

TO_1533	Date	File Name	Note
1	06/01/2018	TO_1533 DRAFT_0529	1st Draft for TO_1533, Bridge:CEXA27001
2	10/20/2018	TO_1533_Optimized_1015	2nd Draft, Bridge changed to CEX952001
		ESTIMATE_Draft	
		ESTIMATE	
3	11/23/2018	TO_1533_1031	1st TO_1533
4	02/12/2019	TO_1533_FINAL_0208	Detour plan updated
4A		ESTIMATE_Final	
4B	04/24/2019	LINK SLAB plan revised	plan revised
4C	04/30/2019	TO 1533 Redline bearing revised	bearing modification revised
4D	06/28/2019	TO 1533 Redline_Revised Page 1 and 3_removal revised	Removal width revised
4E		TO_1533_FINAL_page6_ECC width revised	ECC width revised
4F	07/02/2019	TO 1533 Redline 2_Optimized_REPLACE COMPRESSION SEAL JOINTS AND MODIFY BEARINGS	REPLACE COMPRESSION SEAL JOINTS AND MODIFY BEARINGS
5	08/13/2019	Task Order 1533R2_Final_0813	Revised ECC link slab, bearing modification, sensors info provided, Sensors and overlay added in spec
5A	08/15/2019	Link Slab specs_ECC revised	ECC spec revised
6	08/16/2019	Task Order 1533 Redline 2_0816	ECC material updated

TO_1533 file: 6
Estimate: 3
Page revised: 6

Attachment 1 – Test Results submitted by EA DOT (ASTMC 1202 RCP.pdf in Testing Results EA DOT.zip)



CTLGROUP

Client:	**NAVFAC EXWC**	CTL Project No:	**391327**
Project:	**ASTM C1202 Testing**	CTL Project Mgr.:	**J. Jones**
	PO 1624	Analyst:	**P. Brindise**
Contact:	**Justin Foster**	Approved:	**J. L. Jones**
Submitter:	**David Wilson**	Date Analyzed:	**September 25, 2015**
Date Received:	**September 23, 2015**	Date Reported:	**September 29, 2015**

REPORT of ANALYSIS

ASTM C1202 (AASHTO T277)

Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

Sample ID	Reported Cast Date	Test Date	Age on Test Date	Charge Passed (coulombs)	Chloride Ion Penetrability
EA - 1	Not Stated	9/25/2015	n/a	481	Very Low
EA - 2	Not Stated	9/25/2015	n/a	684	Very Low
EA - 3	Not Stated	9/25/2015	n/a	783	Very Low
EA - 4	Not Stated	9/25/2015	n/a	711	Very Low
Average				**665**	**Very Low**

Interpretation of results:

ASTM C1202 - 12, Table X1.1: Chloride Ion Penetrability Based on Charge Passed

Charge Passed (coulombs)	Chloride Ion Penetrability
>4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very Low
< 100	Negligible

Notes:

1. Source of the cylinder: Client submitted four samples that arrived CTLGroup on 09/23/2015.
2. Location of test specimens: One 4x2-inch nominal disk was saw-cut from the top of each submitted concrete cylinder.
3. Type of concrete: Not known
4. Description: Samples were 4x8-inch concrete cylinders.
5. Curing History: Not known. Samples were prepared for testing upon receipt.
6. This analysis specifically represents the submitted samples.
7. This report may not be reproduced except in its entirety.

Corporate Office and Laboratory: 5400 Old Orchard Road Skokie, Illinois 60077-1030

QLT 39-014

Revision 2

Page 1 of 1

Attachment 2 - EA DOT Material 7-Day Test by UMD (MDTA_LinkslabECC_073119.mem)

The BEST Center
Civil and Environmental Department
University of Maryland
College Park, MD 20742

Memo

To: Mr. Ruel Sabellano, P.E. & Mr. Hua Sheng He, P.E.
Maryland Transportation Authority
Office of Engineering and Construction

From: C. C. Fu, Ph.D., P.E., Director and Research Professor
(Tel: 301-405-2011; ccfu@umd.edu)
CC: Les Komar, P.E.
Wallace Montgomery

Date: 10/14/2019
Re: EA DOT Material 7-Day Test conducted on 7/30/2019

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1. EA DOT Material 7-Day Test Summary:

Test	Number
Compression	7
Flexure	2
Modulus	2
Sensor Test	4

2. Compression Strength (ASTM C39):

Curing Day	Sample Size (in)	Result (psi)
3	3X6	6926*
7	4X8	6920*
7	3X6	5305
7	3X6	5646
7	3X6	5646
7	3X6	5851
7	3X6	5859
7 Day Avg		6008

*Not moist cured

3. Modulus (ASTM C469):

Curing Day	Sample Size (in)	Result (ksi)
7	4X8	1181.3
7	4X8	1087.2
Avg		1134.2

4. Flexure Strength (ASTM 1609):

Curing Day	Sample size (in)	Yield Strength (psi)
7	4X4X14	815.0
7	4X4X14	802.5
Avg		808.8

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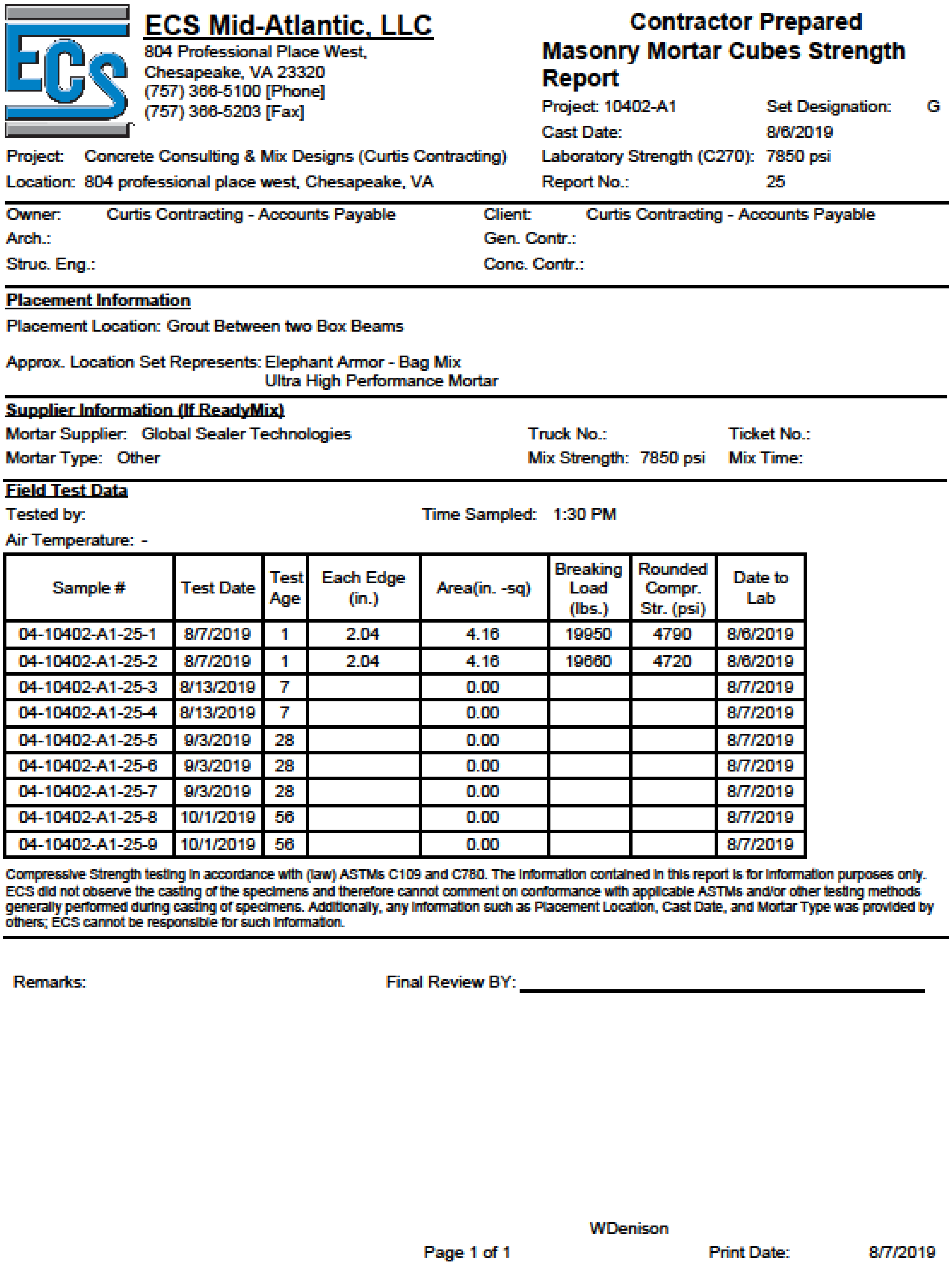
Attachment 3 – 1-Day Test Results by EA DOT contracted laboratory (Curtis 1day Cube Results.pdf)



ECS Mid-Atlantic, LLC
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Contractor Prepared Masonry Mortar Cubes Strength Report

Project: 10402-A1	Set Designation: G
Cast Date:	8/6/2019
Laboratory Strength (C270):	7850 psi
Report No.:	25

Project: Concrete Consulting & Mix Designs (Curtis Contracting)
Location: 804 professional place west, Chesapeake, VA

Owner:	Curtis Contracting - Accounts Payable	Client:	Curtis Contracting - Accounts Payable
Arch.:		Gen. Contr.:	
Struc. Eng.:		Conc. Contr.:	

Placement Information

Placement Location: Grout Between two Box Beams

Approx. Location Set Represents: Elephant Armor - Bag Mix
Ultra High Performance Mortar

Supplier Information (If ReadyMix)

Mortar Supplier: Global Sealer Technologies	Truck No.:	Ticket No.:
Mortar Type: Other	Mix Strength: 7850 psi	Mix Time:

Field Test Data

Tested by: Time Sampled: 1:30 PM
Air Temperature: -

Sample #	Test Date	Test Age	Each Edge (in.)	Area(in. -sq)	Breaking Load (lbs.)	Rounded Compr. Str. (psi)	Date to Lab
04-10402-A1-25-1	8/7/2019	1	2.04	4.16	19950	4790	8/6/2019
04-10402-A1-25-2	8/7/2019	1	2.04	4.16	19660	4720	8/6/2019
04-10402-A1-25-3	8/13/2019	7		0.00			8/7/2019
04-10402-A1-25-4	8/13/2019	7		0.00			8/7/2019
04-10402-A1-25-5	9/3/2019	28		0.00			8/7/2019
04-10402-A1-25-6	9/3/2019	28		0.00			8/7/2019
04-10402-A1-25-7	9/3/2019	28		0.00			8/7/2019
04-10402-A1-25-8	10/1/2019	56		0.00			8/7/2019
04-10402-A1-25-9	10/1/2019	56		0.00			8/7/2019

Compressive Strength testing in accordance with (law) ASTMs C109 and C780. The information contained in this report is for information purposes only. ECS did not observe the casting of the specimens and therefore cannot comment on conformance with applicable ASTMs and/or other testing methods generally performed during casting of specimens. Additionally, any information such as Placement Location, Cast Date, and Mortar Type was provided by others; ECS cannot be responsible for such information.

Remarks: Final Review BY: ____________________

WDenison

Attachment 4 –UMD updated Sensor System EA DOT Material Property Summary (MDTA_LinkslabECC_083019.mem)

The BEST Center
Civil and Environmental Department
University of Maryland
College Park, MD 20742

Memo

To: Mr. Ruel Sabellano, P.E. & Mr. Hua Sheng He, P.E.
Maryland Transportation Authority
Office of Engineering and Construction

From: C. C. Fu, Ph.D., P.E., Director and Research Professor
(Tel: 301-405-2011; ccfu@umd.edu)
CC: Les Komar, P.E.
Wallace Montgomery

Date: 10/14/2019
Re: UMD updated Sensor System EA DOT Material Property Summary

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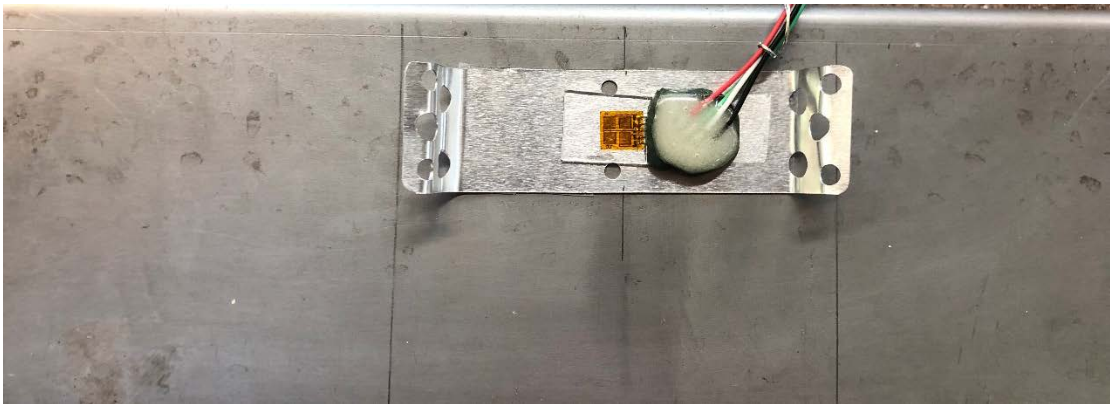
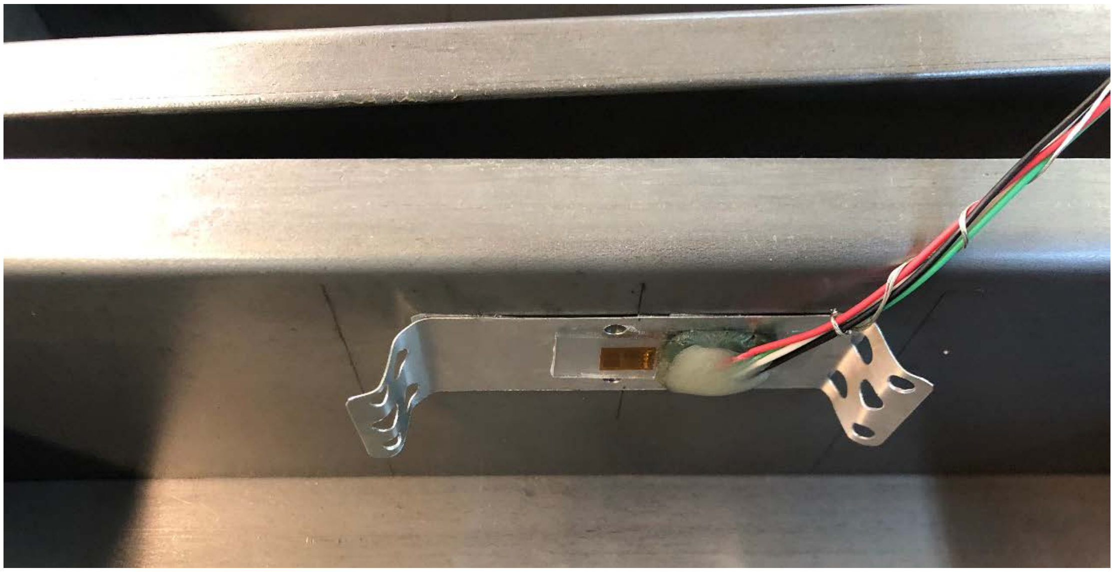
UMD updated sensor system

The new sensor is designed as table-shape with few small holes that avoid blocking concrete along cross section shown in Figs. 1&2. The strain detected by updated sensor system is consistent with strain detected by concrete surface before nonreversible deformation. The sensor system could stably detect strain up to $350*10^{-6}$ shown in Figs. 3&4 which cover FEM truck load simulation result. When applied load is higher than 4000 lbs, nonreversible deformation occurs. The nonreversible deformation might be fine cracks which are invisible but successfully detected by sensor system. While fine cracks form and concrete performs in ductile, sensor system could consistently detect strain up to $1000*10^{-6}$ in our best case shown in Fig. 4.





Figs.1 & 2 Updated Sensor System pre-installed before concrete mixing

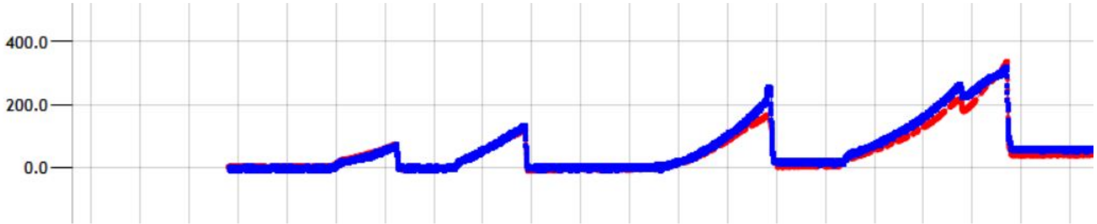


Fig. 3 Fine cracks occur after 4th cyclic loading

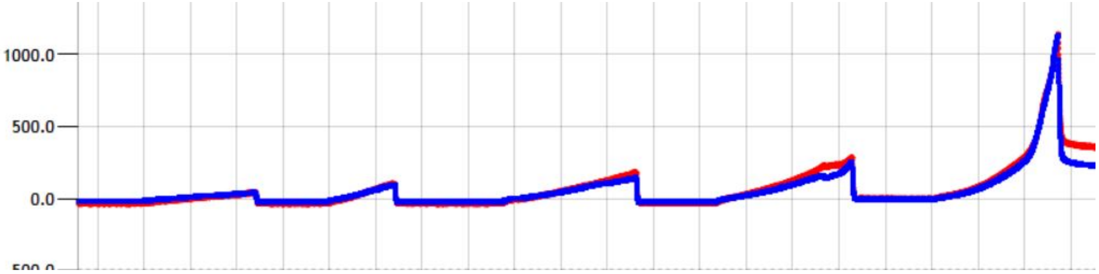


Fig. 4 Sensor system successfully detects strain up to 1000*10^-6

EA DOT material property summary

	7 days		28 days	
	Dry curing	Moist curing	Dry curing	Moist curing
Modulus	1181.32 (ksi)		1252.47 (ksi)	1322.65 (ksi)
	1087.24 (ksi)			
Compression	6000 (psi)		7580 (psi)	6646 (psi)

The conclusions are

(1) regarding curing conditions with standard indoor temperature, it shows not much difference between moist curing and dry curing in the elastic range.

(2) the EA DOT is rapid set in the early stage.
(3) the material has low modulus with moderate compression strength.
(4) moist curing might decrease the compression strength at the same curing period while the ductility of material might increase (**not verified**)
(5) The main concern is the test result provided by EA company shows their modulus is 2207.5 ksi.

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