INNOVATIVE USE OF ULTRA HIGH PERFORMANCE CONCRETE TO ENHANCE THE PERFORMANCE OF BRIDGE INFRASTRUCTURE

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Bridge Infrastructure Overview

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- The numbers:
  - Nation's bridge inventory: 671,000
  - Average bridge age: 44 years (service life of 50 years)
  - Number of structurally deficient bridges: 46,154
  - Functionally obsolete bridges: 94,000
  - Average daily trips over structurally deficient bridges: 178 millions

Source: ASCE infrastructure report card (https://infrastructurereportcard.org/wp-content/uploads/2020/12/Bridges-2021.pdf)

Bridge Infrastructure Overview

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- The problem:
  - Structurally deficient bridges present higher risk for closure or weight restriction.
  - Several older bridges are reaching the end of their service life and are more susceptible to extreme weather events.
  - Overstressed elements from heavier truck loading
- Urgent need of rehabilitation or complete replacement of multiple bridges across the nation

Advances in Concrete Technology

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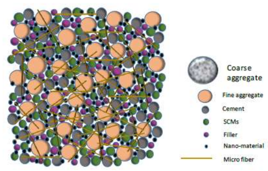
- UHPC as a solution to the rehabilitation and replacement of deteriorated bridges
- UHPC: class of concretes with high mechanical and durability properties
- General characteristics (Graybeal 2014)
  - $f_c' \geq 21.7$ ksi
  - $w/c < 0.25$
  - Sustained post-cracking tensile strength > 0.72 ksi

Typical UHPC Mix Composition

- UHPC Typical Constituents
  - **Binders/Supplemental Cementitious Materials (SMCs)**
    - Cement
    - Slag
    - Silica fume
    - Fly ash
  - **Aggregates**
    - Silica sand
    - Ground quartz
  - **High Range Water Reducer Admixtures) (HRWRAs)**
  - **Fibers**



Ribeiro (2019)

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Benefits of UHPC

- UHPC engineering and durability properties
  - Low porosity
  - High freeze-thaw resistance
  - Higher post-cracking tensile strength
  - No alkali-silica reaction
  - Improved control of deck cracking
  - Reduced penetration of chloride ions into the bridge deck

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UHPC Durability Properties

Table 2. Durability properties of UHPC compared to HPC and NC

Parameter	UHPC	HPC Value	HPC Ratio to UHPC	NC Value	NC Ratio to UHPC
Salt Scaling Mass Lost (28 cycles)	0.010 lb/ft²	0.031 lb/ft²	3.0	0.31 lb/ft²	30
Chloride Ion Diffusion Coefficient	2.2×10^{-13} ft²/s	6.5×10^{-12} ft²/s	30	1.2×10^{-11} ft²/s	55
Chloride Ion Penetration Depth	0.04 in.	0.32 in.	8	0.91 in.	23
Chloride Ion Permeability Total Charge Passed	10 – 25 coulombs	200 – 1000 coulombs	34	1800 – 6000 coulombs	220
Carbonation Depth (3yrs.)	0.059 in.	0.16 in.	2.7	0.28 in.	4.7
Reinforcement Corrosion Rate	4×10^{-7} in./yr	9.8×10^{-6} in./yr	25	4.7×10^{-5} in./yr	120
Abrasion Resistance Relative Vol. Loss Index	1.1 – 1.7	2.8	2.0	4.0	2.9
Resistivity	53.9 kΩ·in.	37.8 kΩ·in.	0.70	6.3 kΩ·in.	0.12

Compiled based on data presented by Lee et al. 2005, Schmidt and Fehling 2005, Roux et al. 1996, Bonneau et al. 1997, Schmidt et al. 2003, Vernet 2004, VSL Proprietary Limited 2003, and Perry and Zakariasen 2004

NC: Normal Concrete
HPC: High Performance Concrete
UHPC: Ultra High Performance Concrete

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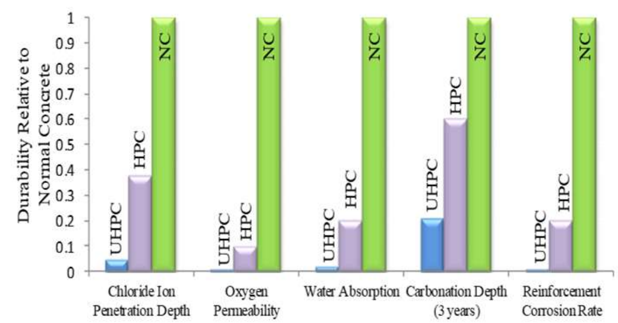
UHPC Durability Properties



NC: Normal Concrete
HPC: High Performance Concrete
UHPC: Ultra High Performance Concrete

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Applications

- UHPC has been used in various structural applications
  - Bridge deck overlays/strengthening
  - Joints between precast bridge elements
  - Pile foundations
  - Waffle slabs
- Accelerated Bridge Construction (ABC)
  - Efficient and lightweight precast modular section
  - Rapid closure pour between adjoining elements

UHPC Knowledge Gaps to Close

- Fatigue behavior of UHPC
- Punching shear strength
- Long-term durability of bond between overlay and existing deck
  - Freeze-thaw cycle effects consideration

Research Efforts at ISU

- The state of California owns and maintains over 7,000 box-girder bridges.
- Many of them have damaged decks from heavier traffic loads and harsh environmental conditions.
  - Concrete fatigue
  - Freeze-thaw damage
  - Punching failure
- Project objective: **Develop a suitable methodology to rehabilitate and strengthened box-girder bridges**

Material Characterization

- Evaluation includes four different UHPC overlay mixes
- Experimental program consists of:
  - Compressive strength test
  - Slope test
  - Interfacial shear strength test including freeze-thaw effects
  - Long-term properties evaluation including creep and shrinkage
- Experimental work to be implemented following appropriate standards

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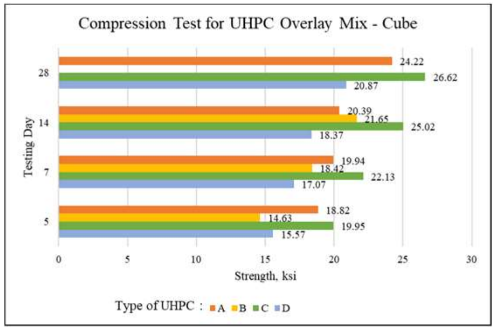
Material Characterization

- Compression test
  - Cube specimens



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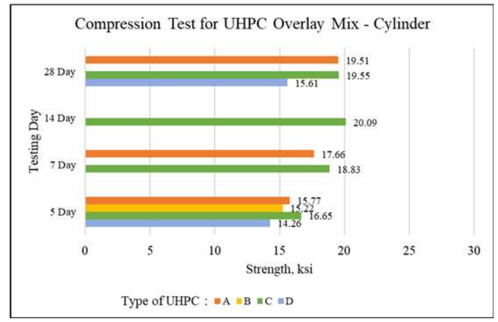
Material Characterization

- Compression test
  - Cylinder specimens



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Material Characterization

- Slope test
  - Conducted on a 24 inch x 12 inch slab with a roughened surface and inclined at 7% slope
  - After mixing, the UHPC is placed on the slab with temporary wood forms to achieve the target overlay thickness.
  - After a few minutes of waiting time, forms are removed and displacement of the UHPC is observed.

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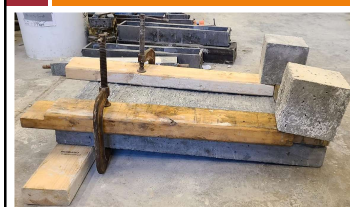
Mix Performance: Slope Test

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Mix Performance: Flow Test

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Mix Performance: Flow Test

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Finite Element Modelling

- Investigate the effects of full and partial deck thickness removal and replacement on local/global structural behavior of box-girders
- Evaluate various demolition/reconstruction sequences depending on bridge type
- Predict short- and long-term performance of rehabilitated decks

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Prototype Bridges

- A simply supported bridge
  - 120-feet span
- A two-span continuous straight bridge
  - Span lengths of 207.5 ft and 210.5 ft
- A three-span curved bridge
  - Span lengths of 125, 180, and 155 ft and radius of 1165 ft
- A three-span skewed bridge
  - Span lengths of 51, 132, and 51 ft and skew of 59.41°

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Task 4: Finite Element Modelling

- CSiBridge
  - Shell elements for box-girder and diaphragms
  - Tendon elements for posttensioning steel
  - Frames elements for columns
  - Link elements for support bearings and foundations
- Time-dependent properties: CEB-FIP Model Code 1990

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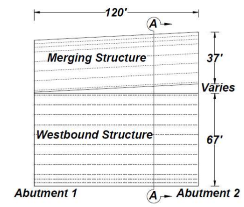
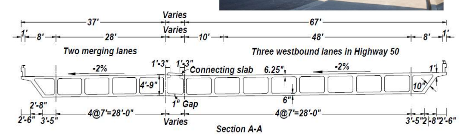
Simply Supported Bridge Model

- 26th Street Undercrossing located in Sacramento, CA
- Northern structure includes 3 westbound lanes and 2 merging lanes and southern structure consists of 4 eastbound lanes.
- Transverse replacement sequence only



(a) Plan



(b) Cross-section

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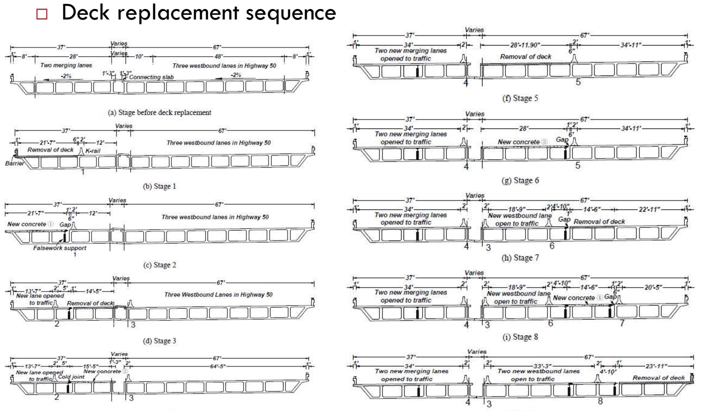
Simply Supported Bridge Model

- Deck replacement sequence



(a) Stage before deck replacement
(b) Stage 1
(c) Stage 2
(d) Stage 3
(e) Stage 4
(f) Stage 5
(g) Stage 6
(h) Stage 7
(i) Stage 8
(j) Stage 9

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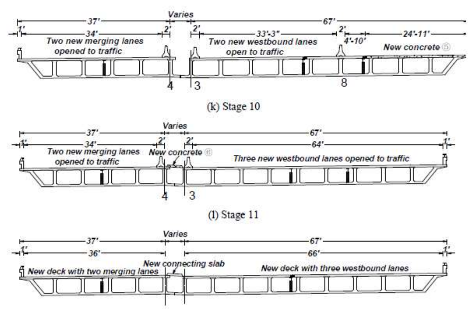
Simply Supported Bridge Model

- Deck replacement sequence



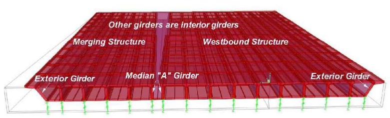
(k) Stage 10
(l) Stage 11
(m) Stage 12

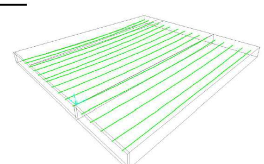
Simply Supported Bridge Model

- f'c = 4600 psi
- Post-tensioning force parameters

Girder type	Median "A" girder	Interior girder	Exterior girder
Target prestressing force (kips)	1210	1131	800
Jacking force (kips)	1322.5	1242	903.5

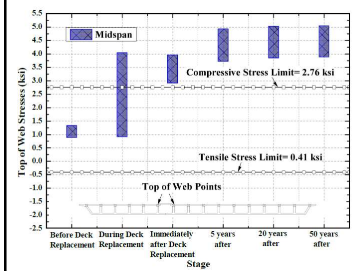
Prestressing loss type	Instantaneous losses				Time-dependent losses		
	Curvature coefficient	Wobble coefficient (/ft)	Anchorage set slip (in)	Elastic shortening stress (ksf)	Creep (ksf)	Shrinkage (ksf)	Steel relaxation (ksf)
Value	0.2	0.002	0.375	0	0	0	0



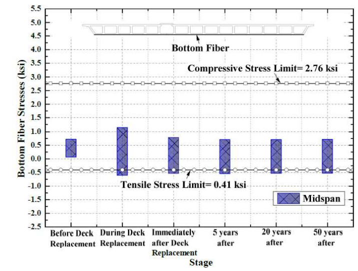


Simply Supported Bridge Model

- Full-depth deck replacement analysis results



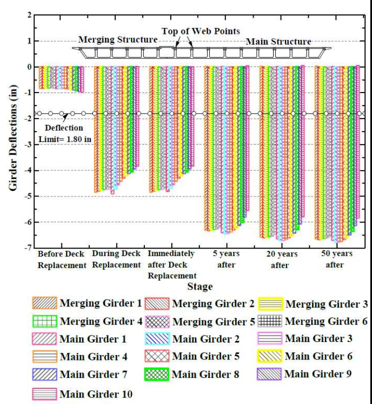
Top of Web Stresses



Soffit Stresses

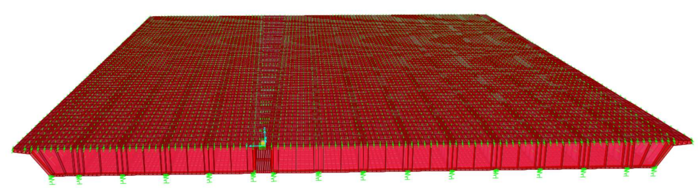
Simply Supported Bridge Model

- Full-depth deck replacement analysis results
- Deflections increased by as much as 400% and 550% immediately and 50 years after rehabilitation, respectively.



Simply Supported Bridge Model

- Partial deck thickness removal/reconstruction as a solution to excessive deflections and stresses
- Implementation of partial deck removal using superposed slabs connected rigidly connected with links
- Evaluate effects of different removal thicknesses on bridge condition



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Simply Supported Bridge Model

- Removal of 0.25 inch with replacement thickness of 1.5 inches
  - 25 to 29% increase in deck top stresses
  - 41 to 48% increase in deflections
- Removal of 1.25 inch with replacement thickness of 1.5 inch
  - 27 to 32% increase in deck top stresses
  - 42 to 49% increase in deflections

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Two-span Continuous Straight Bridge Model

- Route 113/5 Separation Structure located in Woodland, CA and constructed in 1973

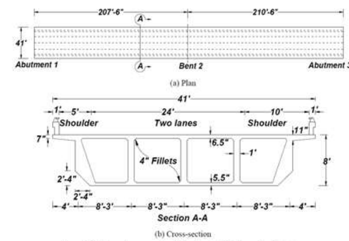

Figure 2.2 Plan and cross-section of the Route 113/5 Separation Structure

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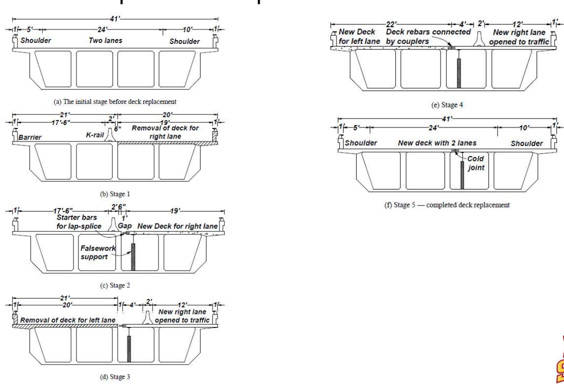
Two-span Continuous Straight Bridge Model

- Transverse replacement sequence



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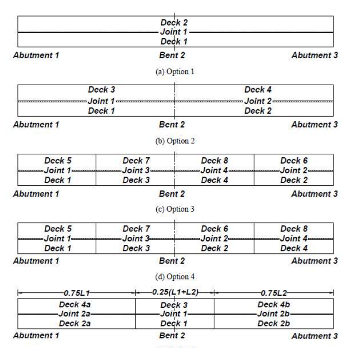
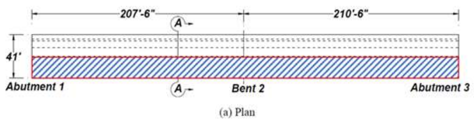
Two-span Continuous Straight Bridge Model

- Longitudinal replacement sequence

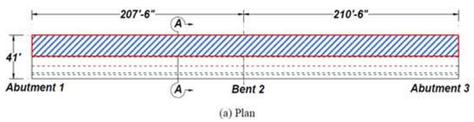


Two-span Continuous Straight Bridge Model

- Transverse deck replacement sequence



Step 1 & 2

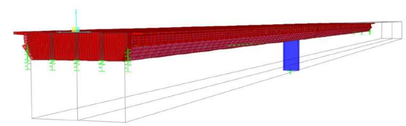


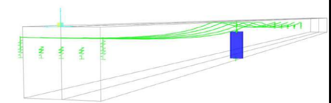
Step 3 & 4

Two-span Continuous Straight Bridge Model

- f'c = 4700 psi
- Post-tensioning force of 3260 kips in each girders

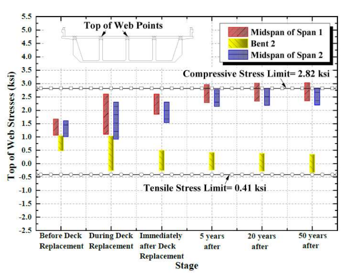
Prestressing loss type	Instantaneous losses				Time-dependent losses		
	Curvature coefficient	Wobble coefficient (/ft)	Anchorage set slip (in)	Elastic shortening stress (ksf)	Creep (ksf)	Shrinkage (ksf)	Steel relaxation (ksf)
Value	0.2	0.0002	0.375	0	0	0	0





Two-span Continuous Straight Bridge Model

- Full-depth deck replacement analysis results



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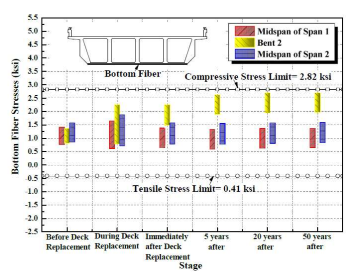

Soffit Stresses

Two-span Continuous Straight Bridge Model

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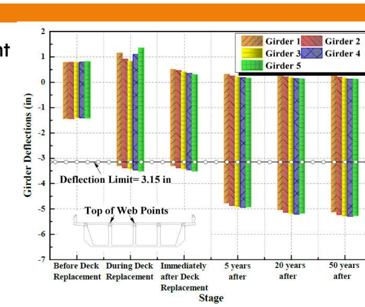

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Ongoing Tasks

- Experimental testing under preparation
  - Creep and shrinkage
  - Freeze-thaw
  - Tensile and compression strength
- Experimental testing
  - Half scale unit anticipated to include 3 cells
  - Positive and negative bending moments to be considered
    - Fatigue load cycles
    - Punching failure
    - Ultimate strength

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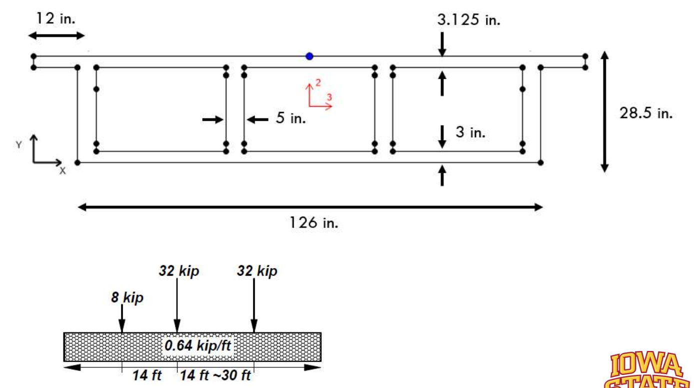
Preliminary Test Unit Design



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Questions/Comments