Accelerated Bridge Construction Link Slabs

Material Tailoring and Structural Response

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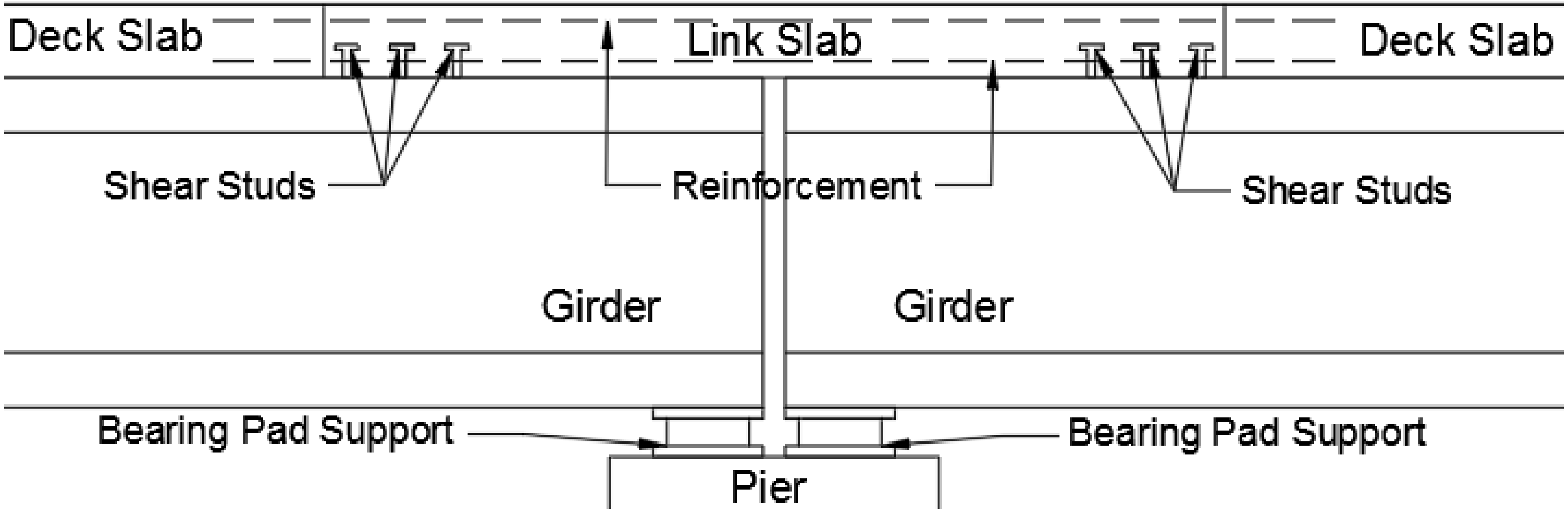
Outline of Presentation

- Introduction
- Link Slab Materials
  - Conventional Fiber Reinforced Concrete
  - Engineered Cementitious Composite
  - Conclusions + Future Work
- Case Study Link Slab Bridge
  - Details
  - Results
  - Conclusions + Future Work

Introduction – Link Slabs

- **Expansion joints leak and cause pre-mature corrosion of the underlying girders and substructure, decreasing the service life of the bridge**
- **Link Slabs replace intermediate expansion joints over piers with a continuous deck system, while the underlying girders remain discontinuous**

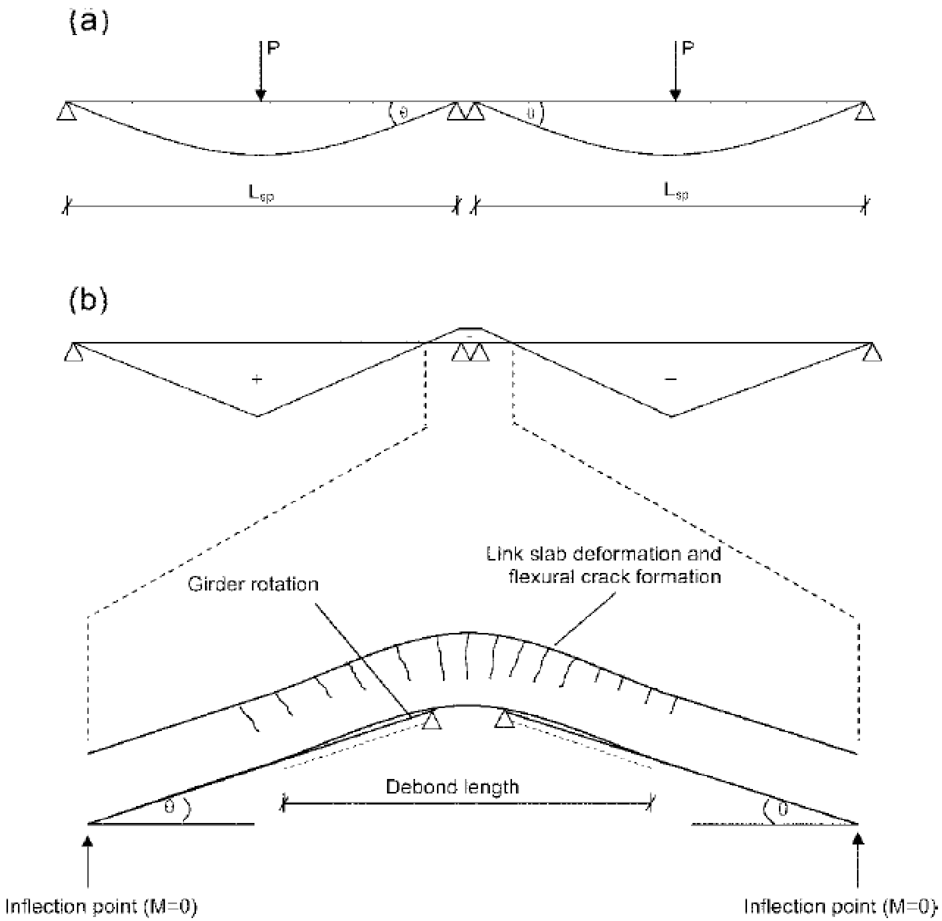


Introduction – Link Slabs

- **Although most new designs avoid intermediate expansion joints, some designs cannot avoid them for which link slabs may be a strong option**
  - Accelerated Bridge Construction pre-cast designs
  - Long bridges where thermal movement cannot be accounted for by integral abutments or expansion joints near abutments alone
  - Existing simple span bridges
- **The structural configuration of a link slab places a combination of thermal and live load induced stresses and strains on the link slab**
  - ✓ Girder end rotations from live loads
  - ✓ Axial deformation from thermal gradient expansion and contraction encountered in the superstructure
  - ❖ No dead load stress/strain since link slab is placed last

Introduction – Link Slabs

- **Girder end rotations from live load cause negative flexure in the link slab, causing tensile stress on the exposed deck surface**
- **AASHTO crack width criteria must be satisfied**
  - Large amount of rebar
  - Fiber reinforced concrete material tailoring
- **Thermal contraction of superstructure adds to tensile stress in the link slab**



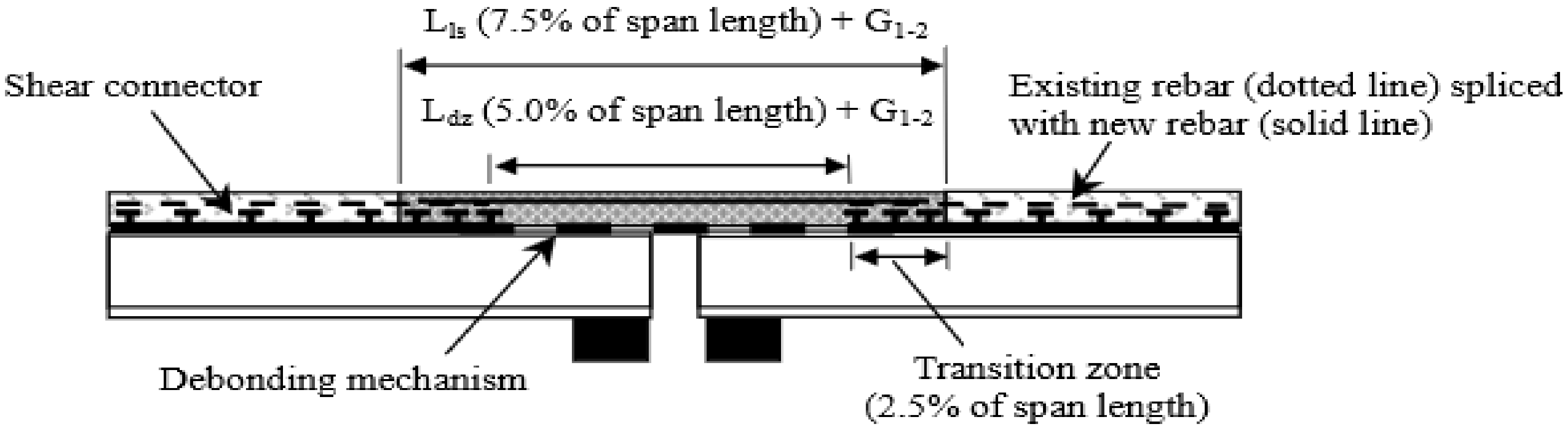
Caption from Kim, Fischer, Li, (2004)

Introduction – Link Slabs

- **Link slabs fill the free space provided by intermediate expansion joints, but the superstructure will still expand and contract under thermal variation**
- **Due to the absence of free space for thermal movement and depending on the relative stiffness of the link slab:**
  - Additional stress can develop in the superstructure and substructure under thermal and live loads
  - These stresses must be considered in design to avoid damage to the bridge
  - Link slab design with low stiffness and high ductility would minimize these effects

Introduction – Existing Link Slab Design

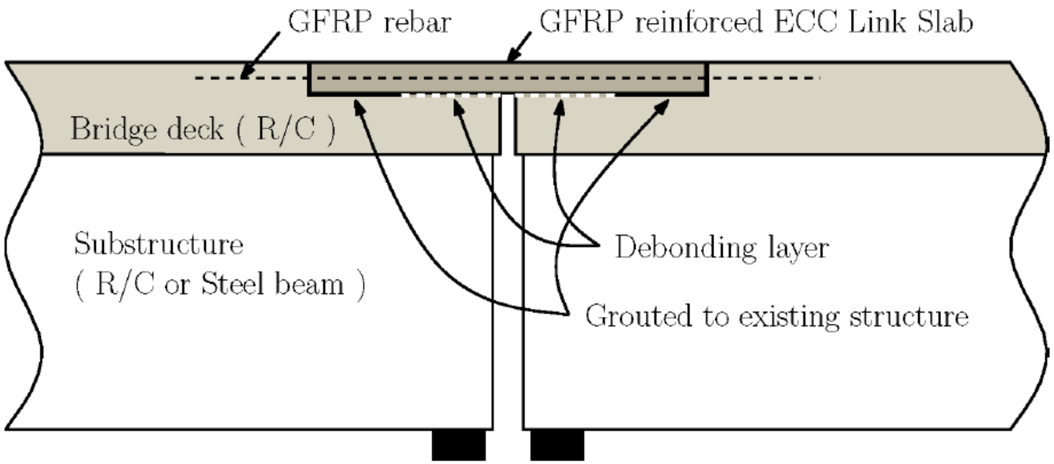
- **Full depth link slabs**
  - De-bonded zone ≈ 5% of adjacent span length
    - Avoid stress concentrations
  - Transition Zone ≈ 2.5% of adjacent span length
    - Increased shear stud concentration for anchorage
  - Continuous top and bottom link slab reinforcement



Caption from Lepech & Li, 2005

Introduction – Existing Link Slab Design

- **Partial depth link slabs – low relative stiffness**
  - De-bonded zone ≈ 5% of adjacent span length
    - Avoid stress concentrations
  - Flexible Engineered Cementitious Composite (ECC) material
    - Thin section less intrusive to global structure
    - Install in such manner to avoid compression buckling
  - Possible pre-cast applications
  - Possible use of Glass Fiber Reinforced Polymer (GFRP) rebar



Caption from Larusson (2013)

Link Slab Materials

- **Ongoing research focuses on ABC link slabs**
- **Desirable Material Properties**
  - High early strength for cast-in-place materials
  - Control crack widths (<0.33 mm) at high strains induced by girder end rotations from live loads and axial deformations caused by thermal movement of the superstructure
  - Durability – Long term performance and corrosion resistance
  - Material properties that are contractor friendly for consistent material performance
    - Adequate workability
    - Simple concrete mixing regime that is easily reproducible
- **Question: Which market available synthetic concrete fiber can provide the highest post crack toughness in FRC without being detrimental to workability?**

Link Slab Materials

Conventional FRC – Contractor Friendly Cast-in-place ABC link slab Material

- Most suited for cast-in-place full depth link slabs
- Similar to previous RC link slabs, but fiber is added to the mix in order to control cracking and improve tensile properties
- Small (3/8”) maximum size aggregate and increased paste content to maximize workability and fiber reinforcing effectiveness
- Need high early age strength for ABC criteria
- Higher fiber content will increase performance but sacrifice workability and economy
- Find balance between fresh properties, performance, and economy
- Literature review and survey of the concrete fiber market resulted in the flexural testing of 4 synthetic fibers for their contribution to residual strength and toughness of FRC, indicating their relative tensile performance

Link Slab Material – Conventional FRC

Investigation 1 - which type of selected synthetic fiber can provide the best ductility and toughness to an FRC mix when subject to tensile stress.

- High Strength Polyethylene (HSPE)
- Polyvinyl Alcohol (PVA)
- Basalt (BSLT)
- Polypropylene (PP)

Cement	Fly Ash	Coarse Agg.	Fine Agg.	Water	Water Reducer	Fiber (% Vol.)
593	254	1548	1266	322	Varied	0.5%-1.5%

Base Mix Design

- Paste + water reducer added for each mix to maintain workability

Link Slab Material – Conventional FRC

Fiber Parameters

High Strength Polyethylene

Polyvinyl Alcohol

Basalt

Polypropylene

	HSPE	**PVA**	**BSLT**	**PP**
S.G.	0.98	1.30	2.10	0.91
Length (in)	0.75	0.75	1.70	1.5
Tensile Strength (ksi)	377	145	157	83-96
E. Modulus (ksi)	11460	3920	6380	690

Link Slab Material – Conventional FRC

- **3 volume percentages (0.5%, 1.0% and 1.5%) were tested for each fiber (except HSPE due to clumping during mixing at lower volumes)**
- **ASTM C1609 – flexural performance of fiber reinforced concrete was utilized to compare the performance of the fibers at different volumes in order to select a “best” fiber type for toughness and residual strength**
  - Flexural performance is a good indicator of tensile performance
- **Fresh properties were monitored using the Vibrating Kelly Ball (VKelly) test**
  - VKelly test indicates static yield stress of fresh concrete similar to slump cone test but additionally measures the response to vibration through the VKelly index

Link Slab Material – Conventional FRC

VKelly Test

- **VKelly Slump**
  - Measures static yield stress of the concrete (similar to slump cone test)
  - Taken by doubling the penetration of the ball into the concrete surface under the weight of the ball.
- **VKelly Index**
  - Measures the mixture's response to vibration for consolidation
  - Taken by vibrating the Kelly ball at a constant rate and measuring the penetration into the concrete as a function of time. The slope of the penetration vs. time curve is the index.

Link Slab Material – FRC Results

VKelly Results

- PVA had no VKelly index reading for 0.5% volume due to the rapid movement of the Kelly ball through the mixture under vibration
- PVA mixtures re-aggregated into clumps during mixing at 1.0% and 1.5%

Fresh Properties				
			VKelly	
Mix ID	% Paste Added	HRWR (oz/cwt)	Slump	Index
PP0.5	0.0	0.6	1.5	0.47
PP1.0	0.5	1.8	1.3	0.33
PP1.5	2.0	3.1	1.0	0.13
PVA0.5	2.4	2.9	2.6	N/A
PVA1.0	6.7	2.8	1.3	0.25
PVA1.5	11.5	6.3	2.0	0.19
BSLT0.5	0.0	1.0	2.3	0.55
BSLT1.0	0.0	2.6	1.9	0.43
BSLT1.5	0.0	2.6	1.3	0.30
HSPE0.5	2.8	2.1	0.7	0.28
HSPE1.0	4.0	5.5	1.7	0.33
HSPE1.5				

- HSPE was not mixed at 1.5% volume due to mixing complications at 1.0% volume. HSPE fibers tend to stick to each other during the mixing process forming clumps in the mix making them impractical to mix at high volumes and non-contractor friendly

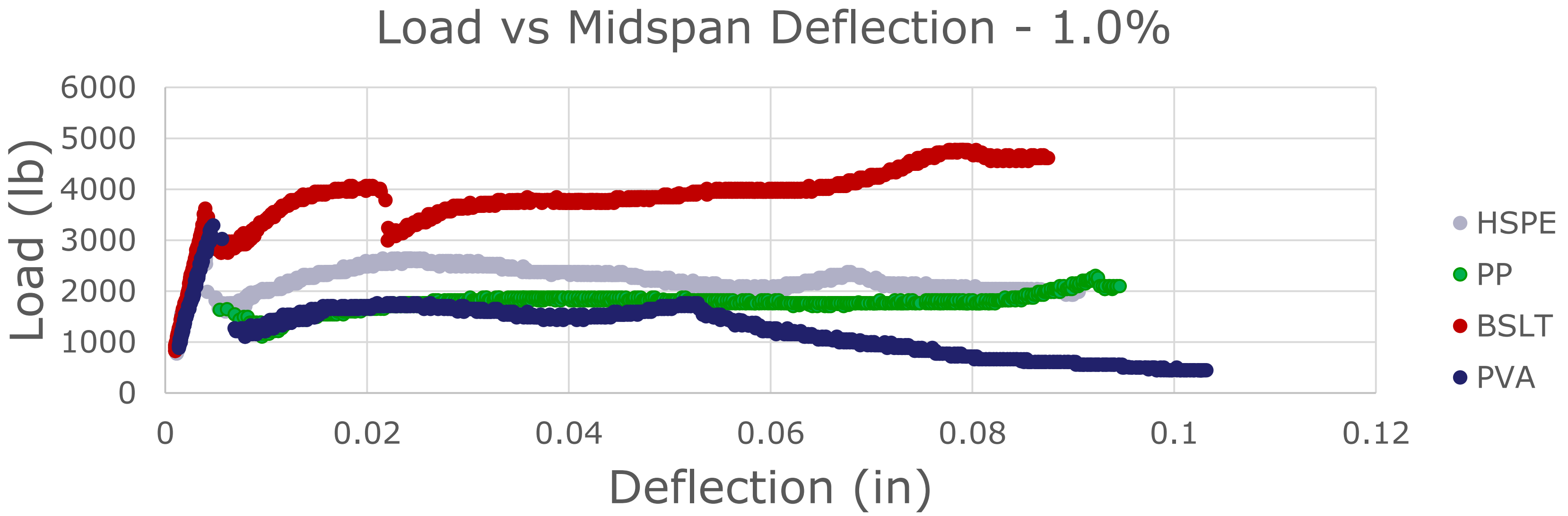
Link Slab Material – Conventional FRC

ASTM C1609 – Flexural Performance of FRC

- 4”x4”x14” beam specimens
- 3rd point bending
- Displacement controlled
- Average mid-span deflection data collected using LVDT sensors
- Load vs. average mid-span deflection plotted and analyzed for flexural performance parameters outlined in ASTM C1609
- Performance parameters include
  - First Peak Strength (Modulus of Rupture)
  - Residual Strengths at L/600 and L/150 deflection
  - Toughness up to L/150 deflection
  - Equivalent Flexural Strength Ratio

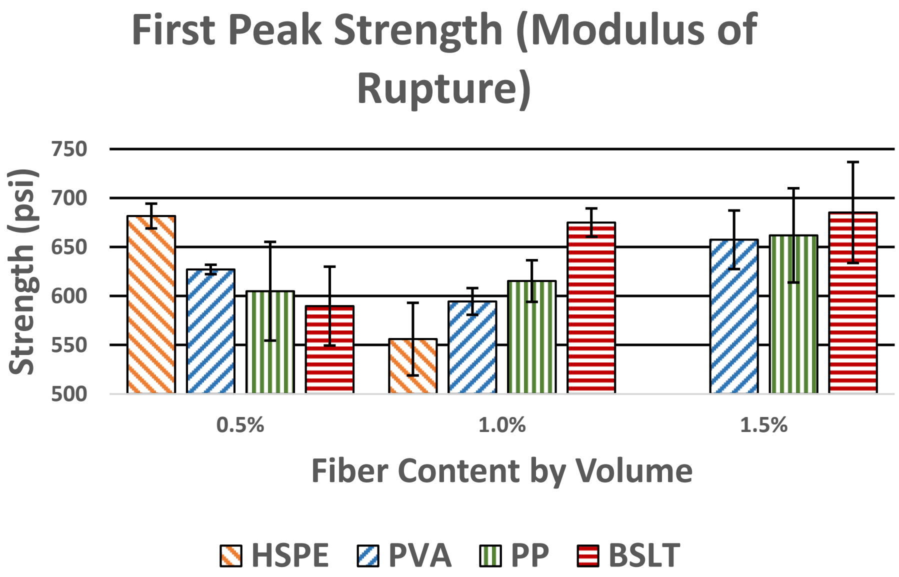
Link Slab Material – Conventional FRC

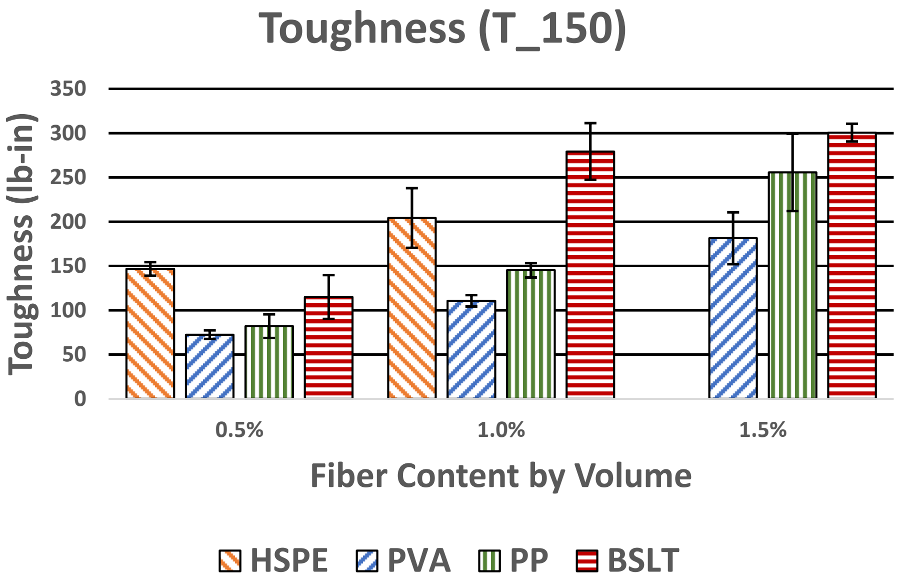
Sample of Load Deflection Curve Comparison – 1.0% Fiber



- **3 beam specimens were cast and tested for each mixture and average performance parameters were computed**
  - First Peak Strength – Flexural strength prior to crack formation
  - Toughness – Area under the load vs. mid-span deflection curve, up to L/150 deflection. Indicates the ability of the fibers to carry load after cracking.

Link Slab Material – FRC Results


First Peak Strength (Modulus of Rupture)


Toughness (T_150)

- First peak strength was not significantly effected by fiber type or volume
  - PP and Basalt showed increasing trend with volume, HSPE and PVA did not
- Toughness (area under load vs deflection curve) increased with increasing volume for all fiber types
  - Basalt > HSPE > PP > PVA for toughness

Link Slab Material – FRC Flexural Testing Conclusions

- **After mixing 4 types of concrete fiber at varying volumes:**

Rank	Mixing Characteristics	Toughness Characteristics
1	Basalt	Basalt
2	Polypropylene	High Strength Polyethylene
3	Polyvinyl Alcohol	Polypropylene
4	High Strength Polyethylene	Polyvinyl Alcohol

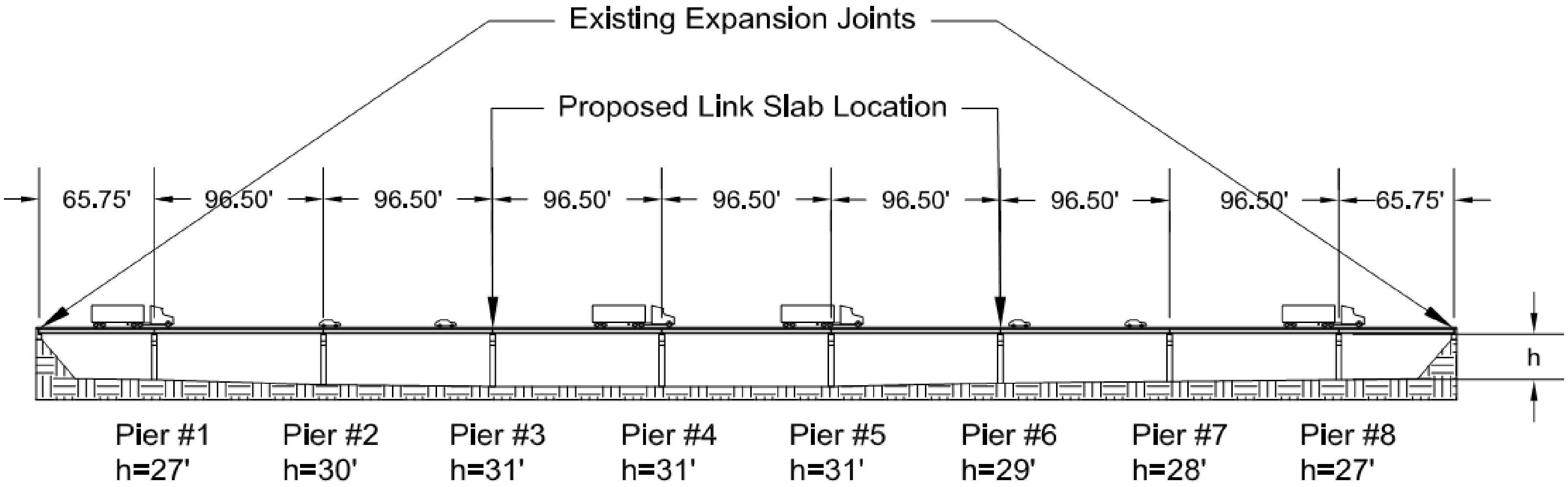
- PVA and HSPE both had dispersion issues, but of a different nature
- HSPE showed promising strength results, but is very challenging to work with during mixing
- Basalt Minibars performed the best in all aspects

Now that optimal macro-fiber has been selected for post-crack performance of FRC, high early strength and shrinkage potential are being evaluated through additional studies. Low stiffness, partial depth pre-cast ECC link slabs will be explored once full depth, conventional FRC cast-in-place link slab mix design is optimized.

Substructure Response from Link Slab Presence - Case Study Bridge - Overview

9 Span Bridge near Vinton, Iowa

- Geometry
  - Continuous supports at piers # 1, 2, 4, 5, 7, & 8
  - Bearing pad supports at both abutments and piers # 3 & 6
- Investigate replacement of expansion joints at piers # 3 & 6 with link slabs



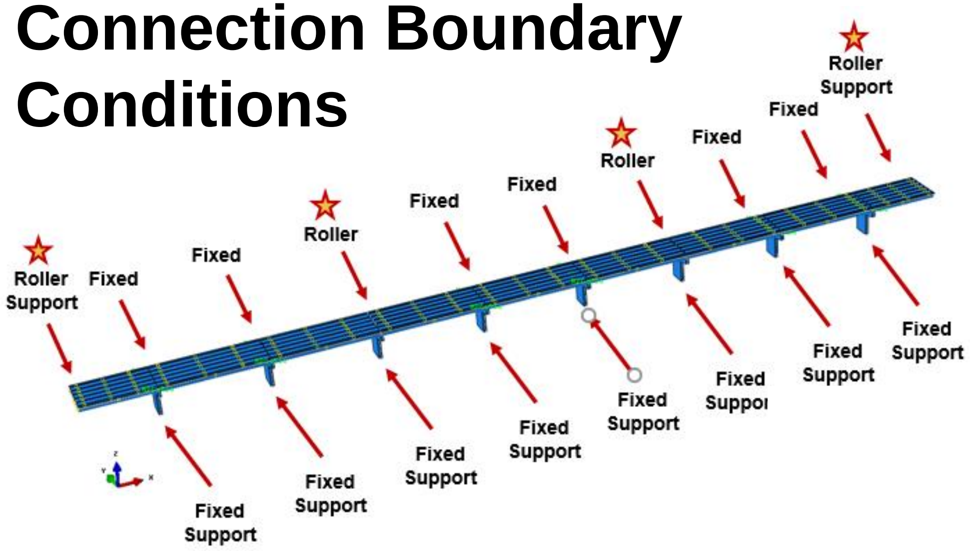
Case Study Bridge

Experimental Investigation

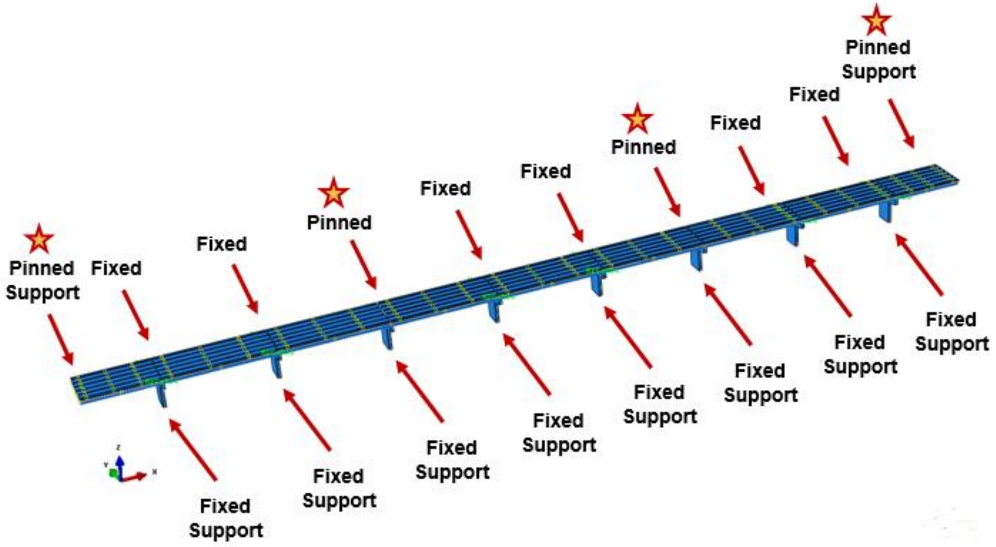
- Replace expansion joints over piers 3 & 6 with link slabs and compare with no link slab case
- Consider 2 idealized support conditions (Roller or Pinned) under expansion joints and link slabs (both abutments and piers # 3 & 6)
  - In-situ bearing pads would act somewhere between these two idealized conditions
  - Lateral stiffness of bearing pads increases with age
    - Roller support lower bound for bearing pad stiffness
    - Pinned support upper bound for bearing pad stiffness
- Results focus on deck/girder displacement and pier reactions

Case Study Bridge

Connection Boundary Conditions



« Roller Support Model



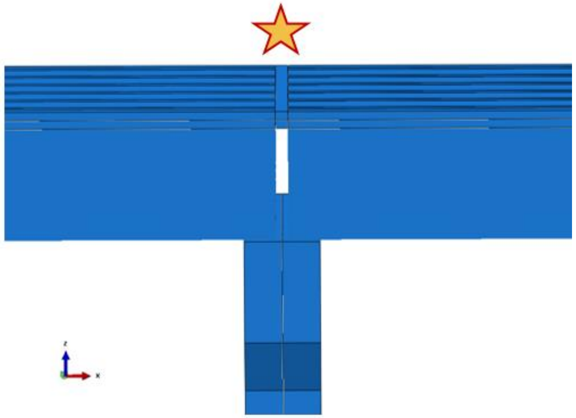
Pinned Support Model »

Case Study Bridge

Experimental Investigation

- **Finite Element Models**
  - 4 bridge models created/analyzed
    - Roller without link slab (RwoLS)
    - Roller with link slab (RwLS)
    - Pinned without link slab (PwoLS)
    - Pinned with link slab (PwLS)
  - Analysis software package ABAQUS utilized
  - Link slabs were modeled by filling 6” expansion gap with concrete material analogous to the concrete deck material
  - 3x smaller mesh used for piers to increase accuracy

Expansion gap filled with concrete for models with link slabs



Case Study Bridge

Experimental Investigation

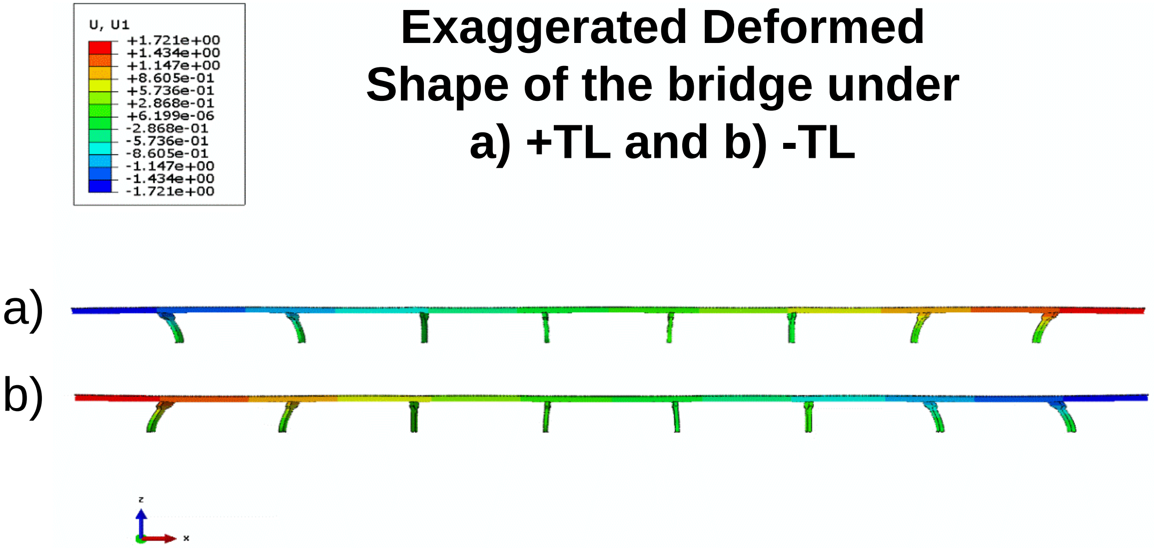
- **Loading Conditions**
  - All 4 models analyzed for 3 loading conditions separately
    - Dead load (DL)
    - Positive temperature load (+TL)
    - Negative temperature load (-TL)
  - Total stresses, moments and forces were calculated by combining either (DL+TL) or (DL-TL)
  - ±TL was taken as 70ºF to produce conservative results
  - DL was calculated as the self weight of the bridge material

Case Study Bridge

Results

- +TL and –TL produced results of the same magnitude for all 4 different bridge models
  - Results and conclusions for +TL and –TL are synonymous
- Due to symmetry, results are analyzed for half of the bridge

Exaggerated Deformed Shape of the bridge under a) +TL and b) -TL

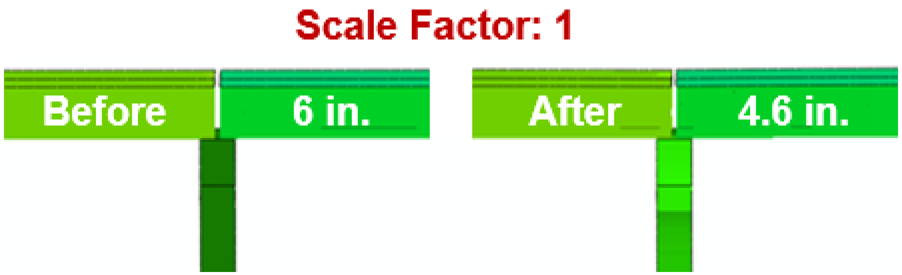


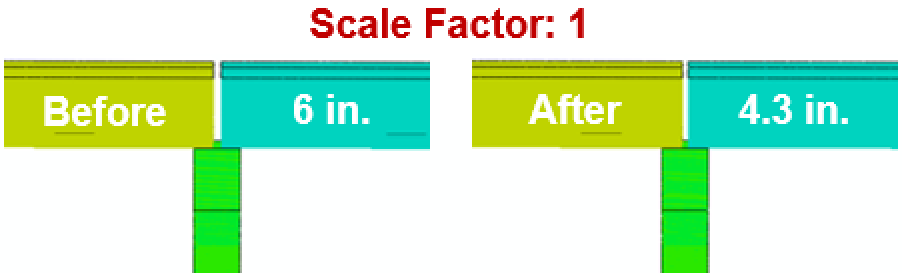
Case Study Bridge

Results – Displacements at Expansion Joints / Link Slabs

No Link Slab

- Pinned Support Condition
  - 1.4 inches displacement
- Roller Support Condition
  - 1.7 inches displacement





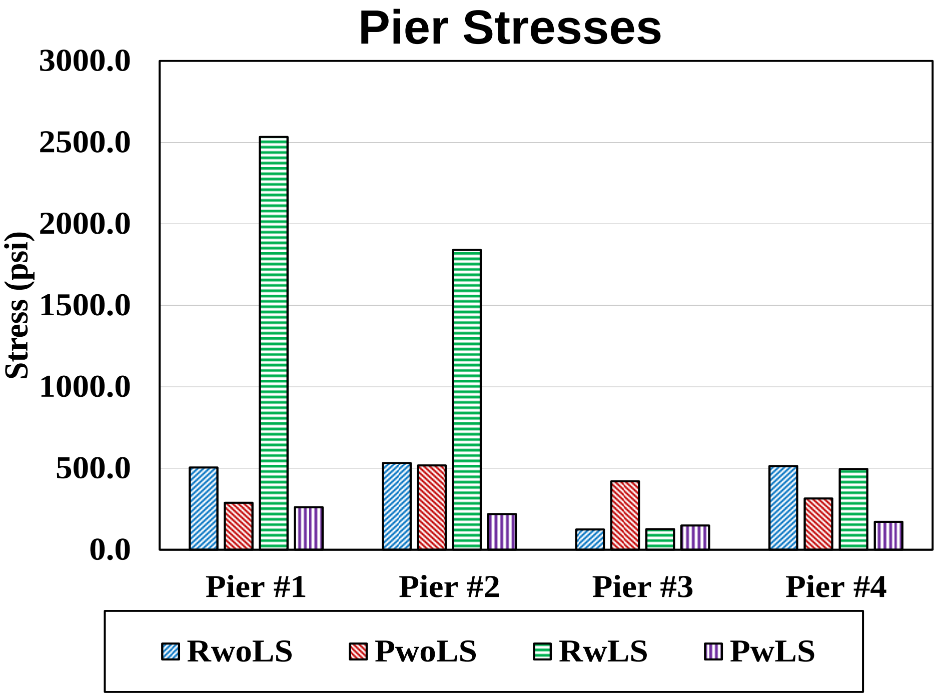
With Link Slab

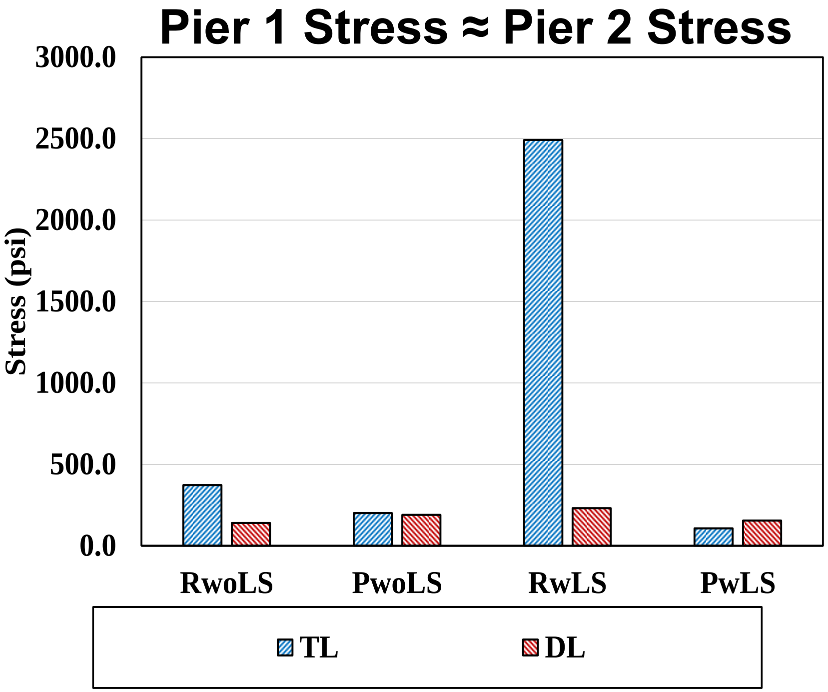
- Lateral Girder / Deck displacements were zero

Case Study Bridge

Results: Substructure Reactions with Link Slabs

- For the RwLS model a build up of stresses, moments and forces was discovered under temperature loading in the outer piers
- The PwLS model had negligible stress, moment or force build up in all piers

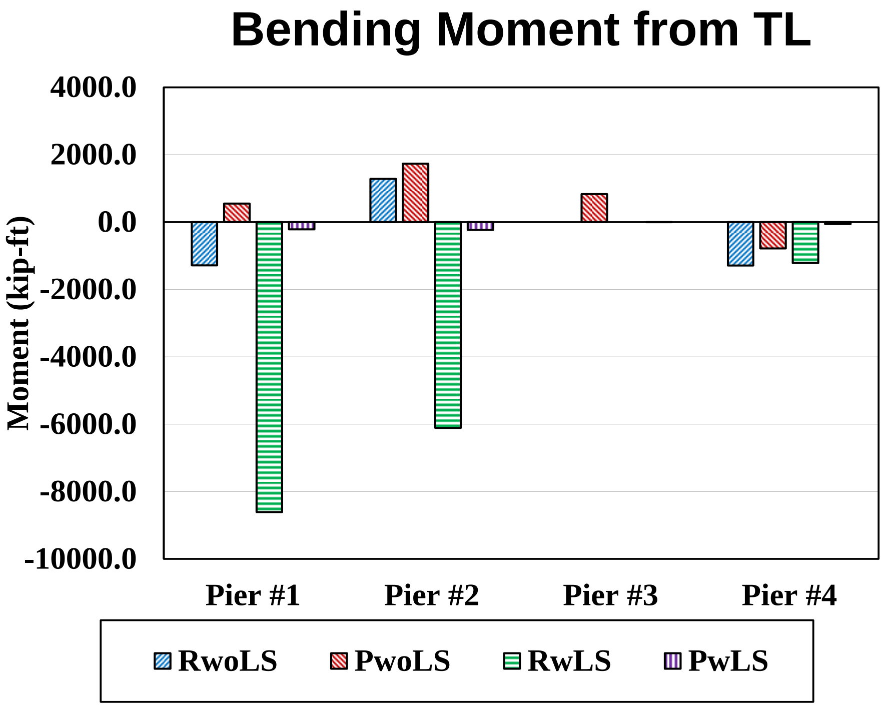

Pier Stresses

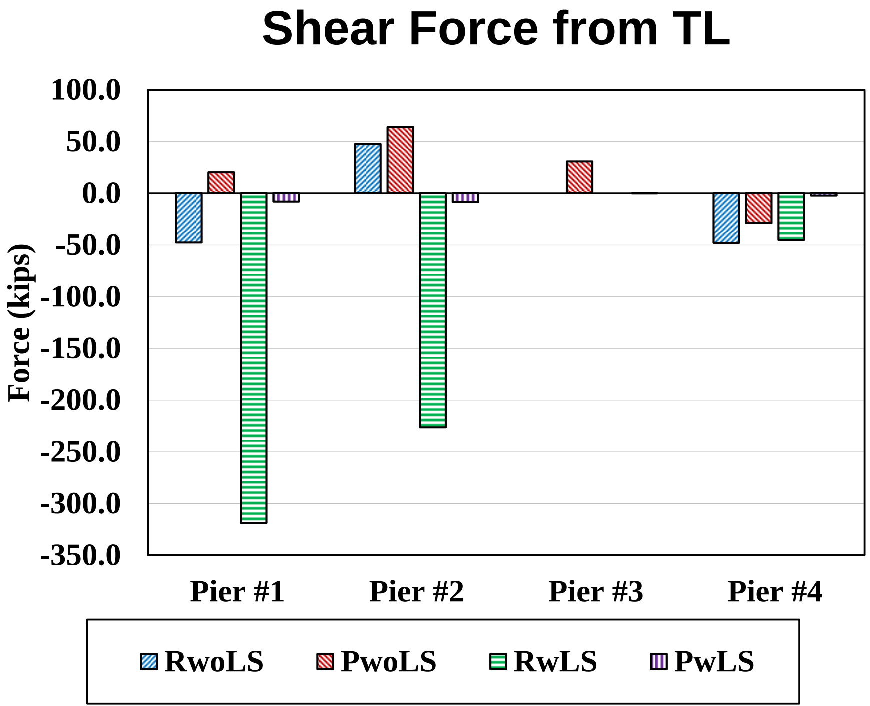

Pier 1 Stress ≈ Pier 2 Stress

Case Study Bridge

Results: Substructure

- Dead loads produced negligible reactions for all cases
- Temperature loads produced substantial reactions in outer piers for RwLS case


Bending Moment from TL


Shear Force from TL

Case Study Bridge

Conclusions

- Displacements were relatively small at the expansion gap – worst case was 1.7” of movement.
- Link slabs may work well in with older, laterally stiff bearing pad supports that act most like ideal pinned connections.
- Link slabs would not work well with bearing pads that have low lateral stiffness, as a build up of stresses, moments and forces would result in the outer piers between the link slab and abutment.
- Retrofit of link slabs to replace expansion joints in older bridges may be beneficial based on the results of this study.

Final Conclusions

- **Material and structural design are closely related for link slab design.**
  - Material tailoring should provide 2-3 different link slab options with varying cost and effectiveness for different scenarios.
  - Cast-in-place ABC FRC link slabs should provide a simple option for contractors.
  - Low stiffness, partial depth, pre-cast ECC or Textile Concrete Link slabs should provide a more advanced and technical solution, hopefully feasible and effective for full scale applications.
- **As shown in the case study bridge investigation, link slabs can have negative effects on the global structure.**
  - Hope to minimize this structural intrusiveness through flexible link slab materials design.

Thank you!

Questions?