Development of longitudinal joint details for Florida Slab Beam incorporating Ultra-High-Performance Concrete

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ABSTRACT
The Florida Slab Beam (FSB) is a precast, prestressed, flat-slab beam currently used for short-span bridges (less than about 65 feet) by the Florida Department of Transportation (FDOT). Current FSB design includes a cast-in-place (CIP) concrete deck and joint between adjacent beams. Modified section and joint details were desired by FDOT to decrease construction time. The new section and connection geometries will not require a CIP deck and will utilize ultra-high performance concrete (UHPC) in female-to-female joints, which will create an ideal section for accelerated bridge construction applications. This paper presents preliminary design and analyses that investigate transverse moment capacity using eight finite element models: three 18-inch depth joint models and five 12-inch depth joint models using both regular concrete and UHPC at the connection. A number of different joint details were found to have similar performance to current joint details with CIP decks and joints. These joints will be evaluated experimentally in future work.

Keywords: Concrete bridges, Short span, Ultra-high performance concrete, Parametric study, Prestressed concrete, Accelerated bridge construction, Florida Slab Beam.

INTRODUCTION

Ultra-high performance concrete (UHPC) is becoming more widely used in bridge construction applications due to its remarkable structural performance. Many departments of transportation have tested and deployed the use of UHPC in bridges around the US. Most of these applications have been to connect precast members (e.g. slabs to beams and slabs, adjacent beams, caps to columns, etc.).

The Florida Slab Beam (FSB) is a recently developed section type used for short-span bridges (less than about 65 feet) by the Florida Department of Transportation (FDOT). The FSB system consists of shallow precast, prestressed concrete inverted-tee beams that are placed immediately adjacent to each other and then involve reinforcement and concrete being placed in the inner joints and top deck all in one single cast. A modified design is desired to eliminate the cast-in-place (CIP) deck and allow for UHPC to be used in the joint region, which will allow for accelerated construction.

The main objectives of this research are:

- Develop modified design details of FDOT's FSB Design Standard to utilize a UHPC longitudinal connection between beams with an asphalt overlay;
- Test modified details developed using finite element models and compare ultimate moment capacity. Detailing requirements will include modifications of the geometry and rebars for the efficient use of UHPC that balances material quantities and long-term durability;
- Propose guidelines to achieve full transverse flexure continuity based on previous research and actual analysis data.

This work will be used to guide future experimental efforts.

BACKGROUND ON FLORIDA SLAB BEAM

FDOT has worked with precast slab units since the late 1940s (Goldsberry [1] and Young [2]). Such systems have undergone several changes to their geometry and rebar configuration at the joint region to avoid longitudinal reflective cracks in asphalt toppings. These cracks cause eventual performance decay by allowing the intrusion of moisture that leads to corrosion of the inner steel rebars at the connection matrix. One of the slab unit iterations was proposed to diminish reflective cracks by using transverse post-tensioning, but this method added cost and time to the project without satisfactory results in terms of crack control according to Bollmann [3].

By January 2016, a new FSB Standard beam shape was proposed: the FSB. It is the last iteration and is limited to off-system bridges with low average daily traffic (ADT) and low average daily truck traffic (ADTT) as its performance is monitored over time by FDOT. The FSB Developmental Design Standard (DDS) follows current AAHSTO LRFD Bridge Design Specifications and Instructions for Developmental Design Standards [4] with Structure Design Guidelines (SDG) [5].

Three FSB section depths are currently available (12, 15, and 18-inch as shown in FIGURE 1) spanning between 30' to 60' and having beam widths ranging from 48 inches to 60 inches by means of one-inch increments. Straight edges are used with transverse reinforcing bars protruding from the web borders; however, these reinforcing bars do not extend beyond the edges of the FSB flanges, which facilitates transportation and placement. A two-inch chamfer is used at the top of the web to minimize abrupt changes avoiding formation of longitudinal reflective cracks.

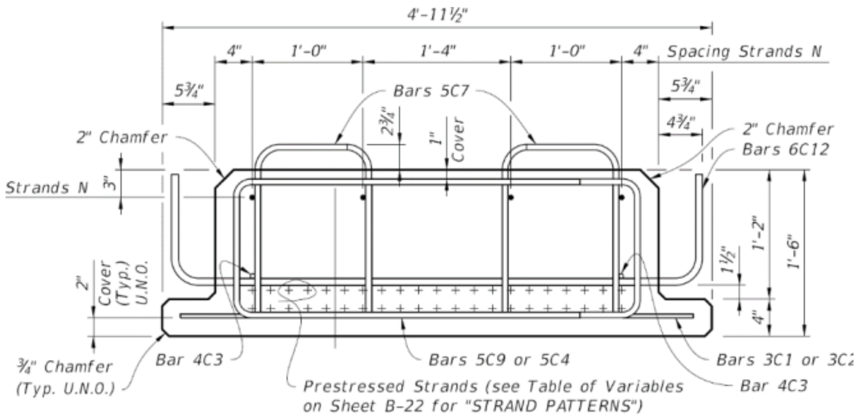


FIGURE 1 Typical FSB Section [4]

The FSB detail currently includes a minimum 6-inch CIP composite deck (FIGURE 2). The CIP deck is used in these sections to connect adjacent members, but also provides additional depth, which enhances the overall section capacity and offers monolithic slab structure with proper live load distribution transversely. Additionally, it requires less forming at the site, less deck steel to place, and a safer working platform with less fall-protection required. Cracking can be further reduced by saturating the FSB with water for at least 12 hours prior to casting of the concrete topping, creating a saturated surface condition [4].

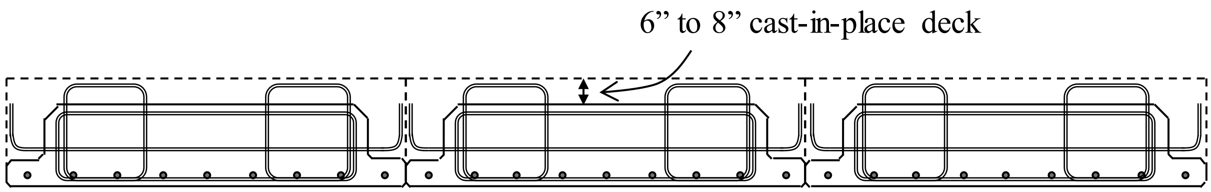


FIGURE 2 Typical FSB section with 6 to 8-inch CIP composite deck

UHPC MATERIALS

As mentioned, the new joint design will utilize UHPC. UHPC is used due to its well-known superior performance, including: high compressive and tensile strength, long-term durability, low permeability, high flowability, and low water-to-cement ratio (all compared to current conventional concrete). Use of UHPC will greatly increase the tensile performance of the joint and has been shown to provide a stronger connection than the slab beam itself [6]. The typical composition of the UHPC matrix is shown in TABLE 1, and the typical-field cast UHPC material properties used in this study are shown in TABLE 2.

TABLE 1 Typical composition of UHPC [7]

Component	**Amount**	**% by Weight**
Portland Cement	1200 lb/yd^3	28.5
Silica Fume	390 lb/yd^3	9.3
Fine Sand	1720 lb/yd^3	41.0
Ground Quartz	355 lb/yd^3	8.5
Superplasticizer	51 lb/yd^3	1.2
Water	218 lb/yd^3	5.2
Steel Fibers	263 lb/yd^3	6.3

TABLE 2 Typical field-cast UHPC material properties [8]

Material Characteristic	**Average Result**
Density	155 lb/ft^3
Compressive strength (ASTM C39, 28-day)	≥ 18.4 ksi
Modulus of elasticity (ASTM C469, 28 day)	7,000 ksi
Direct tension cracking strength (uniaxial tension with multiple cracking)	1.2 ksi
Split cylinder cracking strength (ASTM C496)	1.3 ksi
Prism flexure cracking strength (ASTM C1018, 12-inch span)	1.3 ksi
Tensile strain capacity before crack localization and fiber debond	> 0.003
Long-term creep coefficient (ASTM C512; 11.2 ksi load)	0.78
Long-term shrinkage (ASTM C157; initial reading after set)	555 microstrain
Total shrinkage (embedded vibrating wire gage)	790 microstrain
Coefficient of thermal expansion (AASHTO T259; 0.5-inch depth)	8.2 x 10^{-6} in./in./^{o}F
Chloride ion penetrability (ASTM C1202, 28-day test)	360 coulombs
Chloride ion permeability (AASTO T259; 0.5-inch depth)	< 0.10 lb/yd^3
Scaling resistance (ASTM C672)	No scaling
Abrasion resistance (ASTM C944 2x weight; ground surface)	0.026 oz. lost
Freeze-thaw resistance (ASTM C 666A; 600 cycles)	RDM = 99 percent
Alkali-silica reaction (ASTM C1260; tested for 28 days)	Innocuous

The construction procedure of the system will be expedited by using UHPC. Slab beams can be first laid down side-by-side longitudinally. Next, backer rods or plates can be placed to seal the bottom-most part of the joint. UHPC can then be mixed and cast on site to fill the joint region and connect adjacent members. Finally, an asphalt overlay can then be used to create the driving surface and take care of any differential camber presented or overfills of the closure pour.

NEW CONNECTION DETAILS

The development of the new joint detail follows two main approaches: an adaptation of previously developed details for box beam [8] and full-depth precast deck panel connections with field-cast UHPC, as shown in FIGURE 3, both female-to-female connections by Graybeal [6]. The panel-to-panel joint was studied to incorporate two layers of steel reinforcement for the thicker FSB section. The second approach is a redesigned concept proposed by FDOT engineers based on preliminary tests performed to the original FSB geometry without CIP deck described later.

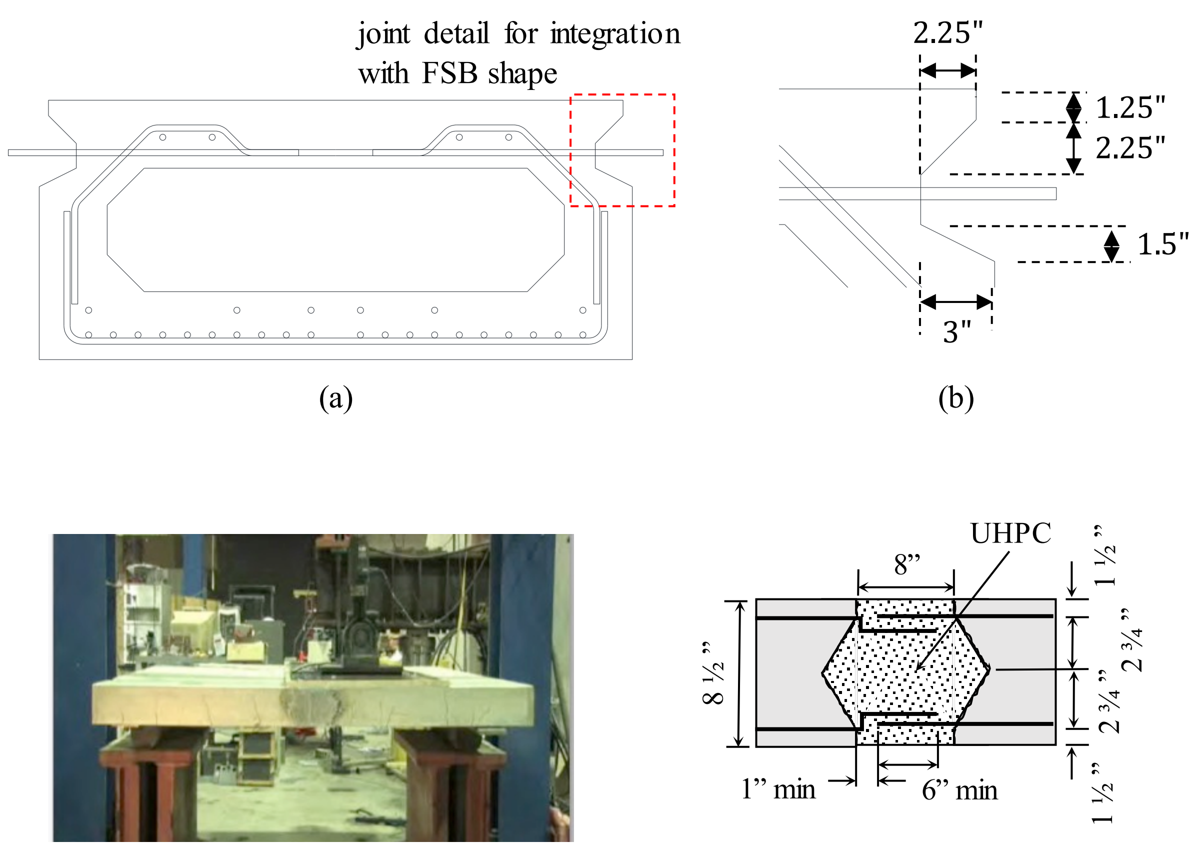


FIGURE 3 (a) Box beam joint detail for UHPC closure-pour [8]. (b) Dimensions of the joint region. (c) Full-depth precast deck panels. [6] (d) Noncontact lap splice steel reinforcement

The joint detail between the adjacent box beam girders features one layer of #4 reinforcement that extends 4.75 inches outside the edge of the concrete and embedded into the precast section 18 inches spaced at eight inches. These bars are staggered or offset between beams for constructability purposes. One advantage is that mechanical reinforcement splice connection (transverse dowel) can be used at the precast section boundary to allow for solid formwork to be used without holes. The reinforcement extending into the joint region is installed after the forms are stripped using the mechanical splice.

The two layers of steel used between adjacent full-depth precast deck panels was considered in connection of deeper modified FSB shapes as feasible solution. It is also designed as a noncontact lap splice with straight #5 steel reinforcement that are staggered between panels for constructability. The initially discussed shapes integrate the abovementioned adjacent box beam detail and precast panels joint geometry with the current FSB cross section shape (FIGURE 4). By using the current FSB cross section shape as the starting point, steel formwork may be designed with inserts for both the existing and proposed FSB section. This would allow precast plants to better accommodate the construction of both designs.

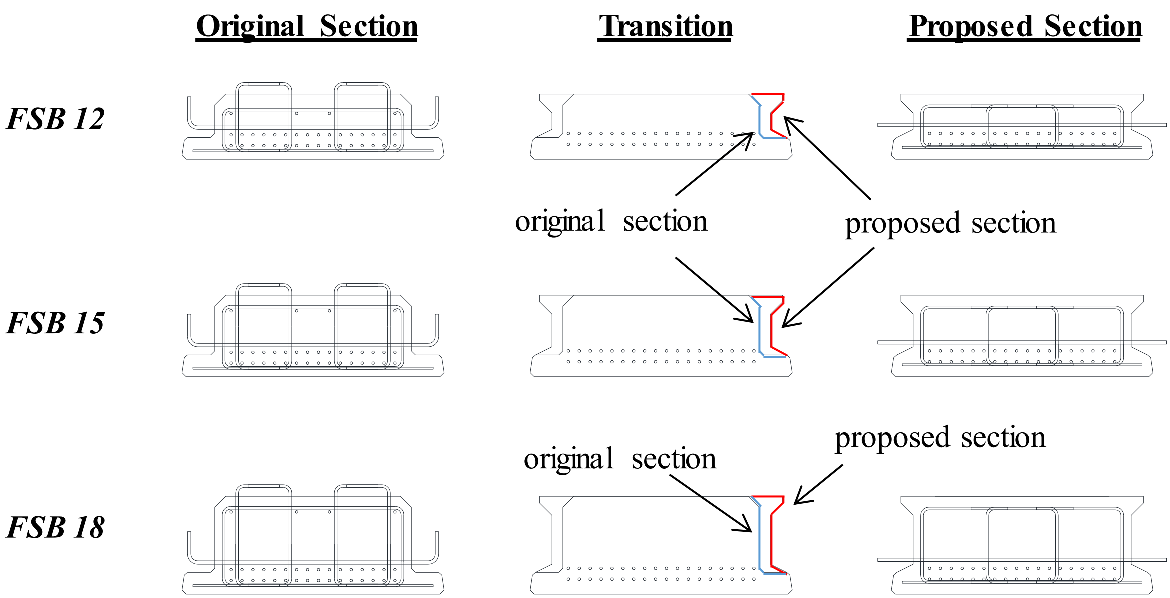
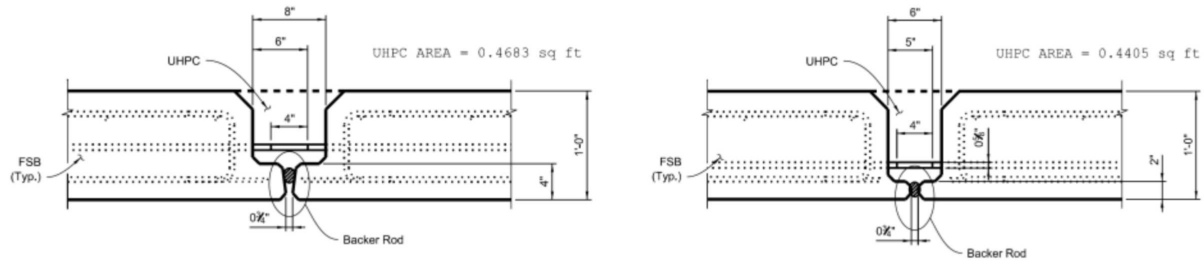


FIGURE 4 Transition from original FSB joint detail to proposed ones

FDOT engineers have also proposed two additional redesigned joint details. Because UHPC provides enhanced development length of mild steel reinforcement, the spliced connection is shorter thus requiring a lower volume of field-cast fill material. Additionally, the ultimate moment capacity of the joint is increased by increasing the lever arm by placing the joint transverse steel lower in the section, as compared to a higher steel location, shown in FIGURE 5.



(a) (b)

FIGURE 5 Redesigned options by FDOT: (a) FSB section with slightly reduced joint width and (b) FSB section with reduced joint width and ledge depth

NUMERICAL EVALUATION

Eight different analysis cases were created using a non-linear finite element model software specifically tailored for reinforced concrete and fiber-reinforced concrete modeling applications, and post-cracking evaluation TABLE 3 and TABLE 4 summarizes the material definitions used in the numerical evaluation for concrete and joint reinforcement respectively. The steel rebar protruding from the concrete face of the beams at the joint region was modeled using bilinear stress-strain law. Case 1 is the existing FSB system with the current joint geometry and reinforcement detail. The initial model was of a 12-inch deep standard FSB section with a 53-inch width (FSB 12x53) and a 6-inch deep CIP reinforced deck (totaling a final system thickness of 18 inches). The next cases were using the modified joint geometry with one-layer (Case 2) and two-layers (Case 3) of joint reinforcement and UHPC material in the joint region. These models both had the same section depth as the total composite section of Case 1 of 18 inches (FIGURE 6).

Three further analyses were performed to 12-inch deep FSB sections without CIP decks. Case 4 and Case 5 were both using the current FSB section geometry. Case 4 had the current reinforcement detailing, modified to not include any CIP deck, but conventional concrete used in the joint region. Case 5 had the same joint geometry and reinforcement as Case 4, but used UHPC in the joint region. Case 6 was the modified FSB joint detail with one layer of straight reinforcement and UHPC in the joint region. (FIGURE 7).

TABLE 3 Concrete definition

Property		**Beams**	**Joints**	**Slab**
Compressive Strength	$f'c\ [ksi]$	8.5	18.3	4.0
Tensile Strength	$f't\ [ksi]$	0.692	1.2	0.474
Young's Modulus	$E\ [ksi]$	5,255	7,000	3,605
Fracture Energy	$G_f\ \left[{}^{lbf}/_{in}\right]$	0.456812	0.588675	0.314058

TABLE 4 Joint reinforcement definition

Property		**Value**
Rebar Diameter	ϕ	0.625 in
Yield Strain	ε_1	0.002
Yield Stress	$f_1 = f_y$	60,000 psi
Ultimate Strain	ε_2	0.05
Ultimate Stress	f_2	90,000 psi

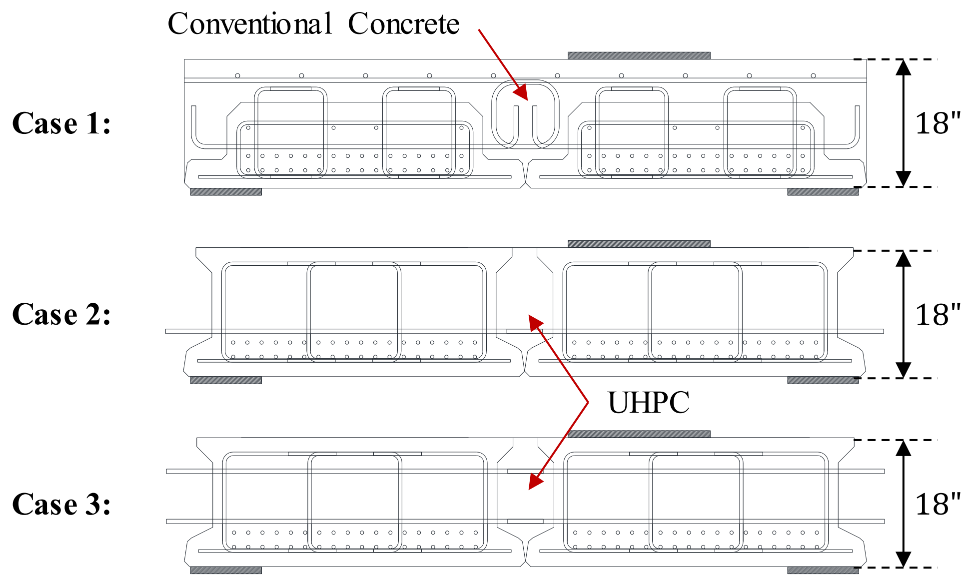


FIGURE 6 First analysis set comparing the current connection detail to proposed UHPC connection detail with one and two layers of steel

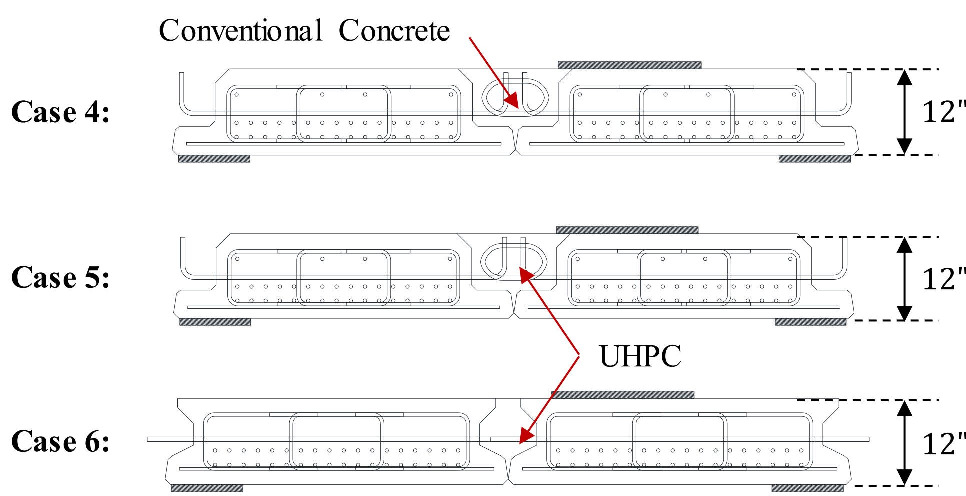


FIGURE 7 Second analysis set comparing the current joint geometry with conventional concrete and UHPC to the modified joint geometry with UHPC

Lastly, Case 7 and Case 8 were analyzed as they were the FDOT alternatives. Both cases maintain the original FSB connection geometry but with a slightly reduced joint width (Case 7) and with a reduced joint width and ledge depth (Case 8). The system with the reduced ledge depth allows for a greater lever arm by placing the joint reinforcement at a lower position so that better capacity can be achieved (FIGURE 8).

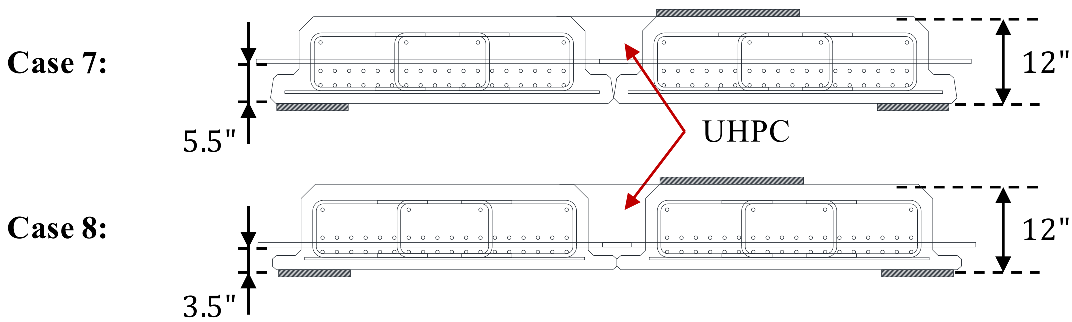


FIGURE 8 Third analysis set comparing the FDOT proposed geometries using UHPC

The loading protocol used in the analyses was based on testings performed on adjacent concrete deck panels performed by Graybeal [9]. This loading protocol involves placement of a 20-inch by 10-inch load (equivalent to a wheel loading footprint of traffic traveling parallely) immediately adjacent to the joint region. Placement of the load adjacent to (rather than on top of) the joint region places combined bending and shear stresses at the joint boundary. The load was defined using a deflection-controlled system in 40 equal load steps so that at least the cracking load and ultimate capacity is evinced in the whole system volume (FIGURE 9). The specimens were placed on top of pin and roller supports

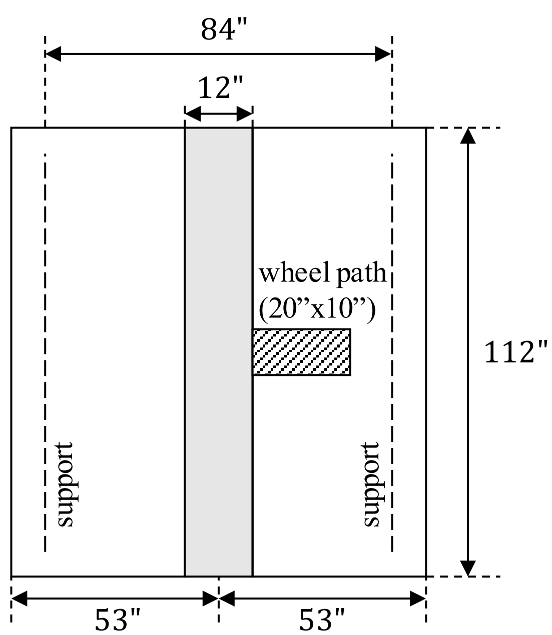


FIGURE 9 Loading protocol used for analyses

RESULTS AND DISCUSSION

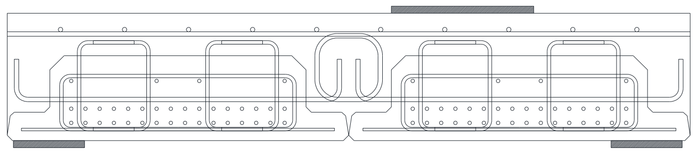
A summary of the eight analyses performed is shown (TABLE 5). The preliminary items measured were the maximum or peak force applied and the vertical displacement at the load point application; in short, the modified joint region with either one or two layers of steel performs better than the current FSB section and joint detail, as can be seen in the comparison between Cases 1 through 3. For the shallower systems, the modified joint detail with UHPC performs as well as the current joint geometry filled with conventional concrete.

TABLE 5 Summary of results from all analyses

Case #	**Type of Section**	**Cracking Load** *(kips)*	**Max. Load** *(kips)*	**Displacement at Max. Force** *(in.)*
1	FSB 12x53	1,020	1,174	0.0868
2	Modified FSB 18x53 (1 layer of steel)	1,250	1,377	0.0872
3	Modified FSB 18x53 (2 layers of steel)	1,220	1,352	0.0731
4	FSB 12x53 (Regular concrete)	700	753.8	0.0988
5	FSB 12x53 (UHPC)	880	945.6	0.1128
6	Modified FSB 12x53 (1 layer of steel)	600	763.0	0.1335
7	FDOT Proposed – Option 1	915	975.7	0.1512
8	FDOT Proposed – Option 2	846	855	0.0886

A more detailed summary of the results for each of the analyses is presented in the following section. These results include a load-displacement curve and a crack pattern registered during all model steps (FIGURE 10). In general, the proposed section design and joint detail seem to perform as well or better than the current FSB section and joint detail; therefore, the intended goal was achieved to substitute the original construction method.

Additionally, in seven of the eight analyses, the crack pattern shown is more representative of a punching shear failure. For these five cases (all but Case 4), the punching shear crack pattern would suggest that the joint region is behaving well and is not controlling the capacity, further supporting the advantage of use of UHPC. In Case 4, there is a significant amount of cracks along the joint boundary. These cracks extend the entire way to the end of the members and is more evenly distributed along the length than the other members. This cracking pattern would suggest that the joint detail is controlling the capacity of this system, which shows that the CIP deck is required to have good behavior of the current FSB section and joint details with conventional concrete closure pours.



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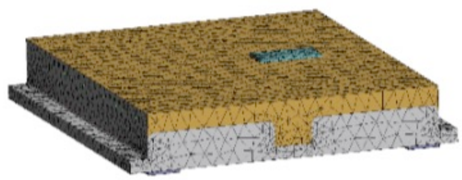

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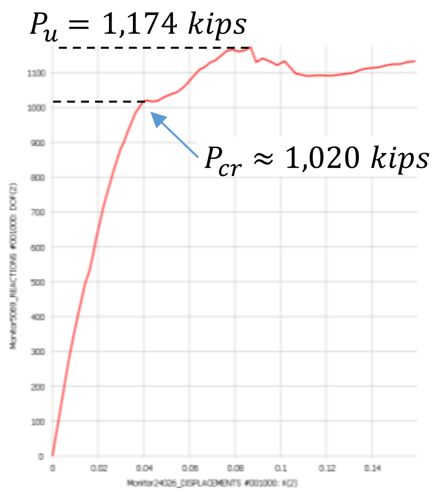

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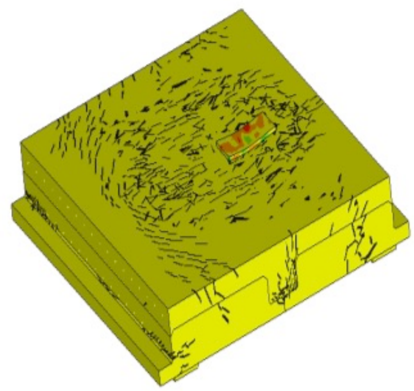

(d)

FIGURE 10 Example of summary of results for Case 1: (a) cross-section geometry and reinforcement detail, (b) model meshing, (c) load-deflection curve, and (d) crack pattern at final step

CONCLUSIONS AND RECOMMENDATIONS

A parametric study was first conducted to determine the allowable span lengths for the three different FSB sections without CIP composite decks. The potential maximum allowable span lengths range from 32 feet for the 12-inch deep FSB section to 55 feet for the 18-inch deep FSB section. Following the parametric study, previously successful UHPC joint details were integrated into the FSB cross section shape. The integration led to the proposed section geometry shown below in FIGURE 11 (a). Two alternative joint details were also developed by FDOT engineers for consideration in the study, shown in FIGURE 11 (b) and (c). The three joint details were then evaluated using numerical models and determined to perform like or better than the current FSB with CIP deck joint detail.

Previous research has shown the benefit of an exposed aggregate finish to improve the bond between the precast section and the joint material [8]. This finish can be achieved by applying a paste-like retarder to the joint formwork prior to casting. It will be recommended that the precast joints for these sections have exposed aggregate finishes and have a saturated surface prior to casting of the joints. The researchers were unable to model this concept numerically, but additional exploration of the idea experimentally is needed. Experimental testing is planned to validate the capacities and displacements achieved during this initial study.

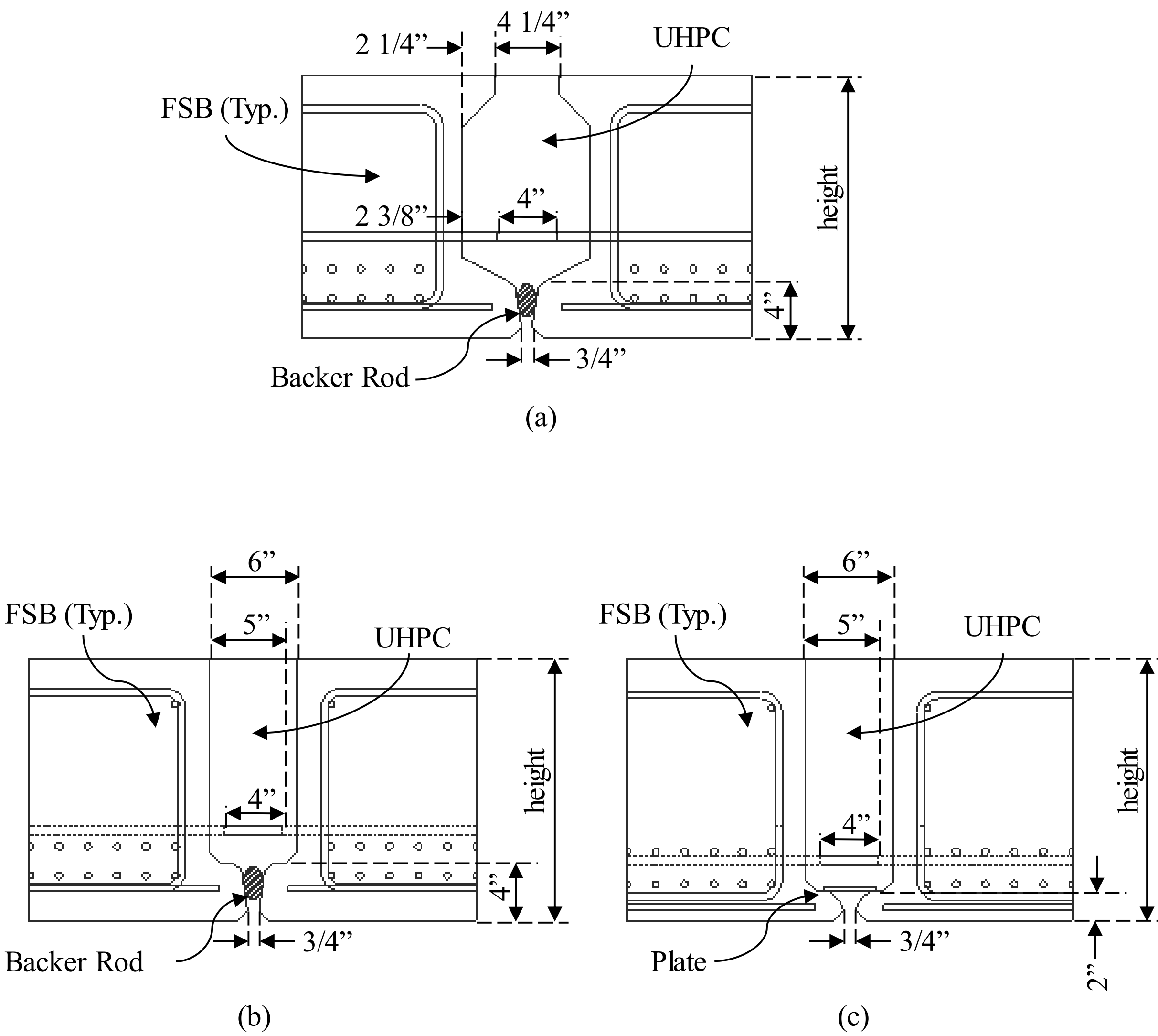

FIGURE 11 **Proposed modified FSB shape and joint detailed geometry**

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