NON-PRESTRESSED BRIDGE DECK-GIRDER COMPOSITE WITH END-GIRDER CONTINUITY DETAIL USING ULTRA HIGH PERFORMANCE CONCRETE (UHPC) WITHIN THE END CONNECTION

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Abstract

Connections are often considered the weakest link in a bridge structure. Connections are critical in transferring the stresses from deck-girder system to the sub-structure and are often under-designed which leads to cracking, intrusion of water and chemicals, corrosion and ultimate failure of the connections and the bridge structure. With Ultra High Performance Concrete's (UHPC) advanced qualities, the connections could be made stronger, ductile, and durable prolonging the bridges life. The main focus of this research was to study the capability of UHPC as a connection-filler material with Missouri Department of Transportation's (MoDOT) typical end-girder detail. Two beams with non-prestressed end-girder detail were connected together with a 152 mm (6-in.) cold-joint of UHPC and a deck was cast on top to simulate a bridge deck-girder composite scenario. Four-point load testing was conducted by inversing the T-section and subjecting the connection to maximum moment to study worst case loading scenario possible. The results indicated that UHPC not only improved the performance, but also improved the ductility and load bearing capacity of the connection.

Résumé

Les connexions sont souvent considérées comme le maillon faible dans une structure de pont. Or elles sont essentielles pour transférer les efforts du tablier vers les appuis et sont souvent mal conçues, d'où des fissures, l'intrusion d'eau et d'agents agressifs, la corrosion et *in fine* la défaillance des connexions et de la structure du pont. Avec les excellentes qualités des bétons fibrés à ultra-hautes performances (BFUP), les connexions pourraient être rendues plus résistantes, ductiles et durables, prolongeant la durée de vie du pont. L'objectif principal de cette recherche était d'étudier la capacité du BFUP en tant que matériau de clavage, en tenant compte des dispositions particulières des extrémités des poutres du Ministère des Transports du Missouri (MoDOT). Deux poutres avec des dispositions d'extrémités de poutres non précontraintes ont été connectées avec un clavage en BFUP de 152 mm (6-in.) et un hourdis supérieur a été coulé par-dessus pour simuler le phasage de réalisation d'un pont à poutres. Un essai de flexion quatre points a été effectué en inversant la section en T et en soumettant la connexion au moment maximum pour étudier le scénario de charge le plus défavorable possible. Le résultat a montré que le BFUP améliorait non seulement la performance d'ensemble, mais aussi la ductilité et la capacité résistante de la connexion.

1 INTRODUCTION

In pre-stressed precast construction, design of joints is often not given enough importance, but joints are critical in transfer of stresses from super structure elements to other structure elements and deterioration often begins within the joint regions. Due to nature of pre-stressing, the camber and loading conditions subject the connection to continuous stresses and concrete used in most cases by DoT's isn't designed to carry these stresses which in turn leads to cracking, intrusion of chemicals, corrosion of reinforcement and ultimately inception of bridge degradation.

Ultra-high performance concrete (UHPC) with dense packing density, steel fibers, very low permeability will eliminate the issues of initial micro-cracking, chemical intrusion and in turn help in pro-longing the bridge's life span. With high compressive strength, tensile strength, durability UHPC is the solution to many of the bridge engineering problems. High-binder content, absence of coarse aggregate, SCC like flow-ability make it the ideal type of concrete to be used in connections where its often hard to get proper compaction due to tightly packed reinforcement detail in the bents in a bridge.

The objective of this research was to study the flexural performance of UHPC with typical end girder continuity detail used by DoT's in a bridge deck-girder composite system. Missouri Department of Transportation's (MoDOT) end girder detail was studied in this project. Test specimens with two non-pre-stressed beams connected with a 6-in. (152 mm) joint with concrete deck cast on top were studied for this project. The connection was designed to be continuous for a live load. UHPC was used in joint and also in deck for a specimen to study if it improves the performance significantly when used against 4ksi conventional concrete used by DoTs for the connections.

2. BACKGROUND

UHPCs advanced cementitious properties make it an ideal solution for many structural problems. In fact, using UHPC would make the connections, which are considered weakest part of structure (often under-designed), a strong link holding the structure together and prolong the life of the Bridge structure. UHPC has been used by USA, Canada, Japan, Europe and Australia (Perry, 2010) in bridge connections and also in structural components. Significant research on using UHPC in longitudinal and transverse bridge-deck level connections was done by Graybeal, B. (2010) for FHWA which much success. Rallabhandhi, Myers (2016) studied the use of UHPC in end girder to girder connections with different continuity details. UHPC was successful in achieving 99% of flexural load carrying capacity of a control specimen without a joint and continuous reinforcement and surpassed the ductile behavior.

MoDOT's Pre-stressed precast girders' strands are modified for intermediate and end bents to facilitate end girder continuity (Figure 1). The strands are cut and bent in the shop. The bottom two rows of strands are cut with 762 mm (30-in.) projection and bent up at 90-degree angle leaving a 152 mm (6-in.) (End bent) / 76.2 mm (3-in.) (Intermediate bent) projection. Top two rows of strands are bent into the deck region at 45-degree angle with 304.2 mm (12-in.) projection. All the remaining strands are cut within 25.4 mm (1-in.) from the end of the girder face. MoDOT uses conventional 28 MPa (4 ksi) concrete for cast-in-place deck and connections, called MoDOT-B mix. This mix is characterized by high proportions of 25.4 mm (1-in.) coarse aggregate, low cement and high water content with fly ash and air entrainment. The UHPC mix used for this research was developed using locally available materials to make the mix more economically viable. UHPC is characterized by high cementitious material, low water content, steel fibers, and no coarse aggregate. High compressive and tensile strength of UHPC enhance the flexural load carrying capacity and ductility of the structure. Steel fibers play important role in increasing the tensile strength, delaying the formation of initial micro cracking in the concrete. The dense packing density of UHPC enabled by absence of coarse aggregate and use of silica fume enable very low permeability, hence no chemical intrusion into concrete and corrosion of steel.

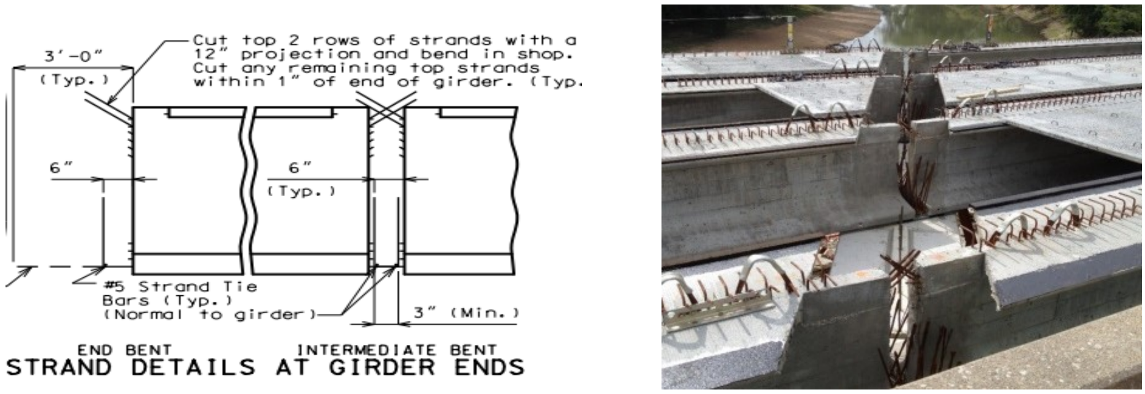

Figure 1: MoDOT End Girder Continuity Detail

3. EXPERIMENTAL PROGRAM

3.1 Test Matrix

The test matrix consisted of 5 beam specimens, 3 control specimens (C1, C2, C3), 1 beam specimen-UHPC joint (B1), 1 beam specimen-UHPC joint and deck (B2) (Table 1). Each specimen was 2134 mm (84-in.) in length. Each specimen consisted of two 990 mm (39-in.) Conventional Concrete (CC) beams 203 mm (8-in.) wide and 305 mm (12-in.) deep in cross-section) connected with a 152 mm (6-in.) joint, cast with UHPC mix or MoDOT-B mix (MB) or CC mix. A 102 mm (4-in.) thick, 508 mm (20-in.) wide deck was cast on top of the beams to create a girder-deck-connection composite (Figure 2). The deck was cast using CC or MB or UHPC mix. The beam specimens were first cast and surfaces were roughened to provide better bonding with joint and deck materials. The joints were then cast followed by deck regions after concrete in joints reached sufficient strength.

Table 1: Test Matrix

Sl.no.	Nomenclature	Beam ID	Beam	Joint type	Deck	Joint detail
1	B-1-C-C-N	C1	CC	CC	CC	None
2	B-2-C-C-M	C2	CC	CC	CC	MoDOT
3	B-3-MB-MB-M	C3	CC	MB	MB	MoDOT
4	B-4-U-MB-M	B1	CC	UHPC	MB	MoDOT
5	B-5-U-U-M	B2	CC	UHPC	UHPC	MoDOT

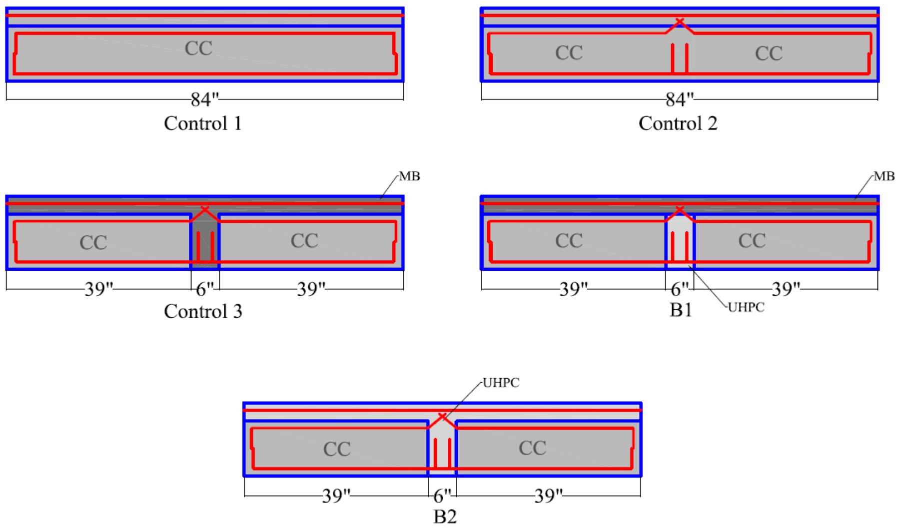

Figure 2: Test Matrix with Reinforcement Detail

All the concrete mix designs were developed at Missouri S&T. To make UHPC more widely applicable, it was designed (Meng, W. *et al.*, 2016) using locally available materials. UHPC has high initial cost because of high binder content and steel fibers. Using locally available materials brings the cost down and long-term benefits may be gained by using UHPC that supersedes the high initial cost. MB mix was adopted from MoDOT specifications.

CC mix in the beams was designed for 55 MPa (8 ksi) to replicate typical pre-stressed girder strength. MB mix yielded 24 MPa (3.5 ksi) using MoDOT mix. UHPC mix was designed for a non-steam cured (i.e. non-temperature cured) compressive strength of 124 MPa (18 ksi); Steel fibers (dia-0.2 mm (0.008-in.), length-12.7 mm (0.5-in.), 2158 MPa tensile strength (313 ksi) were used. UHPC was cast and cured in-situ, while CC and MB mixes were delivered by ready-mix trucks and cured in-situ. Specimens were cured using wet burlap for three days and tested when design strength was achieved in the joint. 2-#4 rebars (grade 60, yield stress-534 MPa/77.5 ksi) were used a tensile reinforcement and 2-#4 were used as compression reinforcement in the beam. 7-#3 rebars (grade 60, yield stress-510 MPa/74 ksi) were used a reinforcement in the deck. The shear reinforcement consisted of modified-U-shaped #3 stirrups which protruded into the deck to create girder-deck composite action. Concrete specimens were cast to measure the fresh and hardened properties of concrete.

3.2 Test method

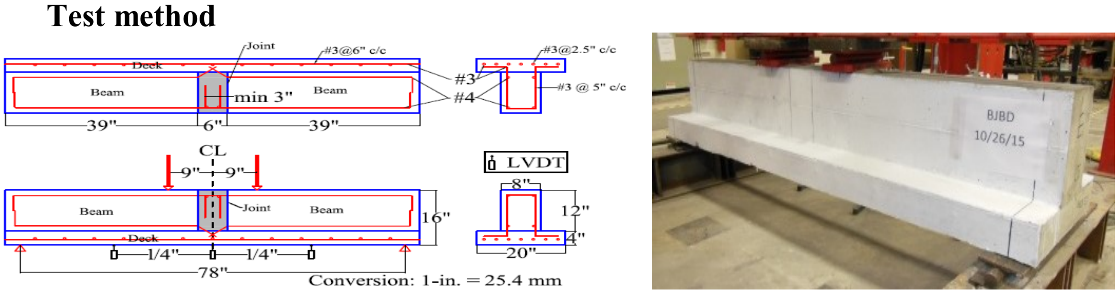

Fig. 3: In-service Example (upper left), Test Setup Schematic (lower left), Test Setup (right)

In a continuous system, the connections are in compression and the deck is in tension. The test setup used created the same effect on the specimen. In order to do this, the beam specimen (essentially a T-section) was tested as an "inverted T" (Fig. 3). This way, the flange at mid-span would be in tension and the connection will be compression. Another objective of the research was to study the performance of UHPC in end connections under flexural loads. This was done by choosing load points 229 mm (9-in.) off the center of the span. This way, the connection would be in complete flexural loading and absence of a support (connections are usually placed over a pier) creates a worst case scenario. Supports were placed 76 mm (3-in.) off the edge of beam. A loading rate of 0.127 mm/min. (0.005-in./min.) was applied to the specimens until failure of specimen or significant drop in load was observed.

Table 2 Test Results

Sl.no.	Beam ID	Joint filler	Deck filler	Joint detail	Peak load kN (kips)	Peak deflection mm (in.)
1	C1	CC	CC	None	378 (85)	96.5 (3.8)
2	C2	CC	CC	MoDOT	330 (74)	58.4 (2.3)
3	C3	MB	MB	MoDOT	285 (64)	58.4 (2.3)
4	B1	UHPC	MB	MoDOT	320 (72)	73.7 (2.9)
5	B2	UHPC	UHPC	MoDOT	441 (99)	30.5 (1.2)

4. RESULTS AND DISCUSSION

The results of the experimental program are summarized in

Table 2. The peak load results ranged from 285 to 441 kN (64 to 99 kips) (Figure 4) while the peak deflections ranged from 30.5 to 96.5 mm (1.2 to 3.8-in.) (Figure 5). Control C1 (378 kN/85 kips) had continuous reinforcement detail. The failure was characterized by flexure and shear crack development followed by a concrete crushing failure, but this was only after significant deformation development due to the continuous reinforcement in the critical "joint" region. Loading was stopped after significant concrete crushing was observed and loading arms reached maximum push limit. Control C2 has MoDOT detail, cast monolithically with CC mix reached 330 kN (74 kips) of peak load. Discontinuity in reinforcement detail, lead to significant concrete crushing failure. Control C3 with MoDOT continuity detail and MB mix in joint and deck reached 285 kN (64 kips). There was significant crushing in the joint and concrete spalled off. This is mainly because of MB mix, which is characterized by high water content and low cementitious material leading to a weak paste. Specimen B1 with UHPC joint and MB deck reached 320 kN (72 kips) of peak load, 85% of C1's peak load capacity. The weak deck (MB) material started spalling off after concrete crushing began in the compression zone. The beam region started slipping with crack completely separating the beam and joint regions. It still surpassed control C3's capacity by 12.5% and reached 97% was C2's capacity. Even with concrete cracking in beam and deck regions, there was no significant cracking or failure which was observed in the UHPC material. Furthermore, UHPC held the structure together and increased the load sustaining capacity without completely failing. Specimen B2 reached a peak load of 441 kN (99 kips) of peak load surpassing all other specimens peak load capacity. B2 joint and deck were cast using UHPC which improved the capacity significantly. The failure was due to rupture in rebar in the deck region. Due to higher stiffness of UHPC, specimen B2 was not able to reach a higher peak deflection and further loading lead to rebar rupturing and significantly drop in load after which the testing was stopped resulting in a less ductile behavior overall. The rebar rupture only occurred after crack propagation started and reached the compression zone of the beam region with concrete crushing initiation.

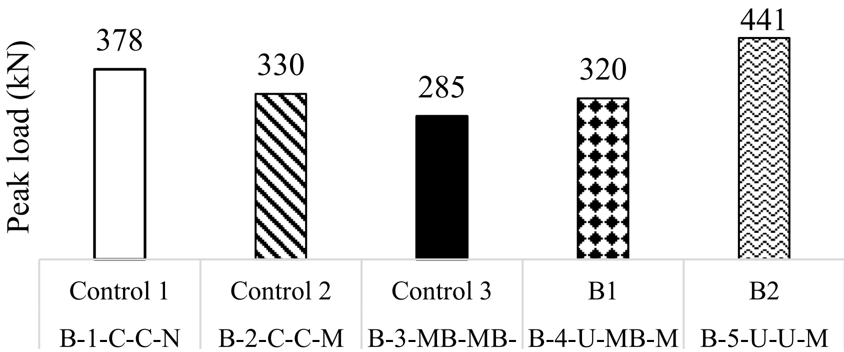

Figure 4: Peak Load Results (kN)

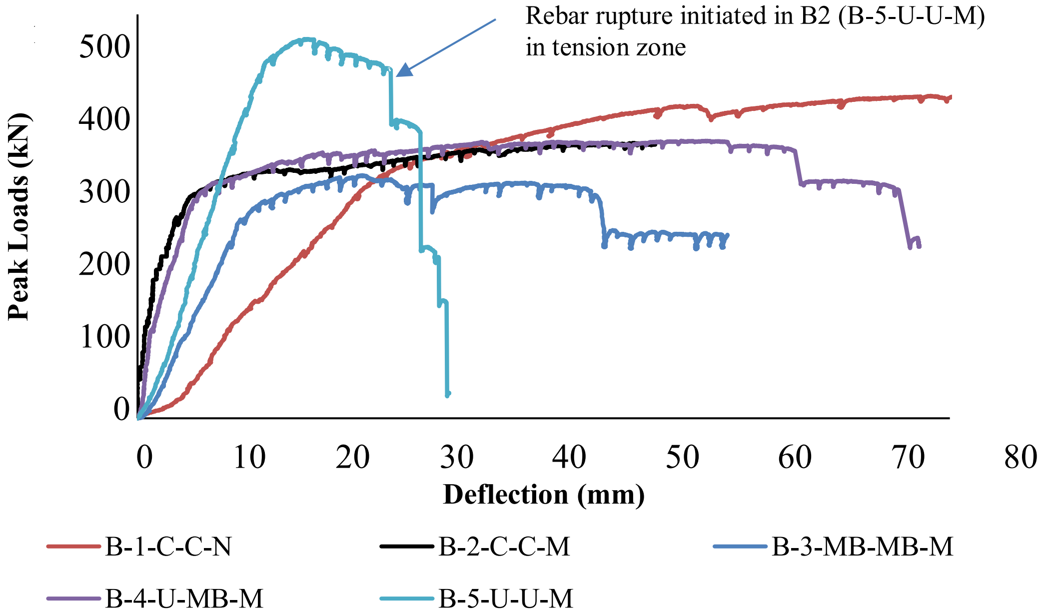

Figure 5: Load versus Deflection Curves

Figure 6: Specimens at failure (Top to bottom): C1, C2

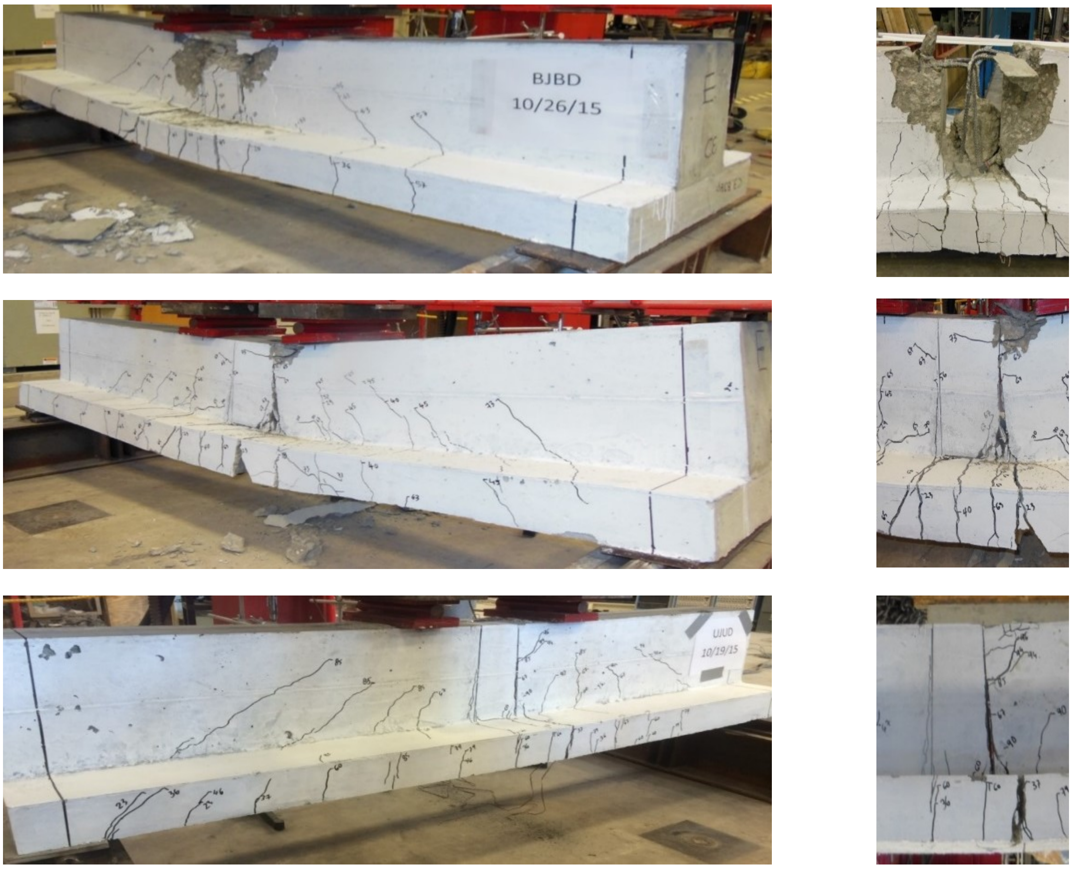

Figure 7: Specimens at failure (From top to bottom): C3, B1, B2

A Ductility Index (DI) study was undertaken. The ductile capacity of each test specimen was compared to the control specimen C1 by calculating the area under the load versus deflection curve for each specimen and getting a ratio with respect to C1. This ratio is defined as the Ductility Index (DI). The number gives an idea of how the specimen sustained load compared to control C1. Results summarized in Table 3.DI of B1 is 1.6 indicating that the UHPC joint-MB deck performed very well in terms of ductility as it surpassed C1's capacity by 60%. This is a clear indicator that UHPC works significantly well when used in connections. It must be noted that the loading was applied so as to create a worst case scenario in the connection and UHPC not only was able to reach but also surpassed the control's ductile behavior (by 60%). Specimen B2 was also successful when flexural capacity is considered reaching 85% of C1's capacity. It is interesting however to see that when UHPC was used in the deck, it was not as ductile reaching only 70% of the control C1's capacity. This can be attributed to that fact that even though UHPC was successful in surpassing the flexural capacity by 18%, higher stiffness lead to rebar rupture and higher deformation capacity could not be sustained. It is positive to note that the UHPC was able to allow yielding of the longitudinal rebar, hence utilizing the full capacity of the rebar.

Table 3: Ductility Index

Sl.no	ID (Nomenclature)	DI-1
1	C1 (B-1-C-C-N)	1.0
2	C2 (B-2-C-C-M)	1.1
3	C3 (B-3-MB-MB-M)	0.9
4	C4 (B-4-U-MB-M)	1.6
5	C5 (B-5-U-U-M)	0.7

5. CONCLUSIONS

UHPC's advanced material properties when used in joint applications demonstrate significant improved structural behavior. The testing conducted on test specimens with a non-prestressed MoDOT style end girder detail yielded favorable results in the following regard. UHPC used with a non-prestressed mild steel MoDOT end girder detail (Beam B-4) improved the ductility behavior compared to the control specimens (Beams C-1, C-2, and C-3), but couldn't equal the peak load capacity of a continuous CC member (Beam C-1) using a modified MoDOT B mix (f'_c = 23 MPa/3.2 ksi) without any joints and continuous longitudinal reinforcement. However, UHPC used in the joint region (Beam B-4, f'_c = 112 MPa/16.2 ksi) did show much greater peak load capacity compared to the control specimen (Beams C-3) with similar detailing. UHPC when used as a combined joint and deck filler (Beam B-5) attained the highest peak load compared to all other specimens investigated. It may be noted that a sudden failure was observed in the form of rebar rupture in the deck region well after yielding of the reinforcement showing the benefit of UHPC in both the joint and joint-deck region. Significant cracking throughout the entire load testing timeframe was not observed in the UHPC joint region in both beams (Beams B-1 and B-2). In both cases, failure was due to crushing of the concrete in the beam specimens under the load points.

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