

# **Ultra-High-Performance Concrete Bridge Decked I-Beam: Design, Production, and Testing**

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## **Abstract**

The paper presents the development of a new UHPC Decked I-Beam (DIB) superstructure system for bridges in Nebraska and discusses its design, production, and testing. The UHPC DIB was developed to achieve maximum deck durability, speed of construction, and structural efficiency. Special formwork was designed and manufactured to fabricate the developed system for both pretensioned and post-tensioned bridges, with options for using either minimized weight ribbed slab or simplified precasting solid slab top flange option. Two 20 ft long, 4.5 ft deep, and 9 ft wide full-scale specimens were manufactured by the two precast bridge producers in Nebraska using a UHPC mix design developed in an earlier project for NDOT using locally sourced materials: a) pretensioned specimen with ribbed slab; and b) post-tensioned specimen with solid slab. The solid slab top flange specimen was produced for the purpose of comparing behavior of the two geometries. Several material/structural tests were conducted on the two specimens to evaluate UHPC mechanical properties, shear strength without transverse reinforcement, wheel load transverse distribution in the DIB flanges, and anchorage zone reinforcement of the post-tensioned option. Test results indicated the adequacy of the developed system capacities when compared to the demand of 100 ft long simply supported bridge and predictions of the latest UHPC design guidelines. Lessons learned from the production of the two specimens are also discussed.

**Keywords:** Accelerated Bridge Construction, decked systems, ribbed slab, post-tensioning.

## **1. Introduction**

Several conceptual design alternatives were initially considered for an Ultra-High-Performance Concrete (UHPC) superstructure system for accelerated bridge construction (ABC) in the state of Nebraska. The main criterion in all these alternatives is to have a UHPC deck to address the common problem of deteriorating concrete bridge decks that leads to shorter service life, high maintenance cost, and frequent road closures. These alternatives include UHPC Decked I-Beam (DIB) with solid slab, UHPC DIB with ribbed slab with and without edge rib, conventional concrete I-beam made composite with UHPC ribbed slab, and UHPC I-beam made composite with UHPC ribbed slab. These alternatives were discussed with Nebraska Department of Transportation (NDOT) bridge engineers and precast bridge producers and were evaluated with respect to weight, ease of production, and speed of construction. It was decided to eliminate the two alternatives with multiple components that need to be made composite as this could slow down the construction and may require further testing of the shear connectors. For the remaining alternatives, UHPC DIB with ribbed slab was determined to be the best alternative with respect to weight, while UHPC DIB with solid slab was determined to be the best alternative with respect

to ease of precasting. A solid slab would also be helpful in the ends of skewed spans. The two alternatives are considered in this study due to the unique advantage of each alternative. The use of edge rib has the advantage of simplifying beam production and forming the cast-in-place longitudinal joints in the field, but it requires different set-ups in the ribbed slab option to accommodate rib block outs, for different top flange widths. On the other hand, the elimination of edge rib has the advantage of simplifying form stripping and accommodating variable width of the top flange, but it requires more complex forming for the longitudinal cast-in-place joints, which would slow down field operations. This alternative is not considered in this study. For the selected UHPC DIB system, two production options are proposed: 1) pretensioned full length DIB; and 2) post-tensioned DIB segments. Although the pretensioned option is preferred due to its cost-effectiveness in North American practice, it imposes a current challenge for precast industry as the production facilities are not equipped to produce the large batches of UHPC as needed for a full-length UHPC DIB, while maintaining continuity of placement. The post-tensioned option is considered as a possible solution that allows the production of short-length UHPC DIB segments that can be match-cast and spliced using post-tensioning. It also reduces precaster financial risk in the early stages of implementation as loss of one 20-ft defective piece is smaller than loss of 100-ft long full beam.

## 2. Form Design

The DIB form was designed using removable rib forms (i.e. pans) to allow for the solid slab option. DIB form was designed in consultation with forming company KESSAB STEEL LLC of the United Arab of Emirates as shown in Figure 1. The manufacturer suggested the use of manually operated cranking system to allow for vertical movement of the soffit forms. The form allows the production of 20 ft long, 4.5 ft deep, and up to 10 ft wide UHPC DIB segments with 4 in. thick web and 8 in. thick slab with 2 ft spaced ribs. In later iterations, several forming companies participated improvements, by creating swiveling top flange forms with polyurethane pan liners. Such improvements are given in other presentations in this conference and are not covered here.

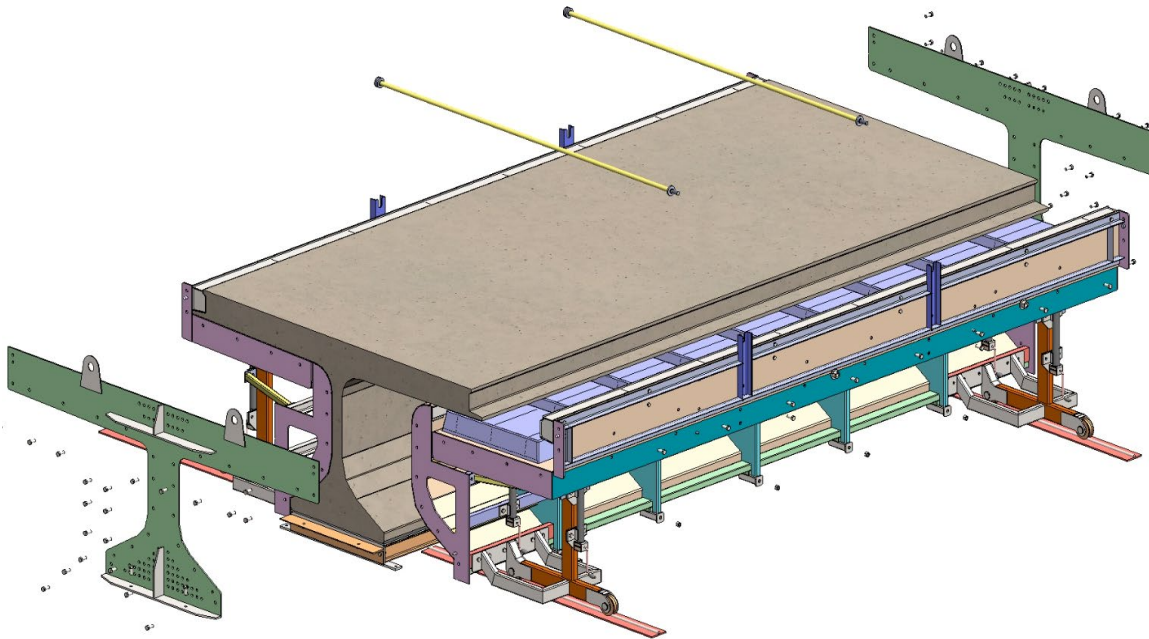


Figure 1: 3D view of the DIB forms and its stripping process

### 3. Production of Precast Pretensioned DIB Specimen

The pretensioned DIB specimen with ribbed slab was produced by Coreslab Structure Inc. (Omaha) using the UHPC mix developed for NDOT by UNL (Mendonca, et al. 2020). The estimated UHPC quantity was 5.6 cy, made in two batches, each was 3.2 cy for a total quantity of 6.4 cy using twin shaft mixer of conventional precast concrete. Silica fume, steel fibers, and chemical admixtures were manually added, while sand, cement, slag, and water were added automatically using the batching control system. To control the temperature of the mixture to be between 50°F and 85°F, either cold water is used or a percentage of water quantity is replaced with ice. In this case, cold water is used as the ambient temperature was 42°F. After the first batch was fully mixed, it was placed in a ready-mix truck to remain agitated until the second batch was ready. The two batches were transported to the prestressing bed and tested for workability before being placed in the form. The flow test according to ASTM C1856 indicated low flowability. Additional dosage of superplasticizer was added to achieve the acceptable (8 – 10 in.) flowability.

Figure 2 shows the form and reinforcement of UHPC DIB pretensioned specimen. The figure indicates that the specimen does not have stirrups in the web or longitudinal reinforcement in the ribbed slab, which simplifies production. The only mild reinforcement used is the top and bottom transverse reinforcement in the ribs (2#5 per rib) and end zone bursting reinforcement at one girder end (2#6). This was made by design to evaluate the cracking at girder ends at release with and without bursting reinforcement. The specimen was pretensioned using 16-0.6 in. Grade 270 low relaxation straight bottom strands tensioned to 75% the ultimate strength with no debonding. Two 0.6 in. straight strands were added to the top and were tensioned to 5 kips to support transverse reinforcement as in common practice. The figure also shows the foam block-outs in the flange to allow bracing chains to go through and stabilize the specimen during transportation.



Figure 2: The form and reinforcement of pretensioned UHPC specimen with ribbed slab

Casting UHPC into the forms was done directly from the truck. UHPC continued to lose workability with time, which required the addition of multiple dosages of superplasticizer to maintain workability. The top surface of UHPC was finished using a concrete screed and with minimal surface vibration to help in leveling the top surface. Plastic sheets were placed over the top surface immediately after finishing to prevent moisture loss and formation of elephant skin and shrinkage cracking. To minimize the negative effect of UHPC early-age plastic shrinkage on form stripping, it was planned to strip the forms the next day at 24 hours from casting UHPC. Earlier stripping was not recommended due to the long setting time of UHPC and the length of

ribbed slab overhangs that could result in top flange cracking. The edge forms were easy to strip, however, the flange pans used to create flange ribs were very difficult to strip. This was attributed to the early-age plastic shrinkage of UHPC, inadequate tapering of the pans, large suction force preventing the pans from popping out when lowering the bottom forms. Possible solution to this problem is to use shrinkage reducing admixture, more tapered pans and plastic-covered pans to reduce friction with UHPC while stripping. These adjustments were planned to be used in the next generation of forms, which is the subject of other presentations in this conference.

Figure 3 shows the compressive strength and flexural strength test results of specimens taken from the combined batches. These results indicate that UHPC meets all the minimum requirements according to PCI TR-9-22, which was the materials component extracted from a larger PCI report on materials and structural design (PCI, 2021). The visual inspection of the DIB specimen indicated that UHPC had good consolidation and the specimen has good surface quality at the shear key, top surface, web surface, and around prestressing strands. The presence of fibers at the top surface is an indication of excellent fiber stability.

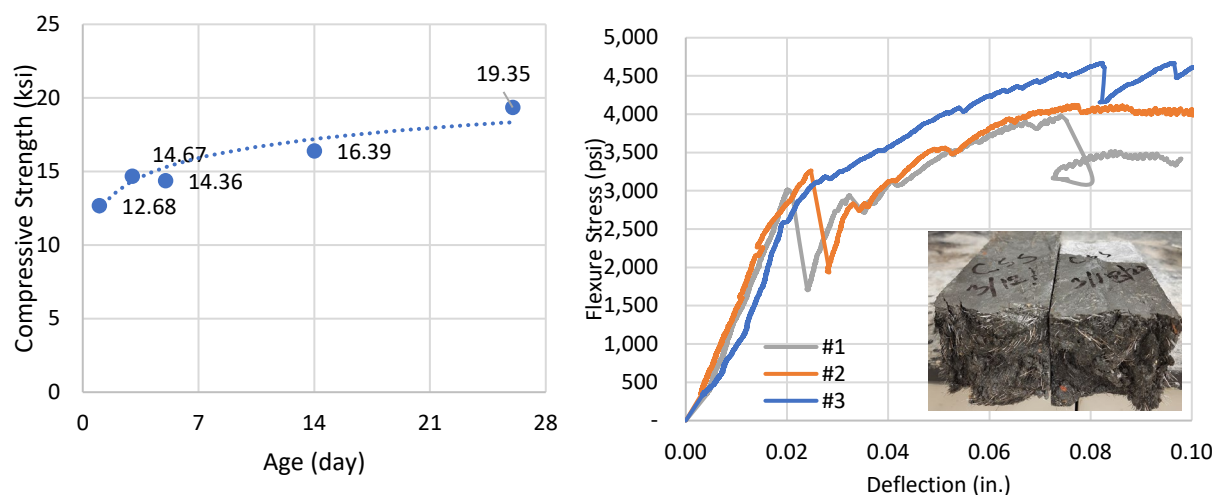


Figure 3: Compressive strength and flexural strength test results

#### 4. Production of Precast Post-tensioned DIB Specimen

This post-tensioned DIB specimen with solid slab was produced by Concrete Industries Inc. (Lincoln) using the same mix as for the pretensioned specimen. The total quantity required for production was estimated at 6.4 cy. The producer decided to make three batches, each batch is 2.2 cy for a total quantity of 6.6 cy. The flow measured for each batch using samples taken from the truck delivering the product to the forms. Ambient temperature was 55°F at the time of batching, therefore, ice was used to keep the temperature within the acceptable limit. Figure 4 shows the form and reinforcement of the DIB post-tensioned specimen with solid slab. The specimen was formed using the same forms shown in Figure 1 but without the pans used to form ribbed slab voids and with different edge form that does not have a lip. The specimen does not have either transverse reinforcement in the web or longitudinal reinforcement in the flange. Figure 4 shows the top and bottom transverse reinforcement (#5@12 in.) in the slab and end zone reinforcement (8#6) at both girder ends. This reinforcement had an L-shape to reinforce around the post-tensioning anchorage as the conventional spiral reinforcement was eliminated due to limited space. The specimen has a 4.25 in. diameter bottom plastic duct to host 19-0.6 in. bottom strands. Foam block-outs in the web were used for bracing the specimen during transportation. This is the

preferred method as opposed to than used by Coreslab through the top flange. It would be desirable to minimize top flange block-outs to avoid possible water intrusion during the life of a bridge.



Figure 4: The form and reinforcement of post-tensioned DIB specimen with solid slab

Casting UHPC into the forms was done using a concrete bucket filled from the truck chute and moved over the form for placing UHPC. At the beginning, UHPC was flowable yet stable, which made filling the bottom flange and web easy and quick. Later, UHPC started to lose flowability, which required adding more superplasticizer for casting the top flange. Also, screed and shovels were used to level and finish the top flange surface. Plastic sheets were placed over the top surface immediately to prevent moisture loss and early-age cracking. Form stripping was done after two days as UHPC early strength exceeded 10 ksi. Edge forms and end forms were easily removed. Then, soffit forms were slightly dropped. Crane was used to remove the side forms. Visual inspection indicated no shrinkage cracks and stability of steel fibers that shows at the top surface.

Figure 5 show the compressive strength and flexural strength test results of cylinders and prisms taken from the combined batches. These results indicate that UHPC meets all the minimum requirements according to PCI TR-9-22. Figure 5 shows a saw cut cylinder to demonstrate fiber distribution, which indicate the excellent fiber stability of the used UHPC mix. The UHPC DIB was shipped to the structural laboratory of UNL in Omaha to be post-tensioned. Specimen was braced during transportation using chains thought the web opening.

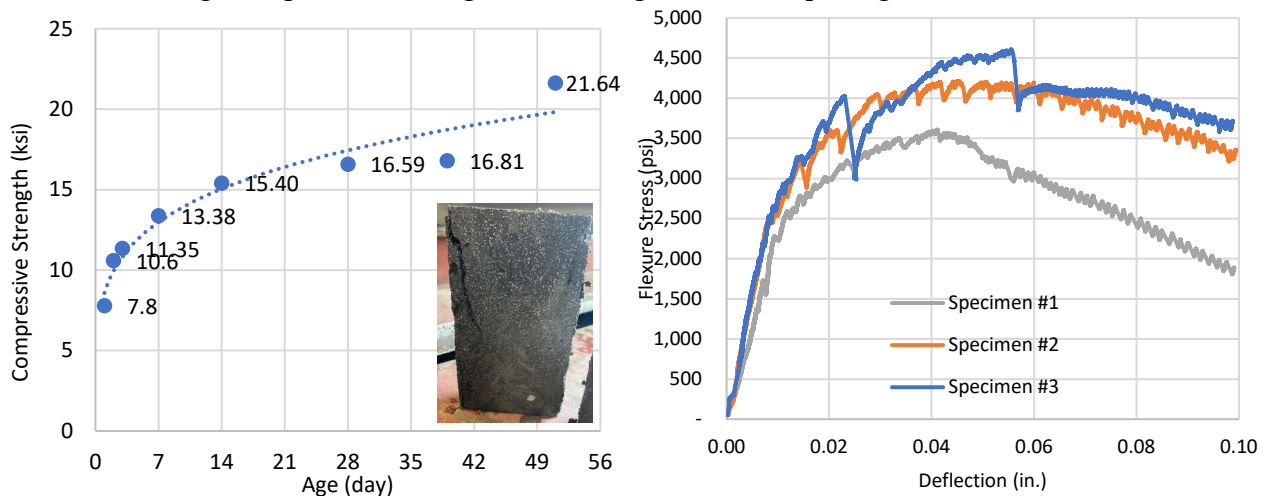


Figure 5: Compressive strength and flexural strength test results

## 5. Experimental Investigation

This section presents the testing of the two full-scale UHPC DIB specimens. This includes measuring the transfer length, vertical shear test, transverse load distribution test, and post-tensioning anchorage test.

### 5.1. Transfer Length Measurements

A total of 12 DEMEC gauges were attached to one end of the pretensioned DIB specimen at the level of prestressing strands and at 4 in. spacing. Measurements were taken before and after prestress release to calculate the elastic strain in the end 4 ft of the DIB. Figure 6 plots strain measurements and the 95% of the maximum average strain is used to estimate the transfer length, which was found to be approximately 13 in., which is in agreement with the PCI prediction method that suggests 20 times strand diameter (12 in.).

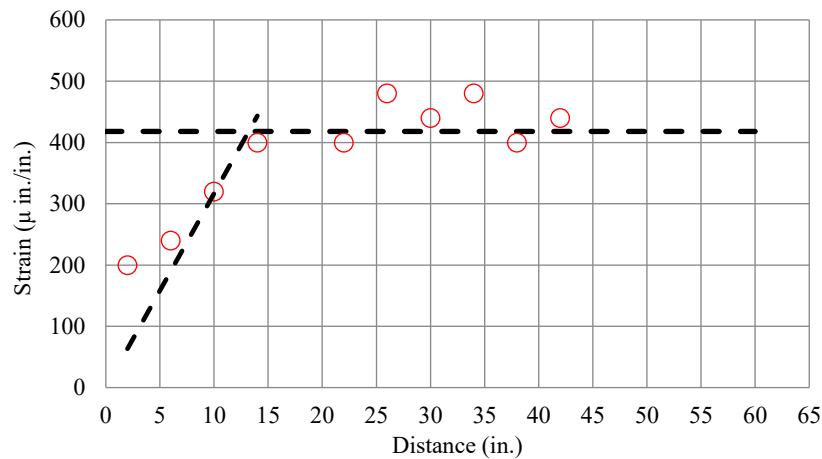


Figure 6: Strain measurements for estimating transfer length

### 5.2. Vertical Shear Test

To evaluate the shear capacity of UHPC DIB without transverse reinforcement in the web, the pretensioned specimen was loaded at the middle of the span, which results in a shear span to depth ratio 2.1 and ensures that the shear failure occurs before the flexural failure of the specimen. Test results indicate that a maximum load of 612 kip was achieved, which corresponds to a shearing force of 317 kip including the self-weight. Loading was stopped as it reached the maximum capacity of the loading frame before reaching the maximum shear capacity of the specimen, which was estimated at 338 kip. This is acceptable as the measured load already exceeds the shear demand of 285 kip estimated for a 100 ft long simply supported bridge with 10 ft girder spacing. Diagonal tension cracks were observed at the middle of the shear span in both sides of the beam. The measured crack angle was found to be approximately 32°deg., which is close to the predicted crack angle of 30.8 deg. It was also observed that end zone cracking occurred only at the girder end that does not have bursting reinforcement, while the other end that had 2#6 is crack free.

### 5.3. Transverse Load Distribution Test

This test was conducted to evaluate the wheel load distribution in the transverse direction for ribbed and solid slabs as their behavior cannot be accurately predicted using current AASHTO

LRFD. The two specimens were tested without longitudinal joints or rail to determine a conservative estimate of the capacity of the overhang. Figure 7 shows the steel spreader beam and loading plates used to simulate the wheel patches. Load was applied between the slab ribs as it is the most critical position. The DIB was supported at the midspan in the longitudinal direction to prevent its deflection while loading. The test of the ribbed slab specimen reached a maximum load of 78 kips, which is more than twice the demand of 37.24 kips and 70% more than the predicted load of 45.23 kip using the AASHTO LRFD primary strip width of 6.1 ft. Figure 7 also shows failure mode of punching shear as well as the rupture of the edge rib due to absence of continuous reinforcement in the edge rib. Note that in a total bridge system with CIP closure pour, there will be longitudinal reinforcement in addition to the transverse rib reinforcement. Thus, the mode of failure shown for the lab specimen may not be totally representative of the two-way resistance in an actual bridge. Figure 8 shows the loading of the post-tensioned specimen with solid slab using the same loading frame, rams, spreader beam, and loading plates used in testing the ribbed slab specimen. The DIB was supported at the midspan in the longitudinal direction to prevent its bending and deflection while loading. The test of the solid slab reached a maximum load of 120 kips then stopped to preserve the specimen for further testing. This load is 3.2 times the demand of 37.24 kips and 2.3 than the predicted capacity of 52.14 kip using the AASHTO LRFD primary strip width of 6.2 ft. Figure 8 also shows the bottom and side transverse cracking, which is considered insignificant given the magnitude of the load of 120 kips.



Figure 7: Ribbed slab test setup and failure mode



Figure 8: Solid slab test setup and failure mode

#### **5.4. Post-Tensioning Anchorage Test**

Due to the limited space at the bottom flange of the DIB, standard PT anchorage was modified by eliminating the standard spiral reinforcement to fit in the bottom flange without casting a special anchorage block. This will simplify the production of DIB segments by using the same prismatic forms used for the pretensioned option. To evaluate the performance of the modified PT anchorage hardware, this test was conducted using multi-strand standard ECI 6-19 anchorage from VSL but without the standard spiral reinforcement around the trumpet. Instead, a special L-shape end zone bursting reinforcement (8#6) was used around the trumpet. A total of 6 DEMEC gauges were installed to the middle section of the specimen at 2.5 in. from the bottom to measure the strain due to post-tensioning and verify the applied force. A mono-strand hydraulic ram and special adapter plate was used to ensure that wedge seating loss is only  $\frac{1}{4}$  in. Tensioning was completed in a symmetrical manner and in two stages 50% then 100% of the full prestressing force to minimize elastic shortening losses. Also, tensioning was conducted from both ends of the specimen to minimize friction losses. Markings were made on the strands to measure the actual elongation and compare to the predicted elongation of 1.65 in. as a verification that the design PT force was achieved. No cracking or any signs of distress was observed, which confirms the adequacy of the provided end zone reinforcement. Also, strain measurements at midspan using DEMEC gauges resulted in an average strain of 0.00024 directly after post-tensioning. This slightly less than predicted strain of 0.00026, which could be attributed to normal variability in stress measurements and/or friction losses that were not counted for.

#### **6. Conclusions**

Production of the non-proprietary UHPC mix in a large quantity (6.6 yd<sup>3</sup>) is successful and its mechanical properties meet all the minimum requirements according to PCI TR-9-22, which was the materials component, extracted from a larger PCI report on materials and structural design. Mixing multiple small batches in a truck mixer is a good practice as it ensures consistency, allows adjusting workability, and prevents the formation of cold joints. Stripping the pans for forming ribbed slab voids is challenging due to friction and shrinkage effects. As a result of this observation, a modified forming system to allow for simplified pan removal in addition to use shrinkage reducing admixtures has been implemented for future applications. UHPC DIB with 4 in. web has adequate shear capacity for 100 ft simple span at 10 ft spacing without the need for shear reinforcement. No spiral reinforcement is needed in the local zone of PT anchorage as the random steel fibers are adequate for providing the necessary confinement.

#### **7. References**

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