The poor condition of many stringer type bridges on U.S. roadways is due to the cracking and deterioration of concrete decks. Concrete shrinkage, temperature changes due to heat of hydration, and differential creep in relation to the support beams often result in cracking of cast-in-place concrete decks shortly after placement. The NUDECK system, a full-depth precast/prestressed concrete bridge deck panel system developed by the University of Nebraska-Lincoln, is presented in this article. The design and construction of the Skyline Bridge in Omaha, Nebraska, is the first implementation of this bridge deck system. The deck is pretensioned in the transverse direction and post-tensioned in the longitudinal direction. Using a combination of high performance precast concrete – where little creep and shrinkage occur after the deck is made composite with the girders – and two-way prestressing ensure continued compression of the deck during its service life. This low maintenance deck system can be used for both concrete and steel bridges and results in significantly reduced construction time and traffic disruption.

The large majority of short to medium span bridge systems in the highway infrastructure of the United States are constructed of a composite beam/slab system. Most of the bridge beams are constructed of precast, prestressed concrete or structural steel I-beams. Bridge decks in North America are built primarily with cast-in-
place (CIP) reinforced concrete. Field adjustments during construction of CIP bridge decks have the advantage of producing a smooth roadway profile and providing composite action, or structural continuity, between the beams, the deck, and the railing for crash protection.

Drawbacks to CIP decks include low speed of construction, the need for strict field quality control, and cracking due to the concrete’s tendency to shorten relative to the beams as a result of cooling during the cement hydration cycle and differential creep and shrinkage.

CONDITION OF U.S. HIGHWAY BRIDGES

As a result of cracking, CIP decks often require major repair or complete replacement within 15 to 25 years of construction, while the bridge beams remain structurally sound. Nearly one-half of the 600,000 highway bridges in the United States are in need of rehabilitation or replacement. Many of these bridges carry heavy volumes of traffic.

Bridge repair, widening, or replacement must be completed as quickly as possible to minimize traffic flow disruption and/or road closure. Many existing bridges require remedial action due to CIP deck slab deterioration. Therefore, deck systems that can be used quickly and efficiently to replace deficient bridge decks are an important development for highway bridge repair and replacement programs.

The Federal Highway Administration (FHWA) has made numerous attempts to address the serious and widespread problem of highway bridge deck deterioration. One of the earliest FHWA efforts was the Giles Road Bridge in Sarpy County, Nebraska, part of a federal high performance concrete (HPC) showcase program. Opened to traffic in 1997, the Giles Road Bridge deck was made with a special low permeability, 8000 psi (55 MPa), HPC under strict curing conditions. Upon inspection of the bridge several weeks after completion, the structure exhibited significant cracking on the bottom surface of the deck.

Similar observations were made at other bridge projects, even in cases where Type K expansive cement and shrinkage compensating admixtures were used in the deck concrete mixture to minimize cracking. Undesirable disruptions to the traveling public and bridge closures resulting from bridge maintenance projects are major concerns for federal and state transportation agencies.

Deck Panel Systems

There are currently two types of precast, prestressed deck panel systems. The more commonly constructed type utilizes 3 to 5 in. (76 to 127 mm) stay-in-place pretensioned panels that span between beam edges and are totally separated over beam top flanges. Precast panels contain the positive transverse moment reinforcement, which is generally pretensioning strand. Negative moment reinforcement is provided in a CIP concrete composite topping.

This system sometimes experiences reflective cracking over panel edges. In addition, experiments in the National Cooperative Highway Research Program (NCHRP) 12-41 Project have confirmed that the lack of beam support anchorage for the transverse strand in individual panels reduces arching action and the system’s load capacity compared to full-bridge-width CIP or precast concrete panel systems. Another major disadvantage of this system is the need for costly construction of conventional forming of the bridge overhangs.

The second precast concrete deck system, often used in replacement projects, is full-depth and full-bridge-width precast panels that are about 8 to 10 ft (2.4 to 3 m) long. These panels are conventionally reinforced in the transverse direction and post-tensioned longitudinally. This system has been placed primarily on steel plate beam bridges with shear stud connectors clustered in pockets at about 24
in. (610 mm) spacing. Pockets are grouted after the panels are post-tensioned. The deck system generally has no transverse prestressing, and is thus subject to cracking under service conditions.

It appears, therefore, that a need exists for a cost-effective concrete deck system with the following characteristics:

1. Precast concrete installed after creep, shrinkage, and heat of hydration have taken effect.
2. Prestressed concrete in which the level of prestressing is high enough to result in zero residual tension at service conditions, both in the longitudinal and transverse directions.
3. A panel system that allows for simple construction and creation of composite action with bridge beams.
4. A panel system that allows for the prestressing to be introduced before composite action takes place, so that the much stiffer beams do not attract most of the prestressing forces.

This paper presents an innovative full-depth precast/prestressed concrete bridge deck system that enables fast and efficient construction, yields superior performance in service, and reduces long-term maintenance and replacement costs.

**SKYLINE BRIDGE**

The bridge chosen as a prototype for the NUDECK system is located at Skyline Drive and West Dodge Road in Omaha, Nebraska (see Fig. 1). The bridge carries Skyline Drive traffic over West Dodge Road (US 6 Expressway). Current average daily traffic is 1445 vehicles, and is estimated to increase to 3110 vehicles per day by 2022.

Total project cost was $682,250 or $61.39 per sq ft ($661/m²). Cost for the 6 in. (152 mm) precast concrete deck panel was $215,292 or a unit cost of $19.37 per sq ft ($209/m²); see Table 1 for a detailed breakdown of project costs. The bridge was completed in December 2003. Minimizing the amount of field work through use of the precast deck panels allowed the contractor to work through the cold winter season.

The Skyline Bridge consists of two spans, 89 and 125 ft (27 and 38.1 m), with a 25-degree skew (see Fig. 2). Total bridge deck area is 11,113 sq ft (1032 m²). Steel plate girder spacing is 10.83 ft (3.30 m). A typical precast concrete deck panel is 7 ft (2.1 m) long, 56.8 ft (17.3 m) wide (full bridge width), and 6 in. (152 mm) thick.

The steel beams are made composite with the deck panel through 1 1/4 in. (32 mm) diameter studs, which have twice the capacity of 7/8 in. (22 mm) standard diameter studs. Joints between the panels are grouted using flowable concrete. The longitudinal open gap over girders and a 2 in. (51 mm) composite overlay are filled with Type K cement, shrinkage compensating, concrete mixture.

**PROPOSED SYSTEM DESCRIPTION**

Fig. 3 shows a typical precast, prestressed panel for the NUDECK system. The system consists of various components, including open gaps over girder lines for shear studs and post-
tensioning; shear keys between panels; precast concrete curbs; and sleeves for barrier post attachment. Also shown is the beam underneath the panel and shear studs. Each typical panel is reinforced with No. 5 (16M) steel bars at 12 in. (305 mm) spacing in the longitudinal direction (see Figs. 4 and 5).

The transverse reinforcement consists of pairs of 1/2 in. (12.7 mm) diameter, Grade 270 ksi (1865 MPa) low-relaxation strands at 24 in. (610 mm) spacing. The two strands in the pair are spaced vertically to allow 1 in. (25.4 mm) clear concrete cover. The effective pretensioning stress (after accounting for time-dependent losses) is about 350 psi (2.4 MPa); considering arching effects and strand continuity, theory has shown this quantity to be adequate for beam spacing up to 12 ft (3.7 m). To ensure a short transfer length of prestressing, an innovative detail was used: high strength wire spirals were placed around the end 24 in. (610 mm) of each strand pair.

Innovations

One of the primary innovations of this precast concrete deck system is the fully open gap in the panel over each of the beam lines. To preserve the tension in the continuing strands and, thus, the pre-compression in the concrete – the absent concrete strip in the gap is substituted with four No. 7 (22M) steel bars at the location of
each pair of strands. These bars can be viewed as “prestressed, or pre-compressed” bars.

The specified concrete strength of the precast concrete panels was 4300 psi (30 MPa) at release and 6000 psi (41 MPa) at service. The actual panel strength was over 8000 psi (55 MPa), as the same mix typically used for precast, prestressed concrete beams was used in the precast plant for the bridge decks.

Within the space in any given gap, the tension in each pair of strands is equal to the compression force in each set of four reinforcing bars. In the solid concrete between beam line gaps, the tension in the strands is equal to the compression force in the concrete. The bar size is determined by its ability to resist buckling during prestress release and bending during handling and erection. The value of a totally open gap is to avoid interference with the composite action studs, and more importantly, to greatly simplify post-tensioning in the longitudinal direction.

**Large diameter steel studs** – In one row, large diameter studs were placed at the centerline of the beam at 6 in. (152.4 mm) spacing (see Fig. 6). Funding provided by the NCHRP 12-41 Project and the Nebraska Department of Roads (NDOR) supported extensive ultimate strength and fatigue studies on 1 1/4 in. (32 mm) diameter studs. These studies demonstrated that each 1 1/4 in. stud is structurally equivalent to two 7/8 in. (22 mm) diameter studs. A bridge had previously been constructed with this larger sized stud and has performed equally well to that of a conventional design. Using these large studs significantly reduces the fabrication costs of steel plate girders, improves safety in the field by allowing more work space on the edges of the narrow girder top flange, and speeds up total construction.

**Panel support system** – A hanging support system, or plastic shim stacks, had been envisioned to be placed at the corners of the panels at each beam line (see Fig. 7). The height of support (or shim stack) is calculated by the bridge designer. The designer calculates the support or shim heights after accounting for deflection due to panel weight. After the panels are set in place on the support or shims, further minor profile adjustments can be accommodated in the CIP concrete topping thickness.

During the bridge construction, the contractor opted to use continuous light gauge shelf angles, similar to the system used for stay-in-place concrete sub-panels and metal decking. The angles provided continuous support and also a dam against leakage of the concrete placed in the open gap over the
High performance grout – Grouting of the transverse shear key joints between panels was done using a flowable HPC mix. There is no need to use shrinkage-compensating admixtures in this mix, as the joints will have in-service residual compression due to longitudinal post-tensioning. The grout strength should match that of the panels – in this case – a minimum specified strength of 6000 psi (41 MPa).

Post-tensioning system – Post-tensioning was done in a unique process using 16 - 0.6 in. (152 mm) diameter strands threaded between the pairs of strands and groups of four bars. The gap over the beams can be viewed as an open channel post-tensioning duct, or sheathing. The criticism in recent years regarding a lack of quality grouting of post-tensioning ducts is totally eliminated here. The tensioning of the strands was done individually, using a light-weight mono-strand jack (see Fig. 8), supplied to the contractor (along with the necessary training) by the University of Nebraska-Lincoln (UNL) Structural Laboratory staff.

Post-tensioning is executed after the transverse joints attain adequate strength [about 1500 psi (10.3 MPa)] and before composite action is affected. In this way, the post-tensioning force is fully applied in the deck alone, rather than inefficiently sharing it with the much stiffer beams. The pre-compression in the deck is about 800 psi (5.5 MPa); this would allow for no tension in the deck even in the negative moment zones over the piers. As a result of post-tensioning, the precast concrete deck is highly resistant to transverse cracking, which has been a major problem in recent years.

Because of the high intensity of the post-tensioning in the open channels within a shallow 6 in. (152 mm) slab, no suitable commercial post-tensioning anchorage system was available. Extensive analytical and experimental studies at the UNL resulted in a simple, locally-fabricated, curved plate system, along with the necessary splitting reinforcement in the two end panels of the bridge.

Expansive grout – The longitudinal channels, or gaps, over beams were
filled with expansive, Type K cement mix; this mix was developed at UNL to achieve high strength, adequate flowability, and expansion during the initial set. The 2 in. (51 mm) concrete composite overlay topping was made of the same mix as that for the open channels.

**PANEL PRODUCTION**

The precast panels were produced at Concrete Industries, Inc., in Lincoln, Nebraska. Fig. 9 shows a typical precast deck panel reinforcement setup. Prestressing steel includes four pairs of 0.5 in. (12.7 mm) diameter Grade 270 ksi (1860 MPa) low-relaxation strands along the width of the panel, or bridge transverse direction. The panel mild steel reinforcement consists of eight No.7 (22M) bottom bars continuous along the pretensioning strands, four No.7 by 5 ft (1.5 m) long top bars at the open channels along the pretensioning strands; and No. 5 (16M) bars at 12 in. (305 mm) on center along the traffic direction.

Steel reinforcing spirals of 4.5 in. (114 mm) outside diameter, and 1/4 in. (6.35 mm) diameter wire at 1 in. (25.4 mm) pitch, were installed at the ends of pretensioning strands; the spirals provided concrete confinement of the strands, and thus ensuring their capacity within the deck overhang. The primary deck reinforcement is determined by the construction load (two CAT 950F front end loaders) provided by the contractor, Hawkins Construction Company, instead of the live load specified in the AASHTO LRFD Bridge Design Specifications.

The production schedule was typically one day to set up the deck reinforcement with concrete casting taking place on the following day. The deck panels remain in the prestressing bed for one day to attain the required concrete strength prior to removal of the forms. Fig. 10 illustrates hoisting of a precast concrete panel in the precast yard.

**Crown Forming Frame**

The bridge skew and the requirement for a sidewalk on one side made the deck panel geometry relatively challenging for the precaster, especially the fabrication of the 2 percent roadway crown. An innovative system to develop a constant-thickness precast pretensioned panel with a crown is described in detail below.

To the authors’ knowledge, the crowned panel system that was successfully used in the Skyline Bridge is
the first time that a constant-thickness precast concrete pretensioned panel with a crown has been created and used commercially.

DEVELOPING A CROWN IN A PRETENSIONED PANEL

Since the panel is transversely pretensioned with two layers of strands, creation of a 2 percent crown was one of the most challenging issues during the NUDECK system development. Developing a crown by increasing the slab thickness towards the centerline of the roadway would have made the panel weight and the bridge dead load unacceptable. The UNL researchers worked closely with the state bridge designers and the local precast producers to develop a crown system.

As a result of these concerted efforts, two demonstration panels were made. Testing was performed to verify the validity of the concept and to simplify its application. The refined crown detail was incorporated in the Skyline Bridge deck. Figs. 9 to 13 illustrate how a typical precast concrete panel was produced.

Crown Development Sequence

The demonstration panels were 55 ft (16.8 m) long, 8 ft (2.4 m) wide and 6 in. (152 mm) thick with a 25-degree skew. To create a 2 percent crown, a solid plastic PVC (polyvinyl chloride) rod, 8 ft (2.4 m) long, and 1 3/4 in. (44 mm) in diameter was placed along the centerline of the crown (see Fig. 10). The center of the plastic rod was located 1 in. (25.4 mm) above the bottom fibers.

The 0.5 in. (12.7 mm) diameter pretensioned strands in the bottom layer were kept continuous along the 55 ft (16.8 m) panel length through holes in the plastic rod. The top 1/2 in. (12.7 mm) diameter strands ran without interruption. Above the plastic rod, a steel plate was placed; the plate had slots at the locations of the top strands to avoid interference with these strands and to allow for its removal after the panel was stripped from the casting bed.

After the prestressing force was released and the panel was lifted out of the prestressing bed, it was completely flat, as shown in Fig. 11. The panel was then placed on a frame, or saddle, that had a top surface corresponding to the prescribed 2 percent crown slope (see Fig. 12). The deformed shape of the panel allowed the slotted steel plate to be easily removed.

Once the top steel plate was removed and the top strands were cut with a saw, the panel assumed the required crowned profile. Three pairs of A706 No. 7 (22M) weldable steel bars that had been cast into the panels in the same layer as the top strands were welded. Pockets were grouted to maintain panel stability during shipping and handling. Crowned panels were stacked up in storage as shown in Fig. 13.

SKYLINE BRIDGE DECK PANEL CONSTRUCTION

All precast deck panels were shipped in three days from the precast yard in Lincoln to the bridge construction site at Omaha, a distance of about 60 miles (97 km). The panels were shipped individually. While the panels could have been shipped in stacks, this was ruled out in this case due to the
relatively small size of the project. The panels were erected by the same crane that was still available after girder erection, instead of the CAT 950F front end loaders as initially proposed by the contractor.

It took about 15 minutes to position each panel at the appropriate location (see Fig. 14). After several panels were placed, a plan view (see Fig. 15) of the Skyline Bridge shows the continuous steel angles as the support system and the 1 1/4 in. (32 mm) studs. Once all the panels were erected, the shear key was grouted. Fig. 16 illustrates curing of the shear key.

Afterwards, the post-tensioning strands were pulled through the channels (see Fig. 17). The strands were anchored by one-time-use chucks. After verifying that no strands were intersected or inter-wound, post-tensioning took place. Each strand was tensioned to a final force of 38.9 kips (173 kN), and checked by both gauge reading and the strand elongation. Use of the mono-strand tensioning device proved very easy to operate. The entire post-tensioning operation was completed by a local non-specialized crew in less than two days.

The channels over the girder lines were grouted as shown in Fig. 18. After the channel concrete was cured and hardened, composite action was established between the beam and precast deck. Type K non-shrinkage ce-
ment was then placed to form the 2 in. (51 mm) concrete overlay and then cured (see Fig. 19). Based on the feedback from the contractor, Type K cement posed no concrete placement problems. However, the ready-mixed concrete supplier had difficulty finding and importing this cement for the job; the supplier indicated that the imported cement was about three times more expensive than Type I/II cements.

The following steps outline a typical bridge deck construction procedure:
1. Determine the elevations of the support system and complete the installation.
2. Set the precast concrete deck panels sequentially from one end, starting with the special anchorage end panel, followed by the typical panels, and then the special end panel. Use two CAT 950F cranes to erect and install each panel.
3. Grout the shear keys between the panels making sure the ends are fully sealed to prevent accidental leakage into open channels.
4. Install the post-tensioning strands and perform the post-tensioning operations.
5. Fill the open channels with grout and place the overlay concrete.

CONCLUDING REMARKS
This paper has presented the design and implementation of a full-depth precast, prestressed concrete bridge deck that will provide superior durability to the overall bridge structure. The deck system is expected to last as long as the supporting steel or concrete bridge beams and can be adopted for deck replacement with significant time savings – up to a 50 percent reduction in construction time (see Fig. 20).

The main points presented in this paper may be summarized as follows:
1. Deck panels are made of high performance precast, prestressed concrete. Most of the creep, shrinkage, and temperature drop due to the cement hydration cycle occurring before the deck is made composite with the rigid steel or concrete beams.
2. The precast concrete deck panel covers the full width of the bridge, so...
there is no need to build formwork for the overhangs.

3. A continuous gap over the beams eliminates any potential problems related to the quality of tendon grouting.

4. The CIP concrete overlay allows for adjustments in the roadway profile and creates an excellent riding surface.

5. All materials used in the deck panels and other components are non-proprietary and, therefore, readily available.

6. Use of fewer larger diameter studs provides savings in fabrication of the steel beams.

7. The deck is compressed in two directions – significantly improving bridge durability.

8. The precast concrete bridge deck panel system is cost competitive with CIP concrete decks, while being much faster to construct, more durable, and demands less bridge maintenance.

9. This precast deck system can be efficiently implemented for both steel and concrete girder bridges.

The Skyline Drive Bridge in Omaha, Nebraska, demonstrates the successful implementation of a full-depth precast prestressed concrete deck panel system that ensures fast, efficient construction, minimal traffic disruption, reduced long-term bridge maintenance, and yields a superior performance and an extended service life. This assessment was reinforced by the PCI judges in describing the project as the co-winner of PCI’s prestigious Harry H. Edwards Industry Advancement Award: “The potential for using full-depth precast concrete panels in new or rehabilitated bridge decks has been demonstrated before, but not fully implemented. The successful implementation of the NUDECK panel system in the Skyline Bridge will go a long way in convincing bridge engineers that such bridge decks can be applied routinely and economically. Construction time is significantly reduced and service life increased.”

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CREDITS

Engineer of Record and Owner: Nebraska Department of Roads (NDOR), Lincoln, Nebraska Deck Design, Research, and Development: University of Nebraska-Lincoln, Omaha, Nebraska General Contractor: Hawkins Construction Company, Omaha, Nebraska Precaster: Concrete Industries, INC., Lincoln, Nebraska

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