

Transversely posttensioned, pretopped box-slab system for precast concrete parking structures

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- This paper presents a new total-precast concrete floor system for parking structures, which includes a pretopped box slab.
- An innovative transverse posttensioning system is proposed. The system creates a grouted, permanently compressed longitudinal joint that is expected to be maintenance free.
- The proposed system was implemented in a three-story parking structure in Abu Dhabi, United Arab Emirates, and has exhibited no longitudinal joint cracking since it was opened in 2015.

Precast concrete parking structures are known to provide an excellent value to owners and developers due to the speed of construction, high quality of plant-produced precast concrete products, and excellent aesthetic appearance of architecturally treated precast concrete spandrel beams and exterior walls. The openness of the precast concrete framing system allows for an exterior column spacing of 36 ft (11 m) and more recently a spacing as wide as 48 ft (15 m).

Figure 1 shows an example of a precast concrete parking structure. The most dominant precast concrete floor element is the 60 ft (18 m) span double tee. Double tees have tremendous economic and constructibility advantages over other products. The floor area covered by a double tee is larger than that by any other building product in existence. It features a high capacity-to-weight ratio and a simple production method. In the past two decades, pretopped double tees have increasingly been used. Generally, the precast concrete top flange is 4 in. (100 mm) thick with no additional cast-in-place concrete topping except at some limited areas of the floor. In current systems, the longitudinal joints are mechanically connected with a special welded connector and then sealed with a caulking sealant. The longitudinal joint is designed to be flexible, allowing for volume change deformation but still resisting the vertical and lateral loads expected to be transferred across the joint.



Figure 1. Precast concrete parking structure with exterior thin-brick load-bearing walls.

The objectives of this research are as follows:

- to develop a structurally efficient, shallow-depth, aesthetically pleasing pretopped precast, prestressed concrete joist for use in parking structures
- to develop a rigid precompressed longitudinal joint between the joists to ensure adequate resistance to shear and flexure, long-term durability, and reduced demand for maintenance
- to investigate optimization of the system to allow it to resist lateral loads with the lowest number of internal walls and spandrel beams

To facilitate discussion and improve relevance to actual structures, the research used an example of a three-story parking structure similar to the one in Fig. 1. The proposed new joist shape, a pretopped box slab, is designated as 12PTB24 and 16PTB24. The first two digits represent the top flange width in feet (12 or 16 ft [3.7 or 4.9 m]), the letters indicate that it is a pretopped box, and the last two digits represent the total depth in inches. A 12PTB24 was found to have equal or better structural performance than the 30 in. (760 mm) deep 12DT30. The research has revealed that the most effective posttensioning system is the one that includes special unbonded transverse posttensioning, which was introduced in the Arbor Rail Line Bridge¹ in Nebraska and further applied in Oregon. The discussion in this paper is limited to the floor system. Additional details are given in Hansen,² specifically on the lateral load system.

Literature review

In the United States, the dominant precast concrete system for parking structures is the double-tee system. The double

tees used in parking structures are 12 ft (3.7 m) and, in some cases, 15 ft (4.6 m) wide. A study of the tables in the *PCI Design Handbook: Precast and Prestressed Concrete*³ reveals that the weight of a 12DT30 is less than 60 kip (270 kN) and its equivalent solid slab thickness is less than 7 in. (180 mm), which demonstrates its high structural efficiency. It is produced in a single-piece form without moving parts, which makes production efficient.

A welded plate connection at a spacing of about 5 ft (1.5 m) is generally used to ensure that the double tees meet the floor diaphragm and vertical load distribution requirements. The longitudinal joints include a sealant that has a life expectancy of about 7 to 10 years, according to the PCI Parking Structures Committee.⁴

A *jointless floor* is difficult to construct. Cast-in-place concrete structures have construction joints separating concrete-placement zones. Moisture can infiltrate these joints and create durability issues. Posttensioning is incorporated into cast-in-place concrete parking structure slabs to reduce this type of cracking and to prevent moisture infiltration by precompressing the deck.⁵ The majority of posttensioning of cast-in-place concrete slabs in parking structures uses unbonded tendons. This paper presents a posttensioning system for precast concrete that has a double-protection system using double ducts. In addition, the high-quality, low-permeability concrete used in precast concrete products would provide better durability than that of cast-in-place concrete slabs.

Some parking structures are built with cast-in-place concrete topping that is composite with the 2 in. (50 mm) flange of precast concrete double tees. Generally, V grooves are cut and then sealed above the flange-to-flange longitudinal joints to help reduce joint leakage^{6,7} and improve riding quality.

Twelve-foot (3.7 m) wide double tees have 6 ft (1.8 m) spacing between stems. Because the column spacing is usually 24 to 36 ft (7.3 to 11 m), spandrel beams are required to support the stems between exterior columns. Walls with large openings to allow for an open atmosphere and good natural light distribution are used as interior supports of the stems.

To provide positive surface drainage, it is possible to avoid member warping by sloping the joists using 1.5% slope in the longitudinal direction and a 0.5% slope in the transverse direction.⁸

Features of the proposed system

To realistically evaluate and optimize a precast concrete parking structure, the authors began with a representative structure. The selected three-story structure comprises

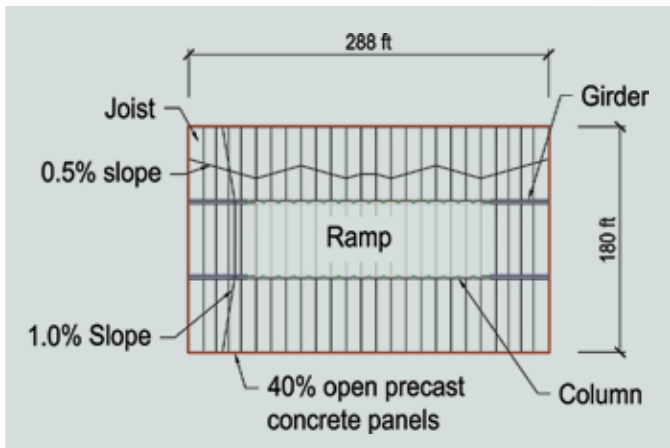


Figure 2. Building layout. Note: 1 ft = 0.305 m.

three bays. It is 180 ft (55 m) wide by 288 ft (87.8 m) long (Fig. 2).

Preliminary analysis indicated that the exterior walls had substantial lateral load resistance. Thus, no additional interior walls were included in the structural system. The elevator and stair walls were considered to be structurally separated from the rest of the frame. The ramps may be considered in the lateral analysis and contribute to the lateral load resistance. These elements of a total system analysis are not covered in this paper because the focus is the gravity load system. The authors believe that the proposed total system is cost competitive due to the elimination of the interior walls and, as will be shown, the reduction in total building height, the elimination of spandrel beams (except at the entrance to the building), and the reduction of the number and complexity of connections.

In the more detailed thesis,² the floor structure shows two options: a 12 ft (3.7 m) wide and a 16 ft (4.9 m) wide joist arrangement. In the interest of brevity, only the 12 ft wide joist arrangement is shown in this paper. Figure 2 shows the proposed drainage slopes. More details are given in Hansen.² For these slopes to be introduced, it is proposed that the total joist be sloped. This is contrary to some practices in which the double tees are twisted to create the drainage slopes. The proposed box may be too stiff trans-

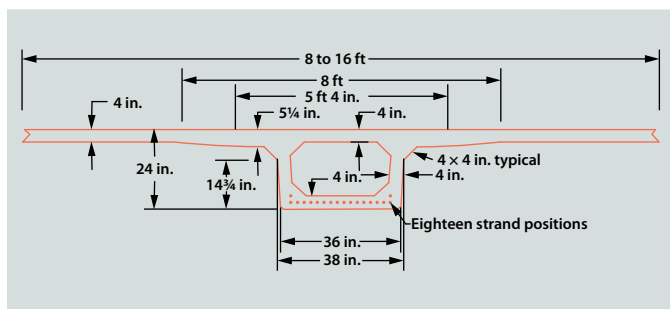


Figure 3. Pretopped box slab dimensions. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

versely to risk deforming it, and it has one stem (rather than the two double-tee stems) making twisting it more challenging.

Joist design

The basis for selecting the general shape of the new section comes from experience with bridge products. The cost per square foot of a double tee is difficult to match, especially in the early stages of introducing a new product. The authors acknowledge that any proposed shape would be more difficult to produce. Thus, it is not the goal of the research to find a less expensive joist. The goal is to improve the total parking structure system so that the premium spent on the floor is more than offset with the savings in the total structure. In addition, the value of improved aesthetics and lower lighting and maintenance costs, while difficult to quantify, must be taken into account.

Strictly based on structural engineering theory, the double-tee shape is not the most structurally efficient. The stiffness is not as high as that of flanged members of equal depth. The placement of strands has to be in the stems in a vertical column, thus losing effective depth. In hollow-core planks, box beams, and I-beams, the presence of a bottom flange allows for placement of the strands near the tension face and corresponds to a large moment of inertia for the same depth as a double tee or a similar stemmed member. Hollow-core slabs are not desirable in parking structures in cold regions due to possible accumulation of moisture and deicing chemicals in the voids. Despite being the most common shape in bridges, I-beams are not as common as joists in parking structures because of the underside appearance and the need for a wide top flange or a cast-in-place concrete deck. The shape that combines the advantages of double tees and I-beams is the box beam. (The names box beam and box slab are used interchangeably in this paper. The authors prefer the term box slab.) Figure 3 shows the final dimensions produced in this research after numerous iterations involving design optimization, production, erection, and compatibility with the proposed building system.

The width of the bottom flange was initially determined so that eighteen 0.5 in. (13 mm) diameter strands could fit in the bottom row of a 4 in. (100 mm) thick bottom flange. The number of strands was based on structural design assuming a superimposed distributed live load of 50 lb/ft² (2.4 kN/m²) and a concentrated area load of 3000 lb (13 kN), over a 20 in.² (13,000 mm²) surface area. The width was also configured so that a 32 in. (810 mm) wide sheet of 3/4 in. (19 mm) plywood can be placed at the top of the stems to form for the top flange above the void in a two-stage production process. Two-stage production, with stay-in-place forms, is discussed in a separate section as a production option. A third factor was to allow a draft (taper) in the webs so that the product could be lifted off the bed

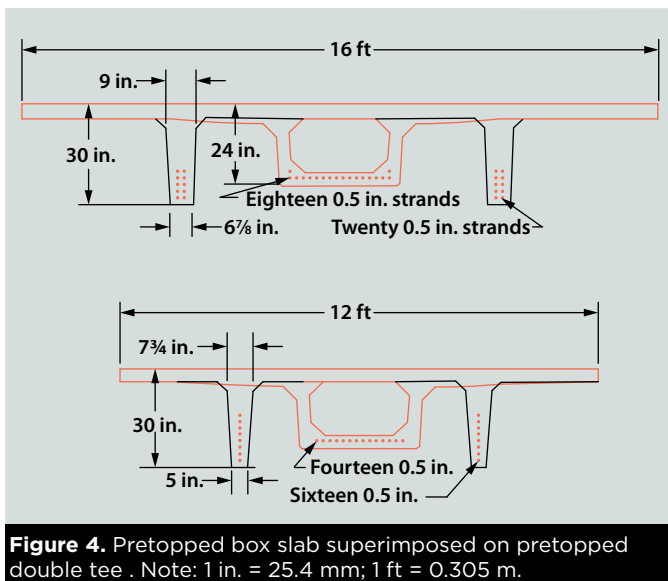


Figure 4. Pretopped box slab superimposed on pretopped double tee. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

while keeping the bottom and side forms as one piece. It was the desire of the research advisory committee to keep the bottom flange width as small as possible to reduce the potential for having wide columns or excessive bearing. These upper- and lower-bound limitations resulted in an optimal bottom width of 3 ft (0.9 m).

The webs need to be wide enough to allow for placement of two rows of no. 4 (13M) bars, two 1 in. (25 mm) covers, and 1 in. clear spacing. A web width of 4 in. (100 mm) was adopted. All dimensions are measured on vertical and horizontal lines. Thus, the thickness of the web perpendicular to the faces is slightly less than 4 in.

Top flange width was determined based on a number of factors. The most common double-tee width in current practice is 12 ft (3.7 m). However, wider sections have been introduced in recent years.⁹ Based on recommendations by the research advisory committee, it was decided to have the new shape accommodate top flange widths up to 16 ft (4.9 m) and to analyze 12 ft (3.7 m) and 16 ft wide sections. The width can be as narrow as 3 ft 10 in. (1.2 m). This width flexibility is advantageous compared with the 12 ft double tees, which cannot be narrower than about 7 ft (2 m). Because the top flange area is a significant part of the total section area and product weight, it needs to be as small as structural design and reinforcement placement dictate. The minimum thickness that has been used with pretopped double tees is 4 in. (100 mm). This thickness was the starting point for the new shape. Through reinforcement placement and structural design the thickness is increased to 5 1/4 in. (133 mm) at the face of the web. To simplify connections for box slabs as narrow as 8 ft (2.4 m), the 4 in. constant section was retained for box-slab widths between 8 and 16 ft. Also, a flat underside just beyond the fillet width is placed for a length of 9 in. (230 mm) to allow for simplified seating of the joist using corbels just under the

top flange. The authors have assumed that high-slump and self-consolidating concrete mixtures are used to produce the proposed product. This assumption proved valid when the test specimen was made. There was no difficulty in placing the concrete from the top of one web and watching it rise up the second web. **Figure 4** compares the proposed pretopped box slab (Fig. 3) with the equivalent double tees. The dimensions of the sections in Fig. 4 were extracted from the design tables of the *PCI Design Handbook*.³ The only difference is that the top flange of the handbook's 15 ft (4.6 m) wide section was stretched horizontally by 1 ft (0.3 m). The comparison is not a direct one because the pretopped box slab is already 6 in. (150 mm) shallower than the double tee. The total benefits of depth reduction cannot be quantified in a joist-versus-joist comparison because they involve total building height and aesthetic factors.

The properties of the two shapes are comparable despite the 20% reduction in depth (**Table 1**). The number of strands required is similar. Of the eighteen 0.5 in. (13 mm) diameter strands for the 16PTB24, 14 strands are placed in the first row and two in a second row.

Alternatively, 13 of the larger 0.6 in. (15 mm) diameter strands may be used in one row. The Federal Highway

Table 1. Comparison of section properties of the 30 in. deep double tee and the proposed 24 in. deep pretopped box slab

Property	12DT30	12PTB24	16DT30	16PTB24
Height, in.	30	24	30	24
Area, in. ²	928	957	1194	1149
Moment of inertia, in. ⁴	59,997	56,514	80,856	60,755
Centroidal depth, in.	22.94	17.01	22.90	17.84
Weight, lb/ft	967	997	1243	1197
Weight, lb/ft ²	81	83	78	75
Volume-to-surface ratio, in.	2.3	2.1	2.5	2.1
Number of 0.5 in. strands*	16	14	20	18
Number of 0.6 in. strands*	n.d.	10	n.d.	13

Note: n.d. = no data. 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 lb = 4.448 N.
* For 60 ft span.

Administration has directed the American Association of State Highway and Transportation Officials (AASHTO) to accept strand spacing of 1.75 in. (44.5 mm) for 0.5 in. (13 mm) diameter strands and 2 in. (50 mm) for 0.6 in. diameter strands. These values have already been adopted by the *AASHTO LRFD Bridge Design Specifications*.¹⁴ Accordingly, it is possible to use eighteen 0.5 in. strands in a single row for the 16PTB24 if the spacing of 2 in. is slightly reduced. As will be seen from the testing program, the specimen was made with thirteen 0.6 in. diameter strands, with no observed harmful effects. In some situations, where two-stage precasting is used, it may be desirable to have two top strands to control end zone stresses and camber, as well as to provide a convenient means of tying the shear reinforcement.

Once dimensions and amount of prestressing were established, longitudinal shear and transverse reinforcement were determined. Auxiliary reinforcement was designed in accordance with the American Concrete Institute's (ACI's) *Building Code Requirements for Structural Concrete (ACI 318-14)* and *Commentary (ACI 3018R-14)*.¹⁵ Research specific to double tees indicated that shear reinforcement may be omitted everywhere other than the outer 5 ft (1.5 m) of double tees.¹⁰ Without the benefit of this research for the pretopped box beam, it was found that shear reinforcement may be omitted in the middle third of a pretopped box beam span of 60 ft (18 m). The end 8 ft (2.4 m) is controlled by shear resistance requirements, and the next 12 ft (3.7 m) is controlled by the ACI 318-14 minimum reinforcement requirement. Figure 5 shows details of the auxiliary shear plus end zone reinforcement as used for the test specimen. The main shear reinforcement was placed at the following spacing from the end face to the midlength: 1 in. (25 mm) end cover, 3 bars at 2 in. (50 mm) spacing, 15 bars at 6 in. (150 mm) spacing, 8 bars at 18 in. (430 mm) spacing, and no bars for 10 ft 1 in. (3.1 m).

Welded-wire reinforcement was used for shrinkage and temperature effects prior to posttensioning.

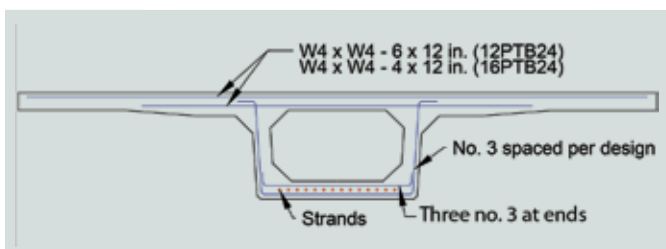


Figure 5. Auxiliary reinforcement for shear, end zone, and top flange. Note: 12PTB24 = 12 ft wide, 24 in. deep pretopped box beam; 16PTB24 = 16 ft wide, 24 in. deep pretopped box slab. No. 3 = 10M; W4 = 6 mm diameter wire; 1 in. = 25.4 mm; 1 ft = 0.305 m.

Ultimate (factored load) requirements were found to not control except for the 16 ft (4.9 m) wide members. Thus, it is proposed that the W4 (MW26) transverse wire size be used at 6 in. (150 mm) spacing for the 12PTB24 and at 4 in. (100 mm) spacing for the 16PTB24. The longitudinal wire may be W4, or even smaller, and may be spaced at 12 in. (300 mm), as is typical for double tees. Posttensioning is employed for in-service conditions to provide crack-free longitudinal joints due to unfactored service live loads, as will be addressed in the Transverse posttensioning section. Transverse reinforcement is proposed to be provided in two layers (**Fig. 5**). This is done to provide room for the posttensioning duct at the center of the top flange.

Joist production

The primary complication in production of the pretopped box beam is the presence of an internal void. Voids in hollow-core slabs are formed using an extrusion or slip-forming process. The same could be employed with the pretopped box slab proposed in this report. However, such process would require more developments in mechanization. The authors are hopeful that associate members of PCI in the United States will step forward and help develop such a system. Until volume is large enough to justify it, a number of alternatives may be used. There are two primary methods of production: one-stage concrete placement and two-stage concrete placement. In the following discussion, only material costs are used in the comparison. Capital improvements such as steel forms are considered to be amortized over many repeated uses and are ignored in this study.

Forming options for one-stage concrete placement

The simplest method for production is the use of expanded polystyrene blocks to form the voids. This method is similar to the method commonly used in the production of box beams used in bridges. It may be the most likely method to be used to start using the pretopped box slab. The cost of expanded polystyrene block for the pretopped box slab shape was found to be \$8.33/ft (\$27.33/m). This is equivalent to \$0.69/ft² (\$7.47/m²) for the 12PTB24 and \$0.52/ft² (\$5.60/m²) for the 16PTB24. Although the lab specimen was made in two stages, expanded polystyrene block was used to form the void and the part of the top flange directly above the void (**Fig. 6**).

The least expensive method in the long term is to use collapsible-steel void forms (**Fig. 7**). Although the mold can be inexpensive if amortized over many uses, still more effort is required for multiple handlings of the void forms and at least 30 ft (9 m) of form is needed at



Figure 6. Tub part of the pretopped box beam using two-stage production as delivered to the laboratory.

each end of the product, assuming the collapsible mold is made in two half-length assemblies.

Forming option for two-stage concrete placement

This method requires that the tub concrete be placed first. When the concrete sets (2 to 4 hours), the inside form is removed. This is followed by the placement of a precut plywood sheet, the top flange reinforcement, and the top flange concrete. Finally, the strands are released, and the product is removed. With this option, it is possible to keep the production cycle to the standard 24 hours. The tops of the webs are intentionally roughened to enhance interface shear. It is conservative to assume that the interface between the tops of the webs and the flange is a cold joint, much like the interface between girders and a deck slab in bridge construction. The top width of the tub is such that a 4 by 8 ft (1.2 by 2.4 m) plywood sheet is cut into three equal parts, each 2 ft 8 in. (0.8 m) long. The pieces are quickly laid end to end. Relatively inexpensive plywood has been used in a similar manner on inverted-tee bridges in Nebraska for the past 15 years without adverse effects. The cost of one sheet is about \$24. One sheet can form 12 ft (3.7 m) along the pretopped box slab. Thus, the plywood costs about \$2.00/ft (\$6.56/m)

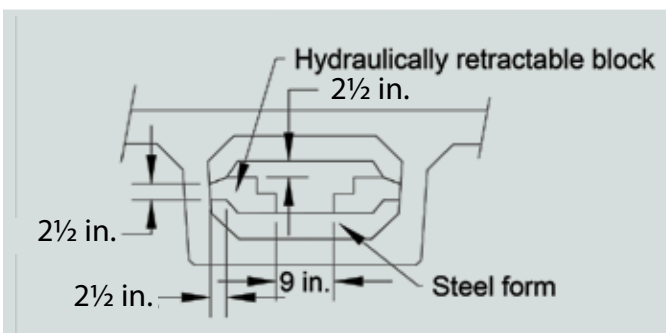


Figure 7. Concept of collapsible steel void form. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

of pretopped box slab, or \$0.17/ft² (\$1.79/m²) for 12PTB24 and \$0.13/ft² (\$1.30/m²) for 16PTB24.

It is possible, with this method, that the tub alone be precast concrete and stored in a more compact storage space in the plant. The top flange could be fabricated at a later date away from the more valuable prestressing bed space.

Joist supports

Figure 8 shows the proposed pretopped box slab support locations at an exterior wall and an interior column. There are a number of attractive features of the proposed support locations. Three-point supports of relatively wide box beams have proved more effective than a four-point or line support system. In addition, support under the top flange rather than under the stem also improves the size of the opening in the wall, which aids in two aspects: the minimum required 40% opening for fire protection without sprinklers and a general feeling of openness in the structure. By using corbels at the exterior walls, spandrel beams can be essentially eliminated. Spandrel beams are one of the most difficult items to design and are expensive to produce. They have been the subject of intense research for the past 35 years.

When an inverted-tee beam is required to support the pretopped box slab, as in areas where column-free turns are required, the overall vertical clearance is still required to be maintained, while a heavily loaded, relatively long-span inverted tee is required. Supports under the flange overhangs keep the total structural floor depth to 24 in. (610 mm). It is possible to support the joist on a 24 in. deep beam using dapped-end pretopped box slabs and conventional beam ledges.² Also, the support beams may be good candidates for ultra-high-performance concrete applications.

Consideration may also be given to precast concrete panels made of segments with horizontal joints, especially when

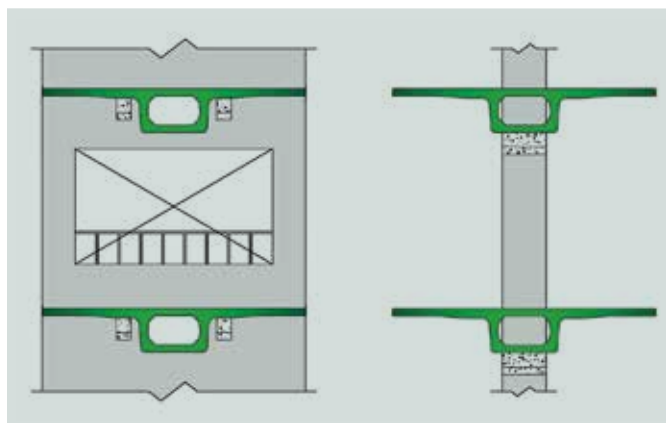


Figure 8. Corbels for joist to wall (left) and column (right) connections.

16 ft (4.9 m) wide joists are used. Also, horizontally segmented exterior walls may allow for easier future vertical expansion of the structure.

Transverse posttensioning

One of the primary goals of this research was to develop a grouted precompressed longitudinal joint between the flanges of pretopped joists to ensure no cracking or potential for leakage, deterioration, or frequent maintenance. Despite the established success of sealants used in current practice, they still need to be inspected, maintained, and possibly replaced in seven- to ten-year intervals.

The proposed grouted connection details are based on previous work on bridges.^{1,11-13} Design of the transverse posttensioned connection was done using finite element analysis and checked using hand calculations. The connection was assumed to have no impact on the transfer of dead load to the flange, which essentially acts as a cantilever beam before the joint is grouted and posttensioned. The applied loads before posttensioning are self-weight and construction loads. After the connection is made, additional loads (it was assumed that these were primarily live loads) are resisted by the top flange as a fully continuous slab over the two webs of each pretopped box slab. Two live-load conditions were investigated: 50 lb/ft² (2.4 kPa) uniformly distributed load and 3000 lb (13 kN) wheel load placed over a footprint of 20 in.² (13,000 mm²).⁶ Analysis showed that the uniform load rather than the wheel load controlled the design of the proposed posttensioned system. The size and spacing of posttensioning were designed to provide 150 psi (1.0 MPa) compression due to prestressing forces only (after allowance for prestress losses) and zero tension due to the combination of prestress and externally applied loads. The 150 psi effective prestress level is based on a combination of factors. However, other levels of precompression may be used. Another level of precompression used in practice is 250 psi (1.7 MPa) for the transverse design of adjacent bridge box beams. ACI 318-14 specifies a minimum of 125 psi (0.86 MPa) in nonaggressive environments and 225 psi (1.55 MPa) for tall slender walls. ACI 362-12¹⁶ and the Post Tensioning Institute¹⁷ recommend a minimum of 150 psi for zone I parking structures and 200 psi (1.37 MPa) for zones II and III.

Zero tension at full load is a conservative requirement because the code allows tension, even in fully prestressed flexural design. The chosen posttensioning system corresponds to two fully tensioned 0.6 in. (15 mm) diameter strands at a spacing of 8 ft (2.4 m) placed in a standard flat posttensioning duct. The proposed posttensioning system can house up to four strands. Using only two strands per duct allows for extra space in the duct for improved tolerance.

Welded connections are commonly provided every 5 ft (1.5 m). The joints with welded connections are assumed to

be flexible. They are designed to allow for alignment at erection, shear resistance, and deflection continuity in service. No flexural capacity is assumed in design. The proposed posttensioning connection was compared experimentally with the typical welded connection only as a way of highlighting the performance of the posttensioning connection, rather than demonstrating any deficiencies in the welded connection.

Figure 9 shows details of a completed posttensioning connection. **Figure 10** shows a photo of the connection components looking through the shear-key joint before the joint is grouted. The connection consists of the following components:

- a flat high-density polyethylene (HDPE) plastic duct that is 1½ in. (38 mm) deep and 3 in. (76 mm) wide, precast within the top flange (It is advised that a 1 in. (25 mm) diameter retractable rod be placed in the duct to ensure that it does not collapse during placement of the top flange concrete.)
- the two 0.6 in. (15 mm) diameter strands, lubricated and fully encapsulated in monostrand polyethylene conduits
- flowable nonshrink grout, with a compressive strength of 2500 psi (17 MPa) before posttensioning and at least equal to the strength of the precast concrete at service

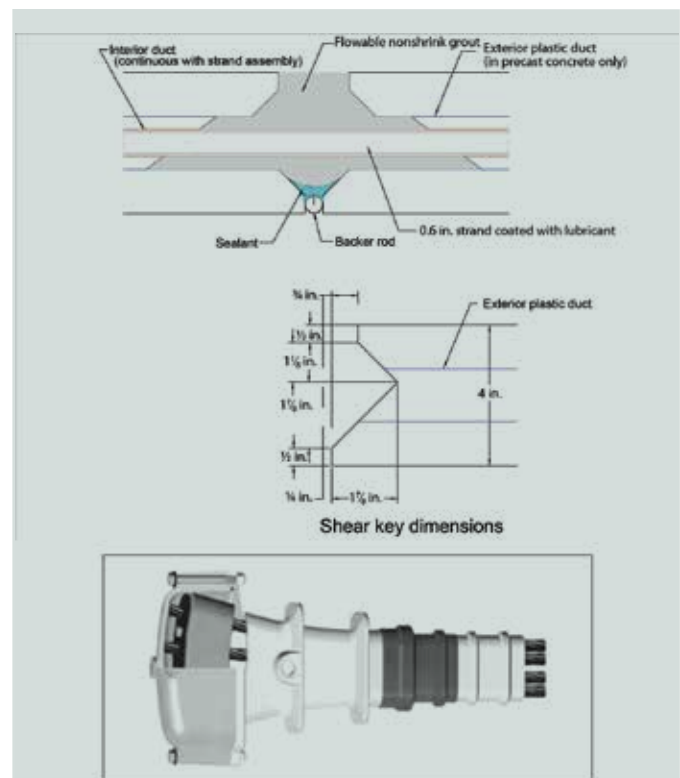


Figure 9. Shear key dimensions, grouted key, and typical end anchorage details. Note: 1 in. = 25.4 mm.



Figure 10. Posttensioned flange-to-flange connection before joint grouting.

Anchorage of the posttensioning may require a pocket in the exterior wall panels that are located at the ends of the transverse joist direction. To avoid undesirable appearance of these pockets, they can be masked by decorative precast concrete cover. They may also be anchored, similar to double tees (**Fig. 11**).

The following construction steps are required for successful implementation of this transverse posttensioning system:

1. Place flat ducts in the top flange during the precasting process. It is important to have accurate horizontal alignment of the ducts before top flange concrete is placed to avoid misalignment in the field.
2. Place the joist on low-friction bearings at the supports. Polytetrafluoroethylene-coated plastic plates may be used for this purpose. The bottom of the shear key must have a backer rod or another sealing material to prevent grout leakage.
3. Thread each preassembled strand-interior conduit assembly through exterior ducts. Threading strands across the entire length of the floor could be viewed as challenging; however, lead lines may be placed as the structure is built to guide strand as it is inserted. Strand is considered flexible enough to avoid issues with the 0.5% slope specified for drainage.
4. Pull strands to approximately 5 kip (20 kN) to keep them taut before grouting.
5. Place grout in longitudinal joints. Highly flowable grout may completely fill the space between the exterior and interior ducts. However, this is not a requirement of the system. It will be adequate to completely fill the shear key. Any additional grout that fills the exterior duct would be inconsequential in securing the posttensioning locations or application of the full posttensioning force.

6. Apply full posttensioning force once the grout reaches its minimum specified initial strength, proposed to be 2500 psi (17 MPa).
7. The deck would be allowed to open to traffic after grout reaches the specified final strength, proposed to be the same as that of the precast concrete product.

There are multiple layers of protection of the strands: the lubricant (grease or graphite), the interior polyethylene conduit, and the exterior HDPE duct. This system allows for the grouting to take place before the posttensioning, thus guaranteeing that the grout will fully receive the required precompression. This is the most important and most innovative aspect of the proposed system.

Transverse posttensioning is not limited to the proposed pretopped box beams. It is equally applicable to the current pretopped double-tee system. It is designed to fit a 4 in. (100 mm) thick top flange, which is the typical thickness for double tees.

The length of a straight continuous unbonded posttensioned tendon is limited by practical considerations, as friction loss is not a major issue in a greased strand system. The floor shortening due to initial posttensioning is small. For a 300 ft (90 m) long parking-structure floor, it is less than ¼ in. (6 mm). It may be preferable to have shorter tendons to facilitate strand placement and to accommodate interruptions such as expansion joints. Figure 11 shows an example of how a posttensioning splice can be accommodated for a double-tee section. A similar arrangement can be implemented for pretopped box beams.

Experimental verification

An experimental program was conducted to evaluate the longitudinal and transverse behavior of a full-scale 16PTB24 specimen. Only an overview of the experimental program is given in this paper. More detailed coverage

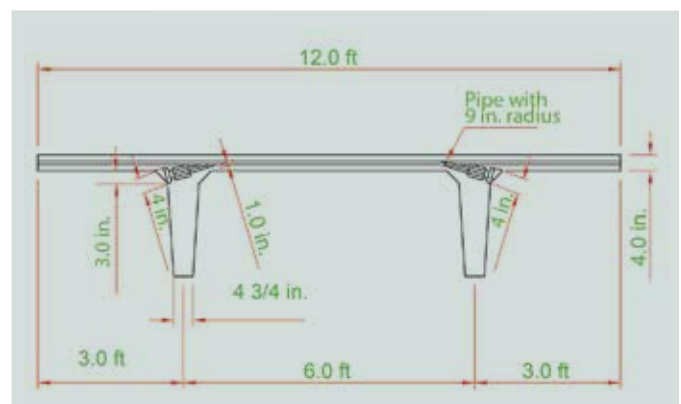


Figure 11. Intermediate anchorage of posttensioning a double tee. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.



Figure 12. End view of full pretopped box-slab specimen.

is available in Hansen.² A two-stage placement was used to simplify production and to test the effects of a cold joint between the tub and the top flange. The longitudinal testing was performed on a 60 ft (18 m) long 16PTB24 (Fig. 12, 13). The main objective of longitudinal testing was to verify the theoretical flexural, shear, end-zone, and deflection behavior. Of particular interest was the interface shear between the tops of the webs and the underside of the top flange.

Figure 14 shows a plot of the midspan moment versus midspan deflection. The graph starts at the midspan moment and deflection contributed by the weight of the member. Deflection due to service live loads is approximately 0.65 in. (17 mm). It meets ACI 318-14 requirements (span/360 equal to 2 in. [50 mm]). Deflection near the failure load was approximately 10.6 in. (269 mm), indicating outstanding ductility.

Figures 15 and **16** present results of shear testing. Failure did not take place until after all strands slipped at the end of the member. Thus, although this type of failure has traditionally been called shear failure, it initiates with bond failure of the strands and transitions to diagonal tension (shear) failure. At that loading level, the tension tie, currently recognized in the design of bridges in shear in the AASHTO LRFD specifications, begins to lose bond

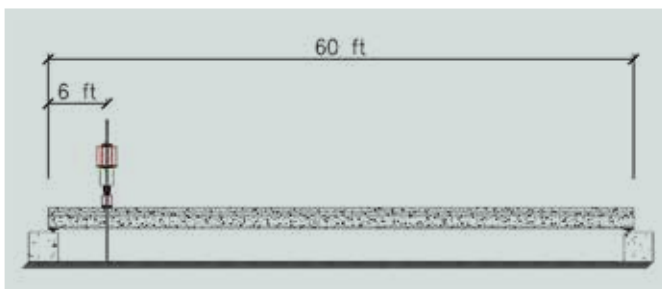


Figure 13. Longitudinal specimen shear test setup. Note: 1 ft = 0.305 m.

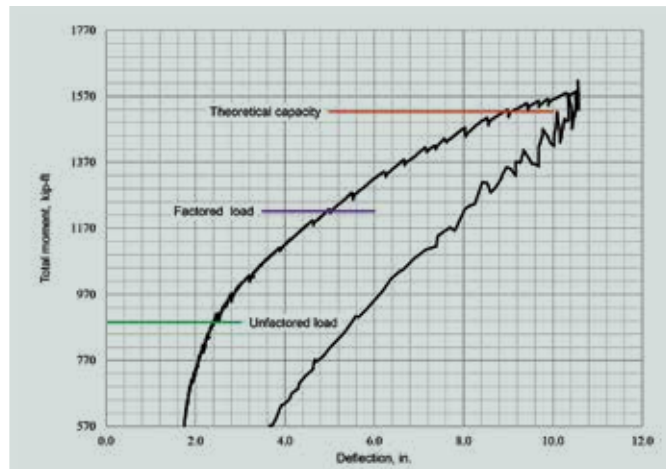


Figure 14. Bending moment versus deflection at midspan. Note: 1 in. = 25.4 mm; 1 kip-ft = 1.356 kN-m.

to the surrounding concrete. For this reason, the AASHTO LRFD specifications allow a higher shear capacity than ACI 318-14. Bending strands into an end diaphragm provides additional tension tie capacity and, in turn, higher ultimate shear capacity. Because of the minimal amount of shear reinforcement required for this application and the additional construction steps required in using end diaphragms, it is generally acceptable to use the ACI 318-14 shear design method. The section's theoretical capacity (Fig. 15) closely correlated to the value calculated by ACI 318-14. It was exceeded in the experiment as shown in the figure. Figure 16 shows the mode of failure due to shear.

The second type of testing performed by the authors was transverse testing. It was conducted on specimens constructed by connecting two 8 ft (2.4 m) long 16PTB24 pieces. **Figure 17** shows the transverse testing setup. A cyclic load was applied to the edge of one of the two box-

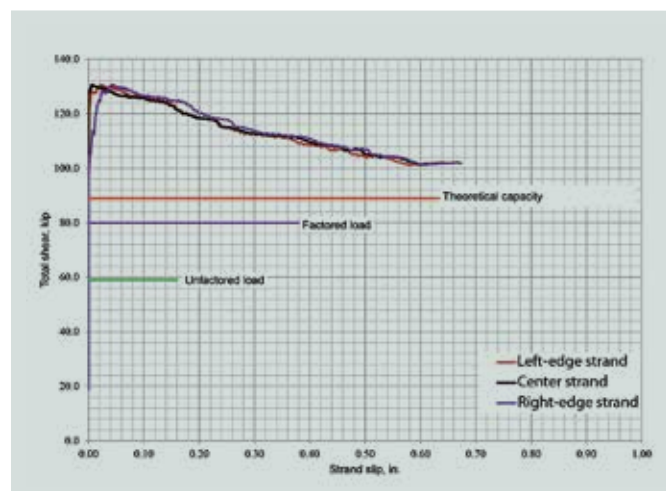


Figure 15. Shear versus strand slip at end. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.



Figure 16. End shear failure and loss of strand bond.

es, not directly to the centerline, so that the joint was fully subjected to shear and bending. The cyclic loading level represented unfactored service loading conditions and was applied for 2 million cycles. The welded connection was only tested to 4000 cycles because it deformed significantly, as should have been expected. The grouted connection showed no signs of distress for the full 2 million cycles. Both types of connections met the required theoretical ultimate load capacity (**Fig. 18**).

System implementation

The system described in this paper was implemented in a three-story underground parking structure in Sector 11, Abu Dhabi, United Arab Emirates. The original design consisted of pretopped double tees, except for the roof, which was heavily loaded with landscaping. Framing of the roof consisted of bridge I-beams and a thick cast-in-place composited concrete slab. Framing of the two suspended floors below the roof were value engineered to the system described in this paper. **Figure 19** shows the box slab cross section. **Figure 20** shows the precast concrete box slab being erected. The structure was opened to occupancy in 2015. This first implementation of the system illustrates the aesthetic appeal of the framing. The inside of the structure looks pleasant, and the floor surface appears to be uniform

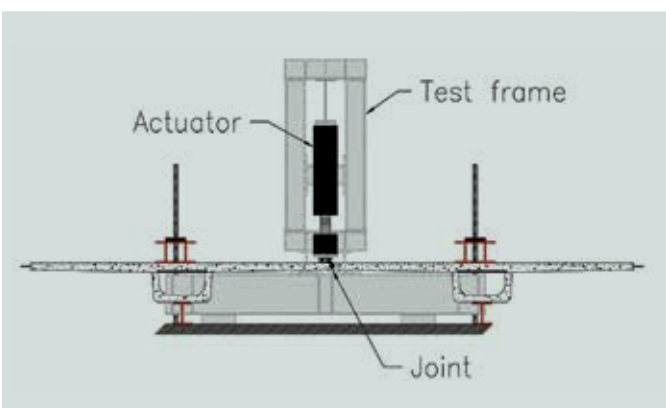


Figure 17. Transverse specimen testing setup.

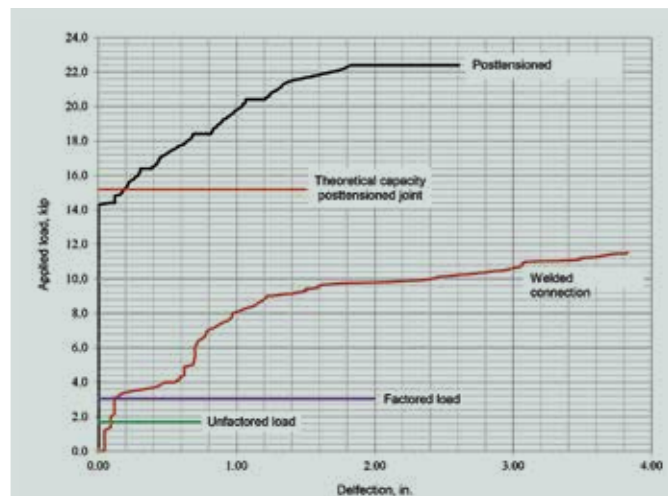


Figure 18. Transverse load versus deflection. Note: 1 in. = 25.4 mm; 1 kip = 4.448 kN.

(**Fig. 21**). There have been no reports of longitudinal joint cracking since completion of the structure in 2015. However, a lesson learned was to avoid a blockout made in the top flange in the space between inside faces of the webs. The blockout was intended to help create a cast-in-place concrete continuity joint over the beam support. However, removal of the full top flange thickness weakened the overhang-to-web corner and created premature overhang cracking.

Conclusion

This research offers an optimized system for structural framing of total-precaster concrete parking structures. Exterior walls that are 12 ft (3.7 m) wide are offered as a substitute for spandrel beams. The walls also contribute to resisting the lateral loads and are an architectural facade.

The primary focus of the research is to investigate the feasibility of replacing the popular double-tee joint floor system with another product that is shallower with wider stem spacing. Transversely posttensioned grouted joints were investigated as a possible alternative to welded sealed

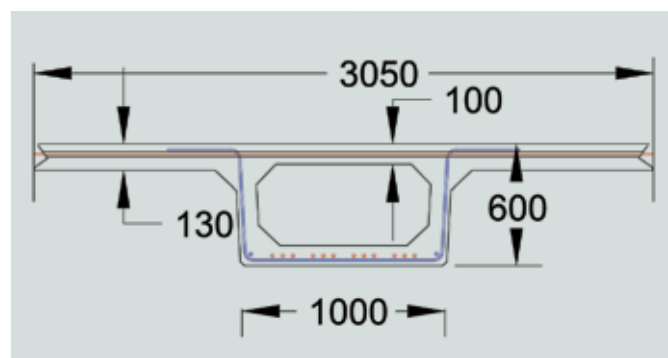


Figure 19. Cross section used in sector E11 of the Abu Dhabi, United Arab Emirates, parking structure. Note: All dimensions are in millimeters. 1 mm = 0.0394 in.



Figure 20. Box-beam slab being erected for underground parking structure in Abu Dhabi, United Arab Emirates.

joints. The following have been found as a result of this research:

- Pretopped box slabs varying in width from 8 to 16 ft (2.4 to 4.9 m) and only 24 in. (610 mm) deep (6 in. [150 mm] shallower than a double tee) have outstanding flexural, shear, and deflection behavior.
- The pretopped box slab shape is expected to be cost competitive in the long term, when factors such as total structure depth, aesthetics, and maintenance costs are included.
- The pretopped box slabs can be produced in one stage using expanded polystyrene or steel void forms.
- The pretopped box slabs can be produced in two stages, if necessary, without interface shear problems between the tops of the webs and the top flange.
- The underside of the floor is aesthetically pleasing and provides for good lighting distribution.



Figure 21. Inside view of a completed parking structure in Abu Dhabi, United Arab Emirates.

Transverse posttensioning was found to be an excellent means of eliminating tension at service loads and producing a rigid two-way prestressed joint behavior. The structural and durability advantages of the grouted posttensioning joint should be assessed against the economy and speed of the traditional welded connections. The system appears to be cost competitive both on an initial and life-cycle cost basis.

Acknowledgments

PCI initiated this project through a Daniel P. Jenny Fellowship to Jenna Hansen. This paper is based on the master's thesis work of Hansen. The financial support of PCI, the University of Nebraska, e.construct.USA (Omaha, Neb.), and Coreslab Structures (Omaha) is gratefully acknowledged. George Morcouc assisted Maher Tadros in supervising Hansen's research after Kromel Hanna accepted a job in California. In addition, the following University of Nebraska individuals gave valuable assistance and advice: Kelvin Lien, Yaohua (Jimmy) Deng, Afshin Hatami, Eliya Henin, Ibrahim Lotfy, Peter Samir, and Jeff Svatora. Todd Culp, Brian Paterson, and John Heimann of Coreslab Structures (Omaha) offered advice and contributed specimens. Brad Schipper of e.construct.USA gave design guidance. Roger Becker, PCI technical services vice president, and the following PCI Research Advisory Committee members provided advice throughout the project: Ken Baur of Northeast Precast Co., Tom D'Arcy of The Consulting Engineers Group Inc., Dave Dieter of Mid State Precast LP, and Sami Rizkalla of North Carolina State University.

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Abstract

Precast concrete parking structures have proved their cost-effectiveness, speed of construction, and architectural elegance. The dominant precast concrete joist product in the United States for parking structures is the double tee. Research over the past 40 years has focused on improving the cost-effectiveness of double tees by increasing their width from 8 to 10 to

12 ft (2.4 to 3.0 to 3.6 m). Recently a 15 ft (4.5 m) wide double tee was introduced in some U.S. regions. Another active area of research has been to make the reinforcement of the spandrel beams simpler.

This paper offers a precast concrete pretopped box slab with a wide top flange. The slab has a total depth of 24 in. (610 mm), compared with the corresponding 30 in. (76 mm) double tee, and a top flange width of 8 to 16 ft (2.4 to 4.9 m). The 12 ft wide, 24 in. deep pretopped box slab is expected to replace the 12 ft wide, 30 in. deep double tee, and the 16 ft wide, 24 in. deep pretopped box slab is expected to replace the 16 ft wide, 30 in. deep double tee. This research shows that the new shape requires fewer strands than the double tee, and it theoretically and experimentally performs well. When considered in the total–precast concrete system described herein, it is expected to be competitive on both an initial and life-cycle cost basis.

This paper also offers an innovative transverse posttensioning system to render the joints maintenance free and to eliminate the need for sealants, which have inspection demands and require occasional replacement. Details are given on how to get the joints precompressed while keeping the construction steps simple.

Keywords

Double tee, flange-to-flange connection, flanged box beam, parking structure, pretopped box beam, transverse posttensioning.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute’s peer-review process.

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