The legacy and future of an American icon: The precast, prestressed concrete double tee

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- This paper traces the origin and development of the double tee, reviewing the advantages and applications of double tees, particularly in relation to parking structures.
- The paper summarizes selected studies and discusses the northeast extreme tee (NEXT), the 16 ft (4.9 m) wide Mega-Tee, and the bulb double tee.
- Examples of future possibilities of double tees using high-strength concrete, self-consolidating concrete, and large-diameter prestressing strands are explored.

The double tee is one of the most widely used structural precast concrete building products in North America.[1–5] It is North America's most popular building commodity, not only because it was invented and developed in the United States but also because it is the most versatile and cost-effective precast concrete product, especially for relatively long spans. Double tees are used as both horizontal and vertical load-bearing members. The double tee is a suitable system for swimming pool roof framing. It offers superior corrosion and fire protection in comparison to steel joists. **Figure 1** shows a double-tee application in the swimming pool roof of the YMCA in Omaha, Neb., which was built in 1981. **Figure 2** illustrates an application of a warehouse-office building with a double-tee wall.

The double tee is the predominant component in parking structures. It has also been used to form the roofs of sporting facilities (such as indoor swimming pools and gymnasiums), auditoriums, schools, colleges, theaters, food markets, warehouses, and many other types of buildings. Double tees have also been used in pedestrian bridges and other crossings, as well as being placed to bear on one end and act as vertical exterior wall panels.

In highway bridges, a new section called the northeast extreme tee (NEXT) beam has become popular in the northeastern United States.[6] Also, a double tee–bulb tee hybrid section, called the pi girder, has emerged through studies by the Massachusetts Institute of Technology, the Federal Highway Administration, and other agencies.[7,8] This section is particularly effective when used with ultra-high-performance concrete and large-diameter strands,[9] thus allowing precast concrete products to have a high load capacity–to–weight ratio.

The purpose of this paper is to trace the evolution of the precast, prestressed double tee and to show that ongoing and future research and development will enhance the span length capacity and create more diverse applications of this versatile member.

Brief history of prestressed concrete

In 1936, at a special meeting of the British Institution of Structural Engineers in London, the French bridge engineer Eugène Freyssinet announced that he had discovered a brand-new material:[10]

> *The author considers himself entitled to state that he has succeeded in creating a theory and the means of giving it practical application, which class the combination of steel and concrete when treated in accordance with these new methods as an entirely new material possessing properties very different from those of ordinary reinforced concrete.*

Freyssinet's concept of prestressed concrete, which was inspired in connection with his work on time-dependent deformations of reinforced concrete arch bridges, occurred well before 1936. However, his London lecture was his first announcement to the English-speaking world of the significance of his work on prestressed concrete's potential.

Freyssinet was justified in making the previous claim, as working stress design was the sole basis for design at that time. He employed prestressing in the manufacture of pipes and poles and in the construction of structures such as bridges, dams, and harbor works. Most of these applications occurred in France and other French-speaking countries.

Both American and European codes of practice treat prestressed concrete as an integral part of what is now called structural concrete. Designers have become accustomed to designing members with prestressing steel as the primary flexural reinforcement and mild reinforcing steel as auxiliary shear and end-zone reinforcement. The effects of prestress are recognized in the codes as requiring appropriate relevant service load and ultimate strength checks within the encompassing class of structural concrete.

Figure 1. Double-tee roof framing a swimming pool in Southwest Omaha YMCA in Omaha, Neb.

Despite the additional checks necessary for the design of prestressed concrete structures, it is widely recognized that prestressing increases the span, minimizes cracking, and increases durability. When combined with the improved quality achieved in plant precasting, the system becomes even more efficient. Today, the use of precast, prestressed concrete is common practice in bridges, parking structures, and long-span building frames.

The start of World War II in 1939 delayed further development of prestressed concrete. Another obstacle was that the technology of producing high-strength concrete and high-strength ductile seven-wire prestressing strand had not sufficiently developed. By 1945, most of Europe's infrastructure, especially its bridges, had been destroyed and needed to be replaced. Because there was a severe shortage of steel, prestressed concrete became the preferred material of construction.[11]

Meanwhile, Gustave Magnel, a Belgian professor of engineering, was aware of Freyssinet's work and was himself

Figure 2. Example of the use of a double tee as a vertical load-bearing wall in an warehouse-office building in Omaha, Neb.

an authority on prestressed concrete.[4] After the war, he conducted in English and French a special course on prestressed concrete, which was well attended by students and teachers from all over the world. Two of those attending his lectures were T. Y. Lin and Charles Zollman, who themselves later became pioneers in prestressed concrete.[4]

In the late 1940s and 1950s, Magnel made several tours of the United States and Canada in which he lectured on prestressed concrete.[3,4] His crowning achievement was the design of the Walnut Lane Memorial Bridge in Philadelphia, Pa. Built in 1950, this 160 ft (49 m) long-span structure was the first major posttensioned, prestressed concrete bridge in the United States. This bridge provided the inspiration for the birth of the precast, prestressed concrete industry in North America.[4]

A major technological breakthrough in the late 1940s and early 1950s was the development of seven-wire stress-relieved strand by the John A. Roebling Co.[5] Seven-wire strand soon became the standard product in North American practice and eventually the rest of the world. In the United States, H. Kent Preston worked to transfer this technology to precast, pretensioned concrete plants.[5]

Due mainly to the influence of Bill Dean, chief bridge engineer at the Florida Highway Department, prestressed concrete became a material of choice in Florida in the 1950s. Two key ingredients helped accelerate this growth. One was the rise of plants that could manufacture standard precast concrete components efficiently and economically using the pretensioning method on long casting beds. The other was the emergence of the interstate highway system in the 1950s, which enabled the transportation of these members easily and safely from plant to construction site.[5]

In the 1950s, the burgeoning precast concrete industry was not limited to bridges. Engineers such as Harry Edwards also found a profitable market for precast concrete components in buildings and other structures.[2] Edwards played a major role in the founding of PCI in 1954 and served as its first secretary/treasurer. He was instrumental in the development of the double tee and standardization of precast concrete products. His firm designed many of the early pretensioned concrete structures in Florida as well as several of the early precasting, prestressing plants.[2,5]

History of the double tee

In 1951 Harry Edwards and Paul Zia designed a 4 ft (1.2 m) wide by 12 in. (300 mm) deep prestressed concrete double-tee section using a tee section as a guide. However, no prestressed concrete double tee was produced in Florida until 1953, although nonprestressed double tees had been constructed in Miami, Fla., in 1951.

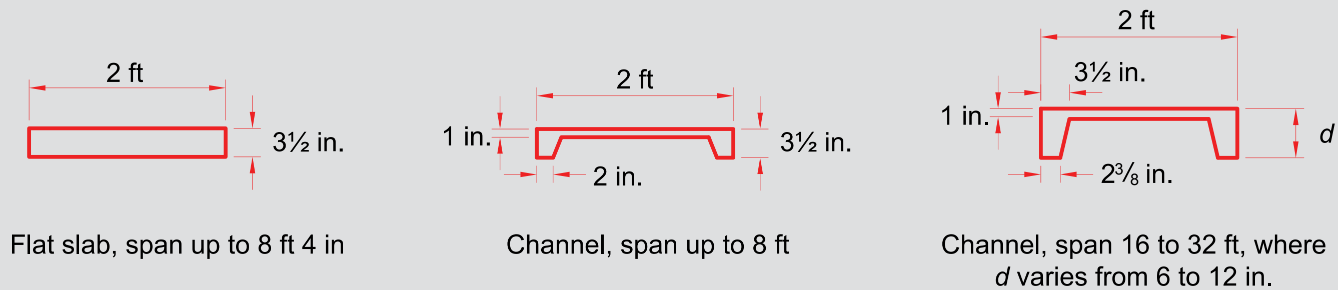

Figure 3. Channel sections that evolved with ribbed thin shells into double tees. Note: d = total depth of member. 1 in. = 25.4 mm; 1 ft = 0.305 m.

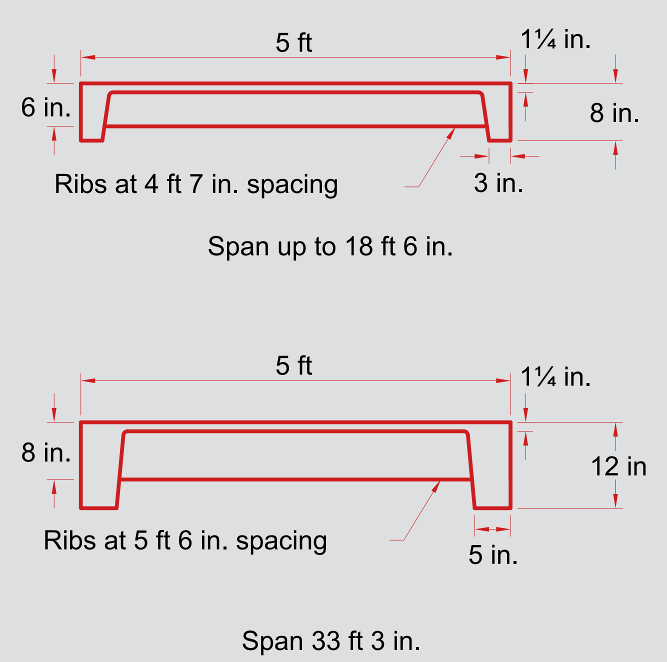

Figure 4. Ribbed thin shells that evolved with channel sections into double tees. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

In the early 1950s, the most prevalent precast concrete members for buildings were I-beams, flat slabs, tapered I-beams, ribbed thin-shell channel sections, tee joists, and various composite members. Some of these members were pretensioned, while others only contained mild-steel reinforcement. However, as the demand for longer spans grew, the need for prestressing became more evident.[2]

Another necessity was standardization. Thus, a demand grew for a more efficient section. The double tee evolved

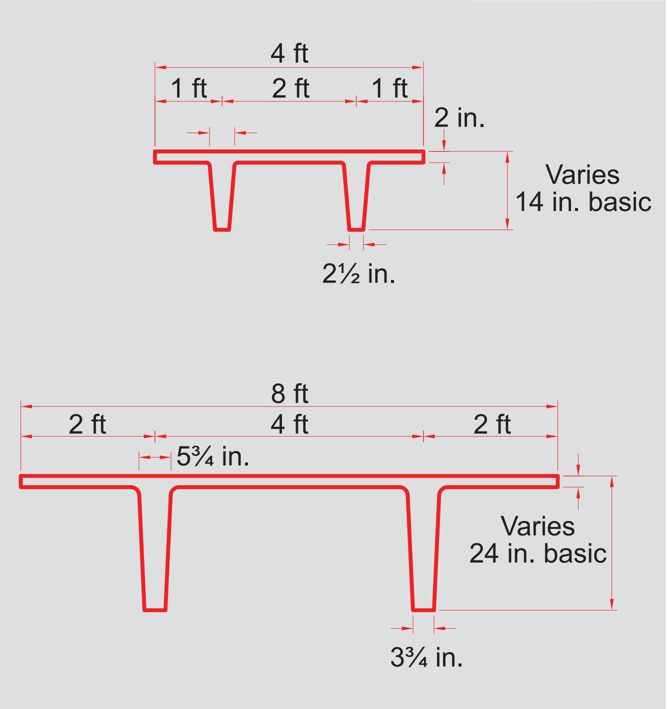

Figure 5. Early 4 ft double tee, span up to 50 ft (top) and later-version 8 ft double tee, span up to 80 ft (bottom). Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

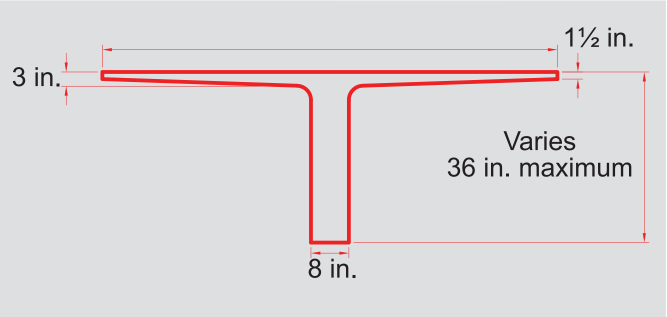

Figure 6. Typical single-tee cross section. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

from the channel section and ribbed thin shell (**Fig. 3** and **Fig. 4**, respectively).[5]

The improvement consisted of deepening and thickening the stems (or legs) and shortening the transverse span but cantilevering the top slab (or flange) beyond each stem. **Figure 5** shows the dimensions of the early prestressed concrete double tee. The member was 14 in. (360 mm) deep and 4 ft (1.2 m) wide and had 1 ft (0.3 m) cantilevers extending over each side. Prestressing steel was placed at the bottom of each stem. In the beginning, most plants used parallel 5⁄16 in. (8 mm) diameter and then 3⁄8 in. (10 mm) diameter 250 ksi (1720 MPa) strands. Soon thereafter, depressed (also known as draped or harped) strand patterns were used to increase the span and loading range.[2,5]

Spans started at 25 ft (7.6 m) but soon reached 50 ft (15 m). While the dimensions and spans of the first double tee may seem minuscule by today's standards, lifting equipment and crane capacity were limited. Nevertheless, the emergence of the double tee had a profound effect on the competitiveness and growth of the precast, prestressed concrete industry.

Competition against the double tee came not only from the steel industry but also from the single tee. Designed and promoted by T. Y. Lin in California in the 1960s, the single tee (**Fig. 6**) was structurally efficient and could carry heavier loads than the double tee.[5]

A later version of the double tee appeared in the late fifties with the dimensions shown in the bottom of Fig. 5. Edwards and Zia, recognizing the single tee's lack of stability during erection, used a 4 ft (1.2 m) wide and 12 in. (300 mm) deep prestressed concrete double tee. In the late 1950s, the depth of the double tee increased to 24 in. (610 mm) and the width to 8 ft (2.4 m).[2,5]

Independent of the work being done in Florida, in late 1952 engineers and producers in Colorado developed the first prestressed concrete double tee.[12] Those responsible for developing it were Nat Sachter (architect), George Hanson (structural engineer), and Jack and Leonard Perlmutter and Michael Atenberg (producers).[13] Their first double tee, which they called a twin tee, was

Table 1. History of the double-tee load tables in the *PCI Design Handbook*

Edition	1st	2nd	3rd	4th	5th	6th	7th	8th
Year Published	**1971**	**1978**	**1985**	**1992**	**1999**	**2004**	**2010**	**2017***
4DT14	X							
5DT18	X							
6DT12, 6DT16, 6DT20	X							
8DT12	X	X	X	X	X			
8DT14, 8DT16, 8DT18, 8DT20	X	X	X	X				
8DT24	X	X	X	X	X	X	X	
8DT32		X	X	X	X	X	X	
10DT24			X	X	X	X	X	X
10DT32	X	X	X	X	X	X	X	X
12DT28					X	X	X	X
12DT32					X	X	X	X
Pretopped 10DT26				X	X	X	X	X
Pretopped 10DT34				X	X	X	X	X
Pretopped 12DT30					X	X	X	X
Pretopped 12DT34					X	X	X	X
Pretopped 15DT26						X	X	
Pretopped 15DT30, 15DT34						X	X	X

*Scheduled publication date

6 ft (1.8 m) wide and had spans between 20 and 25 ft (6.1 and 7.6 m). These spans quickly increased to 50 ft (15 m). The double tee was used for the first time on the cold storage building for Beatrice Foods in Denver, Colo.

The 8DT24 became the most commonly used double tee for 60 ft (18 m) spans for several decades.[12] Double tees are typically identified by their width in feet on the left and depth in inches on the right of the letters "DT." This double tee grew to 10 ft (3.0 m) wide in 1972, then developed into a 12 ft (3.7 m) wide section in 1980. The most commonly used shape appears to be the 12DT30, which has a total depth of 30 in. (760 mm) and a pretopped flange thickness of 4 in. (100 mm) (**Fig. 7**). Double tees with widths of 15 and 16 ft (4.6 and 4.8 m) have become available in some parts of the United States.[19] **Table 1**, provided by Helm Wilden, traces the double-tee sizes reported in the load tables in the first through eighth editions of the *PCI Design Handbook: Precast and Prestressed Concrete*.[14–20]

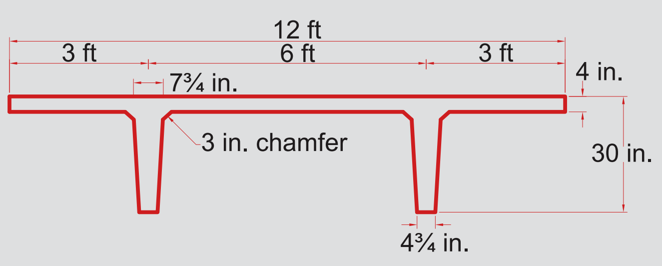

Figure 7. Typical double-tee cross section, 12DT30. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Unfortunately, despite these advantages, the single tee can be bulky and heavy when used for long spans, thus requiring strong straddle carriers to be handled by large cranes. Also, because it has a single stem, the member is unstable until erected and in place. Therefore, it requires temporary lateral supports. Consequently, the single tee is more difficult to store, transport, and erect than the double tee. Today, the single tee is used only in special applications, such as tapered single tees used radially to cover large storage tanks or where tight structure geometry dictates a reduced width. An outgrowth of the single tee is the deck bulb tee used in the Pacific Northwest. The pi shape discussed later in this paper is a hybrid of the double tee and the deck bulb tee.

Current practice

Double tees are designed by licensed engineers in PCI-certified precast concrete plants or by professional specialty engineering firms and are fabricated in PCI-certified precast concrete plants. Engineers of record do not always have the necessary design expertise, and general contractors must usually subcontract the engineering, production, and erection.

In parking structures, the majority of the structural frame comprises double tees. Typical double-tee bed lengths of 500 ft (152 m) or more are subdivided into specific lengths for a particular project. Building layouts with double-tee designs are often submitted prior to other elevations and member design to begin production for efficiency in production and overall project schedule. Speed of precast concrete double-tee construction is a major advantage compared with other construction systems.

Cost of construction varies widely across North America. However, it is reasonable to state that double tees are one of the most cost-effective precast concrete products regardless of region. The attractive low cost in addition to speed of construction and product quality make precast concrete parking structures an attractive option to owners and developers.

The width of standard double tees can be changed by blocking out most of the flange overhangs. The depth of double tees ranges from 18 in. (460 mm) to about 36 in. (915 mm). The typical stem width is about 6 in. (150 mm) at the top, tapering to about 4 in. (100 mm) at the bottom (Table 1). For parking structures, double-tee lengths of about 60 ft (18 m) are common to maintain open clear distances for drive aisles plus two sets of parking stalls. Owners and patrons of parking structures tend to favor these open areas for functional, aesthetic, and security reasons.

The design live load for a double tee used in a parking structure is 40 lb/ft^2 (2 kN/m^2) or a concentrated 3000 lb (14 kN) wheel load applied over an area of 4½ × 4½ in. (114 × 114 mm).[21] Snow and snow drift loads along with ponding must be considered with parking live loads at roof conditions in some parts of the United States.

The double-tee floor decks also typically act as lateral diaphragms for the parking structure. Accordingly, the double-tee flange joints must incorporate diaphragm connections that transfer seismic or wind lateral forces (as well as vertical shear) but also provide allowance for joint displacement. Design and detailing of these double-tee connections and joints must properly consider the induced stresses due to traffic exposure and volume change effects to ensure good long-term performance.

The double-tee member design itself has the inherent advantage of having the primary reinforcement (that is, prestressing strands) embedded deep below the driving surface. The large amount of concrete above the strands protects them from possible corrosion. While this is a beneficial standard feature of precast, prestressed concrete, it has added importance where extended exposure to deicing chemicals is common.

The prestressing strand typically ranges in size from ⅜ to 0.6 in. (9.5 to 15 mm) diameter with ½ in. (13 mm) diameter strand the most common size. The 0.7 in. (18 mm) diameter strand has been introduced in bridge applications and is expected to be used in the future for double tees as well.[9,26]

The design of the prestressing, including strand size, initial tension, and location, must consider final in-service stresses, initial stresses immediately after release, camber, and ultimate flexural capacity. To optimize strand placement, the strands are sometimes depressed from the ends to the midspan of the double tee, creating a larger effective depth at the midspan while spreading out the strands over the full depth at the ends. The stresses at the ends become more uniform and are minimized with the strands spread throughout the cross section while the flexural capacity is maximized when strands are depressed at midspan. There is a balance to be struck between increasing the prestress in double tees to control in-service cracking with limiting camber and concrete release stresses.

It is important to design for realistic in-service loads. Higher release stresses can sometimes be mitigated by debonding strands at the member ends or increasing concrete release strength. However, increased camber can still be problematic for serviceability or construction. Often other members of the design team are not fully aware of camber inherent in prestressed concrete products. Excessive camber can impair drainage slopes, complicate alignment at egress locations, or complicate topping placement when the structure receives a field topping.

Since the late 1990s, especially with the use of 12 and 15 ft (3.6 and 4.6 m) wide double tees beginning in the fifth edition of the *PCI Design Handbook*,[18] there has been a trend toward the use of straight and larger-diameter strands. This tends to simplify production, with the increased strand diameter partially mitigating the need for more strands to satisfy loading requirements, which may result in better overall economy.

In addition to the main reinforcement represented by the strands, welded-wire reinforcement (WWR) is placed in the flange. While the WWR provides temperature and shrinkage reinforcement as well as diaphragm continuity, typically the governing design loading for WWR is the 3000 lb (14 kN) wheel load noted previously. Some producers use carbon-fiber-grid reinforcement in place of conventional WWR. The carbon-fiber-reinforced flanges have

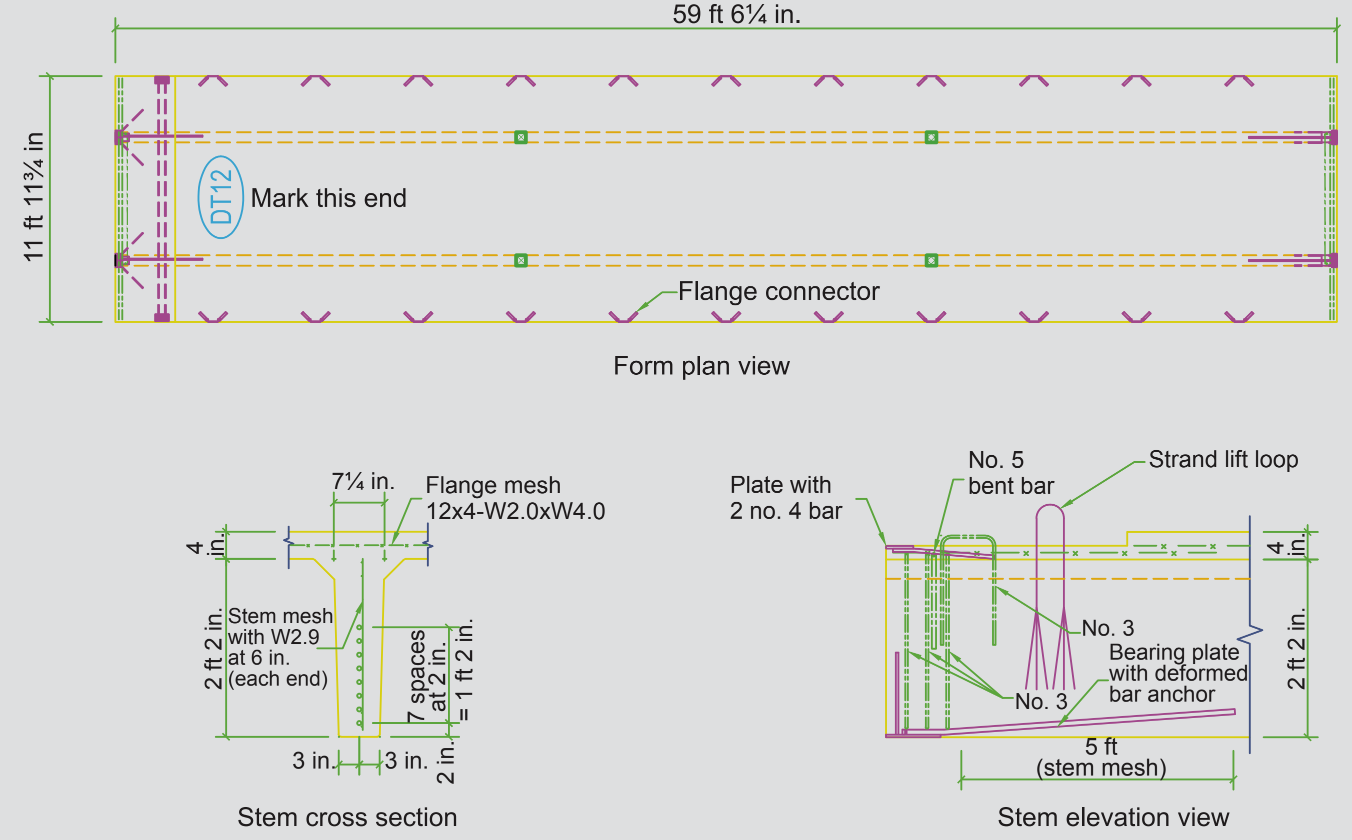

Figure 8. Partial double-tee production ticket. Note: no. 3 = 10M; no. 4 = 13M; no. 5 = 16M; 1 in. = 25.4 mm; 1 ft = 0.305 m.

excellent durability and crack control along with a reduced need for chemical sealers and corrosion inhibitors.[22]

Some designers prefer to use a 4 in. (100 mm) top flange thickness without field topping. This product is commonly called a pretopped double tee. The thickness was increased in the past to meet heat-transmission requirements for higher fire ratings. In the 2015 edition of the *International Building Code*,[24] increased flange-thickness requirements due to heat separation were waived for both open and enclosed parking structures. Both pretopped and field-topped double tees are used, depending on owner preference and

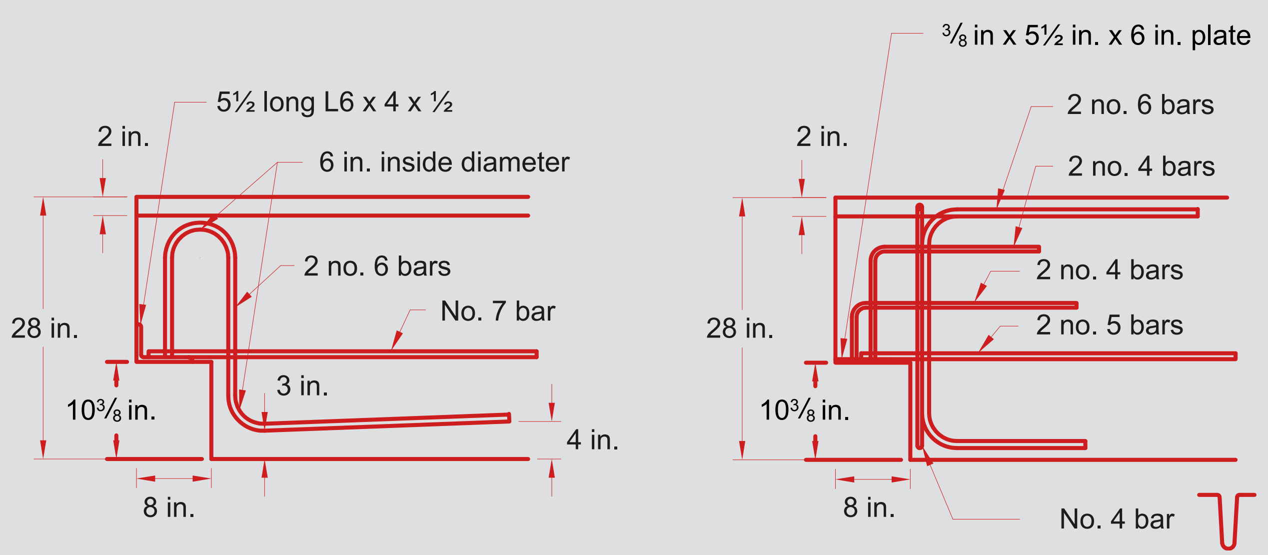

Figure 9. Two example reinforcement details of dapped-end double tees used in parking structures. Note: no. 4 = 13M; no. 5 = 16M; no. 6 = 19M; no. 7 = 22M; 1 in. = 25.4 mm; 1 ft = 0.305 m.

Figure 10. Towson University West Village parking structure in Towson, Md. Courtesy of Tindall Corp.

Figure 13. ConRAK Structure at Logan Airport in Boston, Mass., during erection with 60 ft (18.3 m) inverted-tee beam in foreground. Courtesy of Parsons Brinkerhoff and The Consulting Engineers Group Inc.

Figure 11. San Antonio International Airport long-term parking structure in San Antonio, Tex. Courtesy of Manco Structures Ltd. and The Consulting Engineers Group Inc.

Figure 12. Split 16 ft wide double-tee form. Note: 1 ft = 0.305 m. Courtesy of Hamilton Form.

local material and labor costs. In high seismic zones, the diaphragm design may require a field topping over the double-tee deck.[21] However, some designers have used cast-in-place concrete for boundary elements, rather than the entire floor, to satisfy seismic diaphragm action.

In 2014, PCI submitted a proposal, called IT06-01, to the American Society of Civil Engineers (ASCE) for a change to ASCE 7-10, which will include specific provisions for the design of untopped diaphragms in zones of high seismicity. If the proposal is approved, it will give support to designers who wish to design this system. In contrast to other methods of construction, the quality of double-tee construction has continued to be optimized. Plants provide high-quality concrete (greater than 5000 psi [35 MPa]) with low water-binder ratios (0.4 or lower), resulting in excellent durability.

The double-tee stems must also be designed for shear. At the ends of the stems, shear WWR may be provided adjacent to the strands when required (**Fig. 8**). In addition, the stems are often dapped at the bearing ends to minimize the overall structural depth, thus minimizing floor-to-floor height. There have been discussions about optimization of the details at the ends of double tees to accommodate dapped end stresses and deformations. **Figure 9** gives two examples of currently used details. Only the additional embedment and reinforcement are shown for clarity. Practices vary significantly. PCI-sponsored research under way will hopefully result in unified and optimized details.

Double-tee-joint details have been optimized with proprietary as well as nonproprietary connection and joint details that have proved to have satisfactory long-term performance. Use of high-strength concrete as well as carbon-fiber reinforcement and self-consolidating concrete provide further technology alternatives for double-tee construction.[22]

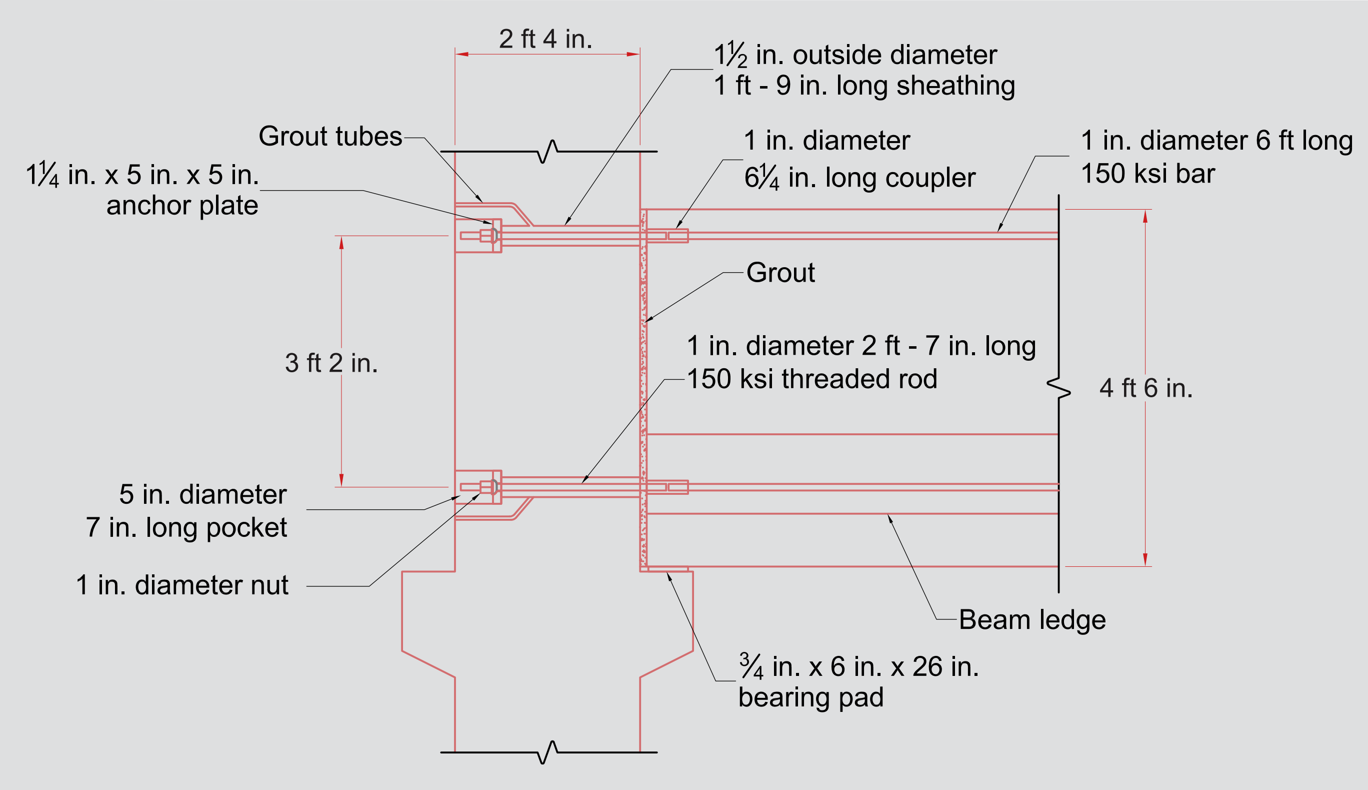

Figure 14. Inverted tee–column connection detail at moment-resisting end, ConRAK facility. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

Double-tee production itself is a multistep process aimed at optimizing both speed and quality. After the double-tee form is cleaned, the strand is pulled (stressed) to the required prestressing force. Embedded plates and welded-wire (mesh) reinforcement are placed prior to the placement of the concrete. The concrete is allowed to cure, and once the minimum design concrete release strength has been reached the strands are detensioned. The double tee is then stripped and typically moved to plant storage before being shipped to the jobsite. There are multiple quality-control checks throughout this process.

The double-tee form finish is generally of good quality and is usually left untouched for parking structure applications. The double-tee top finish may vary depending on whether it will receive a field-placed topping. For parking structures, especially in the south and western United States, it is customary to have a 2 in. (51 mm) double-tee flange thickness with approximately 3 in. (76 mm) of composite topping. These double tees may have a roughened finish to receive the topping. For roofs (without parking access), the topping and roughend finish is typically eliminated.

Figure 10 shows a parking structure for Towson University in Towson, Md., completed in 2011. The six-story, 400,000 ft^2 (37,200 m^2) structure was erected in 17 weeks. The exterior panels for this 1500-vehicle parking facility had two colors of thin brick and two precast concrete finishes.

Figure 11 shows the long-term parking structure at the San Antonio International Airport in San Antonio, Tex., completed in 2007. The structure has curved architectural exterior spandrels with exposed aggregate and light

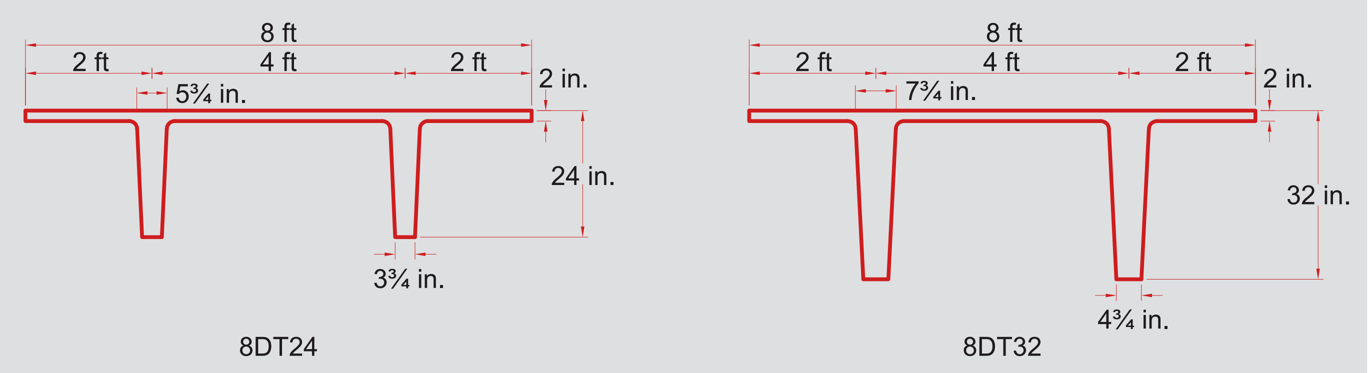

Figure 15. Typical 8 ft wide double tees. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

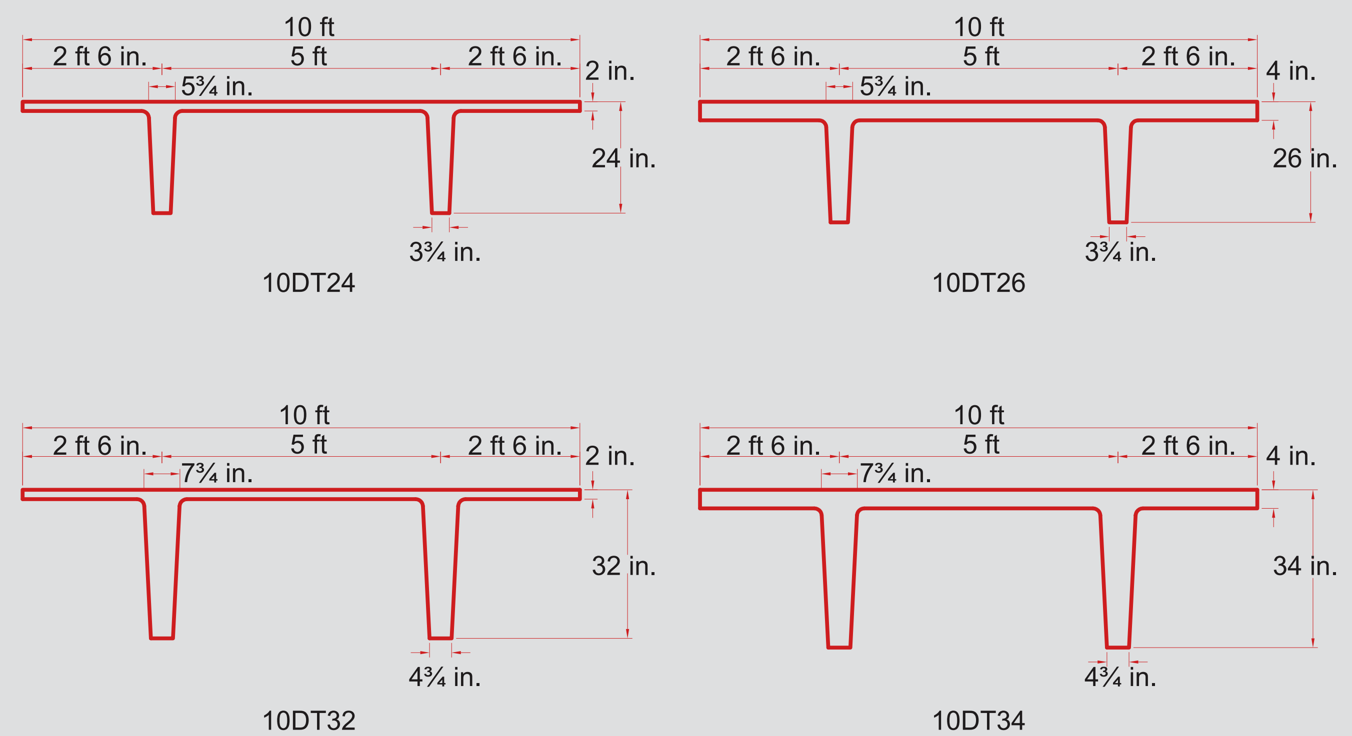

Figure 16. Typical 10 ft wide double tees. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

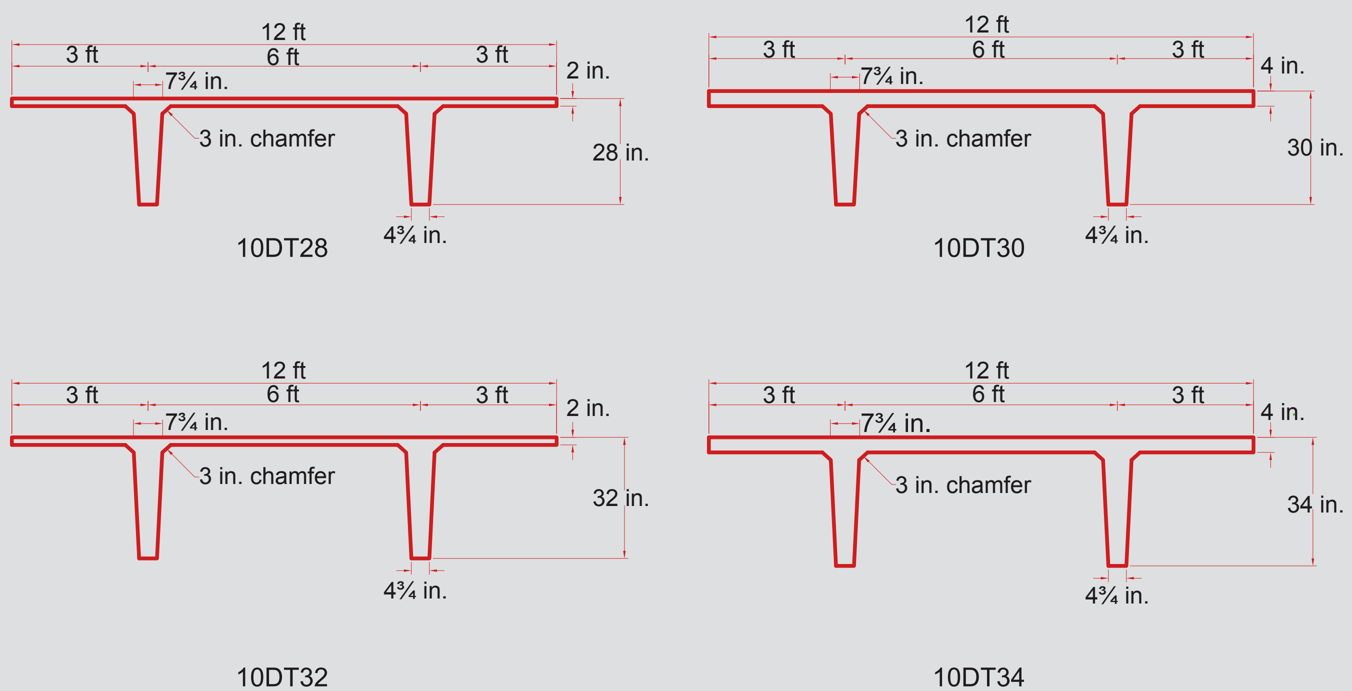

Figure 17. Typical 12 ft wide double tees. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

sandblast. These spandrels are braced to modified L beams that support the double-tee deck and to the spandrels at the middle of the bay for bearing and lateral support.

Economic reasons and competition have driven the width of the double tee to increase to require fewer elements for the same floor area. There is economy in reducing the number of pieces produced, handled, erected, and connected. The most commonly used width is 12 ft (3.6 m). This maximum width is dictated by the transportation laws on highways and the cost of shipping wider products. In Pennsylvania, 15 ft (4.6 m) wide double tees have

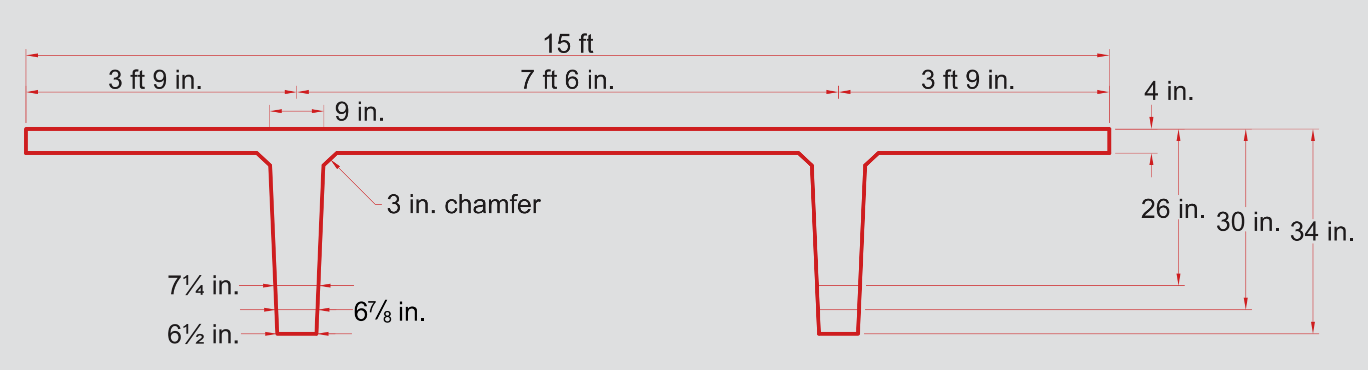

Figure 18. Typical 15 ft wide double-tee cross sections with three different total depths. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Figure 19. Forms for 8DT48. Courtesy of Hamilton Form.

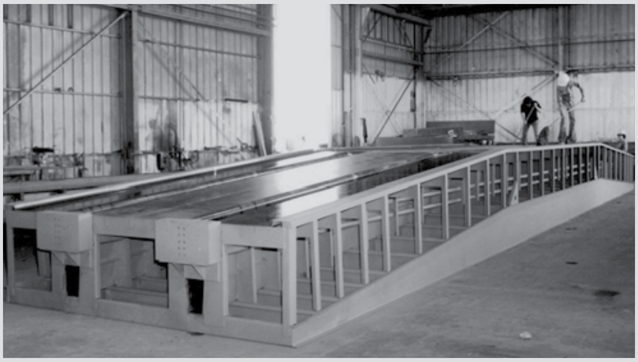

Figure 20. Convex formwork for double tee. Courtesy of Hamilton Form.

Figure 21. Concave formwork for parking ramp double tee. Courtesy of Hamilton Form.

been produced as well as 16 ft (4.9 m) wide double tees (**Fig. 12**). These members are shipped in a tilted position using a proprietary hauling rack so that the entire double tee is within the legal shipping envelope.

Reducing the number of walls in a parking structure is desirable for economy and security. An example of an innovative, open design is the Consolidated Rental Car Parking Facility at Logan Airport in Boston, Mass. While the standard 12 ft (3.7 m) wide double tees are used, an unprecedented 60 ft (18 m) inverted-tee beam span was employed (**Fig. 13**). The car-rental agencies occupying the space benefit from an open floor that allows for different layouts by different agencies. The inverted-tee beam and columns were connected to form a moment frame on one end of the inverted-tee beam and a simple span bearing on the other end. This arrangement allowed for added capacity for gravity loads in the inverted-tee beam and also acted as a part of the lateral-load-resisting system. **Figure 14** shows the inverted-tee beam–column fixed-end connection details. This detail preserved the standard multistory column arrangement, which was important to the precaster and erector. The 5000-vehicle, 1.2 million ft^2 (111,000 m^2) structure also features a facade consisting of terra-cotta veneer panels embedded in structural precast concrete walls. This is believed to be the first use of terra-cotta on structural panels in North America.

Another attribute of double tees is that the top flange provides the floor and ceiling of the structure while the stems impart strength and stability. The width of the top flange plays an important role in the cost of the structure. As mentioned earlier, reducing the number of components in the structure lowers the cost of production, handling, transport, and erection. The equivalent solid-slab thickness of the double tee is shallow, representing an efficient use of materials. For example, a 12DT30 double tee has an area of 928 in.^{2} (600,000 mm^2) and an equivalent solid-slab thickness of 6.44 in. (164 mm). According to the authors' experience, no other precast concrete product can span up to 80 ft (24.4 m) with the same solid-slab equivalence.

Figures 15 through **18** summarize the double tees listed in the seventh edition of the *PCI Design Handbook*.[20] The

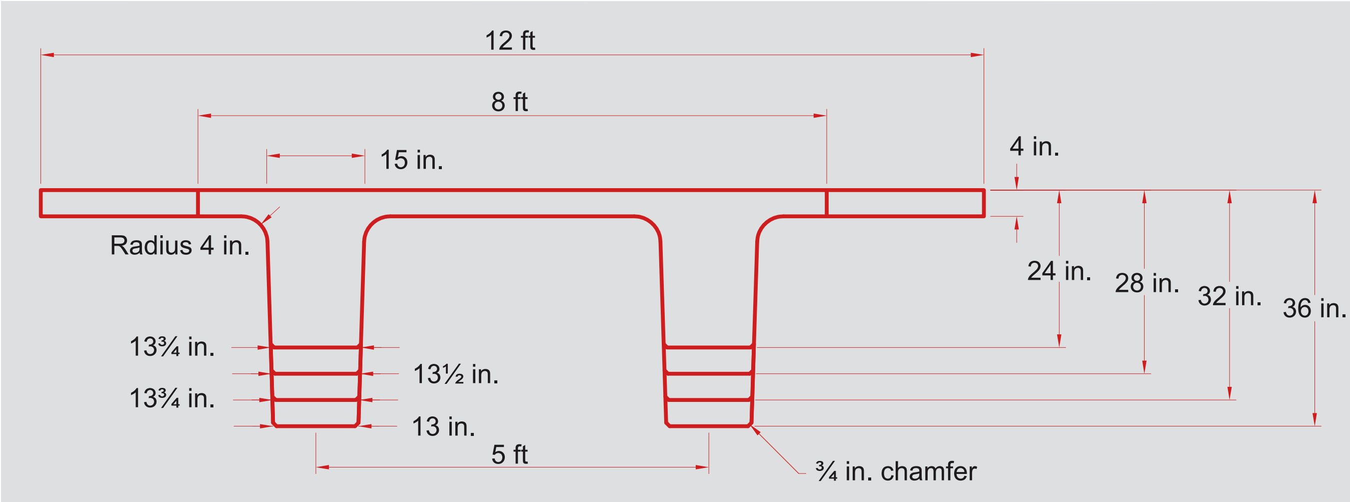

Figure 22. Typical northeast extreme tee beam cross sections. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Figure 23. Northeast extreme tee beam form without jacking plates. Courtesy of Hamilton Form.

width at the bottom of the stem is wider for shallower members (Fig. 16), implying that production is set up with the deepest form and that steel filler blocks may be used to create the shallower depths. The figures show the section dimensions used in the load tables of the *PCI Design Handbook*.[20] These dimensions are not standard and may vary from one precaster to another.

Double tees with special geometry

Variations of standard cross sections have also been applied in project designs. Double tees can be as deep as 48 in. (1220 mm) deep (**Fig. 19**) and as wide as 12 ft (3.7 m). Convex (**Fig. 20**) and concave (**Fig. 21**) double tees have been used in parking structure ramps.

PCI Northeast introduced the NEXT beam for bridges (**Fig. 22** and **23**). The section has special features that are well suited to bridge applications where American Association of State Highway and Transportation Officials (AASHTO)[23] truck loadings are heavy, necessitating high prestress forces and wide stems. The distance between the stems is 5 ft (1.5 m) rather than the standard 6 ft (1.8 m).[6]

The large overhangs can be shaped with curved edges and therefore give a curved bridge deck appearance.[6] The NEXT beam is an attractive alternative for short- to medium-span bridges, especially for accelerated bridge construction because deck forming at the jobsite is reduced or eliminated.

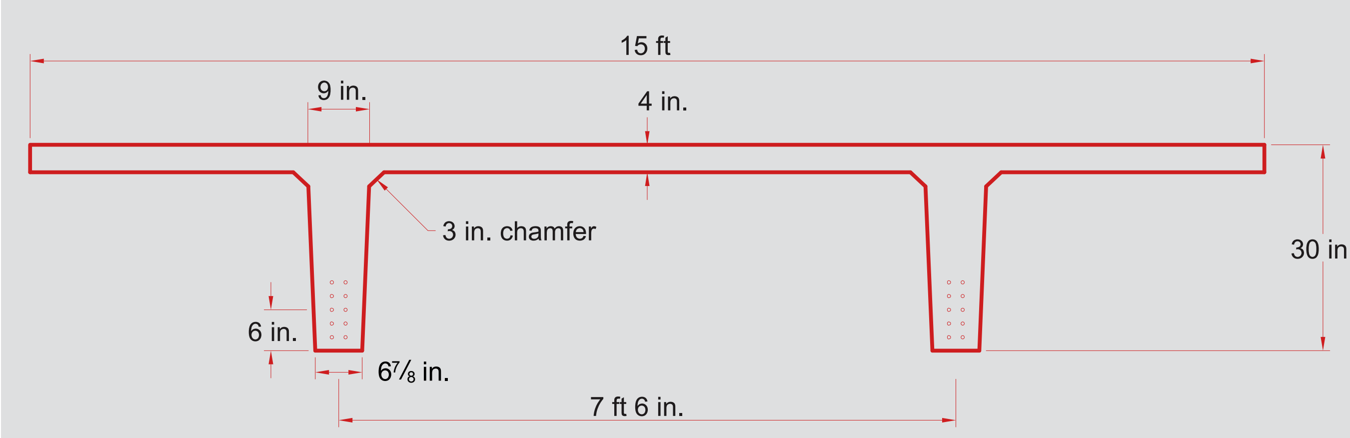

Figure 24. The 15DT30 cross section being analyzed. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

Table 2. Effect of increasing prestress force on superimposed load capacity of a 60 ft long 15DT30

Parameter	15DT30 Strand size for 20 strands		
	0.5 in.	0.6 in.	0.7 in.
Safe superimposed load, lb/ft^2	76	133	201
Required release strength f'_{ci}, ksi	4.8	6.9	9.5

Note: All strands are assumed to be straight (not draped). 1 in. = 25.4 mm; 1 ksi = 6.895 MPa; 1 lb/ft^2 = 47.9 MPa.

Table 3. Effect of increasing prestress force on span length of a 15DT30 for a given roof load

Parameter	15DT30 Strand size for 20 strands		
	0.5 in.	0.6 in.	0.7 in.
Maximum span, ft	72	83	96
Required release strength f'_{ci}, ksi	4.8	7.2	9.3

Note: All strands are assumed to be straight (not draped). 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 ksi = 6.895 MPa.

Extending capacity of double tees

It is possible to increase the span or load capacity of double tees of a given cross section by increasing the diameter of the prestressing strand used. High prestress forces require high concrete strength, especially at release. This can be illustrated with a 15DT30 (15 ft [4.6 m] wide, 30 in. [760 mm] deep, and 4 in. [100 mm] thick pretopped flange).

The 15DT30 has been a standard double-tee component of parking structures since its introduction in the sixth edition of the *PCI Design Handbook*.[19] A span of 60 ft (18 m) is typical for parking structures.[21] It consists of two 18 ft (5.5 m) long parking spaces and a 24 ft (7.3 m) wide two-way driving lane. A single double tee covers an area of 900 ft^2 (84 m^2), and the concrete used in the member is equivalent to that used in a 6.29 in. (160 mm) solid slab of equal width.

The standard concrete strength used is 3500 psi (24 MPa) at prestress release and 5000 psi (35 MPa) at service.[20] The typical amount of steel used is twenty ½ in. (13 mm) diameter standard (or ½ in. diameter special) prestressing strands. Special strand is slightly larger than standard strand: 0.167 in.^{2} (89.7 mm^2) versus 0.153 in.^{2} (108 mm^2). The *PCI Design Handbook* has more details.[19] A baseline of twenty ½ in. standard prestressing strands is used for comparison purposes.

The following analysis demonstrates that existing technology may be used to increase the load capacity and/or extend the span length. The design criteria stated in the *PCI Design Handbook* are used for this comparison. Load factors used are a dead-load factor of 1.4 or a combination of 1.2 dead load plus 1.6 live load.

For convenience in this discussion, the superimposed load is assumed to come from live load only. The dead load is due to the member weight. Prestress losses for flexural capacity calculations are assumed in the *PCI Design Handbook* to be 30 ksi (200 MPa).[20] The following results were obtained using the *AASHTO LRFD Bridge Design Specifications* prestress loss prediction method.[23] It takes into account the effects of high-strength concrete in reducing the creep and shrinkage components of the prestress loss, thus allowing for a reasonable loss prediction for cases where high prestress is used in high-strength concrete.

The amount of predicted prestress loss is nearly the same with high prestress and high-strength concrete as with conventional applications. Thus, 30 ksi (200 MPa) may still be assumed as reasonable prestress losses, even when the prestress is increased. **Figure 24** shows the cross section of the double tee being analyzed.

Table 2 demonstrates the increase in live-load capacity as the strand size increases from 0.5 to 0.6 in. (13 to 15 mm) and to 0.7 in. (18 mm) for a span length of 60 ft (18 m). The primary criteria at midspan are a maximum tensile stress limited to $12\sqrt{f'_c}$, which is one of the limits specified in the *PCI Design Handbook*,[20] and satisfaction of ultimate flexural strength. Ultimate flexural strength controls for this particular span and loading configuration.

There is a significant increase in member capacity when more prestressing steel is used. Although 0.6 in. (15 mm) diameter strand has become a standard product for bridges, its use is still limited in buildings. The 0.7 in. (18 mm) diameter strand is increasingly being used in bridges; for example, in the Pacific Street Bridge in Omaha, Neb., in 2008[25] and in the Oxford South Bridge in Oxford, Neb., in 2013.[9] The 0.7 in. strand is included in ASTM A416 covering the other strand sizes.[27]

Increasing the concrete strength without increasing the prestressing force has a minimal effect on load capacity. For wide flanges, the effect of increasing the concrete compressive strength is limited to reducing the small existing compression-block depth. Thus, the moment arm between the compression block and the centroid of the strands is largely unaffected.

The concrete compressive strength at the time of prestress release, however, needs to be increased when

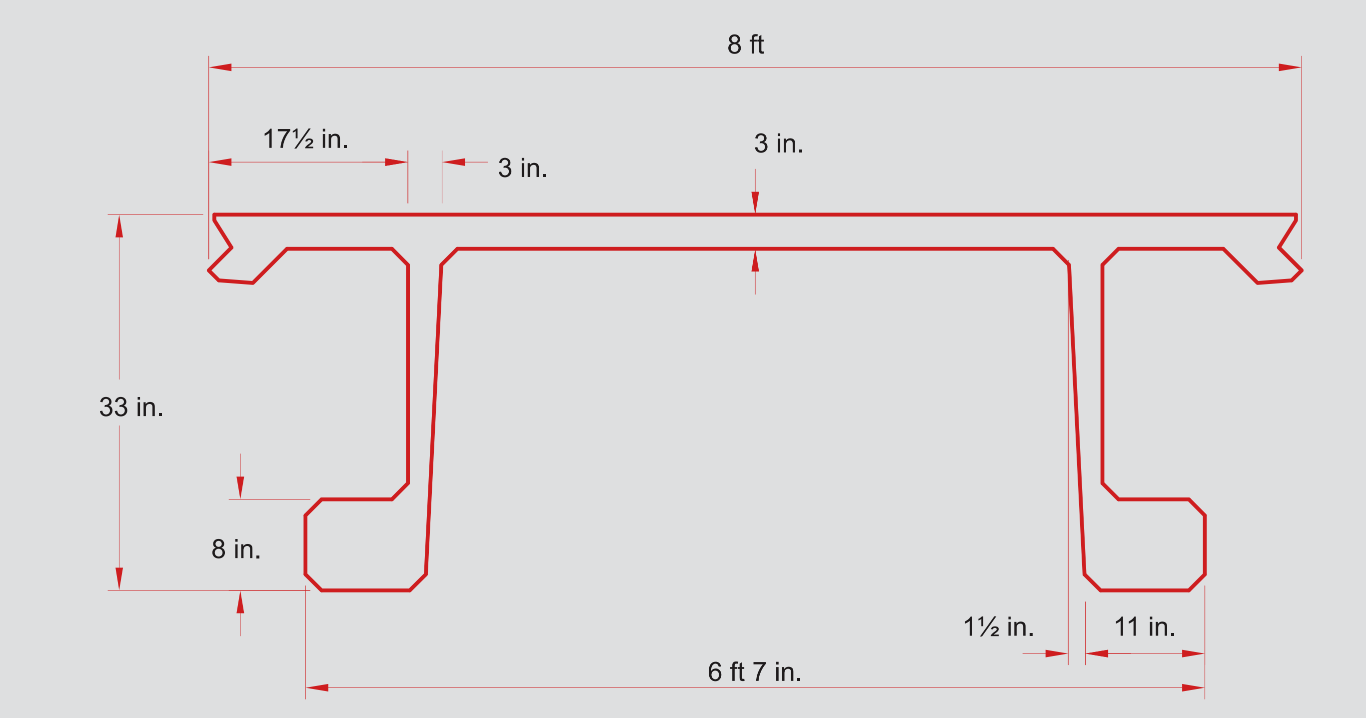

Figure 25. Ultra-high-performance concrete pi girder. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

more prestressing force is added (Table 2). A concrete release strength of 9500 psi (65 MPa) is achievable in laboratories but may be a significant challenge in precast concrete plants. If it is desired to have nearly 200 lb/ft^2 (9.6 kN/m^2) superimposed loading, it can be achieved with little additional effort. Providing 0.7 in. (18 mm) diameter strands and 6500 psi (45 MPa) concrete release strength are easily achievable by precasters in the United States.

Table 3 shows that by using the same assumptions as stated previously, the span of a 15DT30 with a 25 lb/ft^2 (1.2 kN/m^2) snow load and an additional 10 lb/ft^2 (0.5 kN/m^2) dead load can be increased to about 96 ft (29.3 m) with the same 20-strand arrangement if the strand size and concrete release strength are increased accordingly. Initial camber at prestress release, final deflection at service, and vibration due to loads need to be carefully studied before a relatively thin product is adopted in practice.

Ultra-high-performance concrete

Beginning in 2000, several studies have led to concretes with compressive strengths as high as 30,000 psi (200 MPa).[7–9,22,26,28–30] When steel fibers are added to the mixture, the tensile capacity and toughness of the resulting concrete significantly increase.

Due to the high cost of ultra-high-performance concrete, research since the mid-1990s has focused on using generic mixtures produced with local aggregates and minimizing element dimensions to reduce overall cost.[26] Researchers at the University of Nebraska, the University of Michigan, and Georgia Institute of Technology have achieved concrete strengths from 18,000 to 20,000 psi (124 to 138 MPa) using nonproprietary ingredients and local aggregates rather than the silica powder used as aggregate in proprietary mixtures.[22,26,30] This has resulted in a significant reduction in concrete unit cost, from about 20 times to 3 times that of conventional 5000 psi (35 MPa) concrete.

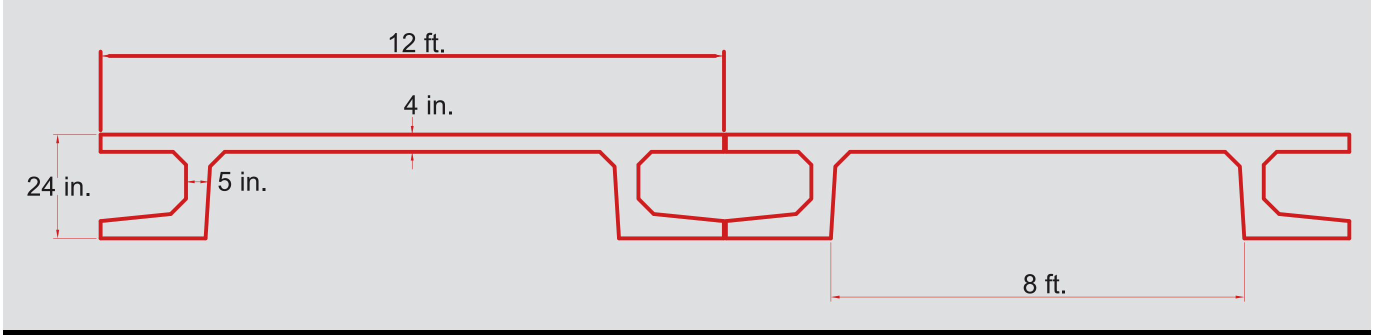

Figure 26. Two adjacent 12 ft wide pi girders forming closed soffit floor. Note: 1 in. = 25.4 mm; 1 ft = 0.305 m.

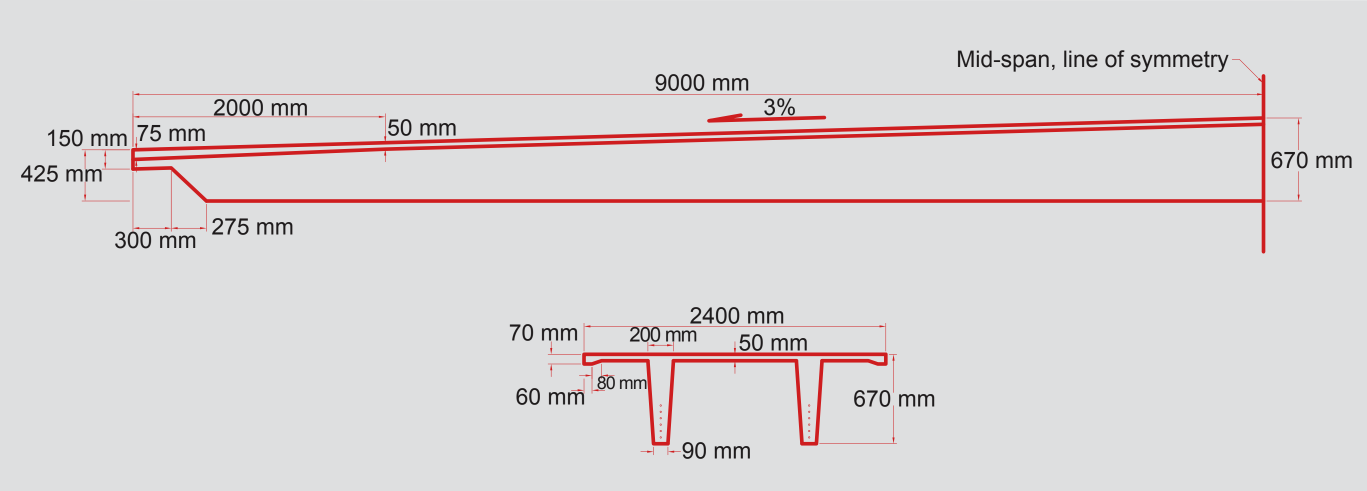

Figure 27. Hungarian variable-depth double tee. Note: 1 mm = 0.0394 in.

The pi girder

Figure 25 shows the dimensions of the pi girder.[7,8] This 8 ft (2.4 m) wide shape was developed for bridges. The stems and the top flange are 3 in. (75 mm) thick. The section is designed to use fiber-reinforced concrete in which randomly oriented steel fibers would replace mild-steel shear reinforcement. Strands are the only reinforcement placed in the two bottom bulbs. The bulbs are necessary to provide adequate space for the strands to be placed at 2 in. (50 mm) spacing near the tension face of the member.

The pi girder has been called the *bulb double tee*. It retains the stability of the double tee while allowing the strands to be concentrated near the bottom of the section. In addition, the bottom bulbs add substantial flexural stiffness to the section while also minimizing vibration and deflection. However, the product is more difficult to produce than the double tee without a bottom bulb. The forms may be made with sides that slide in and out or with embedded blocks that are stripped with the product and then replaced for the next production cycle.

The authors believe that the bulb double tee deserves further investigation. It is essentially a hybrid of the double tee and the I-girder. If it can be produced efficiently and economically, it can have important applications in buildings, bridges, and other structures. One way of incorporating this visionary product is to further develop the pi girder in Fig. 25 into a 12 ft (3.66 m) joist to be used in floors where a shallow depth is required.

The section shown in **Fig. 26** can span more than the 60 ft (18.3 m) required for parking structures and is 6 in. (150 mm) shallower than the standard 12 ft (3.7 m) wide double tee. It can be produced without void forms as in standard box-beam shapes. The bottom flange allows for the strands to be placed in one bottom row, which maximizes the effective depth of the section.

Variable-depth double tees

Double tees are less frequently used as roof joists than they were in the 1950s before their widespread use in parking structures. The authors believe that there is an unmet market need for double tees in roof spans in the 100 to 160 ft (30 to 48 m) range. Such applications would include aircraft hangars, warehouses, manufacturing facilities, data centers, and even big-box retail facilities. The assumption that steel bar joists with relatively short (30 to 60 ft [9 to 18 m]) spans on relatively slender steel columns are difficult to compete against may not be always valid, especially because owners and developers often demand column-free space.

A variable-depth precast, prestressed concrete double-tee roof has been used successfully in other countries. **Figure 27** was taken from the 1989–1990 catalog from Beton- és Vasbetonipari Müvek, a Hungarian precast concrete company. The total length of the double tee is 59 ft (18 m). The member has a width of 7.87 ft (2.40 m), and the depth varies from 17 to 26 in. (425 to 670 mm). To the authors' knowledge, variable top-flange thicknesses in the longitudinal and transverse directions are not favored in North America because of the general desire for simplicity of production.

Double tees for long-span roof applications

Several obstacles need to be overcome to improve the marketability of double tees for long-span roofs. The first is transporting and erecting long-span double tees. A 120 ft (37 m) long double tee weighing an average of 750 lb/ft (11 kN/m) would weigh about 45 tons (40 tonnes). Members as heavy as 100 tons (90 tonnes) have been transported to bridge projects in most parts of the United States. Thus, this weight limit is not insurmountable. Heavy cranes for site erection are continually developed when needed. The more frequently heavy cranes are used and the more comfortable contractors become with their use, the lower their costs. To reduce transportation costs,

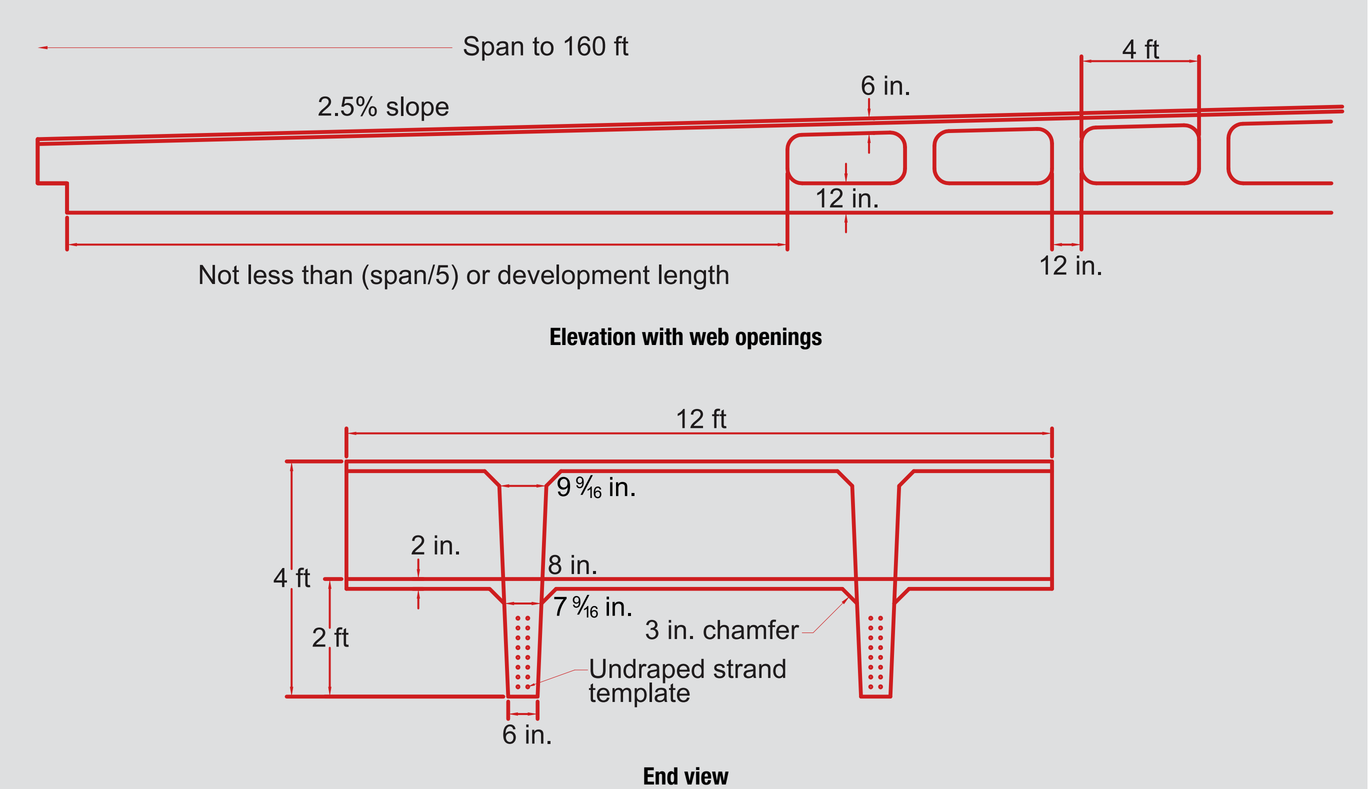

Figure 28. Proposed standard variable-depth double tee. Note: L = span length. 1 in. = 25.4 mm; 1 ft = 0.305 m.

the width of the member can be limited to 12 ft (3.7 m). Lightweight concrete can also be used to reduce product weight.

One attractive option for double tees in roof applications is to produce the member with a center ridge (or crown) and two side slopes. The shape shown in **Fig. 28** is proposed by the authors. The forms can be used for a member as long as 160 ft (49 m), with a depth of 2 ft (0.61 m) at the ends and 4 ft (1.2 m) in the center. Shorter spans can be accommodated with end bulkheads in the forms.

Dapped ends may be used to reduce the depth at the support (Fig. 27). Straight strands can simplify fabrication. Consequently, the stem width at the bottom is selected to be 6 in. (150 mm), to allow for two columns of strands per stem. The stem width is 8 in. (200 mm) at 2 ft (0.6 m) above the soffit and 10 in. (250 mm) at 4 ft (1.2 m) above the soffit to allow for easy removal of the member from the form. This geometry results in a 2.5% roof pitch, a reasonable full depth, and a manageable member weight.

Using high-strength concrete combined with strands larger than 0.5 in. (13 mm) diameter, spans up to 160 ft (49 m) are achievable with the proposed geometry. Thus, the same setup can be used for nearly all roof-framing applications.

One challenge that needs to be met when such forms are used is optimizing the setup in a long-line prestressing bed to try to use the bed for shorter-span double tees while still satisfying the pitched top-surface geometry and producing the largest number of members per production run. This forming optimization should be possible with sufficient attention and collaboration among precasters, form suppliers, and designers. Further optimization of the product could be achieved by placing openings in the web. Savage et al. found that openings can be placed one strand development length away from the member end.[31] Openings, while they increase forming cost, reduce member weight and allow for the passing of utilities within the depth of the member.

Another challenge is the use of self-consolidating concrete in the production of double tees with a sloped top flange. This problem should be relatively easy to overcome through the use of concrete with sufficiently high viscosity to allow finishing the top surface on a 2.5% slope.

The authors believe that the future of the double tee is indeed bright, especially in view of all of the proposed enhancements to the member and the ongoing research.[8]

Method of production

The standard method of manufacturing double tees is the wet-cast method. One of the great benefits of the standard shape is that the form for the full cross section can be fixed in place. A long casting bed can be used to make several double tees in the same production cycle. These advantages make production simple and cost effective. However, compared with hollow-core slabs, more manual labor is required for double-tee production. The authors believe that progress can be made to provide more automation in production and to further optimize an already excellent product. For example, slip-forming methods are used to construct cast-in-place concrete bridge railings. At least one manufacturer in Europe, Nordimpianti, makes 3.3 ft (1.0 m) deep prestressed concrete elements with shear reinforcement throughout their length. For this visionary product to turn into reality, a systems approach would need to be applied, with significant collaboration among precasters, designers, materials specialists, formwork suppliers, and equipment manufacturers.

Conclusion

Based on the information presented in this paper, the following conclusions can be made:

- The double tee is one of the most cost effective, versatile, and widely used building products in North America. It can be used both as a horizontal and vertical load-bearing member.

- A major advantage of the double tee, compared with single tees and other single-stemmed wide-flanged members, is its stability during storage, transport, and erection.

- The top flange of the double tee provides both the floor and ceiling of the structure and also the compression side of its flexural resistance. The stems furnish the tensile component of the flexural strength, shear resistance, and stability of the member. This makes the double tee not only structurally efficient but also functionally efficient.

- The width of the top flange plays an important role in the economy of the structure. Fewer precast concrete pieces in the structure require fewer connections and lower the cost of production, handling, transport, and erection.

- The most popular double-tee width is 12 ft (3.6 m). In most locations of the United States, this is the hauling limit for shipping on the highway without excessive cost. However, new hauling methods have been developed to introduce 15 and 16 ft (4.5 and 4.8 m) wide double tees transported on a special tilt frame to meet the 12 ft (3.6 m) shipping width requirement.

- Due to the wide top flange, concrete strength in service is rarely a controlling design factor compared with concrete strength at time of prestress transfer where the bottom compressive stress is resisted by narrow stems.

- Increasing the prestress force for a given section size enhances its span capability, reduces the likelihood of cracking, and increases the durability of the member.

- Load capacity can be enhanced by increasing the prestress force. However, higher prestress may necessitate higher concrete strength at the time of prestress release. Also, camber, deflection, and vibration may become more critical.

- Increasing the strand size from 0.5 to 0.6 in. (13 to 15 mm) diameter and subsequently to 0.7 in. (18 mm) will significantly enhance the load capacity, provided that there is sufficient concrete release strength.

- Although span lengths of double tees go up to about 100 ft (30 m), they could reach 160 ft (48 m) with currently available technology.

- Because of the large width of the top flange and the fact that the demand for strength at service is not high, the use of ultra-high-performance concrete does not significantly affect capacity under full service loads. However, the more challenging increase in concrete strength at prestress release results in increased ability to apply more prestressing and thus indirectly improves service-load capacity.

- Recent innovative variations of the typical *PCI Design Handbook* section shapes by precast concrete manufacturers hold great promise and will extend the range and applicability of the double tee:

  — PCI Northeast developed a section called the NEXT beam that is mainly applicable to short- and medium-span bridges.

  — The pi girder combines the attributes of the bulb tee and the double tee for use in bridges.

  — Variable-depth double tees, inclined top flange, web openings, and other sophisticated schemes have been proposed.

- The future of the double tee is bright, especially in view of the existing and proposed enhancement schemes as well as ongoing research.

Recommendation

The authors recommend that a PCI fast team comprising designers, precast concrete production experts, formwork experts, handling equipment experts, and researchers be set up to devise a plan for exploiting the full potential of double tees with the aim of doubling the current span capacities while minimizing costs associated with production and construction. This effort would hopefully expand current markets and open new markets for buildings, bridges, and other structures.

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Notation

d = total depth of member

f'_c = specified concrete compressive strength

f'_{ci} = specified concrete compressive strength at release

L = span length

About the authors

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Abstract

This paper traces the origin and development of the double tee, emphasizing the influence it has had on the precast, prestressed concrete industry. It reviews the advantages and diverse applications of double tees, primarily in North America. The major features of the double tee are discussed, especially in relation to parking structures. The paper summarizes the results of selected studies conducted at several universities. It discusses the northeast extreme tee (NEXT), the 16 ft (4.8 m) wide Mega-Tee, and the bulb double tee. Examples of future possibilities of double tees using high-strength concrete, self-consolidating concrete, and large-diameter prestressing strands are explored. It is concluded that the future of the double tee, with all its enhancements and ongoing research, is promising.

Keywords

High-strength concrete, history, large-diameter strand, research, self-consolidating concrete, double tee, northeast extreme tee, parking structure, pi girder.

Review policy

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

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