Long Span UHPC Double Tees for Building Structures – A Design Process

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Abstract: With superior mechanical and durability properties, Ultra High-Performance Concrete (UHPC) is an ideal choice for shallow depth, long span beams in parking and commercial buildings. However, such an application has not been realized due to significantly high material cost. UHPC volume reduction is thus critical and hence the need for an optimal design solution for long span beams. This paper explores the possibility of developing precast, prestressed UHPC Double Tee beams—a concept that has been successfully used with concrete precast, prestressed concrete. This paper presents a suitable design approach after a discussion on the concept of UHPC Double Tee beams. A time-dependent analysis program to calculate long term deflections using different shrinkage and creep properties for UHPC as well as a non-linear strain-compatibility section analysis program have been developed to formulate the design approach. UHPC Double Tees are compared against post-tensioned beams and steel beams in terms of depth and weight.

Keywords: Ultra High-Performance Concrete (UHPC), UHPFRC, Beams, Long-Span, Precast, Prestressed, Double Tee.

1. Introduction

Ultra High-Performance Concrete (UHPC) has superior mechanical and durability properties [Graybeal 2011; Russell et al., 2013] with compressive strengths over 150 MPa (21 ksi) and post-peak tensile strengths between 7 to 10 MPa (1 to 1.45ksi) depending on fiber type and content. UHPC's high elastic modulus ~ 50 GPa (~7250 ksi) can be used to reduce member depths while maintaining required flexural rigidity (EI). The material also exhibits significantly lower creep coefficients (0.2 to 0.8) compared to normal strength concrete (2 to 2.5), thus helping to control the long-term deflection. UHPC's significantly low permeability and its superior performance in freeze-thaw make it a material of choice for use in structures that are susceptible to environmental impact.

The typical framing of parking structures floors in North America is with long-span beams of about 18.3 m (60 ft), spaced at about 6.7 m (22 ft) on centers with one-way slabs spanning between them. Depending on the region, practice, and economics, popular beam systems include post-tensioned beams, composite steel or castellated/cellular steel beams and precast prestressed Double Tees. Typical beam depths are around 762 mm (30 in.) exclusive of a 154 mm (5 ½ in.) deck, yielding a total depth of almost 914 mm (36 in.). Thus, the use of UHPC can add substantial benefits to parking and commercial structures by reducing their weight and thickness, and increasing their durability. Additional benefits include lower labor costs and time due to the elimination of mild reinforcing steel within as demonstrated for the bridge girders [Sritharan 2015].

Analyses and design techniques for the design of UHPC and UHPC-Concrete hybrid Double Tee's (Figure 1) have been developed to calculate the time-dependent long-term strains, stresses and deflections using material specific shrinkage and creep coefficients, and moment capacities using nonlinear strain compatibility method.

Figure 1. Typical Precast Prestressed Double Tee

2. Background

FHWA documents [Russell et al., 2013] provide information on material properties and applications of UHPC for long span beam in bridge structures, and Aaleti et al. (2013) includes information on specified design stress-strain curves and design equations for flexural strength of rectangular and T-beams. This paper uses this information for the design of UHPC beams suitable for parking structures.

Churches et al. (2003) have detailed the design of composite steel beams for long span beams in parking garages. Fares et al. (2016) provide vierendeel design philosophy of castellated and cellular steel beams, which could be adapted to engineer cellular UHPC beams to optimize the material used. The UHPC Double Tee in this paper is the first step towards the use of this philosophy. Cast-in-place post-tensioned parking structures [Freyermuth 1992] are another efficient way to design parking structures. The mass use of UHPC on site is a challenge due to quality control issues with on-site production or ready-mix supply and lack of certified UHPC site inspectors and contractors. Long-span building structures commonly use Concrete precast prestressed Double Tees. The PCI design handbook (2010) provides design tables for the Double Tees with allowable loads, section properties, prestressing, and camber. All the systems mentioned above currently do not use UHPC and hence opens up a new opportunity for this material if its volume can be optimized. This paper takes existing Double Tee sections in the PCI design handbook (2010) and minimizes their size for 18.3 m (60 ft) span beams for parking garages using UHPC. Gilbert et al. (2010) elaborate analytical methods to assess the time-dependent stress, strain, and curvature of sections subjected to axial and bending stresses. They present the age-adjusted effective modulus method (AAEM) and the step by step method (SSM) with examples. The latter method is suitable for the work here. The SSM accounts for varying shrinkage, creep, prestressing relaxation, and elastic properties at different loading ages for sections with different flange and web material. A research study completed by Gilbert et al. (2013) is limited to normal strength concrete.

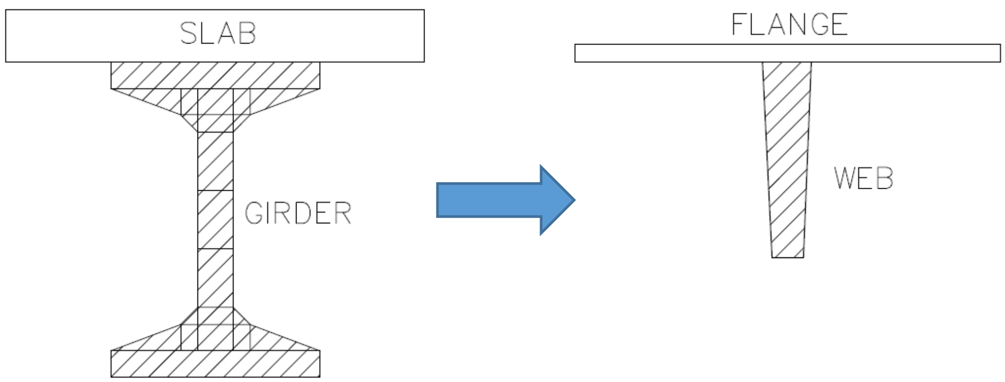
Devalapura et al. (1992) conducted uniaxial tests on prestressing strands and provided a stress-strain relationship to calculate the stress, f_{ps} that provides a good alternative for nominal flexural strength instead of the ACI 318-14 (2014) equation for f_{ps}. Collins et al. (1997) have suggested stress-strain models for concrete strengths of up to 110 MPa (16000 psi). Seguirant et al. (2005) have presented a strength design method for prestressed T-beams with different concrete materials for flange and web, and compared code-based design approach to the strain compatibility approach using nonlinear concrete compressive stress distribution. In this paper, the non-linear strain compatibility approach uses the UHPC stress-strain curves for both tension and compression. The Swiss standard (2016) provides directions on mechanical properties and design of UHPC members and has been used exhaustively in this paper along with Aaleti's et al. (2013) recommendations. The French standards (2016) can also be alternatively used. The design shear capacity of fiber only elements is calculated using the Swiss standard (2016) along with the FIB Model Code (2010) .

3. Testing Methods

3.1 Structural Analyses for Double-Tees

A two-stage section analyses program, at service and strength level, has been developed. The program can analyze a generic composite T-beam (See Figure 2) with the slab and the girder having different mechanical properties. The program could handle pre-tension, bonded or unbonded post-tension type of prestressing although, in this paper is limited to pre-tensioned Double Tees. The age of concrete in the girder at which the composite action starts, and at the time of grouting of the prestressing duct for the bonded post-tension system can be input.

With appropriate dimensional inputs, the girder shape could be varied to suit the intended shape. This paper uses symmetric half of the Double Tee for the analysis. Eq. 1 provides the stress in prestressing steel, f_{ps}, in relation to strain, ε_{ps}, and ultimate tensile strength, f_{pu}, where, A = 887, B = 27,613, C = 112.4, D = 7.36, and K = 1 for imperial units (ksi) and 6.9 for SI units (MPa).



Generic Model | Half Double-Tee

Figure 2. Analytical Model of Half Double Tee

$$f_{ps} = K * \varepsilon_{ps}\left(A + \frac{B}{\left(1 + \left(C \cdot \varepsilon_{ps}\right)^{D}\right)^{1/D}}\right) \leq f_{pu} \tag{1}$$

From the Swiss Standard (2016), the UHPC creep coefficient, φ_U, at ‘t’ days due to loading at time ‘t_0’is given by Eq. 2. UHPC shrinkage strain, ε_{Us}, at ‘t’ days is given by Eq 3, where, $\varepsilon_{Us\infty}$ = 0.075%, c = -2.48, and d = -0.86. Table 1 and Figure 3 provide more details on creep and shrinkage for UHPC at age 4, 28 and 1825 days.

$$\varphi_U(t, t_0) = \varphi_{U,\infty}(t_\infty, t_0).\frac{(t - t_0)^a}{(t - t_0)^a + b} \tag{2}$$

$$\varepsilon_{Us}(t) = \varepsilon_{Us\infty}.e^{\frac{c}{\sqrt{t+d}}} \tag{3}$$

Table 1. UHPC Creep Coefficients per Swiss Standard (2016)

t_0 (days)	Curing	$\varphi_{U,\infty}(t_\infty, t_0)$	A	B
4	20°C	1.2	0.6	3.2
28	20°C	0.9	0.6	10

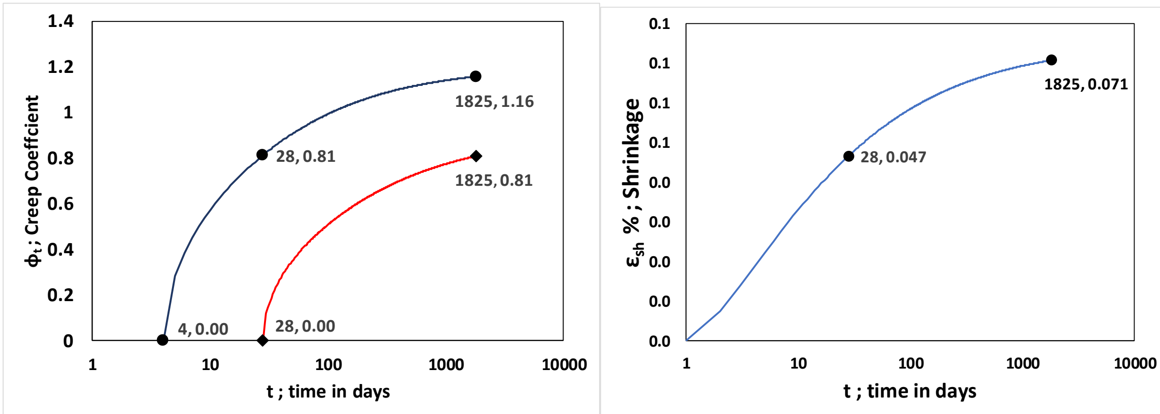


Figure 3. UHPC Creep and Shrinkage Curves per Swiss Standard (2016)

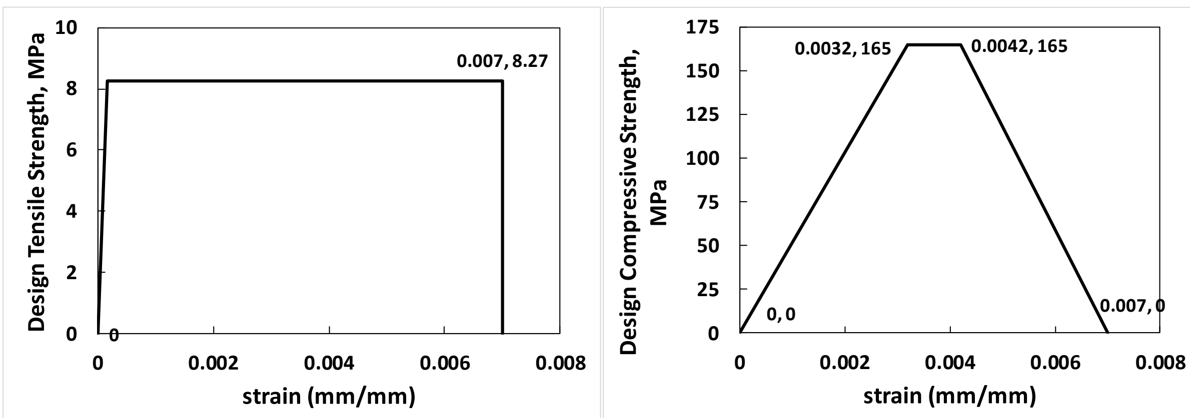


Figure 4. UHPC Design Stress-Strain in Tension and Compression [Aaleti et al. 2013]

Figure 4 shows the UHPC design stress-strain curves for the design of Double Tees based on Aaleti et al. 2013. Loading ages for prestressing and self-weight (DL) is four days. Loading age for superimposed dead load (S_{DL}) of 0.5 kN/m^2 (10 psf), and live load (LL) of 2 kN/m^2 (40 psf) is 28 days. Loading age for long-term deflection and strength check of UHPC is 1825 days (5 years). At concrete age of 4, 28 and 1825 days, the Elastic Moduli (E) are 35, 45, and 52.8 GPa and the prestressing creep, φ_p, values are 0, 0.015 and 0.030 [Gilbert et al. 2010]. The 12.7 mm (1/2 in) dia. 1860 MPa (270 ksi) prestressing strands with an elastic modulus of 200 GPa (29000 ksi) conforms to ASTM A416.

3.2 Section Analysis at Service Level

The Double Tee is designed to remain uncracked at service level loads. Gilbert et al. (2010) have been referenced to develop the section analysis algorithm. The half Double Tee is divided into 1 mm (1/25.4 in.) thick strips and geometric properties, rigidities, R_i, of the flange, web, prestressing strand and reinforcement if any, and the initial prestressing force and moment, fp_{init}, are calculated. Loading steps with corresponding mechanical properties are defined. At each loading step, the force and moment for prestressing relaxation loss, fp_{rel}; the shrinkage loss in flange and web, fsh_f, fsh_w; the creep loss in flange and web, fcr_f, fcr_w; and the load matrix, re, are calculated. The strain and curvature at each load step are obtained from Eq. 4 at the desired reference level. The strains and stresses at other locations of member cross-section are calculated using extrapolation.

$$\varepsilon_j = D^{-1}.\left(\mathrm{re} - (\mathrm{fcr_f} + \mathrm{fcr_w}) + (\mathrm{fsh_f} + \mathrm{fsh_w}) - \mathrm{fp_{init}} + \mathrm{fp_{rel}}\right);\ \text{where} \tag{4}$$

$$D = \begin{bmatrix} R(1) & R(2) \\ R(2) & R(3) \end{bmatrix}\ ;\ R = \sum R_i\ \ ;\ R_i = \begin{pmatrix} A.E \\ B.E \\ I.E \end{pmatrix} \tag{5}$$

$$\mathrm{fsh} = \begin{bmatrix} A \\ B \end{bmatrix}.E.\varepsilon_{Us}(t)\ ;\quad \mathrm{fp_{rel}} = \varphi_{\mathrm{p}}.\mathrm{fp_{init}} \tag{6}$$

A, B, I and E are the area, the first moment of area, the second moment of inertia, and the elastic modulus of the flange, web, prestressing steel and the reinforcement at each step. The creep force, fcr, at time step 'i' can be calculated from Eq. 7.

$$creep\ strain = \begin{bmatrix} A \\ B \end{bmatrix}^{-1}.\left(\frac{1+\ \varphi_U(t,t_0)}{E(t_0)}.re(t_0) + \sum_{i=1}^{j}\frac{1+\ \varphi_U(t_j,t_i)}{E(t_i)}.\Delta re(t_i)\right) \tag{7}$$

3.3 Section Analysis at Strength Level

The flexural strength design is done using a non-linear strain-compatibility section analysis method. Independent mechanical properties for the flange and the web can be incorporated. Sections below provide the flexural models for the analysis. In general, 1 mm (1/25.4 in.) thick strips are used to calculate the section properties, incremental assumption of neutral axis and check for the equilibrium of internal forces. On reaching the force equilibrium, calculate the nominal moment capacity.

3.4 Flexural Design Model of UHPC Flange in Transverse Direction:

The design of flange in UHPC without mild reinforcement simplifies its placement. The flange thickness can also be reduced from 51 mm (2 in.) that is typical of the PCI Double Tees. In the paper, under service loads, the flange section is designed to remain uncracked. At the strength level, the tensile stresses are resisted only by the steel fibers.

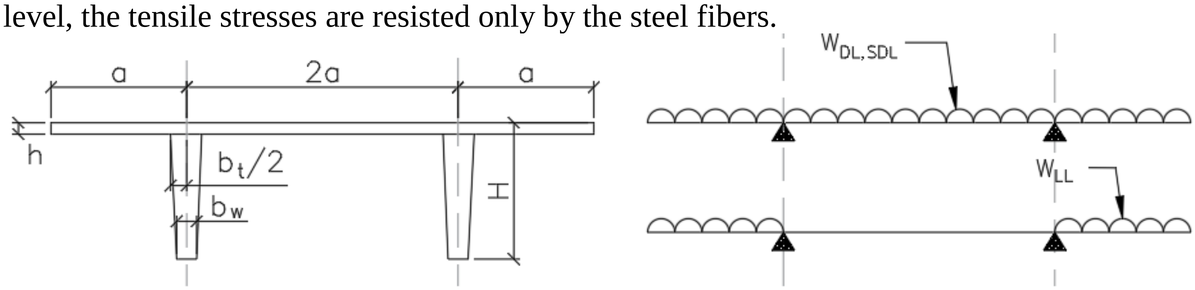


Figure 5. UHPC Flange Design Parameters

Figure 6 depicts the FHWA flexural model [Aaleti et al. 2013] without mild reinforcement. For under-reinforced rectangular section, Eq 8 provides the neutral axis and the nominal moment capacity. In Figure. 6, ε_{cu}, ε_{tu}, f_{cu}, and f_{tu} are, respectively, the maximum design strain and stress in compression and tension while f_c and f_t are the extreme fiber compressive and tensile stress at equilibrium. 'c' denoted the neutral axis depth; C_c and T_u are the internal compression and tension force at equilibrium, h and b are the flange depth and its unit width, and M_n is the nominal moment capacity.

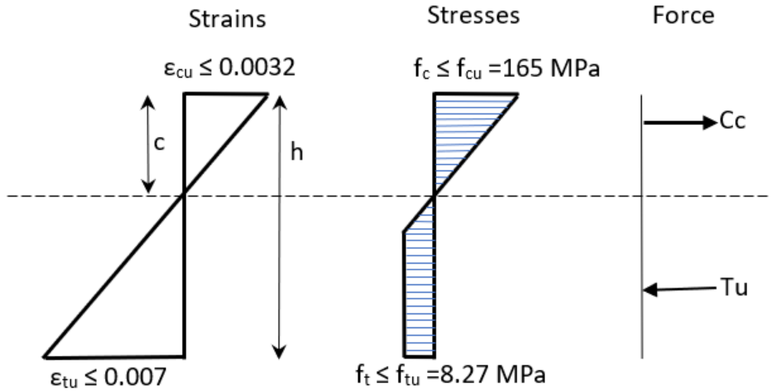


Figure 6. Flexural Model for Design of Flange

$$\boldsymbol{c} = \left(\frac{f_{tu}}{f_{tu} + 0.0035E\left(\frac{c}{h-c}\right)} \right) h;\, and\ \boldsymbol{M_n} = f_{tu} b (h - c) \left(\frac{3h + c}{6} \right) \tag{8}$$

3.5 Flexural Design Model of UHPC Double Tee in Longitudinal Direction

Model the strain, stress, and the force diagram per Figure 7. The neutral axis is within the flange. The FHWA model [Aaleti et al. 2013] limits the extreme fiber tensile strain to 0.007. The limit on the strain also limits the usable compression capacity of the UHPC. The proposed model allows for the extreme fiber tensile strain to cross 0.007 and allow full usage of the design compressive strain. In Figure 7, ε_{sc}, ε_{st}, and ε_{ps} are the strains in the compression reinforcement, tension reinforcement, and the prestressing steel respectively. The corresponding stresses are f_{sc}, f_{ct} and f_{ps} and the internal forces are C_s, T_s, and T_p. The yield stress of steel reinforcement is denoted by f_y.

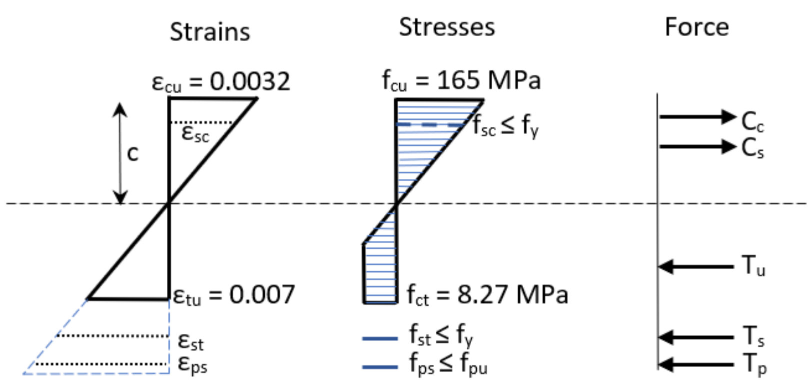


Figure 7. Flexural Model for Design of Double Tee

3.6 Shear Design Model

The Swiss standard (2016) is used here for the shear design model. Ensure the design shear capacity of the flange by limiting the principal tensile strength to be less than or equal to the design value of the elastic tensile strength, f_{Uted}. Use Eq. 9 to calculate the shear capacity of the web with no shear reinforcing. In this equation, V_d is the design shear force, $V_{Rd,U}$ is the design value of ultimate shear resistance capacity of reinforced UHPC, z = 0.9 x effective depth of prestressing at the section under consideration. f_{Uted} and f_{Ucd} are the design values of the compressive and elastic tensile strength respectively, and for the normal case and α is the inclination of the compression field, 30°. The prestressing strands, shall accommodate the additional tensile force, F_{tVd}.

$$V_{Rd,U} = \frac{b_w.z.f_{Uted}}{tan\alpha} \text{ limited to } \frac{V_d}{tan\alpha}. \leq b_w.z.(0.55).f_{Ucd} \tag{9}$$

$$F_{tVd} = V_d(cot\alpha - tan\alpha) \tag{10}$$

3.7 Deflection Model and Limits

Per the ACI 318-14, the instantaneous deflection limit due to live load and the total long-term deflection limit has taken as L/180 and L/240 respectively. For flange overhangs, the immediate end deflection due to self-weight, Δ_{DL}, super-imposed dead load, Δ_{SDL}, and live load Δ_{LL} can be approximated as by Eq. 11. For simply-supported Double Tees of Span 'L', deflection at center-span due to a uniformly distributed load can be represented in terms of curvature 'κ' at mid-span by Eq. 12.

$$\Delta_{DL}, \Delta_{SDL} = \frac{7w(a-\frac{b_t}{2})^4}{24EI_g} \qquad \Delta_{LL} = \frac{15w(a-\frac{b_t}{2})^4}{24EI_g} \tag{11}$$

$$\Delta_{mid} = \frac{5L^2\kappa}{48} \tag{12}$$

4. Results

Three PCI Double Tees have been used in this paper and optimized using UHPC for parking structures for 18.3 m (60 ft.) long span. Refer Table 2; refer Figure 5 for notations.

Table 2. PCI Double Tees [PCI Design Handbook 2010]

Double Tee	h mm	a mm	b_t mm	b_w mm	H mm	$(a-b_t/2)$ mm
8DT24	51	610	146	95	610	537
10DT24	51	762	146	95	610	689
12DT28	51	915	197	121	711	817

Unit conversion: 1 mm = 1/25.4 in.

The flange was depth initially minimized, and then the Double Tee was analyzed with reduced web depths. The factored moment, M_u, was calculated using ACI 318-14 load factors. A strength reduction factor, φ of 0.9 is used in Table 5. Table 3 provides the design moment capacities of the flange, the service level moment, M_a, cracking moment, M_{cr}, and the long-term deflection of the flange in the transverse direction. Double Tee flexural stresses are checked for initial loading at transfer length (TL) of 356 (14 in.) [John et al. 2011]. Harped tendons provide the most optimal results; hence total stresses are checked at 0.4L. Check the initial camber, immediate, and total long-term deflections at mid-span. Refer to Table 4 and 5 for results. Table 6 and 7 compares PCI and UHPC Double Tees.

Table 3. Flexural Capacities of Flange with Reduced Depths and Long-Term Deflection (Transverse Direction)

Double Tee	h mm	c mm	M_n kNm	φM_n kNm	M_u kNm	M_a kNm	M_{cr} kNm	$\Delta_{Total\ (LT)}$ mm
8DT24	38	6.64	5.22	4.68	1.42	0.99	1.99	0.65
10DT24	38	6.64	5.22	4.68	2.17	1.52	1.99	1.52
12DT28	42	6.79	7.33	6.60	3.37	2.37	2.43	2.72

Unit conversion: 1 inch = 25.4 mm, 1 kip-ft = 1.3595 kNm

Table 4. Double Tee Flexural Stresses and Deflection with Reduced Depths

Double Tee	H mm	#S	$e_{0.4L}$ mm	e_{TL} mm	LOC	σ_{init} 4d MPa	$\sigma_{0.4L}$ 28d MPa	$\sigma_{0.4L}$ 5y MPa	Δ_4 mm	Δ_{28} mm	Δ_{LT} mm
8DT24	495	10	413	220	L1	-2.10	-9.76	-10.00	-26	-6	-1
					L2	-3.12	-8.54	-8.63			
					L3	-15.33	6.13	7.83			
10DT24	546	12	463	220	L1	-2.89	-8.61	-8.86	-30	-9	-4
					L2	-3.70	-7.73	-7.82			
					L3	-14.60	4.05	5.96			
12DT28	597	12	518	271	L1	-1.49	-7.44	-7.62	-16	3	7
					L2	-2.22	-6.54	-6.62			
					L3	-11.85	5.26	6.58			

#S is the number of 12.7mm (1/2 in) strands conforming to ASTM A416 Gr.1860, '$e_{0.4L}$' and 'e_{TL}' are the centroid of the strands at 0.4L and TL respectively from the top. Location 'LOC' L1, L2, and L3 are at the flange top, flange bottom and web bottom; respectively; σ_{init} is the initial stress at 4 days at TL, $\sigma_{0.4L}$ is the stress at harp point, i.e., 0.4L at 28 days and 1825 days (5 years); Δ_4, $\Delta_{28,}$ and Δ_{LT} are the deflections at 4 days, 28 days and long term at 1825 days; Sign convention: (-) stress is compressive, (-) deflection is camber; and Unit conversion: 1 inch = 25.4 mm, 145 psi = 1MPa, 4.459 kN = 1 kip.

Table 5. Double Tee Moment and Shear Capacities

Double Tee	c mm	M_n kNm	φM_n kNm	M_u kNm	b_w mm	z mm	V_d kN	$V_{Rd,U}$ kN
8DT24	10	782	704	614	95	232	130	632
10DT24	12	940	846	766	95	232	164	632
12DT28	10	1044	940	956	95	282	210	896

Unit conversion: 1 inch = 25.4 mm, 1 kip-ft = 1.3595 kNm, 4.459 kN = 1 kip.

Table 6. Comparison of PCI Double Tees and UHPC Double Tees (a)

Double Tee	PCI Double Tee			UHPC Double Tee			%	%
	H mm	Area mm^2	Area/4a mm^2/mm	H mm	Area mm^2	Area/4a mm^2/mm	H reduced	Area/4a reduced
8DT24	610	258,709	106	495	202324	83	18.9	21.8
10DT24	610	289,677	95	546	237744	78	10.5	17.9
12DT28	711	412,902	113	597	330126	90	16.0	20.1

Unit conversion: 1 inch = 25.4 mm

Table 7. Comparison of PCI Double Tees and UHPC Double Tees (b)

Double Tee	PCI Double Tee		UHPC Double Tee	
	#S	φM_n kNm	#S	φM_n kNm
8DT24	12	937	10	704
10DT24	12	946	12	846
12DT28	16	1497	12	940

Unit conversion: 1 inch = 25.4 mm, 1 kip-ft = 1.3595 kNm.

5. Discussion

For beam spacing of 6.7 m (22') and 18.3 m (60 ft) span, cast-in-place post-tensioned systems require a 140 mm (5 ½ in) thick slab, web size of 356mm (14 in.) by 762 mm (30 in.) below slab giving Area/flange-width ratio of 180 mm^2/mm compared to about 80 mm^2/mm per Table 6. A composite steel beam of size W33x118 requires concrete Area/flange-width ratio of 140 mm^2/mm and structural steel weight/flange-width of 0.5 kgs/mm (26.8 lbs/in). Steel cellular beams are 30% lighter than W-beams.

It is that the design is not limited by deflections but by the tensile capacity of UHPC. Hence the uncracked service level analyses of Double Tees shall be extended to cracked analyses. Means to maintain high elastic modulus while lowering compressive strength shall be explored to economize the design further. Experimental work shall be performed to substantiate the analyses. The possibility of UHPC-Concrete 'Hybrid Double Tees' and cellular openings in UHPC Double Tees shall be explored to further optimize the use of UHPC in floors of the parking garages.

6. Conclusions

In long-span building structures, UHPC Double Tees are about 20% lower in weight per unit area and shallow in depths compared to concrete precast prestressed Double Tees. They are about 50% lighter than post-tensioned slab-beam systems. The combination of using UHPC and reduced shallower depth lead to a reduction in seismic weight of the structure, reduction in column and foundation sizes, and lower maintenance costs during the service life of the structure. With more competitively priced UHPC material entering into the construction market, UHPC Double Tee's will not only be economical but also be more construction friendly.

7. Acknowledgment and Disclosure

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