RAPID DESIGN OF PRESTRESSED BUILDING TEE MEMBERS

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ABSTRACT

Prestressed concrete double tees have become the major component of precast floor systems for parking garages, office buildings, and other structures. The design is traditionally done through a trial-and-error procedure until certain code and industry limits are satisfied. Due to so many code limits required, it is highly desirable to have a quick procedure to estimate the two most important variables in double-tee design, namely the required number of strands (N) and the required concrete strength at release (f'_{ci}).

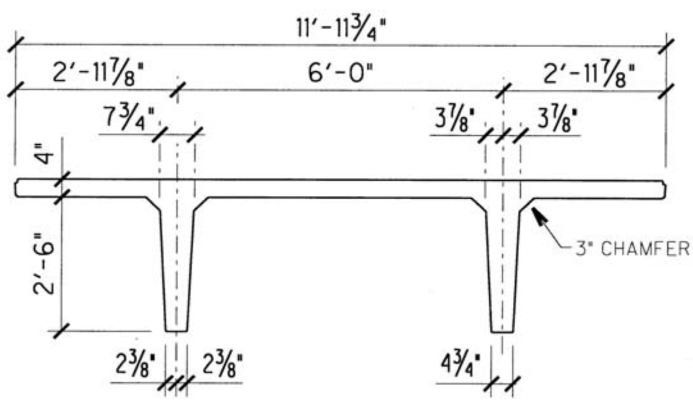
In this study, simply supported, precast double-tee members with various span lengths, live loads, flange widths, and overall section heights are investigated. The objective is to shorten the design process for double tees by using the developed predictor formulas. These formulas can be used to predict N and f'_{ci} values for any number of span combinations, loads, flange widths, and section heights for commonly used tee sections.

The accuracy of predictor formulas is shown to be good. Two illustrative application examples are also presented. It is concluded that the use of exponent-type predictor equations is a valid approach for double tee shapes.

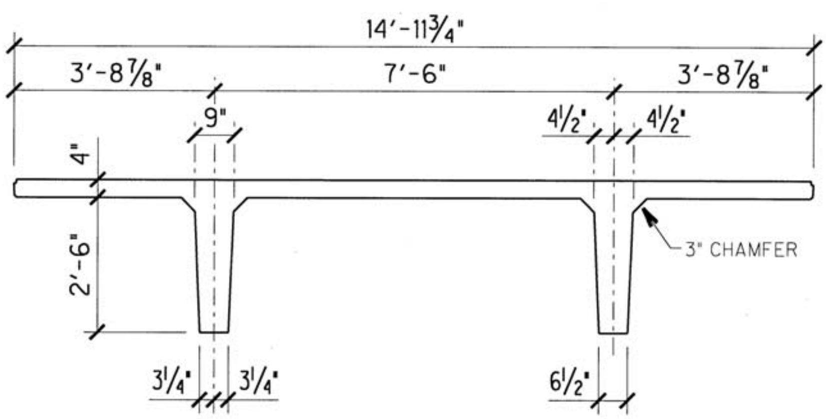
INTRODUCTION

Prestressed concrete offers the ability to span longer lengths and/or support higher loads than reinforced concrete. Prestressing strands add strength to the member while providing compressive forces in areas that are susceptible to cracking.

A common prestressed member used in parking structures and some office buildings is the double tee. Fig. 1 shows typical double tee sections used in parking garages to carry automobiles, snow/rain loads, and in some cases, pedestrians, planters, and loads associated with retail space.



A) Typical double tee section (12-ft wide flange)



B) Typical double tee section (15-ft wide flange)

Fig. 1 Common prestressed concrete double tee types

The double tee member has become the dominant building component of precast parking structures and some office buildings. Some aspects of double tees are consistent from project to project, including stem spacing, 28-day compressive strength (f'_c), and flange reinforcement. However, certain parameters such as loads, member lengths and member widths tend to change. These changes in loads and member dimensions will directly affect the values of N and f'_{ci}. Longer span lengths or heavier loads require more strands than comparable double tee sections with shorter span lengths or lighter loads. Double tees with wider flanges also require more strands than those with narrower flanges for carrying comparable loads per unit area.

The f'_{ci} value is affected by the magnitude of prestress forces in the strands. For example, double tees that require many strands due to high loads or long span lengths require higher release strengths than sections with less strands. The required N and f'_{ci} values are usually determined by the structural engineer using a trial-and-error approach until the following ACI 318-02/05 main criteria are met:[1,2]

- The required moment due to the factored loads (M_u) must be less than the available moment resistance (ϕM_n). Load factors and strength reduction factors (ϕ) are listed in ACI 318, Sections 9.2 and 9.3, respectively.

- For straight strands, the computed extreme fiber stress at service loads in the precompressed tensile zone (at near midspan) shall be less than $12\sqrt{f'_c}$ as stated in Section 18.3. For a simply supported, uniformly loaded double tee with straight strands, the highest tensile stress occurs at midspan in the extreme bottom fibers of the webs.

- Extreme fiber stress in compression shall not exceed $0.60 f'_{ci}$, and extreme fiber stress in tension shall not exceed $6\sqrt{f'_{ci}}$ (at the ends of simply supported members) immediately after prestress transfer according to Section 18.4.

It is worthy of note that these criteria must be met while staying within the bounds set locally by the precasters. Concrete strengths must be attainable. Prestressing forms must be able to safely carry the prestress forces and be physically capable of meeting the overall dimensions (length, depth, and width) of the product.

Some options may be more economical or feasible than others. Preliminary design is a necessary step to determine which options are viable and obtain an idea of the approximate cost for each option. Compared to conventional engineering, preliminary design should be done quicker to obtain information often needed during the pre-bid and initial stages of design.

RESEARCH OBJECTIVES

The objective of this study was to develop general formulas that would enable the user to rapidly and easily predict the required number of strands (N) in double tee members based on section geometry, span length, and loading. These formulas would also rapidly predict the approximate required concrete release strengths (f'_{ci}) of double tees, which are not available in the preliminary design load tables contained in Chapter 2 of the PCI Design Handbook.[3]

EXISTING PRELIMINARY DESIGN INFORMATION

The load tables of the PCI Handbook[3] indicate when f'_{ci} is over 3,500 psi; however, they do not indicate by how much. A warning to the user of excessive release strengths is desirable since it can prevent unforeseen problems. For example, a release strength of 4,500 psi may take a longer curing time to attain than that is allotted in the precaster's casting schedule. An indication of high release strengths during preliminary design will prompt necessary changes in the production schedule sufficiently early to prevent potential threats to the flow of fabrication.

The prediction procedure presented in this paper offers the user the option of investigating double tee shapes that are not included in the PCI Handbook and provides important release strength information. Hence, the formulas are more versatile than the available load tables.

SCOPE OF RESEARCH

This research was based on studies performed on a variety of prestressed double tee members. Close to 900 different loading/dimensional scenarios were simulated, and the results were compiled for analysis. The precast concrete double tee sections investigated included the following common parameters prevailing in the mid-Atlantic region:

- f'_{ci} = 3,500 psi minimum as required by the industry, and f'_c = 7,000 psi.
- Normal concrete weight = 150 pcf.
- Web spacing = 6 or 7.5-ft.
- Overall flange width = 96-180 in.
- Overall depth = 26-34 in.
- Design live loads = 25-99 psf.
- Flange thickness = 4 in. typically.
- Span length = 34-96 ft.
- Number of ½" strands (N) varied from 6 to 26, and strand profile was straight.
- Tensile stress of strands = 176-202 ksi.
- f'_{ci} = 3,500-5,700 psi.

METHODOLOGY

The predictor formulas used in this paper are multi-variable power equations expressed by:

$$N = K(L)^x (W)^y \tag{1}$$

These equations were derived based on a large database of exact solutions of double tee members. Each data point was a unique combination of section depth, flange width, span length, and live load. N and f'_{ci} values were computed iteratively for different scenarios and then used to develop the general predictor formulas.

All double tee solutions were performed using the well-known computer program PRESTO[4] to obtain the data points for the database. PRESTO is a program designed to lessen the burden of prestressed member design by performing the calculations involved in meeting applicable design requirements.

Exact solutions from the PRESTO program were then compiled in a Microsoft EXCEL[5] spreadsheet. The following information was captured for each scenario of flange width (B), overall height (H), and live load (W):

- span length, L
- required strand quantity, N
- required release strength, f'_{ci}

Microsoft EXCEL was used to determine the coefficients and exponents for the predictor formulas by way of the "least squares" method. By taking the logarithms of both sides of Eq. (1), the problem is simplified to be a linear regression analysis with multi variables. The coefficient of determination, R^2, was computed, which has a value less than 1.00 (unity indicating a perfect correlation of the data sample). Also determined was the standard error for the estimates of the predictor formulas.

DESIGN ASSUMPTIONS

The double tee members investigated used ½" diameter 'special' low-relaxation prestressing strands (A_{ps} = 0.167 in^2 per strand) with an ultimate tensile strength (f_{pu}) = 270 ksi and a straight strand profile. The 12-ft wide double tee was assumed to have one vertical column of strands per stem while the 15-ft wide double tee was assumed to have two vertical columns of strands per stem (see Fig. 2). Vertical strand spacing was the same for both types (1.75 in. on centers with the first row starting at 1.75 in. from the bottom of the stem shown in Fig. 2).

All designs assumed a lifting location at 1.5 ft from each end at time of prestress transfer (i.e., when the strands are cut and the member is removed from the prestressing form). The member length was assumed to equal the span length for the final condition.

The governing load combination for ultimate strength for all solutions was assumed to follow Section 9.2 of ACI 318[1,2], i.e.:

$$w_u = 1.2\, w_{DL} + 1.6\, w_{LL} \tag{2}$$

where: w_u is the factored total load per unit length or area, w_{DL} represents the unfactored dead load per unit length or area, and w_{LL} is the unfactored live load per unit length or area.

Critical sections (i.e., locations at which stresses control) and allowable stress limits at time of release and final condition for double tee members with a straight strand profile are listed in Table 1. The solutions were assumed to be governed by these limits adapted from Sections 18.3 and 18.4 of ACI 318 and from Section 10.5 of the PCI Design Handbook.[3] Consistent with the industry standard practice, the jacking stress of all exact solutions fell within the range of 0.65-0.75 f_{pu}.

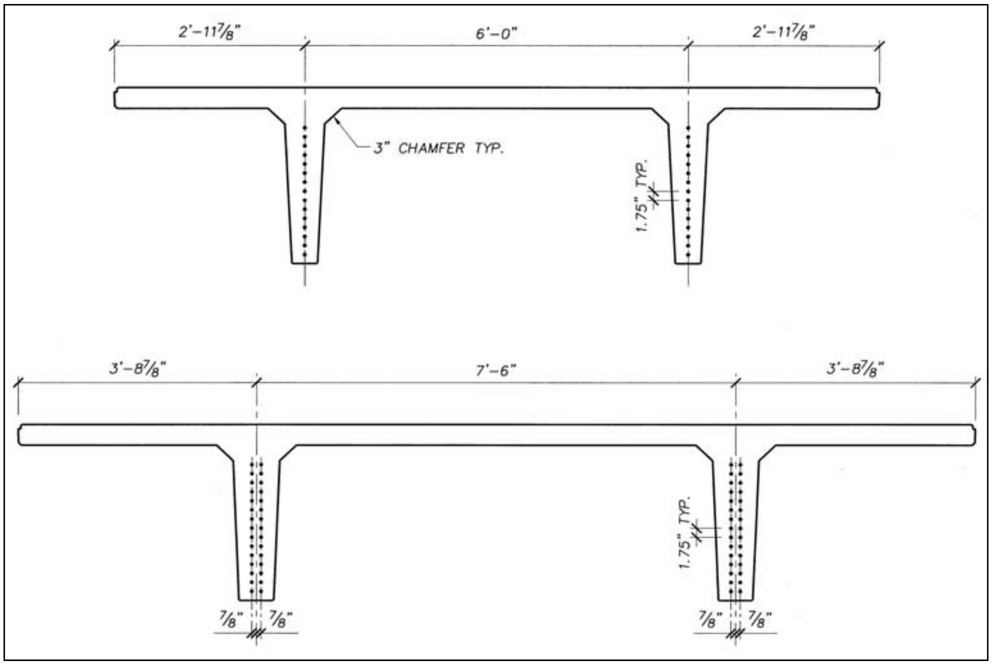


Fig. 2 Typical strand spacing for 12-ft and 15-ft wide double tees

Section 18.4.1 of the ACI 318[1,2] states that extreme fiber stress in compression shall not exceed 0.60f'_{ci} immediately after prestress transfer. It is worthy of note, however, that precasters commonly allow a compressive stress level up to 0.70 f'_{ci} according to Section 10.5 of the PCI Design Handbook.[3] Therefore, an allowable compressive stress of 0.70 f'_{ci} was adopted in this research project.

Table 1 Allowable stresses in concrete in prestressed double tee members

Time	Location	Allowable stress (psi)
release	2.08 ft from ends	$6\sqrt{f'_{ci}}$ (tension)
release	2.08 ft from ends	$0.70f'_{ci}$ (compression)
release	midspan	$3\sqrt{f'_{ci}}$ (tension)
final	2.08 ft from ends	$0.45f'_c$ (compression) under sustained loads
final	2.08 ft from ends	$0.60f'_c$ (compression) under total loads
final	midspan	$12\sqrt{f'_c}$ (tension)
final	midspan	$0.45f'_c$ (compression) under sustained loads
final	midspan	$0.60f'_c$ (compression) under total loads

DATABASE OF EXACT SOLUTIONS

A graphical summary of the exact solutions for a 30-in. deep, full-width 15-ft wide double tee is shown in Figs. 3 and 4. These plots display the relationships between *N* and span length and those between f'_{ci} and span length respectively for various superimposed live loads ranging from 25 psf to 99 psf.

As expected, the required number of strands increases as the span length increases. The required concrete release strength also increases as span length and number of prestressing strands increase.

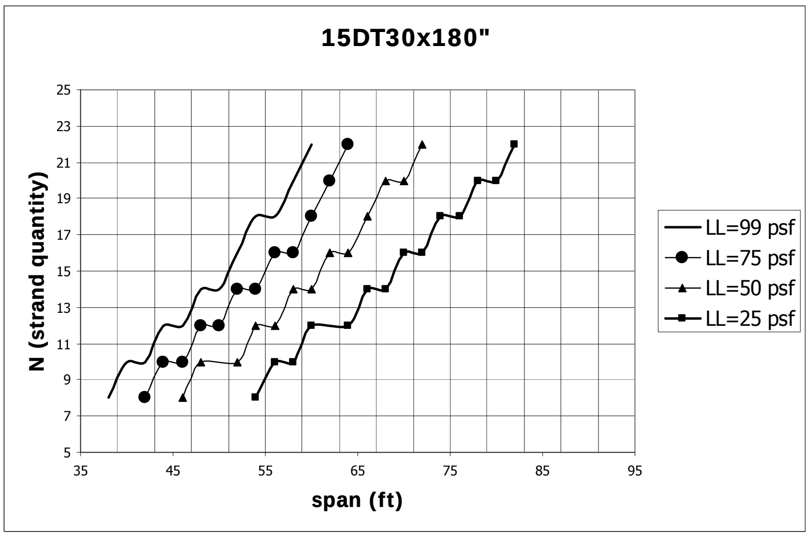


Fig. 3 Exact solution plot for *N* for a 15-ft wide double tee

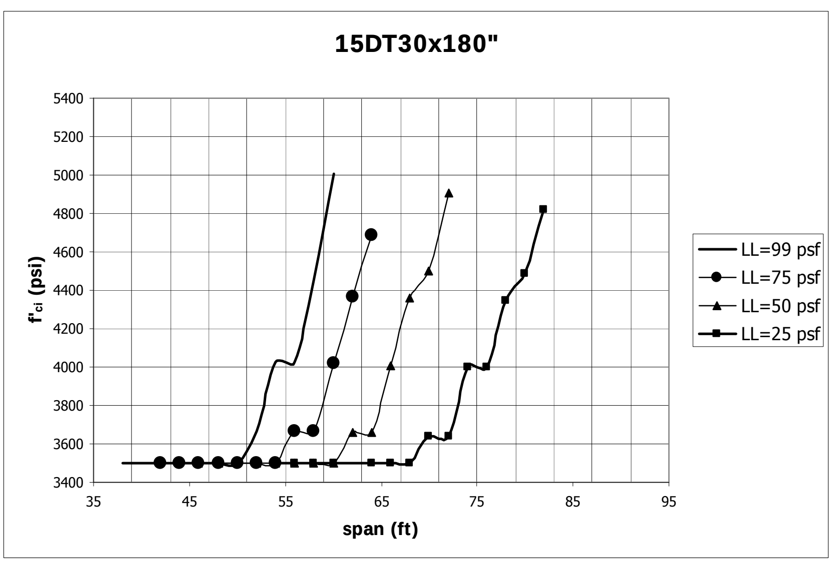


Fig. 4 Exact solution plot for f'_{ci} for 15-ft wide double tees (180-in. wide flange)

The flat slope in the curves of Fig. 4 implies the lower bound of 3,500 psi for f'_{ci} as adopted by the industry. Also, a close inspection reveals a slight drop or leveling off in f'_{ci} over a small increase in span length in certain areas. The reason behind this stark change in slope is that the compressive stresses in the concrete are reduced due to the additional selfweight from the longer span without additional strands. This added weight creates a small increase in bottom tensile stress that lessens the effect of the compressive stress in the bottom of the stems which, in turn, reduces the required release strength slightly. An indication of strands being added to the double tee section is evident when a positive slope is resumed.

PREDICTOR FORMULAS FOR REQUIRED NUMBER OF STRANDS (*N*) AND CONCRETE RELEASE STRENGTH (f'_{ci})

Presented below are the predictor formulas for 12-ft and 15-ft wide double tee members. The formulas assume that *N* and f'_{ci} are both functions of span length (*L*), combined superimposed dead and live service load (*W*), flange width (*B*), and overall section height *(H)*. *K*, *C*, and *D* are constants, while *i*, *s*, *a*, *q*, *t*, *x*, *y*, *z*, *d*, *u*, *v*, *r*, and *p* are exponents:

$$N = K\,(L)^x\,(W)^y\,(B)^z\,(H)^d \tag{3}$$

$$f'_{ci} = C\,(N)^i(L)^s(W)^a(B)^q(H)^t \tag{4}$$

or:

$$f'_{ci} = D\,(L)^u\,(W)^v\,(B)^r\,(H)^p \tag{5}$$

Using basic mathematics, Eqs. (3) and (4) were combined by inserting *N* into Eq. (4) to create Eq. (5). Based on the multi-variable, linear regression analysis, Tables 2 and 3 present the best-fit values for the constants and exponents of the predictor formulas for both the 12-ft and 15-ft wide double tees. It is observed that the exponents *d*, *t*, and *p* for section height, *H*, in Eqs. (3) to (5) are negative values, signifying that as *H* increases both *N* and f'_{ci} decrease.

Table 2 Predictor formula constants and exponents

Section Type	*K*	*C*	*i*	*s*	*a*	*q*	*t*
12DT	0.0001193	346.4	0.6521	0.4294	0.08527	0.06200	-0.5258
15DT	0.0002778	718.0	0.7828	0.3185	0.07529	0.06767	-0.7375

Table 3 Predictor formula constant and exponents

Section Type	*D*	*x*	*y*	*z*	*d*	*u*	*v*	*r*	*p*
12DT	0.9572	2.268	0.4887	0.8673	-1.137	1.909	0.4040	0.6276	-1.267
15DT	1.181	2.012	0.4243	0.7792	-0.8942	1.893	0.4074	0.6776	-1.437

Tables 4 and 5 show the coefficients of determination and standard errors for Eqs. (3) and (4), respectively. The 3% relative prediction error for *N* is considered very good.

Table 4 Coefficients of determination, R^2

Section Type	*N* Eq. (3)	f'_{ci} Eq. (4)
12DT	0.95	0.95
15DT	0.95	0.97

Table 5 Standard errors

Section Type	N Eq. (3)	f'_{ci} Eq. (4)
12DT	3.3%	1.0%
15DT	2.9%	0.8%

The plots in Figs. 5 and 6 represent the computed values from the predictor formulas compared to those of the exact solutions for a 30-in. deep, 10-ft wide double tee with a 6-ft stem spacing and a live load of 75 psf. Inspection of the plots shows a fairly strong correlation between the exact and predicted values for N values. On the other hand, a comparison between the predicted and exact values of f'_{ci}, reveals a slightly less correlation as upper values are reached.

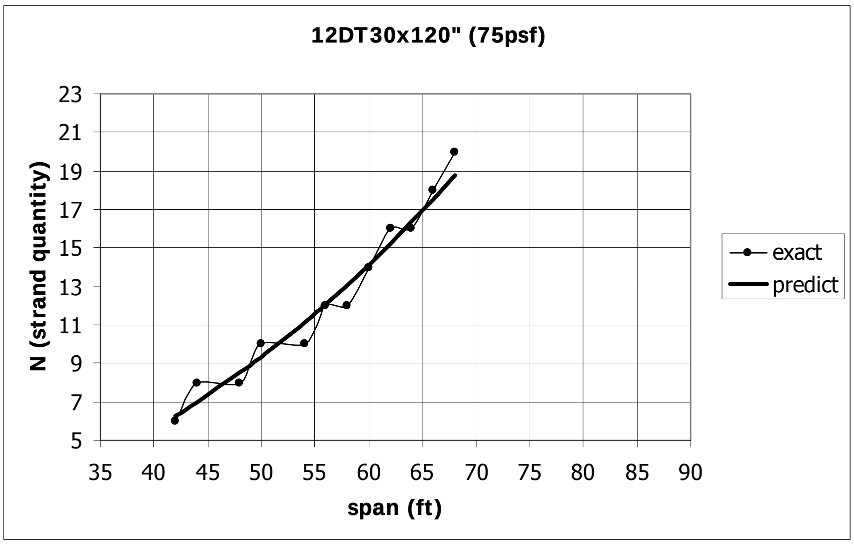


Fig. 5 Predicted and exact solution plot for N (typical 12-ft wide double tee)

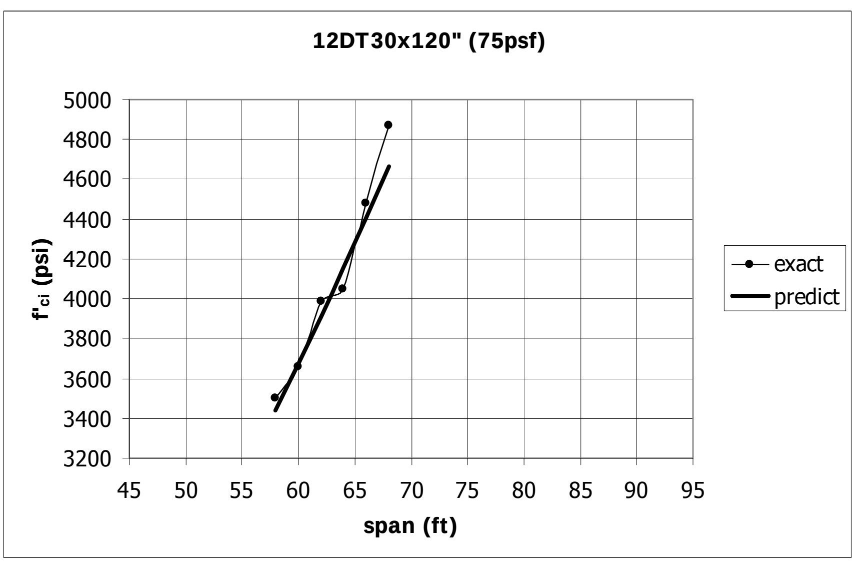


Fig. 6 Predicted and exact solution plot for f'_{ci} (typical 12-ft wide double tee)

DESIGN EXAMPLE 1

The following problem demonstrates the applicability of the predictor equations through generating a solution for a double tee floor member in a parking garage. The desired values are N and f'_{ci} for a member with the following parameters:

- Flange width (B) = 133 in.
- Stem spacing = 6 ft center to center (using the nominal 12-ft wide form).
- Overall section height (H) = 28 in.
- Design live load (W) = 50 psf.
- Span length (L) = 60 ft.

Tables 6 and 7 list the applicable constants and exponents which are extracted from Tables 2 and 3.

Table 6 Predictor formula constant and exponents for Eq. (3)

Section Type	***K***	***x***	***y***	***z***	***d***
12DT	0.0001193	2.268	0.4887	0.8673	-1.137
15DT	0.0002778	2.012	0.4243	0.7792	-0.8942

Table 7 Predictor formula constant and exponents for Eq. (5)

Section Type	***D***	***u***	***v***	***r***	***p***
12DT	0.9572	1.909	0.4040	0.6276	-1.267
15DT	1.181	1.893	0.4074	0.6776	-1.437

Based on the above assumptions and using the general formulas in Eqs. (3) and (5) along with Tables 6 and 7 for a nominal 12-ft wide double tee shape, the predictors' solution is determined as follows:

$$
\begin{aligned}
N &= K\,(L)^{x}\,(W)^{y}\,(B)^{z}\,(H)^{d} \qquad (3)\\
N &= 0.0001193\,(L)^{2.268}\,(W)^{0.4887}\,(B)^{0.8673}\,(H)^{-1.137}\\
N &= 0.0001193\,(60)^{2.268}\,(50)^{0.4887}\,(133)^{0.8673}\,(28)^{-1.137}\\
N &= 13.7 \text{ strands}
\end{aligned}
$$

$$
\begin{aligned}
f'_{ci} &= D\,(L)^{u}\,(W)^{v}\,(B)^{r}\,(H)^{p} \qquad (5)\\
f'_{ci} &= 0.9572\,(L)^{1.909}\,(W)^{0.4040}\,(B)^{0.6276}\,(H)^{-1.267}\\
f'_{ci} &= 0.9572\,(60)^{1.909}\,(50)^{0.4040}\,(133)^{0.6276}\,(28)^{-1.267}\\
f'_{ci} &= 3{,}641 \text{ psi}
\end{aligned}
$$

The actual values taken from an output of the PRESTO[4] software revealed N = 14.0 strands and f'_{ci} = 3,693 psi. The predicted values are very close to the exact values. By inspection, the required number of strands (N) is proportional to $L^{2.27}$, to the approximate square root of W, and to $B^{0.87}$. It is also inversely proportional to $H^{1.14}$.

DESIGN EXAMPLE 2

The second design example involves a double tee member with the following parameters:

- Flange width (B) = 165 in.
- Stem spacing = 7.5 ft center to center (using the nominal 15-ft wide form).
- Overall section height (H) = 34 in.
- Design live load (W) = 80 psf.
- Span length (L) = 62 ft.

Based on the same assumptions and equations as the previous example along with Tables 6 and 7 for a 15-ft wide double tee, the predictors' solution is determined as follows:

$$N = K\ (L)^x\ (W)^y\ (B)^z\ (H)^d \tag{3}$$
$$N = 0.0002778\ (L)^{2.012}\ (W)^{0.4243}\ (B)^{0.7792}\ (H)^{-0.8942}$$
$$N = 0.0002778\ (62)^{2.012}\ (80)^{0.4243}\ (165)^{0.7792}\ (34)^{-0.8942}$$
$$N = 16.4 \text{ strands}$$

$$f'_{ci} = D\ (L)^u\ (W)^v\ (B)^r\ (H)^p \tag{5}$$
$$f'_{ci} = 1.181\ (L)^{1.893}\ (W)^{0.4074}\ (B)^{0.6776}\ (H)^{-1.437}$$
$$f'_{ci} = 1.181\ (62)^{1.893}\ (80)^{0.4074}\ (165)^{0.6776}\ (34)^{-1.437}$$
$$f'_{ci} = 3{,}487 \text{ psi}$$

The actual values taken from an output of the PRESTO[4] software revealed N = 16.0 strands and f'_{ci} = 3,500 psi. Again, the predicted values are very close to the exact values.

CONCLUSIONS AND RECOMMENDATIONS

The derived predictor formulas, Eqs. (3) and (4), are very useful in assisting engineers with the rapid selection and preliminary design of 12-ft and 15-ft wide double tee members that vary in length, load-carrying capacities, flange widths, and depths. These formulas result in the required strand number (N) and the required concrete release strength (f'_{ci}), the two dominant design parameters, fairly accurately. Estimators can also utilize these formulas to perform a cost analysis. Architects can determine feasible combinations of span, section, and allowable load for 12-ft and 15-ft wide double tees.

The derived predictor formulas are intended for preliminary designs. Although they yield good approximations to N and f'_{ci} values, the engineer is reminded to use a more exact method to perform final designs and to use judgment in rounding-off N to an even number.

The number of strands required for double tees cast in the 12-ft wide double form tee is proportional to $L^{2.27}$, to the approximate square root of W, and to $B^{0.87}$. It is also inversely proportional to $H^{1.14}$. The number of strands required for the 15-ft wide double tee is proportional to L^2, to $W^{0.42}$, to $B^{0.78}$, and inversely proportional to $H^{0.89}$. It is interesting to note that the exponent for L is somewhat lower for the 15-ft than for the 12-ft wide tee. This is probably due to the more efficient strand layout in the 15-ft tee which uses two vertical columns of strands instead of one.

Due to limitations in scope, some areas relating to this research remain to be investigated. The following list suggests areas for future research:

- Investigate more double tee sections such as the 10-ft and 16-ft wide double tees to increase predictability of shapes outside of the 12 to 15-ft range.
- Expand the sample range of exact solutions with higher release strengths to improve accuracy of formulas for sections with higher concrete release strength requirements.
- Address double tees which receive topping in the field (resulting in a composite section) and develop predictor formulas for such cases.
- Develop formulas to possibly predict long-term camber values.

ACKNOWLEDGEMENT

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APPENDIX A – NOTATION

K, C, D = constants in predictor equations
f'_c = concrete compressive strength at 28-days (psi)
f'_{ci} = specified concrete compressive strength at release (psi)
f_{pu} = specified ultimate tensile strength (ksi)
B = overall flange width (in)
w_{DL} = dead loads (psf, plf)

H = precast depth (in)
L = span length (ft)
w_{LL} = live loads (psf, plf)
ϕM_n = available design moment or moment resistance
M_u = required moment due to factored loads
N = number of prestressing strands
W = live load for predictor formula input (psf)
w_u = factored total load per unit length or area
i, s, a, q, t = exponents in predictor equations
x, y, z, d = exponents in predictor equations
u, v, r, p = exponents in predictor equations