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Development Length Variables in Pretensioned Concrete Ties

SUMMARY
This research, conducted from 2011 to 2015, is part of a larger project, “Quantifying the Effect of Prestressing Steel and Concrete Variables on the Transfer Length in Pretensioned Concrete Crossties,” conducted by Kansas State University (KSU) and sponsored by the Federal Railroad Administration (FRA). This report highlights advances in quantifying the development length in pretensioned concrete railroad ties. This information is needed to accurately determine the nominal flexural capacity of these ties along their length. Experimental results from load tests on pretensioned, prestressed concrete prisms revealed a significant relationship between wire reinforcement type and concrete release strength on the development length and flexural capacity of the reinforced concrete specimens. A full technical report of this research may be found on the K-State Research Exchange.

BACKGROUND
Concrete railroad ties require prestressing force to carry service loads. This force must be fully introduced into the tie outboard of the rail seat location for the tie to have maximum cracking resistance at the rail seat. The distance from the end of the tie to the point where the force from the pretensioned reinforcements is fully transferred to the concrete is called the transfer length (TL).

The distance from the prestressing load transfer point to the point where the ultimate flexural strength of the concrete tie is reached (ultimate reinforcement stress (f_{ps})) is called flexural bond length [1],

Development length (L_d) is the sum of the transfer length and the flexural bond length. There is limited data describing the relationship between L_d, wire reinforcement and concrete strength characteristics to impact concrete tie performance. The interaction of these variables affects the ultimate flexural capacity of the tie. When a tie is loaded to the point of flexural cracking, tensile forces are transferred from the concrete to the steel reinforcements. If the reinforcements are sufficiently anchored to the concrete, through bond, the stress in the prestressing steel can exceed the yield stress during an extreme overload and approach the ultimate theoretical stress (f_{ps}) for the nominal flexural capacity of the tie.

OBJECTIVE
The objective of this research was to improve the industry’s state of knowledge of wire-reinforcement variables and their impact on the prestressing wire development length in concrete railroad ties. The team investigated the following variables:

- Reinforcement wire indentation type (13 total types, all 5.32-mm diameter)
- Concrete compressive strength at de-tensioning (3500, 4500, or 6000 psi)

METHODS
This project studied the effect of various wire reinforcement types and concrete release strengths on development length within concrete prisms. Researchers designed concrete prisms to represent the concrete cover distance and prestressing wire spacing found in typical wire-reinforced concrete ties. Three 69-inch long, 4-wire pre-tensioned concrete prisms were fabricated for each set of parameters. The team

used a consistent concrete mixture with a Type III cement, a water-to-cementitious ratio of 0.32 and a 6-inch slump for all prisms. Researchers determined the concrete release strengths using temperature-match cured compressive strength cylinders [2].

Researchers first tested 13 different 5.32-mm diameter wire types with a 4500 ± 200 psi concrete release strength. Five of the thirteen wire types were in use by industry, and these were selected for additional testing at varying release strengths (Figure 1). These five were smooth wire (WA), spiral wire (WE), shallow chevron wire (WG), deep chevron wire (WH), and dot-patterned wire (WK).

Figure 1: Five 5.32 mm diameter wires with different indentation types

All wires were tensioned to 7000 lbs. each, consistent with industry practice. Brass inserts were cast into the sides of these prisms at 1-inch intervals to allow the accurate measurement of concrete axial displacements. Transfer lengths were calculated from the measured longitudinal strain profile using a least-squares algorithm.

After aging them for 1 year, the team load tested two of the three prisms to failure, at each end, in 3-point bending to estimate the development length of each combination. Researchers applied loads at 20 and 13 inches from the ends of one prism and 16.5 and 9.5 inches from the ends of the second. Varying the embedment lengths (distance from the end of the prism to the loading point) allowed the experimental determination of the moment capacity at that section, expressed as a percentage of the total capacity when the wire bond is fully developed.

For load testing, prisms were placed on two roller supports with a center-to-center distance equal to 38, 24, 31 and 17 inches corresponding to embedment lengths of 20, 13, 16.5, and 9.5 inches. Figure 2 shows a schematic of the setup to evaluate a 20-inch embedment length.

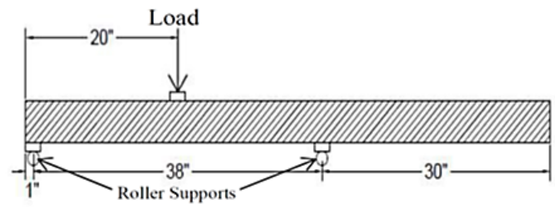

Figure 2: Test setup for loading test with 20 in. embedment length

Researchers conducted 92 load tests (5 wire types x 3 concrete release strengths x 4 embedment lengths, plus 8 wire types x 1 release strength x 4 tested embedment lengths). A concentrated load was applied at the rate of 300 lbs/min at mid-span until the prism failed. Values of load, mid-span deflection, and wire end-slip were continuously monitored and recorded during each test (Figure 3). The corresponding load for the first observed crack and type of failure were documented for each test.

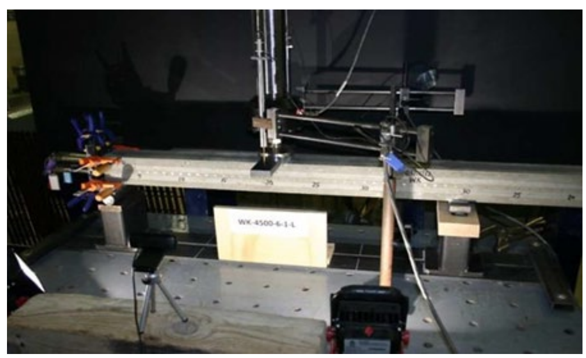

Figure 3: Photo of load test setup

RESULTS

The team found significant differences between the 13 different wire types when tested at the same embedment length (Figure 4). The lower curves in the image (i.e., WA, WK, WL) correspond to wire bond failures and slippage during the load tests. This indicates that these wires must have longer development lengths, since they were all the same diameter and had essentially the same tensile strength.

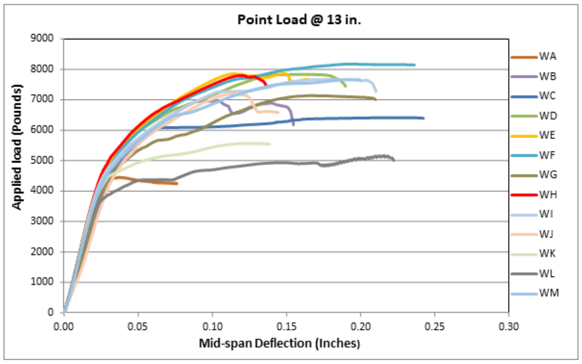

Figure 4: Load vs. deflection response of prisms with different wire types at 13 in. embed. length

The team used the maximum load prior to failure to determine the maximum experimental moment (M_{exp}) by equilibrium of forces. This moment was then compared to the theoretical nominal moment capacity (M_n) that would be achieved if the wire bond was fully developed. The nominal moment capacities were calculated using the stress-strain relationships developed by Chen [3] and a concrete compressive strength of 12,000 psi. This strength was the average long-term strength determined from 4 x 8-inch compression strength cylinders fabricated with the concrete mixture. The team compared the ratio of (M_{exp}/M_n) versus embedment length to estimate the development length to achieve full moment capacity. This is illustrated in Figure 5 for Wire WA at a 6000-psi release strength.

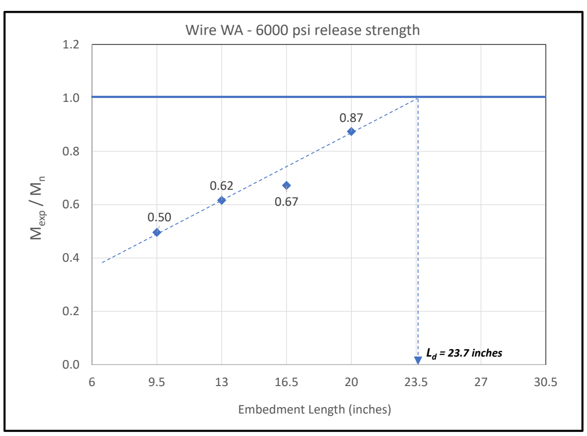

Figure 5: Determination of development length for Wire WA at 6000 psi release strength

Table 1 presents the experimentally determined transfer lengths and development lengths for each wire type and concrete release strength.

Table 1: Summary of Experimentally Determined Development Lengths

Wire Type	Wire Name	Concrete Release Strength (psi)	Transfer Length L_t (in)	Development Length L_d (in)
Smooth	WA	3741	21.4	29.4
		4664	16.3	22.5
		6128	13.5	23.7
Spiral	WE	3486	10.5	11.4
		4650	7.4	9.5
		6020	7.1	9.5
Shallow Chevron	WG	3561	13.8	16.5
		4697	11.8	11.9
		5825	9.8	12.5
Deep Chevron	WH	3614	10.2	13.0
		4695	7.5	11.3
		6059	7.3	11.4
Dot (4 Rows)	WK	3528	17.7	20.5
		4572	14.0	19.3
		5857	11.1	16.5
Chevron	WB	4453	11.6	14.3
Spiral	WC	4701	8.9	14.7
Chevron	WD	4400	11.1	11.6
Diamond	WF	4466	8.5	9.5
Chevron	WI	4547	10.1	10.4
Chevron	WJ	4521	9.0	13.0
Dot (2	WL	4476	18.7	25.3
Chevron	WM	4506	9.8	11.9

CONCLUSIONS

Researchers found that wire indentation type and concrete strength at de-tensioning both have a significant effect on transfer length. For the best bonding wires (WE and WH), there was a diminished effect on transfer length values when increasing from 4500 to 6000 psi, as transfer length values for these two wires ranged from 7.1 to 7.5 inches (Table 1). This suggests there may be a minimum transfer length attainable for any given wire diameter.

Development lengths were also affected by concrete strength at de-tensioning. The development length shortened by 3.26 inches on average when release strengths increased from 3500 to 4500 psi. However, increasing release strengths from 4500 to 6000 psi had a lesser effect, reducing average L_d values by only 1.18 inches.

On average, the L_d was 3.1 inches longer than transfer length for all wires except smooth and dot-patterned (i.e., WA, WK, and WL). For these wires, development length averaged 6.4 inches longer than transfer length.

The team concluded that concrete ties made using wires with shallow to moderately deep indents should be released at higher concrete strength levels. Doing so will yield shorter transfer lengths that provide full flexural crack resistance at the rail seat and will also reduce the risk of longitudinal splitting cracks that can result from using wires with deep indents and inadequate concrete cover. This combination of higher release strengths and shallow to moderate indent depth will also result in significant reserve capacity in the event of overloads.

FUTURE ACTION

Researchers plan to study the development length of larger diameter wires currently employed in new pretensioned concrete tie designs.

REFERENCES

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KEYWORDS

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