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UNDERSTANDING THE SPLITTING AND BURSTING FAILURE OF CONCRETE CROSSTIES

SUMMARY

Under the sponsorship of the Federal Railroad Administration, finite element (FE) analyses were conducted at the Volpe National Transportation Systems Center (Volpe Center) between 2016 and 2017 to understand the contributing factors to the concrete tie splitting/bursting failure mode. This was carried out by simulating the responses of concrete ties to the pretension release process during production and dynamic loads in service. The Volpe Center used the bond and transfer length test data from Kansas State University (KSU) to calibrate and/or validate the FE models, including an elastoplastic bond model that characterized the interactions between various prestressing steel tendons and concrete.

FE analyses of the given concrete tie designs identified low concrete release strength, along with the underdeveloped steel-concrete bond during production, as leading contributing factors to the bursting or splitting failure in some well-known cases. In addition, manufactured surface indentations in some prestressing wires, intended for improving the transfer length performance, can make a concrete tie more prone to bursting/splitting failure when combined with the low concrete release strength-underdeveloped bond condition. Ongoing work is aimed at recommending and incorporating requirements related to these factors into the industrial standards such as the American Railway Engineering and Maintenance-of-Way Association (AREMA) Tie Manual.

BACKGROUND

Pretensioned concrete crossties are made by casting steel tendons with prestresses in concrete and then releasing the prestresses in steel once the desired concrete strength is reached. The concrete strength at release (or concrete release strength) is measured in compression and typically ranges from 4,000-4,500 psi minimally in concrete tie production.

A splitting/bursting failure mode has been identified for pretensioned concrete crossties in railroad tracks. Figure 1 (left-hand side) shows a typical horizontal crack observed in concrete ties on Amtrak's Northeast Corridor, sometimes after 10 years in service; each of these crossties was embedded with eight prestressing strands arranged in two rows (Mayville et al., 2014). Figure 1 (right-hand side) shows bursting cracks branching out from the steel-concrete interfaces in a tie made with 20 prestressing wires (NDT Corporation, 2014). These failures have increased railroad maintenance costs, shortened the expected service lives of concrete ties and presented potential track safety hazards.

Figure 1. Splitting (left) and bursting cracks (right) observed in pretensioned concrete ties.

OBJECTIVES

The main objective was to determine the contributing factors to the splitting/bursting failures observed in pretensioned concrete crossties. The research results are expected to help improve the industry standard and practice in making concrete ties, and improved concrete tie products will lead to safer railroad tracks.

METHODS

The Volpe Center employed the FE modeling method to study the main factors contributing to the splitting/bursting failures of concrete ties. Two key modeling components were: a damaged plasticity model that can predict the onset and propagation of concrete tensile degradation, and a bond model that characterized the interface bond-slip mechanisms and dilatational effects responsible for the concrete splitting forces (Yu, H., and Jeong, D. Y., 2014) (Yu, H., and Jeong, D. Y., 2015).

Figure 2 shows the tensile stress-strain curve employed in the concrete damaged plasticity model. The tensile damage variable d_t measures the degree of post-peak tensile strength degradation, with $d_t=0$ indicating undamaged concrete and $d_t=1$ indicating completely degraded tensile strength and formation of macro-cracks. This is a built-in model of the commercial FE software Abaqus used in this study.

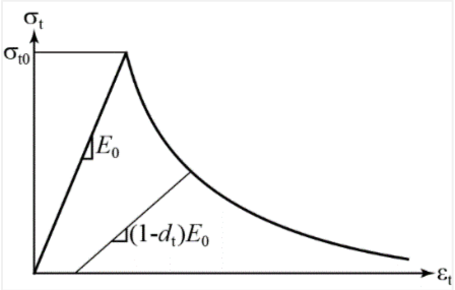

Figure 2. Concrete stress-strain response to uniaxial tension, and definition of tensile damage variable d_t.

The bond model was developed at the Volpe Center and integrated into the commercial FE software as a user material subroutine. The model was developed within the elastoplastic framework and can differentiate bond behavior dependent on such factors as steel reinforcement characteristics, concrete release strength, etc. The bond model parameters were calibrated from the bond and transfer length test data provided by KSU.

The KSU tests included untensioned pullout tests, pretensioned concrete prism tests and pretensioned concrete tie tests, conducted in laboratories or at a concrete tie plant (Arnold, M. L., 2013) (Bodapati, N. N. B., et al., 2013). The concrete surface strain profiles obtained in the two latter tests were used to calculate the transfer lengths in the pretensioned concrete members. Fifteen commercially available prestressing wires and strands were tested, and 5 of them, shown in Figure 3, were selected for the bond model calibration and validation. Of the four wires, WA was smooth, but WE, WG and WH had manufactured surface indentations designed to improve the transfer length performance.

Figure 3. Representative prestressing wires (WA, WE, WG and WH) and strand (SA) in KSU tests.

The test and FE bond model matrix for the five tendons are summarized in Table 1. Two variables in addition to the tendon type were the concrete release strength and the water-to-cement (w/c) ratio of the concrete mix. Because 0.32 is the typical w/c ratio used in U.S. concrete railroad tie plants, FE bond models were calibrated and/or validated only for ties made with a w/c ratio of 0.32. The combination of 6,000 psi release strength and the 0.32 w/c ratio had the most comprehensive set of test data, and the corresponding FE bond models were fully calibrated and validated. The FE bond models for the lower 3,500 and 4,500 psi release strengths were simply calibrated from the pretensioned concrete prism test data. With lower concrete release strengths, not only was the concrete more prone to damage but also the steel-concrete bond was less developed and weaker at holding the two components together.

FE simulations were conducted for concrete ties subjected to pretension release during production, fastener installation, and/or dynamic loading cycles (Yu, H., 2017a) (Yu, H., 2017b). The dynamic load was determined by assuming an axel load of 82 kips and an impact factor of 200 percent. Although actual concrete strengths evolve over time, the concrete strengths remained at the release strength level throughout the simulations owing to a material model limitation with the FE software.

Table 1. Test and FE bond model matrix for the five prestressing tendons in Figure 3.

Concrete		Prestressing Steel Tendon				
w/c Ratio	Release Strength	WA	WE	WG	WH	SA
≥0.42	3,500 psi	T1	T1	T1	T1	T1
	4,500 psi	T1	T1	T1	T1	T1
	6,000 psi	T1	T1	T1	T1	T1
0.32	3,500 psi	T2 FE5	T2 FE5	T2 FE5	T2 FE5	T2 FE5
	4,500 psi	T2 FE5	T2 FE5	T2 FE5	T2 FE5	T2 FE5
	6,000 psi	T123 FE4	T123 FE4	T123 FE4	T123 FE4	T123 FE4

T1 - Untensioned pullout test; T2 - Pretensioned concrete prism tests; T3 - Pretensioned concrete tie tests; FE4 - Fully calibrated and validated FE bond model; FE5 - Simply calibrated FE bond model.

RESULTS

Figure 4 shows the tensile damage or d_t contours, predicted by FE simulations of pretension release at three concrete release strengths, 3,500, 4,500 and 6,000 psi, for an Amtrak tie similar to the one shown in Figure 1. The bond model for the seven-wire strand SA was employed in the simulations. The d_t contours were shown only for elements satisfying $d_t \geq 0.05$. Figure 5 shows the FE predicted evolution of the maximum tensile damage ($d_{t,max}$) for the Amtrak tie through pretension release, fastener installation and three dynamic loading cycles.

At all concrete release strength levels, the tensile damage was initiated at the steel strand-concrete interfaces. Once initiated, both the spatial extent and degree of the tensile damage at pretention release appear to increase with decreased concrete release strength. At the 6,000 psi release strength, the damage pattern was discrete and disconnected. At 4,500 psi, the tensile damage connected locally. At 3,500 psi, the damage interconnected in the upper strand plane and developed into the "horizontal" pattern observed in the field (Figure 1).

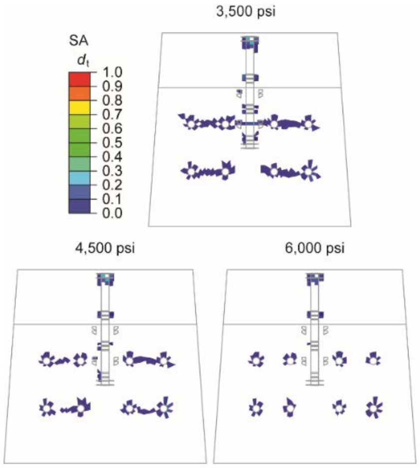

Figure 4. Tensile damage or d_t contours upon pretension release at three concrete release strengths, predicted by FE simulations of an Amtrak tie similar to the one in Figure 1 using the bond model for the strand SA.

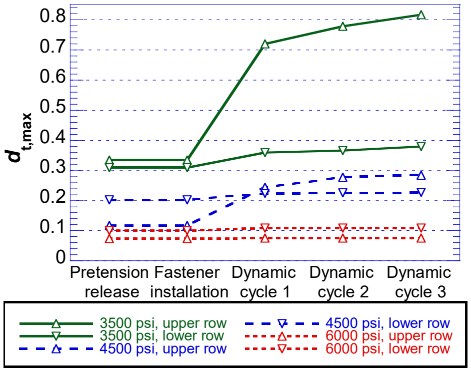

Figure 5. FE predicted evolution of $d_{t,max}$ for the Amtrak tie at three concrete release strengths.

The maximum tensile damage $d_{t,max}$ was about three times as much with 3,500 psi as with 6,000 psi concrete release strength. With the 3,500 psi concrete release strength, $d_{t,max}$

increased consistently with each dynamic loading cycle and can conceivably approach one (i.e., crack formation) after experiencing a sufficiently large number of additional dynamic loading cycles. On the other hand, with the 6,000 psi concrete release strength, $d_{t,max}$ remained at the same low level through the dynamic loading cycles, therefore, macroscopic cracks were unlikely to form at this release strength level.

Figure 6 shows the d_t contours, and Figure 7 shows the $d_{t,max}$ evolution based on simulations of concrete ties made with 20 prestressing wires, similar to the tie in Figure 1. All four wire types were considered. Only the results with the 3,500 psi concrete release strength are shown, as insignificant d_t and/or $d_{t,max}$ evolution were observed with the two higher concrete release strengths.

Ties made with WG or WH showed a bursting damage pattern similar to the one shown in Figure 1, whereas those with WA or WE showed insignificant tensile damage. Further, WH was associated with higher $d_{t,max}$ and more rapid $d_{t,max}$ evolution, thus a higher propensity to develop bursting cracks, than WG. Concrete tie FE models with wires predicted similar bursting damage characteristics with or without a fastener shoulder model.

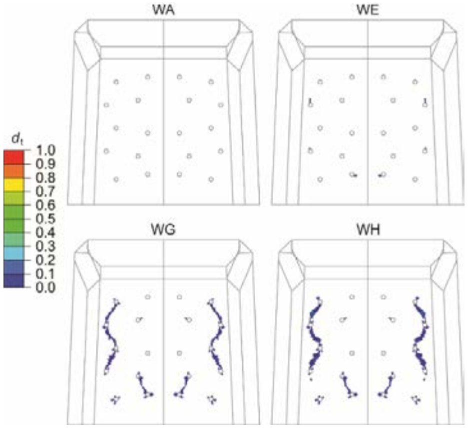

Figure 6. FE predicted tensile damage or d_t contours upon pretension release at 3,500 psi concrete release strength for the four wires.

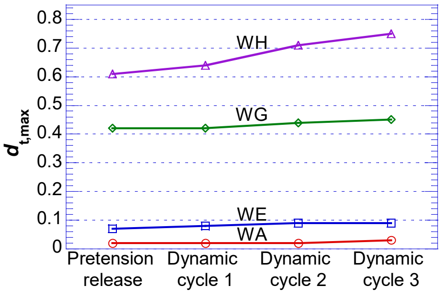

Figure 7. FE predicted evolution of $d_{t,max}$ for the four wires at 3,500 psi concrete release strength.

CONCLUSIONS

With the given concrete tie designs, the FE analyses determined that concrete release strength, bond strength and steel tendon type were factors that contributed to splitting/bursting failures in pretensioned concrete crossties. For concrete ties pretensioned with some wire types and a seven-wire strand, concrete release strengths as low as 3,500 psi, along with weakly developed bond during production, can lead to initial concrete degradations that can further develop into macroscopic cracks under cyclic dynamic loads. In addition, prestressing wires with manufactured surface indentations (e.g., WH) were more likely to cause bursting cracks than a smooth wire (WA) under such conditions.

FUTURE ACTION

The factors of concrete release strength, bond strength and surface indentation on steel tendons need to be revisited or considered in the industrial standards for making pretensioned concrete ties to prevent the splitting/bursting failure. Using pretensioned concrete prisms, KSU is currently developing qualification tests aimed at minimizing the risk of splitting/bursting failure of ties in service. The bond model developed at the Volpe Center is being applied in the FE analyses of the splitting/bursting propensity of the concrete prisms. Further, it is noted that the bond strength development varies with the w/c ratio of the concrete mix, and the bond strength development data need to be obtained experimentally for the prevailing w/c ratio at the concrete tie production plants.

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KEYWORDS

Pretensioned concrete crosstie, splitting crack, bursting crack, concrete release strength, prestressing wire, prestressing strand, bond strength, finite element analysis