A Parametric Study on the Splitting/Bursting Damage of Prestressed Concrete Prisms

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Abstract: *Prestressed concrete crossties have become an important component of the railroad track structure as loading demands have been increasing. However, several premature failure patterns of concrete crossties, including the splitting/bursting failure, are of concern to the railroad community owing to their adverse effect on track integrity and safety. Previous studies demonstrated that small-scale pretensioned concrete prisms had excellent correlations with concrete ties in the bond performance, and similar prisms are being used to establish the splitting/bursting performance of concrete ties. This parametric study focuses on characterizing the splitting/bursting damage of prestressed concrete prisms during the de-tensioning process with respect to the design parameters of the prisms and the concrete release strengths. The design parameters include: 1) type of reinforcing tendons, 2) indentation type of reinforcement, 3) concrete cover thickness, and 4) reinforcement center-to-center spacing. Finite element analyses (FEA) are conducted for the pretension release in the prisms, and indicators of concrete splitting/bursting damage are examined. A previously developed UMAT bond model, calibrated and validated with bond and prism test data, is employed to reflect the effects of different tendon types and indentations. The FEA results indicate that releasing the prestressing tendons before the concrete reaches a sufficiently high compressive strength could cause significant splitting/bursting damages. For the conditions considered in the parametric study, the concrete cover thickness less than 0.75 in. should be avoided in order to prevent premature splitting/bursting damages. Finally, a design guideline for prestressed concrete prisms is recommended, with implications on preferred practices to reduce or prevent the splitting/bursting failure of concrete crossties.*

Keywords: *Bond-slip, Prestressed Concrete, UMAT, Cohesive, Splitting/bursting*

1. Introduction

The railroad industry in North America started the application of prestressed concrete crossties (PSCCs) in the 1960s, and it has continued as loading demands of freight cars and interests of high-speed trains have been growing. PSCCs have been placed on multiple railroad tracks including passenger, freight, and mixed-use tracks. However, some concrete crossties failed prior to their expected service lives, i.e. 50 years, and these failures were identified as the causes of some well-known derailment accidents.

In the early 1990s, a well-known train accident occurred related to premature failures of PSCCs on Amtrak's concrete crosstie tracks on the eastern seaboard (Coleman, 2001). The failures demonstrated that there was the significant loss of prestressing force of prestressing wires originating from the developed cracks on the concrete crossties. Many investigators identified that the issue was associated with degradation of the concrete material, i.e. alkali-silica reaction (ASR). Since they found the degradation of the concrete material was an issue, the manufactures of prestressed concrete crossties made their effort to improve their quality of concrete crossties such as ASR, and freezing and thawing damage. However, concrete damage and cracks were reported again even for the high-quality-controlled concrete crossties which had been placed on the Northeast Corridor and other places. Amtrak had to replace the ties with new concrete ties between 1990 and 2000 on tracks and found that more than 1 million ties had similar problems (Coleman, 2001). Federal Railroad Administration investigated main failure mechanisms of those concrete ties, and it turned out the horizontal cracks of the concrete crossties were initially developed and propagated because of high imposed prestress together with ASR (Mayville *et al.*, 2014). Figure 1 shows examples of damaged concrete crossties with horizontal cracks (Mayville *et al.*, 2014).

Figure 1. Example pictures of concrete crossties with horizontal cracks (Mayville *et al.*, 2014)**.**

Some of the main failure modes of PSCCs include but are not limited to: splitting/bursting failure (e.g. horizontal crack), center binding (vertical crack), rail seat deterioration (RSD), and loss of cover concrete. The manufacturers of PSCCs in North America use different types of prestressing wires, indentations, strands, and thickness of cover concrete, patterns, and numbers of wires etc., which result in wide range of structural performances. In order to improve the structural integrity of PSCCs, many studies have been conducted at the various institutions. A research team at the University of Illinois at Urbana-Champaign (UIUC) investigated how to improve the current design practice by conducting extensive laboratory and field experiments while concurrently developing an analytical tool using a finite element analysis (Chen *et al.*, 2014a; Chen *et al.*, 2014b). Another research team from Kansas State University experimentally examined the effects of different indented wires on structural performances of prestressed concrete crossties currently used in North America (Momeni *et al.*, 2015, 2016). Furthermore, based on the experimental test results obtained by the KSU research team, researchers at the John A. Volpe National Transportation Systems Center, U.S. Department of Transportation (DOT) have developed 3D finite element models of concrete crossties which are capable of simulating bond -slip behaviors between concrete and various prestressing wires (Yu and Jeong, 2014, 2015, 2016; Yu, 2017). In order to represent the different bond-slip behaviors in the interface between concrete and prestressing steels, a thin layer of cohesive elements was employed and assigned traction-displacement relations (bond-slip). The bond-slip model was defined with a yielding function and a plastic flow rule representing adhesive, frictional and/or dilatational bonding mechanisms (Yu and Jeong, 2014, 2015, 2016; Yu, 2017). Then, the parameters for describing the bond-slip model were calibrated with untentioned pullout tests and pretensioned prism tests conducted by the research team at KSU (Arnold, 2013).

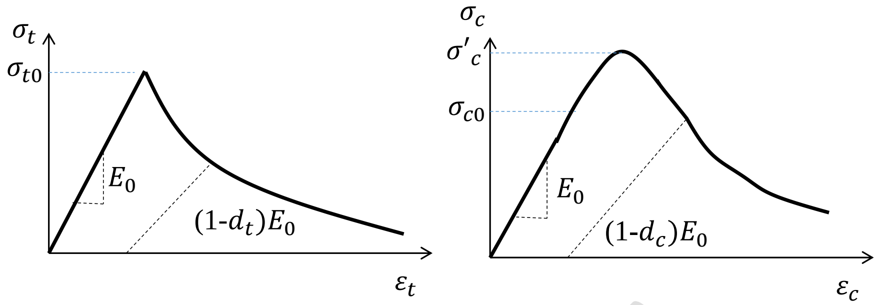
One of the main objectives of this study is to optimize the various (geometrical or mechanical) design parameters of PSCCs: 1) type of reinforcing tendons, 2) indentation type of reinforcement, 3) concrete cover thickness (*CV*), 4) reinforcement center-to-center spacing (*S*) and 5) compressive strength of concrete (*f'c*) when prestressing reinforcement is released. An extensive parametric study is carried out in order to ensure structural performances of prestressed concrete prisms in splitting mode and prevent splitting/bursting failure during their de-tensioning process. Prestressed concrete prisms with single wires are used to perform the parametric study.

2. Material models

2.1 Constitutive model for concrete

Concrete is one of the highly complex heterogeneous materials, and it can be numerically represented as a nonlinear solid material. In this study, a concrete model, Concrete Damaged Plasticity Model, available in Abaqus (ABAQUS User Manual, 2014), which enables to simulate failures of brittle materials such as cracking in tension and crushing in compression is used. Figure 2 shows the uniaxial stress-strain curves of the concrete model. In tension, concrete exhibits a linear elastic behavior until it reaches the cracking strength (σ_{t0}), and the stress-strain curve is followed by softening behaviors. In compression, the stress-strain curve follows a linear-elastic behavior until the elastic limit (σ_{c0}), and a hardening behavior until the compressive strength (σ'_c), and then finally a softening behavior until the ultimate strength. The two damage parameters (d_t and d_c) can be defined to simulate damage progressions at each cyclic loading after the elastic limits and represent the reduction of the initial elastic modulus of concrete. The damage indices d_t and

d_c should be between 0 and 1 (ABAQUS User Manual, 2014).



(a) In tension (b) In compression

Figure 2. Uniaxial constitutive behaviors of concrete: a) in tension and b) in compression.

2.2 Bond-slip model

Bond-slip behaviors between concrete and prestressing tendons have been traditionally understood by three mechanisms: 1) adhesion force between the materials, 2) mechanical interlocking between concrete and a wire due to the existence of indentations, and 3) frictional force between two materials. Tepfers was one of the pioneers who studied on the subject of prestress transfer (Tepfers, 1973). Many of them recognized them potential splitting cracks due to the Hoyer effect (Hoyer, 1939). Prestressed concrete structures are prone to be split by cracks when high radial stress a surrounding prestressing wire is induced.

Recently, a bond-slip model capable of simulating slip and dilatation mechanisms of steel tendons upon de-tensioning were developed (Yu and Jeong, 2014, 2015, 2016; Yu, 2017), and in return, the splitting damage of concrete due to bond-slip and dilatation mechanisms of the reinforcement can be examined. This bond-slip model was adopted to simulate the interface interaction between reinforcement and concrete. Tables 1 and 2 summarize the important mechanical properties and parameters of the materials. The parameters for the bond-slip models (Table 2) were dependent upon indentation types and concrete release strengths. In order to calibrate the bond-slip model parameters and validate the model, series of untensioned pullout and pretensioned concrete prism testing results were used (Arnold, 2013). Figure 3 shows the comparison of the experimental (Test) and numerical (FEA) untensioined pull-out test results on concrete prisms with a single tendon with different indentation patterns. They showed good agreements while capturing the slip starting points, which indicate the bonding failure. Five different types of reinforcement were used; WE (spiral), WH (deep chevron indentation), WG (shallow chevron indentation) and WA (smooth) are a single wire with different indentations, and SA represents a 7-wire strand. As shown in the figure, WA (smooth wire) had the poorest bonding behavior, and the indentation patterns significantly affected the bonding characteristics in the pullout tests. More detailed descriptions, calibration procedures of the bond-slip models and the material properties can be found in the previous work done by one of the authors (Yu *et al.*, 2011; Yu and Jeong, 2012, 2014, 2015, 2016; Yu, 2018).

Table 1. Material properties.

Concrete			**Steel**	
Release strength	3500 psi	4500 psi	**Yield stress**	274000 psi
Elastic modulus	3259 ksi	3655 ksi	**Elastic modulus**	30000 ksi
Compressive strength	3586.0 psi	4570.2 psi		
Tensile strength	366.0 psi	439.4 psi		

Table 2. Material parameters for the bond-slip models.

Parameters	3500 psi release strength			4500 psi release strength		
	WE	WG	WH	WE	WG	WH
Normal elastic stiffness (lb/in3)	9022650	9022650	5413590	12245025	10311600	7733700
Shear elastic stiffness (lb/in3)	187972	187972	112783	255104	214825	161119
Coefficient of friction	0.350	0.280	0.273	0.475	0.320	0.390
Initial adhesive strength (psi)	385	280	420	522.5	320	600
Plastic slip at which the adhesive (or cohesive) state ends (in.)	0.12	0.067	0.05	0.12	0.067	0.05
Maximum dilatational coefficient	0.01	0.0145	0.035	0.01	0.0145	0.025
Dilatational coefficient at which the adhesive (or cohesive) state ends	0.005	0.0045	0.0045	0.005	0.0045	0.0045
Plastic slip at which dilatational coefficient reaches zero (in.)	0.15	0.07	0.053	0.15	0.07	0.053

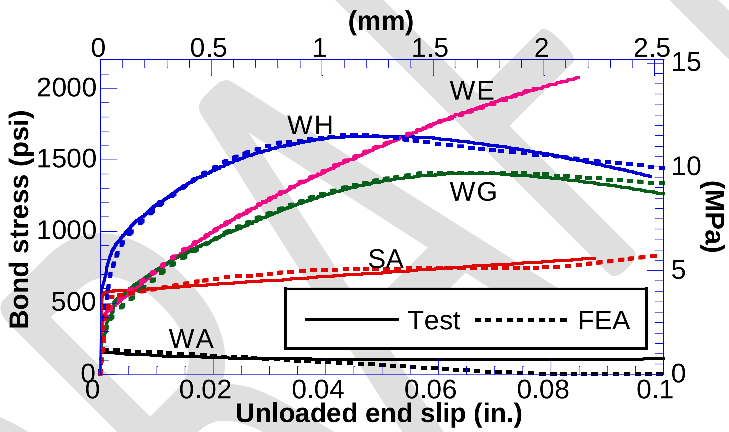


Figure 3. Comparisons of the pull-out test results.

4. Parametric study

4.1 Prestressed concrete prisms

The effects of the design parameters on the splitting/bursting performance of prestressed concrete prisms were examined by incorporating the bond-slip model into a finite element analysis (FEA). The important geometric/mechanical parameters were as follows: reinforcement type, initial pretension force (*P*), concrete cover (*cv*), reinforcement center-to-center spacing (*s*), and release strength of concrete. Two different prisms were considered: 1) single-wire prisms in order to examine the effect of cover concrete, and 2) four-wire prisms to evaluate the center-to-center spacing between wires. Figure 4 shows schematics of a single reinforcement prism and a four reinforcement concrete prism. The concrete cover (*CV*) is defined as the distance from the center of a wire to the outside wall of the prism. Spacing (*S*) is defined as the distance between the center of one wire to another. The length of the prisms is 69 in (1752.6 mm). In this numerical analysis, X, Y, and Z axis symmetry are applied and only 1/8 of the prism is modeled. The three different wire types were denoted by WE, WG and WH, herein. The diameter of the wires is 0.209 in (5.32 mm). Figure 5 shows pictures of the used reinforcement. WE is a spiral-indented wire, WG and WH are both chevron indented wires while WH indicates a deeper indentation.

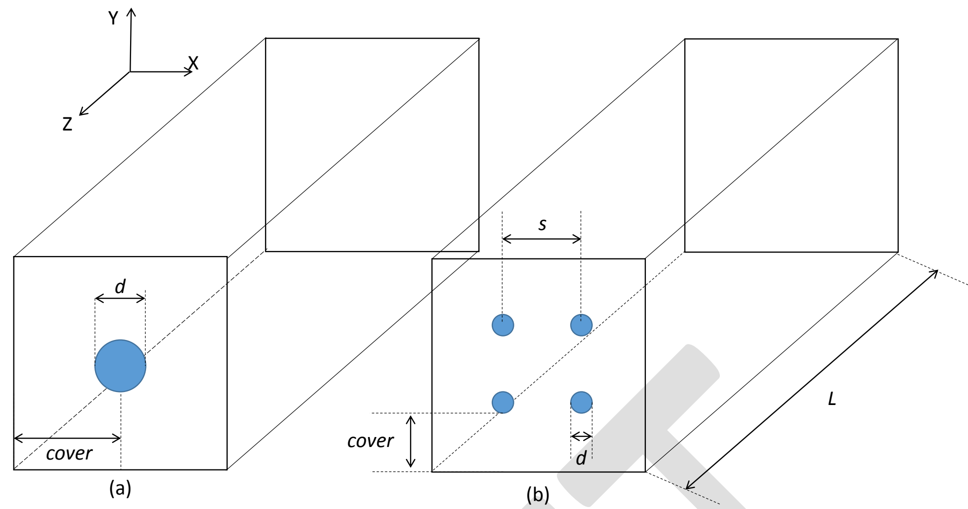


Figure 4. Schematics of a single-wire prism (a) and a four-wire prism (b).

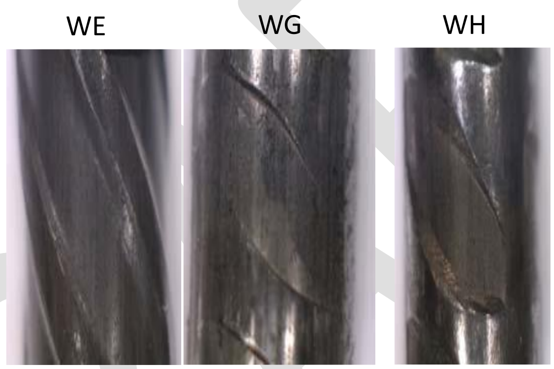


Figure 5. Thee wires with different indentations (Holste, 2014)**.**

4.2 Parameters of single-wire prism

The effects of cover concrete, indentation types, and release strengths were examined via single-wire concrete prisms. The concrete cover was tested at four different thicknesses. Table 3 summarizes the values of the parameters used in this section. Two different concrete release strengths were explored: 3500 psi (24.1 MPa) and 4500 psi (31.0 MPa). These values were chosen to demonstrate the effects of prematurely de-tensioning the wires within a few hours or a day after pouring the concrete. Three pretension forces were tested:1) P1 - 7000 lb (31.1 kN), 2) P2 - 6300 lb (28.0 kN), and 3) P3 - 5250 lb (23.3 kN). Those prestress values were preassigned to a prestressing wire, and the prestress was released once a simulation began.

Table 3. Design parameters of single-wire prisms.

Cover Concrete	Indentation	Pretension force	Release strength
1 in	WE	P	3500 psi
0.875 in	WG	0.9 P	4500 psi
0.750 in	WH	0.75 P	
0.650 in			

4.3 Parameters of four-wire prism

The effect of the spacing between the adjacent wires was examined along with three indentation types and the two releasing strengths. The cover concrete of 1.0 in (25.4 mm) and the pretension force of 7000 lb (31.1 kN) was used for the four-wire prisms. In Table 4, the design parameters of a four-wire prism are presented.

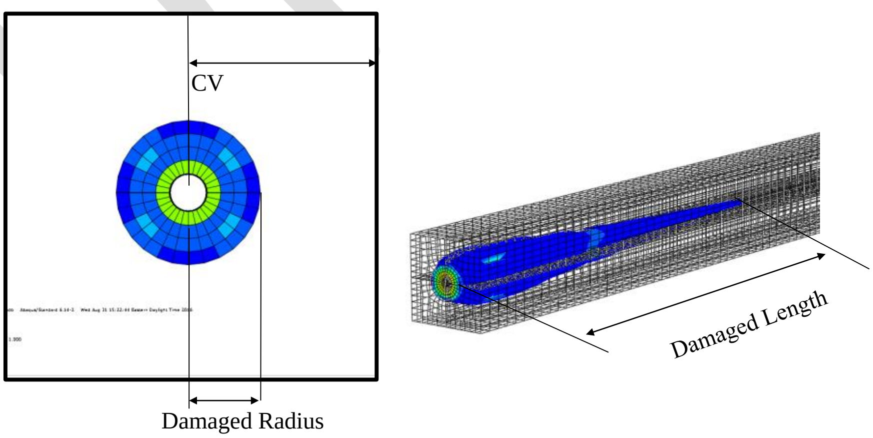
Table 4. Design Parameters of four-wire prisms.

Spacing, S	Indentation	Release strength
S1: 2.00 in (50.8 mm)	WE	3500 psi (24.1 MPa)
S2: 1.75 in (44.5 mm)	WG	4500 psi (31.0 MPa)
S3: 1.50 in (38.1 mm)	WH	
S4: 1.25 in (31.8 mm)		
S5: 1.00 in (25.4 mm)		

5. Simulation Results

5.1 Single-wire prism

A total of 72 simulations was carried out (3 indentation types x 2 release strengths x 4 cover thicknesses x 3 pretension force). The models were created using Abaqus/CAE, and Abaqus/Standard analysis with a user-subroutine option was performed. Three different outputs were examined to evaluate the performances or damage of single-wire prisms: 1) maximum d_t, 2) Damaged length and 3) Damaged Radius/CV. Figure 6 shows contour plots of a damaged concrete prism after the simulation. Any elements experienced tensile damage (beyond the cracking strength, σ_{t0}) were highlighted. Herein, d_t greater than 0.001 was used for indicating cracking elements. Damaged length is the distance where the concrete is damaged in the longitudinal direction, measured from the front face to the furthest damaged point. The Damaged radius/CV is a ratio that indicates the relative severity of the damage caused to the concrete due to the de-tensioning. A value of 0 means there is no tensile damage to the concrete, a value of .5 means that the damaged radius reached halfway to the concrete cover, and a value of 1 means that the concrete is damaged to the cover.



(a) (b)

Figure 6. Examples of the damaged radius and damaged Length of a concrete prism after releasing a prestressing wire.

Figure 7 shows qualitative comparisons of damaged areas of the concrete prisms with respect to different indentations and release strengths under the pretension force of 7000 lb (31.1 kN) and the cover concrete of 1 in. (25.4 mm). WE (spiral indentation) shows least radial damage, while WH (deeper chevron indentation) indicated that the damaged radius reached to the cover when the prestressing wire was de-tensioned at 3,500 psi (24.1 MPa). The bottom row of Figure 7 shows the damaged areas when the release strength of 4,500 psi (31.0 MPa) and the cover concrete of 1 in (25.4 mm) were used.

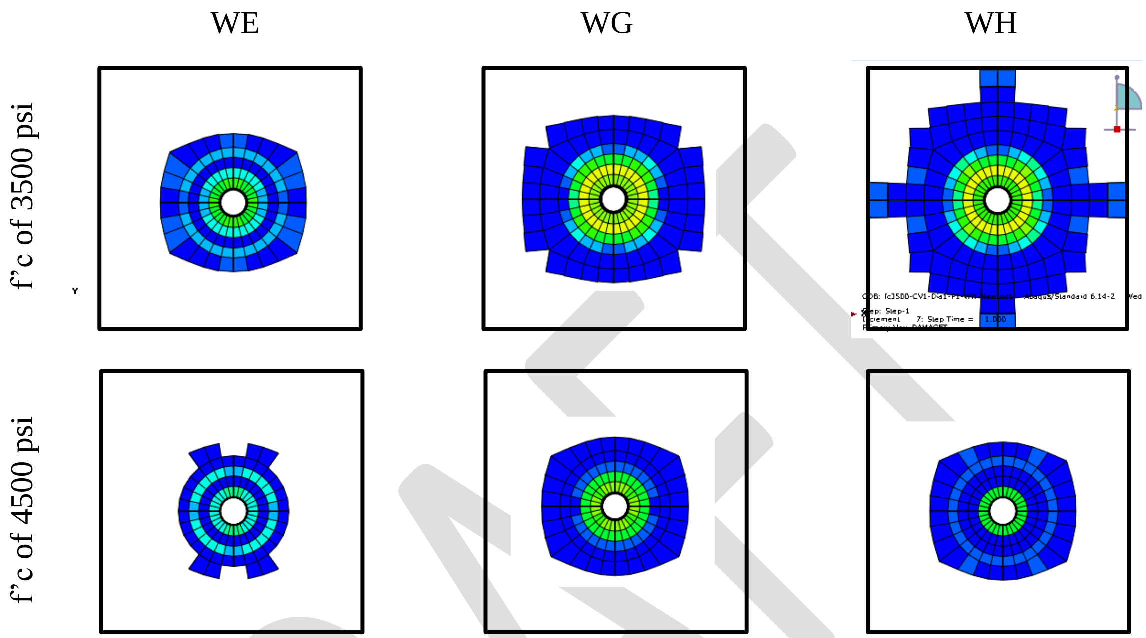


Figure 7. Qualitative comparisons of the damaged radius of a cross-section of single-wire concrete prisms after the de-tension.

In Figure 8, the damaged radius/CV ratio (Figures 8.a) and the damaged length (Figure 8.b) for concrete prisms with the conditions of the pretension force of 7000 lb (31.1 kN) and the release strength of 3,500 psi (24.1 MPa) are shown with respect to the concrete cover thicknesses. The bottom row of Figure 8 shows the damaged radius/CV and the damage length under the release length of 4,500 psi (31.0 MPa). The damaged radius/CV ratios for WH at the low release strength were found to be always 1.0 regardless of the thickness of the concrete cover. The ratios for WG and WE became 1.0 when the cover concrete was reduced less than or equal to 0.875 in. (22.22 mm) and 0.75 in. (19.05 mm), respectively. When the release strength became 4,500 psi (31.0 MPa), the ratios became 1.0 when the cover thickness was reduced less than or equal to 0.75 in. This indicated that using too small cover concrete would result in splitting cracks, although the prestressing wires are de-tensioned even at higher release strengths. WH (deeper chevron indentation) was prone to have severe tensile cracks upon de-tensioning at the release strength of 3500 psi (24.1 MPa) with 7000 lb (31.1 kN) pretension force. However, when the cover thickness is too small, the potential splitting cracks exist for all three indentations. Figures 8.b and d show changes of the damaged lengths of each wire under the release strength of 3,500 psi (24.1 MPa) and 4,500 psi (31.0 MPa), respectively. WG (shallow chevron indentation) tended to slip longer than the others except when the concrete cover became 0.65 in (16.51 mm) for WH (Figure 8.b). For the case of the cover concrete of 0.65 in (16.51 mm), the cover concrete was insufficient to develop the strong bonding with WH, because the surrounding concrete had severely failed, which resulted in the longer damaged length. In addition, the simulation results demonstrated that as the thickness of the concrete cover increased, the max damage (d_t) decreased rapidly.

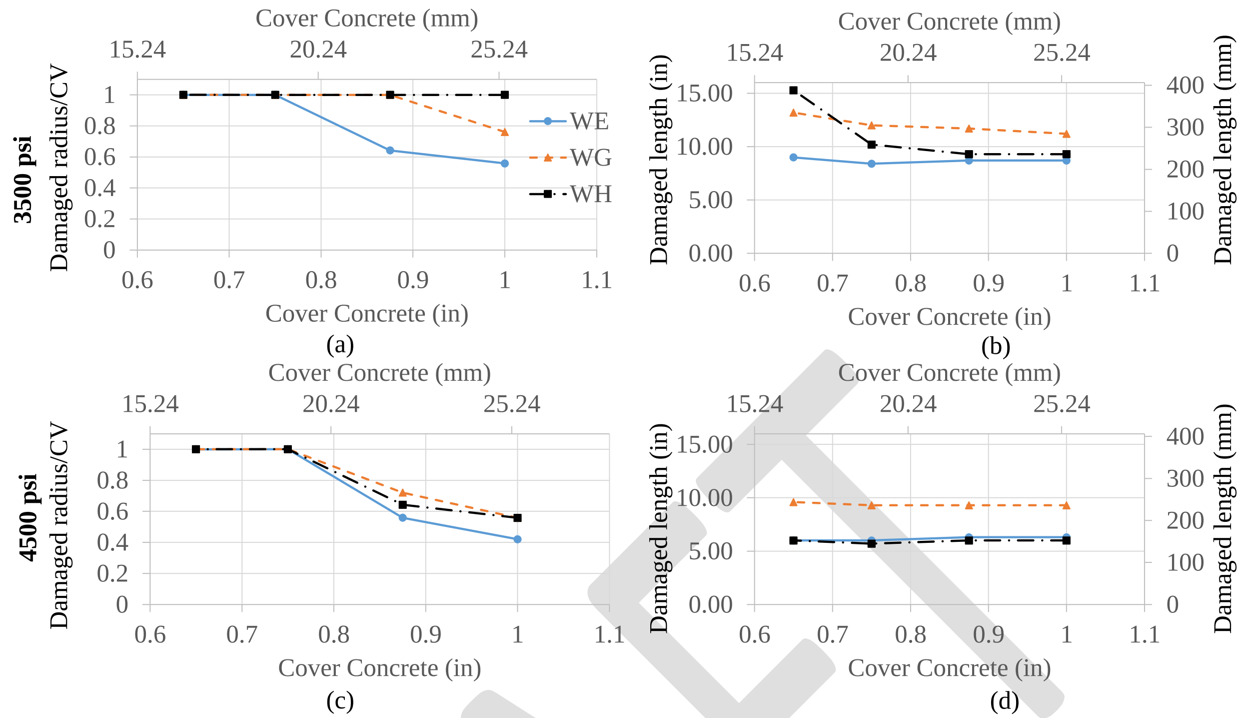


Figure 8. Damaged Radius/CV ratio and Damaged length of single-wire concrete prisms under the release strength of 3500 psi (a and b) and 4500 psi(c and d).

5.2 Four -wire prism

A total of 30 simulations was carried out (3 indentation types x 2 release strengths x 5 spacings), while the cover concrete and the pretension force were kept constant at 1.00 in. (25.4 mm) and 7000 lb (31.1 kN), respectively. With the previously defined three damage indicators (mainly maximum d_t, Damaged length and Damaged Radius/CV), a Damaged Spacing ratio was newly introduced. The Damaged Spacing Ratio is defined as the maximum damaged radius from the center of a wire (S'_{max}) divided by the half of spacing (S') (see Figure 9). The damaged spacing ratio of 1.0 indicates that the cracks are interconnected between the adjacent prestressing wires.

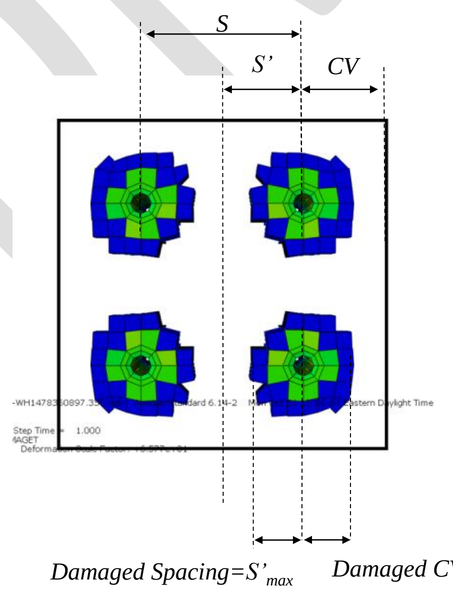


Figure 9. Damaged spacing ratio of a four-wire prism.

The Damaged Spacing Ratio (S'_{max}/S') of the four-wire prisms under the release strength of 3,500 psi (24.1 MPa) with respect to five different spacings were plotted in Figure 10. The Damaged Spacing Ratio of WH was 1.0 regardless of the spacings, while the cracks of WG and WE became interconnected when the spacing was reduced to 1.5 and 1.25 in. (38.1 and 31.75 mm), respectively. It is noteworthy that the cracks tended to get interconnected before the cracks propagated toward the outside of the concrete prism when the cover concrete of 1.0 in. (25.4 mm) was used.

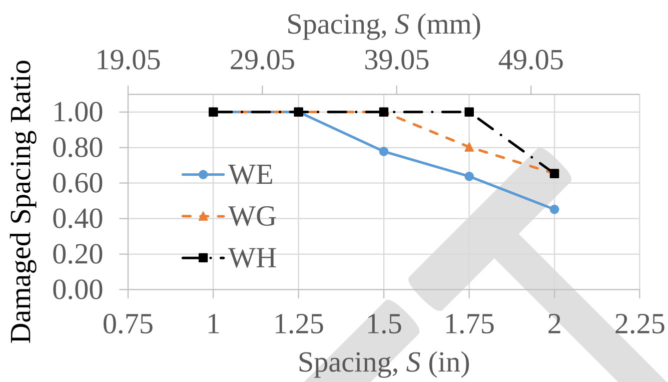


Figure 10. The Damaged Spacing Ratio of four-wire concrete prisms under the release strength of 3500 psi with respect to the spacing.

6. Conclusions

In this numerical study, the effects of geometrical and mechanical parameters on the splitting performances of prestressed concrete prisms due to de-tensioning of prestressing wires were examined. In the railroad industry, various types and sizes of concrete crossties have been manufactured with different prestressing wires. In order to ensure the structural integrity of prestressed concrete prisms with different indented wires, an extensive parametric study was performed using a newly developed bond-slip model. Two different concrete prisms were prepared: 1) a single-wire prism for the effect of the concrete cover thickness and 2) a four-wire prism for the effect of the spacing between prestressing wires. Furthermore, three different indentation patterns were explored: 1) spiral indentation, 2) chevron with shallow indentation, 3) chevron with deeper indentation. The release strength of 3500 and 4500 psi (24.1 and 31.0 MPa), and three levels of a pretension force were considered. The single-wire prism simulation results indicated that a thickness of cover concrete less than or equal to 0.75 in. (19.05 mm) is not recommended when de-tensioning the wires at the early stage due to the tendency of having splitting cracks. The deeper chevron indentation wire was prone to show more damage at the early stage of concrete. The cracks could be interconnected between the adjacent wires when the spacing is less than 1.5 in. (38.1 mm). Finally, de-tensioning prestressing wires at the very early stage of concrete's strength should be avoided.

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