PRESTRESSED CONCRETE RAILROAD TIE BURSTING STRAIN DEVELOPMENT

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ABSTRACT

Concrete railroad ties are often made as one continuous concrete structure in long-line prestressing beds and saw-cut into individual railroad ties. Indented strands or wires are used to prestress the concrete ties. As the forces spread out from the steel-concrete interface to the full concrete cross section, strains in the transverse direction are created called bursting strains. Short transfer lengths lead to larger bursting strains. These bursting strains have been linked to splitting cracks seen in concrete railroad ties after saw-cutting the large prestressed concrete element into individual ties. A recent study was undertaken to measure the bursting strains created in prestressed concrete railroad ties with time to quantify their magnitude and growth.

Keywords: Prestressed Concrete, Concrete Saw-cutting, Railroad Ties, Bursting Strains.

INTRODUCTION

Concrete railroad ties have been growing in use because they provide better fuel efficiency and superior load capacities than alternative tie materials such as wood for heavy-haul and high-speed rail lines. In the US alone, one million ties are installed in track annually [1]. While these ties improve the quality and cost efficiency of rail operation, they still have some issues that are being tackled by researchers all over the world. One of most common issues in these ties, is the rail-seat deterioration, whether this deterioration manifest as surface abrasive or cracking [2]. Cracking of prestressed concrete can be the result of impact loading, insufficient transfer length, excessive prestressing, weak or marginal concrete strength, or freeze-thaw. All the stresses caused by any of these phenomenon have to exceed the concrete capacity for the cracking to start.

The prestressing force in the wires or strands is transferred to the concrete over a distance known as the transfer length. This distance is dependent on the level of bond between the steel and the concrete. As a result of the compressive strains applied to the concrete tie during prestressing spreading out from the prestressing wire or strand location to fill the entirety of the concrete cross-section, tensile strains occur in the direction perpendicular to the prestressing. These tensile strains in the disturbed region of the tie end are referred to as bursting strains. For a given prestressing force, the shorter the transfer length, the higher the average force transferred per unit length of wire or strand. A high amount of force transferred per unit length of wire or strand can give high perpendicular tensile strains. When the tensile stress in the transverse direction exceeds the tensile strength, spalling or splitting cracking can occur [3]. After cutting prestressing wires it is typical for the strain in the concrete to keep increasing due to the transfer of the prestressing force from the wire to the concrete because of creep and shrinkage [4]. In order to quantify the strains that cause cracking, strain gauges and vibrating wire gauges can be used [5]. In addition to the length needed to transfer the prestressing forces, studies have shown that the concrete cover also is essential to prevent the cracking. Additional cover provides additional material to resist the bursting strains, reducing cracking [6].

When testing prestressed concrete for freeze-thaw durability, ASTM C666 allows samples to be excised from the concrete by saw cutting or coring. Some railroads require railroad tie manufacturers to saw-cut samples from ties for freeze-thaw testing because there is a concern that cast prisms in molds would not undergo the same vibration history of the ties and have a different air void system. Excising small samples out of these prestressed concrete ties can lead to stress release and in some cases cracking. This cracking also happens due to the lack of proper cover, which is the result of a dense reinforcement wire or strand pattern. After saw-cutting, the prestressing force tries to transfer to the concrete but it results in cracking the section in a direction parallel to the prestressing force [7]. Little information exists however about the extent of strain that the concrete actually experiences after saw-cutting. In order to quantify the strains in the samples saw-cut from prestressed concrete railroad ties, ties were made with vibrating wire gauges pre-installed in them. The strains before and after each saw-cut was made, were recorded to see the bursting strains in the smaller samples. This paper will address bursting strains resulting from the saw-cutting and excising samples for freeze-thaw testing.

METHODOLOGY

Vibration wire gauges were installed in six concrete railroad ties in a triaxial configuration as shown in Figure 1. These gauges (Geokon 4202x) were placed at 6.5 in. (165.1 mm) from both ends of the ties, leading to six gauges placed in each tie. The gauges were not attached to any prestressing wires but were suspended in the concrete between the wires as shown in Figure 2. The installation process was performed at a prestressed concrete manufacturing facility. Ties were made upside down in a long-line bed as shown in Figure 3. Separators with holes allowing the wires in a bed to pass were used on each tie end. Once the prestressing wires were, the concrete was placed into the forms. After the concrete hardened, the prestressing wires were saw-cut at each tie ends'. Two of the concrete railroad ties made were unreinforced. Figure 4 shows the unreinforced tie cover in plastic for curing. Another two were made with twenty-four 0.209 in. (5.32 mm) diameter wires but not prestressed. The remaining two ties were made with the same twenty-four 0.209 in. (5.32 mm) diameter wires and were prestressed to 7000 lbs per wire. The prestressed and non-prestressed ties were made with two stirrups at each end for each tie. These wire stirrups fully encircled the prestressing wires, as shown in Figure 2. The manufactured ties were 8.5 ft (2.6 m) long, with a trapezoidal cross section 10 in. (254 mm) wide on top, 10.5 in. (267 mm) on the bottom and 10.5 in. (267 mm) in height.

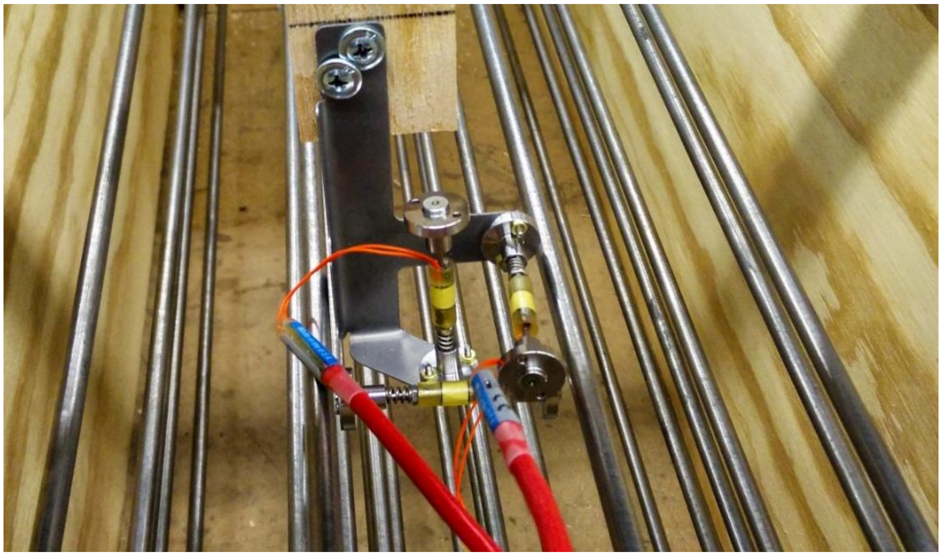

Figure 1: Vibration wire gauges setup inside the ties

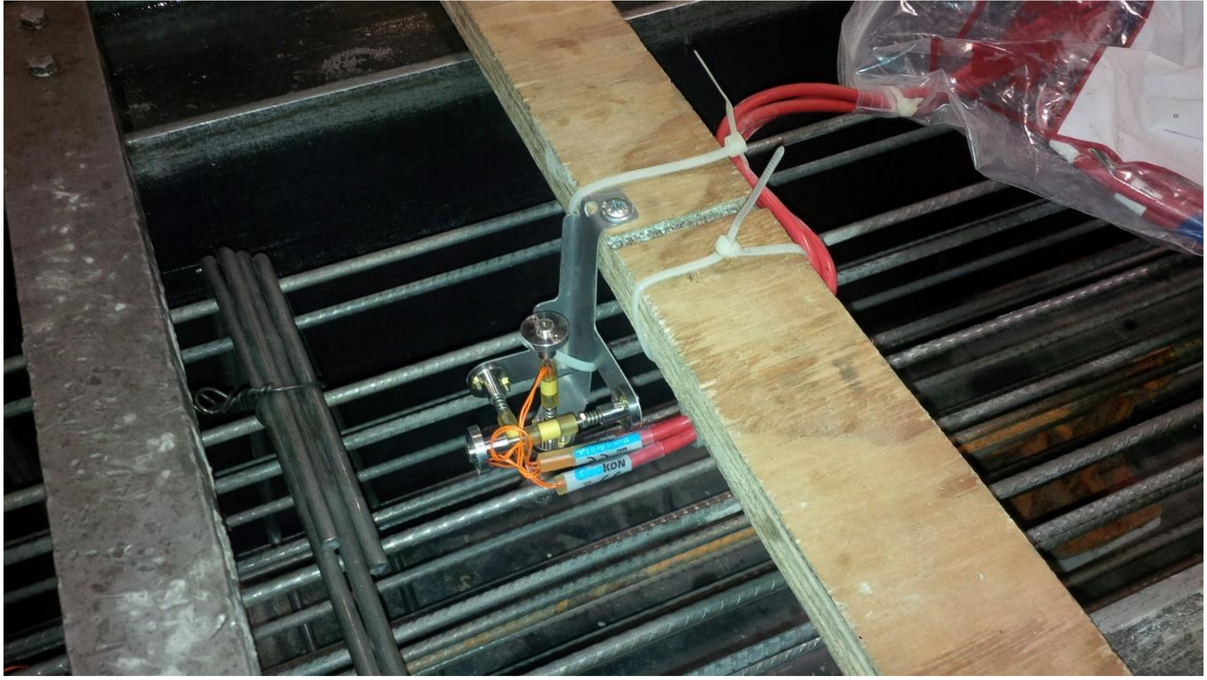

Figure 2: Vibrating wire gages in the tie next to the two stirrups

Figure 3: Ties in a long-line bed form

Figure 4: Unreinforced tie covered in plastic

A handheld vibrating wire gage reader (GK-404) was used to take strain and temperature readings; after hardening, after detensioning, after demolding and wires saw-cutting, after delivery to the K-State labs, after saw-cutting the ties in half and after excising the ASTM C666 samples. Unfortunately some of the delicate vertical and transverse gauges stopped working either after the concrete hardened or after detensioning. The locations of the cuts made and the gauge are shown in Figure 5.

The reading recorded from the handheld GK-404 device were for the apparent strains (ε_{ap}) and needed to be corrected in order to obtain the actual strains (ε_{actual}). Equation (1) was used in order to correct for the temperature and to obtain the actual strains.

$$\boldsymbol{\varepsilon_{actual} = \left(\left(\varepsilon_{ap}\right)_{current} - \left(\varepsilon_{ap}\right)_{initial}\right) B + \left(T_{current} - T_{initial}\right)\left(C_s - C_c\right)} \quad (1)$$

Where B is the batch calibration factor, $T_{current}$ is the current temperature, $T_{initial}$ is the initial temperature, C_s is the steel coefficient of expansion and C_c is the concrete coefficient of expansion. List of all the gauges used, the ties they were installed in, and the types of the ties they were installed in are presented in Table 1. Two types of concrete were utilized to make these ties, one with air entrainment agent and one without. The properties of these two types of concrete are presented in Table 2.

Table 1: Summary of ties made and vibrating wire gauges used.

Vibrating Wire Gage #	Type				Tie/End
	Air Entrained	Prestressed	Not Prestressed	No Wire	
L 1 A			●		1 / Dead End
T 2 A			●		
V 3 A			●		
L 4 A			●		1 / Live End
T 5 A			●		
V 6 A			●		
L 7 A	●		●		2 / Dead End
T 8 A	●		●		
V 9 A	●		●		
L 10 A	●			●	3
T 11 A	●			●	
V 12 A	●			●	
L 13 A	●		●		2 / Live End
T 14 A	●		●		
V 15 A	●		●		
L 1 B				●	4
T 2 B				●	
V 3 B				●	
L 4 B		●			5 / Dead End
T 5 B		●			
V 6 B		●			
L 7 B		●			5 / Live End
T 8 B		●			
V 9 B		●			
L 10 B	●	●			6 / Dead End
T 11 B	●	●			
V 12 B	●	●			
L 13 B	●	●			6 / Live End
T 14 B	●	●			
V 15 B	●	●			

* L represents the longitudinal direction, T represents the transverse direction and V represents the vertical direction.

Table 2: Properties of the concrete used.

	Non-Air Entrained	**Air Entrained**
Temperature (°F)	82.2	83.6
Unit Weight (lb/ft3)	148.4	138
Fresh Air Content (%)	0.9	7
Compressive Strength at Release (psi)	6850	6630
Splitting Tensile Strength at Release (psi)	410	560
Compressive Strength at 28 days (psi)	13570	12380
Splitting Tensile Strength at 28 days (psi)	740	760

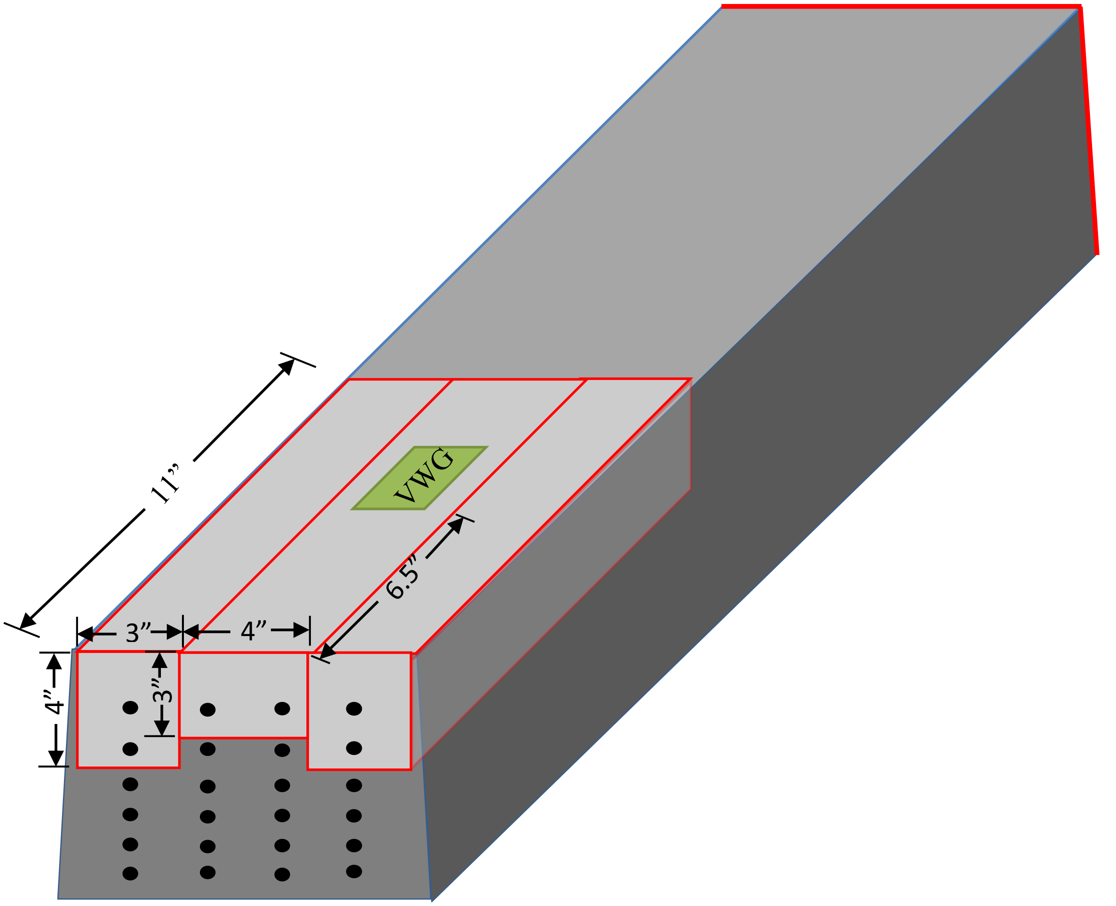

Figure 5: Saw-cutting locations made on the ties are colored red and the gauge (VWG) is colored green

RESULTS AND DISCUSSION

Table 3 includes a list of all the gauges that remained functional after concrete hardening. The large number of non-functional gages can be the result of either the strains going beyond limits of the gauge (4000 με) or the gauges were damaged during the placement or the hardening process. The results obtained shows that the ties in the longitudinal direction underwent compression as a result of the prestressing as shown in Figure 6. Furthermore, no apparent effects on the strains in the longitudinal direction were seen as a result of air entrainment, as expected. While one of the gauges in the non-air entrained samples failed after saw-cutting the tie in half, it is most likely that the strains jumped to values beyond the limits of the gages. Transfer length was measured using surface strain measurements and was found to be on average 11.7 in. for the ties studied.

Table 3: Vibrating wire gauges that remained operational after concrete hardening.

Vibrating Wire Gage #	Functional	Vibrating Wire Gage #	Functional
L 1 A		L 1 B	
T 2 A		T 2 B	
V 3 A		V 3 B	
L 4 A	●	L 4 B	●
T 5 A		T 5 B	
V 6 A		V 6 B	
L 7 A	●	L 7 B	●
T 8 A		T 8 B	
V 9 A		V 9 B	
L 10 A	●	L 10 B	●
T 11 A	●	T 11 B	●
V 12 A	●	V 12 B	
L 13 A	●	L 13 B	
T 14 A	●	T 14 B	
V 15 A	●	V 15 B	●

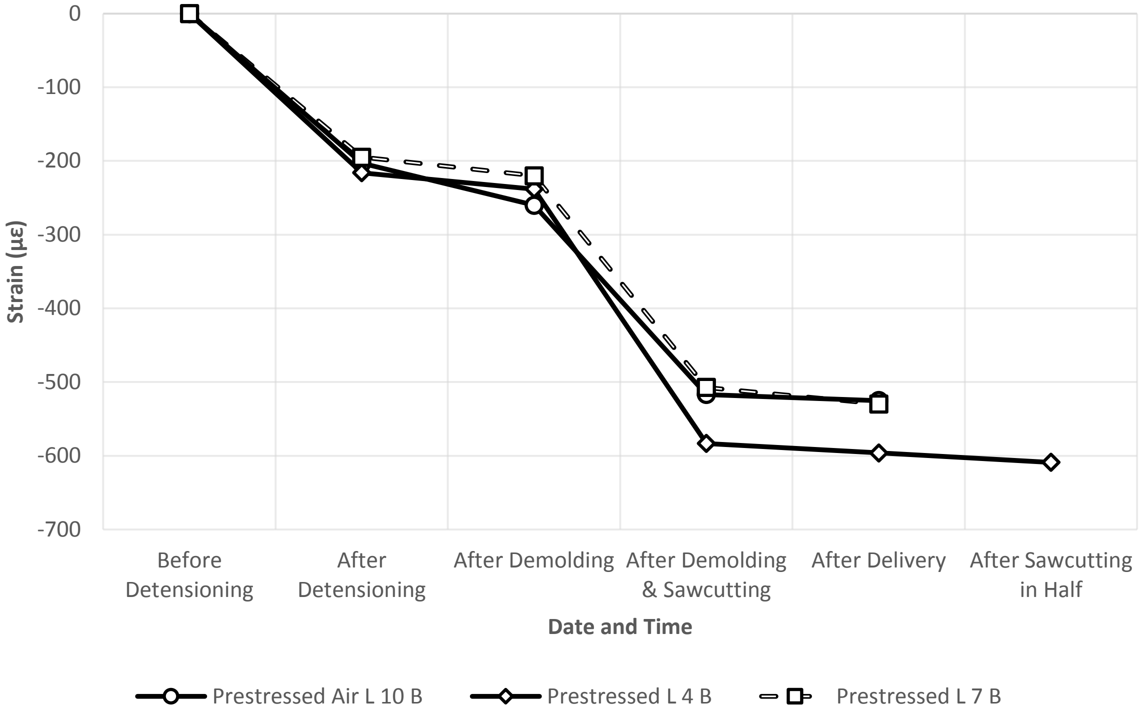

Figure 6: Longitudinal strains development in non-air entrained concrete samples vs air entrained concrete

When comparing the prestressed strains to the non-prestressed strains of non-air entrained concrete in the longitudinal direction in Figure 7, it can be seen that there are compression strains even in the non-prestressed tie. While the longitudinal strains in the prestressed tie are three times that of the non-prestressed tie. The presence of these longitudinal strains in the non-prestressed tie can be the result of shrinkage and thermal stresses. The transverse strains recorded for the air entrained samples are presented in Figure 8. The transvers strains shows that the samples were under tension in the transverse direction resulting either from the prestressing force in the case of the prestressed sample or the shrinkage in the non prestressed samples.

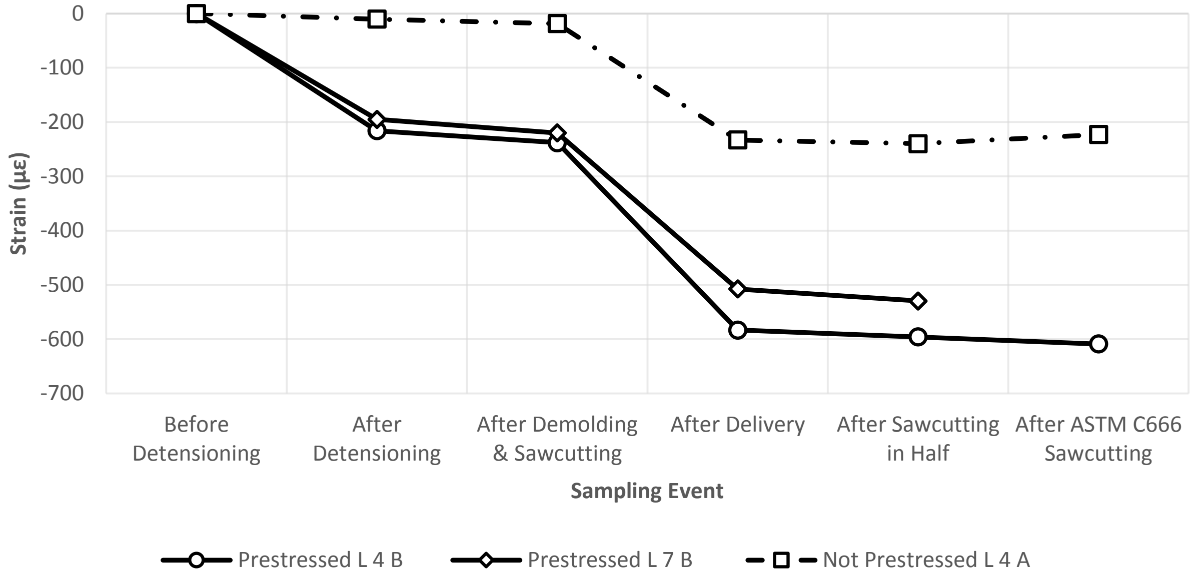

Figure 7: Longitudinal strains development in non-air entrained concrete samples

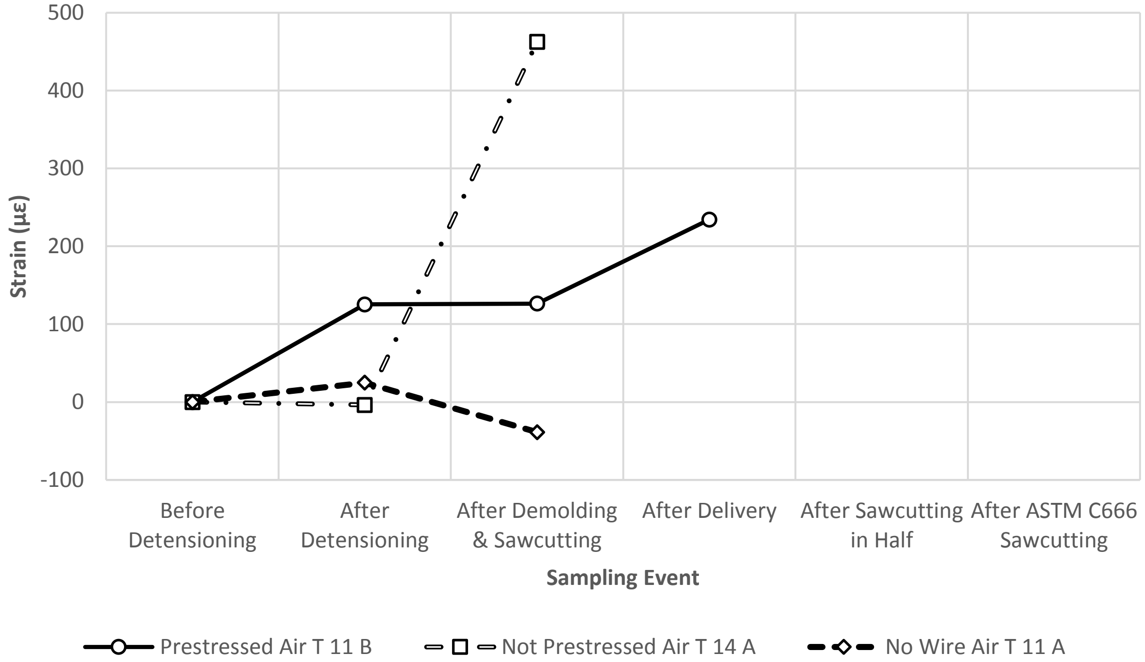

Figure 8: Transverse strains development in air entrained concrete samples

As for the air entrained concrete ties, the longitudinal strains in the non-prestressed and plain ties varied between +290 με and -50 με. These variation in compression and tension can be the result of variation in the thermal and shrinkage stresses inside the ties. These longitudinal strains, in the non-prestressed and plain ties, remain smaller than that of the prestressed tie since the prestressed tie had the prestressing force on top of the thermal and shrinkage stresses. Figure 9 represent the variation in the longitudinal strains of the air entrained non-prestressed and plain concrete ties in comparison to the prestressed air-entrained tie. Similar to the non-air entrained concrete, the longitudinal strain in the prestressed tie tends to increase from one stage to the next. This increase was more prominent in the case of vibrating wire gage L 10 B which can be the result of gauge failure.

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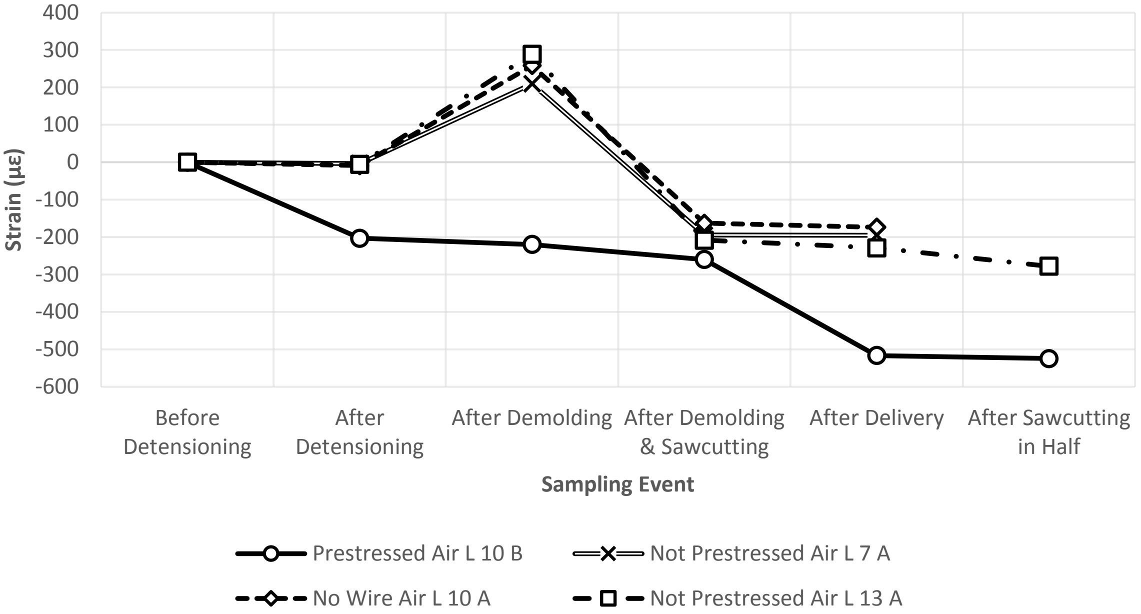

Figure 9: Longitudinal strains development in air entrained concrete samples

While no transverse gauges remained working in the case of the air entrained concrete ties, the vertical gauges remained operational to a certain stage as shown in Figure 10. The recorded vertical strains in the case of the air entrained non-prestressed tie were higher than that of the air entrained prestressed and the plain tie. This can be the result of: shrinkage, creep, temperature variation between the concrete and the gauges. Concrete tends to shrink as its water content diminishes and swells when it absorb water. These shrinkage and swelling lead to increases in the recorded strains which are not related to load or stress changes.

The bursting strain required to exceed the concrete tensile strength can be estimated using the concrete unit weight, compressive strength at release, splitting tensile strength, and ACI equation for elastic modulus as seen in equation (2):

$$\boldsymbol{\varepsilon_{cracking}} = \frac{\boldsymbol{f_t}}{\boldsymbol{w_c^{1.5} 33\sqrt{f_c}}} \tag{2}$$

Where $\varepsilon_{\text{cracking}}$ is the bursting strain required to cause cracking (με), ft is the concrete tensile strength (psi), w_c is the concrete unit weight (lb/ft^3), and f_c is the concrete compressive strength (psi). This gave 83 and 128 με for the non-air-entrained and air-entrained concrete mixtures, respectively. These strain values were easily exceeded in the vertical direction between sawcutting and delivery. The ties instrumented included stirrups to prevent the ties from cracking during fabrication, which may explain why cracking was not seen in the ties until after saw-cutting small ASTM C666 samples.

All these increases in the strains in the various directions, but especially in the longitudinal direction, can be described as bursting strains. The effects of these bursting strains, increase in strains, can be very apparent when the saw-cut samples crack on their own without any freeze-thaw testing, as can be seen in Figure 11. It was noticed that many of the samples saw-cut to the small ASTM C666 compliant sample sizes tended to crack in a direction parallel to the prestressing wires. Even when increasing the concrete cover, which could only be increased to 0.75 in (19 mm) in the case of the tested ties, the concrete still cracked in some of the saw-cut samples. In addition, some of the wires in some of the samples slipped inside the concrete for 0.04 in (1 mm) indicating a new sample transfer length was created when the sample was saw-cut, creating stresses and cracking. This cracking and reinforcing wire shrinkage could be exaggerated when the samples containing any of these outcomes of bursting strains are subjected to freeze-thaw cycles.

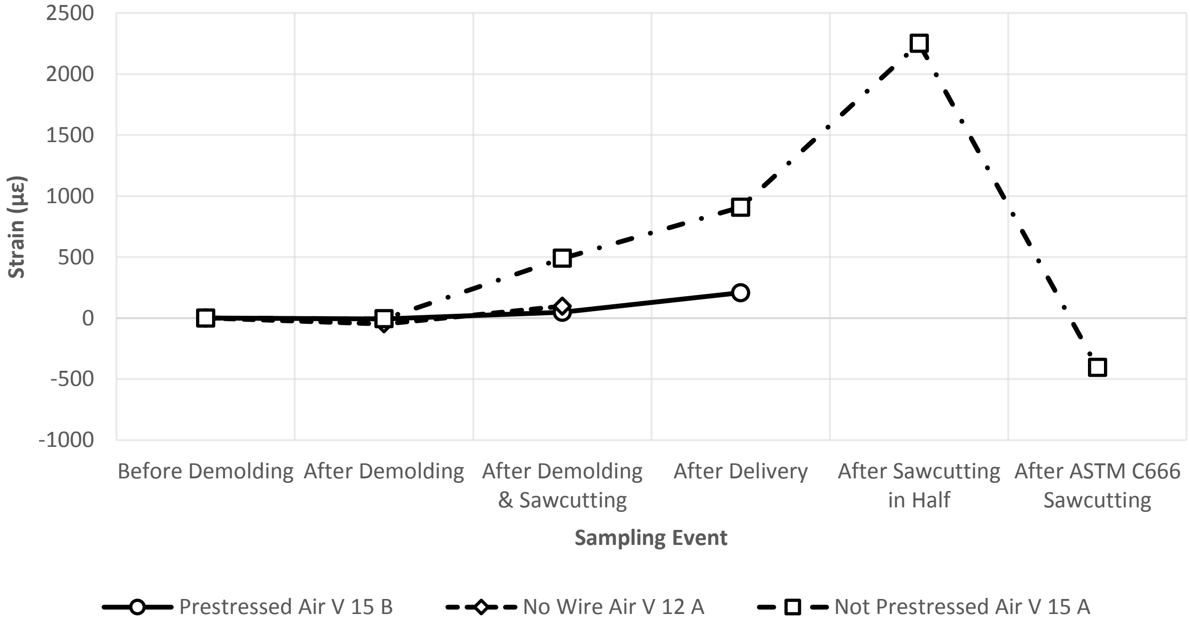

Figure 10: Vertical strains development in air entrained concrete samples

Figure 11: Cracking due to the stress release from saw-cutting

CONCLUSIONS

In order to understand what causes cracking in saw-cut samples that were not subjected to freeze-thaw testing, it is important to quantify the amount of strains inside these samples and how these strains increase due to the stress release caused by the saw-cutting process. These bursting strains were recorded after various stages using vibrating wire gages embedded in variously reinforced ties with two types of concrete, air entrained and non-air entrained concrete. The strains in the prestressed non-air entrained concrete were tensile and close to calculated values for cracking. Additional stresses caused by saw-cutting samples for ASTM C666 testing was enough to cause cracking in the ties and could cause potentially misleading deterioration in freeze-thaw testing.

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REFERENCES

[1] W. Ferdous and A. Manalo, "Failures of mainline railway sleepers and suggested remedies – Review of current practice," *Engineering Failure Analysis*, vol. 44, pp. 17-35, 2014.

[2] A. J. Reinschmidt, "Rail-seat abrasion: Cause and the search for the cure," *Railway Track and Structures*, vol. 87, no. 7, pp. 24-25, 1991.

[3] J. Pawluk1, A. Cholewa, W. Kurdowski and W. Derkowski, "Some Problems with Prestressed Concrete Sleepers Durability," *International Journal of Research in Engineering and Technology,* vol. 3, no. 13, pp. 153-157, 2014.

[4] S. D. Boone, P. J. Barr and M. W. Halling, "A Comparison of Prestress Losses in a Prestressed Concrete Bridge Made with High Performance, Self Consolidating Concrete," in *Structures Congress 2010,* Orlando, FL, United states, 2010.

[5] K. Ravisankar, S. Parivallal, T. Narayanan, K. Kesavan and R. Narayanan, "Vibrating wire strain gauges for long-term monitoring of structures," *The Indian concrete journal,* vol. 75, no. 8, pp. 535-541, 2001.

[6] J. Gálvez, J. Benítez, B. Tork, M. Casati and D. Cendón, "Splitting failure of precast prestressed concrete during the release of the prestressing force," *Engineering Failure Analysis,* vol. 16, no. 8, p. 2618–2634, 2009.

[7] RJ Lee Group, Inc., "Flawed Freeze-Thaw Testing Standards Unreliable for Predicting Concrete Tie Failures," RJ Lee Group, Inc., Pittsburgh, 2012.