Railroad Concrete Tie Failure Modes and Research Needs

Hailing Yu[1], David Jeong, Brian Marquis, and Michael Coltman
Structures and Dynamics Division
John A. Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142

Hailing Yu
Phone: (617) 494-2554
E-mail: Hailing.Yu@dot.gov

David Jeong
Phone: (617) 494-3654
E-mail: David.Jeong@dot.gov

Brian Marquis
Phone: (617) 494-2922
E-mail: Brian.Marquis@dot.gov

Michael Coltman
Phone: (617) 494-2591
E-mail: Michael.Coltman@dot.gov

Submitted to: 2015 Transportation Research Board 94th Annual Meeting

Number of words from text excluding references: 4,238 words
Number of figures: 11 (=2,750 words)
Number of tables: 0
Number of references: 35
Total number of words excluding references: 6,988

[1] Corresponding author.

ABSTRACT
This paper reviews the main failure modes of concrete ties observed in the U.S. railroads, including chemical degradation, prestress cracks, flexural cracks, rail seat deterioration, freeze-thaw cracks, and shoulder/fastener wear or fatigue. The observed characteristics, probable causes and detrimental effects of each failure mode are described. A finite element analysis framework aimed at achieving a better understanding of the basic failure mechanisms of concrete ties is presented. The ability of the modeling approach to simulate and predict critical failure modes of concrete ties is demonstrated. To meet the new challenges and demands placed on the U.S. rail infrastructure by increased high speed and heavy haul applications, concrete tie performance issues need to be addressed at both material and structural levels. Continued research needs to quantitatively characterize concrete tie failure under realistic track load and support conditions and to improve existing test and inspection standards are further discussed.

INTRODUCTION

The main functions of railroad ties are to hold rails securely to maintain gauge and vertical position, transmit traffic loads to the ballast with diminished contact pressures, and anchor the rail-crosstie structure against lateral and longitudinal movements (*1*). The largest market share of railroad ties in North America is for traditional timber ties. However, the shortage of timber in Europe immediately after World War II and improved concrete technology and prestressing techniques have led to significant development of concrete ties (*2*). Concrete ties can be engineered to meet specific service requirements and add overall stability and performance to a railroad track structure. Moreover, concrete ties were estimated to last twice as long as timber ties and therefore can lower life cycle costs despite higher initial costs. These desirable qualities led to great interest and the first major installation of prestressed concrete ties in the U.S. in 1966 (*3*). It is estimated that over 30 million concrete ties exist in track in North America.

Nevertheless, concrete ties have displayed multiple failure modes that have shortened their expected service lives or caused derailment accidents. To address the concrete tie performance issues under the more general goal of reducing track and infrastructure related failure, the Federal Railroad Administration (FRA) has solicited and supported comprehensive concrete tie and fastener research since 2010. The Volpe National Transportation Systems Center (Volpe Center) has contributed to this research initiative by developing computational models for concrete ties and applying them in track failure analyses. This paper first reviews the main concrete tie failure modes observed in the U.S. tracks. The finite element (FE) analysis framework developed at the Volpe Center is then presented, and its ability to simulate and predict critical failure modes of concrete ties is demonstrated. Continued research needed to understand the basic failure mechanisms and improve the test and inspection standards for concrete ties is further discussed.

REVIEW OF CONCRETE TIE FAILURE MODES

A Railway Tie Association (RTA) sponsored project examined approximately 29 million concrete ties installed on freight and passenger lines in U.S. and Canada since the 1970's and found that 7.9-9.2% of these ties have failed or been replaced over the years (*4*). More recently, University of Illinois at Urbana-Champaign (UIUC) conducted an international concrete crosstie and fastening system survey and ranked the various failure modes according to their criticalness viewed by infrastructure owners and operators, researchers and tie manufacturers (*5*). These studies indicate that the main failure modes of concrete ties in North America include, but are not limited to:

- chemical degradation,
- prestress cracks,
- flexural cracks (including rail seat cracks and center negative cracks),
- rail seat deterioration,
- freeze-thaw cracks, and
- shoulder/fastener wear or fatigue.

Chemical Degradation

Deleterious chemical reactions or processes include alkali-aggregate reactions (AAR) and sulfate attack. AAR has two forms: alkali-silica reaction (ASR) and alkali-carbonate reaction. In ASR, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a bulky gel that swells as it absorbs water from the surrounding cement paste. The swelling gels can induce enough expansion pressure to damage the concrete. Sulfate attack may be either internal or external. A particular form of internal sulfate attack is delayed ettringite formation (DEF). Damage to the concrete occurs when the ettringite crystals exert an expansive force within the concrete as they grow.

The RTA study found that nearly 1 million concrete ties, installed mainly during the 1970s and 1980s, have failed due to known Alkali reactivity causes. Another 177,000 ties, installed during the 1990s, have failed and been removed due to DEF (*4*). The more recent UIUC study, however, ranked "cracking from environmental or chemical degradation" at the bottom of the eight "most critical concrete crosstie and fastening system problems" in a North American survey (*5*).

Prestress Cracks

Concrete ties are made by casting concrete around pretensioned steel wires or strands. The concrete forms a bond with the steel reinforcement as it cures. As the pretension in the steel reinforcement is released, there can be relative slip and dilation along the reinforcement-concrete interface. Figure 1 illustrates the micromechanics along an indented reinforcement-concrete interface. The reinforcement is initially pretensioned with a traction t_0. As the traction is reduced by Δt at one end upon pretension release, the steel reinforcement slips relative to the surrounding concrete. In addition, the reinforcement dilates radially due to Hoyer effect, thus applying radial (normal) pressure on the concrete's inner wall.

For indented wires as well as strands with natural spiral surfaces, additional radial dilation is produced via mechanical interaction with the concrete. As shown in Figure 1, as the reinforcement slips relative to the concrete, the surface mismatch between the two materials also leads to radial dilation resulting in additional radial (normal) pressure on the concrete's inner wall. These pressures can split the concrete longitudinally, creating splitting/bursting cracks especially near the ends of the concrete ties. Figure 2 shows some splitting/bursting cracks that NDT Corporation has attempted to detect and assess using the sonic/ultrasonic pulse velocity method (*6*). Typically, these cracks originate near the tie ends at the reinforcement-concrete interfaces. As they propagate toward the rail seats, the cracks reduce in number and eventually coalesce to form horizontal or even vertical cracks.

There was a widespread horizontal cracking pattern observed in concrete ties installed during the 1994-98 period on the Northeast Corridor (Figure 3). It was generally believed that the splitting/bursting mechanisms contributed to the formation of these cracks (*7*). However, the strong preference in orientation (horizontal cracking) and location (along the top row of the strands) indicates that other mechanisms might have been at work as well. Two other possible contributing factors are: (1) the specific design of the tie, and (2) initial stresses surrounding the fastener shoulders as a result of the fastener force application. The splitting/bursting and horizontal cracks are grouped into "prestress cracks," because they are believed to result mainly from the prestresses generated during manufacturing and/or installation processes of concrete ties.

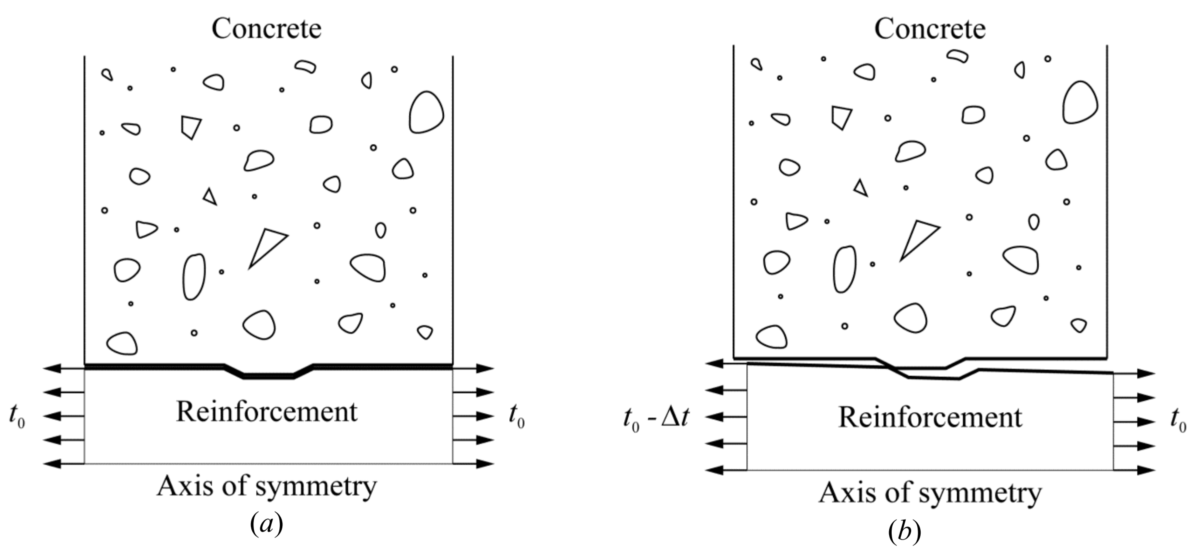


FIGURE 1 Relative slip and dilation of an indented reinforcement-concrete interface as the concrete tie changes from (a) the pretensioned phase to (b) the pretension released phase.

FIGURE 2 Splitting/bursting cracks (*6*).

(*a*) (*b*)

FIGURE 3 Horizontal cracks observed on the Northeast Corridor (*7*).

Rail Seat Cracks

Flexural cracks can develop from the bending of a tie. With relatively good ballast support and under high rail seat positive moments, rail seat positive cracks can develop at the bottom of concrete ties. These cracks may propagate upward and then longitudinally, leading to premature tie failure. Figure 4(*a*) shows the example of a severe rail seat positive crack (*8*). Cracks seen on top of rail seats may be referred to as rail seat negative cracks as they are likely related to negative bending moments in local rail seat areas.

The RTA survey identified rail seat cracking as one of the main causes of concrete tie failure over the years (*4*). The UIUC survey did not have a specific "rail seat cracking" category, but it may fit in the "cracking from dynamic loads" category that was ranked third among the eight most critical failure problems (*5*).

Rail seat cracking occurs when the concrete tensile strength limit is overcome locally in a tie subjected to bending moments. With a given concrete tie and its designed strength limits, a reasonable approach to prevent rail seat cracking is to limit the track loads applied on the tie to within its design limits. Wheel impact load detectors (WILD) have been installed worldwide to detect excessive wheel impact loads on tracks, so that defective wheels causing these damaging impact forces can be identified and targeted for removal. The long term benefits of WILD include not only extended service lives of track components but also reduced energy cost and increased productivity (*9*).

Center Negative Cracks

Flexural cracks can develop at the top center of concrete ties due to high center negative moments. The cyclic track loading causes the ties to oscillate and deform vertically; over time this pumping action abrades the bottoms of the ties and pulverizes the supporting ballast. When the pulverized ballast is not timely removed and replaced with new ballast, depression in the pulverized ballast under the ends of the ties may develop, altering the ballast support to the center of the ties while allowing the ends to behave like cantilever beams. This can cause large negative moments in the center and consequently "center negative" or "center bound" cracks in the concrete ties (*10*). According to the UIUC survey, center bound cracks rank fifth among the eight most critical concrete tie and fastener failure modes in the North American railroads (*5*).

Figure 4(*b*) illustrates multiple center negative cracks observed on some concrete ties. The bottoms of the ties also appear to be abraded significantly from dynamic interactions with ballast. Both tie abrasion and ballast pulverization contribute to the uneven voids or gaps formed between the ties and the ballast. The detrimental effects of tie abrasion in this case are twofold: (1) it worsens the center binding support conditions, and (2) it reduces the bending moment capacities of the ties making them more prone to failure. The phenomenon of tie abrasion from repeated dynamic interactions with ballast may be treated as an additional concrete tie failure mode worthy of additional research.


(*a*)


(*b*)

FIGURE 4 Examples of flexural cracks: (*a*) rail seat positive crack (*8*), and (*b*) center negative cracks on concrete ties with abraded bottom.

Rail Seat Deterioration

Rail seat deterioration (RSD) refers to the gradual loss of the concrete material directly underneath the rail. The UIUC survey indicates that RSD is the failure mode of most concern in the North American railroads (*5*). RSD lowers the service lives of concrete ties and increases the maintenance cost associated with in situ repair or replacement of deteriorated ties (*4*). If excessive RSD occurs on a sufficient number of consecutive ties, wide gage and ultimately rail rollover may occur. RSD in concrete ties has been determined as the probable cause of two Amtrak derailments on curved tracks in Home Valley, Washington on April 3, 2005 and Sprague, Washington on January 28, 2006, respectively (*11*).

RSD surfaces may be uneven, as is the case with the concrete ties involved in the derailment in Home Valley, Washington (*11*). Figure 5 shows the rail seats of these ties with reverse cant indicating increased risk of wide gage (*12*). Alternatively, RSD may degrade the concrete surfaces more uniformly resulting in "vertical deterioration" of the rail seats. Factors contributing to RSD include: presence of water, high tonnage, steep track grades, track curvature greater than two degrees, etc. Concrete ties in regions with freeze-thaw cycles may experience RSD at accelerated rates due to increased paste deterioration below the rail pads.

Despite the costliness and prevalence of RSD failure in concrete ties, there has not been a consensus on its root cause. An alternative term, rail seat abrasion, is commonly used in the concrete tie community to describe RSD failure. However, abrasive interactions appear to require relatively loosened fit of the rail seat components (i.e. rail base, rail pad and concrete surface) to allow their relative movements, which is not perceived to be an existing condition in newly installed concrete ties. Such a condition may become existent, however, if any of the following occurs: (1) the rail clips are comprised and provide insufficient toe loads, or (2) a certain amount of concrete/pad/insulator materials has deteriorated and been lost underneath the rail. In the latter case, concrete crushing and/or pad/insulator deterioration from high multi-axial compressive stresses can be plausible contributing mechanisms.

Previously developed analytical methods characterized the dependence of rail seat pressure on both the vertical load and the lateral to vertical load ratio L/V (*12-13*). The studies indicate that combinations of vertical and lateral wheel forces resulting from track geometry irregularities have the potential to cause very large compressions in the rail seat areas. Further, matrix based tactile surface sensors (MBTSS) were employed to measure rail seat pressure distribution in concrete crossties under different L/V ratios (*14-15*). Preliminary findings indicate that as the L/V ratio increases, the pad-concrete contact pressure tends to redistribute toward the field side of the rail seat.

(*a*) (*b*)

FIGURE 5 Deteriorated rail seat surfaces with reverse cant (*12*).

Freeze-Thaw Cracks

Freeze-thaw cracking is observed in cold climates and formed when the water in concrete freezes, expands in volume, and stresses the internal concrete structure. Freeze-thaw cracking may be prevented by creating closely-spaced air voids in cement paste with air entrainment. Freeze-thaw cracking is believed to also affect RSD failure (*16*).

Shoulder/Fastener Wear or Fatigue

Many rail fastener configurations exist, but their common purpose is to provide restraining forces to the rail in the form of toe loads. Over time with cyclic loading, fastener components (such as spring clips and ductile iron shoulders) can experience metal fatigue, the consequences of which include: movements of the rail, deterioration of the pads, and decreases in the fastener toe loads applied to the rail. In addition, excessive wheel loads in combination with poor support conditions can lead to structural failure of the fasteners. This failure mode ranks as the second most critical in both the international and the North American railroad surveys (*5*).

Summary

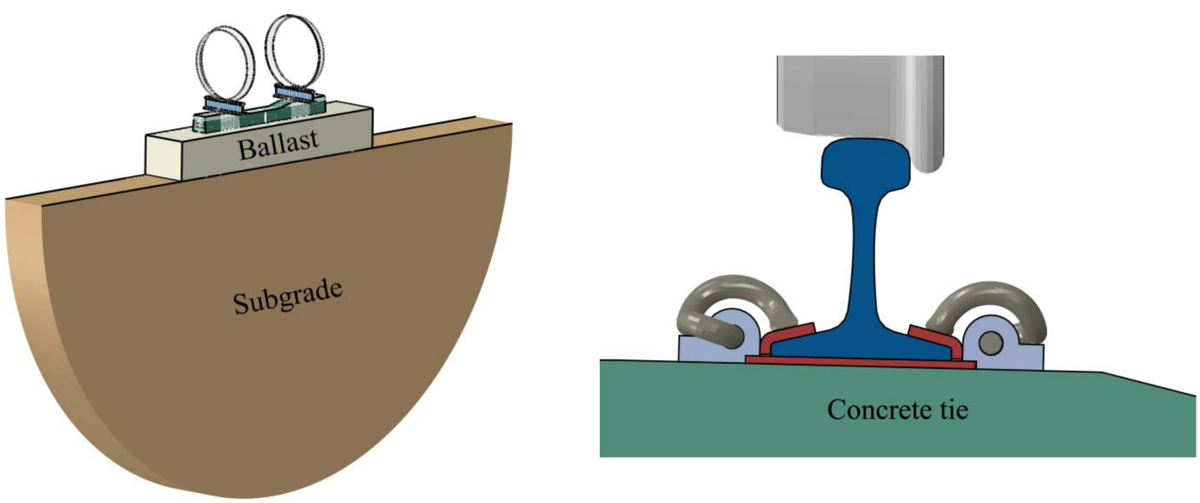
Seven main failure modes of concrete ties observed in U.S. railroads are discussed: chemical degradation, prestress cracks, rail seat cracks, center negative cracks, rail seat deterioration, freeze-thaw cracks, and shoulder/fastener wear or fatigue. The majority of these failures are concealed within the structure or under the ballast and thus not visible to inspectors. Further, the fundamental failure mechanisms are not well understood in several cases, thus hindering the efforts aimed at improved design and performance of concrete ties. Computer modeling, when applicable, can uncover internal failure mechanisms and predict tie failure with given loading and support conditions, and it has been increasingly applied in the concrete tie research.

FINITE ELEMENT ANALYSIS FRAMEWORK

The Volpe Center has been developing computational FE models to examine the structural performance of concrete ties under various ballast support and track loading conditions (*17-22*). As shown in Figure 6(*a*), our track FE model, currently covering one tie's space, has fully defined super- and substructures. The concrete tie is supported by ballast and subgrade. A rail fastening system that includes clips, shoulders, insulators and pads can be included in modeling, as shown in Figure 6(*b*). The wheel passes vertical and lateral loads to the rail and then to the fasteners and the concrete tie. Complete modeling of the fastening system is necessary when the complex stress states in the rail seats and the fasteners are needed to predict, e.g. fastener failure and RSD. When the vertical track loads are of primary interest, the fastening system may be omitted and the loading simplified as rail seat pressures.

Figure 7 shows four concrete tie models developed at the Volpe Center with different geometries and varying wire/strand configurations. Concrete ties are modeled as a heterogeneous medium composed of prestressing wires/strands, concrete and their interfaces. A damaged plasticity model available in commercial FE software has been applied in the material modeling of concrete. The model defines different concrete behaviors in tension and compression and uses tensile and compressive damage variables to monitor the respective strength degradations (*23*). The constitutive equations and material parameters needed to apply this model are described in detail in previous publications (*17-18*).

The strength of the bond between concrete and the prestressing wires/strands significantly affects the load bearing capacity of pretensioned concrete ties prior to failure. Accurate characterization of the bond behavior, including bond-slip and normal stress-dilation as depicted in Figure 1, is critical to the accurate characterization of the overall concrete tie behavior. Existing bond models in commercial FE software are inadequate because they omit the radial (normal) dilation and the coupled tangential-normal behavior in the interface. To fill this gap, Volpe Center has been developing phenomenological (or macro-scale) bond models that (1) define smooth interfaces by homogenizing the surface indents and (2) indirectly account for the dilatational effects by assigning interface constitutive equations that reflect observed interface behaviors. The elastoplastic framework of the FE method is adopted for the bond modeling at this scale (*24*).



(*a*) (*b*)

FIGURE 6 Track FE model: (a) full view, and (b) rail fastening system.

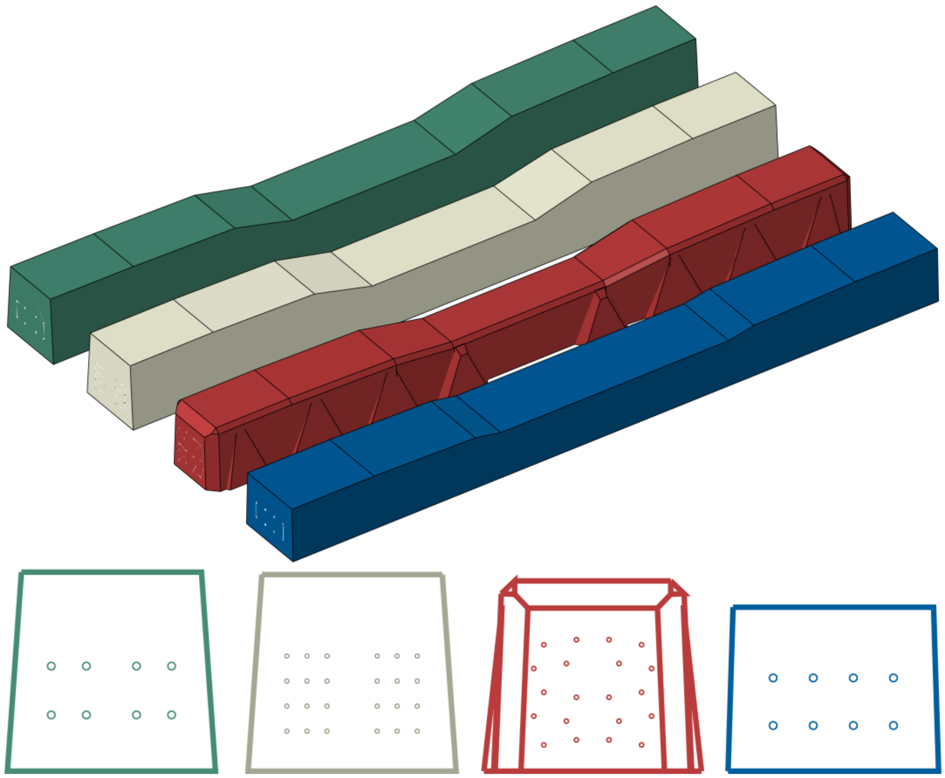


FIGURE 7 Concrete tie models developed at the Volpe Center.

FRA sponsored an experimental study at the Kansas State University (KSU) that examined the bond behavior of over a dozen prestressing wires/strands. Untensioned and tensioned pullout tests, pretensioned concrete prism tests and transfer length measurements on actual concrete ties were conducted, and the effects of reinforcement and concrete variables on transfer length were investigated in the KSU study (*25-28*). Volpe Center has been employing the KSU test data to calibrate and validate our user defined bond models. As a first step, we developed, calibrated and validated an elastoplastic bond model for the adhesive and frictional interface of a smooth prestressing wire (*21*). We will continue to develop bond models for several representative reinforcement types including indented single wires and a seven-wire strand.

As discussed, the ballast support condition significantly influences the flexural failure mode of a concrete tie. With completely defined concrete tie and substructure models, the effect of ballast support can be further examined. Figure 8 shows the quarter symmetric FE model of a concrete tie supported by a uniform and homogeneous ballast layer (the ballast model is similar to that shown in Figure 6) and the tensile damage variable contour when the tie model is subjected to rail seat pressure. The analysis indicates that a rail seat positive crack initiates at the tie bottom under the rail seat when the rail seat loading is sufficiently large (*17*).

A recent study (*22*) simulated center negative cracks under two assumed center binding conditions: the center negative moment test specified in the American Railway Engineering and Maintenance-of-Way Association (AREMA) manual (*29*), and an assumed scenario with deteriorated ballast support shown in Figure 9. In the latter case, a gap (or void) is assumed to exist between the concrete tie and the ballast. The gap is assumed to initiate at 1/3 of the half tie length from the tie center and grow linearly toward the tie end. The maximum gap is Δh at the tie end. Figure 10 shows the center bound cracking patterns predicted by FE simulations of both scenarios. Figure 11 shows the equivalent wheel load-relative rail seat displacement curves obtained from the simulations. The equivalent wheel load is calculated based on the assumption that a single rail seat carries a maximum of 50% of the wheel load. The average rail seat displacement is calculated relative to the displacement of the center of the tie.

Two observations are made based on the simulations: (1) fewer cracks form in the AREMA test than under deteriorated ballast support (Figure 10), and (2) the AREMA manual specifies a much lower pass/fail load than commonly observed loads in the field (Figure 11).

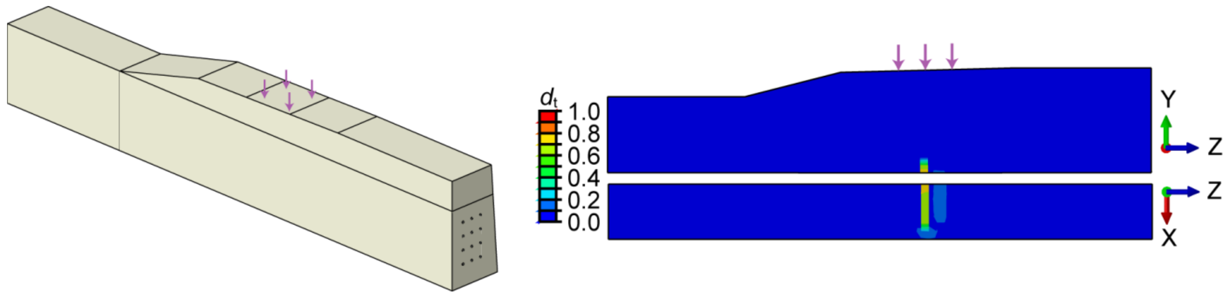


FIGURE 8 Prediction of the onset of rail seat positive cracking with a quarter symmetric concrete tie model (*17*). The tensile damage variable d_t indicates the extent of tensile strength degradation.

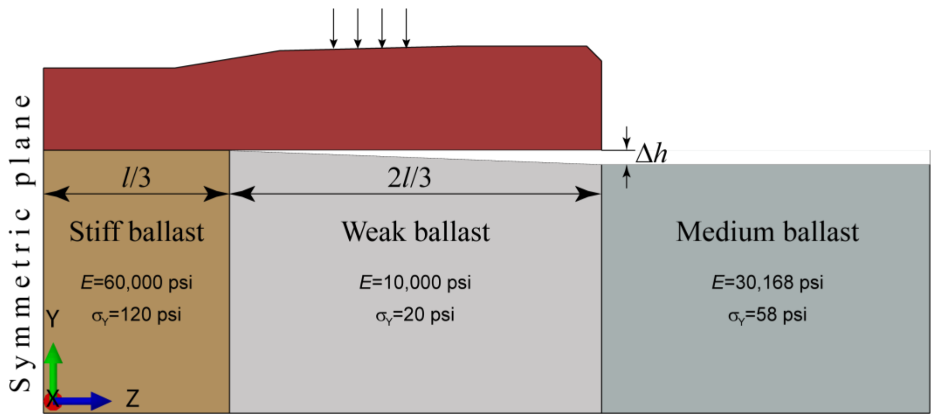


FIGURE 9 A simulated center binding condition with deteriorated ballast support.

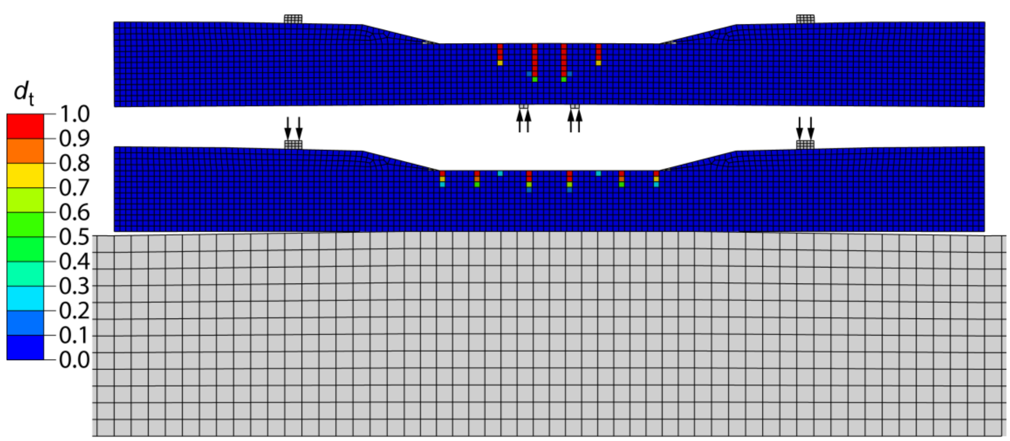


FIGURE 10 Center negative cracks predicted by FE simulations of two assumed center binding conditions: AREMA center negative moment test (top) and a scenario with deteriorated ballast support (Δh=0.5 in., bottom).

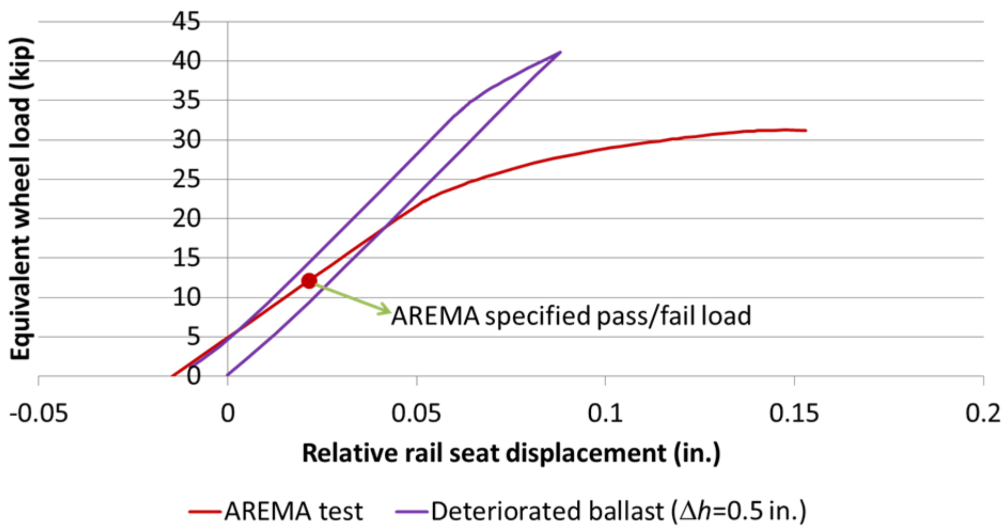


FIGURE 11 Equivalent wheel load-relative rail seat displacement relations obtained from FE simulations of center binding scenarios.

RESEARCH NEEDS

The FRA continues to support research projects aimed at improving inspection technologies that can automatically detect and characterize concrete tie failure. Furthermore, FE analysis can be a powerful tool to uncover internal or hidden damage mechanisms that are elusive to even very sophisticated inspection technologies. After gaining a better understanding of the concrete tie failure mechanisms, FE analysis can further optimize design, assist accident investigation, and recommend improvements to existing standards, including AREMA and American Society for Testing and Materials (ASTM) standards and FRA track inspection standards (*30*).

Indented wires can improve the bonding quality with concrete and thus reduce the transfer length. However, it has been observed that splitting/bursting cracks are more likely to occur with some surface indent geometries, probably due to increased dilatational interactions in the reinforcement-concrete interfaces. Additional research is needed to better understand the relationship between wire indent geometry and concrete splitting propensity. This may require detailed (or micro-scale) FE simulations of wire-concrete interfaces in addition to the ongoing bond modeling work at the Volpe Center. Research results can provide recommendations to the ASTM standard that specifies prestressing steel wires for use in railroad concrete ties (*31*).

Flexural capacities of concrete ties prior to complete failure depend on not only the concrete strength but also the bond strength, as ultimate failure occurs when the bond has deteriorated significantly. The user bond models being developed at the Volpe Center will be critical to evaluating flexural capacities of concrete ties.

Preliminary FE analyses have shown that the AREMA center negative moment test needs to more closely reflect the support and load conditions observed in the field. Continued FE modeling coupled with testing is expected to yield results that will help to make recommendations to this test specification. In addition, center bound cracks indicate the existence of voids between ties and ballast that can result from fouled ballast and/or abraded ties. FE analysis can correlate the pattern of center cracks with the pattern of tie-ballast voids. Such quantitative correlations can provide valuable information to guide track inspections.

To assess concrete crushing and pad deterioration as possible contributing mechanisms to RSD, complete rail, fastener and concrete tie models, as shown in Figure 6(*b*), will be subjected to realistic dynamic track loading, and the resulting multi-axial stress states in the rail seats will be examined. The FE analysis is expected to provide additional insight into RSD failure.

AREMA Test 6 evaluates the rail seat wear/abrasion performance on a complete rail, fastener and concrete tie system (*29*). The test uses an L/V ratio of 0.52 and conducts a million simulated track load cycles. For material level studies aimed at developing high strength, high abrasion resistance concrete, however, AREMA Test 6 setup is unnecessarily cumbersome. On the other hand, standard ASTM abrasion tests on concrete specimens have at least two drawbacks (*32-33*): (1) they do not replicate the high magnitudes of track loads, and (2) they represent steel-on-concrete abrasion only, whereas pad-on-cement and aggregate-on-pad abrasion can precede steel-on-concrete abrasion in RSD. Therefore, a material level test is needed to evaluate abrasion (1) from multi-material interactions and (2) under realistic track loads. The same need applies to studies of tie abrasion from dynamic "pumping" actions with ballast.

The accelerated freezing and thawing test specified by ASTM (*34*) has been used on saw cut specimens to assess concrete tie freeze-thaw durability. However, the saw cut concrete specimens have much smaller sizes and volume-to-surface area ratios than those of concrete ties. Moreover, saw cut concrete specimens may exhibit prestressing eccentricities, stress relief, micro-cracking and sample variability, and their test results may not represent whole tie performance accurately. Research has been underway to understand the freezing and thawing mechanisms in whole concrete ties (*35*). Furthermore, it is unclear if and how the presence of cracks in concrete ties (e.g. Figures 2-4) may affect their freeze-thaw durability in cold climates.

Last but not least, high performance concrete mixtures (e.g. steel fiber reinforced concrete) may be further explored for the concrete tie application. An ideal mixture would decrease the usage of prestressing steel by increasing the concrete strength and thus reduce the prestress level and associated failure, and it would increase the flexural capacities, abrasion resistance and long term durability of concrete ties. Advanced material technology can provide key solutions to the new challenges and demands imposed on the rail infrastructure by the increasingly higher travel speeds and heavier axle loads.

ACKNOWLEDGEMENT

The work described in this paper was sponsored by the Office of Research and Development, Federal Railroad Administration, U.S. Department of Transportation. Directions provided by Messrs. Gary Carr, Cameron Stuart and Ali Tajaddini of the Track Research Division are gratefully acknowledged.

REFERENCES

1. Kerr, A. D. *Fundamentals of Railway Track Engineering*. Simmons-Boardman Books, Inc., 2003.
2. Esveld, C. *Modern Railway Track*. MRT-Productions, 2001.
3. Hanna, A. N. State-of-the-Art Report on Prestressed Concrete Ties for North American Railroads. *PCI Journal*, September-October, 1979, pp. 32-61.
4. ZETA-TECH. *Assessment of Concrete Tie Life on U.S. Freight Railroads*. Railway Tie Association Tie Report #12, 2010.
5. Van Dyk, B. J., M. S. Dersch, and J. R. Edwards. *International Concrete Crosstie and Fastening System Survey – Final Results*. Report submitted to Federal Railroad Administration, 2012.
6. NDT Corporation. *Assessment of Pulse Velocity Testing to Rate Concrete Cross Tie Conditions*. Intermediate progress report submitted to Federal Railroad Administration, 2014.
7. Mayville, R. A., L. Jiang, and M. Sherman. *Performance Evaluation of Concrete Railroad Ties on the Northeast Corridor*. DOT/FRA/RPD-14/03. FRA, U.S. Department of Transportation, 2014.
8. Zeman, J. C. *Hydraulic Mechanisms of Concrete-Tie Rail Seat Deterioration, Figure 2.3 on Page 22*. M.S. Thesis, University of Illinois at Urbana-Champaign, 2010.
9. Moody, H. G. Dynamic Wheel Load Detector Extends Life of Concrete Railroad Ties. *TR News*, January-February, 1987.
10. Lutch, R. H., D. K. Harris, and T. M. Ahlborn. Prestressed Concrete Ties in North America. *AREMA Conference*, 2009.
11. National Transportation Safety Board. *Railroad Accident Brief*. NTSB/RAB-06/03, 2006.

12. Marquis, B. P., M. Muhlanger, and D. Y. Jeong. Effect of Wheel/Rail Loads on Concrete Tie Stresses and Rail Rollover. In *Proceedings of the ASME 2011 Rail Transportation Division Fall Technical Conference*, Minneapolis, Minnesota, 2011.
13. Choros, J., B. P. Marquis, M. N. Coltman. Prevention of Derailments Due to Concrete Tie Rail Seat Deterioration. *American Society of Mechanical Engineers*, Paper No. JRC/ICE2007-40096, 2007.
14. Rapp, C. T., M. S. Dersch, J. R. Edwards, C. P. Barkan, B. Wilson, and J. Mediavilla. Measuring Concrete Crosstie Rail Seat Pressure Distribution with Matrix Based Tactile Surface Sensors. In *Proceedings of the 2012 Annual AREMA Conference*, 2012.
15. Rapp, C. T., M. S. Dersch, J. R. Edwards, C. P. Barkan, B. Wilson, and J. Mediavilla. Measuring Concrete Crosstie Rail Seat Pressure Distribution with Matrix Based Tactile Surface Sensors. In *Transportation Research Record: Journal of the Transportation Research Board, Vol. 2374*, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 190-200.
16. Zeman, J. C., J. R. Edwards, D. A. Lange, and C. P. Barkan. Laboratory Testing to Address the Potential for Damaging Hydraulic Pressure in the Concrete Tie Rail Seat. TRB 11-3395, 2011.
17. Yu, H., D. Y. Jeong, J. Choros, and T. Sussmann. Finite Element Modeling of Prestressed Concrete Crossties with Ballast and Subgrade Support. In *Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, DETC2011-47452, 2011.
18. Yu, H., and D. Y. Jeong. Railroad Tie Responses to Directly Applied Rail Seat Loading in Ballasted Tracks: A Computational Study. In *Proceedings of the ASME/ASCE/IEEE 2012 Joint Rail Conference*, Philadelphia, Pennsylvania, 2012.
19. Jeong, D. Y., and H. Yu. Overview of FRA/Volpe Research on concrete ties. Presented at the International Concrete Crosstie & Fastening System Symposium, University of Illinois at Urbana-Champaign, 2012.
20. Yu, H., and D. Y. Jeong. Finite Element Analysis of Wood and Concrete Crossties Subjected to Direct Rail Seat Pressure. Presented at the International Concrete Crosstie & Fastening System Symposium, University of Illinois at Urbana-Champaign, 2012.
21. Yu, H., and D. Y. Jeong. Bond between Smooth Prestressing Wires and Concrete: Finite Element Model and Transfer Length Analysis for Pretensioned Concrete Crossties. In *Proceedings of the 2014 ASCE Structures Congress*, Boston, Massachusetts, 2014.
22. Yu, H., D. Y. Jeong, B. Marquis, and M. Coltman. Railroad Concrete Tie Failure Analysis. Presented at International Concrete Crosstie & Fastening System Symposium, University of Illinois at Urbana-Champaign, 2014.
23. *Abaqus Analysis User's Manual*. Dassault Systèmes, 2012.
24. Zienkiewicz, O. C., and R. L. Taylor. *The Finite Element Method. Vol. 2: Solid and Fluid Mechanics Dynamics and Non-Linearity. Fourth edition*. McGraw-Hill, London, 1991.
25. Arnold, M. L., R. J. Peterman, N. N. B. Bodapati, B. T. Beck, and C. H. J. Wu. Development of a Standard Bond Test for Indented Prestressing Wires. In Proc. *2013 Joint Rail Conference*, JRC2013-2461, 2013.
26. Holste, J. R., R. J. Peterman, N. N. B. Bodapati, B. T. Beck, and C. H. J. Wu. Transfer Bond Test Used to Predict Transfer Length of Concrete Railroad Tie. In *Proc. ASME 2013 Rail Transportation Division Fall Technical Conference*, RTDF2013-4726, 2013.
27. Bodapati, N. N. B., W. Zhao, R. J. Peterman, C. H. J. Wu, B. T. Beck, M. Haynes, and J. R. Holste. Influence of Indented Wire Geometry and Concrete Parameters on the Transfer Length in Pretensioned Concrete Crossties. In *Proc. 2013 Joint Rail Conference*, JRC2013-2463, 2013.
28. Bodapati, N. N. B., R. J. Peterman, W. Zhao, B. T. Beck, C. H. J. Wu, J. R. Holste, M. L. Arnold, R. Benteman, and R. Schweiger. Transfer-Length Measurements on Concrete Railroad Ties Fabricated with 15 Different Prestressing Reinforcements. In *Proc.2013 PCI Convention and National Bridge Conference*, 2013.
29. *Manual for Railway Engineering, Chapter 30, Part 4: Concrete Ties*. American Railway Engineering and Maintenance-of-Way Association, 2010.

30. *49 CFR Part 213 Track Safety Standards*. Federal Railroad Administration, U.S. Department of Transportation.
31. *Standard Specification for Steel Wire, Indented, Low-Relaxation for Prestressed Concrete Railroad Ties*. American Society for Testing and Materials, ASTM A881/A881M, 2010.
32. *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces*. American Society for Testing and Materials, ASTM C779/C779M, 2012.
33. *Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)*. American Society for Testing and Materials, ASTM C1138M, 2012.
34. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. American Society for Testing and Materials, ASTM C666/C666M, 2008.
35. Riding, K., M. Albahttiti, A. Ghadban, and C. Stuart. *Freeze-Thaw Performance Testing of Whole Concrete Railroad Ties*. DOT/FRA/ORD-13/39. FRA, U.S. Department of Transportation, 2013.