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Failure Mode and Effect Analysis of North American Concrete Ties

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Summary

The Railroad Engineering Program at the University of Illinois at Urbana-Champaign (UIUC) is investigating rail seat deterioration (RSD) on concrete ties through funding from the Association of American Railroads' Technology Scanning Program. This project is being performed to gain knowledge of concrete deterioration mechanisms through laboratory experiments for a better understanding of how to design and repair concrete ties and their components and effectively mitigate the effects of RSD.

RSD was selected as the focus of the research after the results of a concrete tie survey of North American railroads and transit authorities revealed that RSD is the most critical concrete tie problem for the major railroads. The survey results for the most critical concrete tie problems and beneficial concrete tie research are summarized here and include responses from six major (Class I) freight railroads, two regional and shortline freight railroads, and four transit authorities and commuter agencies.

The survey was created as part of a modified failure mode and effect analysis to evaluate which concrete tie failure modes, or problems, should be addressed first. The survey results provide an indication of railroad industry needs pertaining to improved concrete tie performance. In addition to RSD, other critical problems were identified in the survey such as fastener component wear, center binding, and resistance to impacts and dynamic loads.

In order to recommend effective improvements to the design and repair of concrete ties and components, a greater understanding of the deterioration mechanisms that occurs during RSD is needed. UIUC is undertaking an experimental investigation to understand why concrete ties in moist environments are more susceptible to RSD. The experimental setup involves a laboratory concrete specimen representing the rail seat, which is submerged in a water tank while it is subjected to load cycles under different conditions to evaluate theories about the concrete deterioration. In one phase of the experiment, specimens will experience many load cycles, measuring the concrete deterioration over time. In the second phase of the experiment, specimens will be instrumented so that the water pressures that develop during loading can be characterized and compared to the resistance of concrete to cracking and cavitation.

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BACKGROUND AND INTRODUCTION

Prestressed concrete ties have the potential to withstand heavier axle loads and higher traffic volumes than ties constructed of other materials. However, due to their higher initial costs, concrete ties are only economical in applications where they last longer and require less maintenance than timber ties. A primary concern is that concrete ties have unresolved performance problems that shorten their service life and require unplanned maintenance. In North America, axle loadings have steadily increased, and this trend can be expected to continue due to both higher loads and speed. Consequently, it is important to investigate ways to improve the durability of concrete ties to take full advantage of their potential.

The Railroad Engineering Program at UIUC is investigating RSD on concrete ties through funding from the Association of American Railroads' Technology Scanning Program. The objective of the research is to gain knowledge of concrete deterioration mechanisms through laboratory experiments for a better understanding of how to design and repair concrete ties and their components and effectively mitigate the effects of RSD.

PROCEDURES

Failure Mode And Effect Analysis

A modified failure mode and effect analysis (FMEA) was applied to ballasted concrete tie track in North America to focus our research efforts on the most critical concrete tie problems. A FMEA is typically used to systematically predict and prevent failures in systems and components. The general FMEA process is used to identify all the ways a product can fail (failure modes), identify the potential consequences of the failures (failure effects), understand why these failures might occur (failure causes), determine which failures should be addressed first, and select the appropriate preventive measures to reduce the risk of failure.

For our analysis, a modified ranking procedure was followed that applied the qualities of a FMEA. A survey on concrete ties was used to rank the most critical problems. From the average ranking provided by major freight railroads, the most critical problem was selected as the focus of our research.

Concrete Tie Survey

Working in cooperation with researchers at Transportation Technology Center, Inc. and industry experts, we developed a survey for North American railroads and transit authorities to obtain information about their experiences with concrete ties. The survey consisted of a series of questions addressing the most critical concrete tie problems and how the railroads make decisions about using and maintaining concrete ties. The eight-question surveys were sent to individuals at 19 North American railroads and transit authorities with experience and expertise in the maintenance and performance of concrete tie track.

Six major (Class I) railroads, two regional and shortline railroads, and four transit authorities responded to the survey.

The critical concrete tie problems that each group cited in the survey differed due to variable loading environments. The major freight railroads, with their higher traffic volumes and heavier axle loads, had more load-related problems, such as RSD (also known as "rail seat abrasion"), fastener wear, and center binding. By comparison, the transit authorities and commuter agencies reported installation or tamping damage as their most critical problems. In response to an open question, "What are the most critical problems with concrete ties on your railroad?" most participants cited the maintenance required at the rail seat area, which was attributed to either fastener wear or RSD.

Participants were asked to rank a list of eight concrete tie failure modes, including "Other," in order of criticality, and the average responses are summarized in Table 1, with a score of 8 representing the most critical. The top two problems with concrete ties for major railroads are RSD and fastener wear. Only one response had anything listed under the category "Other," so the truncated list of failure modes was sufficient to encompass most North American concrete tie problems.

Table 1. Ranking of the Most Critical Concrete Tie Problems

Concrete Tie Problems	Rank (Average Score)		
	Major Railroads	Regional & Shortline Railroads	Transit & Commuter Agencies
Rail Seat Deterioration (RSD)	**1** (6.83)	**--** (0.00)	**7** (1.00)
Shoulder/Fastener Wear or Fatigue	**2** (6.67)	**1** (6.50)	**3** (4.00)
Derailment Damage	**3** (4.83)	**3** (3.50)	**8** (0.75)
Cracking from Center Binding	**4** (4.58)	**3** (3.50)	**5** (2.50)
Cracking from Dynamic Loads	**5** (1.83)	**--** (0.00)	**4** (3.25)
Tamping Damage	**5** (1.83)	**2** (4.00)	**2** (4.25)
Other (ex: Manufactured Defect, Installation Damage)	**7** (1.33)	**--** (0.00)	**1** (5.50)
Cracking from Environmental or Chemical Degradation	**8** (1.25)	**5** (3.00)	**6** (1.50)

Two primary themes among the responses were that the concrete tie system is expensive and that there is too much uncertainty in maintenance planning and estimation of the service life of concrete ties. Four of the 12 participants in the survey have largely ceased installing concrete ties in track for these reasons. Most of the survey participants, however, currently use concrete ties on a portion of their track.

Participants also ranked a list of five areas of concrete tie research from most to least beneficial. The results are shown in Table 2, and they largely reflect the problems identified by the participants in Table 1. For Table 2, a score of 5 represents the most beneficial.

We selected RSD as the initial failure mode to investigate due to the survey results in Tables 1 and 2, further guidance from the AAR, and input from the concrete tie subcommittee of AREMA Committee 30 - Ties.

Table 2. Ranking of the Most Beneficial Concrete Tie Research Areas

Concrete Tie Research	Rank (Average Score)		
	Major Railroads	Regional & Shortline Railroads	Transit & Commuter Agencies
Fastener Design: clips, insulators, inserts, tie pads	**1** (3.83)	**1** (4.00)	**1** (5.00)
Prevention of Rail Seat Deterioration or repair of abraded ties	**2** (3.67)	**2** (3.00)	**5** (1.25)
Materials Design: concrete mix, prestress strand arrangement	**3** (2.75)	**2** (3.00)	**3** (3.25)
Optimal Tie Design: tie spacing, cross-section, body shape, for specific uses (curves, grades, etc.)	**4** (2.67)	**2** (3.00)	**2** (3.50)
Track System Design: determining the track service environment and required tie characteristics	**5** (1.58)	**5** (2.00)	**4** (2.00)

Rail Seat Deterioration

The concrete rail seat and the fastening assembly work together in concrete ties to hold the rails at proper cant and gage. When a component in this rail seat system deteriorates, the hold on the rail is loosened, allowing movement during loading cycles. This loose condition can lead to deterioration of other components, resulting in a self-accelerating process. As a result, RSD and fastener wear are often concurrent failure modes, and it is thought that there is a cause-and-effect relationship between the two. In our research, we focused on concrete deterioration, understanding that this is one part of the larger RSD process.

Factors that contribute to RSD are thought to be axle load, traffic volume, curvature, grade, the presence of abrasive fines (e.g., locomotive sand or metal shavings), and climate. Based on service experience and concrete tie tests at the Facility for Accelerated Service Testing, Pueblo, Colo., heavy axle loads, abrasive fines, and moisture are the three factors that appear to be necessary for RSD to occur.[2] The other factors listed above can influence the rate of deterioration.

The wear patterns of RSD observed in track vary based on the specific climate and traffic conditions, and where the concrete tie is located in track. Figure 1 shows two examples of concrete rail seats that have been damaged in service. The figure on the left is a view of the top of the rail seat. This rail seat has worn more on one side because of its location in a curve, and the lateral forces caused the deterioration to occur under the field side of the high rail (the top of the image). The figure on the right shows the concrete's coarse aggregate exposed because the mortar wore down first. This appears similar to a surface that was eroded by the movement of water.

Figure 1. Examples of Rail Seat Deterioration[1]

A previous laboratory study at UIUC concluded that RSD may be a result of abrasion, hydraulic pressure cracking, freeze-thaw cracking, or some combination of these mechanisms.[3] Abrasion is surface wear due to some combination of rubbing of the tie pad, grinding of abrasive fines, and impacting between the rail and the tie. Freeze-thaw cycles may result in tensile cracking due to expansion of freezing water, flow of water during freezing, or other processes. Hydraulic pressure may result in tensile cracking due to passing wheel loads forcing water in and out of the concrete pores. A theory related to hydraulic pressure is that passing wheel loads force water over the surface of the rail seat, resulting in cavitation erosion. A recent investigation into a high-profile derailment on concrete-tie track in the US concluded that poor track geometry may cause concentrated stresses at the rail seat sufficient to crush or fatigue the concrete.[4] Currently, there is little evidence to support or discredit these theories.

Research Approaches

RSD is difficult to detect in its early stages and costly to repair, particularly if repairs are required between rail relay cycles. Fastening components, such as the insulators and the tie pads, must be replaced periodically. As rail life continues to increase, the rail seat and fastening components are required to sustain more traffic before requiring repair or replacement.

Different approaches for mitigating the RSD problem include improving the early detection of RSD, improving the repair of deteriorated rail seats, and improving the resistance to RSD through concrete tie design changes. But these efforts are less effective when the physical deterioration process is not sufficiently understood. As an example, an effective approach to reduce deterioration due to abrasion might be different than an approach to reduce cavitation erosion. Therefore, this research focuses first on understanding the concrete deterioration mechanisms that occur during RSD.

Concrete deterioration due to abrasion, freeze-thaw damage, or crushing is understood with current ASTM standard tests and experience with concrete in structures and highway pavements. It is not as clear whether the conditions exist in a concrete tie track for hydraulic pressure cracking or cavitation erosion to contribute to RSD. Simple models have been proposed that predict that these theories are feasible, but little experimental data exists that is relevant to either theory. The lack of experimental data is one of the reasons why these deterioration mechanisms will be evaluated with laboratory testing at UIUC.

FUTURE WORK

UIUC is developing an experimental program that will evaluate the theories about why moisture seems to be necessary for RSD to occur. The experimental setup involves a laboratory concrete specimen representing the rail seat, which is submerged in a water tank while it is subjected to load cycles under different conditions to evaluate theories about the concrete deterioration. Figure 2 shows the experimental setup, absent the 100-kip actuator and loading frame that will be used to simulate the field loading environment.

In one phase of the experimental testing, specimens will experience many load cycles, and the concrete deterioration will be measured over time. In the second phase of the experimental testing, specimens will be instrumented so that the water pressures that develop during loading can be characterized and compared to the resistance of concrete to cracking and cavitation. Testing the validity of the concrete deterioration theories will lead to more effective design and repair solutions to mitigate RSD.

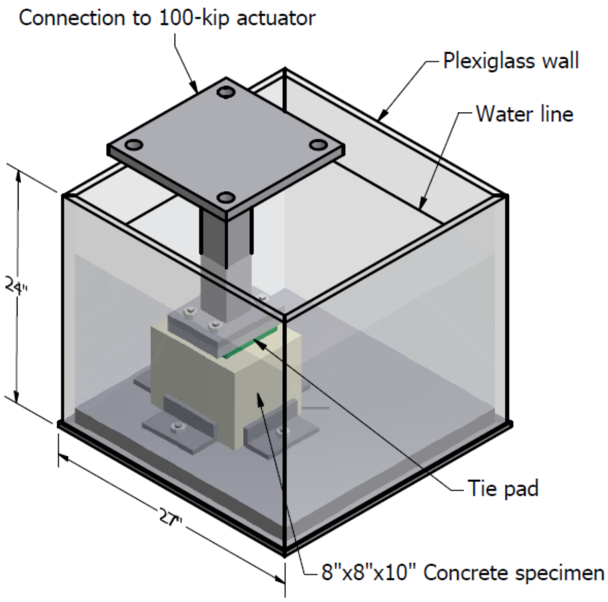

Figure 2. Experimental Setup for RSD Research

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