

# Failure Mode and Effect Analysis of Concrete Ties in North America

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**Summary:** A failure mode and effect analysis (FMEA) was applied to improve the design of concrete ties in ballasted track for North American heavy haul applications. A literature review was conducted on concrete tie failure modes, failure effects, and failure causes. A survey of railroads and transit authorities in North America provided a ranking of the most critical concrete tie failure modes. The most important problem for heavy haul service was found to be rail seat deterioration (RSD). The contributing factors, related failure modes, and deterioration mechanisms of RSD are discussed.

**Index Terms:** concrete crosstie, railseat, railway maintenance, track system, sleeper, fastener, wear, abrasion

## 1. INTRODUCTION

The railroad track structure is a complex system of components that interact to provide a smooth running surface for rail traffic. As traffic conditions change and new technologies develop, it becomes necessary to reevaluate the track structure and its components in the context of the system. An analysis procedure that is commonly used to predict and prevent failures in systems and components is the Failure Mode and Effect Analysis (FMEA), and we are applying this approach to the design of concrete ties [1].

Prestressed concrete ties were first used in Europe in the early 1940's, and they were first installed in test sections in North America in the early 1960's [2, 3]. North American railroads, particularly those in the United States, do not use concrete ties as extensively as the rest of the world. Concrete ties typically account for about five percent of the ties in track in North America, whereas many nations of the world use concrete ties as their primary form of track support and restraint [4].

As a material, prestressed concrete has the potential to withstand higher axle loads and more traffic volume than other tie materials [2]. Furthermore, it offers the potential to be engineered to match the service requirements of a particular application. Despite these advantages, concrete ties are often less economical than wood ties in North America. Due to their relatively higher initial costs, concrete ties are only economical in applications where they last longer and require less maintenance than wood ties. A primary concern is that concrete ties have unresolved performance problems that shorten their service life and require unplanned maintenance. In North America, the demands on the track in terms of heavy axle loading 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.

FMEA is an efficient procedure for organizing an analysis of a complicated product or system, identifying potential problems, and addressing the most critical failures. Failure is defined as

“the inability...to perform based on the design intent” [1, p. 74]. The general analysis process is to identify all the different 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 [1].

## **2. FMEA OF CONCRETE TIES**

### **2.1 Scope**

Using input from railroad engineers, concrete tie manufacturers, and industry committees, combined with our own knowledge of the subject, we applied a simplified form of a design FMEA to concrete ties in ballasted track in heavy haul service on major North American railroads. The purpose of the analysis was to identify the existing problems with concrete ties in North American heavy haul service, prioritize them, and then investigate the most critical failures. In this analysis, “concrete tie” refers to a typical prestressed, monoblock tie that is an assembly of concrete, prestressed strands or wires, tie pads, shoulder inserts, insulators, and spring clips.

### **2.2 Concrete Tie Functions**

Like any railway track system, ballasted concrete-tie track provides support and stability to train traffic by properly distributing the loads and maintaining the required track geometry. Concrete ties fit into this system by supporting the rails under load, distributing the stresses at the rail seat to acceptable levels for the ballast layer, and, with the ballast and subgrade, holding the rails in proper track geometry. Because of their poor dielectric qualities, concrete ties require an insulator in the fastening system to electrically isolate the rails if a track circuit system of traffic control is used.

### **2.3 Concrete Tie Failure Modes**

The failure modes of concrete ties in ballasted track can be categorized into support failure, stability failure, and electrical isolation failure. Each failure mode can be quite complex and related to failure modes of other components of the track system. It is important to understand the specific failure modes to get an idea of what causes the problems and how to reduce the probability that the failure effects will occur.

#### *Support Failure*

Failing to adequately distribute loads from the rails into the ballast may manifest itself through deterioration of other parts of the track system, as in ballast crushing, subgrade failure, rail flaws, or rail breaks. These support failure modes relate to the strength, stiffness, spacing, and bearing area of the concrete ties.

The strength and stiffness of concrete ties come from the compressive strength of the concrete and the amount of prestress in the section [5]. Excessive stiffness can lead to higher stresses at the bottom of the tie and at the rail seat [2]. A loss of stiffness can lead to excessive deflections of the rail and damage to the ballast and subgrade [5].

Flexural strength and stiffness can be lost if the prestress force is lost through corrosion, concrete deterioration, or poor bond with the concrete due to improper manufacturing. The prestressing strands/wires may corrode if insufficient concrete cover or concrete cracking allows the intrusion of moisture and oxygen.

Today, concrete ties are sufficiently strong to withstand normal service loads in flexure without significant cracking. The kind of cracking that could reach the prestress and result in risk of corrosion would require high dynamic loads, such as those caused by out-of-round wheels, a

center-bound condition, or by impact damage from derailments or dragging equipment [2]. Ties can also be damaged during handling, such as shipment, storage, installation, or maintenance.

Concrete that deteriorates due to chemical attack, environmental degradation (e.g. freeze-thaw expansion), or shear cracking may directly lose the bond with the prestressing strands or wires, or else cause cracking that leads to corrosion [6]. Poor manufacturing can lead to concrete that is not strong enough to take the high prestress forces, or it may be that the bond between the concrete and prestress never adequately developed because of an undesirable surface finish on the prestress strands or wires [2, 7].

The bearing areas at the rail seats and at the bottom of the tie are important for distributing loads at acceptable stresses. If the bearing areas are reduced by concrete deterioration, damaged fasteners, or non-uniform ballast distribution, the stresses at these locations may increase and cause damage to the ballast, rail, or subgrade. Rail cant, referring to the inward tilt of the rails, is important for transferring the lateral and vertical traffic loads through the web of the rail for stress distribution. Concrete deterioration or damaged fasteners may lead to improper cant resulting in concentrated rail seat stresses.

The spacing of the ties is also important for load distribution. Ties can become unevenly spaced, or bunched, if longitudinal forces due to thermal stresses in the rails overcome the resistance of the crib ballast and the weight of the ties. This shoving action is also related to the number of fasteners in a group of ties that are tight against the rail [5].

### *Stability Failure*

The stability failure modes all relate to track geometry. Failure to maintain proper track geometry could be improper gauge, surface, line,

or superelevation [5]. Track geometry problems are generally caused by insufficient restraint of the rails at the rail seats or by displacement of the ties.

Gauge problems are most commonly caused by failure modes like missing or damaged fasteners or rail seat deterioration. A weakened fastening system along a stretch of track allows gauge widening and possible rail rollover. A typical fastening assembly on concrete ties in North America is comprised of cast-in, steel-shoulder inserts, spring clips attached to the shoulder inserts that hold the rail, insulators between the clips and the rail (some designs place insulation on the shoulder inserts instead), and a tie pad between the base of rail and the concrete rail seat. Any one of these components can wear and allow the rail to rotate or translate laterally. These deflections of the rail, whether permanent or only under load, may result in loss of gauge.

Aside from the fastening components, the concrete beneath the base of the rail can also deteriorate; this failure mode is commonly referred to in North America as rail seat abrasion or, more correctly, rail seat deterioration (RSD). Figure 1 shows RSD on a concrete tie removed from service. As with fastener wear, RSD may lead to loss of cant or loss of gauge. RSD and fastener wear are often concurrent failure modes.

Vertical or lateral displacement of the ties can also cause geometry problems. Track buckling is an extreme failure mode that occurs when the lateral resistance from the ties and ballast is insufficient to restrain the thermal stresses in the rails. Oftentimes, the weight of the concrete tie, the roughness of surfaces on the sides and bottom of ties, and the amount of shoulder ballast contribute to how much the ties will resist loads and thermal rail stresses that work to push the track out of line. Settlement is mostly caused by



**Figure 1: Concrete tie rail seat deterioration (RSD)**

failures in the ballast and subgrade layers, but the ties influence these failures by how well they distribute traffic loads.

#### *Electrical Isolation Failure*

A shunted track circuit can occur if there is a failure to electrically isolate the rails. Electrical isolation is typically achieved by using an insulating material in the fastening assembly, since moist concrete ties conduct enough electricity to shunt the track circuit [7]. Broken, worn, or missing insulators or tie pads on each rail seat of a tie may lead to track shunting if the concrete has a high moisture content.

## **2.4 Concrete Tie Failure Effects**

The principal consequences or effects of the concrete tie failure modes – support failure, stability failure, and electrical isolation failure – such as reduced train performance, increased track maintenance costs, equipment damage, and increased risk of derailments could be the consequences of deterioration of any track structure and are not unique to concrete ties.

Reduced train performance refers to the effects that degraded track conditions have on operations: slower speeds, more delays due to maintenance, and reduced line capacity. These result in higher operating costs and lower service quality. Studies suggest that well-maintained concrete-tie track offers less train resistance than comparable wood tie track because of the stiffer track modulus [2]. This benefit from use of concrete ties is lost if the overall condition of the track is allowed to degrade to the point where this extra stiffness is lost.

## **2.5 Concrete Tie Failure Causes**

For each of the general failure modes listed above, there may be multiple potential root causes known as failure causes. Table 1 lists some potential causes for failure mode processes that are linked to the design and manufacture of concrete ties. Understanding the underlying cause is important when trying to prevent the initiation of failure modes.

It is important to remember that many failure modes in ballasted concrete-tie track are not caused by a deficiency in the ties. For example, internal rail defects, weak subgrade soil conditions, poor drainage, insufficient ballast depth, track transitions, and other track problems may themselves lead to the failure modes discussed here, or they may be potential root causes for concrete tie problems.

**Table 1. Potential failure causes for processes within the failure modes**

Failure mode processes	Potential failure causes
<b>Concrete deterioration</b>	low concrete strength; low prestress force; high curing temperature; reactive aggregates; fines intrusion; moisture intrusion; low abrasion resistance (concrete); poor pore system in cement; prestress diameter too large; too much steel in the cross-section; pad too soft; pad too hard; pad geometry creates high hydraulic pressures; pad stiffness changes too much over time
<b>Fastener damage</b>	fines intrusion; moisture intrusion; pad too soft; pad too hard; pad geometry creates high hydraulic pressures; pad stiffness changes too much over time; insulator not durable enough; fastener design creates concentrated stresses; spring clip too stiff; spring clip too flexible; low fatigue strength for spring clip
<b>Loss of prestress</b>	low concrete strength; high prestress force; poor bonding surface on prestress; prestress diameter too large
<b>Poor bearing</b>	undersized bearing areas
<b>Longitudinal shoving</b>	low bottom and side friction with ballast
<b>Lateral shoving</b>	low bottom and side friction with ballast
<b>Excessive stiffness</b>	high concrete strength; high prestress force

## 2.6 Concrete Tie Failure Modes Prioritized by Criticality

The criticality of each failure mode is influenced by how likely it is to cause the failure effect, the severity of its possible effects, and how difficult it is to detect the mode before the failure effect occurs. In a more formalized FMEA, these three factors are treated separately and are referred to as the occurrence, severity, and detection factors, respectively. One method for prioritizing failure modes is to assign ranking values (typically from 1 to 10) to each of these factors. The product of these factors is a ranking metric called the “risk priority number [1].”

A formal FMEA uses the risk priority numbers to prioritize failure modes. Determining the values for each of the factors is a collaborative effort that uses performance data, surveys, and expert opinion. For our analysis, a simplified ranking procedure was followed that applied the qualities of FMEA, but without as much detail. A rigorous FMEA of concrete ties was considered unnecessary and would have been mostly qualitative because adequate performance data are not available for some concrete tie failure modes. Failure modes are often only recorded

after severe failures such as derailments. A more involved process may lead to the same relative ranking of failure modes as achieved with this simpler approach.

Working in cooperation with the Association of American Railroads (AAR), we developed a survey for North American railroads and transit authorities to learn about their experiences with concrete ties. The survey was a series of questions about the most critical concrete tie problems, and how the railroads decide whether to use concrete ties. The surveys were sent to individuals at railroads and transit authorities with experience and expertise with concrete ties.

Six major railroads, two smaller railroads, and four transit authorities responded to the survey. The critical problems that each group cited in the survey differed because of the different loading environments. The major railroads, with their higher traffic volumes and heavier axle loads, had more load-related problems, such as RSD, fastener wear, and center binding. By comparison, the transit authorities reported the critical problems to be installation or tamping damage.

**Table 2: The most critical concrete tie problems for major North American railroads; ranked from 1 to 8, with 8 being the most critical (based on six railroads' survey responses)**

Most Critical Concrete Tie Problems	Average Rank
<b>Rail seat deterioration (RSD)</b>	6.83
<b>Shoulder/fastener wear or fatigue</b>	6.67
<b>Derailment damage</b>	4.83
<b>Cracking from center binding</b>	4.58
<b>Cracking from dynamic loads</b>	1.83
<b>Tamping damage</b>	1.83
<b>Other (ex: manufactured defect)</b>	1.33
<b>Cracking from environmental or chemical degradation</b>	1.25

In response to an open question, “What are the most critical problems with concrete ties on your railroad?” most respondents cited the maintenance required at the rail seat area, whether the problem is attributed to the fasteners or to rail seat deterioration.

Respondents were asked to rank a list of eight concrete tie failure modes, including “Other,” in order of criticality (Table 2). The top two problems with concrete ties for major railroads are RSD and fastener wear. Only one response had anything listed under “Other,” so the truncated list of failure modes apparently was sufficient to encompass most heavy haul concrete tie problems in North America.

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 service life of concrete ties. Some North American railroads continue to use concrete ties, while others have largely ceased using them.

Because of the results in Table 2 and further input from the AAR and the concrete tie subcommittee of the American Railway Engineering and Maintenance-of-Way Assoc. (AREMA) Committee 30 - Ties, we selected rail seat deterioration as the first failure mode to investigate.

## 2.7 Investigation of Rail Seat Deterioration

RSD is a complicated failure mode that involves multiple contributing factors, interrelated failure modes, fastener damage, and concrete deterioration. Contributing factors are thought to be heavy axle loads, high traffic volume, curvature, grade, mainline speeds, the presence of abrasive fines (like locomotive sand or metal shavings), and a cold, moist climate. The factors that appear to be necessary for RSD to occur are heavy axle loads, abrasive fines, and moisture [8]. RSD predominantly occurs in North America, most likely because of some unique combination of heavy axle loads, high traffic volume, and the necessary environmental conditions. Abrasive fines are typically present between the tie pad and the rail seat when RSD is discovered. Experiments at the AAR Transportation Technology Center Inc. (TTCI) demonstrated that RSD will not occur without moisture present at the rail seats. Concrete ties in the high tonnage loop showed no sign of RSD until a sprinkler system was installed [8]. The other contributing factors accelerate RSD, but they do not appear to be necessary for it to occur.

One laboratory study concluded that RSD may be a result of abrasion, hydraulic pressure cracking, freeze-thaw cracking, or some combination of these mechanisms. 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. Hydraulic pressure may result in tensile cracking due to passing wheel loads forcing water in and out of the concrete pores. Freeze-thaw cycles may result in tensile cracking due to expansion of freezing water, flow of water during freezing, or other processes [9]. A recent investigation into a high-profile derailment on concrete-tie track in the US concluded that track geometry may cause concentrated stresses at the rail seat sufficient to crush or fatigue the concrete [10].

The wear patterns observed in track vary from wear of the cement paste that exposes the coarse aggregate to wear of all concrete components, and from flat wear that begins on the perimeter of the rail seat to a triangular pattern that wears the field side of the rail seat on the high side of a curve [9, 10, 11]. Figures 2 and 3 illustrate the range of RSD wear patterns. The wear pattern in Figure 2 is horizontal with loss of the cement paste exposing the coarse aggregate, which is relatively intact. By contrast, in the triangular wear pattern in Figure 3, all the concrete components at the surface are equally worn.

RSD is commonly related to, and may be caused by, broken, loose, or missing fastening components. Movement of the rail that results from a loosened fastening assembly can contribute to RSD by allowing intrusion of fines and moisture, abrasive action, or concentrated stresses.

There is currently a somewhat standard qualification test for concrete ties in North America that is intended to simulate RSD. In the test, cyclic loads are applied at a lateral-to-vertical (L/V) ratio of 0.52, with water and sand present at the rail seats of a fully assembled tie

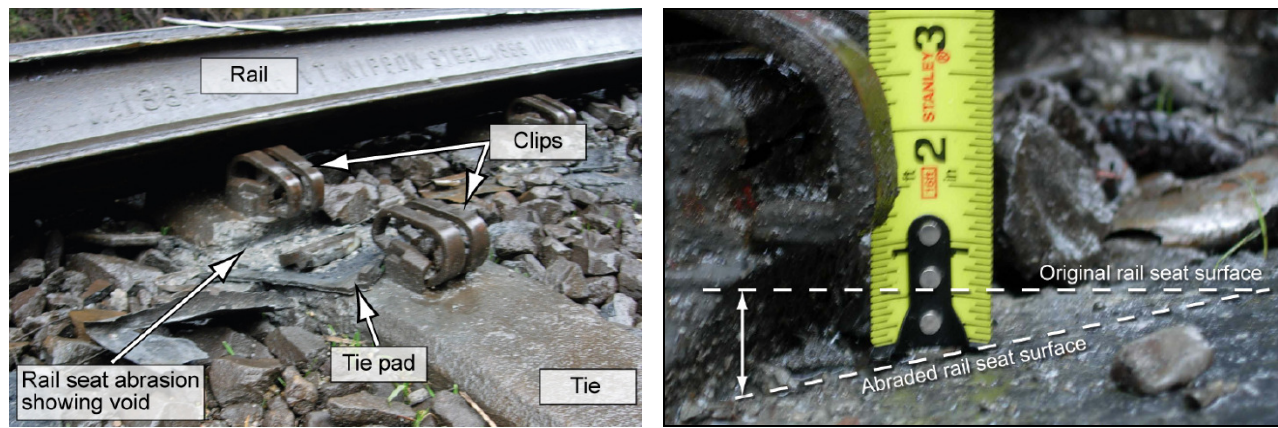


**Figure 2: RSD, with horizontal pattern and cement paste wear [9]**

[11]. The test evaluates the performance of the fastening assembly and the concrete at the rail seat.

Automated inspections for RSD are typically done by geometry cars that apply lateral loads to the rails, using a gauge restraint measurement system. The geometry cars can identify gauge problems, but they cannot identify what caused them – possibly rail damage, fastener damage, or RSD [13]. Visual inspections can readily identify RSD if the rail and fastening assembly have been removed. If RSD is identified in its early stages, the rail seat surface can be restored by applying epoxy, extending the service life of the tie.

The failure effects directly associated with RSD are increased maintenance and increased possibility of derailment. RSD is best detected and repaired during rail relays, when the fasteners are disassembled and the rail replaced [8]. RSD may sometimes require repair or replacement between rail relays, which is costly. At least two derailments in the US were caused by RSD and involved injuries and hundreds of thousands of dollars in damage to track and equipment [12].



**Figure 3: RSD, with triangular wear of concrete surface toward the field side on the high side of a curve [12]**

Isolation and consideration of the levels of causation for RSD helps illustrate different approaches for addressing the problem. By understanding the higher-level contributing factors, railroad engineers can predict when to expect RSD in their concrete-tie track. Some of the contributing factors can be mitigated, such as accelerated wear on curves, which may be reduced with proper rail lubrication and preventive rail grinding. But most of the contributing factors are more difficult to avoid. Mitigating fastener damage and other related failure modes may effectively prevent the onset or acceleration of RSD. Developing a better understanding of the deterioration mechanisms can lead to design solutions for improving the resistance of the concrete rail seat to RSD.

There are many potential root causes of RSD, but only some of them can be controlled through design. These include the durability of the concrete, the durability of the fastening components, the intrusion of moisture, and the intrusion of fines.

Some fastening assembly design approaches that railroads in North America are taking include widening the bearing area between the shoulder insert and concrete shoulder [2], improving the pad geometry or material [8], casting a steel plate at the rail seat [11], and improving the wear resistance of the insulators [14].

For resistance to abrasion and crushing, a less porous cement paste and a stronger concrete may help. For freeze-thaw and hydraulic pressure, a well-designed pore system, proper air content, and tensile crack resistance would help. Generally, abrasion and freeze-thaw are well understood, and standard tests have been used to evaluate the resistance of concrete to these mechanisms. Hydraulic pressure and crushing mechanisms are not as well understood and warrant further investigation.

At least one concrete tie manufacturer is attempting to place higher quality concrete at the rail seat than in the body of the tie [15]. If this does not create additional problems such as delamination of the concrete layers, this could make concrete improvements economical. The compatibility of this method with current concrete-tie manufacturing processes should be examined.

## 2.8 Next Steps

By design, the FMEA approach is meant to result in continuous improvement. A design FMEA continues until modifications can no longer be made to the product or it is discontinued [1]. Continuing with the concrete tie FMEA would entail pursuing more fastener-specific problems, investigating the performance of ties under heavy impacts (as in the case of a



derailment), and investigating the performance of ties in the center-bound loading condition. In addition to analyzing tie design, the manufacture, installation, and repair of concrete ties could be analyzed by one or more process FMEA's.

The FMEA presented here on concrete ties in ballasted track in North America could be modified to analyze other tie materials or other types of track structures such as slab track. The failure effects and the categories of failure modes will be similar, regardless of the system being analyzed. The specific failure modes and their causes will distinguish one system from the other. Also, a design FMEA could be created for the development of new track components that would predict potential failure modes, rather than analyze known failure modes.

This simplified design FMEA was effective for organizing concrete tie failure modes, facilitating a simple and quick survey, and directing research toward the most critical failure mode. However, some of the advantages of performing a formal FMEA were lost through simplification. Because only one ranking metric was used to prioritize failure modes, the process lost the depth achieved by assigning severity, occurrence, and detection values. There were also disadvantages to performing an FMEA on one track component before first performing a track system FMEA to identify which components are the most critical. Once a thorough system FMEA establishes the problem areas with track, design or process FMEA's could be implemented to pursue these.

### **3. CONCLUSION**

A simplified design FMEA was performed on concrete ties in ballasted track in North American heavy haul service. The analysis resulted in enumeration of the concrete tie failure modes, a ranking of the most critical ones

in North America, and initiated an investigation into rail seat deterioration (RSD), which was found to be the most critical failure mode.

More investigation is required to understand the contributing factors, related failure modes, and deterioration mechanisms associated with RSD. With a better understanding of how and why RSD occurs, it may be possible to find cost-effective design solutions. It is not clear whether RSD is a failure mode that can be prevented throughout the service life of a concrete tie, or whether the more realistic goal is mitigating the rate at which RSD occurs. In either case, the risk of RSD must be reduced to allow concrete ties to meet their full potential in heavy haul service.

### **4. ACKNOWLEDGMENTS**

This research was funded by the AAR Technology Scanning Program. The authors would like to thank David Davis and Richard Reiff of TTCL, Ernie Barenberg of the University of Illinois at Urbana-Champaign (UIUC), William Riehl of RailAmerica Inc., the AAR Technology Scanning Committee, and the members of AREMA Committee 30 – Ties, Subcommittee 4 – Concrete Tie Technology for their invaluable contributions to this research. John C. Zeman has been supported in part by a CN Research Fellowship in Railroad Engineering. J. Riley Edwards has been supported in part by grants to the UIUC Railroad Engineering Program from CN, CSX, Hanson Professional Services, Norfolk Southern, and the George Krambles Transportation Scholarship Fund.

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