Investigating the Role of Moisture in Concrete Tie Rail Seat Deterioration

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ABSTRACT

Rail seat deterioration (RSD) is the most critical problem with concrete tie performance on North American freight railroads. Currently, the causes and mechanics of RSD are not sufficiently understood, limiting effective approaches to RSD prevention and mitigation. It has been observed that heavy axle loads, moisture, and abrasive fines are necessary for RSD. Past research and field experience with concrete ties identified five concrete deterioration mechanisms that may occur during RSD: abrasion, crushing, freeze-thaw cracking, hydraulic pressure cracking and cavitation erosion. Currently, little empirical evidence exists to substantiate these theories. The mechanics of moisture's contribution to concrete deterioration during RSD will be investigated through a set of laboratory experiments. The experiments are designed to isolate cavitation erosion and hydraulic pressure cracking from the other potential mechanisms to challenge the theory that these two mechanisms contribute to RSD. One phase of the testing program will subject submerged, unreinforced concrete specimens to many load cycles to understand if and how deterioration occurs due to cavitation and hydraulic pressure cracking. In the second phase of the research, we will instrument the concrete specimens with a pressure transducer to measure the water pressure between the pad and the concrete during loading. The results of these laboratory experiments will guide the development of effective methods for mitigating RSD, with the goal of reducing the life-cycle cost of concrete-tie track.

INTRODUCTION

As a material, prestressed concrete ties have the potential to withstand heavier axle loads and higher traffic volumes than other tie materials. However, due to their higher initial costs, concrete ties are only economical in applications where they last longer and require less maintenance than wood ties. Concrete ties account for approximately five percent of the ties in track in North America, whereas many other countries in the world use concrete ties as their primary form of track support and restraint *(1)*. Though concrete ties represent a small percentage of the ties in North America, concrete ties are used in some of the most demanding conditions in terms of track geometry and traffic volume. Of primary concern to the railroad industry are the unresolved performance problems that shorten the service life and increase the maintenance cost of concrete-tie track. Consequently, it is important to investigate ways to improve the durability of concrete ties to take full advantage of their potential. In order to effectively mitigate the problems that shorten the service life and increase the maintenance cost of concrete ties, the nature of these problems must be understood. The objective of this research is to understand the most critical failure mechanisms of concrete ties to identify effective methods to improve their performance.

CONCRETE TIE SURVEY

Working with researchers at the Transportation Technology Center Inc. (TTCI) and industry experts on a failure mode and effect analysis of concrete ties *(2)*, we developed a survey for North American railroads, commuter rail agencies, 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 the installation and maintenance of concrete ties. The eight-question surveys were distributed to individuals at nineteen North American railroads, commuter rail agencies, and transit authorities with experience in the maintenance and performance of concrete-tie track.

Six major (Class I) railroads, two regional and shortline railroads, and four commuter rail agencies or transit authorities responded to the survey. The most critical problems that each group cited in the survey differed due to their varied loading environments. The major freight railroads, with higher traffic volumes and heavier axle loads, had more load-related problems, such as rail seat deterioration (RSD) (also known as "rail seat abrasion"), fastener wear, and center binding. By comparison, the commuter agencies and transit authorities 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 rail seat maintenance, which could be attributed to either the fastening system or RSD.

Two primary themes among the responses were that the concrete tie system is expensive and that there is significant uncertainty in maintenance planning and estimation of the service life of concrete ties. Four of the twelve 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.

Respondents were asked to rank a list of eight concrete tie failure modes, including "Other," in order of criticality, and the average responses for major freight railroads, regional and shortline railroads, and commuter agencies and transit authorities are summarized in Table 1. The top two problems with concrete ties for major freight railroads are RSD and fastener wear.

We selected RSD for further investigation due to the survey results shown in Table 1, guidance from researchers at the Association of American Railroads (AAR), and input from the concrete tie subcommittee of American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 30 - Ties.

RAIL SEAT DETERIORATION

The concrete rail seat and the fastening assembly work together in concrete ties to hold the rails at proper cant and gauge. When a component in this rail seat system deteriorates, the hold on the rail is loosened, allowing movement during load cycles. This loosened condition can lead to deterioration of other components through a self-accelerating process. As a result, RSD and fastener wear are often concurrent failure modes, and there is thought to be a cause-and-effect relationship between the two. In our research, we focus on concrete deterioration, understanding that this is only one part of the 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 North American freight railroad experiences and concrete tie tests at TTCI's Facility for Accelerated Service Testing (FAST), heavy axle loads, abrasive fines, and moisture are the three factors that appear to be necessary for RSD to occur *(3)*. The other factors appear to influence the rate of deterioration.

The RSD wear patterns observed in track vary based on the specific climatic and traffic conditions and the location of the concrete tie in track. Figures 1 through 3 show three distinct examples of concrete rail seats that have been damaged in service. Figure 1 is a view looking downward at 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 deterioration to occur under the field side of the rail (the top of the image). The rail seat in Figure 2 appears to be crushed on both its gauge and field sides. This could be the result of the rail pivoting back-and-forth because of a loose fastening system. Figure 3 shows the concrete's coarse aggregate exposed after the mortar was worn away, leaving an appearance similar to a surface eroded by the movement of water.

RSD is a maintenance challenge because relatively small amounts of wear can lead to significant track geometry problems, typically in the form of wide gauge. The site of a 2005 derailment in the state of Washington had RSD as deep as 2 inches at one location. Researchers from the Volpe National Transportation Systems Center studying this derailment estimated that, depending on the pivot point at the base of the rail and the amount of rail head wear, 1 inch of RSD wear on the field side can result in 1 to 2.5 inches of gauge widening. To keep track within gauge limits for Federal Railroad Administration (FRA) track classes 4 and 5, the researchers suggested that the depth of RSD wear on the field side of the rail seat should be no more than 0.38 inch for new rail, 0.31 inch for 0.25-inch rail head wear, and 0.19 inch for 0.50-inch rail head wear *(4)*.

RSD is difficult to detect in its early stages and costly to repair, particularly if repairs are required between rail relay cycles. Currently, diagnosing and repairing RSD requires removing the fastening system and lifting the rail from the rail seat, a labor intensive and expensive task. Under extreme conditions, RSD can develop on new ties within one to two years. Fastening components, such as the insulators, tie pads, and spring clips, must be replaced periodically. In order to maximize track capacity and minimize maintenance-of-way track windows, it is more efficient to repair the rail seat and replace the fastening components during rail replacement. As rail life continues to increase through practices such as rail lubrication, grinding and the use of head-hardened rail, the rail seat and fastening components are required to sustain more traffic before repair or replacement. Therefore, in addition to preventing the initiation of RSD, an important objective of this research is to determine methods to increase the rail seat's resistance to RSD so that it can last one or two rail relay cycles.

Approaches to mitigating RSD include improving the early detection of RSD, improving the materials and procedures for repairing deteriorated rail seats, and improving the resistance to RSD through changes in concrete tie design. Current mitigation and repair efforts are less effective given that the physical deterioration process is not sufficiently understood. For example, if abrasion is the primary mechanism, it may be most effective to reduce the concrete porosity to increase abrasion resistance or provide a protective coating or plate; however, if freeze-thaw or hydraulic pressure cracking is the primary mechanism, it may be most effective to increase the concrete porosity to relieve the damaging pore pressures. This research focuses on understanding the concrete deterioration mechanisms that occur during RSD.

Concrete Deterioration Theories

According to industry knowledge and previous studies, the concrete deterioration in RSD may be abrasion, crushing, freeze-thaw cracking, cavitation erosion, hydraulic pressure 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 the impact between the rail and the tie. "Crushing," in the context of this research, refers to local concrete damage caused by concentrated stresses that either exceed the concrete's strength or are high enough to lead to fatigue damage after many loading cycles. Freeze-thaw cracking results from the expansion of freezing water, flow of water during freezing, or other processes during freeze-thaw cycles that create internal stresses in the concrete. Cavitation erosion is surface wear due to bursts of high pressure created by sudden changes in water flow over the concrete surface, presumably when water trapped beneath the pad is compressed by wheel loads. Hydraulic pressure cracking is thought to be the result of high pore pressures in saturated concrete caused by the wheel loads forcing water in and out of the concrete pores.

A previous microscopy study concluded that a sample of concrete ties taken out of service with RSD showed characteristics of abrasion and possibly hydraulic pressure cracking or freeze-thaw cracking. Hydraulic pressure cracking and freeze-thaw cracking have similar appearances because they both result from high concrete pore pressures. The study did not find microscopic evidence of cavitation erosion in the samples *(5)*. Evidence for cavitation erosion has been discovered in examples of worn rail seats such as the one documented by Peters and Mattson in Figure 3 *(6)* and a video recorded at TTCI's FAST showing bubbles forming at the edge of the tie pad during loading *(5)*. The bubbles may be the result of sudden pressure changes in the water, suggesting cavitation. For the crushing theory, an investigation into the Washington state derailment concluded that poor track geometry may cause concentrated stresses at the rail seat sufficient to crush or fatigue the concrete *(4)*.

Contribution of Moisture to Concrete Deterioration

Experimentation and field knowledge suggest that moisture is necessary for significant RSD to occur. Possible explanations for this are that hardened concrete is less resistant to abrasion or crushing when it is wet, higher stresses can develop during freeze-thaw cycles when concrete is wet, or the forced movement of water under traffic load may deteriorate the concrete through cavitation erosion or hydraulic pressure cracking.

Concrete deterioration due to abrasion, freeze-thaw cracking, or crushing in wet versus dry conditions is understood through standard laboratory tests and experience with structural concrete and highway pavements. For example, researchers have shown that concrete abrasion under wet testing conditions may be as little as 10% or as much as 100% more than the abrasion under air-dry conditions *(7)*. The conditions for abrasion have been observed when locomotive sand and metal shavings (from rail or wheels) enter beneath the tie pad *(3)*. Freeze-thaw damage is possible in regions with the necessary climate, though the entrained air in concrete ties should mitigate the problem. Volpe researchers presented evidence that rail seat stresses can become highly concentrated in certain combinations of degraded track geometry and damaged rail seats on a curve *(4)*. Compared with abrasion, freeze-thaw cracking, and crushing, it is not as clear whether conditions exist for hydraulic pressure cracking or cavitation erosion to contribute to RSD. Simple models have predicted that these theories are feasible, but little experimental data exists that is relevant to either theory. This led us to further refine the focus of our investigation to cavitation erosion and hydraulic pressure cracking, the least understood concrete deterioration theories.

Cavitation Erosion may occur when water trapped beneath the tie pad is squeezed out at high pressure, and the pressure bursts created by bubbles in the escaping water erodes the cement paste, exposing the coarse aggregate. Unlike abrasion, which wears the coarse aggregate as well as the cement paste, a concrete surface subjected to cavitation erosion should have a rough, pitted appearance *(5)*. Cavitation erosion most commonly occurs in hydraulic structures, such as dams and spillways, where water flow is interrupted.

As part of an earlier investigation into the mechanics of RSD, Pandrol, Ltd. developed the Jetmil test to create cavitation erosion by spraying a test surface with water at a pressure of 6000 pounds per square inch (psi) from a set of rotating nozzles *(5)*. Bakharev used the Jetmil apparatus on different concrete mixes and recorded depths of wear between 0.06 and 0.10 inch on a 5.25 inch-diameter surface after ten minutes. The Jetmil created surfaces that appeared similar to the RSD surfaces found in service (Figure 3), but at the microscopic level, the wear on new ties subjected to Jetmil tests was not consistent with that found in the RSD field samples *(5).* While Bakharev did not find evidence of cavitation in her sample set of RSD ties, she did not find conclusive evidence to eliminate cavitation erosion as a potential deterioration mechanism.

Hydraulic Pressure Cracking may occur when water beneath the tie pad is forced into the pore system near the surface, creating tensile stresses in the solid concrete skeleton. If the tensile stresses exceed the tensile strength of the concrete, then microcracking may result. This cracking may propagate with further hydraulic pressure cycles. Cracking would be expected near the surface because the water could not travel very deep into the concrete during one load cycle. This cracking could accelerate the wear caused by other mechanisms, such as abrasion, cavitation erosion or crushing. Because compressive stresses are also acting near the surface, coming both from the wheel loads and from the prestressing steel, the net stress in some direction has to be tensile for damage to occur. Also, the concrete may need to be saturated, at least locally, for damaging pressures to develop. If the concrete pores were not saturated, water might escape to empty pores, relieving the pressure. A similar phenomenon is suspected to occur in highway bridge decks along the wheel paths *(5).*

Bakharev tested the hydraulic pressure cracking hypothesis with a simple two-dimensional model. The location of stresses predicted by her model was consistent with the subsurface cracking she observed in the sample RSD ties. The ties had characteristic cracks described as vertical cracks reaching as deep as 0.8 inch below the surface and horizontal cracks at depths of 0.2-0.6 inch. According to her model, there should be a section of the concrete two to four inches below the rail seat surface that will experience significant tensile stresses, even when the compressive wheel stresses are superimposed onto the pore pressures *(5).* This analysis did not account for the effects of the prestress, which results in a horizontal compressive stress that may counteract tensile pore pressures in the horizontal direction. Concrete ties are prestressed so that the concrete is in compression while at rest. When the ties are loaded in flexure by axle loads, the precompression from the prestress cancels out the flexural tension, allowing the ties to withstand higher loads without cracking. Part 4 of AREMA Chapter 30 recommends that precompression at any point in the tie should be at least 500 psi but no more than 2500 psi *(8).* The precompression is significant and should be superimposed on the pore pressure and load stresses in a hydraulic pressure cracking model.

The theory of hydraulic pressure cracking hinges on tensile stresses damaging concrete. Concrete is much weaker in tension than in compression, and a general rule is that the tensile strength is approximately 10% of the compressive strength. Another relevant approximation is that cyclic stresses greater than half of the concrete's strength can lead to fatigue damage *(9).* AREMA recommends a minimum 28-day compressive strength of 7000 psi *(8)*. For the hydraulic pressure cracking theory to be plausible, net tensile stresses in the concrete should be on the order of 350 to 700 psi or greater.

Models have been created to characterize the dynamic movement of water through saturated asphalt pavements under highway traffic, similar to the hydraulic pressure cracking theory for concrete ties. One model predicted that higher pressure gradients, water velocities, and shear stresses would be found in the upper 0.4-1.6 inches of the pavement and that the pore pressures and water velocity varied nonlinearly as a function of depth due to the heterogeneity of the asphalt concrete *(10).* Another model predicted that, in the upper pavement layer, hard asphalt experienced higher pore pressures (290 psi) and lower water velocities (70 microns per second), while soft asphalt experienced lower pore pressures (2.9 psi) and higher water velocities (20,000 microns per second) *(11).* These models suggest that pore pressures near the surface could be in the magnitude of stresses that could lead to fatigue cracking if cycled, but that the water may not be moving fast enough to penetrate deeply in the pore structure during one load cycle.

LABORATORY TESTS

The University of Illinois at Urbana-Champaign (UIUC) has developed a laboratory setup to test the hypothesis that concrete deterioration can occur in a saturated concrete tie rail seat in the absence of abrasion, freeze-thaw cycles, or crushing. The test setup includes a laboratory concrete specimen that represents the rail seat, which will be submerged in a water tank while being subjected to load cycles of varying magnitudes and frequencies. The load will be applied normal to the concrete surface, to minimize any lateral friction that could lead to abrasion. The plate applying the load will cycle through a small displacement on the order of 0.25 inch or less, simulating the uplift of the rail that occurs before and after a wheel passes. According to the theories on cavitation erosion and hydraulic pressure cracking, these test conditions would be a worst-case scenario for moisture-related RSD, where the concrete is saturated during loading and the fastener system is providing minimal restraint. The concrete rail seat blocks will be tested through two separate methods; they will be loaded for many cycles to demonstrate potential wear and wear rates, and they will be instrumented so that the surface water pressure can be measured during loading. At the time of publication of this paper, initial tests are being conducted, and the full testing program will follow.

The load magnitudes were estimated assuming 286-kilopound (kip) cars, 1:40 rail cant, 0.52 lateral-to-vertical (L/V) ratio, 28-inch tie spacing, and a 200% impact factor for high dynamic loads. The 0.52 L/V was taken from the Bodycote accelerated RSD test, which is documented in AREMA Chapter 30, Part 2 *(8).* The 28-inch tie spacing was used to ensure a conservative load distribution factor was selected from AREMA Chapter 30, Part 4, and the 200% impact factor was also taken from AREMA Chapter 30, Part 4 *(8).* With these assumptions, the static normal force on one rail seat is approximately 20 kips, while the dynamic normal force on one rail seat is as high as 60 kips.

The load frequency was estimated based on the average axle spacing for a fifty-foot car, which is 12.5 feet. Three different speeds were considered: 25 miles-per-hour (mph), 40 mph, and 60 mph, corresponding to FRA track classes 2, 3, and 4, respectively. These speeds correspond to average load frequencies of 3 Hertz (Hz), 5 Hz, and 7 Hz, respectively. Higher frequencies were not considered due to limitations of the hydraulic equipment.

To imitate the vertical wave deflection of the rail caused by passing wheels, a plate representing the base-of-rail will be displaced vertically through a small distance between load cycles. The Talbot equation for vertical track deflection was used on a range of hypothetical cases to estimate the limits on the movement of the base-of-rail *(12).* For our tests, the maximum movement of the base-of-rail (including pad compression and uplift) will be limited to 0.25 inch.

Materials

Figure 4 is a drawing of the full test apparatus with a 100-kip servo-hydraulic actuator, load arm, and water tank, with the concrete specimen in place. The specimens are unreinforced concrete with Type III cement, made using a mix design from Bakharev's previous concrete tie research that is similar to mix designs presently used by US concrete tie manufacturers. This mix is considered the high strength mix in our experiment, while the low strength mix differs only by increasing the water-to-cement ratio, reducing the cement content, and removing the superplasticizer. The low strength mix has an average 28-day compressive strength just over 5000 psi. The high strength mix has an average strength over 8000 psi. Because this testing program is investigating the feasibility of the deterioration mechanisms, we will first investigate the low strength concrete to see if any deterioration occurs. Plain, 5000 psi concrete should be more susceptible to hydraulic pressure cracking or cavitation erosion. If no deterioration occurs with the low strength concrete, it is unlikely that deterioration will occur with the 8000 psi concrete.

As illustrated in Figure 4, specimens will be placed in a tank with six inches of water above the top of the specimen. The bottom of the water tank is a steel plate, while the walls are transparent plexiglass. The specimen will be positioned directly below an actuator that will apply load via a steel pipe that extends into the water and is welded to a steel plate that acts as the base-of-rail. A tie pad was adhered to this "base-of-rail" plate with epoxy and will be the contact surface against the concrete.

Five tie pads will be used in the instrumented tests: dimpled polyurethane, flat polyurethane, grooved polyurethane, dimpled EVA, and dimpled santoprene. Concrete tie experts have noted that flat pads held more moisture than pads with some surface geometry – such as grooved, studded, or dimpled *(5)*. Besides surface geometry, pad material will also be investigated as a variable because differences in material stiffness may affect how much water pressure develops beneath the pad. This set of pads was selected to understand the effects of changing the interface properties, and not to conclude which materials provide optimal RSD resistance. That is why a multiple-part abrasion pad (sandwich pad) was not considered.

High Cycle Tests

The primary variables in the high cycle experiments will be the concrete strength (low or high), the load magnitude (20 kips or 60 kips), and the load frequency (3 Hz or 7 Hz). All high cycle tests will have a dimpled polyurethane tie pad and will run to a maximum of one million cycles. Most tests will be carried out with six inches of water above the rail seat surface for the saturated condition, but some air-dry tests will be conducted for comparison.

Axle loads for a 286-kip car are 35.75 gross tons. For each high cycle test run to one million load cycles, the rail seat block will be effectively subjected to 36 million gross tons (MGT) with saturated concrete and loose fasteners. Because these conditions would not be simultaneously present every time a train passes, the 36 MGT in the worst-case test setup would translate into higher gross tonnage under actual service conditions, possibly equal to years of service on a high traffic volume corridor. For this reason, it is expected that if no deterioration occurs in the first one million load cycles, it is unlikely that anything will occur with subsequent cycles.

The wear on the high cycle specimens will be measured using a digital caliper and an aluminum template with a matrix of twenty-five points evenly spaced across the concrete bearing surface. Measurements will be taken at regular intervals for the duration of each test.

Instrumented Tests

The primary variables in the instrumented tests will be the location where the pressure is measured (center, corner, or edge of bearing surface), the type of tie pad (dimpled polyurethane, flat polyurethane, grooved polyurethane, dimpled EVA, or dimpled santoprene), the load magnitude (20 kips, 40 kips, or 60 kips), and the load frequency (3 Hz, 5 Hz, or 7 Hz). All instrumented tests will have high strength concrete specimens and saturated conditions.

A submersible pressure transducer will be used to measure hydrostatic pressure near the tie pad-concrete interface. The pressure transducer will be able to withstand a maximum pressure of 6000 psig.

During initial tests with the setup, a steel plate will be placed in the water tank (instead of the concrete block) to experiment with the pressure transducers and their ability to measure the pressure at the tie pad to tie interface. To instrument the concrete blocks with the pressure transducers, a 1.25-inch-diameter stainless steel pipe was cast into the specimens, along with a 0.75-inch deep cavity at the top. Into this cavity will be inserted a stainless steel coupling that the transducer will thread into, allowing the transducer to be located near the surface, without being directly loaded by the tie pad. This configuration is illustrated in Figure 5 and will allow reuse of the pressure transducers.

The water pressures measured between the tie pad and the concrete surface will be compared to the Jetmil test's 6000 psi pressure that is known to lead to significant cavitation damage. Further efforts will be made to establish if there is a threshold of water pressure below which concrete typically will not deteriorate. The measured pressures will also be valuable as input surface pressures to any model of hydraulic pressure cracking. While the actual pore pressures will not be measured, measuring the water pressure entering the concrete pores may lead to better estimates of the pore pressures some depth below the surface.

CONCLUSION

RSD is the most critical problem with concrete ties on major North American freight railroads. Mechanisms causing RSD may include abrasion, crushing, freeze-thaw cracking, cavitation erosion, hydraulic pressure cracking, or some combination of these. There is evidence that the conditions may exist for abrasion, crushing, and freeze-thaw cracking at the rail seat of a concrete tie. It has not been demonstrated whether the conditions exist for cavitation erosion or hydraulic pressure cracking at the rail seat. The new laboratory testing program described in this paper will provide empirical evidence that will support or discredit the theories that cavitation erosion or hydraulic pressure cracking occurs during RSD. The test setup can also be adapted for future research on abrasion and crushing mechanisms to understand rates of wear and possible interactions between mechanisms. Historically, most attempts to solve the RSD problem have stemmed from trial-and-error methods. With empirical knowledge of the potential concrete deterioration mechanisms, more effective concrete tie designs and repairs can be made to mitigate the effects of RSD. Concrete ties have the potential to be cost-effective solutions for demanding heavy haul conditions if problems such as RSD can be managed.

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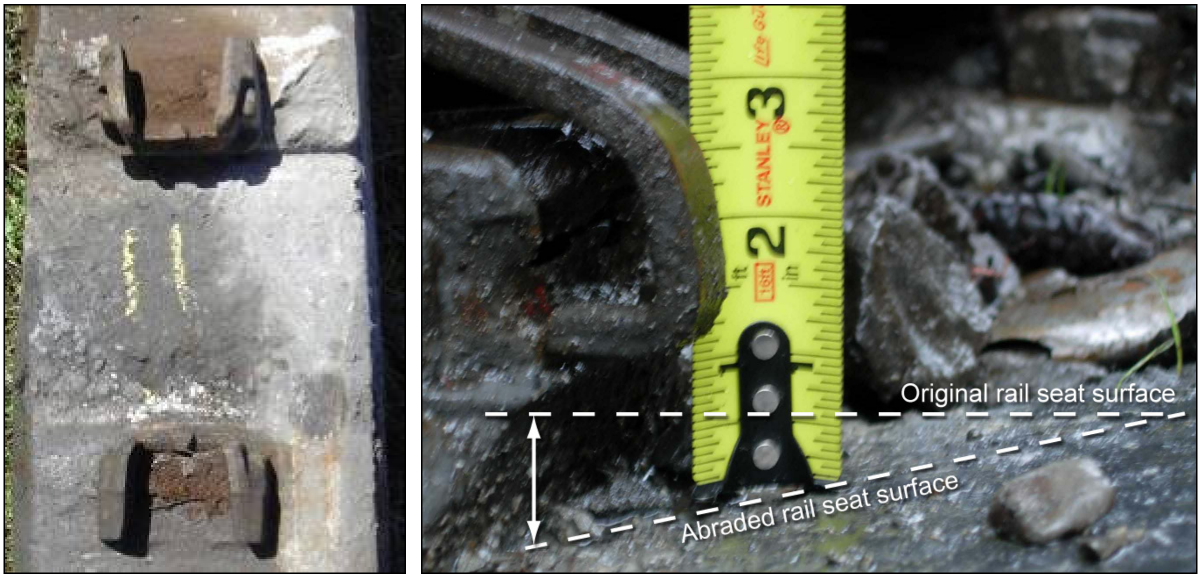
TABLE 1. Ranking of the Most Critical Concrete Tie Problems

Concrete Tie Problems	Rank (Average Value)		
	Major Railroads	Regional & Shortline Railroads	Commuter Agencies & Transit Authorities
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)
Manufactured Defect or 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)

**no responses for this category from this group of survey participants*



PLAN **PROFILE**

FIGURE 1. Service Examples of Rail Seat Deterioration

Suggesting Lateral Forces on a Curved Section of Track *(13)*

FIGURE 2. Service Example of Rail Seat Deterioration

Suggesting Loosened Fastening Components

FIGURE 3. Service Example of Rail Seat Deterioration

Suggesting Erosion of the Cement Paste *(5)*

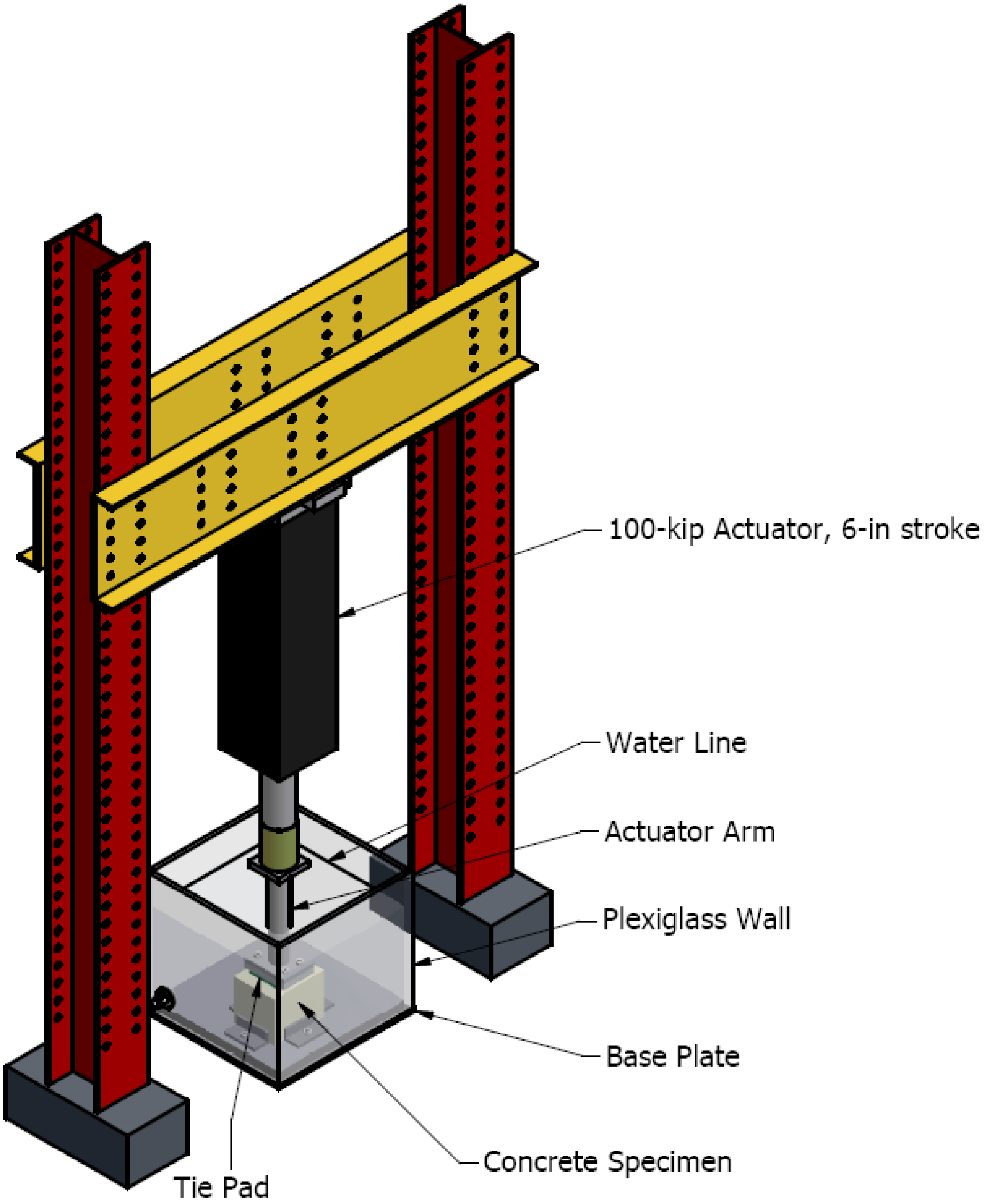


FIGURE 4. Test Setup with a Servo-hydraulic Actuator Loading a Concrete Block Specimen in a Water Tank

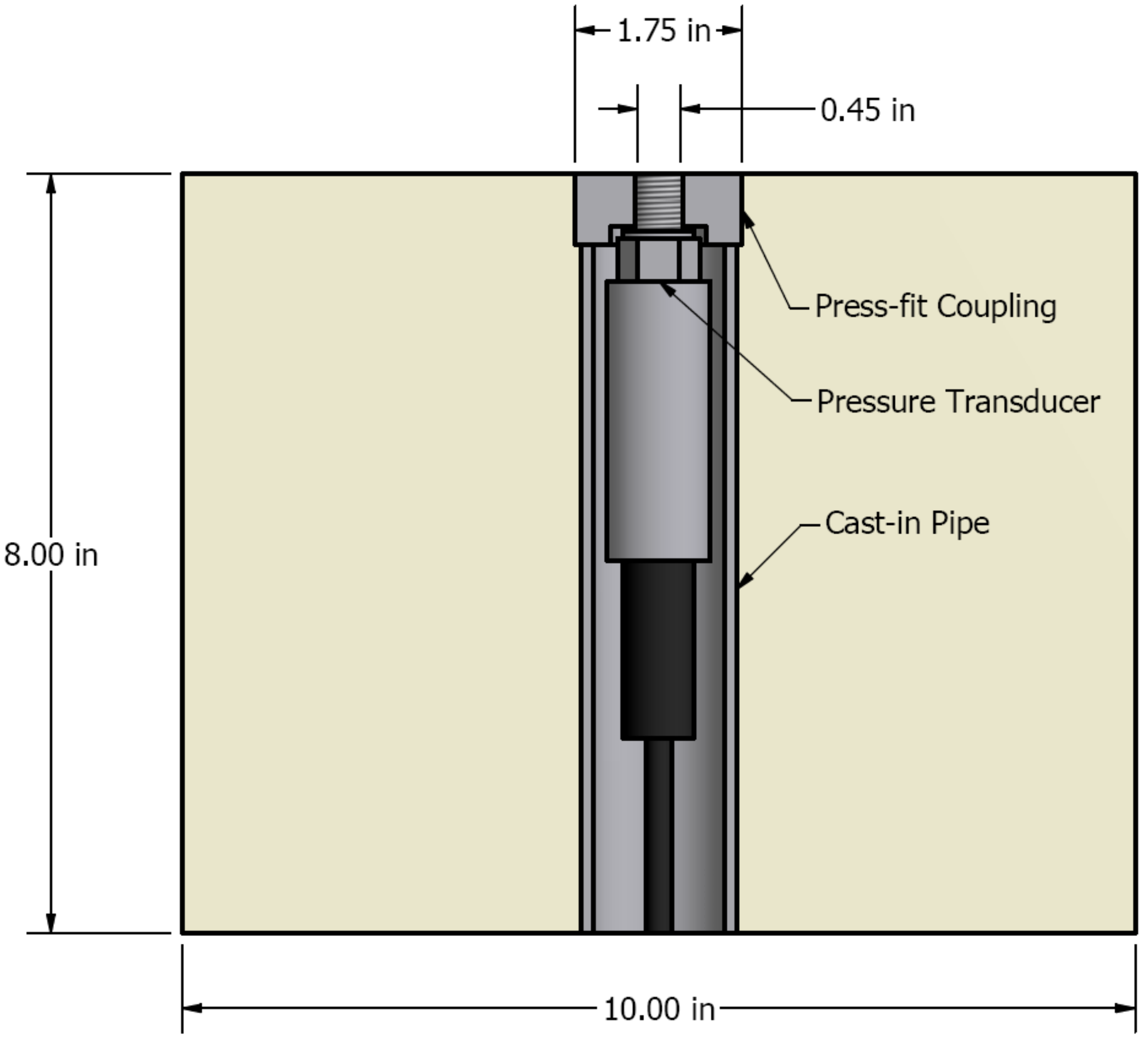


FIGURE 5. Profile View of a Cross-Section of a Concrete Specimen Instrumented with a Pressure Transducer

TABLES

FIGURES