Investigation of Potential Concrete Tie Rail Seat Deterioration Mechanisms: Cavitation Erosion and Hydraulic Pressure Cracking 10-2411

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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 mitigation and prevention. Past research and field experience with concrete ties identified five concrete deterioration mechanisms that may occur during RSD: abrasion, crushing, freeze-thaw cracking, cavitation erosion, and hydraulic pressure cracking. Currently, little empirical evidence exists to substantiate theories on cavitation erosion and hydraulic pressure cracking. A set of laboratory experiments has been developed to isolate cavitation erosion and hydraulic pressure cracking from the other potential mechanisms to challenge the theory that conditions exist in concrete tie track for these two mechanisms to contribute to RSD. We have instrumented submerged, unreinforced concrete specimens with a pressure transducer to measure the hydraulic pressure between the tie pad and the concrete rail seat during loading. Preliminary results relevant to hydraulic pressure cracking suggest that the magnitude of the applied load and the tie pad geometry significantly influence both the water pressure pulse magnitude and the pressure dissipation rate with subsequent load cycles. 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 currently 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 their service life and require unplanned maintenance. 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-tie track, 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.

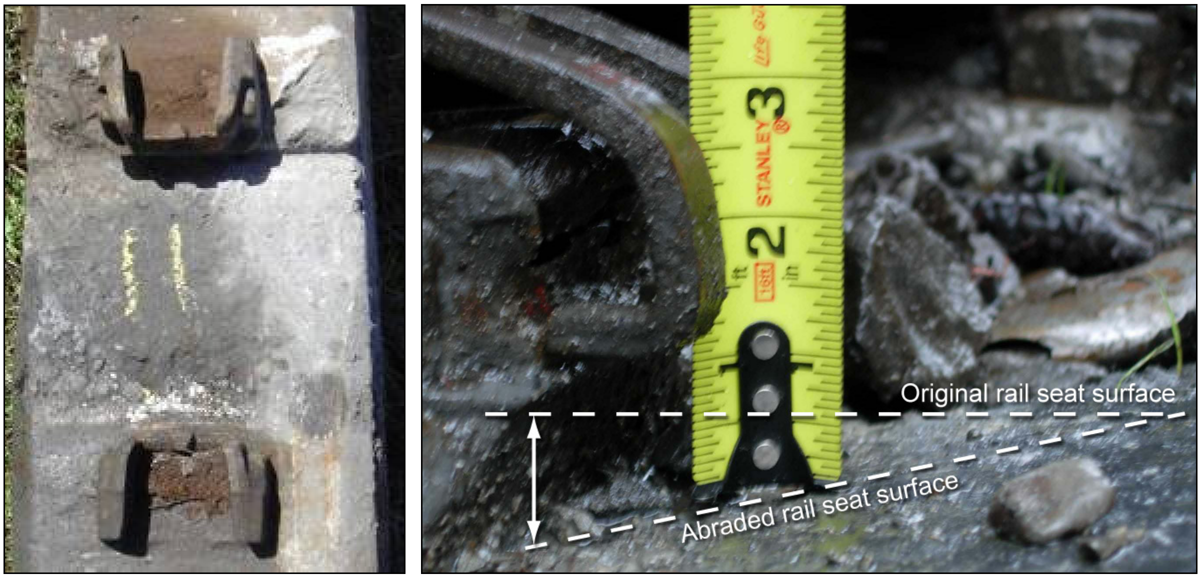
Working with researchers at the Transportation Technology Center Inc. (TTCI) and industry experts on a failure mode and effect analysis of concrete ties *(2)*, we developed a survey for North American railroads, commuter rail agencies, and transit authorities to obtain information about their experiences with concrete ties. Six major (Class I) railroads, two regional and shortline railroads, and four commuter rail agencies or transit authorities responded to the survey. The top two performance and maintenance problems with concrete ties for major freight railroads are rail seat deterioration (RSD) and fastener wear. We selected RSD for further investigation due to the survey results, 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 fastening assembly work together in concrete ties to hold the rails at proper cant and gauge. Cant is the tilt of the rails toward the track centerline that maintains the proper wheel-rail interface and directs the wheel loads through the web of the rail creating a stable system. Gauge is the distance between the inner sides of the heads of the rails that must be maintained (within tolerances) for the safe operation of trains. 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 full-scale field testing of concrete ties at TTCI's Facility for Accelerated Service Testing (FAST), heavy axle loads, abrasive fines, and moisture are the three primary factors that are present with significant RSD *(3)*.

The RSD wear patterns observed in track vary based on the specific climatic, traffic, and track geometry conditions. 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 due to 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 that has been eroded by the movement of water.



PLAN **PROFILE**

FIGURE 1. Service examples of rail seat deterioration suggesting lateral forces on a curved section of track *(4)*

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)*

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 *(6)*.

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. Systems are being developed that attempt to use track geometry car laser-based or machine vision-based inspection systems to identify RSD without disassembling the fastening system. 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 withstand more tonnage 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 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 Mechanisms

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 compressive 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 damaging 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 tie pad is accelerated by vertical rail motion. 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 pore water pressures. The study did not find microscopic evidence of cavitation erosion in the samples *(5).* Anecdotal evidence for cavitation erosion has been found in examples of worn rail seats such as the one documented by Peters and Mattson in Figure 3 *(7)* and a video recorded at TTCI's FAST showing bubbles forming at the edge of the tie pad during loading *(5)*. The bubbles may have been 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 *(6).*

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 two 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 of the potential concrete deterioration mechanisms.

Cavitation Erosion

Cavitation is a phase transition from liquid to vapor that occurs during a drop in the liquid's pressure to the vapor pressure at a given temperature. This process is sometimes referred to as "cold boiling" and is analogous to the phase transition from liquid to vapor that occurs due to an increase in temperature. The vapor bubbles that form are unstable, and when they burst against a surface, as much as tens of thousands of pounds per square inch (psi) of pressure can be released over very small areas, eroding the surface over time *(8)*.

Cavitation can have multiple causes, such as flow obstructions at dams, spillways, or turbine blades; ultrasonic vibrations (20 kHz or greater frequency) in fluids; water jet demolition of concrete surfaces; and sudden changes in flow in hydraulic systems, such as may be caused by a water hammer *(8, 9, 10)*. It is the water hammer example that is most like the rail seat cavitation theory that we are discussing. In each of the previous examples, the velocity of the fluid changes rapidly, causing the fluid pressure to change to maintain conservation of energy, and, under the right conditions, this can lead to cavitation *(8)*. Cavitation may occur when water trapped beneath the tie pad is accelerated by passing wheels vibrating the rails if the resulting water pressure reaches negative gauge pressures, or suction, on the order of the vapor pressure of water [0.36 psi absolute; -14.34 psi gauge (psig) at 70°F] *(11)*.

In concrete, cavitation tends to erode the weaker cement paste, exposing the coarse aggregate *(5)*. Although most examples of cavitation erosion of concrete result from continuous exposure to cavitating flows, it has been found that as little as two seconds of exposure to cavitation can lead to measurable damage *(9)*.

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 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 either.

Hydraulic Pressure Cracking

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. 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 explored 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 sample ties showing signs of RSD. 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 a portion of the tensile pore pressures in the horizontal direction. Concrete ties are prestressed so that the concrete is in compression 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 *(12)*. 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 the 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 *(13)*. AREMA recommends a minimum 28-day compressive strength of 7000 psi *(12)*. 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 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 *(14)*. 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) *(15)*. These models suggest that pore pressures near the surface might be in the magnitude of stresses that could lead to fatigue cracking if cycled, but that the water pressure may not be moving fast enough to penetrate deeply in the pore structure during one load cycle.

RAIL SEAT HYDRAULICS

A sudden change in flow in hydraulic systems, such as a system of pipes, is referred to as transient flow. The abrupt type of transient flow is referred to as a "water hammer." A water hammer is a pulse of pressure that is created by a sudden acceleration of flow that was originally in a steady state. In a system of pipes, this could be caused by suddenly opening or closing a valve *(10)*. Both the cavitation erosion and hydraulic pressure cracking theories rely on a water hammer, or pulse of water pressure, developing in the thin film of water between the tie pad and the concrete rail seat during a load cycle.

The rail seat, including the rail, the tie pad, fastening system, and concrete rail seat, can be considered a hydraulic system when it is saturated. There is some volume of water in the interface between the tie pad and the concrete. As wheels pass over a stationary point on a section of track, the rail is subjected to a vertical wave action that causes uplift of the rail ahead and behind a wheel and a downward deflection beneath the wheel *(16)*. The water will be pressurized by passing wheels in up to two different ways: the wheel load will generate a positive water hammer as the wheel passes directly above the rail seat, and, if the rail is not securely restrained in the vertical direction, the rail may lift under the rail car body, leading to a negative water hammer, or suction. If the rail is not restrained vertically to the rail seat by the fastening system (if the fastening system is loose or components are broken or missing), some relative motion will occur, allowing a gap to form between the rail and the tie pad and/or between the tie pad and the concrete rail seat.

Suction may be created during uplift depending on the upward acceleration, the amount of water present in the interface, and whether a seal is created between the pad and the concrete. As the wheel rolls over the rail seat and the gap closes, the water is accelerated and may develop a pulse of pressure or water hammer. Some water may then exit the interface out the sides, some may move into the concrete pores if the concrete is not fully saturated, or some water may remain filling the interface or wetting the surfaces. With each load cycle, the volume of water in the interface will most likely decrease until the next precipitation event, unless the rail seat is in a location with standing water as a result of poor drainage. The worst case for creating high water pressure will be a saturated interface that does not lose much water between load cycles, and where the rail is poorly restrained vertically and the tie pad adheres to the base of the rail, allowing vertical motion of the tie pad relative to the rail seat.

The first question to answer is whether the water pressure generated at the rail seat has the potential to damage the concrete. If the suction generated during uplift is on the order of -14.3 psig, then the water may be cavitating. If the pressure generated during a load application is enough to create tensile effective stress in the concrete near the surface of at least 400 psi, then the concrete may develop fatigue cracking with many cycles. Although the surface water pressure generated by a load is not the same as the concrete pore pressure, it is expected that the interfacial water pressure could be considered the maximum for the concrete pore pressure. This is assuming that the non-ideal, viscous conditions in the micro- and nano-scale concrete pores only reduce the input pressure, and do not amplify it. According to Pascal's Law in fluid mechanics, a fluid will apply the same normal pressure equally to all walls of its container, assuming the viscous effects are negligible *(11)*. However, the free water in hardened concrete is stored in capillary pores that range from 10 nanometers to 10 micrometers in size *(13)*. At this scale, the viscous effects in the fluid may be significant because of the nature of the flow in micro- or nano-channels and at low velocities *(11)*. This is why any pressure measured at the rail seat surface may not be the same pressure developed in the concrete pores. However, it is expected that, due to the low permeability of the concrete and the viscous fluid effects in the pores, the pore pressure will decrease with depth as the water hammer loses energy. For these reasons, it is assumed that the pressure measured is the maximum possible pressure that could be generated in the concrete pores.

LABORATORY TESTS

The University of Illinois at Urbana-Champaign (UIUC) has developed a laboratory setup to test the theory that positive and negative water hammers occur in a saturated rail seat during load cycles, causing cavitation erosion and hydraulic pressure cracking at the concrete surface. The test setup includes a laboratory concrete specimen that represents the rail seat, which is submerged in a water tank while being subjected to load cycles of varying magnitudes and frequencies. The load is applied normal to the concrete surface, to minimize any lateral friction that could lead to abrasion. The plate applies the load cycles 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. As discussed previously, these test conditions would be a worst-case scenario for cavitation erosion and hydraulic pressure cracking, where the concrete is saturated during loading, the fastener system is providing minimal restraint, and the tie pad is adhered to the base-of-rail. The concrete rail seat blocks were instrumented so that the surface water pressure can be measured during loading. Early testing suggested that the positive water hammer caused by applied load and the suction caused by uplift are effectively independent phenomena, so they are being evaluated with separate tests.

The load magnitudes were chosen assuming 286-kilopound (kip) cars, 1:40 rail cant, 0.52 lateral-to-vertical (L/V) load ratio, 28-inch tie spacing, and a 200% impact factor for high dynamic loads. The 0.52 L/V was based on the Bodycote accelerated RSD test, which is documented in AREMA Chapter 30, Part 2 *(12)*. 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 *(12)*. 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 three load frequencies of 0.5 Hertz (Hz), 2.0 Hz, and 4.0 Hz were selected to work within the oil flow limits of the actuator and the vibrations of the test frame. These load frequencies translate to effective track speeds of 2 miles-per-hour (mph), 17 mph, and 34 mph, respectively, based on the average axle spacing for a fifty-foot car, which is 12.5 feet.

To imitate the vertical wave deflection of the rail caused by passing wheels, a plate representing the base-of-rail is 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 *(16)*. For our tests, the maximum movement of the base-of-rail (including pad compression and uplift) is limited to 0.25".

The motion of the actuator is adjusted by selecting different waveforms and loading frequencies. A square waveform provides the maximum acceleration that can be achieved with the actuator. Similar to the square waveform, a trapezoidal waveform can be used to move the actuator at a slightly lower acceleration. Both the square and trapezoidal waveforms are applied at 0.5 Hz because their motion is independent of the time between cycles and this allows for each load application to be considered individually. A sinusoidal waveform can be used to apply cycles at a higher frequency, such as 2 Hz and 4 Hz, and this more closely approximates the motion of the base-of-rail under passing wheels. The sinusoidal acceleration and velocity are functions of the loading frequency, and they are slower than the motion of the other waveforms. The actual acceleration of the actuator under these different waveforms will be measured and compared with the typical motion of the rail.

Materials

Figure 4 shows both a drawing and a photo 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 *(5)*. The mix used in this study had an average 28-day strength over 8,000 psi. As illustrated in Figure 4, specimens are placed in a tank with up to six inches of water above the top of the specimen. The bottom of the water tank is a thick steel plate, while the walls are transparent plexiglass. The specimen is positioned directly below an actuator that applies 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 is placed beneath this "base-of-rail" plate and acts as the contact surface against the concrete. For the uplift tests, the tie pad is adhered to the base-of-rail plate with epoxy to ensure that relative motion occurs between the pad and the concrete.

The initial five tie pads considered in our experiment are: dimpled polyurethane, flat polyurethane, grooved polyurethane, dimpled ethyl-vinyl acetate (EVA), and dimpled santoprene. It is expected that the surface geometry and the pad material will influence both the magnitude of the water pressure at a certain load and how much water is expelled from the pad-concrete interface with each load cycle. Comparing the indented geometries with the flat pad, the dimpled pads have a 28% reduction in surface area and introduce 0.27 in^3 of dimples per surface, while the grooved pads have a 22% reduction in surface area and introduce 1.12 in^3 of grooves per surface.

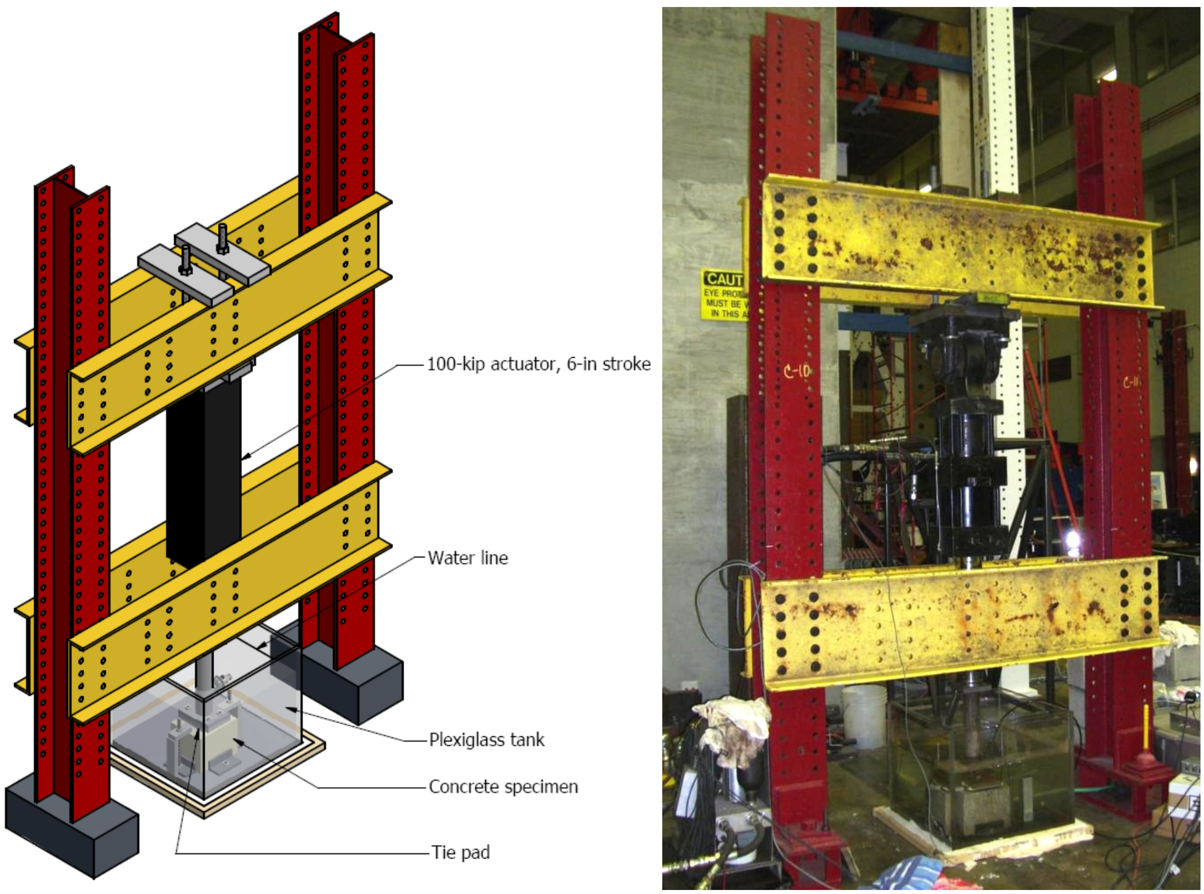


FIGURE 4. Test setup with a servo-hydraulic actuator loading a concrete block specimen in a water tank

Submersible pressure transducers are used to measure the water hammer action at the pad-concrete interface. The load tests require a transducer that can withstand at least 2,000 psig without being damaged, while the uplift tests require a low-range transducer that can measure suction. 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 was inserted a stainless steel coupling that the transducer threads into, situating the transducer orifice at the rail seat surface. This configuration is illustrated in Figure 5 and allows for removal and reuse of the pressure transducers.

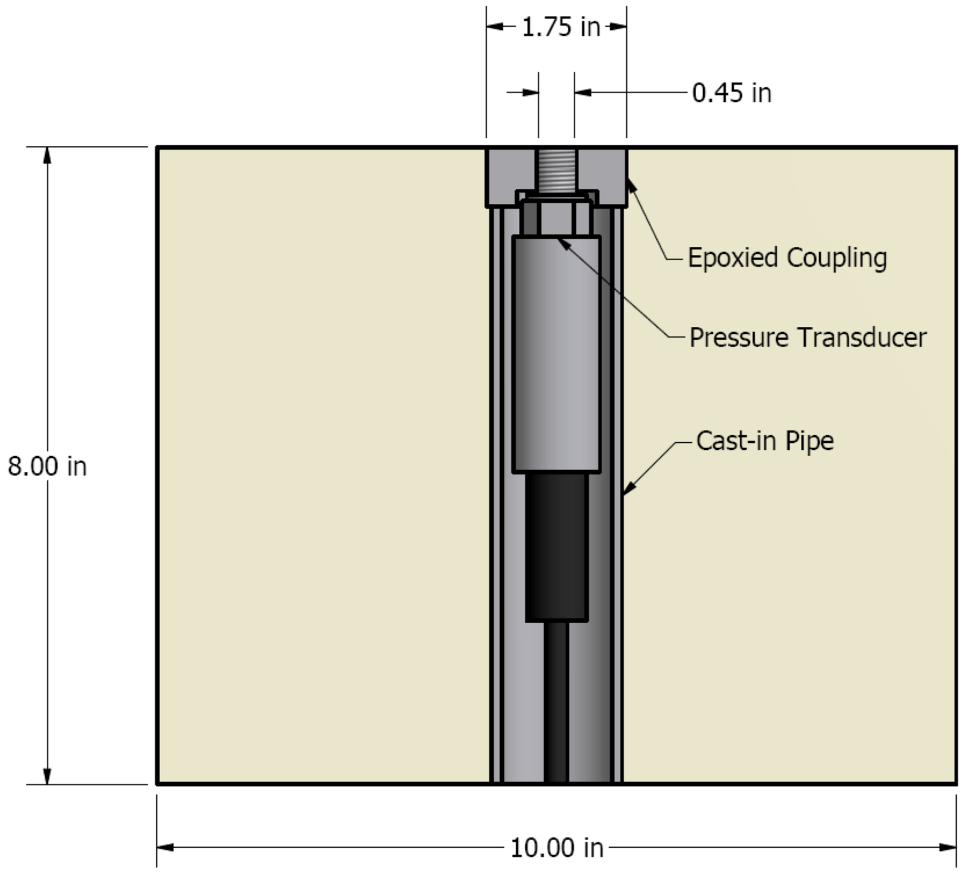


FIGURE 5. Profile view of a cross-section of a concrete specimen instrumented with a pressure transducer

Load Test Procedure

The objective of the load tests is to identify which parameters in the rail seat system create the greatest positive water pressure. The actuator was controlled by specifying the applied load, loading from a minimum of 5 kips (which is similar to the toe load applied by elastic fasteners) up to a maximum load of 20, 40, or 60 kips. The load magnitude, frequency, and waveform are specified for many different test conditions. The water level was varied from a thin film of water on the surface of the concrete to 3 inches and 6 inches above the surface, respectively. Different tie pads were tested, and the alignment of the pad indentations with the pressure transducer was controlled because it was found that the pressure was a function of the indentation alignment. Some modified pad geometries were also tested, where channels were cut to provide paths for the water to escape in one case, the indentation above the transducer was filled in another, and all indentations but the one above the transducer were filled in a third. Each test was run more than once to provide at least one replication.

Uplift Test Procedure

The objective of the uplift tests is to identify which parameters in the rail seat system create the greatest suction. The actuator is controlled by specifying its position, so that the tie pad can be lifted off the concrete. The displacement above the concrete (uplift), displacement into the concrete (compression), frequency of motion, and waveform are specified for many different test conditions. The water level will be varied as with the load tests. Different tie pads will be tested, but the alignment will not be controlled because the relative motion between the pad and the concrete prevents it from holding an alignment within an eighth of an inch. Each test will be run more than once to provide at least one replication.

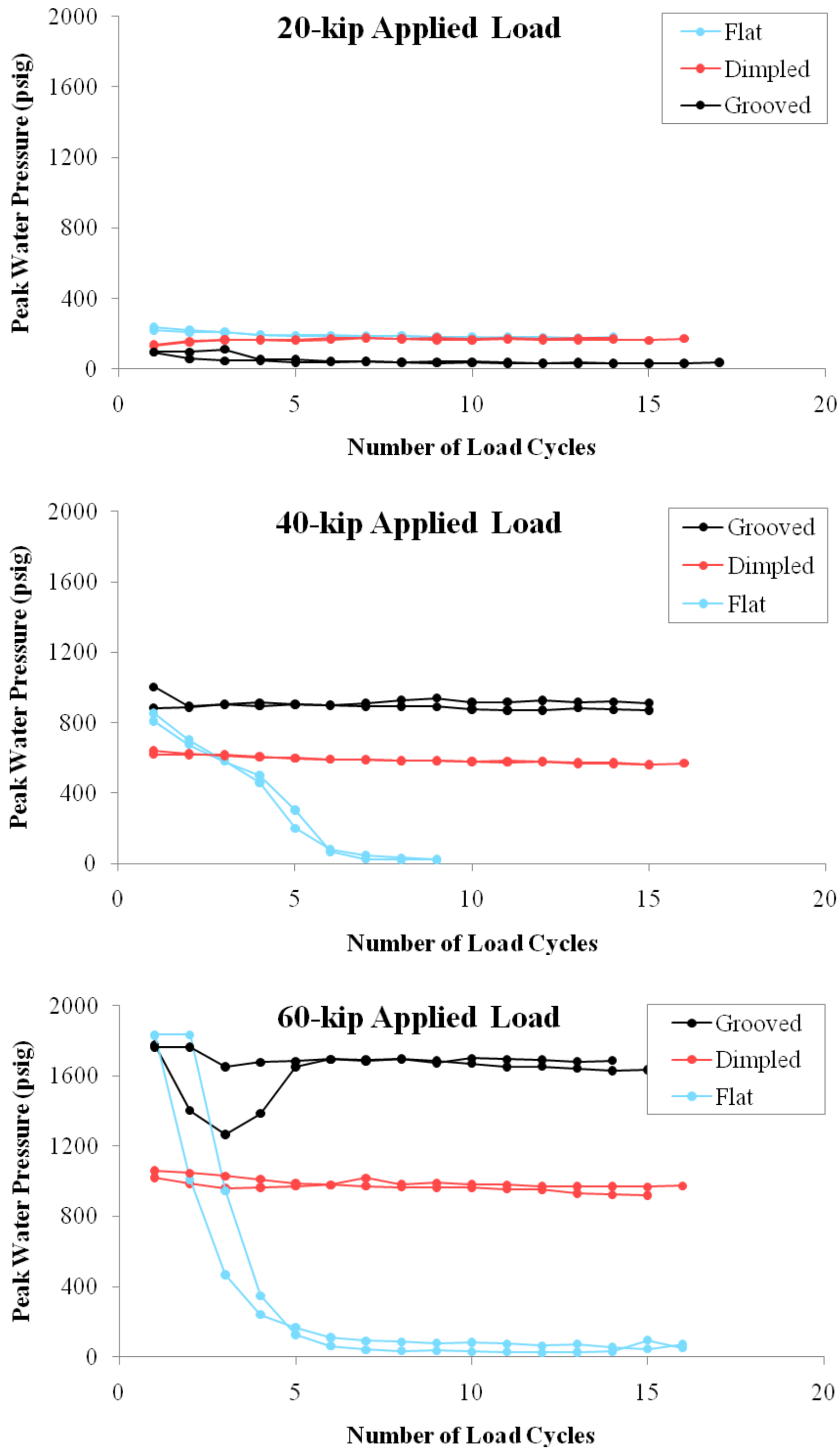


FIGURE 6. Results of load tests on three different polyurethane pads using square waveform and 6-inch water level

Preliminary Results

The preliminary results from one set of load tests are summarized in Figure 6. In this set of tests, the load was applied with a square wave, and the water level was 6 inches above the top of the rail seat. The data plotted in these graphs come from two trials for each test, and each test was run for 15 to 20 load cycles.

Comparing the three graphs with increasing applied load, it is evident that the load magnitude strongly influences the peak water pressure magnitude. Another observation is that both the water pressure magnitude and dissipation with further load cycles varies significantly among the three polyurethane pads tested, and is visible in the 40-kip and 60-kip graphs. The flat pad developed high maximum peak pressure, but this pressure quickly dissipated to an insignificant magnitude within 10 load cycles. By contrast, the grooved and dimpled pads exhibited very slow pressure dissipation or none at all. This suggests that the indented pads may be able to hold water under load and continue to generate significant peak pressures for a number of load cycles (at least 15). Considering that a 100-car train may apply over 400 load cycles to the rail seat, these preliminary results suggest that the indented pads have the potential to apply more high water pressure pulses to the concrete than the flat pad, which may only apply a handful of these pulses. It remains to be determined whether these pressure pulses are damaging to the concrete, and that question will be explored in subsequent research.

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 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. Preliminary results from load tests suggest that the magnitude of the applied load and the tie pad geometry significantly influence both the water pressure pulse magnitude and the pressure dissipation rate with subsequent load cycles. Testing will continue in order to understand what combination of parameters creates the worst cases for both load pressure and uplift pressure. The maximum pressures and the conditions under which they are generated will be analyzed to determine whether concrete damage due to hydraulic action is possible in a concrete tie rail seat. 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-efficient solutions for the most demanding heavy haul conditions if problems such as RSD can be managed.

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REFERENCES

(1) Jimenez, R., J. LoPresti, "Performance of Alternative Tie Material under Heavy-Axle-Load Traffic," *Railway Track & Structures*, Jan 2004, v 100, no. 1, pp. 16-18.

(2) Zeman, J.C., J.R. Edwards, C.P.L. Barkan, D.A. Lange, "Failure Mode and Effect Analysis of Concrete Ties in North America," *Proc. of the 9th International Heavy Haul Conference*, Shanghai, China, June 2009.

(3) Reiff, R., "An Evaluation of Remediation Technologies for Concrete Tie Rail Seat Abrasion in the FAST Environment," *American Railway Engineering Association Bulletin*, v 96, no. 753, Dec 1995, pp. 406-418.

(4) National Transportation Safety Board, Railroad Accident Brief, Accident No. DCA-05-FR-010 (NTSB/RAB-06/03), October 18, 2006.

(5) Bakharev, T., *Microstructural Features of Railseat Deterioration in Concrete Railroad Ties,* M.S. Thesis, University of Illinois at Urbana-Champaign, Urbana, Illinois, 1994, pp. 1-28 and 68-97.

(6) Choros, J., B. Marquis, M. Coltman, "Prevention of Derailments due to Concrete Tie Rail Seat Deterioration," *Proc. of ASME/IEEE Joint Rail Conference and the ASME Internal Combustion Engine Division, Spring Technical Conference 2007*, pp. 173-181.

(7) Peters, N., S.Mattson, "CN 60E Concrete Tie Development," *AREMA Conference Proc. 2004*, American Railway Engineering and Maintenance-of-Way Association (AREMA), Landover, Maryland.

(8) Franc, J.-P., J.-M. Michel, *Fundamentals of Cavitation*, Fluid Mechanics and Its Applications Series, v 76, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2004, ch. 1, pp. 1-14.

(9) Momber, A.W., "Short-Time Cavitation Erosion of Concrete," *Wear*, 2000, v 241, pp. 47-52.

(10) Haestad Methods, T.M. Walski, D.V. Chase, D.A. Savic, W. Grayman, S. Beckwith, E. Koelle, *Advanced Water Distribution Modeling and Management*, 1st ed., Haestad Press, Waterbury, Connecticut, 2003, ch. 13, pp. 573-623.

(11) Munson, B.R, D.F. Young, T.H. Okiishi, *Fundamentals of Fluid Mechanics*, 5th ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2006, ch. 2, 8, and 9 and Appendix B, pp. 39, 402-407, 489-492, 761.

(12) *AREMA Manual for Railway Engineering*, American Railway Engineering and Maintenance-of-Way Association (AREMA), Landover, Maryland, 2009, v 1, ch. 30, parts 2 and 4.

(13) Mindess, S., J.F. Young, D. Darwin, *Concrete*, 2nd ed., Pearson Education Inc., Upper Saddle River, New Jersey, 2003, ch. 4 and 13, pp. 68-76 and 342-344.

(14) Kutay, M.E., A.H. Aydilek, "Dynamic Effects of Moisture Transport in Asphalt Concrete," *Journal of Transportation Engineering*, American Society of Civil Engineers, July 2007, v 133, no. 7, pp. 406-414.

(15) Kettil, P., G. Engstrom, N.-E. Wiberg, "Coupled Hydro-Mechanical Wave Propagation in Road Structures," *Computers and Structures*, 2005, v 83, pp. 1719-1729.

(16) Hay, W.W., *Railroad Engineering*, 2nd ed., John Wiley & Sons, Inc, New York City, New York, 1982, ch. 15, pp. 239-273.