Proceedings of the 2012 Joint Rail Conference
JRC2012
April 17-19, 2012, Philadelphia, Pennsylvania, USA

JRC2012-74092

MEASURING CONCRETE CROSSTIE RAIL SEAT PRESSURE DISTRIBUTION WITH MATRIX BASED TACTILE SURFACE SENSORS

Christopher T. Rapp
Univ. of Illinois at
Urbana-Champaign
Dept. of Civil and
Environ. Engineering
205 N Mathews Ave, Urbana, IL 61801
ctrapp3@illinois.edu

J. Riley Edwards
Univ. of Illinois at
Urbana-Champaign
Dept. of Civil and
Environ. Engineering
205 N Mathews Ave, Urbana, IL 61801
jedward2@illinois.edu

Marcus S. Dersch
Univ. of Illinois at
Urbana-Champaign
Dept. of Civil and
Environ. Engineering
205 N Mathews Ave, Urbana, IL 61801
mdersch2@illinois.edu

Christopher P.L. Barkan
Univ. of Illinois at
Urbana-Champaign
Dept. of Civil and
Environ. Engineering
205 N Mathews Ave, Urbana, IL 61801
cbarkan@illinois.edu

Jose Mediavilla
Amsted RPS
8400 W 110th St, Suite 300
Overland Park, KS 66210
jmediavilla@amstedrps.com

Brent M. Wilson
Amsted Rail
1700 Walnut St
Granite City, IL 62040
bwilson@amstedrail.com

ABSTRACT

A sustained increase in gross rail loads and cumulative freight tonnages, as well as increased interest in high and higher-speed passenger rail development in the United States, is placing an increasing demand on railway infrastructure. According to a railway industry survey conducted by the University of Illinois at Urbana-Champaign (UIUC), rail seat deterioration (RSD) was identified as one of the primary factors limiting concrete crosstie service life. Therefore, it can be seen that there is a need for infrastructure components with increased strength, durability, and ability to maintain the tighter geometric track tolerances under demanding loading conditions. Researchers have hypothesized that localized crushing of the concrete rail seat is one of five potential mechanisms that contribute to RSD. Therefore, to better understand this mechanism, UIUC is utilizing a matrix based tactile surface sensor (MBTSS) to quantify the forces acting at the interface between the bottom of the rail pad and the concrete tie rail seat. The MBTSS measures the forces and distribution of pressure as a load is applied to the rail seat. Preliminary laboratory testing has shown that higher modulus rail pads distribute forces poorer than lower modulus rail pads, leading to localized areas with high contact pressure and a higher probability of crushing. Testing has also shown that as the lateral/vertical (L/V) force ratio increases, the pressure on the field side of the rail seat also increases, possibly accelerating RSD. The objective of future field testing is to be able to validate the assumptions made from this preliminary

laboratory data. Data collected and analyzed throughout this research project will provide valuable insight into developing future concrete crosstie and fastening system component designs that meet the operational and loading demands of high speed rail and joint passenger/freight corridors.

INTRODUCTION

Concrete crossties are considered to be most necessary and economical in conditions that place high demands on the railroad track structure. They were developed in response to the inability of timber crossties to perform as designed in certain severe service conditions, such as areas of high curvature, heavy axle load traffic, high annual gross tonnages, and steep grades (1). The cast-in shoulders and molded rail seat of concrete crossties increase their ability to hold gage under these loading conditions (1).

Concrete crossties are not without their design and performance challenges. In a survey issued to North American Class I Railroads, rail seat deterioration (RSD) was ranked as the most critical problem with concrete crossties (2). Problems that arise from the deterioration of the concrete rail seat surface include widening of gauge, reduction in toe load of fastening clips, and insufficient rail cant (2). All of these problems have the potential to create unsafe operating conditions and a heightened risk of derailment. A suspected cause of RSD is high forces acting on the concrete rail seat surface, often in concentrated areas.

In North America, concrete crosstie track is often much stiffer than the more commonly used timber track, especially in areas where the aforementioned operational conditions are not present. A stiffer track structure results in less resiliency in response to impact loads, causing higher loads to be imparted onto the concrete rail seat surface. To better understand the forces acting at this surface, researchers at the University of Illinois at Urbana-Champaign (UIUC) are using matrix based tactile surface sensors (MBTSS) as a means to measure load magnitude and distribution. MBTSS have been used previously in experimentation on timber crossties, however, researchers at UIUC using this technology to explore the pressure distribution on the rail seats of concrete crossties.

There are many factors present that affect this pressure distribution, one of which is the transfer of forces at the wheel/rail interface. As the load is transferred from the wheel to the rail, it moves through the web of the rail and into the base of the rail. Next, the load is distributed through the rail pad onto the rail seat of the crosstie. The profile of the wheel (e.g. wear pattern), which partially governs the angle of the resultant force of the load, can cause great variation in what areas of the rail seat are receiving concentrated loadings as the load passes through the base of the rail. The L/V ratio of this resultant force also varies greatly depending on track geometry conditions. Horizontal curvature can greatly increase the lateral forces due to flanging forces of wheels. Trains travelling at speeds above or below the balancing speed of a curve can cause shifts in the vertical and lateral load to the high or low rail, respectively. These loading scenarios are especially likely on shared corridors, where both freight and passenger trains run on the same track at different speeds. Shared corridors present the diverging engineering requirements for track that can accommodate the heavy axle loads of slower speed freight trains with the lighter loads of higher speed passenger trains.

Design of the fastening system components also plays a crucial role in the distribution of pressure in the rail seat. Given the stiff nature of concrete crosstie track, the fastening system must provide some of the resiliency necessary to attenuate high axle loads without damaging the concrete surface (3). These variables in the distribution of pressure in concrete rail seat are further explored in this paper and addressed through laboratory experimentation.

SENSOR TECHNOLOGY AND PROTECTION

The sensor technology currently being employed for quantifying forces and pressure distribution at the rail seat for this research effort are MBTSS manufactured by Tekscan® Inc. The MBTSS is comprised of two thin sheets of polyester with a total thickness of 0.004 inches (0.01 cm) (Figure 1). On one of the sheets, a pressure sensitive semi-conductive material is printed in rows. On the other sheet, the same semi-conductive material is printed in columns, which form a grid when overlaid. Conductive silver leads extend from each column and row to the area of the sensor from which data is collected. Glue is applied around the edges so as to bond the two sheets together and avoid the intrusion of foreign materials or moisture into the pressure sensing area.

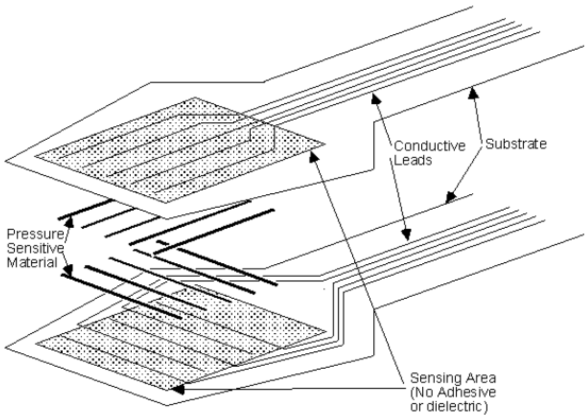


FIGURE 1. EXPLODED VIEW OF A TEKSCAN® SENSOR (4)

The behavior of these sensors is similar to that of a resistive transducer (e.g. strain gauges). That is, as a force is applied to the pressure sensitive area, the resistivity in the overlain circuits changes and the output is collected by the Data Acquisition Handle (DAH), which connects the sensor to a computer via USB cable. The intersection of each printed row and column creates a sensing location, which represents one cell of data output to the computer software. The number of sensing locations is dependent upon the number of rows and columns in the matrix. For example, the Tekscan® sensor model/map 5250, currently being used by UIUC researchers, is comprised of 44 rows and 44 columns, creating 1936 pressure sensing locations (5). For this model, each row and column has a width of 0.22 inches (0.56 cm), thus each sensing location has an area of 0.0484 in^2 (0.31 cm^2) (5). This creates a resolution of approximately 21 sensing locations per square inch (3.23 per cm^2). The computer software is able to output the contact area of an imparted load by multiplying the number of sensing locations receiving force by the area of each.

The concrete rail seat can be a coarse and uneven surface, often due to the steel forms and other aspects of the long-line manufacturing process of concrete crossties. Abrasive fines consisting of cement particles and aggregate from the deteriorated concrete surface, sand or other fines from the surrounding environment, and metal filings from the rail or cast-in iron shoulders are often present even in well maintained track. Given the sensor's sensitive nature and susceptibility to being punctured or damaged by irregular surfaces, it is important to provide protection for the sensing surface. Any puncture or physical interference to the sensor can cause permanent damage and erroneous data collection. To protect from puncture damage a thin polyester film (Mylar) approximately 0.007 inches (0.02 cm) thick is placed on each side of the sensor when installed on a rail seat (Figure 2). Because loads are rarely applied purely perpendicular (vertical) to the rail seat, there can also be shear forces occurring at this interface from lateral loads. To protect the sensor from these shear forces, thin sheets of Teflon are also layered on either side between the sensor and the Mylar (Figure 2). Teflon's low coefficient of friction makes it an appropriate choice to mitigate excessive lateral loads or frictional forces from longitudinal stress in the rail.

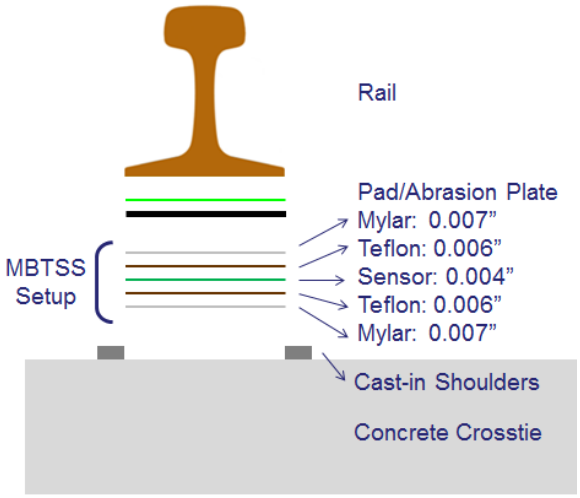


FIGURE 2. MBTSS LAYERS AND THICKNESSES

DATA ACQUISITION

Initially, the data are not given in a unit of force, but rather are output in a value called a "raw sum unit". The sensors, having an 8-bit output, measure force on a scale of 0-255, with a value of 255 indicating that a sensor is fully saturated at that location and cannot measure any increase in load. To obtain useable engineering units from the raw sum units, a calibration file must be applied. Calibration of MBTSS is conducted by applying known loads and correlating the loads with the respective raw sum units. This process places an emphasis on the importance of laboratory testing and familiarization with the technology prior to performing field testing.

PREVIOUS RAIL SEAT INSTRUMENTATION

Previous research has been conducted using the sensors produced by Tekscan® to analyze loads at the tie plate and timber crosstie interface (4). This work was conducted by the University of Kentucky (UK) to develop a non-intrusive and non-invasive means to measure the forces and pressures imparted into the timber crosstie (4). UK researchers first experimented with calibration tests in laboratory settings, and then performed initial field tests on timber crossties. It was determined from field data that there was an uneven distribution of pressure given the rigid surfaces interacting at this interface. Moreover, there were several high contact points present that bore most of the load. It was also determined that the sensors needed protection from puncture and shear forces, as discussed previously in this paper. Tests to evaluate the variability of plate material on pressure distribution were then performed, using machined steel, polyurethane, rubber pads, and plates (4). From these tests it was concluded that machined steel plates continued to create points of peak pressure, whereas the presence of a softer material at this interface, such as rubber or polyurethane plastic, increases contact area resulting in more evenly distributed forces and lower contact pressures.

UK's research confirmed the feasibility of using MBTSS to measure pressures at the timber tie rail seat surface in both the laboratory and the field. However, since the research was conducted solely on timber crossties, further validation was needed to determine MBTSS' viability for concrete crosstie rail seat pressure measurement. Researchers at UIUC are expanding the use of this technology to analyze the loads imparted on the concrete rail seats, and to provide future design recommendations to mitigate issues such as RSD.

EXPERIMENTAL SETUP

Full-scale concrete crosstie and fastening system testing is currently performed at UIUC's Advanced Transportation Research and Engineering Laboratory (ATREL). A pulsating load testing machine (PLTM) is used to perform the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6: Wear and Abrasion, as well as other experimental testing related to concrete crossties and fastening systems. The loading conditions for AREMA Test 6 are meant to simulate severe service conditions, like those experienced on horizontal curves greater than 5 degrees (6). The PLTM consists of one horizontal and two vertical actuators, both attached to a steel loading head that encapsulates a short section of rail attached to one of the two rail seats on a concrete crosstie. This setup allows a load to be applied to simulate those imparted by actual train wheels. The benefit of this actuator arrangement is the ability to vary the lateral to L/V ratio without changing the physical arrangement of the actuators, loading frame, or concrete crosstie. Using MTS MultiPurpose TestWare® (MPT) allows for the creation of a wide variety of test procedures in an attempt to simulate various field conditions. UIUC testing included installing a MBTSS in the concrete crosstie fastening system and loading the tie using the PLTM (Figure 3). The same MBTSS was used throughout each respective experiment to remove the possibility of sensor variability.

FIGURE 3. MBTSS INSTRUMENTATION AT UIUC

RESULTS OF PRELIMINARY EXPERIMENTATION

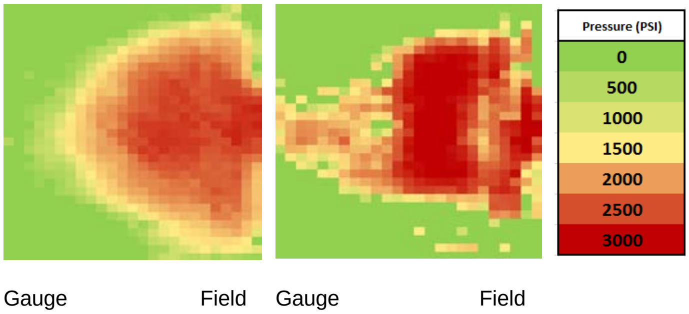
Several preliminary experiments have been performed at UIUC to collect data on the distribution of pressure on the concrete crosstie rail seat based highly on theoretical loading conditions at this interface. It should be noted that the experimental setup is not meant to replicate the common loading conditions seen in the field, but rather simulate the common atypical damaging load conditions that occur in the field. Therefore, this experimental setup simulates a single wheel load imparted onto a single crosstie. These tests were conducted to analyze and quantify the loading behavior at this interface depending on a variety of inputs. The first series of tests was performed to determine a relationship between the rail pad modulus (a proxy for stiffness) and pressure distribution at the rail seat. Additionally, various L/V ratios were explored in an attempt to simulate a variety of rail vehicle and track interaction conditions that could occur at the wheel/rail interface. The overall objective of this testing was to determine a relationship between L/V ratio and pressure distribution at the rail seat. The following sections present the testing protocol and results from the aforementioned preliminary experiments.

RAIL PAD MODULUS

Concrete crosstie fastening systems typically include a single or multi-layer rail pad assembly. Part of this assembly includes a rubber or polyurethane rail pad to attenuate the load and provide protection for the concrete rail seat (1). When viewed as a single structural element consisting of the subballast, ballast, crosstie, fastening system, and rail, concrete crosstie track in North America is often more rigid than the traditional timber track. Because of this, concrete crossties can impart higher stresses onto the ballast layer under train loading. An important purpose of the rail pad as an individual element is to provide increased resiliency for the concrete crossties. The increased resiliency provides the advantages of increased comfort for passengers and protection of the rolling stock (7). Rail pads are manufactured from a variety of materials and cast into different geometries, which in turn govern the rail pad modulus. Rail pad modulus is a value that defines the stiffness of the material.

Part of the research being conducted at UIUC is investigating the effect of the rail pad's modulus (stiffness) on mitigating high loads imparted on the rail seat while also protecting the concrete rail seat. Researchers at the UIUC are exploring the possibility that a rail pad of a lower modulus (i.e. a softer rail pad) will distribute the applied load over a wider area of the concrete rail seat. Although a softer rail pad may better mitigate high impact loads, its high resiliency allows for greater rail deflection, increasing wear and fatigue of other components of the fastening system (1). In the aforementioned survey of North American Class I railroads, shoulder/fastener wear or fatigue ranked second behind RSD as the second most critical concrete tie problem (2). Also being explored is the possibility that a rail pad with higher modulus (i.e. a stiffer rail pad) will help reduce the stress on the fastening system as a whole, but places a higher concentration of load on the concrete rail seat surface.

An experiment was performed to compare the pressure distribution of a high modulus polyurethane rail pad with that of a low modulus santoprene rail pad. The rail pads used were provided by Amsted RPS, and were cast with a flat surface specifically for this experiment to remove variation in pad geometry. Loading conditions were consistent for both tests, having a vertical load of 32,500 lb (144.56 kN) and a lateral load of 16,900 lb (75.17 kN), simulating an L/V ratio of 0.52. To compare the relative performances of the two rail pads, the maximum loaded frame for each pad showing the gauge and field sides was obtained (Figure 4, Table 1).



LOW MODULUS SANTOPRENE

HIGH MODULUS POLYURETHANE

FIGURE 4. COMPARING DIFFERENT RAIL PAD MODULI

TABLE 1. RESULTS OF RAIL PAD MODULUS TEST

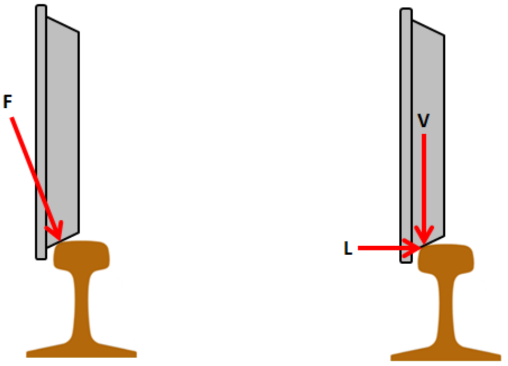
	Low Modulus Santoprene	High Modulus Polyurethane
L/V Ratio	0.52	0.52
Vertical, kips kN	32.5 (144.56)	32.5 (144.56)
Lateral, kips kN	16.9 (75.17)	16.9 (75.17)
Contact Area, in^2 cm^2	25.94 (167.35)	20.52 (132.39)
% of Rail Seat	69	55
Peak Pressure, psi kN/cm^2	2,631 (1.81)	3,563 (2.46)

This experiment shows that the high modulus polyurethane rail pad distributed the same applied load over a notably smaller area of the rail seat than the low modulus santoprene rail pad. The contact area of the load for the high modulus polyurethane rail pad was 20.52 in^2 (132.39 cm^2), which is only 79% of the 25.94 in^2 (242.00 cm^2) of contact area recorded for the low modulus santoprene rail pad. This reduced the total percentage of rail seat area being loaded from approximately 69% to 55%. Peak pressures for this rail pad were measured at 3,563 psi (2.46 kN/cm^2) with the possibility of higher values that were not able to be collected.

The fact that possible higher values may not have been collected is due to the fact that many of the cells were at maximum saturation level, meaning that even higher peak pressure values may have been present within that area. This 3,563 psi (2.46 kN/cm^2) is approximately 35% greater than the peak pressure of 2,631 psi (1.81 kN/cm^2) recorded for the santoprene rail pad, despite distributing the load over 14% less of the rail seat surface. From this experiment it can be inferred that a direct relationship exists between a high rail pad modulus and concentrated loading of the rail seat. It is also important to note that a highly concentrated loading of the rail seat areas of track with high axle loads could lead to crushing of the concrete surface.

L/V RATIOS

The distribution of pressure could also be affected by the angle of the resultant force that transfers the load from the wheel to the head of the rail. The angle of the resultant force can vary greatly based on both the wear conditions of the rail and the wheels. This resultant force can be broken into lateral and vertical components to allow for a more detailed analysis of the wheel/rail interface (Figure 5).



RESULTANT FORCE OF WHEEL LOAD

L/V COMPONENTS OF RESULTANT FORCE

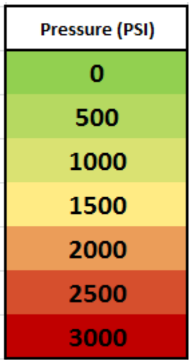
FIGURE 5. FORCES AT WHEEL/RAIL INTERFACE

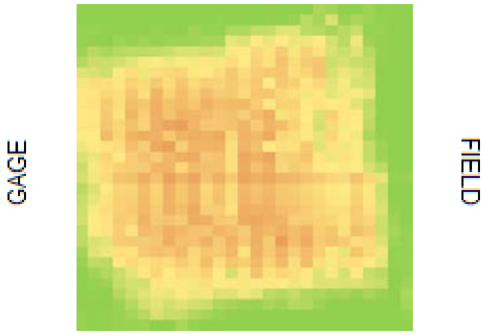
There are many variables that can affect the L/V ratio, including the curve radius, wheel/rail interface profiles, suspension characteristics of railcar trucks, and train speed (9). It is possible for trains to operate above or below balancing speed on sections of curved, superelevated track. At times, freight trains operate below the balancing speed for a particular curve, shifting the highest loads toward the inside of the curve. This is known as an overbalanced condition, where the center of mass of each car is inside of the equilibrium point, causing the car to lean towards the low rail. In this scenario, the low rail seat of a crosstie will be experiencing a much higher load than the high rail seat due to the shift of the vertical load (8). If a train is operating in an underbalanced condition, where the center of mass of each car is outside of the equilibrium point, loads will also not be evenly distributed, and will concentrate to the field side.

Researchers at UIUC are researching the possibility that a high L/V ratio places an excessive amount of strain on the fastening system components. This could greatly affect the system's structural integrity and its ability to remain an elastic, load-absorbing element in the especially stiff structure that is concrete crosstie track. A high L/V ratio increases the risk of rail rollover scenarios, which can lead to a derailment (9). To gain a better understanding of the distribution of pressure at this interface, an experiment was performed to test four different L/V ratios (Figure 6, Table 2). Since the L/V ratio of 0.52 is the standard used in the AREMA Test 6 to simulate severe service conditions, it was chosen as one of the values to test (6). Two lower values of 0.25 and 0.44 were chosen to simulate curvature of a lower degree and possibly a tangent track condition. A higher value of 0.60 was also chosen to collect data for a more extreme condition with very high lateral forces. This test was originally performed using a vertical load of 32,500 lb (144.56 kN) along with the given lateral load for each respective L/V ratio. However, during this test the L/V ratio of 0.60 triggered the lateral safety displacement limit set on the PLTM. The peak load was not safely achievable due to the excessive deflection in the system and therefore, it was decided to present a loading sequence utilizing a maximum vertical load of 26,000 lb (115.65 kN).

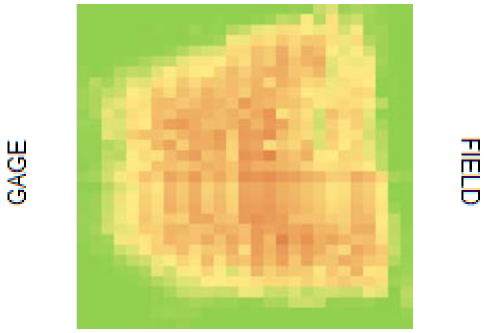
TABLE 2. RESULTS OF VARYING THE L/V RATIO

L/V Ratio	0.25	0.44	0.52	0.60
Vertical, kips (kN)	26 (115.65)	26 (115.65)	26 (115.65)	26 (115.65)
Lateral, kips (kN)	6.5 (28.91)	11.4 (50.71)	13.5 (60.05)	15.6 (69.39)
Contact Area, in^2 (cm^2)	33.98 (219.23)	32.23 (207.94)	28.17 (181.74)	21.78 (140.52)
% of Rail Seat	84	80	70	54
Peak Pressure, psi (kN/ cm^2)	1,477 (1.02)	1,694 (1.17)	2,085 (1.44)	2,498 (1.72)

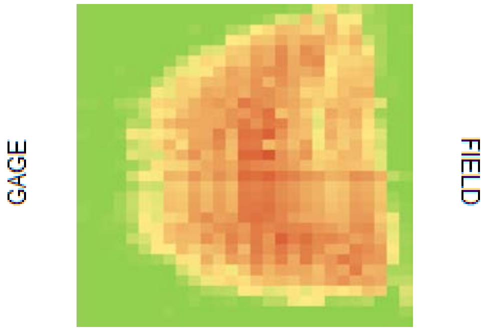




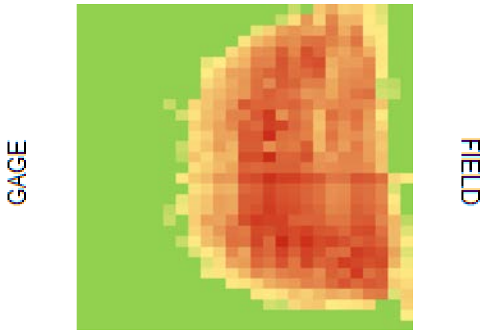
0.25 L/V RATIO



0.44 L/V RATIO



0.52 L/V RATIO



0.60 L/V RATIO

FIGURE 6. COMPARING VARIOUS L/V RATIOS

It can be seen from this experiment that a higher L/V ratio results in a lower contact area for pressure distribution. The contact area tends to be concentrated towards the field side of each rail seat. Between the L/V ratios of 0.25 and 0.60, the area of the rail seat being loaded is reduced by 12.2 in^2 (78.71 cm^2), resulting in peak pressures of almost 1,000 psi (0.69 kN/cm^2) higher.

Researchers at UIUC theorize that this high concentration of field side loading could be seen on the high rail seat on a section of superelevated track with a train operating in an underbalanced condition. Inversely, a field side concentration on the low rail seat would be expected for a train operating in an overbalanced condition. This is also based on the fact that the researchers have seen sections of track in the field with varying types of concrete crossties and fastening systems, as well environmental conditions, where more deterioration has occurred on the field side of rail seats, and even more so on curves. In these observations it was assumed that the various concrete crossties were designed to meet similar specifications and thus would have similar strength and hardness values, allowing for a qualitative comparison between the locations.

CONCLUSIONS AND FUTURE WORK

The following conclusions can be drawn from the analysis of data collected in these preliminary experiments:

- Lower modulus rail pads distribute rail seat loads over a larger contact area, reducing peak pressure values and mitigating highly concentrated loads at this interface
- Higher modulus rail pads distribute rail seat loads in more highly concentrated areas, possibly leading to localized crushing of the concrete surface
- A lower L/V ratio of the resultant wheel load distributes the pressure over a larger contact area
- A higher L/V ratio of the resultant wheel load causes a concentration of pressure on the field side of the rail seat, resulting in higher peak pressures

Given the projected increase in the use of concrete crossties in the railroad industry, work will be continued at the UIUC to develop a comprehensive instrumentation plan to better understand interactions at this interface. The preliminary experiments described in this paper were theoretical in nature, with the loading conditions chosen by researchers based on industry expert opinion and working knowledge rail seat loads.

Future laboratory testing planned by researchers at UIUC includes installing MBTSS on rail seats of concrete crossties with various models of fastening systems to view the effect that variations in design have on rail seat pressure distribution. More rail pad modulus testing will take place to better understand the material properties of this component and the effect it has on mitigating rail seat pressures. Since a load applied to a larger contact area appears to result in lower peak pressure values, testing will also be conducted on crossties with various rail seat dimensions and degrees of deterioration and/or repair via epoxy or other materials.

Having run several preliminary tests in the laboratory, as well as developing a means to modify and protect the sensor for more accurate data collection, researchers at UIUC plan to instrument MBTSS on concrete crossties in the field. Field testing will allow analysis of actual loading conditions on the concrete rail seat surface with varying configurations of train loads, speeds, and track geometry.

Field testing will also play a crucial role in guiding the future of laboratory experimentation. A good working relationship between field data and experimental data is expected as the pressure distribution data collecting process is refined, and field conditions are better simulated in the laboratory. MBTSS appear to be a feasible, non-intrusive means to instrument concrete crossties to measure rail seat pressure distributions. Furthermore, the data collected from MBTSS in the laboratory and field will be used as an input for rail seat loads into finite element model analysis of the concrete crosstie and fastening system currently being performed at UIUC.

ACKNOWLEDGEMENTS

This research was funded by Amsted RPS / Amsted Rail and the Federal Railway Administration (FRA). For providing direction, advice, and resources the authors would like to thank Jose Mediavilla, Director of Engineering at Amsted RPS, Brent Wilson, Direct of Research and Development at Amsted Rail, Mauricio Gutierrez from the University of Illinois at Urbana-Champaign, Professor Jerry Rose and Graduate Research Assistant Jason Stith from the University of Kentucky, and Vince Carrara from Tekscan®, Inc. The authors would also like to thank Marc Killian and Don Marrow from the University of Illinois at Urbana-Champaign for their assistance in laboratory experimentation.

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