Analyzing Rail Seat Load Distributions on Concrete Sleepers using Matrix Based Tactile Surface Sensors

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Abstract

The demands on North American heavy haul railroad infrastructure continue to increase. Additionally, results from multiple surveys of North American Class I railroads have indicated that rail seat deterioration (RSD), the degradation of the concrete surface at the sleeper rail seat, is among the most critical challenges currently facing concrete sleepers. RSD can lead to wide gauge, cant deficiency, and an increased risk of rail rollover and considerable effort has been invested in better quantifying the failure mechanisms leading to RSD. Past research has identified abrasion to be a primary failure mechanism leading to RSD. However, because crushing as a failure mechanism has not yet been rejected and principles of tribology indicate that as pressure increases and displacement is held constant, the rate of abrasion increases, it is critical to quantify the factors affecting the magnitude and distribution of force imparted to the concrete sleeper rail seat to determine if crushing is a feasible failure mechanism. This paper summarizes the most critical findings from laboratory and field experimentation aimed at quantifying rail seat pressures and contact area when varying the following parameters: rail seat wear profile, rail clip health, rail pad modulus, presence of particles at the rail seat, and design rail cant. Matrix-based tactile surface sensors (MBTSS) were used to quantify the pressures and contact area during the laboratory and field experimentation and has provided valuable insight to further RSD research. Though none of the experiments conducted exceeded the ultimate strength of the concrete, pressures measured during several experiments exceeded the fatigue strength of concrete, suggesting repeated heavy loads could indeed lead to crushing of concrete in extreme conditions. Furthermore, the rail seat pressures were quantified under representative heavy haul loading and can now be considered when designing future concrete sleepers and fastening systems. This work was performed as part of a larger ongoing research effort aimed at improving the design and performance of concrete sleepers and elastic fastening systems.

1. Introduction

The combined trends of growing heavy haul traffic and increasing passenger train speeds *(1)* have meant that railroads across North America are striving for improvement in performance and durability of concrete sleepers and fastening systems *(1)*. However, rail seat deterioration (RSD) has been preventing concrete sleepers from realizing their potential in terms of durability and performance. RSD is the degradation of the concrete surface underneath the rail and can lead to track maintenance issues such as wide gauge, cant deficiency, and rail rollover. Previous surveys identify RSD as the most critical challenge facing concrete sleepers in North America *(2, 3)*. Previous research at the University of Illinois at Urbana-Champaign (UIUC) has attempted to better understand the failure mechanisms behind RSD. Zeman's research helped identify as many as six potential mechanisms of RSD *(2)*. He determined that as many as four of the five feasible mechanisms were influenced by the pressure distribution across the rail seat *(2)*. Subsequent research has focused on quantifying the effect of variables on the pressure distribution across the rail seat and determining the feasibility of concrete crushing as a failure mechanism of RSD.

This paper summarizes the most critical findings from laboratory and field experimentation performed by UIUC researchers, aimed at quantifying rail seat pressures and contact area when varying the following parameters: rail seat wear profile, rail clip health, rail pad modulus, presence of particles at the rail seat, and design rail cant.

2. Instrumentation Technology

Matrix-based tactile surface sensors (MBTSS) have been extensively used by UIUC researchers to measure the pressure distribution across the rail seat (1, 4, 5, 6, 7, 8, 9). The MBTSS systems used by UIUC are manufactured by Tekscan® Inc. and consist of rows and columns of sensing locations which can detect the pressure and relay that information to the data acquisition system. The data acquisition handle is used to collect data from the MBTSS and is connected to a computer with the requisite software using a USB cable. Along with collecting information on the magnitude of pressure, data on contact area are easily obtained based on the number of sensing locations that detect force and the fact that their area is known (3). MBTSS are a sensitive instrumentation type and are susceptible to shear damage and puncture. To provide protection, layers of polyethylene terephthalate (BoPET) and polytetrafluoroethylene (PTFE) were used during all experimentation (7).

3. Overview of Experimentations

Experimentation was performed in both laboratory and field. The laboratory experiments were carried out on the Pulsating Load Test Machine (PLTM), and the Track Loading System (TLS) located in the Rail Transportation and Engineering Center's (RailTEC) Research and Innovation Lab (RAIL) at UIUC. The PLTM has a 222 kN (55,000 lb) vertical actuator and a 156 kN (35,000 lb) lateral actuator and has the ability to simulate various representative lateral/vertical (L/V) force ratios that are present in revenue service track (10). The TLS has a full-scale, full-depth track-bed with 11 sleepers, ballast, sub-ballast, and subgrade (10). Representative forces are applied to a wheelset using two 222 kN (55,000 lb) hydraulic actuators, and one 403 kN (100,000 lb) hydraulic cylinder (10). The field experiments were performed at the Transportation Technology Center (TTC) in Pueblo, Colorado, USA; a research and testing facility that consists of 77.2 kilometers (48 miles) of railroad track (7).

A common theme that transcends the experiments described in this paper was to vary the vertical and lateral force applied to the rail(s). For tests on the PLTM, the wheel load was assumed to be 178 kN (40 kips), representing the 95th percentile nominal vertical wheel load in North American heavy haul freight service (11), and the maximum force applied to each rail seat was 75% of this, or 133.5 kN (30 kips). The maximum vertical wheel loads applied for rail seat wear and fastener wear tests were 89 kN (20 kips) and 178 kN (40 kips), respectively. The rail seat loads were assumed to be 50% of the wheel load in both scenarios. Unless stated otherwise, during each experiment the lateral force applied was varied to have L/Vs of 0.0 to 0.6 in increments of 0.1, and three L/V force ratios were chosen to be presented below - 0.0, 0.25 ± 0.05, and 0.55 ± 0.05.

3.1 Rail seat wear profile

Experiments investigating the effect of rail seat wear profile were carried out in field at the TTC (7). One rail seat per sleeper, within each of the three sections of 20 sleepers, was ground to a specified target depth to simulate a common RSD wear profile and then installed in a section of service track. The wear depth was gradually increased from both ends of each section until the target depth was achieved at the center of the section (7). The target wear depth of Section 1 (tangent track) was 6.35 mm (0.25 in.) and the wear depths for Sections 2 (8.9° (195-m) curve) and 3 (3.9° (445-m) curve) were 9.53 mm (0.375 in.) and 19.05 mm (0.75 in.), respectively. Rail seats in Section 1 were ground to a uniform wear depth preserving the 1:40 design cant. Rail seats in Sections 2 and 3 were ground to simulate triangular wear across the entire rail seat, resulting in reverse rail cant. The Safelok I fastening system was used for all three sections.

Forces were applied to the track structure with the FRA T-18 gage restraint measurement vehicle. The vertical wheel load remained constant at 89 kN (20 kips). Assuming 50% load transfer, this resulted in a 44 kN (10.0 kip) rail seat load. The lateral wheel load was varied to generate L/Vs ranging from 0.0 to 0.8 in increments of 0.2, though the results within this paper will only focus on data from 0.0 – 0.6.

3.2 Fastener clip wear

Experiments investigating the effect of fastener clip wear were carried out at two locations; the experiments using worn fasteners were performed in field at TTC while the experiments using new fasteners were performed on the TLS *(5)*. For field experiments, a section of 15 concrete sleepers with Safelok I shoulders was installed in a section of tangent track. Eight rail seats, on five sleepers, at this site were instrumented with MBTSS. The fastening clips used had been subjected to 5 million gross tons (MGT) of traffic and 3 cycles of removal and reapplication. For the laboratory experimentation, five consecutive rail seats on the TLS were instrumented with MBTSS and all fastening clips used were new and had never been installed before. Furthermore, any clips that were removed during experimentation were replaced by new clips to maintain an unworn condition.

The application of forces at TTC was accomplished using the Track Loading Vehicle (TLV) *(5)*. During laboratory experimentation on the TLS, vertical and lateral forces were applied to the track structure via hydraulic cylinders loading a standard 91.4 cm (36 inch) wheelset. In the field the TLV applied vertical loads of 89 kN (20 kips) and 178 kN (40 kips) and varied the lateral loads such that the L/V force ratios would increase in increments of 0.1 so as to achieve L/Vs up to 0.6. In the lab the wheelset applied vertical loads of 44 kN (10 kip), 89 kN (20 kip), 133 kN (30 kip), and 178 kN (40 kip) and varied the lateral loads such that the L/Vs would increase in increments of 0.1 so as to achieve L/Vs up to 0.6.

3.3 Rail pad modulus

Experiments investigating the effect of rail pad modulus were performed on the PLTM at RAIL, UIUC *(6)*. Three different rail pads were used: the standard Safelok I, *two-part pad assembly* (TPPA) made up of a nylon abrasion plate and a 95 Shore A thermoplastic polyurethane pad; a higher-modulus, 60 Shore D *medium-density polyethylene* (MDPE) pad with a flexural modulus of 827.4 MPa (120,000 psi); and a 86 Shore A lower-modulus *thermoplastic vulcanizate* (TPV) pad with a flexural modulus of 103.4 MPa (15,000 psi). A constant vertical force of 144.6 kN (32.5 kips) was applied to a single rail seat for all three rail pads. The lateral loads were applied so as to obtain L/Vs of 0.25, and then 0.44 to 0.6 in increments of 0.04.

3.4 Particle intrusion

Experiments investigating the effect of particle intrusion were performed on the PLTM at RAIL, UIUC *(4)*. The test variables were particle size, and zone of intrusion. Locomotive sand and virgin class B crushed stone ("B-Stone") aggregate were the particles used and the zone of intrusion was either the entire rail seat or the field-side one inch, as previous research suggested it was the critical zone *(5)*. The case of no intrusion was also tested. Vertical forces of 44 kN (10 kip), 89 kN (20 kip), and 133 kN (30 kip) were applied. The lateral loads were applied to obtain L/Vs of 0.0 to 0.6 in increments of 0.1.

3.5 'Design' rail cant

Experiments investigating the effect of 'design' rail cant were performed on the PLTM at RAIL, UIUC *(9)*. Tests were performed on a single sleeper for two rail seat cants – 1:40 and 1:30. Vertical forces of 44 kN (10 kip), 89 kN (20 kip), and 133 kN (30 kip) were applied. The lateral loads were applied to obtain L/V force ratios of 0.0 to 0.6 in increments of 0.1. It is to be noted, that the effect of artificially created 'negative' cant was also investigated as described in Section 3.1.

A summary including the setup, components, and loading for each experiment is provided in more detail below (**Table 1**).

Table 1 : Summary table of rail seat pressure distribution quantification experiments

Test description	Setup	Rail Pad(s)	Fastening Clips	Rail Seat Load kN (kips)	Highest L/V
Effect of rail seat wear profile	Track system	TPPA	Safelok I	44 (10)	0.6
Effect of fastener wear	Track system	TPPA	Safelok I	89 (20)	0.55
Effect of rail pad modulus	Single sleeper	TPPA, TPV, MDPE	Safelok I	144.6 (32.5)	0.6
Effect of particle intrusion	Single sleeper	TPPA	Safelok I	133 (30)	0.5
Effect of 'design' rail cant	Single sleeper	TPPA	Safelok I	133 (30)	0.56

4. Results of Experimentation

The analyses involve identifying the extent to which the factors affect rail seat maximum pressure, the highest value of pressure recorded by any sensing location, and contact area. The maximum pressure is the most critical parameter to test the feasibility of crushing as a failure mechanism. Therefore, the maximum pressure obtained from all the experiments at three L/Vs were compared (**Figure 1**). To provide additional insight into the maximum pressure values recorded, the corresponding contact areas were also compared (**Figure 2**). The contact area was calculated based on the number of MBTSS sensing locations that recorded non-zero pressure. It was assumed that the sensing locations recording zero pressure indicated a loss of contact from the rail seat.
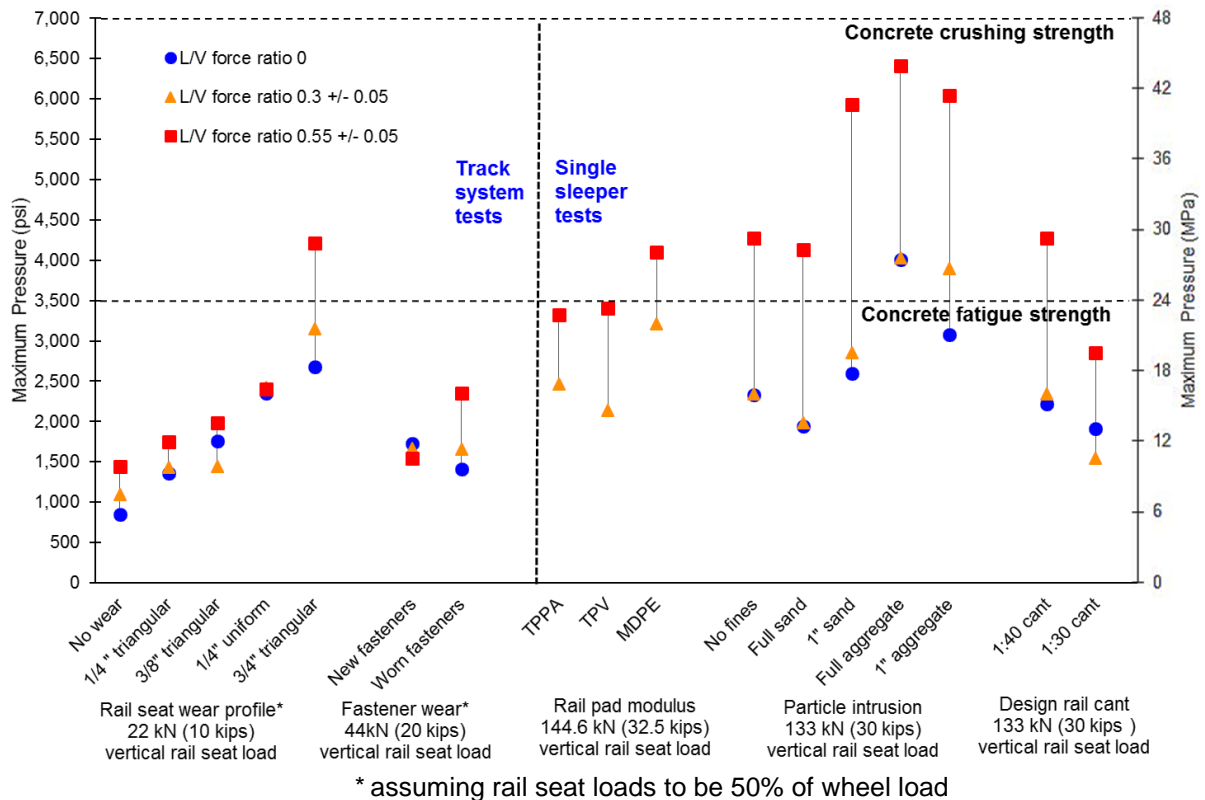
Figure 1: Plots for rail seat maximum pressure for all experiments conducted.
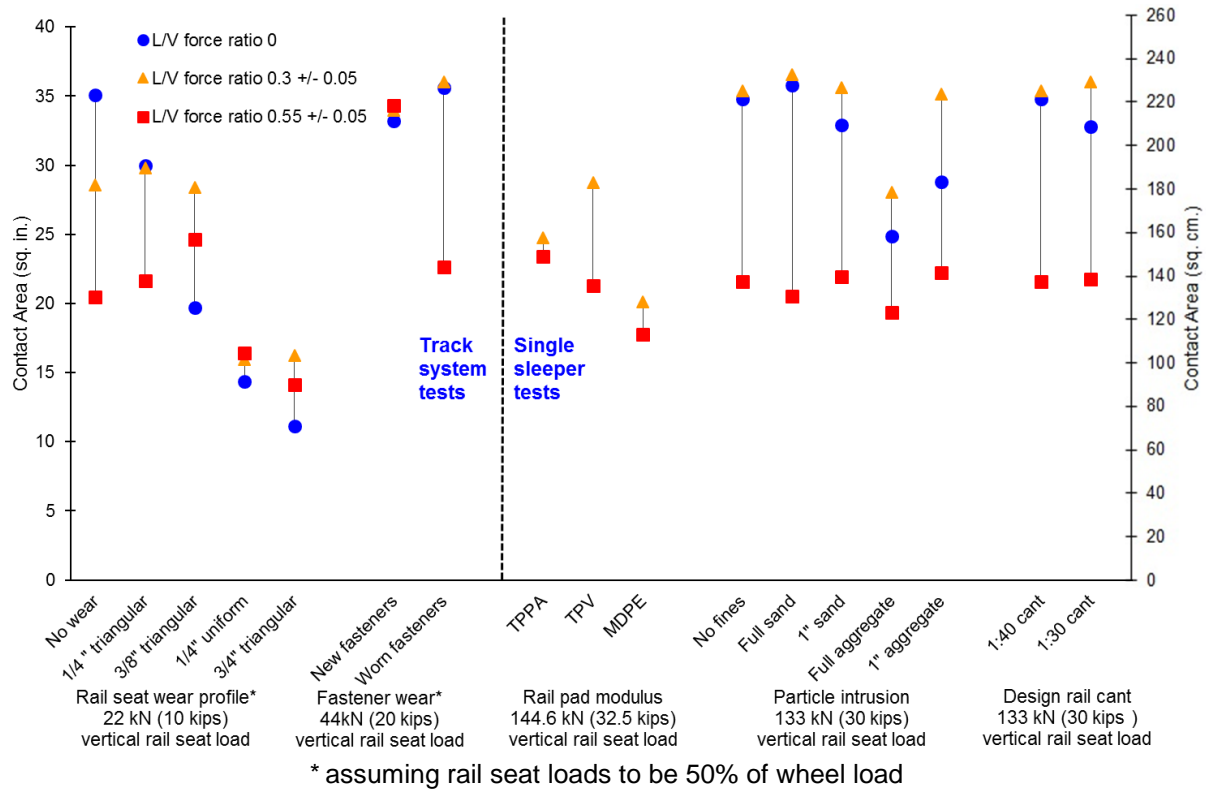
Figure 2: Plots for rail seat contact area for all experiments conducted.

The data show that the maximum pressure recorded never exceeded the design concrete ultimate strength. However, the maximum pressure did exceed the fatigue limit in several cases, which is typically 50 to 60% of the ultimate strength *(12)*. The highest pressures on the rail seat were achieved during the particle intrusion experiments. In all five particle intrusion cases, the pressure exceeded the fatigue strength and even approached the ultimate strength within 500 psi (3.5 MPa) when aggregate was covering the entire rail seat. Other cases that exceeded the fatigue limit were ¾" triangular wear profile, 1:40 rail cant, and the MDPE pad assembly. Within the limitations of experimentation, it can be thus concluded that the critical factors that affect pressure distribution on the rail seat are the intrusion of particles, cant of the rail seat, and stiffness of the rail pad.

The results from wear profile experiments indicate an increase in pressure with increasing wear depth. As wear depth increases, the clamping force by fastener clips decreases which then allows greater rail rotation. The data on contact area show that for triangular profiles other than ¼", contact actually increases from 0.0 to 0.3 L/V, and then decreases, possibly due to the negative cant profile. With the exception of ¾" triangular wear, all triangular profiles yield lower pressure than uniform wear. A possible explanation could be that there is a significant reduction in the clamping force, due to the uniform worn profile inducing a greater gap between the rail/insulator and gage side clip, thus giving rise to greater rail rotation.

The results from fastener wear experiments indicate that worn fasteners give rise to greater variation in maximum pressure than new fasteners, over the same range of L/V force ratios. It is hypothesized that the lower clamping force by worn fasteners again leads to greater rail rotation and thus gives rise to greater pressure values at higher lateral forces.

It is to be noted that the tests on rail pad modulus were not done at 0.0 L/V. The results shown pertain to L/Vs of 0.25 and 0.6. The results indicate that the harder and stiffer MDPE rail pad gives rise to the highest pressures. The softer TPV rail pad results in lower pressures than MDPE, but exhibits the largest variation between aforementioned L/Vs, suggesting greater rail rotation. This could result in greater wear and fatigue of other fastening components, such as the shoulders *(6)*. These findings are supported by data from contact area. The TPPA, which has both stiff and soft components, appears to perform the best given the maximum pressure was the lowest when subjected to the highest L/V force

ratio and that the range between the maximum and minimum values was the smallest suggesting adequate rail restraint.

The results from the particle intrusion experiments show the highest pressure values across all tests, most likely because of the reduced contact area and discrete points of high pressure due to foreign particles. The values are significantly higher for L/V force ratio 0.55 when compared to L/V force ratios of 0.0 and 0.3, suggesting a critical L/V force ratio beyond which the rail goes through excessive rail rotation. Aggregate intrusion gives rise to greater pressures than sand intrusion indicating that larger particles reduce the effective contact area. Intrusion on the field side 1" yields a higher pressure than intrusion of the entire rail seat in case of sand, but not for the aggregate. Data on contact area show that the highest contact area for all cases is at L/V of 0.3, and not 0.0.

The results from design rail cant experiments indicate that the steeper 1:30 cant reduces the maximum pressure by approximately 33% when compared to the 1:40 cant. The data on contact area suggest that 1:30 cant has the most uniform pressure distribution at an L/V force ratio of 0.3 and not 0.0. This suggests that a steeper rail cant may have a non-zero optimal L/V force ratio.

A general trend across all experiments conducted is that the highest pressures are generated when the L/V force ratio is 0.55, but the contact area is highest at an L/V of 0.3. Additionally, there is a greater increase in pressure between 0.3 L/V and 0.55 L/V than between 0.0 L/V and 0.3 L/V, particularly for single sleeper tests, again indicating that there is a threshold L/V force ratio at which rail rotation increases. Though there is a general trend that the maximum pressure values do increase from an L/V force ratio of 0.0 to 0.3, the trend is not always present; in some cases the pressures are the same and in others the pressures are higher at 0.0 than 0.3.

5. Conclusions

Because the rail seat pressure distribution can affect the rate and severity of RSD, this paper summarizes how various factors affect the pressure distribution across the concrete sleeper rail seat. The pressure distribution has been assumed to be uniform but research has consistently shown that it is non-uniform and typically concentrates on the field side as lateral loads are imparted to the rail. It was hypothesized that crushing of concrete at the rail seat could be a feasible mechanism of RSD. Though no pressure recorded exceeded the ultimate strength of the concrete, pressures recorded during several experiments did exceed the concrete fatigue strength. This suggests that repeated heavy loads could lead to crushing of concrete in extreme conditions. Furthermore, crushing as a mechanism cannot yet be dismissed given the maximum wheel load imparted into the system was 178 kN (40 kips) and wheel load data has shown that the 99.5% peak wheel load of loaded freight cars is 377 kN (84.7 kips). Therefore, additional research will be needed.

The maximum pressure values were looked at for three L/V force ratios, 0.0, 0.3, and 0.55. The general trend across all experiments was a marked increase in the maximum pressure for 0.55 L/V as compared to 0.0 and 0.3 L/Vs. The pressure values from 0.0 and 0.3 L/Vs showed a less clear trend, with test conditions that had a steeper effective rail cant, showing that they had the lowest pressure values for 0.3 L/V. The highest contact area across a majority of the tests were obtained at 0.3 L/V. Of all the experiments conducted, particle intrusion in the rail seat resulted in the highest pressures, with pressures as high as 44.6 MPa (6,500 psi). Results from experimentation suggested that the pressure on the rail seat increased with an increase in intruding particle size, stiffness of rail pad, and depth of wear. The use of worn fastener clips resulted in a relatively lower pressure values from the other variables tested.

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