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LABORATORY AND FIELD INVESTIGATION OF THE RAIL PAD ASSEMBLY MECHANISTIC BEHAVIOR

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ABSTRACT

To achieve the performance demands due to growing heavy-haul freight operations and increased high-speed rail service worldwide, advancements in concrete crosstie fastening systems are required. A mechanistic design approach based on scientific principles and derived from extensive laboratory and field investigation has the potential to improve the current best practices in fastening system design. The understanding of failure modes and effects on each component, associated with an improved understanding of load distribution and mechanical behavior, will ultimately increase production and operational efficiency while reducing unscheduled maintenance, track outages, and unplanned additional costs. Improvements on the rail pad assemblies, the components responsible for attenuating loads and protecting the concrete crosstie rail seat, will enhance the safety and efficiency of the track infrastructure. Understanding the mechanistic behavior of rail pad assemblies is critical to improving the performance and life cycle of the infrastructure and its components, which will ultimately reduce the occurrence of potential failure modes. Lateral, longitudinal, and shear forces exerted on the components of the fastening system may result in displacements and deformations of the rail pad with respect to the rail seat and rail base. The high stresses and relative movements are expected to contribute to multiple failure mechanisms and result in an increased need for costly maintenance activities. Therefore, the analysis of the mechanics of pad assemblies is important for the improvement of railroad superstructure component design and performance. In this study, the lateral displacement of this component with respect to the rail base and rail seat is analyzed. The research ultimately aims to investigate the hypothesis that relative displacement between the rail pad and rail seat occurs under realistic loading environments and that the magnitude of the displacement is directly related to the increase in wheel loads.

INTRODUCTION

The rail pad assembly, also known as rail pad, is a key element in the transfer of wheel-rail forces into the track substructure. The rail pad assembly, also referred as rail pad, has a fundamental influence in system performance parameters such as track gauge, rail seat inclination, track vertical stiffness, and electrical insulation [1]. This component is also important to the track structure because of its versatility as an engineered product that can be designed with multiple layers, a variety of materials, and optimized geometry. As a result, it can be conceived to achieve specific mechanical properties as it functions within the fastening system, which can ultimately affect the way the track structure responds to the loading demands.

Previous laboratory experiments conducted at UIUC focused on determining the capability of relative lateral displacement between different rail pad materials and concrete rail seats to trigger an abrasion process that can deteriorate the rail seat of concrete crossties. This deterioration, called rail seat deterioration (RSD), is the degradation of the concrete material directly beneath the rail pad on the bearing surface of the concrete crosstie [2]. The aforementioned study was part of a novel laboratory test called the Large-Scale Abrasion Test (LSAT), where a servo-hydraulic system was used to produce lateral displacements in a rail pad sample with respect to a concrete specimen. Based on the results, researchers concluded that the imposed displacements were capable of wearing the components in a pattern that resembled RSD cases [3, 5]. However, the experimentation did not consider the confinement these components are subjected to within the fastening system, which constrains the displacements of the rail pad relative to the rail seat. Combined, the various interfaces of the fastening system produce interactions among components that may significantly impact the mechanics of abrasion.

After an extensive literature review and analysis of previous experiments conducted at UIUC, several hypotheses were formulated in order to systematically investigate the behavior of the rail pad assembly within the fastening system. It was hypothesized that (a) rail pad assemblies are, indeed, subjected to lateral displacements relatively to the rail seat, but in a magnitude much smaller than the displacements that were simulated with the LSAT [1/8 inch (3.175 mm)]. Furthermore, it was hypothesized that (b) the increase of train speed is expected to have a direct effect on the magnitude of the lateral wheel load, which will impose larger displacements and forces on the rail pad assembly. In other words, the increase in train speed is expected to induce higher lateral forces on the track that will result in larger relative displacements between the rail pad and crosstie rail seat. Further experimentation focused on determining the causes of rail pad assembly slippage, and the relationship between the applied loads and the magnitude of displacements. Therefore, this set of laboratory and field experiments is suggested to explain the effects of different loading scenarios on the displacement and deformation of rail pad assemblies. The ultimate goal is to gain a greater understating about the mechanistic behavior of this component, which will ultimately assist the analysis of the deterioration process the rail pads suffer when submitted to realistic loading environments.

LABORATORY EXPERIMENTAL SETUP

A representative laboratory setup facilitated controlled experiments, which were ideal for measuring rail pad assembly displacements. The Pulsating Load Testing Machine (PLTM), which is owned by Amsted RPS and was designed to perform the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6 (Wear and Abrasion), was used to execute the laboratory experiments within this study. Regarding the configuration of the PLTM, it consists of one horizontal and two vertical actuators, both coupled to a steel loading head that encapsulates a 24 inch (610 mm) section of rail attached to one of the two rail seats on a concrete crosstie. The concrete crosstie rests on wooden boards placed on the top of the steel frame that forms the base of the testing fixture, representing stiff support conditions. Loading inputs for this experimentation are applied to the rail in the vertical and lateral directions, and no longitudinal load is applied due to constraints of the current test setup.

A high-sensitivity potentiometer mounted on a metal bracket was bolted to the concrete next to the gage side clip shoulder. The potentiometer plunger was in direct contact with the abrasion frame (Figure 1) and captured the lateral displacement of the pad assembly. In this case, the pad assembly consisted of a polyurethane pad and a nylon 6/6 abrasion frame.

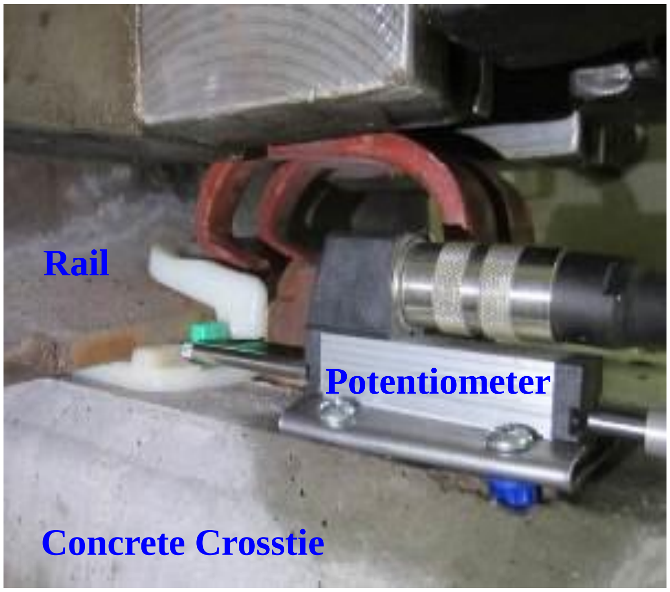

FIGURE 1. LABORATORY EXPERIMENTAL SETUP

LABORATORY RESULTS

Lateral and vertical loads were applied to the rail, with L/V force ratios varying from 0.1 to 0.5. The maximum lateral load applied was 18,000 lbf (80kN). Initially, only static loads were applied, beginning with a low L/V ratio and consistently increasing the lateral force for each constant vertical force (18,000 lbs (kips), 30 kips, and 32.5 kips). The dynamic test used the same loading protocol, and the loading rate was 3 Hz. The measured maximum displacement was 0.042 in (1.05 mm) for a 0.5 L/V ratio and a 36,000 lbf (160kN) vertical load. The displacement gradually increased with the variation of the lateral load, presenting a linear behavior. Even for a lateral load less than 2 kips, displacements were recorded, indicating the occurrence of relative slip between the rail pad assembly and the rail seat even under loading scenarios commonly encountered in less demanding track sections (low lateral forces). As expected, the magnitudes of these displacements were small if compared to the dimensions of the rail seat, since there are very minimal gaps between the rail pad assembly and the shoulders in the rail seat area that allow the rail pad to displace. When this test was repeated with different crossties, there was a variation in the maximum displacement of up to 50% based on the geometry and manufacturing differences.

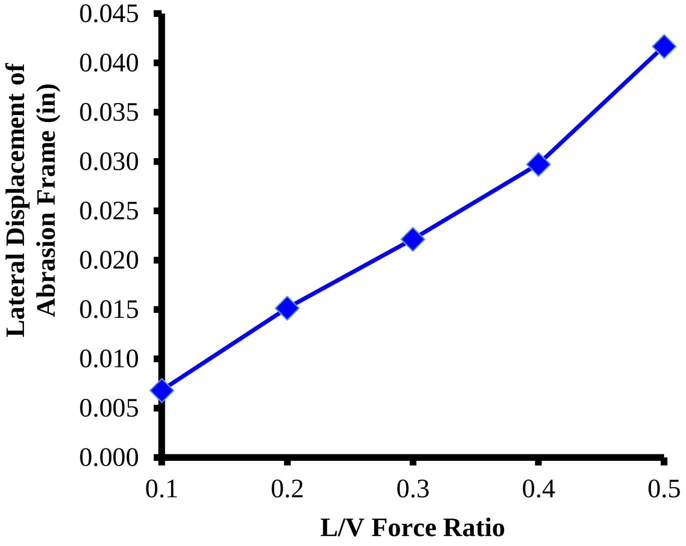

FIGURE 2. LATERAL DISPLACEMENT OF ABRASION FRAME WITH 36 KIPS VERTICAL LOAD FOR INCREASING L/V FORCE RATIO

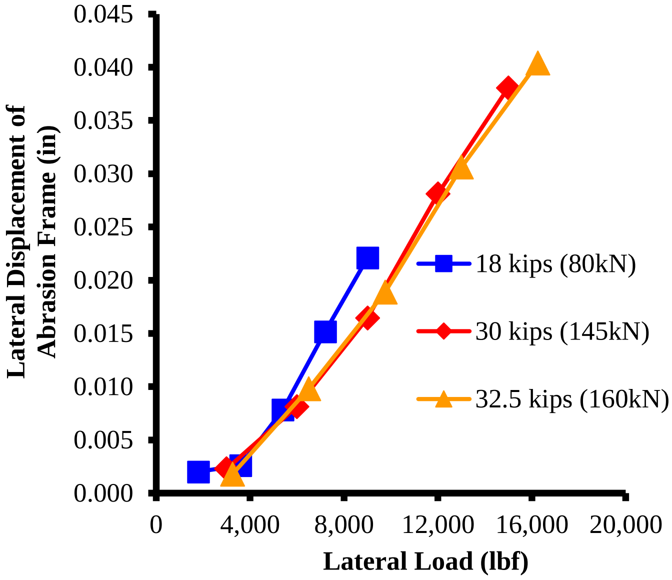

FIGURE 3. LATERAL DISPLACEMENT OF THE ABRASION FRAME FOR INCREASING LATERAL LOADS AND CONSTANT VERTICAL LOADS (18 KIPS, 30 KIPS, and 32.5 KIPS)

Although the magnitude of the vertical loads applied in the system have a large impact on the longitudinal elastic deformation of the rail pad assembly [1, 4] its effects on the lateral displacement behavior are not evident when lateral loads less than 6.3 kips were considered. For lateral loads up to 6,300 lbf (28kN), vertical forces ranging from 18,000 lbf (80kN) to 32,500 lbf (145kN) did not exhibit differences in the pad assembly lateral displacement. The results recorded for these three different vertical loading cases were similar for lateral loads up to 6.3 kips despite the 14,600 lbf (65kN) difference between the minimum and maximum vertical force applied. However, given the results obtained from this experiment, it is plausible that for lower lateral loading cases, the pad assembly is capable of overcoming the static frictional forces existent at the rail pad assembly – rail seat interface. In contrast, for higher lateral loads, the vertical forces reduced the magnitude of the lateral displacement, pointing to the influence of friction on the shear behavior of the pad assembly. Under severe loading cases, where high L/V ratios and high lateral loads are encountered, the magnitude of the wheel load will likely affect the lateral displacement of the pad assembly. It is also important to notice that the lateral and longitudinal motion of the rail pad assembly is restrained by the shoulders and is highly dependent on the condition of the rail seat. Based on the results from laboratory testing, larger lateral and longitudinal displacements are less likely to occur when the rail pad assembly fits tightly within the rail seat. Comparing the displacements obtained by the laboratory experiments and the imposed displacements used to run the LSAT experiments [3, 5], it is possible to affirm that relative translation between rail pad and crosstie rail seat equal to 1/8 inch (3.175 mm) is unrealistic for new components, since the maximum displacement measured, 0.04 inches, corresponds to only 30% of the LSAT motion. It is important to emphasize that the objective of setting a large displacement in the LSAT was to simulate a deteriorated fastening system where insulators or clips were missing, providing a larger gap and less restraint to the rail pad motion.

FIELD EXPERIMENTAL SETUP

In the pursuit of data to investigate the relative displacement between rail pad and crosstie rail seat, UIUC has undertaken a comprehensive effort to formulate a realistic testing regime to analyze forces and motions generated through the fastening system. Two track sections were instrumented at the Transportation Technology Center (TTC) in Pueblo, CO. A tangent section was instrumented at the Railroad Test Track (RTT) while a section of a 2 degree curve was instrumented on the High Tonnage Loop (HTL). It is important to mention that the HTL theoretical curvature was 5 degrees, but additional measurements pointed that the actual value was 2 degrees. For each location, 15 new concrete crossties were placed on new ballast, spaced at 24 inch centers, and machined tamped. The HTL was exposed to over 50 million gross tons (MGT) of freight traffic prior to testing [6]. Three distinct loading methodologies were employed as a part of the field instrumentation. First, the loads were applied through the Track Loading Vehicle (TLV). The TLV is composed of actuators and load cells coupled to a deployable axle that facilitates application of known static loads. Therefore, it was used to create a static loading environment comparable to the one developed for laboratory instrumentation. The other two loading environments consisted of a passenger consist and a freight consist moving along the track. These two cases were implemented to capture the responses of the track components under real dynamic loading scenarios. The primary objective of this field instrumentation was to characterize the behavior and quantify the demands placed on each component within the crosstie and fastening system under field condition.

A set of strain gauges, linear potentiometers, and pressure sensors were installed on the infrastructure at strategic locations to map the responses of the track components. The lateral displacements of the rail base and rail pad assemblies were recorded using linear potentiometers mounted to the crossties with metal brackets at 6 different rail seats (Figures 4 and 5). Brand new rail pad assemblies were used in the field instrumentation. These components were the same model used for the laboratory experiments. The lateral forces exerted by the trains on the rail were captured using strain gauges placed on a full (Wheatstone) bridge configuration. These strain gauges were installed in the cribs between rail seats C-E, E-G, S-U, and U-W.

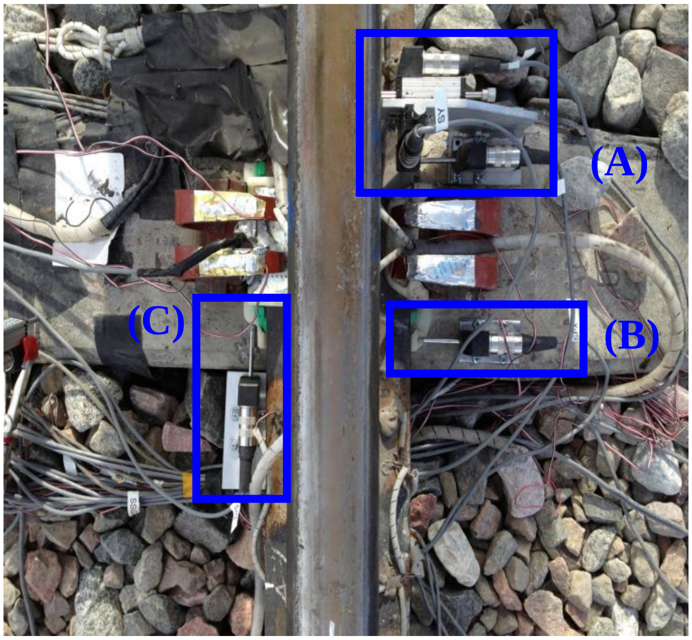

FIGURE 4. FIELD EXPERIMENTAL SETUP SHOWING INTRUMENTATION TO MEASURE (A) RAIL BASE TRANSLATION, (B) RAIL PAD LATERAL TRANSLATION, AND (C) RAIL PAD LONGITUDINAL TRANSLATION

Both track sections had the same instrumentation layout and naming convention identifying the location of the instruments used to measure rail pad assembly lateral displacement, and rail base lateral displacement (Figure 5). This study will only reference the instrumented crossties (BQ, CS, EU, and GW). For some locations, the various forms of instrumentation do not overlap, which was intentional in the design of the instrumentation plan.

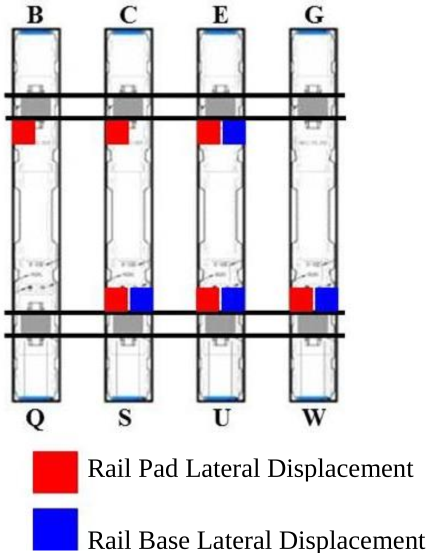

FIGURE 5. LOCATION OF INSTRUMENTATION AND NAMING CONVENTION FOR RAIL SEATS AND CRIBS LOCATED AT THE RTT AND HTL TRACK SECTIONS

FIELD RESULTS

This study will be focused on the freight train runs on the HTL. This is the loading scenario expected to impose higher demands on the track components, resulting in higher components deformation and displacement. The data presented is related to 315,000 lbs rail cars with axial loads of approximately 40 kips. Additionally, this paper focuses on rail seats "S" and "U", on the low rail, since these two locations had the necessary overlapping instrumentation to simultaneously measure the rail pad, rail base lateral displacement, and also the lateral wheel loads imposed on the rail. This factor is of paramount importance when investigating the relationship between these variables, since the previously stated hypotheses aim the understanding of the correlation among them.

During the freight train runs, the speed was increased from 2 mph up to 45 mph. Initially, the strain gauges captured lateral wheel loads of 18 kips and 21 kips being applied to the rail at the rail seats "S" and "U" location respectively. These wheel loads gradually decreased with the increase of train speed, reaching a minimum value of 7.90 kips at rail seat "S" and 9.58 kips at rail seat "U" (Figure 6). The potentiometers placed on the rail pad "U" captured a maximum lateral displacement close to 0.004 inches, which presented an increase in magnitude for increasing lateral wheel loads. The behavior of rail pad "S" has also showed a trend to increase the magnitude with respect to the increase in wheel load. However, the displacements were smaller if compared to the adjacent rail pad assembly (Figure 7). The behavior of the rail base lateral displacement has also presented a direct relationship with the increase in lateral wheel load. Both potentiometers positioned at rail seats "S" and "U" have captured an increase in lateral displacement magnitude for the increase in wheel load (Figure 8). The maximum rail displacement was close to 0.22 inches, value much higher than the displacements recorded for the rail pads. A possible explanation for the variation in displacements between these adjacent rail seats is probably related to differences in rail seat geometry and variation in shoulder spacing, which are two parameters that restrain the pad assembly motion. Regarding the difference in magnitude between rail pad and rail base lateral displacement, it is likely to be related to frictional forces on bearing interfaces geometric restraints, since the rail base sits on the top of the rail pad and is not in contact with the shoulders, which is a condition that gives more freedom for this component to move within the rail seat area. Additionally, the pad assembly is subjected to the action of frictional forces at most of its bearing surfaces, which forces all the interfaces of this component to interact within the fastening system.

Based on the field results, the relative displacement between rail pad and crosstie rail seat and also the relative displacement between rail base and crosstie were successfully captured on the train runs, confirming the hypotheses that forecast the existence of this motion under realistic loading environments (hypothesis "a"). The final displacement observed for the rail pads were approximately 40% than the initial measurements. Compared to the static results obtained from the laboratory experiments (Figures 2 and 3), these displacements were also significantly smaller, one order of magnitude lower.

Another result that should be pointed out is the difference in lateral wheel loads associated with the rail pad displacements for the two analyzed rail seats. In other words, loads of similar magnitudes imposed different displacements to the rail pads of rail seats "U" and "S". This variation is likely due to the inherent difference in support conditions of crossties, possible distinct local stiffness of the fastening systems, and also geometric variations in the rail seats, which may lead to differences in gaps between rail pad and shoulders. This last parameter is a function of the manufacturing tolerances, a parameter that allow a tighter or looser fit of the rail pad depending on the shoulder to shoulder distance.

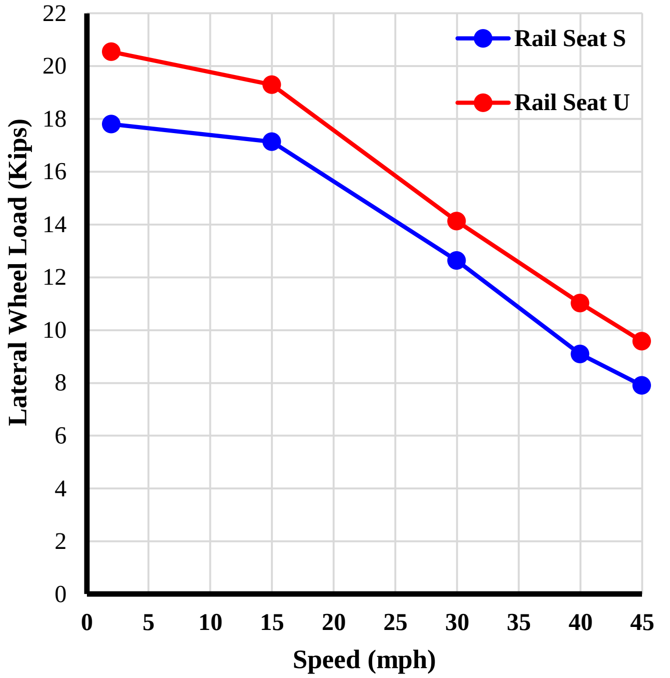

FIGURE 6. LATERAL WHEEL LOAD IN RAIL SEATS "S" AND "U" FOR INCREASING SPEED

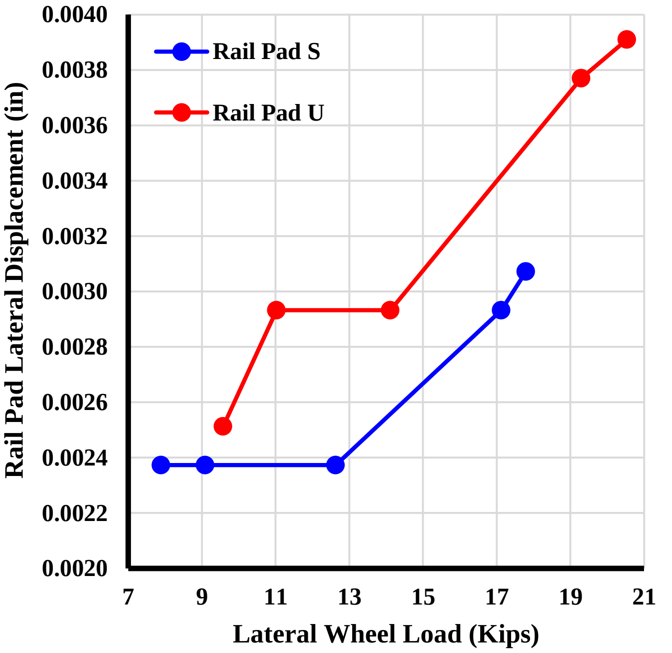

FIGURE 7. RAIL PAD LATERAL DISPLACEMENT FOR INCREASING LATERAL WHEEL LOAD

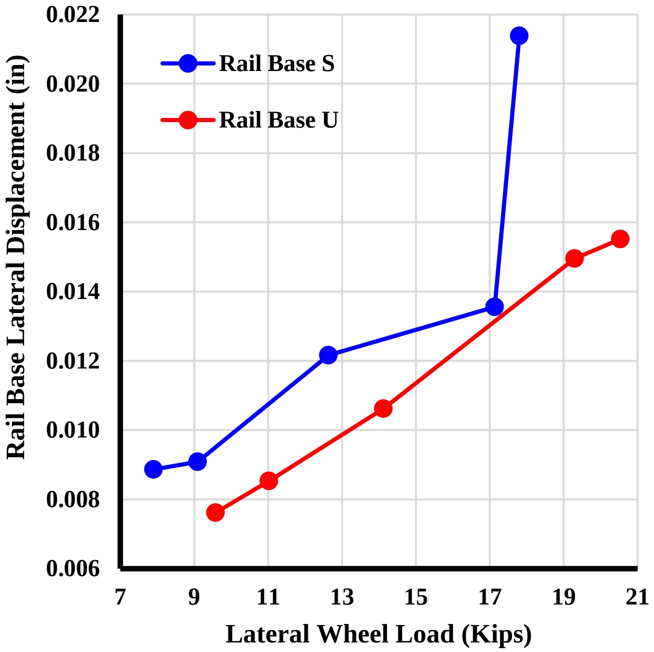

FIGURE 8. RAIL BASE LATERAL DISPLACEMENT FOR INCREASING LATERAL WHEEL LOAD

The impact of speed on the lateral wheel loads and forces imposed on the fastening system components resulted in an inverse relationship between these variables, with lateral forces acting on the rail pad and rail base going down with the increase in speed. Another notable factor is the relative slip between rail pad assembly and rail base, because there is a significant difference in magnitude of slip between these two components. This relative slip indicates a possible occurrence of shear at the rail pad interfaces, which points out to the need for further investigation of the shear capacity of current materials used in the design of rail pad assemblies and how they should appropriately resist shear forces, minimizing the occurrence of component degradation.

CONCLUSIONS

The understanding of the mechanistic behavior of the rail pad assembly and how it interacts within the fastening system is important in the development of improved track components. The relative displacement of the rail pad assembly is frequently associated with RSD failure mechanisms, especially the abrasion mechanism. The occurrence of relative displacement between the rail pad and rail seat was identified and successfully measured in the experiments carried out in the laboratory at UIUC and in the field at TTC. As previously hypothesized, the occurrence of these displacements was observed under realistic train runs, but with reduced magnitude when compared to the laboratory experiments. Comparing the displacements obtained by the laboratory experiments and the imposed displacements used in the previous abrasion experimentations at UIUC [3, 5], the maximum measured displacement, 0.04 inches, corresponded to only 30% of the LSAT motion. Despite the fact that the recorded displacements were small compared to the dimensions of the rail seat, its effects on the microstructure of the concrete might be harmful to the integrity of the crosstie rail seat. Therefore, further experimentation should focus on analyzing the relationship between this measured relative displacement and the severity/rate of abrasion.

Another aspect associated with the lateral displacement is related to the high dependency of this variable on the lateral wheel loads applied to the system. The consistent increase in the lateral wheel load directly affected the magnitude of the lateral displacement of rail pad and rail base for both lab and field investigations. The vertical load imparted to the rail has also affected the lateral displacement of the rail pad for lateral forces greater than 6.3 kips for the lab experimentation. This result is likely due to the increase in frictional forces in the bearing area of the rail seat when higher vertical loads are considered.

For increasing train speeds, the lateral wheel loads presented a decrease in magnitude on the low rail, which was reflected in smaller lateral displacements of the rail pad and rail base. This result points out the need to analyze the wheel loads and displacements on the high rail, which are expected to increase with the increase in train speed, one of the hypothesis suggested during this study.

Additionally, future work should be able to determine if under cyclic loading cases, displacements of similar magnitudes to the ones found on this research are capable of triggering a wear process on the fastening system components, especially the rail pad assembly and the rail seat. Moreover, the shear capacity of current materials used in the design of rail pad assemblies and how they should appropriately resist shear forces should also be a topic of investigation in order to avoid the occurrence of shear failures.

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