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Mechanistic Behavior of Concrete Crosstie Fastening System Rail Pad Assemblies

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ABSTRACT
To support the increasingly rigorous performance demands due to growing heavy-haul freight operations and increased high-speed intercity passenger rail development worldwide, advancements in concrete crosstie fastening system designs are needed. Improvements to the components responsible for attenuating loads and protecting the concrete crosstie rail seat will enhance the safety and efficiency of the track infrastructure. Rail pad assemblies are designed to provide a protective layer between the rail base and crosstie and attenuate the dynamic loads imposed on the rail seat, reducing the stresses to acceptable levels. 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 such as rail seat deterioration (RSD). Lateral, longitudinal, and shear forces exerted on the components of the fastening system can result in displacements and deformations of rail pad assemblies with respect to the rail seat. The high stresses and relative movement are expected to contribute to multiple failure mechanisms and result in an increased need for costly maintenance activities. Thus, the analysis of the mechanics of pad assemblies is of paramount importance for the improvement of railroad superstructure component design and performance. In this study, the shear behavior of this component will be investigated from a mechanistic perspective that combines laboratory and field experiments to explain how the surfaces interact, show how the materials deform, and quantify the amount of relative displacement between the fastening system components. The expected results will lay the groundwork for the development of a mechanistic design approach that enhances the performance, efficiency, and durability of current concrete crosstie fastening systems.

INTRODUCTION

Even though the fastening system is a dimensionally small component within the railway infrastructure, it is a key element in the transfer of wheel-rail forces into the track structure. The fastening system has a fundamental influence in controlling system performance parameters such as track gauge, rail seat inclination, track stiffness, and electrical insulation (1). The rail pad assembly is the core of the fastening system, and governs the transfer and attenuation of vertical loads. This component is 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. Given the rail pad assembly is in contact with most components in the concrete crosstie and fastening system, undesired changes in the rail pad assembly behavior will ultimately affect the performance of all other fastening system components. The pad assembly-rail seat interface is of paramount interest due to the fact that one of the most common failure mechanisms related to concrete crossties in North America, rail seat deterioration (RSD), occurs on the bearing area of the rail seat, where the pad assembly is in contact with the crosstie (2).

The mechanical characteristics of the rail pad assembly's movement at the rail seat surface can be understood as the combination of three distinct phenomena that ultimately dictate the displacements and deformations experienced by this component. *Compressive motion*, also known as Poisson's effect, is the tendency of elastic materials to expand in directions orthogonal to the direction of the compressive stress. Therefore, the rail pad assembly tends to deform laterally and longitudinally as vertical loads are transferred from the rail to the crosstie. *Rigid body motion* is a simplified characterization of the component translation assuming no relative displacement between the rail pad assembly interparticle distances. The *shear behavior* of rail pad assemblies can be described as the interlayer transfer of forces and relative slip of the pad assembly surfaces in relationship to the concrete crosstie and rail base. All these effects are combined to explain the behavior of the rail pad assemblies. However, this concept is broader than the intrinsic component material properties, since the rail pad assembly is surrounded by a variety of other fastening system elements that also affect the load transfer and responses within the track structure.

Previous research conducted at the University of Illinois at Urbana-Champaign (UIUC) hypothesized that the shear behavior of the rail pad assemblies is highly dependent on the frictional forces that exist at the component interfaces. The dynamic characteristics of the loads are also considered to be an important factor affecting this shear behavior. Laboratory experiments have shown a variation of the frictional coefficient of the rail pad assemblies depending on the type of material, geometry of the pad bottom, and the existence of abrasive fines or moisture in the bearing surfaces (3). Therefore, the current study is critical in the development of improved fastening systems, where the deformation and mitigation of relative displacement between components may be used to prevent excessive demands on the track superstructure (1,4). The need for maintenance and/or premature failure of components may be significantly reduced if the design process of fastening systems takes into consideration the mechanistic characteristics of the rail pad assemblies. The capacity of the component to shear and dissipate the high stresses generated on the track under severe operating conditions can be used to improve the performance and increase the life cycle of the fastening system.

Motivation and Objectives

Prior research at UIUC focused on investigating the physical mechanisms that contribute to RSD (5). Abrasion was found to be one of the feasible causes of this phenomenon (5). Other failure mechanisms include freeze-thaw cracking, hydro-abrasive erosion, hydraulic pressure cracking, and crushing (5). The abrasion process occurs when the shear forces at the surfaces in contact overcome the static frictional forces between the bottom of the pad abrasion frame and the rail seat. The components then move relative to each other, wearing the pad assembly and the rail seat (6). Thus, quantifying the magnitude of this relative motion when the system is subjected to a variety of loading scenarios constitutes one the primary focuses of this research. The relative displacement between rail pad assembly and rail seat has been described by experts as one of the main causes of component failure, but the magnitude of relative slip has not been quantified in published literature (3,5,6). The pad assembly displacements and deformations under current load environments must be analyzed in order to understand the failure processes affecting the fastening system.

Rail Pad Assembly Failure Mode and Effect Analysis (FMEA)

In North America, the geometry and materials used in rail pad assembly design have changed significantly over the past thirty years. Single-layer components made out of synthetic rubber were later substituted by higher density polymers and eventually multi-layer components. Today, the most common rail pad assemblies consist of polyurethane rail pads on top of nylon 6/6 abrasion frames. The design intent of a layered component is to provide abrasion resistance and also impact attenuation, combining materials with distinct qualities to obtain an improved rail pad assembly. These material and design effects on load distribution have been observed in previous laboratory testing at UIUC (7). Even though the rail pad assembly design has improved over the past thirty years, these components still experience failure prior to the end of their intended life due to a variety of mechanisms. After obtaining input from laboratory and field investigations, railroad infrastructure experts, fastening system manufacturers, and railway industry technical committees, the failure patterns were identified and described as part of a failure mode and effect analysis (FMEA).

The FMEA is a technique developed in the mid-1960's by reliability engineers in the aerospace industry to increase the safety of products on the development or manufacturing process. The FMEA is used to define, identify, evaluate, and eliminate known and/or potential failures from the system before they occur. The emphasis is to minimize the probability of failure and mitigate its effects. Therefore, this process involves the systematic analysis of failure modes related to the product in order to detect possible causes and investigate their effects on the system. From this analysis, it is possible to identify actions that must be taken to reduce the probability of failure occurrence (8,9). The intent of performing a FMEA was to guide the process of answering questions related to the component behavior and identify the next actions that must be taken to reach the ultimate goal of the research: provide design and material properties recommendations to enhance the safety and durability of rail pad assemblies.

Many types of failures were identified as a part of the FMEA (Figure 1). Tearing and crushing of rail pad components was identified in some pads, which also indicate a loss of material (Figure 1A-C). The effects of abrasion can also be noticed on the worn dimples and grooves (Figure 1-A). Another common failure related to this component is the rail pad assembly translating out of the rail seat (often referred to as "walking out") (Figure 1-D). In this phenomenon, the pad assembly slips in one direction so that it is partially or completely removed from the rail seat.

(A) (B) (C) (D)

FIGURE 1 Typical Failure Modes Associated with Concrete Crosstie Rail Pad Assemblies.

Among the principal causes of the aforementioned failures, the relative displacement between the pad assembly and rail seat is of special importance, since it is likely to be associated with most of these failure modes (5,6). High localized compressive and shear stresses, large variation in temperature, presence of abrasive fines in the rail seat bearing area, and the presence of moisture are also other causes that might contribute to the degradation of the rail pad assembly. To help understand the consequences of a rail pad assembly failure, it is beneficial to divide the effects into three parts: 1) the effect on the component itself, 2) the effect on the next higher assembly (i.e. the adjacent components of the fastening system), and 3) the effect on the track system as a whole. The failure effect on the pad assembly is the loss of the original geometry, usually manifested as loss of thickness, permanent deformations, and changes in the material properties. The effects on the fastening system components are considered to be the change in the desired load path through each component, possibly triggering intensification in the wear process. Regarding the track system, the consequences lead to more periodic maintenance, reduction in the life cycle of components, and loss of track geometry resulting in the possibility of derailments. This analysis is motivated by the cause and effect relationships developed for the most common failure modes observed for pad assemblies, and is our guide for the mechanistic investigation of component behavior.

INVESTIGATION OF THE MECHANISTIC BEHAVIOR OF RAIL PAD ASSEMBLIES

Previous researchers have shown that the longitudinal shear behavior of rail pad assemblies is a key component in crosstie skewing (1). The studies indicate that pad assemblies must allow the largest possible elastic displacement of the rail before slip occurs, giving to the system a large capacity to elastically accommodate more displacement (1,4). This shear elasticity is also important in the lateral direction because it allows the fastening system to absorb the energy from the lateral loads and causes the pad assembly to deform instead of translating rigidly relative to the rail seat. Based on results from an extensive literature review, UIUC researchers determined that additional experimentation should focus on determining the causes of rail pad assembly slippage, the conditions in which it occurs, the relationship between the applied loads, and the magnitude of displacements. The pad assembly deformation characteristics and shear capacity are also topics that deserve research because they have an impact on the dissipation of the energy transferred in the system and also determine the elastic behavior of the fastening system.

Laboratory Experimental Setup

The development of a representative experiment to quantify the total lateral displacement of rail pad assemblies is critical to the understanding of the mechanistic behavior of this component. UIUC's experimental testing was performed at the Advanced Transportation Research and Engineering Laboratory (ATREL). 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 paper. 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 [7]. UIUC researchers recognize that moving wheel loads impart longitudinal forces onto the track structure that add complexity to the analysis of loads imparted to the track components.

A high-sensitivity potentiometer mounted on a metal bracket was attached to the gage side clip shoulder to capture the lateral motion of the pad assembly. The potentiometer plunger was in direct contact with the abrasion frame (Figure 2). In this case, the pad assembly consisted of a polyurethane pad and a nylon 6/6 abrasion frame (Table 1).

TABLE 1 Material Properties of the Experimental Rail Pad Assembly

Component	Material	Young's Modulus (psi)	Poisson's Ratio	Area (in^2)	Mass Density (lb/in^2)
Abrasion Frame	Nylon 6/6	440,000	0.350	38.250	0.049
Rail Pad	Polyurethane	7,500	0.394	36.600	0.068

(A) (B)

FIGURE 2 PLTM (A) and potentiometer (B) used to measure the rail pad assembly lateral displacement.

Field Instrumentation

In the pursuit of data to support mechanistic design of improved fastening systems, UIUC has undertaken a comprehensive effort to formulate a testing regime to analyze forces distributed through the track superstructure (10). 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, sufficiently tamped, spaced at 24 inch centers. The HTL was exposed to over 50 million gross tons (MGT) of freight traffic prior to testing. The loading environment was composed of a passenger train consist, a freight train consist, and a Track Loading Vehicle (TLV) with a deployable axle to achieve known static loadings (10). 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.

The experimentation was focused on understanding the load path through the system and its impacts on the track structure behavior. 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 pad assemblies were recorded using linear potentiometers mounted on metal brackets at 6 different rail seats (Figure 3). The pad assemblies were the same model used for the laboratory instrumentation, with material properties specified in Table 1.

Regarding the rail base lateral displacement, it was only recorded at the four rail seats located in the center part of each section (Figure 4).

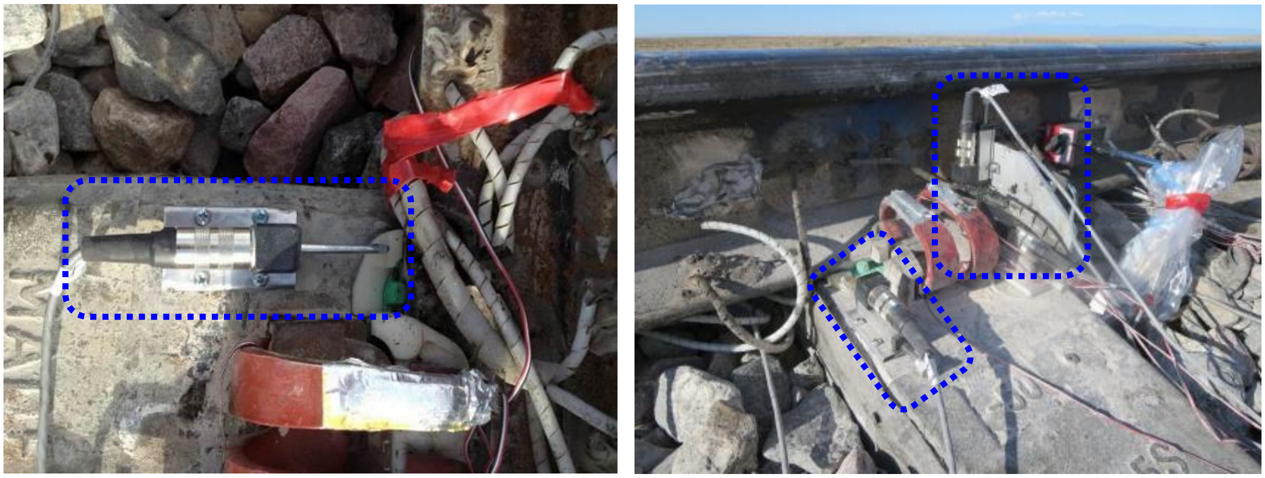

FIGURE 3 Potentiometers used to capture pad assembly lateral displacement and rail motion.

To aid the analysis of data, both track sections had the same instrumentation layout and naming convention. Figure 4 presents the naming convention and the location of the instrumentation used to measure rail pad assembly lateral displacement, and rail base lateral displacement. 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.

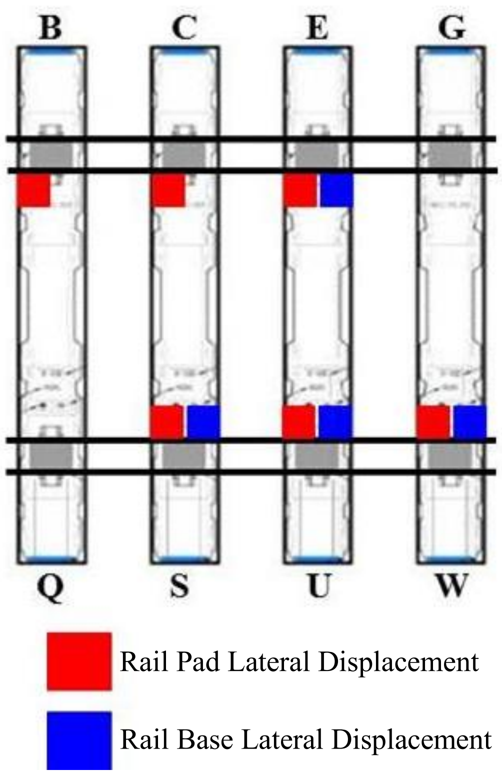

FIGURE 4 Location of instrumentation and naming convention for rail seats and cribs located at the RTT and HTL track sections.

RESULTS FROM EXPERIMENTATION

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 and vertical forces. The dynamic test used the same loading protocol, and the loading rate was 3 Hz. For each test the maximum lateral displacement was recorded. The behavior of the pad assembly can be observed in Figures 5 and 6. The maximum displacement was equal to 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, almost assuming a linear behavior. Even for small lateral loads, displacements were recorded, indicating the occurrence of relative slip between the rail pad assembly and the rail seat even under less severe loading scenarios. As expected, the magnitudes of these displacements were relatively small, since there are small gaps between the rail pad assembly and the shoulders in the rail seat area. 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. Based on these results, we believe that manufacturing tolerances and the resulting fit of components have a measurable impact on the maximum recorded displacements.

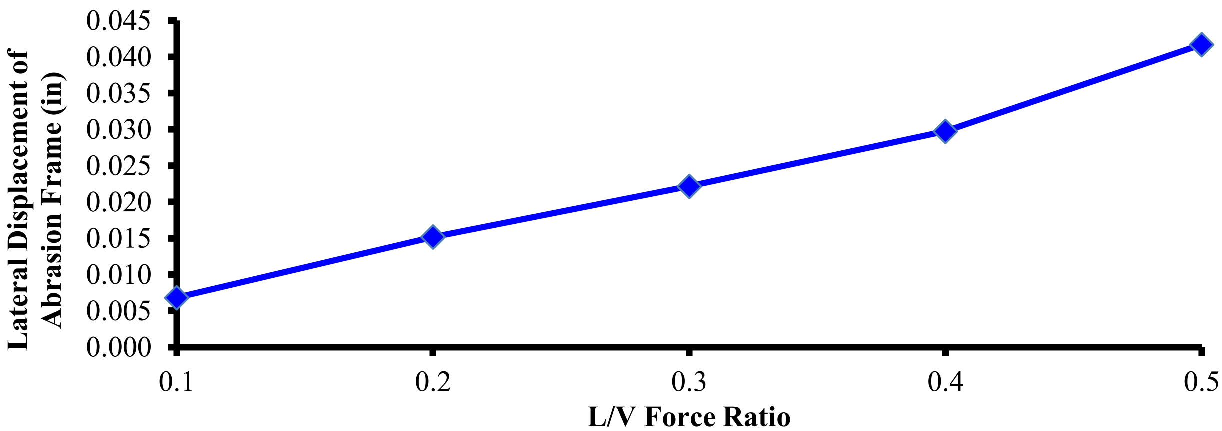

FIGURE 5 Lateral displacement of the abrasion frame with 36,000 lbf (160kN) vertical load for increasing L/V force ratio.

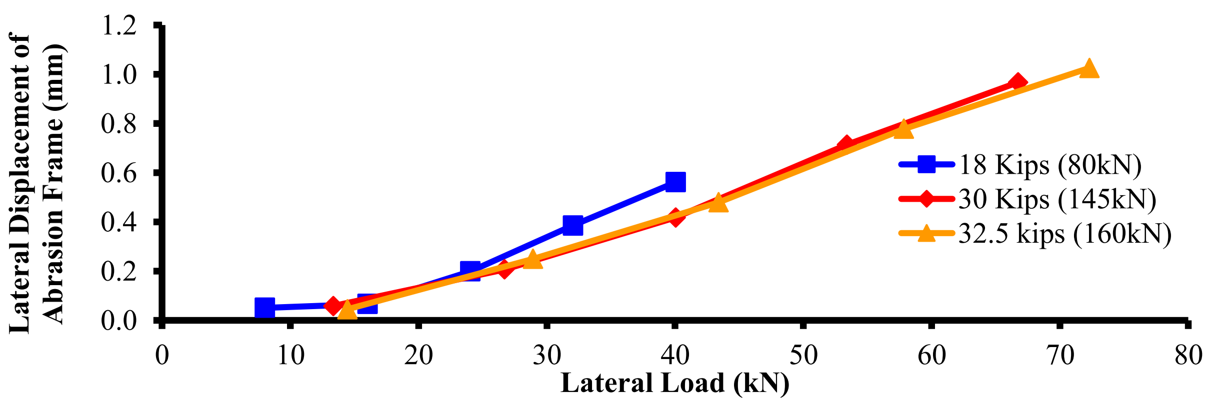

FIGURE 6 Lateral displacement of the abrasion frame for increasing lateral loads.

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), its effects on the lateral displacement behavior are not evident when lower lateral loading cases 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, despite the 14,500 lbf (65kN) difference between the minimum and maximum vertical force applied. However, given the results obtained from this experiment, it is plausible that lower lateral loading cases are 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 clip 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.

Field Results

Three distinct loading methodologies were employed as a part of 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. For comparison purposes, the field instrumentation analyses will be focused on the TLV data to allow a parallel investigation of the pad assembly behavior for the field and laboratory results obtained. 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 and they will be the focus of future work.

During the TLV runs, vertical loads of 20 kips (89kN) and 40 kips (178kN) were applied to the track statically, with the L/V force ratio varying from 0.1 to 0.55. These L/V ratios represent the wide range of loads that are encountered, including severe loading conditions that are typically observed on high tonnage freight service. For a 40 kip (178kN) vertical load applied at crosstie CS on the RTT, the maximum lateral pad assembly displacement recorded was approximately 0.006 in (0.15 mm) at rail seat E for a 0.55 L/V. The rail base lateral displacement behavior was similar to what was recorded for the pad assembly, however, the magnitude of the displacement was higher. The maximum displacement recorded for the rail base was approximately 0.04 in (1 mm) at rail seat S, at the same location of the load application. An increase in lateral load resulted in the increase of lateral displacement for both the rail base and the rail pad, which is similar to the behavior captured on the PLTM. The difference in the displacement magnitude between the two components is evident in Figure 7, where the rail base has experienced a lateral movement seven times higher than the rail pad assembly. A variety of factors may have led to difference in displacement magnitude and the location where the maximum displacements occurred. Differences in the rail seat geometry and variation in shoulder spacing are two parameters that can significantly restrain the pad assembly motion. 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, since all the interfaces of this component interact within the fastening system. At rail seats C and S, where the vertical load was applied, the vertical force is likely to have increased the frictional forces in the rail pad assembly interfaces, since the maximum displacement for this component was recorded at rail seat E. For vertical loads applied at different locations, similar behavior and magnitudes of displacements were captured. Subtle differences may be due to variations in supporting conditions at each crosstie, lack of perfect orthogonally in the lateral load application, and differences in seating loads at each rail seat.

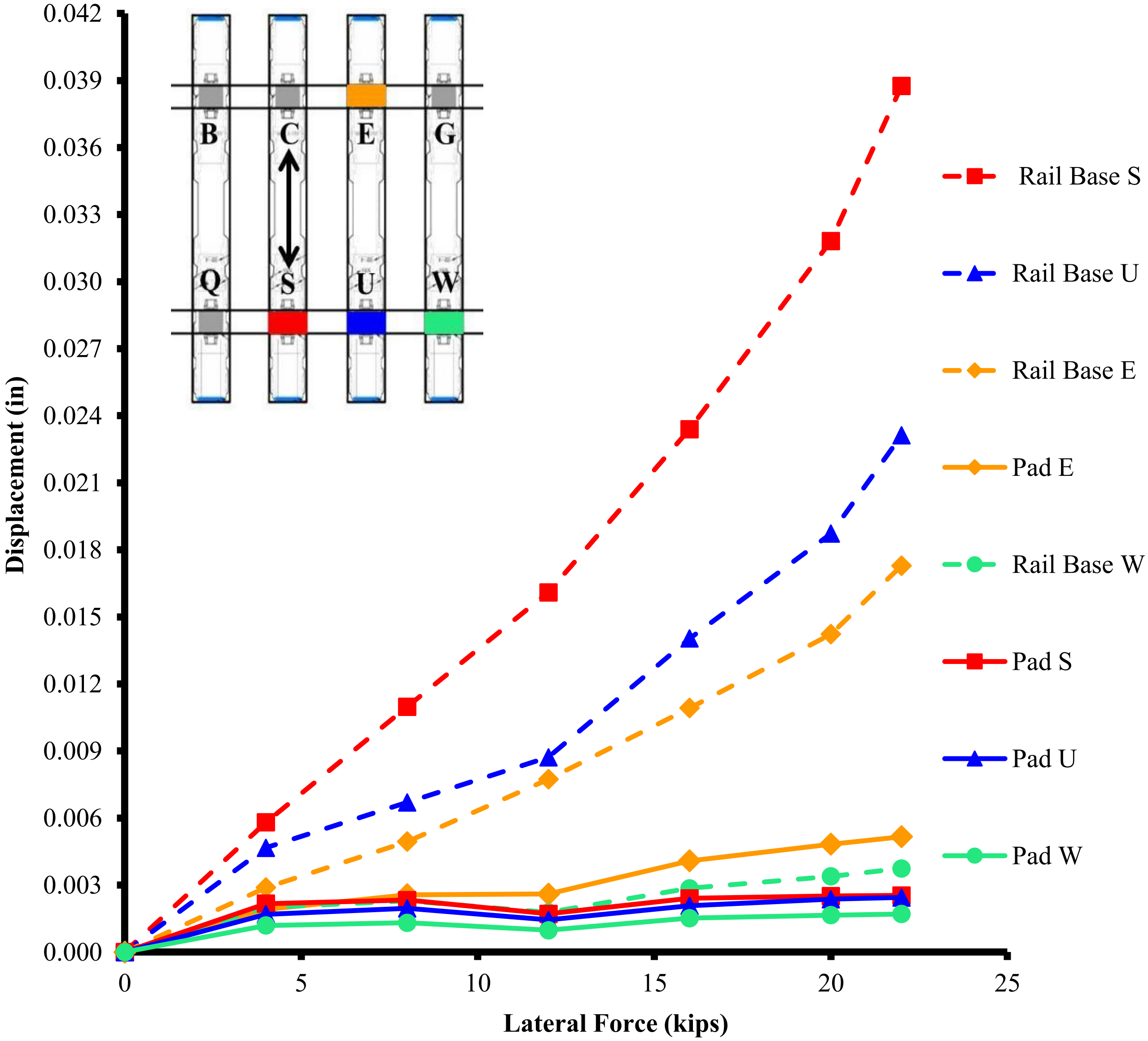

FIGURE 7 Rail base and rail pad assembly lateral displacement for increasing lateral loads with a 40 kip (178 kN) vertical load (RTT, tangent track).

The magnitude of the displacements observed in the field was smaller than the measurements recorded using the PLTM. This result is likely due to the restraint of adjacent fastening systems, resulting in better lateral load distribution throughout the track structure. Additionally, the rail longitudinal rigidity appears to have contributed to the distribution of loads, by reducing the rail pad assembly and rail base movement. In the PLTM, the actuators are enclosed in a head that encapsulates the rail, preventing this component from providing additional resistance to the forces applied in the system.

Relative slip between the rail base and the pad assembly was recorded for all analyzed rail seats (Figure 8). The difference in relative displacement increased as the lateral force on the system increased. The relative slip between the rail base and pad assembly indicates that a possible occurrence of shear at the rail pad assembly interfaces. If further experimentation indicates that shear is one of the predominant behaviors of the pad assembly, shear must be taken into consideration in the design of rail pad assemblies.

For crosstie GW, which is located two crossties away from the load application, the rail base and the rail pad assembly lateral displacements were significantly smaller than the displacements measured on the other crossties. This result points the range of action of lateral displacements as a result of loads action applied to the track. After two crossties, approximately 48 inches (1219mm), the track is able to absorb and completely transfer all the loads throughout the system. Only minor displacements and/or deformations on the components should be observed at distances greater than 48 inches (1219mm) (Figure 8-D). The rail base lateral displacement has a clear tendency to increase as the lateral load increases, but this trend is less evident for the rail pad assembly. As previously discussed in this paper, factors related to the rail seat geometry, frictional forces, and boundary constraints at these components interfaces are likely causes of this difference in lateral displacement magnitude.

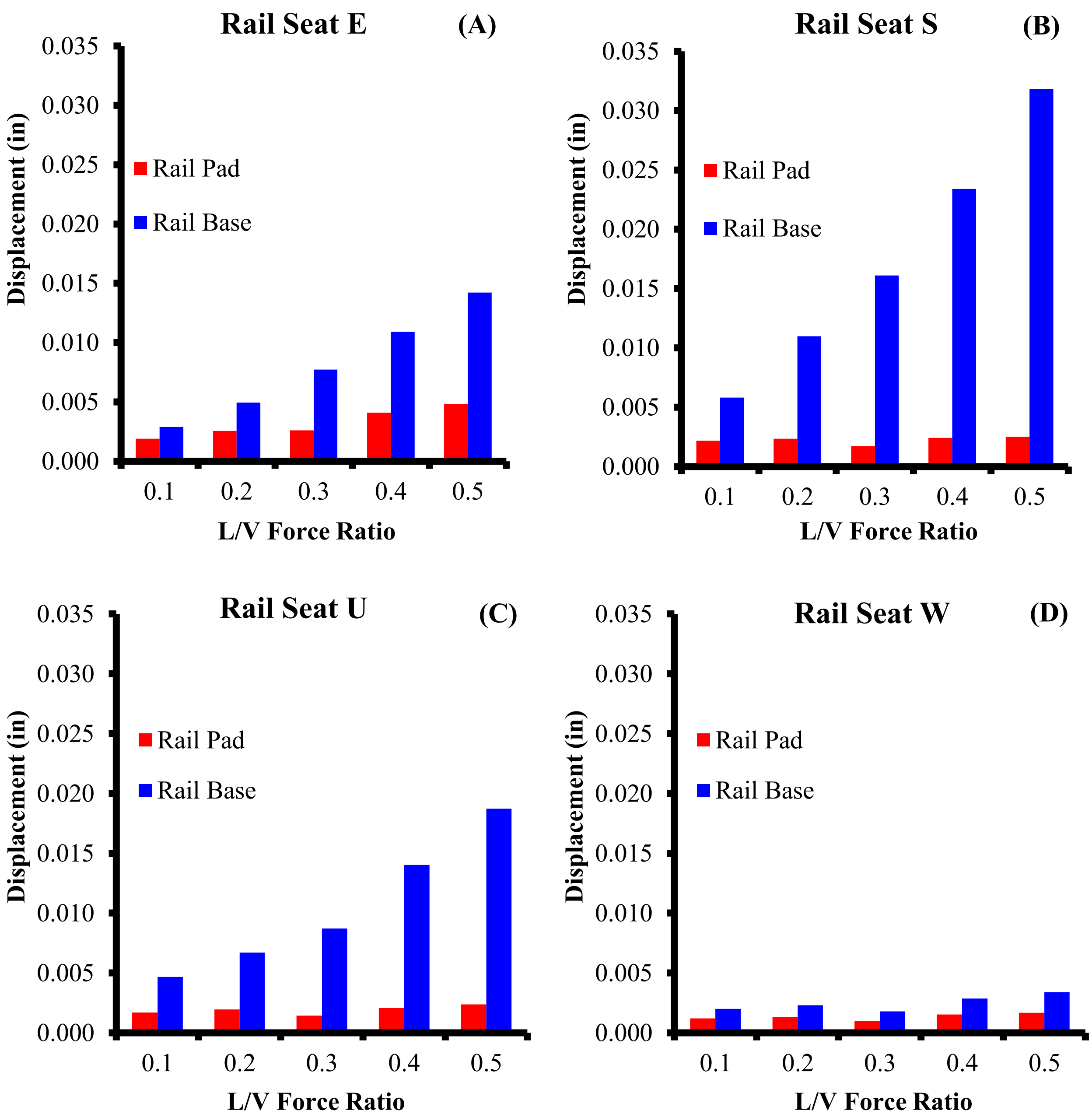

FIGURE 8 Relative lateral displacement between rail pad assembly and rail base for varying L/V force ratio at 40 kips vertical load applied at crosstie CS.

CONCLUSIONS

Gaining a greater understanding of the mechanistic behavior of the rail pad assembly is of paramount importance in the development of improved fastening system components. The lateral and longitudinal displacement of the pad assembly is frequently associated with failure modes related to the fastening system, especially the abrasion mechanism. The occurrence of relative displacement between the pad assembly and rail seat was measured in the experiments carried out in the laboratory at UIUC and in the field at TTC.

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 concrete crosstie rail seat, possibly initiating a wear and degradation process that is intensified by severe loading cycles. Another important aspect associated with the lateral displacement is related to the high dependency of this variable on the lateral loads applied on the system. The consistent increase in the lateral load directly affected the magnitude of the lateral displacement for both lab and field investigations. On the other hand, only high magnitudes of vertical loads appeared to affect the lateral displacement of the rail pad assembly from the results obtained with the laboratory experimentation. Considering that lateral and longitudinal displacements must be eliminated or minimized to prevent abrasion, additional research should focus on the relationship between component tolerances and geometry and its impact on life cycle of the fastening system and potential mitigation of RSD.

The range of displacement influence (in the longitudinal direction of the track) due to the application of the loads on the rail pad assembly was approximately two crossties. Relative lateral slip between the rail base and the rail pad assembly was identified during the field tests. Based on our results, these two components displace relative to each other with an increase in lateral loads, likely resulting in increased shear demands exerted on the pad assembly. This result points 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.

FUTURE WORK

Future work will be focused on analyzing the field data collected for train runs over both of the instrumented track sections. This research will determine the effects of realistic loading scenarios on the lateral and longitudinal movement of the rail pad assembly. Additionally, possible research topics at UIUC will investigate the influence of the clamping force and rail pad assembly design on the shear behavior of this component. An improved design of rail pad assemblies must take into account the characteristics of the shear behavior under different service levels. After fully developed, this research will lead fastening system design into a mechanistic approach, resulting in recommendations that will reduce the need for preventive measures and maintenance related to track component deterioration.

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