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Concrete Crosstie Fastener Sub-System Testing and Modeling

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Concrete Crosstie Fastener Sub-System Testing and Modeling

Introduction

The primary objective of this project is to identify methods of improving concrete railroad crosstie fastening system design and performance by conducting a thorough investigation of the behavior of the fastening system using Finite Element Analysis (FEA) and fundamental laboratory experiments.

This project will focus specifically on the rail pad assembly and its contact interfaces with the concrete rail seat and rail base, respectively. The propensity of rail pad assemblies to resist lateral translational movement at the most critical interfaces will be evaluated for a variety pad moduli, thicknesses, frictional characteristics, etc. The effectiveness of altering the flow of shear forces through the pad assembly will be evaluated. By improving our understanding of the forces and displacement at various interfaces within the fastening system, sacrificial layers and components can be designed in order to ensure that relative movement and shear force transfer occurs at the most wear-resistant interfaces.

Approach and Methodology

The work will begin with a thorough literature review of all previous research aimed at understanding the behavior of the crosstie and fastening system as well as concrete bearing pads (i.e. rail pads). This literature review will add to a detailed load path mapping exercise that is being developed with matching funding that will allow for the characterization of forces that are transferred through the fastening system using a free body diagram approach.

By a combination of fundamental laboratory testing and analytical modeling, this project will initiate an effort to characterize and quantify the effect that the properties of the components that make up the fastening system, specifically the rail pad assembly, have on the magnitude of displacement that occurs a critical interfaces (e.g. concrete rail seat). The fundamental small-scale laboratory tests will be designed to quantify the load-deformation behavior of full-scale pad assemblies under static loading.

The results from these tests will serve to calibrate a model of the pad assembly that will be used to test a variety of hypotheses related to the movement of the pad layers relative to the rail seat and rail base. A parametric analysis will be performed in order to understand the relationship between the coefficients of friction at each interface, the stiffness of each layer, and the shape of the pad and abrasion frame.

Additionally, full-scale system testing in the laboratory and field instrumentation will be conducted with matching funding that will facilitate the comparison of the results from this study with pad movement in the field. Strong participation from fastening system manufacturers enable us to test and understand the behavior of pad assemblies.

Findings

This study investigates the mechanical responses of rail pad assemblies within the concrete crosstie fastening system, focusing on the lateral relative displacement between this component and the concrete crosstie rail seat and rail base. This work, coupled with previous rail seat deterioration research at UIUC, will facilitate more effective designs (e.g. improved materials selection or geometric design). Research in the future can include refined models of the fastening system, and parametric analyses of the fastening system with a variety of components designed as sacrificial layers.

Conclusions

The results indicate that the relative displacement is highly dependent on the magnitude of the lateral wheel load applied to the system. Higher displacements were captured for increasing lateral forces. Laboratory and field experiments have shown that vertical wheel loads appear to affect relative displacements, probably caused by the increase in frictional forces in the bearing area of the rail seat. The geometry of the rail seat and the dimensions of the rail pad (e.g. rail seat area, cast-in shoulders face to face distance, etc.) were also factors that seemed to play a role in the magnitude of relative displacement between rail pad assembly and crosstie rail seat, indicating the importance of more strict geometric design tolerances to ensure a tighter fit of components. Additionally, differences in lateral displacement of the rail base and the rail pad were captured, pointing to the possible occurrence of shear slip at this interface.

Recommendations

Uncertainties related to the fastening system deterioration causes coupled with a lack of understanding regarding the mechanical interactions among components, led the railroad industry to pursue design modifications. Attempts to enhance the life cycle and performance of components were developed based on empirical design approaches, usually relying on the increase of robustness and stiffness to overcome the loading demands and withstand wear rates. An improved design methodology for rail pad assemblies should be based on a mechanistic approach, where material properties, relative displacements, stress distribution, and component deformation are taken into consideration when optimizing its geometry and performance. The authors of this report suggest conducted funding in the arena of mechanistic design of infrastructure components, including but not limited to the rail pad assembly.

Publications

do Carmo, T.B., J.R. Edwards, R.G. Kernes, B.O. Andrawes and C.P.L. Barkan. 2014. Laboratory and Field Investigation of the Rail Pad Assembly Mechanistic Behavior. *In: Proceedings of the 2014 Joint Rail Conference*, Colorado Springs, USA, April 2014.

do Carmo, T.B., J.R. Edwards, R.G. Kernes, C.P.L. Barkan and B.O. Andrawes. 2014. Mechanistic Behavior of Concrete Crosstie Fastening System Rail Pad Assemblies. *In: Proceedings of Transportation Research Board 93rd Annual Conference,* Washington, D.C, January 2014.

do Carmo, T.B., J.R. Edwards, R.G. Kernes, B.O. Andrawes and C.P.L Barkan. 2013. Analysis of the Shear Behavior of Rail Pad Assemblies as a Component of the Concrete Sleeper Fastening System. *In: 2013 World Congress on Railway Research*, Sydney, Australia, November 2013.

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SECTION 1 INTRODUCTION

1.1 *Background and Motivation*

To meet the increasingly rigorous performance demands due to growing heavy-haul freight operations and increased high-speed inter-city passenger rail development worldwide, advancements in concrete crosstie fastening system designs are imperative. In North America, a limited understanding of the complex loading environment affecting the concrete crosstie and elastic fastening system components led to an empirical design process based primarily on previous timber crosstie fastening system design techniques, which fail to incorporate loading demands and loading paths of a concrete crosstie (Van Dyk 2013). This process has generated components that are unable to achieve their intended design life.

Given the rail pad assembly is in contact with most components within the concrete crosstie fastening system, undesired changes in its mechanical behavior and material properties may ultimately affect the performance of all other components. The investigation of the mechanical responses of rail pads subjected to a realistic loading environment must be considered as a key factor in the development of this product, since its deformation and relative displacement may be used to prevent excessive demands on the track superstructure (Rhodes 2013). Additionally, the capacity of the rail pad assembly to dissipate the high stresses that are generated under severe operating conditions can also be used to improve the performance and increase the life cycle of the fastening system (Rhodes 2013).

1.2 *Study Objectives*

This study investigates the mechanical responses of rail pad assemblies within the concrete crosstie fastening system, focusing on the lateral relative displacement between this component and the concrete crosstie rail seat and rail base. Initially, a Failure Mode and Effect Analysis (FMEA) was conducted to define, identify, and evaluate failures causes and effects related to rail pads. This study can serve to guide the process of answering questions related to the component behavior and set the groundwork for future phases of research. Laboratory and field experiments were carried out at the University of Illinois at Urbana-Champaign (UIUC) and the Transportation Technology Center (TTC) in Pueblo, Colorado, where multiple realistic loading regimes were imposed to the fastening system to gain understanding of the mechanics of rail pad assemblies.

SECTION 2 FAILURE MODE AND EFFECT ANALYSIS (FMEA) OF CONCRETE CROSSTIE RAIL PAD ASSEMBLIES

2.1 Failure Mode and Effect Analysis (FMEA)

A failure mode and effect analysis (FMEA) is a technique developed in the mid-1960's by reliability engineers in the aerospace industry to increase the safety of products through the development or manufacturing processes. Later, the automotive industry recognized the advantage of using this tool to reduce risks related to poor quality (McDermott 2009). In summary, the FMEA is used to define, identify, evaluate, and eliminate failures before they occur. The FMEA represents a proactive process, and involves the systematic analysis of failure modes with the objective of detecting potential causes and investigating their effects on the system. From this type of analysis it is possible to identify actions that must be taken to reduce the probability of failure (Stamatis 1995). Additionally, the FMEA provides historical documentation for future reference to aid in the analysis of field failures and the possible evolution of design, manufacturing, installation, and maintenance practices.

The general FMEA procedure (Figure 2.1) begins by determining the desired functions of the product, and these functions serve as guiding parameters for the study. Then, the different manners in which failures manifest themselves in the product (i.e. failure modes) are identified. Next, the potential consequences, usually referred to as "failure effects", are analyzed. After these steps, the causes are identified and investigated, allowing the development of preventive measures to reduce the risk of failure occurrence. This chapter will focus on the detection, causes, and effects of failure mechanisms in rail pad assemblies, since the development of preventive measures demand a deeper understanding of the component mechanics.

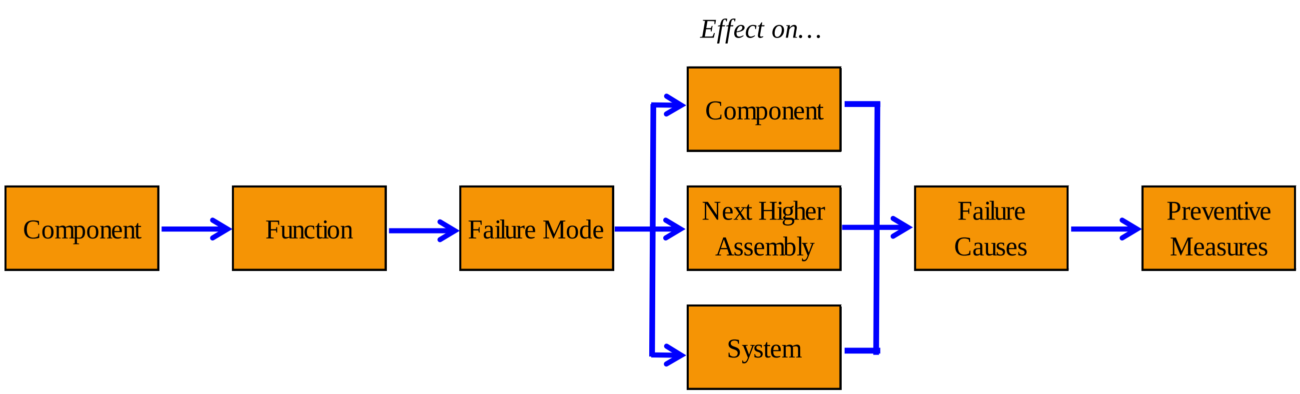


Figure 2.1 FMEA diagram characterizing the critical steps related to the analysis process

After combining the input from laboratory and field investigations, railroad infrastructure experts, fastening system manufactures, and railway industry technical committees, a simplified FMEA for the rail pad assembly was developed. The FMEA guided the process of answering questions related to component behavior and helped to propose design and material properties recommendations to enhance the safety and durability of rail pad assemblies.

2.2 Rail Pad Assembly Functions

The rail pad assembly is the core of the fastening system, and directly affects the transfer of vertical wheel loads through the track superstructure. It provides an interface for force distribution between the rail and the crosstie rail seat. Therefore, one of its main functions is to provide impact attenuation and protection for the rail seat bearing area. Furthermore, the rail pad assembly is designed to insulate the crosstie from track circuits, preventing the occurrence of track circuit shunting. The preservation of desired track geometry is also another function required of the rail pad assembly. Possible failures within this component may significantly affect the original configuration of the fastening system and ultimately result in loss of clamping force, rail seat deterioration (RSD), and gage widening.

2.3 Failure Modes

Failure modes result from the failure of a component to perform its designed function, and represent the way in which it "functionally" fails at a component level (McDermott 2009, Stamatis 1995). Rail pad assemblies fail in different patterns, usually involving the degradation of the component's materials and loss of original geometry. The following sections will discuss typical failure modes associated with rail pad assemblies.

Tearing

Tearing is a common failure mode observed in rail pad assemblies. It is defined as shear stresses acting parallel to the plane of the crack and perpendicular to the crack front, which break the interparticle bonds of the material (ISO 34-1 2004). In the context of the fastening system, cyclic loads exerted on the rail seat area act on the rail pads, generating stresses on the component capable of breaking the material into multiple pieces. Materials present different levels of susceptibility to tearing and, even though some provide high resistance while they maintain their original shape, they become weak and compromised as their geometry changes. The tearing process is likely to be accelerated with material degradation, which increases the vulnerability of the component to an aggressive degradation process. This failure mode has been observed in different kinds of rail pad assemblies and is not related to a specific type of design or geometry (Figure 2.2). Furthermore, torn pad assemblies are usually unable to appropriately attenuate vertical loads and maintain the desired track geometry, since this failure mode often intensifies the component's loss of material, changing its geometry.

Figure 2.2 Example of tearing as a failure mode of rail pad assemblies

Crushing

Crushing is a failure mode associated with the concentration of vertical and lateral forces acting on the rail pad assembly. When loads overcome the compressive strength of the component, it is permanently deformed and loses its original configuration (Figure 2.3). This failure mode can be extremely harmful to the fastening system because it prevents the pad assembly from properly attenuating the loads imposed on the rail seat. After reaching the yield strength, which is an intrinsic material property, the accommodation of elastic deformation on the rail pad assembly is compromised. As a result, the distribution of stresses within the rail seat area is affected and the pressure demands on the crosstie are intensified, which may also contribute to rail seat deterioration (RSD). The likelihood of crushing occurring on rail pad assemblies is greater on tracks that operate heavy axle load freight service, since the vertical, lateral, and dynamic loads imposed on the fastening system components are much higher.

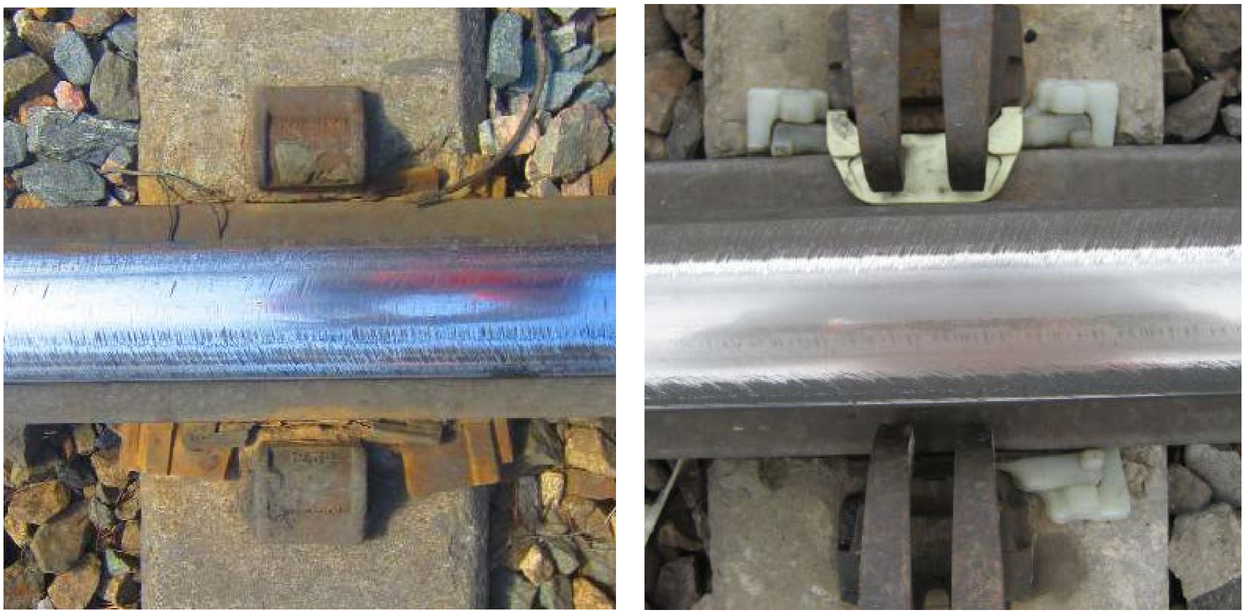


Figure 2.3 Examples of crushing as a rail pad assembly failure mode

Abrasion

Abrasion occurs as frictional forces act between two surfaces that move relative to one another, and a harder surface cuts or ploughs into the softer surface resulting in the removal of a portion of the softer material (Bayer 2004, Williams 1997, Kernes 2013). Typically, abrasion is classified as either two-body abrasion or three-body abrasion. Two-body abrasion occurs when the contact points, often referred to as protuberances (or asperities), on one surface are harder than the other surface. Three-body abrasion occurs when hard particles that are not part of either surface are present at the contact interface and slide and roll between the two surfaces (Bayer 2004, Williams 1997, Kernes 2013).

In rail pad assemblies, abrasion can be caused by relative slip between fastening system components. The abrasion process usually manifests itself as three body-wear, and involves the concrete crosstie rail seat, rail pad assembly, and abrasive fines. Additionally, three-body wear can also be observed on the top surface of the rail pad assembly, where relative slip occurs between this component and the rail. This phenomenon is likely associated with the accumulation of corrosion debris and abrasive particles between the sliding interfaces. Typically, this failure mode can be easily noticed, since worn dimples and grooves are often visible on the abraded surfaces of the rail pad assembly (Figure 2.4).

Figure 2.4 Rail pads showing signs of abrasion effects

Rail Pad Assembly Slippage ("Pad Walk Out")

Another common failure mode related to the rail pad assembly is commonly referred to as pad "walk out". In this failure mode, the rail pad assembly translates partially or completely out of the rail seat area. As a result, the rail is in contact with the rail seat without any protective layer to reduce the impact loads and distribute the stresses (Figure 2.5). The wheel loads are then directly transferred from the rail to the crosstie, which can be extremely harmful for the integrity of the track superstructure, especially the rail seat. Furthermore, rail pad assembly slippage is a failure mode that can trigger other failure modes at important track components. The RSD process, for example, is much more likely to occur on a rail seat where the pad assembly has walked away rather than on a rail seat with a properly assembled fastening system. In many cases, improper installation of the rail pad assembly leads to this failure mode, which can also be intensified by the loss of the cast-in shoulders or the spring clips.

Figure 2.5 Examples of rail pad assemblies "walking out" of the rail seat

2.4 Failure Effects

To aid in understanding the consequences of a rail pad assembly failure, it is beneficial to divide the failure effects into three parts: 1) the effects on the component itself, 2) the effects on the next higher assembly (i.e. the adjacent components of the fastening system), and 3) the effects on the track system as a whole.

The failure effect on the pad assembly itself is the loss of the original geometry, usually observed as loss of thickness, permanent deformation, and changes in material properties. The loss of thickness is often related to the abrasion process, which is defined by the removal of material particles. Additionally, permanent deformations due to high loads can also reduce the thickness of the rail pad assembly if they are capable of overcoming the yield strength of the materials that make up the component (e.g. the pad assembly subjected to crushing). Lateral and shear forces may also act on this component contributing to the intensification of the demands that degrade the pad assembly original geometry. Once the degradation process has initiated, the aforementioned failure modes have the capability to impact the component original material properties. Tearing strength, abrasion resistance, shear strength, compressive strength, water absorption, and impact attenuation are a few properties that are likely to change as failure modes act on rail pad assemblies.

The effects on the next higher assembly, the adjacent components of the fastening system, are considered to be the change in the desired load path through each component. The rail pad assembly loss of original geometry associated with a change in material properties is likely to impact the intended behavior of the fastening system components. The reduction of thickness, for example, is able to directly impact the desired clamping force, since the vertical displacement on the rail clips is reduced. As a result of less restraint, the movements of the rail and also the other fastening system components are increased, allowing components to undergo higher relative displacements. Another interesting case of change in the desired load path occurs when the pad walks out of the rail seat. When this phenomenon takes place, the vertical, lateral, and shear forces on the system are directly transferred from the rail to the crosstie rail seat without a layer that provides impact attenuation and stress distribution. The demands on the concrete significantly increase, and the concrete, which was not designed to withstand such high demands starts to wear, and possibly fail. Therefore, failure modes associated with rail pad assemblies are likely to trigger more intense wear processes on the other components of the fastening system.

Regarding the track system, the effects most commonly manifest in terms of the geometry of the track superstructure. Gauge widening, which is the increase of the distance between rails beyond the design limits, is one common system effect related to rail pad assembly failures. Loss of cant, usually associated with the RSD mechanism, is also another possible system effect that results in higher forces and moments on the rail. As a consequence, longitudinal rail movement can be observed in tracks with deteriorated rail pad assemblies. All of the aforementioned effects result in the need for more periodic maintenance, a reduction in the life cycle of fastening system components, a loss of track geometry, and increase in the risk of derailments.

2.5 Failure Causes

The rail pad assembly was used as the focus of a FMEA study, which has identified four principal failure modes of this component: crushing, tearing, rail pad "walk out", and abrasion. For each of the failure modes, there are multiple root causes that result in a loss of functionality. Some of these causes are listed in Table 2.1 to assist the prevention of failure modes.

Table 2.1 Potential failure causes related to rail pad assemblies failure modes

Failure Modes	Potential Failure Causes
Tearing	High localized compressive stress High localized shear stress Low tearing strength of material Rail pad assembly material deterioration
Crushing	High compressive stress Low compressive strength of material Rail pad assembly change in stiffness Concentration of stresses on a particular area of the rail seat
Abrasion	Relative slip between rail pad assembly and crosstie rail seat Relative slip between rail pad assembly and rail Intrusion of abrasive fines Intensified slip and deterioration caused by the intrusion of moisture Rail pad assembly material deterioration
Pad Assembly "Walk Out"	Damage or loss of the cast-in shoulder Damage or loss of the spring clip Rail seat deterioration Relative slip Erroneous installation

The FMEA provides a qualitative understanding of the degradation processes observed in the fastening system, particularly in the rail pad assembly, and also its effects on the system structure. This study sets the foundation for the mechanistic investigation of the rail pad assembly behavior, which is motivated by the cause and effect relationship developed for the failure modes observed on this component.

The criticality of each failure mode is strongly related to its likelihood of causing failure effects, the severity of these effects, and the difficulty to detect them when failures occur (Stamatis 1995). Prior research conducted at UIUC focused on investigating the criticality and the behavior of physical mechanisms that contribute to RSD (Zeman 2011, Kernes 2013). Abrasion was found to be one of the principal causes of this phenomenon. The abrasion process occurs when the rail pad assembly moves relative to the rail seat, in a process that wears one or both of these components (Zeman 2011, Kernes 2011, Shurpali 2013, Kernes 2013). Therefore, quantifying the magnitude of this relative motion when the system is subjected to a variety of loading scenarios is of paramount importance to the understanding of the mechanics and life cycle of rail pad assemblies. Even though relative displacement between the rail pad assembly and rail seat has been consistently described by experts as one of the main causes of failure (Kernes 2013), there is a lack of studies quantifying relative slip between these components. The rail pad assembly displacements and deformations under current load environments must be analyzed for the understanding of critical failure processes affecting the fastening system.

SECTION 3 LABORATORY AND FIELD INVESTIGATION OF RAIL PAD ASSEMBLY MECHANICAL BEHAVIOR

3.1 Laboratory Experimental Setup

To generate data to investigate the relative displacement between rail pad and crosstie rail seat, UIUC conducted experiments to formulate a realistic testing regime to simulate forces and motions generated through the fastening system. The experiments were performed at the Advanced Transportation Research and Engineering Laboratory (ATREL), on the Pulsating Load Testing Machine (PLTM). The PLTM 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). This equipment 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, simulating stiff support conditions. Loading inputs for this experiment were applied to the rail in the vertical and lateral directions, and no longitudinal load was applied due to constraints of the current test setup. 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, and the effect of longitudinal forces is an area in need of further research.

A high-sensitivity potentiometer mounted on a metal bracket was attached to the gage side cast-in shoulder to capture the lateral motion of the pad assembly. The potentiometer was in direct contact with the abrasion frame (Figure 3.2b). In this case, the rail pad assembly consisted of a polyurethane rail pad and a nylon 6/6 abrasion frame manufactured by Amsted RPS (Table 3.1 and Figure 3.1).

Table 3.1 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

Figure 3.1 Rail pad assembly used for the laboratory and field tests

(a) **(b)**

Figure 3.2 Images of (a) PLTM and (b) linear potentiometer and test set up used to measure the rail pad assembly lateral displacement

3.2 *Field Instrumentation Setup*

To quantify relative displacements of the rail pad assembly and rail base with respect to the rail seat, as well as many other response variables, researchers at UIUC formulated a testing regime to analyze forces distributed throughout the concrete crosstie and the fastening system (Grassé 2013). Two track sections were instrumented at the Transportation Technology Center (TTC) in Pueblo, CO. A tangent section was instrumented in 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 design curvature for the body of the curve was 5 degrees, but the local value was 2 degrees due to a geometry deviation that resulted from tamping around the instrumented section of track. For each location, 15 new concrete crossties and fastening systems were placed on the existing ballast, spaced at 24-inch centers, and machined tamped. The new crossties on the HTL were exposed to over 50 million gross tons (MGT) of freight traffic prior to testing (Grassé 2013).

Three distinct loading methodologies were employed as part of the field experimentation. First, loads were applied through the Track Loading Vehicle (TLV). The TLV is comprised of actuators with load cells that are coupled to a deployable axle that facilitates application of known loads through actual wheel-rail contact. Therefore, the TLV was used to create a static loading environment comparable to the one designed and deployed for laboratory experimentation. The other two loading scenarios consisted of a passenger train consist and a freight train consist operated at varying speeds. These two cases were implemented to capture the responses of the track components under dynamic and impact loading scenarios.

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 concrete crossties with metal brackets at six different rail seats (Figures 3.3 and 3.4). The components were the same type as those used for the laboratory experiments. Additionally, the lateral forces exerted 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.

Both track sections had the same instrumentation layout and naming convention for identifying the location of the instruments used to measure rail pad assembly lateral displacement and rail base lateral displacement (Figure 3.3). This study will only reference the instrumented crossties (BQ, CS, EU, and GW). At some locations, unique types of instrumentation do not overlap, which was intentional in the design of the instrumentation plan.

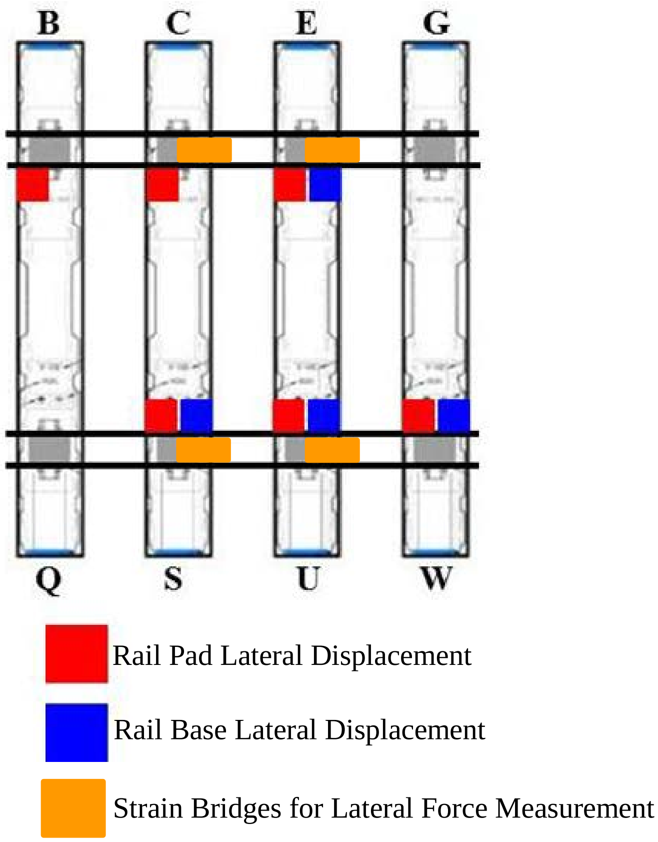


Figure 3.3 Location of instrumentation and naming convention for rail seats and cribs located at the RTT and HTL track sections

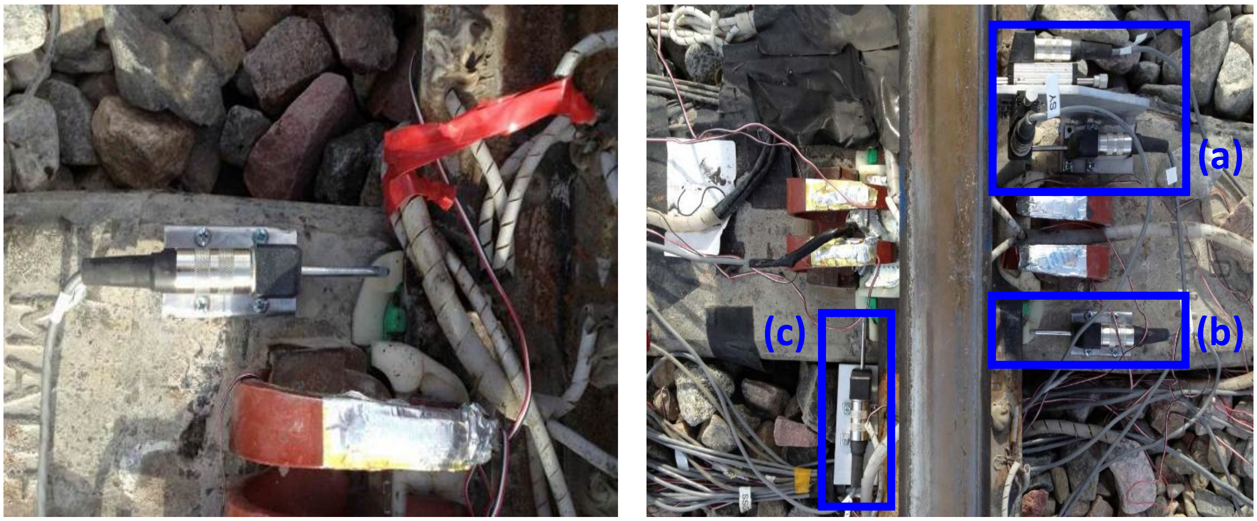


Figure 3.4 Field experimental setup showing instrumentation to measure (a) rail base translation, (b) rail pad lateral translation, and (c) rail pad longitudinal translation

3.3 *Laboratory results*

Lateral and vertical loads were applied to the rail during the tests carried out at ATREL on the PLTM, 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. Next, lateral loads were increased for each constant vertical force (18 kips, 30 kips, and 32.5 kips). The dynamic test used the same loading protocol, and the loading rate was 3 Hertz (Hz). The measured maximum displacement was 0.042 in (1.05 mm) for a 0.5 L/V ratio and a 36,000 lbf (160 kN) vertical load.

The displacement increased linearly with the variation of the lateral load (Figure 3.5). Even for a lateral load less than 2 kips, displacements were recorded, indicating the potential of relative slip between the rail pad assembly and the rail seat even under loading scenarios commonly associated with less demanding track geometry (e.g. tangent or shallow curves). As expected, the magnitudes of these displacements were small compared to the dimensions of the rail seat, since there are very small gaps between the rail pad assembly and the shoulders in the rail seat area that allow the rail pad to displace (Figure 3.6). When this test was repeated with different crossties, there was a variation in the maximum displacement higher than 50% based on the geometry and manufacturing differences. Therefore, it is likely that manufacturing tolerances and the resulting fit of components have a measurable impact on displacements.

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 (Rhodes 2005, Rhodes 2013) its effects on the lateral displacement behavior are not evident when lateral loads less than 6.3 kips (28 kN) were considered. For lateral loads up to 6,300 lbf (28 kN), vertical forces ranging from 18,000 lbf (80 kN) to 32,500 lbf (145 kN) 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 6,300 lbf (28 kN) despite the 14,500 lbf (65kN) difference between the minimum and maximum vertical force applied (Figure 3.6). 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. This is more evident when comparing the inclination of the curves, where the tests that were carried out using a vertical load 18 kips presented a much steeper curve compared to the other results.

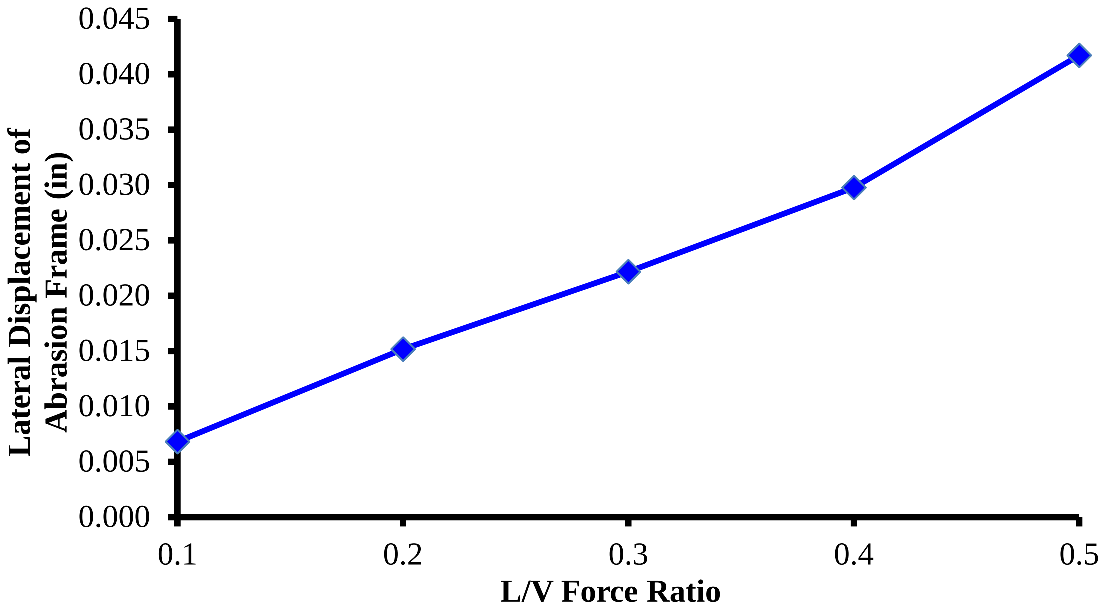


Figure 3.5 Lateral displacement of the abrasion frame with 36,000 lbf (160kN) vertical load for increasing L/V force ratio

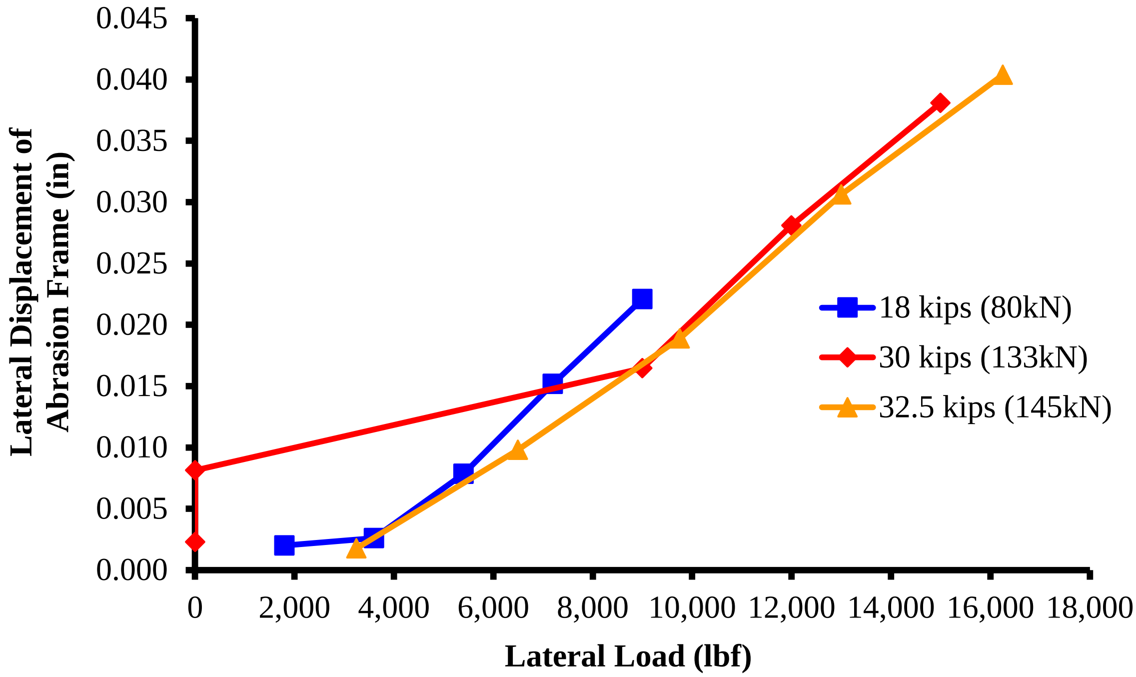


Figure 3.6 Lateral displacement of the abrasion frame for increasing lateral loads and constant vertical loads (18 kips, 30 kips, and 32.5 kips)

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, large 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 (Kernes 2013), it is possible to conclude that relative translation between the rail pad and crosstie rail seat equal to 0.125 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.

3.4 <u>Field results</u>

Track loading vehicle (TLV)

This section presents the results obtained for the TLV and train runs. First, the TLV static runs were analyzed to allow a comparison between laboratory and field experiments. Second, the data from the moving passenger and freight trains were investigated to allow the understanding of the track component responses under realistic dynamic loading scenarios.

During the TLV runs, static 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 common range of loads that are encountered in the field, including some of the 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 was approximately 0.006 in (0.15 mm) at rail seat E for a 0.55 L/V. 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 3.7, where the rail base has experienced lateral movement seven times higher than the rail pad assembly.

A variety of factors may have led to this difference in displacement magnitude and the position 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 gives more freedom for this component to move within the rail seat area. 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. Differences in behavior may be caused by variations in supporting conditions at each crosstie, challenges in alignment during the lateral load application, and differences in the load required to settle and close gaps at each rail seat (seating loads).

The magnitude of the displacements observed in the field was smaller than the measurements recorded using the PLTM. This result is likely due to lateral load distribution throughout the track structure provided by the restraint of adjacent fastening systems. Additionally, the rail's longitudinal rigidity appears to have contributed to the distribution of loads, by reducing the rail pad assembly and rail base movement. In the PLTM, unlike the field, the entire lateral force is resisted by one rail seat.

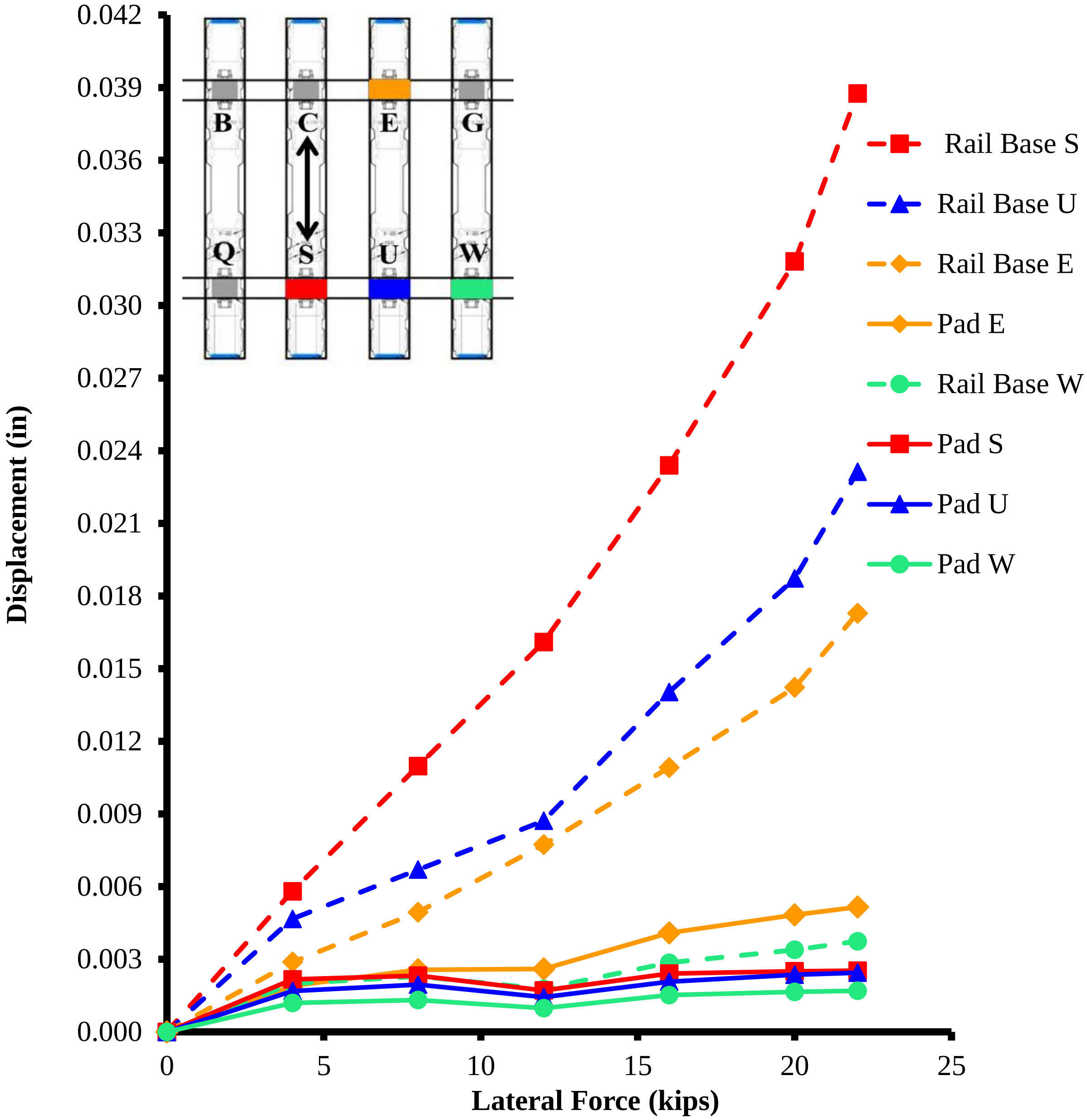
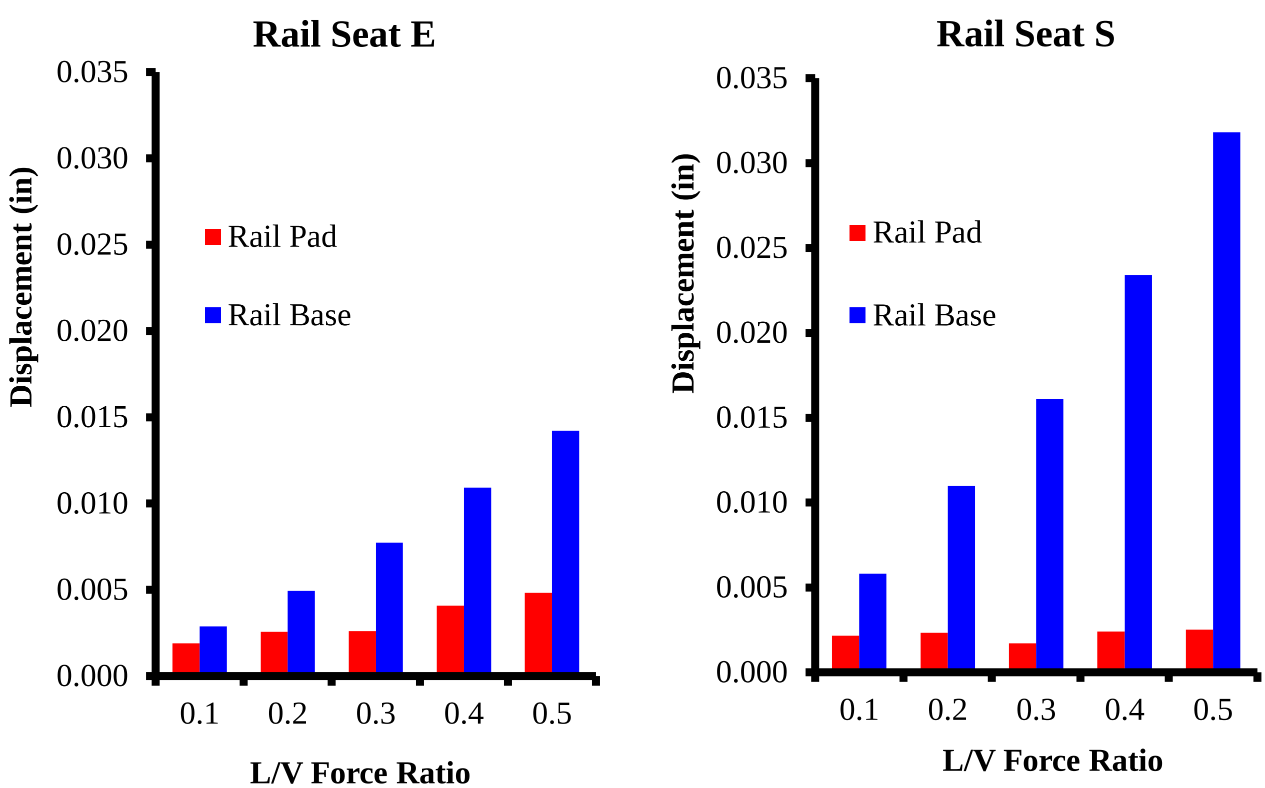


Figure 3.7 Rail base and rail pad assembly lateral displacement for increasing lateral loads with a 40 kip (178 kN) vertical load (RTT, tangent track)

Relative slip between the rail base and the pad assembly was recorded for all rail seats (Figure 3.8). 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 a possible occurrence of shear at the rail pad assembly interfaces, which supports the feasibility of hypothesis “b”. Therefore, this motion should 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 lateral displacements were significantly smaller than the displacements measured on the other crossties. This result points to lateral load path and lateral load distribution as the demands are dissipated in the structure. The track is able to resist and transfer all the lateral loads throughout the system among three crossties (24 inches in either direction from point of load application). Only displacements and/or deformations smaller than 0.003 inches on the components were observed at distances greater than 48 inches (1220 mm) (Figure 3.8d). 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 thesis, 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.



(a) (b)

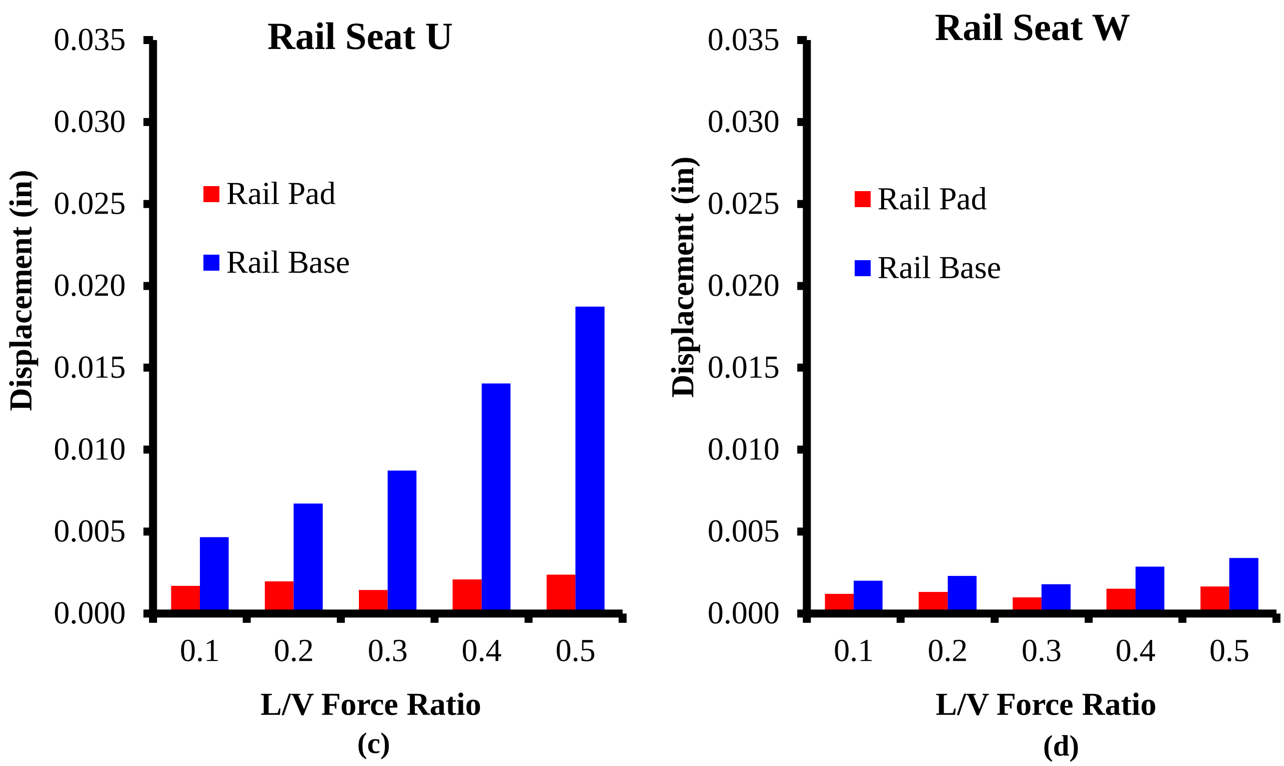


Figure 3.8 Relative lateral displacements between rail pad assembly and rail base for varying L/V force ratio at 40 kips vertical load applied at crosstie CS

Train runs

The freight train consist was the loading scenario that was expected to impose the highest demands on the track components, resulting in higher deformations and displacements. This section will focus on results from 315,000 lbs (1400 kN) rail cars with vertical wheel loads of approximately 40 kips (178 kN). Rail seats "S" and "U" on the low rail are highlighted because these two locations had the necessary overlapping instrumentation necessary to simultaneously measure the rail pad displacement, rail base lateral displacement, and the lateral wheel loads imposed on the rail.

During the freight train runs, the speed was increased from 2 mph up to 45 mph. Initially, the strain gauges captured lateral average wheel loads of 18 kips (80 kN) and 21 kips (94 kN) 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 7.9 kips (35 kN) at rail seat "S" and 9.6 kips (43 kN) at rail seat "U" (Figure 3.9). The potentiometers placed on the rail pad "U" captured a maximum lateral displacement close to 0.004 inches (0.10 mm), which presented an increase in magnitude for increasing lateral wheel loads. The behavior of rail pad "S" also showed a trend of increasing in magnitude with respect to the increase in wheel load. However, the displacements were actually smaller as compared to the adjacent rail pad assembly (Figure 3.10). The behavior of the rail base lateral displacement also presented a direct relationship with the increase in lateral wheel load. Both potentiometers positioned at rail seats "S" and "U" captured an increase in lateral displacement magnitude for the increase in wheel load (Figure 3.11). The maximum rail displacement was close to 0.22 inches (5.5 mm), a value that is much higher than the displacements recorded for the rail pads. A possible explanation for the variation in displacements between these adjacent rail seats are differences in rail seat geometry and variation in shoulder spacing, which are two parameters that restrain the pad assembly's motion. The difference in magnitude between rail pad and rail base lateral displacement is likely related to the bearing restraints. Cast-in shoulders confine the rail pad assembly while insulators confine the rail base, and shoulders are stiffer than insulators. Additionally, the rail pad assembly is subjected to frictional forces at most of its surfaces, which forces this component to interact within the fastening system on its top and bottom surfaces, reducing its movements. Loads of similar magnitudes resulted in different displacements of the rail pads on rail seats "U" and "S". This variation is likely due to the inherent crosstie-to-crosstie variability in support conditions, possible variable and distinct local stiffness of the fastening systems, and geometric variations in the rail seats that may lead to differences in gaps between rail pad and shoulders. This last parameter is a function of the manufacturing tolerances, which are largely governed by the shoulder-to-shoulder distance.

As a result of field experimentation, the relative displacement between the rail pad and crosstie rail seat and the relative displacement between rail base and crosstie were successfully captured during train runs, supporting the hypothesis that predicted the existence of this motion under realistic loading environments (hypothesis "a"). The final displacement observed for the rail pads were approximately 40% greater than the initial measurements. Compared to the static results obtained from the laboratory experiments (Figures 3.5 and 3.6), these displacements were one order of magnitude smaller.

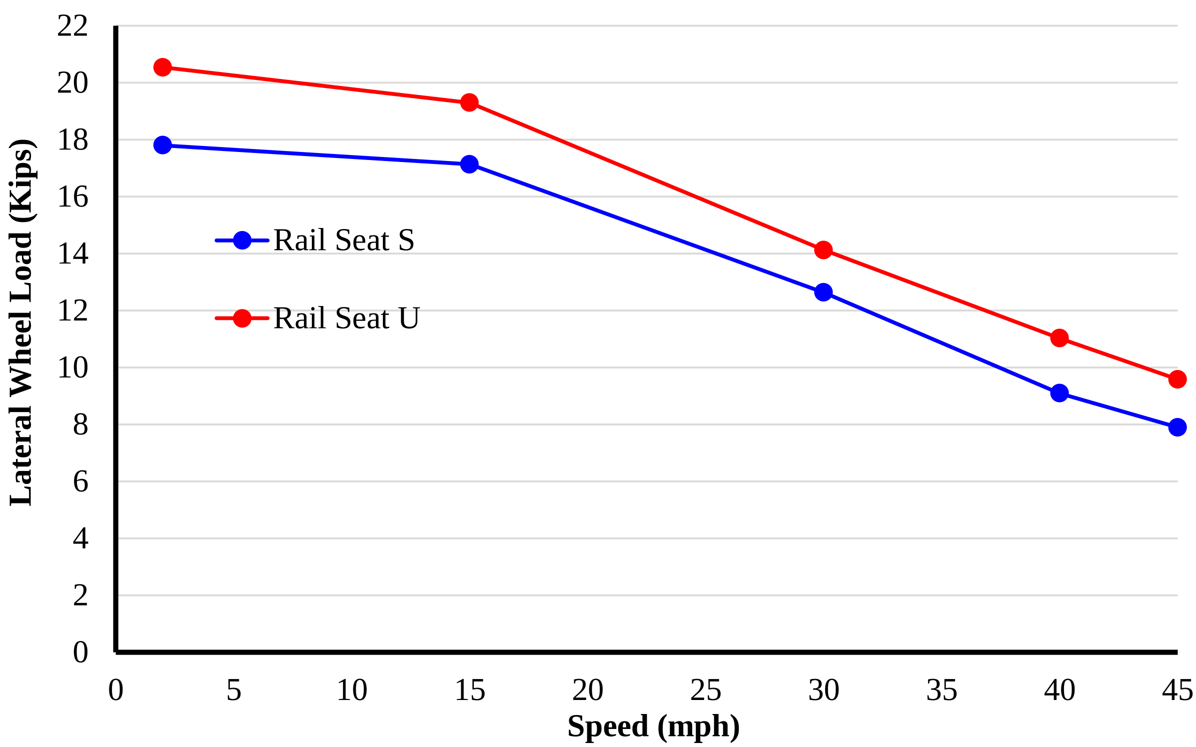


Figure 3.9 Lateral wheel load in rail seats "S" and "U" for increasing speed

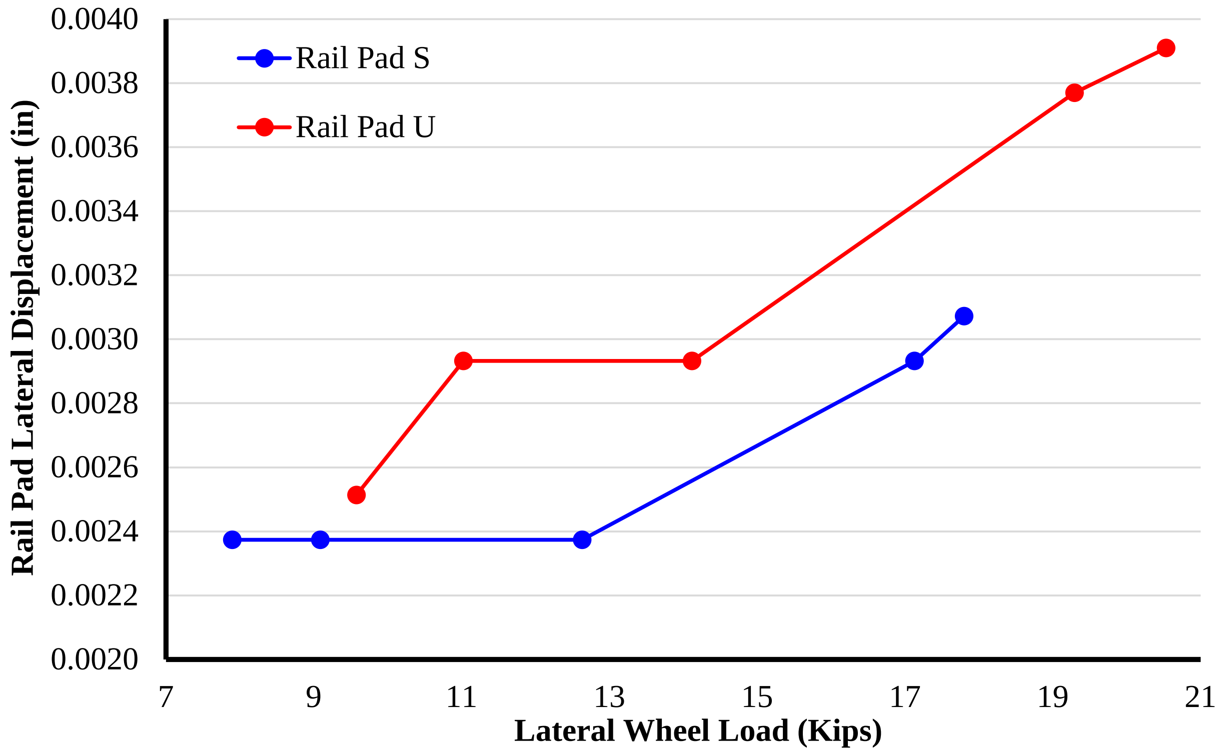


Figure 3.10 Rail pad lateral displacement for increasing lateral wheel load

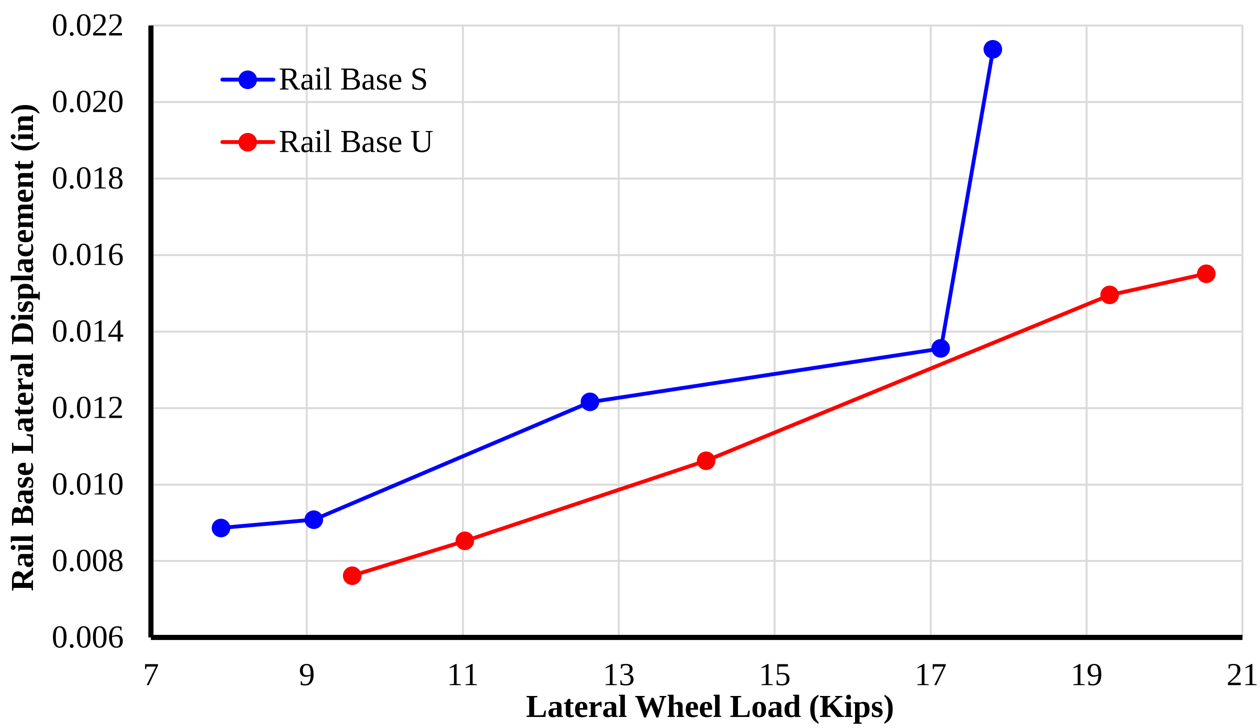


Figure 3.11 Rail base lateral displacement for increasing lateral wheel load

On the low rail of a curve, 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 increased speed. Another notable factor is the relative slip between rail pad assembly and rail base, and the significant difference in the magnitude of slip between these two components. This relative slip indicates a possible occurrence of shear at the rail pad interfaces, which identifies 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.

SECTION 4 CONCLUSIONS

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

4.1 Summary

This study has addressed the primary objectives:

1. Lateral relative displacement between rail pad assemblies and the crosstie rail seat has been successfully identified and measured in laboratory and field tests. The results indicate that the relative displacement is highly dependent on the magnitude of the lateral wheel load applied to the system. Higher displacements were captured for increasing lateral forces. Laboratory and field experiments have shown that vertical wheel loads appear to affect relative displacements, probably caused by the increase in frictional forces in the bearing area of the rail seat. The geometry of the rail seat and the dimensions of the rail pad (e.g. rail seat area, cast-in shoulders face to face distance, etc.) were also factors that seemed to play a role in the magnitude of relative displacement between rail pad assembly and crosstie rail seat, indicating the importance of more strict geometric design tolerances to ensure a tighter fit of components. Additionally, differences in lateral displacement of the rail base and the rail pad were captured, pointing to the possible occurrence of shear slip at this interface.
2. The increase of lateral wheel loads directly affected the magnitude of the lateral displacement of rail pad and rail base for both lab and field investigations. A reduction of displacements was obtained for increased vertical wheel loads, probably caused by the increase in frictional forces between components. Observations also indicated that cast-in shoulder face-to-face distance is another key factor that plays a major role in relative displacement, since they are a physical barrier to confine components movements. Therefore, more strict geometric tolerances should be considered in design codes to reduce the occurrence of relative displacements and prevent it from triggering an abrasion process at the rail pad-rail seat interface.
3. Results have also shown a translation up to ten times higher for the rail base when compared to the rail pad values. This difference may be related to bearing restraints and variation in frictional forces, but it is also a good indication of shear slip occurrence. If confirmed, fastening system manufacturers may use this material property to control the lateral load path in the system, reducing the stress demands on components at critical interfaces (e.g. insulator). If rail pads were designed to deform and present shear slip, part of the energy usually transferred to the insulator post interface could be dissipated, reducing the demands on the other fastening system components. Additional investigation of the shear deformation of current materials used in the design of rail pad assemblies should be conducted to determine how they may appropriately resist and absorb the lateral forces in the system.

4.2 Future Research Directions

The present research addressed the challenge of quantifying lateral load distribution in the track system, at least as it relates to the rail pad assembly. Future research can be conducted in a number of directions; some examples are listed as follows.

1. Develop laboratory tests to determine how wear intensity is related to rail pad assembly relative displacement magnitude and loading cycles.
2. Use the Lateral Load Evaluation Device (LLED) developed by Williams (2013) to determine if rail pad assemblies with different elastic moduli present variation in the lateral loads being transferred to the cast-in shoulder.

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