

Analysis of the Shear Behavior of Rail Pad Assemblies as a Component of the Concrete Sleeper Fastening System

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Abstract

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 sleeper fastening system designs are imperative. Improvements to the rail pad assemblies that protect the bearing area, or rail seat, of concrete sleepers will enhance the safety and efficiency of track infrastructure for railways all over the world. Rail pad assemblies provide a protection layer between the sleeper and rail base by reducing the dynamic loads imposed on the sleeper rail seat and distributing the loads to acceptable stress levels. Additionally, the assembly, typically composed of a rail pad and abrasion frame, interacts with the other fastening system components in order to restrain the rail and maintain desirable track geometry. Understanding the shear behavior of pad assemblies is critical to improve the performance of track components and avoid potential failure modes such as rail seat deterioration (RSD), that are caused by large lateral forces in curves. Normal and shear forces exerted on the components of the fastening system can result in displacements and lateral 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 of the fastening system and result in an increased need for costly maintenance activities. Thus, the study of the mechanics of the rail pad is of paramount importance for the improvement of railroad superstructure components. In this study, the shear behavior of rail pad assemblies 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 allow the industry to develop a mechanistic design approach that enhances the performance, efficiency, and durability of current fastening systems. Furthermore, this work will lead fastening system design to a new level of sophistication by including considerations for shear design, ultimately resulting in recommendations that will reduce the need for preventive measures and maintenance related to track component deterioration.

1. Introduction

The rail pad assembly is the core of the fastening system. It is in contact with multiple components, and, therefore, has special interaction characteristics on each contact interface. The pad assembly-rail seat interface is of paramount interest to the rail industry, since one of the most common failure processes in North America related to concrete sleepers, rail seat deterioration (RSD), occurs on the bearing area of the rail seat, where the pad assembly is in contact with the sleeper [1].

The shear behavior of rail pad assemblies can be described as the transfer of forces and relative slip of the pad assembly surfaces in relationship to the concrete sleeper and rail base. This concept is broader than the intrinsic material properties of the rail pad assemblies, since this component is surrounded by a variety of other fastening system elements that also affect the load transfer between wheel and 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 on the bearing surfaces at 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 on 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 pad assembly bearing surfaces [2]. 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 [3]. Thus, premature need for maintenance and failure of components may be significantly reduced if the design process of fastening systems considers the capacity of the rail pad assemblies to shear and dissipate the high stresses generated on the track under severe service levels.

Prior research conducted at UIUC focused on investigating the physical mechanisms that contribute to RSD [4]. Abrasion was found to be one of the feasible causes of this phenomenon, which has also included freeze-thaw cracking, hydro-abrasive erosion, hydraulic pressure cracking and crushing of the rail seat concrete [4]. The abrasion process occurs when the shear forces at the surfaces in contact overcome the static frictional forces between the bottom of the pad and the rail seat. The components then move relative to each other, wearing the pad assembly and the rail seat [2,4,5,6]. Thus, quantifying the magnitude of this relative motion when the system is subjected to a variety of loading scenarios constitutes the primary focus of this research.

2. Failure Mode and Effect Analysis (FMEA) of Rail Pad Assemblies

In North America, the geometry and materials used in the design and manufacture of rail pad assemblies has changed significantly over the past thirty years. Single-layer components made out of synthetic rubber were later substituted by higher density polymers and eventually to double-layer components. Today, the most common rail pad assemblies consist of polyurethane rail pads on the top of Nylon 6/6 abrasion frames. The idea behind a double-layer component was to provide abrasion resistance and also impact attenuation, combining two materials with distinct qualities to obtain an improved rail pad assembly. These properties 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 failure mechanisms. Rail pad assemblies generally fail as a result of specific failure mechanisms, which result in recognizable failure patterns. After intensive field investigation, these patterns were identified and analyzed to serve as base of the preliminary section of this study, a failure mode and effect analysis. The failure mode and effect analysis is a technique developed on the 1950's by military engineers to increase the reliability of products on the development or manufacturing process [8]. This tool involves the systematic analysis of group activities related to the product in order to detect possible failures and investigate the effects of these failures on the system. From this analysis, it is possible to identify actions that must be taken to reduce the probability of failure occurrence [8].

In Figure 1, failure modes related to different pad assembly designs were registered. Tearing and crushing of these components is evident in some pads (Figure 1A-C); as they have experienced significant loss of material. The effects of abrasion can also be noticed on the completely worn dimples and grooves. In the last image another very common failure related to this component can be observed: the rail pad assembly slippage. Slippage refers to the phenomenon when the pad assembly slips in one direction so that it is completely displaced from the rail seat.



Figure 1 - Failure modes associated with rail pad assemblies [10]

Systematically understanding the causes and effects of the failures observed on rail pad assemblies is the first step in the development of this study. It constitutes a path that guides the process of answering questions related to the component behavior and leads to 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. The rail pad assembly has been used as the focus of a FMEA study, which has identified four principal failure modes of this component: crushing, tearing, seat slippage, and abrasion. Among the principal causes of the listed 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 [2,4]. 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: the effect on the component itself, the effect on the next higher assembly (i. e. the adjacent components of the fastening system), and the effect on the track system. The failure effect on the pad assembly is the loss of the original geometry, usually observed 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 on each component, triggering a possible wear intensification process. Regarding the track system, the consequences imply more periodic maintenance, reduction in the life cycle of components, loss of track geometry and ultimately the possibility of derailments. The relative displacement between rail pad assembly and rail seat has been consistently described by experts as one of the main causes of component failure [5], but there is a lack of studies showing if this relative slip, also mentioned as shear behavior, actually occurs. The pad assembly displacement must be analyzed in order to better understand the failure mechanisms affecting the fastening system.

3. Mechanics of Wear and Shear Behavior of Rail Pad Assemblies

Wear may be defined as the removal of material from solid surfaces as a result of mechanical action [9]. The occurrence of abrasive wear is related to the relative motion between bodies of distinct hardness and the removal of particles in the contact points at the slip area [9]. In the context of rail pad assemblies, slip occurs when the shear forces at the rail pad assembly – rail seat interface overcome the static frictional forces between the bottom of the abrasion frame and the concrete surface. Each time slip occurs, strain is imparted into the concrete system. Over time, this strain exceeds the fatigue limit of the material and a brittle failure occurs, dislodging individual particles of mortar paste [2]. The frictional interface between the rail pad and the rail seat surface is significantly altered by the presence of moisture and abrasive fines, which intensifies the wear process initiated by the relative displacement of components [2]. As a result of this phenomenon, the pad assembly loses thickness and the rail seat is deteriorated, changing the original load path for which the components were designed. This process might lead to a cyclic degradation where the change in geometry of the fastening system components accelerates the RSD.

Previous researchers have shown that the longitudinal shear behavior of pad assemblies is a key component on sleeper skewing. 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 [3]. This shear elasticity is also important in the lateral direction because it gives the fastening system the capability of absorbing the energy from the lateral loads and causes the pad assembly to deform instead of rigidly moving relative to the rail seat. Based on results from an extensive literature review, UIUC researchers determined that additional experimentation on rail pad assemblies should be pursued. Specifically, experimentation should focus on determining the origins of the pad assembly slippage, the conditions in which they occur, the relationship between the applied loads and the displacement magnitudes. These topics were found to be of great importance to the understanding of the shear behavior of rail pad assemblies. The nature of the deformation is another topic that deserves further exploration in future work because it has an impact on the dissipation of the energy transferred in the system and also determines the elastic behavior of the fastening system.

5. Analysis of the Lateral Displacement of Rail Pad Assemblies

As wheel loads are transferred from the rail to the underlying pad assembly, they induce a compressive deformation on this component. Vertical and lateral deflections occur due to the Poisson's effect associated with the material properties of the pad assembly. The Poisson's effect is a measure of the tendency of a material to deform in directions perpendicular to the application of

loads. Also, internal shear deformation occurs when lateral loads are transferred to the rail – rail pad interface, causing the internal surfaces of the rail pad assembly to slide past each other. From a mechanistic perspective, it is important for the understanding of the shear behavior to distinguish between rigid body motion and lateral deformation of the component. Using the theory of elasticity, the Poisson effect, and considering the material properties shown in Table 1, it is possible to analytically calculate the lateral deflection of the pad assembly. A comparison between the lateral displacement of the pad assembly and the pure lateral deformation of this component will be later addressed on this section.

The development of an experiment to quantify the total lateral displacement of rail pad assemblies is critical to understand the shear behavior of this component. In this case, the test setup consisted of an instrumented concrete sleeper and fastening system mounted on the Pulsating Load Testing Machine (PLTM) at UIUC. The PLTM, which is used to perform the American Railway Engineering and Maintenance-of-way Association (AREMA) Test 6 (Wear and Abrasion), as well as other experimental testing related to concrete sleepers and fastening systems, was used to execute these experiments. The loading conditions for AREMA Test 6 are meant to simulate heavy-haul severe-service conditions, such as those experienced on horizontal curves with greater than five degrees of curvature. Regarding the configuration of the PLTM, it consists of one horizontal and two vertical actuators, both attached to a steel loading head that encapsulates a short section of rail attached to one of the two rail seats on a concrete sleeper. This actuator arrangement allows for the lateral force over vertical force relationship, also known as L/V ratio, to be varied without changing the physical arrangement of the actuators, loading frame, or concrete sleeper [7].

A high-sensitivity linear potentiometer was used to capture the lateral motion of the pad assembly. In this case, the pad assembly consisted of a polyurethane rail pad and 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 ³)
Abrasion Frame	Nylon 6/6	440,000	0.350	38.250	0.049
Rail Pad	Polyurethane	7,500	0.394	36.600	0.068

The potentiometer was fixed on the sleeper using a metal bracket placed adjacent to the clip shoulder, in a position that allowed the plunger to perfectly touch the abrasion frame. Figures 2 and 3 show the test set up.



Figure 2 - PLTM



Figure 3 - Location of linear potentiometer

Lateral and vertical loads were applied to the rail, with L/V ratio varying from 0.1 to 0.5. The maximum lateral load was 80 kN (18,000 lbf). First, the loading cases were all static, beginning with a low L/V ratio then consistently increasing the 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 4 and 5. The maximum displacement was equal to 1.05 mm for a 0.5 L/V ratio and 160 kN (36,000 lbf) of 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 the rail pad assembly fits tight in the rail seat area. When this test was repeated with different sleepers, there was a variance of up to 50% on the results of maximum displacements based on the geometry and manufacturing differences among the sleepers tested. The manufacturing allowance for geometry deviations has a significant impact on the maximum displacements measured.

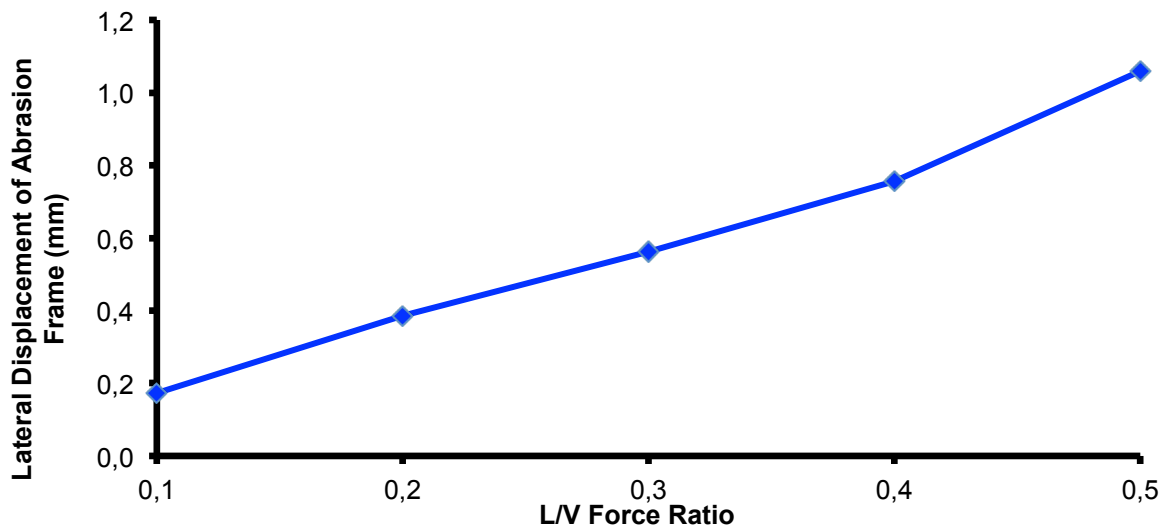


Figure 4 –Lateral displacement of the abrasion frame with 160 kN (36,000 lbf) vertical load for increasing L/V

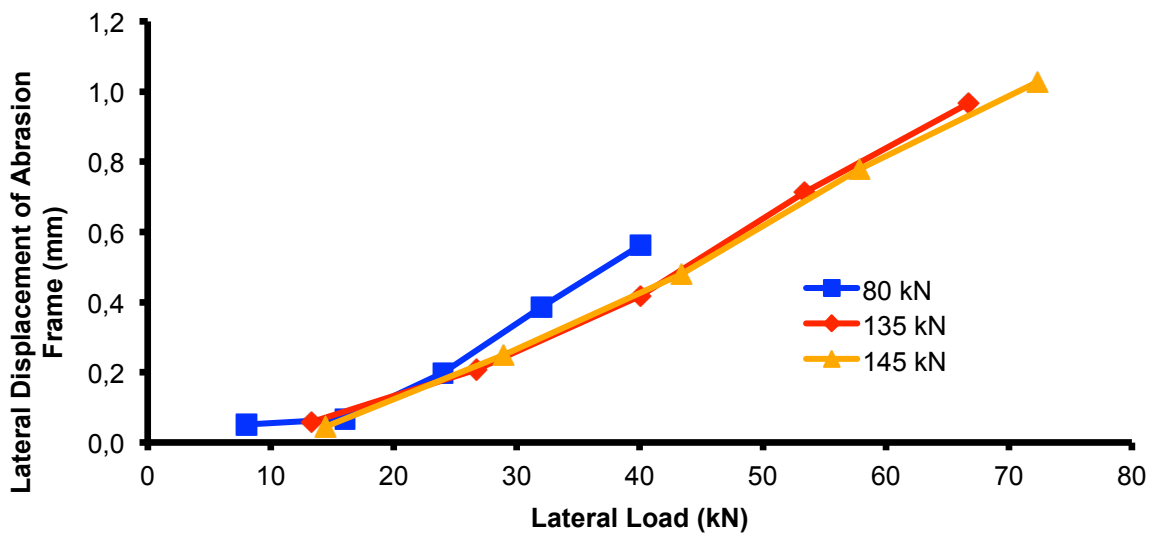


Figure 5 – Lateral displacement of the abrasion frame for increasing lateral loads at vertical loads of 80 kN, 135 kN, and 145 kN

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, its effects on the lateral displacement behavior is not evident when less severe lateral loading cases were considered. For lateral loads up to 28kN (6,300 lbf), vertical forces ranging from 80kN (18,000 lbf) to 145kN (32,500 lbf) did not show considerable differences in the pad assembly lateral displacement. The recorded results were similar, despite the 65kN (14,600 lbf) difference between the minimum and maximum vertical load applied. However, given the results obtained from this experiment, it is plausible to think that even less severe lateral loading cases are capable of overcoming the static frictional forces existent between the pad assembly – rail seat interface. In contrast, for higher lateral loads, the vertical forces reduced the magnitude of the lateral displacement, pointing the influence of the dynamic friction on the shear behavior of the pad assembly. Under severe loading cases, where high L/V ratio and high lateral loads are encountered, the wheel load magnitude will probably 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. The tighter the pad assembly fits in the rail seat, the smaller is the probability of large lateral and longitudinal displacements occurring.

Taking into account the previous discussion about the lateral deformation of the pad assembly, it is important to address a brief comparison between the total lateral displacement measured in the aforementioned experiment and the pure lateral deformation of this component. Considering the material properties of the abrasion frame and a rail seat load of 80kN, the expected lateral deflection of the abrasion frame is approximately 0.05mm. This value only corresponds to 5% of the total lateral displacement recorded. Therefore, this result indicates that the rigid body motion is likely to be the predominant movement associated with the lateral displacement of the pad assembly.

6. Conclusion

The understanding of the shear behavior of the rail pad assembly is of paramount importance for the development of improved fastening system components. The lateral and longitudinal displacement of the pad assembly is usually associated with failure modes related to the fastening system, especially abrasion. The occurrence of relative displacement between the pad assembly and rail seat was measured in the experiments carried out at UIUC. These displacements are highly dependent on the geometry of the rail seat and the shoulder spacing. Considering that lateral and longitudinal displacements must be avoided or significantly minimized to prevent abrasion, a rigorous process of manufacture, with very small tolerances for geometry deviations may increase the life cycle of the fastening system and reduce the probability of RSD. Despite the fact that the recorded displacements were considerably small compared to the dimensions of the rail seat, its effects on the micro-structure of the concrete might be harmful to the integrity of the sleeper rail seat, possibly generating a wear degradation process 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. On the other hand, only high magnitudes of vertical loads appeared to affect the lateral displacement of the rail pad assembly.

Future work will be focused on analyzing the longitudinal shear behavior of the pad assembly. Data collected during field investigation conducted at the Transportation and Technology Center (TTC) in May 2013 will determine the effects of different loading scenarios on the lateral and longitudinal movement of the rail pad. Additionally, possible research topics at UIUC will further 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 new level of sophistication, resulting in recommendations that will reduce the need for preventive measures and maintenance related to track component deterioration.

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