Hydraulic Mechanisms of the Deterioration of Concrete Sleeper Rail Seats

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Abstract

Based on the results of a 2008 railway industry survey on concrete sleepers, rail seat deterioration (RSD) is the most critical problem with concrete sleeper performance on North American freight railroads. RSD is the degradation of the concrete underneath the rail and results in track geometry problems and loss of fastening toe load. Currently, mechanisms behind RSD are not sufficiently understood to allow for effective solutions. RSD is considered to have five potential mechanisms, and this research investigates three of them: hydraulic pressure cracking, hydro-abrasive erosion, and abrasion. In order to investigate the two hydraulic-driven mechanisms, a laboratory test setup and procedure were developed to measure the surface water pressure in a laboratory rail seat using rail pads of differing material composition and surface geometry. To evaluate hydraulic pressure cracking, a model of the effective stress in a concrete-sleeper rail seat was created to determine which water pressures on the rail seat surface could lead to damaging pore water pressures in the concrete. To estimate the potential for hydro-abrasive erosion, the measured surface water pressures were used to estimate the potential water velocity. Both hydraulic pressure cracking and hydro-abrasive erosion appear to be feasible mechanisms of RSD. The focus of this paper is to summarize the results from laboratory tests undertaken at UIUC to obtain greater insight into the potential hydraulic-driven failure mechanisms associated with RSD and to introduce a laboratory test that will be used to evaluate the parameters that affect the abrasion mechanism.

1. Introduction to Rail Seat Deterioration Mechanisms

Rail seat deterioration (RSD) is degradation beneath the rail on a concrete sleeper. This deterioration leads to track geometry defects such as wide gauge and insufficient rail cant, and allows for accelerated deterioration of the rail-to-sleeper fastening system. Currently, there is evidence that abrasion, freeze-thaw cracking, crushing, hydro-abrasive erosion, and hydraulic pressure cracking are mechanisms that may contribute to RSD [1, 2, 3]. Little evidence has been found to suggest that alkali-silica reactivity (ASR) is contributing to RSD, and research and experimental testing at UIUC has ruled out cavitation erosion as a feasible RSD mechanism [1, 3].

The theory of hydraulic pressure cracking claims that pore pressures in the concrete become large enough that the concrete's tensile strength is exceeded, resulting in cracking or spalling [1]. In order to evaluate the feasibility of this theory, two elements were examined: the specific pore pressure required to damage the concrete and the expected pore pressure in a typical concrete sleeper. An effective stress model was developed to examine the hydraulic pressure cracking mechanism [4].

Hydro-abrasive erosion, also called abrasive erosion or suspended particle erosion, refers to concrete wear through the action of flowing water [5, 6]. The potential for hydro-abrasive erosion was evaluated by comparing the particle flow velocities estimated from the measured surface water pressure to the critical flow velocities found in literature that caused erosion [5].

2. Laboratory Test Results for Hydraulic Driven Mechanisms

An original experiment and procedure were developed to determine the rail seat surface water pressure at the Newmark Structural Engineering Laboratory (NSEL) at UIUC. The surface water pressure generated by applying a load on a submerged, mock concrete sleeper rail seat was measured using a pressure transducer [6]. The applied loads varied from 89 kN (20 kips) to 267 kN (60 kips), with 89 kN approximating the static rail seat load under a 130-metric-ton (286-kip) gross rail car load [5, 6].

Nine rail pads composed of different materials and with different surface geometries were considered in the study, including three types of pad assemblies. Each assembly had a thermoplastic pad in contact with the rail base, which in the experiment was a steel loading plate designed to mimic the rail seat loading surface. After plotting the maximum surface pressure for each pad versus the applied load, it was determined that all the rail pads could be grouped into one of three categories: flexible (flat and grooved polyurethane, dimpled santoprene), semi-rigid (flat and dimpled EVA, dimpled polyurethane), or assembly with a rigid layer (all three pad assemblies). The pads were placed in these categories solely by their load-pressure behavior, and these names were assigned to the groups in an attempt to explain the differences between them. The mean regression lines that fit the experimental data were plotted on the same graph, sorted by these pad groups (Fig. 1). For the case of a perfect seal, the surface pressure would be equal to the load divided by the area of the rail seat, and this is plotted on Fig. 1 for comparison, labeled “uniform load stress.”

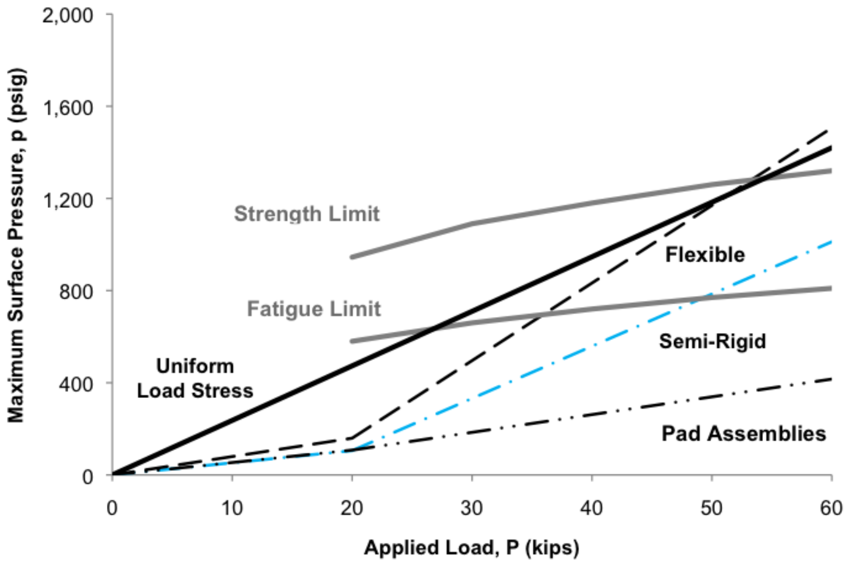

FIGURE 1: Comparing the Mean Load-Pressure Models and the Uniform Load Stress on the Rail Seat Maximum Surface Pressure, p (psig)

The load-pressure model for the flexible pads is close to the ideal uniform load stress (Fig. 1), suggesting that the flexible pads created a nearly perfect seal. Allowing some of the water to escape or flow rather than to become pressurized may explain the difference between the flexible and semi-rigid pads. These results suggest that some rail pads create more effective seals than others, explaining the difference in their load-pressure behavior. Comparing the pressure measurements with estimates for concrete damage limits (labeled “strength limit” and “fatigue limit” in Figure 1), hydraulic pressure has the potential to crack the concrete at the rail seat. However, one apparent approach for preventing hydraulic pressure cracking is to use pad assemblies because they do not form effective seals under load.

The potential for water flow and hydro-abrasive erosion were estimated from our experimental results. Using Bernoulli’s equation to estimate the maximum surface water velocity, the estimated velocity was applied to the mean load-pressure models. The resulting estimates for water velocity were scaled down to 72% to estimate the potential suspended-particle velocity (Fig. 2). The smallest value of particle velocity in the literature associated with concrete erosion was approximately 50 m/s (165 ft/s), and this value was for flow parallel to the surface, similar to the condition for flow underneath the tie pad [3, 6]. This critical particle velocity was also plotted for comparison (Fig. 2).

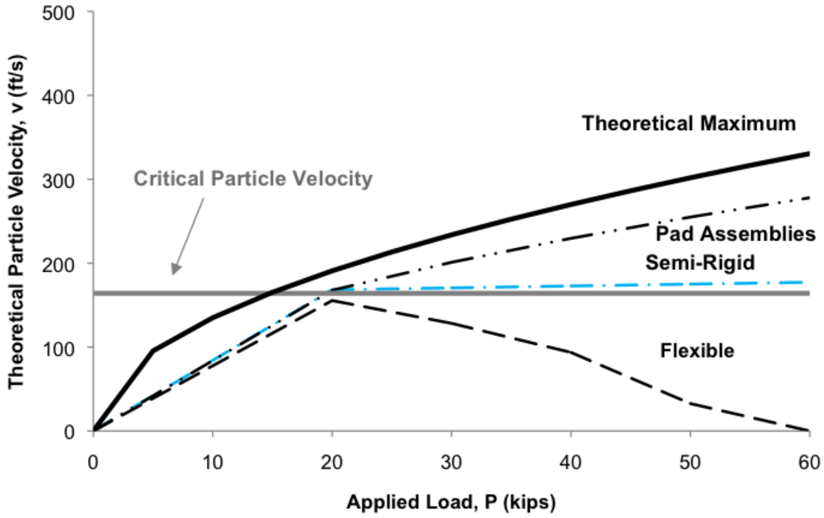

FIGURE 2: Theoretical Particle Velocity, Scaled as 72% of the Flow Velocity

The estimates shown in Fig. 2 suggest that hydro-abrasive erosion is a feasible RSD mechanism. It is difficult to predict how much this mechanism might contribute to RSD without conducting experiments that specifically measure the velocity of the particles and the resulting wear in a concrete sleeper rail seat. The estimates of particle velocity suggest that pads with less effective seals have a higher potential for causing hydro-abrasive erosion. To prevent hydro-abrasive erosion, a rail pad should maintain a tight seal both at rest (to minimize intrusion of moisture and fines) and under load (to minimize flow).

The measurements of surface water pressure and the estimates for maximum surface water velocity present conflicting design objectives for rail pads. A tight seal may generate damaging pressure if water seeps under the pad; conversely, an ineffective seal may allow additional intrusion of moisture and fines, as well as damaging flow under load. Further research is needed to understand whether hydraulic pressure cracking or hydro-abrasive erosion and abrasion should dictate the design of the rail pad seal, considering both the loaded and unloaded seal.

3. Future Investigation of Abrasion Mechanism

Abrasion is widely considered to be one of the viable mechanisms that lead to RSD, based on field observations and experimental evidence from existing wear and abrasion tests. Abrasion is defined as the wear of concrete particles on the rail seat surface as frictional forces act between the rail pad and the concrete rail seat, which move relative to one another. When combined with abrasive fines and water that penetrate into the rail pad-rail seat interface, the frictional forces and relative movement of the concrete sleeper and the fastening system equate to a seemingly ideal situation for the occurrence of abrasive wear.
Abrasion is related to the previously-investigated, hydraulic-driven mechanisms by its dependence on the seal of the tie pad. The frictional interface between the rail pad and the concrete sleeper rail seat surface is significantly altered by the presence of moisture and abrasive fines that can penetrate into the interface when an effective seal is not achieved.

Currently, the development of a novel laboratory test is underway at UIUC designed to produce measurable abrasive wear of mock rail seat surfaces. This test will allow for the isolation of variables that are believed to affect the abrasion mechanism and will facilitate the acquisition of quantitative and qualitative data on each variable. Test variables will include the normal load that will be applied to the rail seat, the amount of horizontal displacement of the specimen relative to the abrading head, the type and amount of abrasive fines, and the moisture condition of the concrete specimen. Also, a variety of rail seat surfaces including a variety of concrete mix designs, coatings, and exposed aggregate surfaces will be investigated in order to understand methods of mitigating abrasion.

4. Conclusion

Based on the results of the previous laboratory experiments and the damage limits defined by the effective stress model, hydraulic pressure cracking appears to have the potential to initiate or contribute to RSD as a concrete deterioration mechanism. It appears that the most effective way to prevent hydraulic pressure is to use pads or pad assembly bottoms that do not seal water. When thermoplastic pads are in contact with the concrete rail seat, it appears that designing the pad with direct escape channels for the water effectively ejects the surface water upon load application rather than pressurizing it. It seems advisable and relatively simple to incorporate these considerations into future pad and pad assembly designs; however, these design considerations for hydraulic pressure must be balanced with the possibility that allowing water and fines to flow in and out might increase wear due to hydro-abrasive erosion and abrasion.

The potential for hydro-abrasive erosion to damage concrete seems feasible, but more research is needed to understand how important this mechanism is before design recommendations can be made. Like hydro-abrasive erosion, abrasion appears to be a feasible mechanism of RSD. More information is required to understand how abrasive wear initiates and accelerates due to various causes and factors of track conditions. A laboratory experiment is underway that will evaluate the parameters that affect the rate of abrasion of mock concrete sleeper rail seats. By identifying the factors that contribute to RSD, this investigation will seek to mitigate the effects of abrasion, with an overall goal of improving the performance and service life of concrete sleepers.

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