Design and Performance of Elastic Fastening System Assemblies and Measurement of Rail Seat Pressure Distribution for Concrete Sleepers for Heavy-Haul Service

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ABSTRACT

As freight car axle loads and cumulative gross tonnages increase, the need for improved concrete sleepers and fastening systems is becoming increasingly important. In addition to increased service demands, poor performance of the fastening system is often correlated to the occurrence of rail seat deterioration (RSD), one of the primary maintenance concerns with concrete sleepers on North American heavy-haul railroads. Reducing life cycle costs of concrete sleeper fastening systems is of paramount importance to the railway industry to ensure the continued acceptance of concrete sleepers as a viable means of rail restraint. Recent advancements in fastening system design for concrete sleepers in heavy haul and passenger service stem from research and testing addressing current problems the industry is facing, including RSD and insufficient rail restraint. This paper will include a review of fastening system characteristics and performance criteria for concrete sleepers in heavy-haul service throughout the world. In addition, the paper will report the latest research and testing results of rail seat surface treatments and their effect on the fastening system performance and rail seat pressure distribution with varying loading conditions and fastening system elasticities. These results were obtained through full-scale laboratory testing of concrete sleepers and fastening systems at the University of Illinois at Urbana-Champaign (UIUC).
INTRODUCTION

The purpose of a railway sleeper is to support and transmit axle loads from the rail to the next layer of the track structure (typically the ballast) with a reduction in pressure. The sleeper, which is embedded in the ballast, anchors the track against lateral, longitudinal, and vertical movement (1). The loads acting on a concrete sleeper depend not only on railcar axle loads and sleeper spacing, but also on the size of the rail, its vertical stiffness, and the properties of the rail fastening system (2).

Concrete sleeper fastening systems are comprised of various components and materials designed to safely transmit forces exerted by the rail to the concrete sleeper while restraining the rail to the proper gauge and cant as required by the Federal Railroad Administration (FRA) and individual railway engineering maintenance standards. Forces acting on the fastening system are vertical, lateral, rotational (both planes), and longitudinal, and are the result of repeated loading cycles from passing axles, as well as longitudinal stresses in the rail (Figure 1). Fastening system components are constructed from a variety of materials (with variable properties) to securely attach the rail to the sleeper and properly attenuate and/or transfer loads.

Figure 1: Vertical, lateral, rotational (both planes), and longitudinal forces that are applied to the fastening system and rail seat under rail vehicle and thermal loading

Additionally, modern elastic fastening systems are also designed to operate in conjunction with railway signaling systems. In areas where track circuits are used, the fastening system should provide electrical insulation for the rail (relative to the sleeper) in order to provide electrical impedance, which is accomplished through the use of insulators typically made from high strength polymers and nylon. Sleepers should also facilitate load attenuation to minimize the pressures exerted on the ballast at the bottom of the sleeper and mitigate impacts from vibration, which may lead to abrasion and crushing damage of fastener components and the rail seat.

Stiffness of Fastening Systems

The stiffness of a fastening system is one of the most important characteristics that directly impacts the fastening system's long-term performance under repeated axle loading. Stiffness closely relates to the degree of wear fastening system components experience, and the resulting life of the system. The dynamic rail / fastening system interaction can be viewed as a complete set of springs and dampers (Figure 2). The stiffness of each component determines how much the rail is allowed to move within the rail seat (3). For the purpose of studying fastening system component behavior, it is possible to isolate a force vector and analyze how each fastening system component will perform under a discrete loading event.
Figure 2: The dynamic interaction of the rail, sleeper, and fastening system

Types of Fastening Systems

Fasteners are typically classified into two categories: rigid and elastic (1). Rigid fasteners refer to systems developed in the early 1900s that rigidly bolted the rail to the sleeper (4). Rigid fasteners were superseded by elastic fasteners, which allow more resilience relative to rigid fasteners. Resilience, which is also referred to as elasticity, is a proxy for the amount of movement the rail experiences within the rail seat (5). By design, most of today’s fastening systems allow some resilience to facilitate load attenuation. Within elastic fastening systems, there are large variations in design resilience and the degree of resilience that is tolerated in the field.

Elastic fastening systems have four primary components: an imbedded anchor, a clip or spring, an insulator, and a rail pad (or pads) between the rail and concrete sleeper (2). Each of these elements is designed to perform a specific function within the fastening system. The clip or spring is designed to apply an appropriate clamping force (toe load) to the base of the rail. The clamping force is one factor that determines the rigidity of the fastening system (6). The anchor is designed to hold the clip or spring to the sleeper, and is cast-in during the sleeper manufacturing process. The rail pad is designed to properly attenuate the loads exerted by the rail onto the sleeper, and should be constructed of a material that is averse to wearing the concrete rail seat and the base of the rail. The insulator is designed to properly insulate the fastening system from the rail to facilitate reliable operation of the signal system.

Typical elastic fastening systems designed for heavy-haul service can be classified by how they develop their clamping force at the base of the rail. Clamping forces can be developed by either bolting or screwing an elastic clip into a cast-in shoulder. Alternatively, a clip can be driven into a cast-in shoulder, which forces the clip to hold the base of rail with the prescribed clamping force. We will refer to these two systems as “bolt or screwed clip systems” (Figure 3a) and “driven clip systems” (Figure 3b).
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Figure 3: (a) Example of a bolted or screwed clip fastening system (b) Example of a driven clip fastening system

In bolted or screwed clip systems, the clip is anchored by a bolt or screw which is threaded into an insert that is cast into the concrete. Bolted or screwed clip systems generally have the advantage of allowing field adjustment of clamping forces. Additionally, many designs allow for efficient replacement of components in the field (e.g. clips, bolts, and/or screws). With some bolted clip systems, it is possible to vary rail height in order to maintain proper track geometry. A disadvantage for some bolted or screwed clip systems is that their installation tends to be operator-sensitive, thus it is difficult to achieve a consistent clamping force at every rail seat without the use of specialized tools or machinery (2). In some bolted or screwed clip systems, it is important to identify whether the movable portion of the clip is fixed onto the bolt or screw. If it is, the movable portion of the clip tends to loosen the bolt or screw and the fastening system will need to be inspected to ensure there is no loss of torque.

Driven clip systems generally include a cast-in steel shoulder (or anchor) and a clip, which is driven into the shoulder to achieve the required clamping force. These systems tend to be less operator-sensitive since their correct installation can be confirmed by visual inspection. Captive driven clip systems (which are fully assembled with the sleeper at the sleeper manufacturing plant) are generally less labor-intensive to install and remove. One possible disadvantage of driven clip systems is the inability to make adjustments in the field to vary the clamping force.

Objective Comparison of Fastening Systems

Given the wide variety of fastening system designs, a standard method for objectively comparing the performance of fastening systems is needed to accurately analyze design variations. Fastening systems may vary in durability, elasticity, ease of installation, ease of maintenance, amount of maintenance required, clamping force, contact area with the rail, cost, design life, and whether or not they provide a vandal-proof design.

One way to objectively compare fastening systems is to analyze the elasticity of each system. The elasticity of a fastening system refers to the amount of rail movement allowed within the rail seat area. The elasticity of a fastening system provides a measure for how they should perform in the field. In addition to objectively comparing fastening systems on the basis of their elasticity, the durability of fastening system components should also be compared when comparing systems. The durability of a fastening system refers to its ability to resist wear.

Current Problems with Fastening Systems

Previous concrete sleeper research at the University of Illinois at Urbana-Champaign (UIUC) included a survey of concrete sleeper experts at major North American freight railroads, regional and shortline railroads, and commuter and transit authorities designed to obtain information about their current problems with concrete sleepers (6). The survey was formulated as a failure mode effect analysis (FMEA), and the results showed that RSD and fastener system wear are the most critical problems experienced by North American freight railroads (Table 1). It is important to note that both of these
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concrete sleeper problems occur in the rail seat area and they are often considered to be concurrent failure modes.

Table 1: Rankings of concrete sleeper problems according to North American freight and passenger railroad operators (6)

<table>
<thead>
<tr>
<th>Concrete Sleeper Problems</th>
<th>All Responses</th>
<th>Rank (Average Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Major Railroads</td>
</tr>
<tr>
<td>Shoulder/ fastener wear or fatigue</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Rail seat deterioration (RSD)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Cracking from center binding</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Derailment damage</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Tamping damage</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Other (ex: manufactured defect, installation damage)</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Cracking from dynamic loads</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Cracking from environmental or chemical degradation</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Many fastening system problems, and consequently concrete sleeper problems, can be traced back to the stiffness of the fastening system. For the purpose of this discussion, the terms elastic and rigid are used to describe the overall behavior of a particular fastening system or fastening system component. Specifically, the terms define whether the component will allow (elastic) or not allow (rigid) rail movement within the rail seat. In general terms, an elastic fastener, used in a system with a soft pad (e.g. rubber), will result in lower loads on the components and on the concrete rail seat (7). Conversely, a more rigid fastening system with a stiffer pad (e.g. hard polyurethane) will cause higher loads on the concrete rail seat.

Accelerated component wear can occur when concrete sleepers have elastic fasteners that are not designed with properties commensurate with the rail pad. For example, a system with a very elastic fastener but a very rigid pad, or vice versa, may see increased component wear due to the relative motion between the two components. A soft pad (e.g. rubber) is capable of following all movements of the rail within the rail seat under loading cycles, which is typically not observed with stiffer pad materials. If a very elastic fastener is used in conjunction with a stiff pad, the rail will not have continuous support during loading cycles, which can cause unwanted impacts and accelerated component wear. Conversely, if a very rigid fastener is used in conjunction with a very soft pad, the rail will not be significantly displaced within the rail seat, but the softer pad will wear in an accelerated manner. Wear on insulators, clips, shoulders, and pads can lead to loss of clamping force, loss of gauge, loss of cant, and RSD, which ultimately results in increased fastener and rail seat maintenance between rail replacement cycles and a higher life cycle cost for sleepers and fasteners.

The occurrence of rail seat deterioration (RSD) is related to fastening system elasticity (7). With elastic fastening systems that are designed with significant elasticity, energy will be dissipated through rail movement at the rail seat, thus the rail seat will experience lower loads. However, rail movement at the rail seat can allow the intrusion of abrasive fines between components, which tend to accelerate fastener component wear. Rigid fastening systems will dissipate less energy at the rail seat, thus the rail seat will experience higher loads. Higher rail seat loads are not a problem if the concrete sleeper and rail are designed appropriately, but higher pressures will be transferred to the
ballast, which may cause ballast crushing (e.g. degradation) or other problems. In summary, there is a trade-off between fastening system designs based on their elasticity. More elastic fastening systems tend to have accelerated component wear (which can cause RSD and other problems) while more rigid fastening systems may cause problems such as rail breakage, pumping, or ballast crushing.

Advancements in Fastening System Design by Manufacturers

Fastening system designs have evolved to accommodate increased loads, speeds, and the overall increased performance requirements (e.g. reduced life cycle costs (LCC)) expected of the fastening system. Modern fastener designs typically focus on improving the overall performance of the fastening system by increasing the clamping force, increasing component fatigue limit, and by reducing installation costs (e.g. captive systems). Any advancement in fastening system performance must be undertaken to ensure the total life cycle cost of concrete sleepers is competitive to other sleeper materials.

Pandrol has performed several design modifications to their heavy-haul fastening systems throughout the years. The “PR” series fastening system, introduced in 1974, was one of the first driven clip systems used in concrete sleepers and is still in use today. The PR fastening system provides high fatigue limit components with lower clamping force compared to many newer fastening systems. After the PR system, Pandrol introduced the “e” series clips in 1986. The e-clips were the next design advancement as they offered a higher clamping force and a lower cost through the use more efficient clip geometry. “Safelok” I fasteners were acquired by Pandrol in the late 1980’s when Pandrol acquired the railroad division assets of the McKay Company. Pandrol developed the “Fast Clip” in 1992. PandrolFastclip is a fully captive system which was developed to reduce installation and maintenance costs. PandrolFastclip provides a high clamping force and can be used in passenger or heavy-haul freight service. Pandrol has also developed a fastener known as the “Safelok III”. The Safelok III system is pre-assembled at the concrete sleeper manufacturing plant. In this system, the pad, the side post insulators, the spring clip and the clip insulator are all captive. Captive systems allow for more secure transportation to site and facilitate greater efficiency in either manual or automated track installation. Safelok III provides an increase clamping force compared to all of its predecessors and the same captive capability of the Fastclip, but with the use of a flat bar instead of a round bar.

Vossloh has also worked to modify their fastening system designs. The “W HH” is a captive fastening system assembly for heavy-haul service and the “SKL” is the type of spring clip used for that particular fastening system assembly. The SKL 1 was developed in the 1960’s and was superseded by the SKL 14 in the 1990’s. The SKL 14 has a longer middle bend, which works as an anti-rollover device for the rail and has a higher fatigue limit than the original SKL 1. The SKL 14R is a variation of the SKL 14 with a thicker diameter and allows for a higher clamping force on the base of rail. With the development of the SKL 30 it was possible to further increase the fatigue limit and keep the toe load at a high level.

Unit Rail continues to develop the U2000 spring clip from a piece-meal elastic fastener clip into a fully captive elastic fastening system for all concrete sleeper applications. This clip is referred to as the “One-Unit” captive fastener. A new spring clip called the U6030, with more metal and a larger clamping force than the U2000, is currently being developed. For this type of fastening system, the greatest bending moment occurs at the rear of the clips – away from the base of rail. The new clip U6030 has more metal in this region, and the extra steel reduces the stress level per unit area. In addition, the rear of the clip is the location where the clip fitting forces are applied, thus the likelihood of clip damage during fitting due to excessive forces is greatly reduced.

Concrete Sleeper and Fastening Research at the University of Illinois at Urbana-Champaign

Research aimed at gaining a greater understanding of the mechanisms behind rail seat deterioration (RSD) is currently underway at the University of Illinois at Urbana-Champaign (UIUC). Specifically, research to investigate the moisture-driven mechanisms including hydraulic pressure cracking, cavitation erosion, and hydro-abrasive erosion have been thoroughly investigated using models and
Experimental testing (12, 13, 14, 15). Future research will be directed at investigating the mechanism of abrasion, thought to be a primary contributor to RSD.

Additionally, full scale concrete sleeper and fastening system research and testing is underway at UIUC’s Advanced Transportation Research and Engineering Laboratory (ATREL) (16). Concrete sleeper and fastener testing equipment at ATREL includes a Pulsating Load Testing Machine (PLTM), which has the capability of objectively comparing the overall performance of the concrete sleeper and fastening system while changing key variables including the fastening system type, rail pad materials and geometry, rail seat surface treatment, concrete mix design, and the overall sleeper design. This research is sponsored by Unit Rail, Inc., a subsidiary of Amsted Rail, Inc., and focuses on continued development of the captive clip insulator assemblies, which are installed at the sleeper manufacturing plant. In addition, the testing focuses on the post insulator and abrasion resistant rail pad assembly design.

The PLTM consists of three 35,000 pound (lb) actuators with a 10-inch stroke (Figure 7). It is used to simulate severe load conditions on concrete sleepers using AREMA Test 6 (Wear and Abrasion) to test the performance and durability of different fastening system components and determine an optimal level of load attenuation and rail pad durability, while reducing rail seat pressures.

Figure 4: (a) Full scale concrete sleeper and fastening system testing at UIUC, (b) Vertical and lateral actuators connected to the loading head, (c) The loading head at rest of the head of the rail, with the fastening system applied
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PRELIMINARY RESULTS

Rail Seat Surface Treatments

Rail seat surface treatments are used for two purposes in North America. The first purpose is to repair the rail seat of a concrete sleeper with RSD using an epoxy based product to repair ties. The second purpose, adopted by only a few railroads, is to apply a thin membrane of an epoxy-based product at the sleeper manufacturing plant. This thin membrane would theoretically seal the rail seat from moisture and abrasive fines.

Preliminary results from the full-scale concrete sleeper testing and research at UIUC’s ATREL, using different types of fastening systems and rail seat treatments, have shown that all rail seat surface treatments have failed to resist wear after extended loading cycles. After completion of each three-million-cycle test with epoxy treated rail seats, the epoxy on the field side has entirely worn away from the rail seat (Figure 5). Once the rail seat surface treatment is worn away from a portion of the rail seat, the behavior of the fastening system could be adversely affected due to the relative decrease in rail seat height with respect to the fastening system shoulder. This decrease in height could reduce the clamping force. The worn epoxy within the rail seat may also generate abrasive fines that have the potential to cause increased abrasion on rail seat pads and insulators. Further testing is needed to validate the preliminary results described in this section.

Figure 5: Worn rail seat surface treatment on the field side after 3 million cycles

Rail Seat Pressure Distribution Measurement

In order to better understand the forces that occur at the rail seat, researchers at the University of Illinois at Urbana-Champaign are currently engaged in a project to measure the pressure distribution at the concrete rail seat. The objective of the study is to measure rail seat pressures and their distribution with different loading conditions (magnitude, L/V) and different fastening systems elasticities. This will enable us to compare the distributions and investigate how rail pads of different stiffnesses affect load attenuation and RSD. To accomplish this objective, we are using Tekscan® sensors.

The loads acting on a concrete sleeper depend, not only on railcar axle loads and tie spacing, but also on the size of the rail, track modulus, and the properties of the rail fastening system. A change in any of the aforementioned variables would impact the pressure and its distribution at the rail seat. In controlled testing facilities such as UIUC’s ATREL and TTCI’s FAST, most of the factors...
affecting the stresses at the rail seat can be determined with great accuracy. In these controlled facilities, for any given load combination the total stress at the rail seat is known and the change in pressure distribution can be measured (using Tekscan® sensors) and studied with slight changes in any of the variables (particularly the fastening system components).

**Tekscan® Pressure Measuring System Overview**

Tekscan’s pressure measuring system provides an array of force sensitive cells that enable the user to measure the pressure distribution between the two contacting surfaces. The sensors consist of two thin, flexible polyester sheets which have electrically conductive electrodes deposited in varying patterns. The surface of the inner face of one sheet forms a column pattern and the inner surface of the other sheet form a row pattern. The intersection of each row and column creates a sensing cell, (also known as a sensel™). The spacing between the rows and columns varies according to sensor application.

The sensors come in a wide variety of shapes, sizes, and spatial resolutions. The sensors are extremely thin and flexible (e.g. on the order of 0.004 in) and their semi-conductive ink printed in rows and columns varies with the applied force. Sensors can be manufactured for use with a wide range of pressures, including the range found at the rail seat and within the fastening system. Teflon paper and mylar sheets are recommended to be used as general protection of the sensors from shear forces and sharp edges. These protection layers thicken the sensor by 0.012 in, which must be considered when recording and reporting results.

The Tekscan system includes the sensors, the handle and the software. The handle provides a connection between the sensor and computer converting the sensor output to a digital image. The handle uses pogo pins to clamp over the lead of the sensor and make individual contact with each of the silver leads. The software serves as the primary means of evaluating and viewing the data and allows the user to control how the data is collected. The software additionally enables different sensor sensitivities for more accurate data collection.

Calibration of the sensor is an important step to validate any results. The level of precision of the final pressure values will strongly depend on how well the calibration process was carried out. Generally, calibration is conducted before the actual tests, but it could be completed after testing is complete. Calibration is completed by applying a known force to the system, using areas and surface geometries that are representative of the ones that will be tested. The raw values obtained by the sensor are then matched with the known values. A calibration factor is obtained and is used for future tests with that particular sensor type.

**Tekscan Sensors at Rail Seat and Fastening System Pad Interface**

The thin sensors are placed at the rail seat and fastening system pad interface. Then the fastening system is fastened and the sensor is able to record the applied toe load and the weight of the rail section above it. Figure 6 shows how a sensor is placed at the rail seat, with the handle protruding on the right. It is important to select the correct sensor size to accurately cover the entire rail seat area. For this initial feasibility study, the sensor model 5150 was used. This sensor can accurately measure pressures of up to 1500 psi.
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Figure 6: (a) Tekscan sensor bent along the base of the rail, (b) Proof-of-concept test with sensor on PLTM, (c) Sample frame of pressure distribution obtained during proof-of-concept test
Challenges to Rail Seat Pressure Measurement

Thus far, precise calibration of the system was our biggest challenge, and it plays a major role in achieving valid results. Our second challenge at the early stages of the investigation was that the type of sensor used at the beginning of the investigation was larger than the rail seat area and had to be bent along the base of the rail (Figure 6). Applying large forces while having the sensors bent on sharp edges (e.g. base of the rail, edge of post insulators, etc) caused damage to a considerable section of each sensor in every proof-of-concept test. As a result, the sensor reading will not have the accuracy level required for this investigation and a precise calibration is also compromised.

A smaller sized sensor which fits the rail seat flat without being bent will be obtained for future testing and research. The Tekscan® sensor model that meet this requirement is model 5150N. The sensor model 5150N will allow us to better compare the repeatability of the results. Also, using a smaller sensor will keep sensors from getting damaged in every trial run.

CONCLUSIONS

As freight railcar axle loads increase in North America, the need for improved performance of concrete sleepers and fastening systems is becoming increasingly important. The occurrence of rail seat deterioration (RSD), one of the primary maintenance concerns with concrete sleepers on North American heavy-haul railroads, can also be correlated with the performance of the fastening system and concrete sleepers. Significant research has been undertaken by universities, testing laboratories, and sleeper and fastening manufacturers, aimed at increasing fastening system component durability while making installation and maintenance more cost effective. Also, laboratory research has focused on understanding the mechanisms behind RSD and finding practical ways to prevent the occurrence of RSD. By using the Tekscan® sensors to measure pressures and the distribution of these pressures at the rail seat with different loading conditions (magnitude, L/V) and different fastening systems elasticities, we would be enabled to compare pressure distributions and investigate how pads of different stiffnesses affect load attenuation and RSD. To meet the needs of the railway industry, extensive research and advancements are still needed, and they will most likely focus on the areas of fastening system component durability, concrete sleeper and fastening system cost effectiveness, and prevention of RSD.

FUTURE RESEARCH

Future research in the area of fastening system elasticity will include laboratory validation and field experimentation of our rail seat surface treatment and rail seat pressure distribution investigations. It is important to understand and validate how surface treatments can affect the fastening system performance. Another important step in concrete sleeper and fastening system research is determining how the rail seat surface pressure distribution measurements will help us understand how the loading path of the rail infrastructure is affected with different fastening systems. Also, an analysis of how the pressure distribution underneath the concrete sleeper is affected with varying fastening systems elasticity will be conducted. Using the results obtained in the aforementioned future research, we propose the development of a stiffness model to classify the fastening systems according to their elasticity and recommend the optimum stiffness for a pad in order to properly attenuate the load to maximize component durability.

Future research in the area of rail seat deterioration (RSD) in concrete sleepers will include the study of the crushing and abrasion mechanisms thought to contribute to RSD. The abrasion mechanism will be addressed through modeling and experimental testing, which is currently underway. Research on this mechanism will lead to a better understanding of how concrete mix designs, sleeper pad materials, and other materials and sleeper design choices relate to one another and will help to maximize the effectiveness of the overall design of the sleeper and fastening assembly.
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