Considerations for Mechanistic Design of Concrete Sleepers and Elastic Fastening Systems in North America

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Abstract

A sustained increase in heavy axle loads and cumulative freight tonnages, as well as increased interest in high speed passenger rail development, has placed an increasing demand on railway infrastructure and its components. One of the most critical areas of the infrastructure in need of further research and analysis is the concrete sleeper and elastic fastening system used in heavy haul and shared infrastructure applications. A limited understanding of the complex loading conditions affecting the concrete sleeper and elastic fastening system components led to a design process based primarily on practical experience and previous techniques, which fails to include key variables that relate to actual field loading conditions. This process, which is typically driven by production and installation economics, has generated components that do not achieve their design life. While initially functional, they ultimately require more frequent maintenance or fail prematurely, causing track outages, reduced capacity, and added cost. To address this challenge, the University of Illinois at Urbana-Champaign (UIUC) is analyzing and comparing the existing heavy haul and shared infrastructure loading environment to current recommended design practices within the international railway community. This paper discusses the use of field experimental data, as well as complete sleeper and fastening system analytical modeling, and how they can be used to improve the current understanding of the loading demands on each component within the system. Results from these tests and modeling efforts, along with probabilistic considerations with respect to dynamic and impact loading, will contribute to a greater understanding of the loading regime present in the concrete sleeper and elastic fastening system in heavy haul and shared infrastructure applications. Ultimately, this improved understanding will provide a basis for a mechanistic design process, contributing to improved recommended practices for concrete sleeper and fastening system design and improving safety, reliability, and rail capacity.

1. Introduction

Historically, the North American sleeper (or crosstie) and fastening system have been designed through a process that is generally based on practical experience, without a clear understanding of failure mechanisms, their causes, and the loading environment. This design methodology has led to performance challenges and service failures that cannot be adequately explained or predicted. Without a clear framework for the design and expected performance of concrete sleepers and fastening systems, inefficiencies in component design and maintenance may exist, with a resulting negative impact on the economics of concrete sleepers and fastening systems. Improvements in the design of these systems will provide a more robust railway superstructure, where the loading environment is more fully understood, failures are reduced, and the possibility of predicting performance and wear rates exists.

The North American loading environment differs from that throughout much of the rest of the world, due to the prominence of rail freight transport and sharing of infrastructure between freight and passenger traffic. This paper will investigate the particular loading conditions found in North America and draw comparisons between the varied international design considerations where the loading environment may be different.

2. Current Recommended Design Practices

Internationally, there are many unique design methodologies for the manufacture of concrete sleepers and fastening systems. Many countries have their own version of design standards or recommended practices that railways and manufacturers follow to varying degrees. This paper will briefly discuss the similarities and differences in design methodologies found in North America, Europe, Australia, and Japan.

The American Railroad Engineering and Maintenance-of-way Association's (AREMA) Manual for Railway Engineering is the primary source of guidance for the design and construction of North American railway infrastructure. It is a set of recommended practices, and is typically modified by individual railways to meet their specific loading or performance objectives [1]. Chapter 30 of the Manual for Railway Engineering provides guidance for sleepers, and Part 4 of that chapter focuses on concrete sleepers. While this section of the AREMA manual offers helpful information for railways and sleeper manufacturers, there are opportunities for improvement, particularly in terms of the sleeper design process (hereafter referred to as the "AREMA Method").

One opportunity for improvement of AREMA Chapter 30 is the consideration of component interactions and system performance. In the 2012 International Concrete Sleeper and Fastening System Survey conducted by UIUC, fastening system manufacturers indicated that component and system interaction plays a large role in their design [2]. This concept should be included in the development of improved design recommendations for concrete sleepers and fastening systems.

There are two design parameters used in the AREMA Method for determining concrete sleeper geometric and strength characteristics: allowable ballast pressure and flexural performance. In determining the allowable ballast pressure, the AREMA Method considers sleeper spacing (leading to the determination of a load distribution factor), wheel load, an assumed impact factor, and sleeper bearing area. Another portion of the AREMA Method for concrete sleepers contains the flexural performance requirements. These requirements consider sleeper length, sleeper spacing, speed, and tonnage to determine the positive and negative design bending moments at the center of the sleeper and at the rail seat. Some consideration was given to impact or dynamic factors and axle loads in the fabrication of the method, but they are not explicitly used in the recommended practices for flexural design. Therefore, the flexural design of a concrete sleeper as found in AREMA Chapter 30 does not consider many important design criteria, such as track geometry (e.g. curvature and grade), design life, or impact factors and axle loads that reflect the intended loading environment.

Because it is typically the primary design criteria of concrete sleepers, the authors have reviewed the design bending moment design methodologies in multiple standards and recommended practices. Within each methodology, different design principles are considered and used.

The European Standard offers recommendations for the design of concrete sleepers, and, like the AREMA Method, its primary focus is the design bending moment. However, EN 13230 states that the specific design method is the responsibility of the purchaser, considering static and dynamic wheel loads, design and maintenance of the track (including longitudinal distribution of wheel loads), climatic conditions, magnitude of prestressing force, strength of concrete, and particular, non-standard designs [3].

The Australian Standard calculates positive and negative rail seat and center bending moments using sleeper spacing, static wheel load, track modulus, rail modulus, rail second moment of area, quasi-static and dynamic design load factor, sleeper length, gauge, and support conditions [4]. An intermediate step to this process incorporates Talbot's method for determining rail seat loads [5]. The standard also explicitly states that sleeper sections need not be checked for stresses other than flexural stresses [4].

The Japanese Industrial Standard (JIS) simply provides "bending forces" that must be exceeded during testing of concrete sleepers [6]. The design methodology is not explicitly provided in the JIS, and is therefore determined by the manufacturer, as long as it meets the performance criteria as stated in the JIS.

After reviewing the above international design methodologies, it is evident that the concrete sleeper design process is not uniform throughout the international railway community. There are many criteria to be considered from design recommendations and best practices worldwide. These principles can be applied to the development of an approach that is centered on science and materials properties to govern the design of concrete sleepers and fastening systems in North America. However, the operating environment in North America, which is often different than that found elsewhere in the world, must be better understood before mechanistic design recommendations can fully be developed and placed into practice.

3. Principles of Mechanistic Design

The mechanistic design process is one derived from analytical and scientific principles, considering field loading conditions and performance requirements. Mechanistic design has been used in other disciplines, such as the design of rigid and flexible highway pavements using particular input values, performance analyses, and alternative evaluations [7].

Historically, North American concrete sleepers and elastic fastening systems have been designed through a design process that does not include all of the critical variables relating to actual field loading conditions. A lack of understanding regarding the complex loading conditions of the system has led to a design methodology driven by production and installation economics, where very high priority is placed on manufacturing and installation efficiency. Oftentimes, this process is not directly based on actual performance of the sleeper and fastening system or a thorough understanding of the demands on each component.

Therefore, UIUC is developing a mechanistic design process that uses the existing loading environment and sleeper and fastening system components. This exercise will create an improved understanding of failure causes and effects on performance. Design would typically be directed toward a specific failure mode (often grouped into one of three categories; support, stability, or isolation failure [8]), creating predictable wear and fatigue rates and leading to repair cycles that coincide with other planned maintenance intervals. This improved design procedure will increase production and operational efficiency while reducing unscheduled maintenance and track outages.

3.1. Shared Use Loading Environment in North America

The railway operating environment in North America is different than much of the rest of the world. As enthusiasm for higher-speed intercity passenger service grows, some “incremental” systems are developing that require passenger and freight traffic to share the same infrastructure. Shared railway infrastructure provides an effective method for providing an incremental approach to higher-speed passenger transportation, and reduces the first cost associated with opening a new system. One of the many challenges facing shared use infrastructure is the design and performance of critical components. To better understand loads applied to the infrastructure, UIUC has acquired Wheel Impact Load Detector (WILD) data from sites throughout the United States from both Amtrak’s Northeast Corridor, (a shared use corridor in operation for many decades), and the Union Pacific Railroad.

WILD sites are typically constructed on well-maintained tangent track with concrete sleepers. Although loads experienced elsewhere on the network will vary and may have a higher magnitude due to track geometry deviations, these data still provide insight to the varied loading landscape at representative sites throughout North America. Specific loading properties such as peak vertical load, peak lateral load, impact factor, and speed are analyzed by creating various distributions of these properties and determining relationships between them. An example of this type of distribution is shown in **Figure 1**.

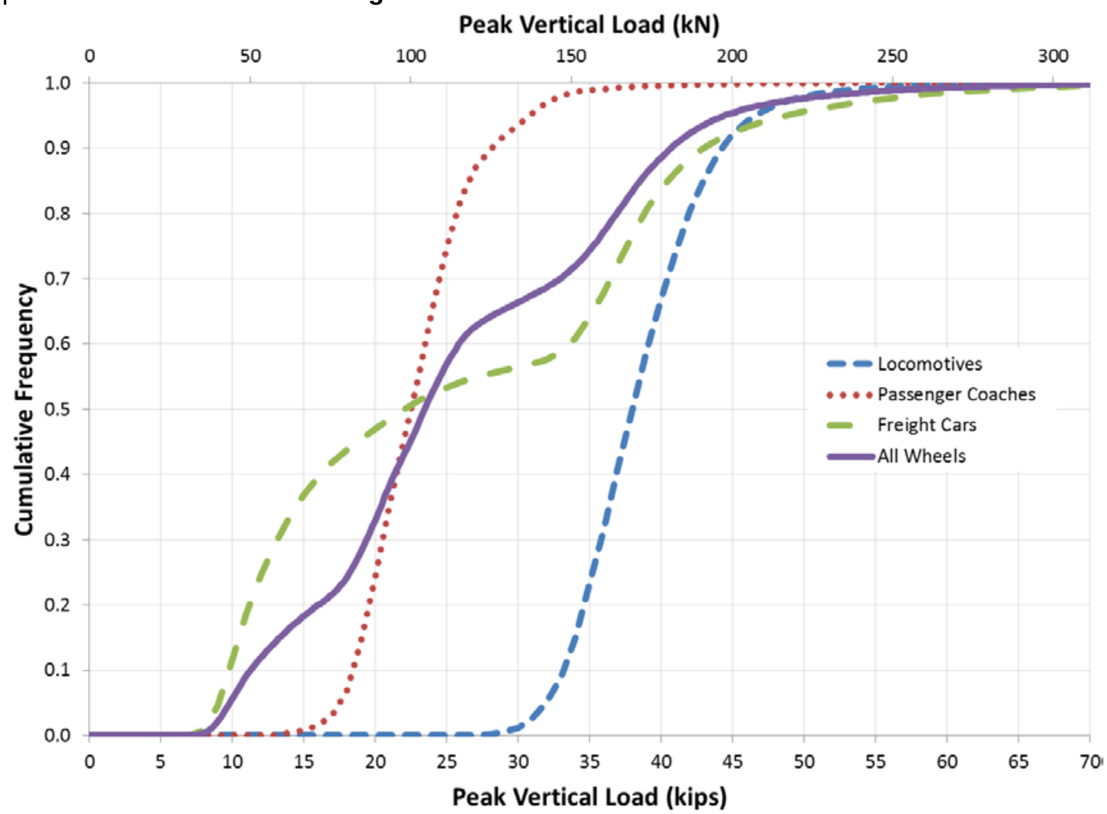

Figure 1: Cumulative Frequency of Peak Vertical Loads on Amtrak at Edgewood, Maryland (WILD Data from November 2010)

As **Figure 1** shows, at Amtrak’s Edgewood, MD WILD site, locomotives, freight wagons, and passenger coaches all impart different magnitudes of vertical load onto the track structure. Once the loading spectrum is adequately determined, one must decide how to effectively design the system and its components accordingly. The relationship between extreme loading events (e.g. wheel impact loads) and failure mechanisms is not well-defined, so it is difficult to sufficiently determine the required robustness of design. Probabilistic considerations must be made throughout the design process, reflecting safety, financial, and capacity decisions. The disparity in the magnitude of loads between passenger and freight traffic and their respective weighted traffic volumes must also be addressed in designing for specific loading environments.

Results from the 2012 UIUC International Concrete Sleeper and Fastening System Survey provide a comparison of the North American and international loading environments and are summarized in **Table 1** [2]. According to both the international and North American responses, the average maximum freight static axle load exceeds the design axle load based on responses from the concrete sleeper manufacturers. The load and tonnage values are, on average, substantially higher in North America than in the remainder of the world, according to the respondents (**Table 1**) [2].

Table 1: Loading Environment Summary from the 2012 International Concrete Sleeper and Fastening System Survey [2]

	International Responses	North American Responses
Average maximum freight axle load*	26.8 tonnes (29.5 tons)	35.4 tonnes (39.1 tons)
Average maximum passenger axle load*†	19.6 tonnes (21.6 tons)	26.4 tonnes (29.1 tons)
Average concrete sleeper design axle load	25.0 tonnes (27.6 tons)	33.9 tonnes (37.4 tons)
Average annual tonnage (per track)	35.1 million gross tonnes (38.7 million gross tons)	90.8 million gross tonnes (100.0 million gross tons)

*Interpreted from responses due to discrepancies in axle or wheel loads
†Light rail response excluded

Both the WILD data and survey results provide a better understanding of the loads imparted into the superstructure, but this understanding is not sufficient for the design of concrete sleepers and elastic fastening systems. The load's attenuation and progression through the track provides information critical to the design of the superstructure components.

3.2. Qualitative Establishment of Load Path

At their core, mechanistic design practices use actual loading data to develop a design that functions adequately under the expected loading conditions. To better determine the demands on each component, an analysis of the load path was conducted at UIUC. An example of this effort for one specific fastening system and loading scenario is shown in **Figure 2**. This static analysis of interface loads and component deflections helped to establish the locations for load transfer that may require additional analysis.

Given a particular input loading condition and appropriate simplifying assumptions, the magnitude of forces at each interface can be determined. UIUC has developed a spreadsheet that accepts particular input parameters, such as material and geometrical component properties, and produces forces at interfaces and component deflections. Therefore, the spectra of loads such as those shown in **Figure 1** can be traced throughout the remainder of the fastening system (and the sleeper, ballast, and subgrade), providing estimates of the magnitudes of forces that should to be measured at each interface given a particular traffic type.

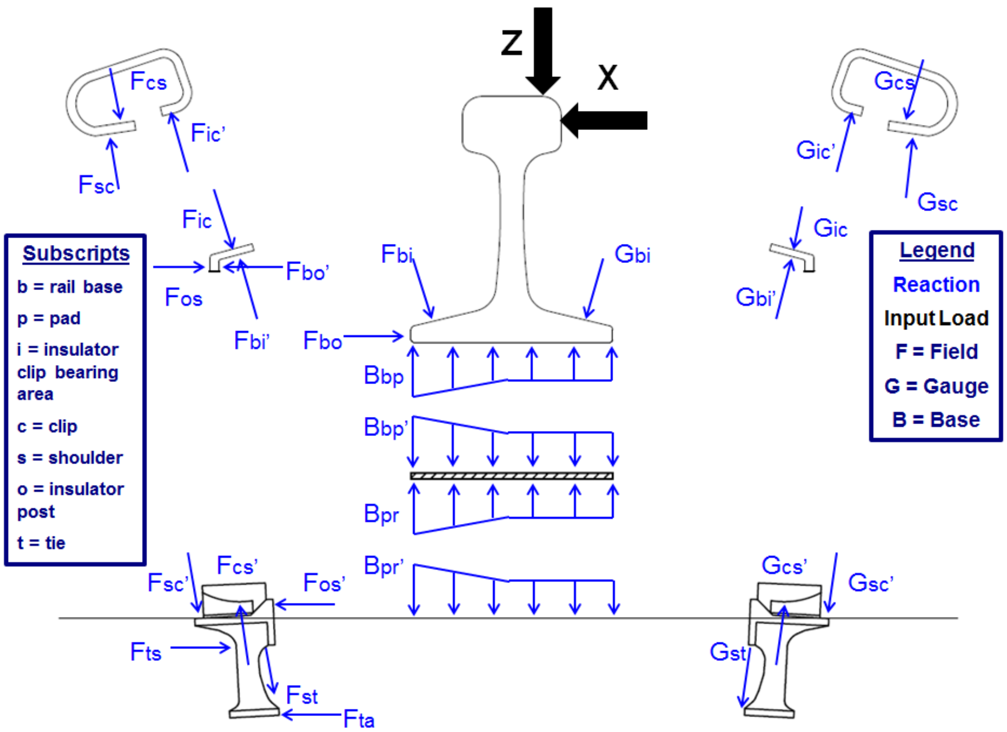

Figure 2: Concrete Sleeper Fastening System Load Path Map and Component Free Body Diagram

In addition to this initial analysis, the effect of accelerating wheel loads and clamping force on longitudinal forces must also be considered in a comprehensive exploration. Because many simplifying assumptions were used to complete this initial investigation, its results must be used as an adequate estimation, providing feasible values to be compared with other load quantification efforts. To evaluate the loads within the system more accurately, lab and field instrumentation and more sophisticated analyses, such as finite element analysis techniques, must be employed.

3.3. Laboratory Experimentation, Field Instrumentation, and Analytical Modeling

After identifying locations where the load is transferred throughout the system, it is necessary to try to accurately quantify the loads that were qualitatively derived. This quantification process defines the demands on each component, focusing primarily on determining the magnitude of forces that are transferred at component interfaces. Laboratory experimentation, field instrumentation, and analytical modeling are tools used to quantify the loading conditions and displacements at each interface between components.

Both laboratory and field instrumentation provide quantitative information regarding the load path through the concrete sleeper and fastening system. Using known input loads from full-scale testing in the laboratory and revenue service testing in the field, UIUC has developed a method for determining loads applied to the components within the system and their associated deflections. To correlate the interfacial loads with wheel loads applied at the wheel/rail interface, significant instrumentation is used on the rail as well. In all, the following magnitudes are measured in the laboratory and field settings: vertical wheel load, lateral wheel load, vertical rail strain, rail base bending stress, vertical rail displacement, lateral rail displacement, global vertical displacement, internal sleeper strain, external sleeper strain, vertical rail seat load, rail seat stress distribution, insulator post stresses, and fastening clip stress. These values provide a significantly improved understanding of the behavior of the concrete sleeper and fastening system as a whole.

In addition to the instrumentation performed on the physical system, significant three-dimensional (3D) analytical methods are also employed. Using the qualitative free body diagrams as shown in **Figure 2** as a framework and basic statics principles, a fundamental analysis is performed to determine estimated loads and deflections of the components. Simplified two-dimensional (2D) finite element models are created to confirm the basic analysis and provide further guidance to the forces present within the system. In parallel with both the instrumentation and basic analysis, a comprehensive finite element model is created incorporating the geometry and materials of each component and its interaction with those surrounding it. This tool can model different loading scenarios, including dynamic loads, and provide valuable insight into the component response and interdependencies. Parametric analyses are performed, guiding our understanding of component properties and how they relate to the performance within the expected loading regime. Once validated, the model will ultimately be the primary tool for running iterations that will facilitate the development of mechanistic design practices.

3.4. Design Process

After gaining an improved understanding of the loading environment, one must look at the current geometry and material properties of the components and evaluate whether or not those properties are appropriate for the existing and expected loading environment. If not, alternative component geometries or materials that perform better in response to the loading demands should be pursued.

The next step in the design process is to relate the loading conditions to specific failure modes. This is done by identifying certain types of failure that occur specifically because of the loading demands on that particular component. Taking advantage of the modeling techniques, innovative designs can be developed and tested using the instrumentation plan already in place. Some novel component designs are evaluated and existing geometry and materials can continually be improved. Ultimately, this process will lead to improved mechanistic design practices. This set of recommendations will be based on both theoretical and empirical relationships, leading to a more thorough understanding of the behavior and performance of each component.

4. Conclusions

The complex loading conditions found within the concrete sleeper and fastening system in North America were not fully considered when the AREMA recommended practices were developed. An improved understanding of the existing loading environment will provide greater insight into failure mechanisms. The cause of these failure modes can be addressed by improvements to design recommendations based on the science of those mechanisms. Ultimately, the mechanistic process of design will lead to improved performance of concrete sleepers and fastening systems, increased safety, and decreased life cycle costs.

5. Future Research

As this research continues to progress, further insight will be gained regarding the complex loading conditions present in the concrete sleeper and fastening system. Additional fastening systems will be tested and analyzed to better reflect their use throughout the railway industry. WILD data from North American railways will continue to be analyzed and relationships will be developed, creating a more complete picture of loads being applied to the infrastructure. This information will be applied to instrumentation and modeling efforts currently underway at UIUC, continually improving the understanding of the existing environment causing critical failures. Improved recommended design practices will contribute to the mitigation of these failure modes and should improve performance of concrete sleepers and fastening systems in North America.

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