Resilient Concrete Crosstie and Fastening System Designs for Light Rail, Heavy Rail, and Commuter Rail Transit Infrastructure

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Abstract
Light rail, heavy rail, and commuter rail transit agencies face a myriad of loading conditions that must be considered in the design and maintenance of their track infrastructure and its components. It is not uncommon for a single rail corridor to experience a wide variety of loading conditions due to a variety of factors, all of which must be considered in order to design "optimized" sleeper and fastening systems that are capable of performing well under a wide range of service conditions. For a variety of reasons, concrete sleepers are a dominant material choice for construction of light rail, heavy rail, and commuter rail transit systems. Currently, the methods of designing concrete sleepers and fastening systems for rail transit systems are not developed based on mechanistic design practices considering actual field loadings and service demands, but rather are largely based on empirical results and practical experience derived from other sectors of rail transportation. The need for mechanistic design practices and resilient component designs is recognized by the manufacturers of the sleepers and fastening systems, and rail transit operators. Additionally, deficiencies in concrete sleeper performance have been noted on passenger and transit corridors in the US. Extreme weather events, such as Hurricane Sandy in 2012, emphasize the need for more resilient infrastructure components with increased robustness, adaptiveness, and readiness to allow transit operators to resume service quickly and safely after extreme weather events. To address the need for an optimized, resilient sleeper and fastening system for rail transit properties in the US, a multi-faceted research project is underway to study loading conditions, and design, produce, and install prototype sleepers and fastening systems for rail transit systems. This paper will present the need for transit-specific infrastructure components designed using mechanistic design, and provide preliminary results from field and laboratory experimentation.

1. Introduction

Throughout the world, the majority of railroad track infrastructure is ballasted sleepers. The most commonly used material for sleepers in the United States is timber, making up 90-95% of the sleepers in revenue service *(1)*. Concrete sleepers make up the majority of the remaining 5-10%, with steel and composite sleepers adding a negligible share *(1)*.

Historically, concrete sleepers manufactured for all markets in the US have been designed based on practical experience, rather than through clear understanding of the load environment in which they will be installed and failure mechanisms and causes that can be expected *(2, 3, 4, 5)*. This design methodology has led to significant performance challenges and service failures on passenger and transit corridors (i.e. Amtrak, Metro-North Commuter Railroad, etc.) including chemical deterioration of the concrete, premature deterioration of the rail pad, and other structural failures *(6, 7)*. Improvements in the design of sleepers and fastening systems will provide more robust and resilient railway track systems with components that have a reduced risk of failure and whose wear and deterioration rates can be predicted based on performance metrics *(2, 8)*.

Many rail transit systems employ ballasted track with sleepers on a portion of their system, and concrete sleepers have become a common component in the construction of new systems, often due to superior ride quality *(9, 10)*. These systems will often experience a wide variety of loading conditions due to internal factors such as railcar loading and speed, and external factors such as climate and extreme weather events, and must all be considered when designing "optimized" track components *(11)*.

Rail transit systems provide an important service to the communities they serve. The livelihood of many residents of these communities is dependent on the efficient, reliable transportation that these systems provide. This dependency is prominently shown when a rail transit system, or part of a system is shut down unexpectedly, such as the shutdown of New York City Transit (NYCT) in the weeks and months following Hurricane Sandy in 2012 *(12)*. Extreme weather events emphasize the need for resilient infrastructure components that allow systems to be returned to revenue service promptly, while ensuring safe operations *(13)*.

The Federal Transit Administration (FTA) of the United States Department of Transportation (US DOT) provides definitions of light rail, heavy rail, and commuter rail in the National Transit Database (NTD) Glossary. These definitions make distinctions between the three types of rail transit based on right-of-way (ROW) type (exclusive versus shared), motive power type (electric versus diesel, self-propelled versus locomotive hauled) and distribution system (catenary versus third rail), and platform type (high versus low level), as well as other mode-specific characteristics *(14)*.

To address the need for optimized, resilient concrete sleepers and fastening systems for rail transit applications, the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) has begun work on a multi-year research project entitled "Resilient Concrete Crosstie and Fastening System Designs for Light Rail, Heavy Rail, and Commuter Rail Transit Infrastructure" (hereafter referred to as "the project") to investigate rail transit loading conditions and use mechanistic design principles to design more resilient infrastructure components for rail transit infrastructure. The mission of this project is to characterize the desired performance and resiliency requirements for concrete sleepers and fastening systems, quantify their behavior under load, and develop resilient infrastructure component design solutions for concrete sleepers and fastening systems for rail transit operators. The approach for the project includes a paper study to quantify static vehicle loads, field and laboratory experimentation to quantify in-service and dynamic vehicle loads, analytical finite element (FE) modelling of rail transit sleepers and fastening systems, and development of an optimized prototype sleeper which will be deployed in the field on a partner transit agency. This project also aims to address one of the primary strategic goals of US DOT – State of Good Repair – by ensuring that critical transportation infrastructure is functioning as designed, or reducing the cost of maintaining track infrastructure *(15)*.

This paper will focus on the vision and objectives of the project, introduce and describe the principles and process of mechanistic design, present key findings from work that has already been undertaken, and describe the future work to be included in this project.

2. Mechanistic Design

Mechanistic design is a practice for designing infrastructure components based on the load environment in which they will be installed. The process considers in-field loads and service demands ensuring that components are designed specifically for the load environment in which they will be expected to perform, and drastically reduces the likelihood of premature or unexpected failures [8]. Mechanistic design of components can also serve to reduce life cycle costs associated with improperly designed components. Mechanistic design principles are currently utilized in other civil engineering applications, such as the design of highway pavements *(16)*.

Limit-state design is a similar method for the design of concrete sleepers based on the expected load environment which they will be subjected to. This design method includes three limiting conditions which bound the wheel loads expected and their anticipated damage to the sleepers. Like mechanistic design, limit-state design considers the actual loads that a sleeper is expected to be subjected to. These limit states are further defined by the percentage of sleepers that should be expected to fail within a 100- or 200-year return period and the percentage of wheel loads that are expected to cause the described amount of damage *(17)*. These limit states can then be used to design a sleeper that fits all requirements based on the expected loads.

The mechanistic design process employs multiple steps to define the load environment in which a component will be expected to perform, determine the path for loads to be transferred to, through, and from the component (i.e. load path to the sleeper via the rail, internal transfer of load through the sleeper, and transfer from sleeper to ballast), and design the component to withstand the demands on it due to the load environment and load path. The design of the component involves multiple steps to confirm the material choice for the component, design of the component itself, including geometry and other properties, and finally the entire assembly (i.e. sleeper and fastening system). The steps of the mechanistic design process are as follows *(5)*:

1 Define input loads
2 Initiate qualitative establishment of load path
3 Define design criteria
4 Execute design process
    a. Materials level verification
    b. Component level verification
    c. Assembly level verification
5 Conduct system level verification

3. Survey of Rail Transit Track Superstructure Design and Performance

In order to understand the problems associated with concrete sleepers and fastening systems designed for rail transit use, a survey of rail transit agencies within the United States, titled "Survey of Rail Transit Track Superstructure Design and Performance" (hereafter referred to as the "Transit Survey"), was conducted. The survey consisted of a series of questions addressing the use of, maintenance practices for, and future plans for installation of concrete sleepers on their system. The survey was distributed to rail transit agencies within the United States, and intended to be taken by the individual with the most knowledge of their track system. The results of the survey will help guide the research efforts associated with this project by identifying the most critical concrete sleeper and fastening system failures observed on rail transit systems.

Audience

The Transit Survey was distributed to professionals in various positions and organizations within the rail transit industry, including infrastructure owners, operators, and maintainers and concrete sleeper and fastening system manufacturers throughout the United States. This wide coverage offers varied perspectives on the usage and performance of concrete sleepers and fastening systems from light rail, heavy rail, and commuter rail systems to manufacturers of the components in question.

Development

The Transit Survey was developed with input from rail transit experts around the United States. Questions were developed internally at UIUC regarding the use and performance of concrete sleepers and fastening systems on rail transit systems. An initial test survey was then developed and distributed to the project's industry partners and the entire UIUC team for review and subsequent revision. The industry partners, who include rail transit operators, concrete sleeper and fastening system manufacturers, and trade organizations, provided valuable feedback based on transit experience and information the industry would like to garner from such a survey.

Content

The content of the Transit Survey explored the types and quantities of concrete sleepers installed on each system, operational characteristics including maximum vehicle weight and shared corridor operations, future expansion plans using concrete sleepers, and relevant research areas and perceived concrete sleeper deficiencies.

Results

Respondents were also asked to comment on the criticality of sixteen track structure conditions in terms of contributing to the occurrence of railway accidents on concrete sleeper track. Of these sixteen conditions, thirteen were related to concrete sleepers and fastening systems, the reported criticality of which are shown in Table 1. Rail seat deterioration (RSD) and other forms of cant deficiency were perceived to be the most critical concrete sleeper problem among rail transit operators (3.00 ranking), followed by missing rail pad and broken or worn shoulder (both with a ranking of 2.71).

TABLE 1 Most critical concrete sleeper problems for North American transit agencies; ranked from 0 to 5, with 5 being most critical (based on six transit operators' survey responses)

Concrete Sleeper Problem	Average Criticality
Rail seat deterioration (RSD) and other forms of rail cant deficiency	3.00
Broken or worn shoulder	2.71
Missing rail pad	2.71
Shoulder/fastener wear or fatigue	2.57
Worn or missing insulator	2.50
Cracking from dynamic loads	2.43
Concrete sleeper with deteriorated bottom	2.43
Derailment damage	2.43
Missing clip	2.29
Cracking from environmental or chemical degradation	2.29
Tamping damage	2.00
Cracking from rail seat positive bending	2.00
Cracking from center binding	1.86

4. Experimental Plan to Address Survey Results and Design Components

Based on the results of the survey and parameters for design of concrete sleepers and fastening systems, researchers with RailTEC developed a list of questions to be investigated as part of this project. These questions include, but are not limited to, the following:

- What are the maximum vertical and lateral wheel loads experienced by the concrete sleeper at the rail seat? How much of this load must be borne by the sleeper?
- How much lateral restraint force is necessary to prevent the rail from displacing outside of allowable tolerances?
- What magnitudes of flexural forces are imparted by transit vehicles into the sleepers?
- How much variability is there in the support conditions underneath the sleeper?
- What strategies are to mitigate corrosion of the fastening system are feasible for rail transit applications?
- How do environmental factors affect concrete sleepers in rail transit applications?
- How do deteriorated sleepers perform in rail transit applications?
- Are there other material types that can improve the performance of concrete sleepers in rail transit applications?

Field and laboratory experimentation is planned in order to address the questions and hypotheses stated above. Field experimentation will aim to quantify the load environment for light rail, heavy rail, and commuter rail transit and gather data on the performance of current designs of concrete sleepers and fastening systems. This data will facilitate laboratory testing, through establishment of in-service dynamic load environment, and ensure that components designed in later steps of the project meet or exceed current component designs in the performance criteria measured.

5. Progress to Date

In addition to the Survey of Rail Transit Track Superstructure Design and Performance, researchers have made significant progress in other aspects of this project, including quantification of static wheel loads and preliminary field experimentation.

Quantification of Static Wheel Loads

Research by RailTEC has quantified the static load environment for light rail, heavy rail, and commuter rail infrastructure by quantifying the distribution of including the empty load (AW0) and crush load (AW3) for rail transit vehicles in revenue service in the United States *(18)*. These loads (AW0 and AW3) are the empty vehicle weight and maximum expected loaded vehicle weight, as defined by Parsons Brinckerhoff *(9, 18)*. Figure 1 shows the distribution of AW0 and AW3 axle loads for light rail, heavy rail, and commuter rail vehicles. The distributions shown include data for 100% of light rail vehicles, 85% of heavy rail vehicles, 72% of commuter railcars, and 91% of commuter rail locomotives currently in revenue service in the US *(18)*.

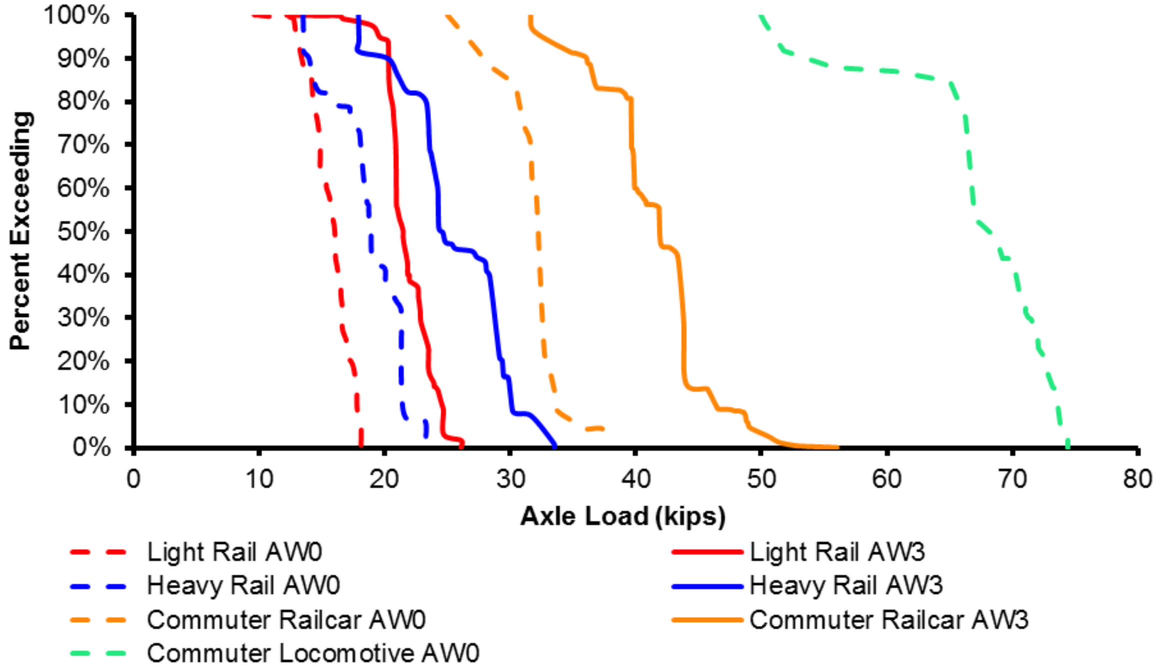

FIGURE 1 Rail transit static axle loads

Preliminary Field Experimentation

Preliminary field experimentation was performed on the MetroLink light rail system in St. Louis, Missouri using a subset of the instrumentation shown in Figure 2. Instrumentation installed included rail-mounted strain gauges to measure vertical and lateral wheel loads, linear potentiometers to measure rail base vertical and lateral displacement relative to the sleeper, and sleeper-mounted strain gauges to measure sleeper flexure. One purpose of this preliminary installation effort was to confirm that all measurement devices, which have been proven in North American heavy-haul freight experimentation, could be used reliably for rail transit experimentation with lighter axle loads and presumably smaller displacements and bending moments. Preliminary data analysis has proven these sensors can be reliably used for transit research as well as heavy-haul freight research.

6. Path Forward and Future Work

Future field experimentation will include sites on the other partner agencies for this project, including a full build-out on MetroLink, and installations on New York City Transit (heavy rail, New York City, NY, USA) and Metra (commuter rail, Chicago, IL, USA). The instrumentation map for these future sites is shown in Figure 2.

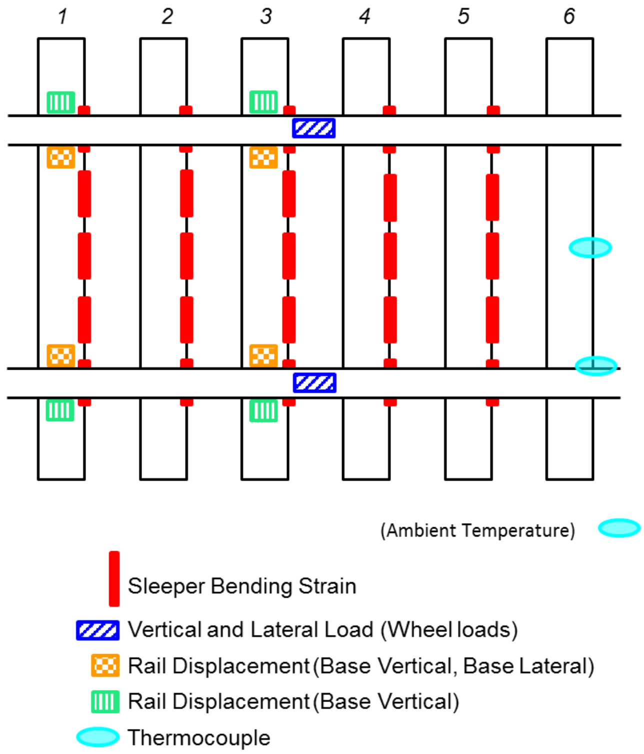

FIGURE 2 Instrumentation map for field installations

The instrumentation shown in this map will be deployed in tangent and curve locations on each of the above mentioned systems. The curve location will be chosen by radius of curvature (degree of curvature) for consistency with previous installations as part of this project and previous heavy-haul freight research efforts within RailTEC. This will facilitate comparison of results from previous research efforts. All instrumentation has been proven through field experimentation on heavy-haul freight railroads and rail transit systems, as well as laboratory experimentation *(8, 19, 20)*.

Based on data gathered from the field, laboratory experimentation will be conducted to further investigate performance and resiliency requirements for concrete sleepers and fastening systems. A finite element model will be developed concurrently with laboratory experimentation using system properties determined in the field and laboratory.

A finite element analysis of current rail transit sleeper designs will be undertaken to analyze the expected performance of these sleepers based on the load environment in which they are placed. This analysis will allow researchers to better evaluate current transit sleeper designs and investigate ways to further optimize current sleeper designs. This could be preferred by concrete sleeper manufacturers, as they have significant investments in forms for the sleepers they manufacture

Researchers are also investigating corrosion mitigation strategies for transit fastening systems to help prevent deterioration of components placed in damp or otherwise corrosive environments. Additionally, researchers are investigating different types of concrete material to determine if changes in materials can benefit the life cycle or strength of existing component designs.

The final deliverable of the project will be prototype concrete sleepers manufactured by established North American concrete sleeper manufacturers. These prototype sleepers are planned to be installed on revenue track on a partner rail transit agency.

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