

# MECHANISTIC DESIGN OF CONCRETE MONOBLOCK CROSSTIES FOR RAIL TRANSIT LOADING CONDITIONS

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## ABSTRACT

Light rail, heavy rail, and commuter rail transit systems experience a complex range of loading conditions that must be considered in the design of their track infrastructure and its components. Both internal factors (e.g. wheel load and speed) and external factors (e.g. climate and extreme weather) affect the loads applied to the track system and the system's response. These factors must be considered when designing optimized crosstie and fastening systems capable of performing under a wide range of operating conditions. Concrete crossties are widely used for rail transit applications, but the current design method is empirically derived from freight railroad design practices, and does not consider actual field loadings and service demands. These should be considered, and are an integral part of a new design process that we will propose known as mechanistic design. The need for a mechanistic design approach is recognized by manufacturers of concrete crossties and fastening systems, rail transit operators, and researchers, and will provide the framework for optimized component design. The focus of this paper is to introduce mechanistic design and its principles, and introduce a project that is aimed at using these principles in the design of concrete crossties and fastening systems for rail transit systems.

## INTRODUCTION

Throughout the world, the majority of railroad track infrastructure is supported by ballast. A ballasted track system typically consists of rail, fastening systems, crossties, ballast, sub-ballast, and subgrade. The most commonly used material for crossties in the United States is timber, which is used for approximately 90-95% of the crossties in revenue service [1]. Concrete is the second most common material for crossties, making up most of the remaining 5-10%. Steel and composite crossties are also used, but they make up a negligible share of the total number of crossties [1]. Typically, concrete crossties are used in the most demanding service environments and stringent operating conditions (e.g. high curvature, steep grades, heavy tonnage, high speed passenger traffic, rail transit systems, etc.).

The primary purpose of the crosstie is to maintain track geometry (e.g. gauge, cross level, etc.) and to transfer applied

wheel loads to the track substructure [2]. When a concrete crosstie supported on ballast is loaded vertically, the load is transferred from the wheel to the track system through the rail, fastening system, crosstie, ballast, sub-ballast, and subgrade. The ballast support conditions play a critical role in the type and severity of bending that the crosstie will experience under loading from a passing train [3]. The ballast support is affected by a variety of factors that include loading during train operations, tamping, fouling, and voids [4].

Historically, North American concrete crossties and fastening systems for all applications have been designed based on practical experience, without a clear understanding of the loading environment or failure mechanisms and their causes and effects. This design methodology has led to significant performance challenges, shorter life cycles, and service failures that are difficult to explain and predict. Improvements in the design of crossties and fastening systems will provide more robust railway track infrastructure with components that consider the loading environment more fully, have reduced risk of failure, and whose wear and deterioration rates can be predicted based on performance metrics [5].

Many rail transit systems use ballasted track with concrete crossties on a portion, or all of their system. It is not uncommon for these systems to experience a wide variety of loading conditions due to vehicle speeds, axle loads, track geometry characteristics, and environmental conditions. These factors are both internal (i.e. railcar loading, speed, etc.) and external (i.e. climatic, extreme weather events) to the crosstie and fastening system, and must all be considered when designing "optimized" crosstie and fastening systems that are capable of performing well under a wide range of service conditions.

The Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) has recently been awarded a 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 applications. The purpose of this paper is to introduce the project, introduce mechanistic design and its principles, examine rail transit loading environments, and preliminarily analyze the

effect of these load environments on crosstie flexural performance in preparation for early phases of the project, which is scheduled to begin in August of 2015.

## **RESILIENT CONCRETE CROSSTIE AND FASTENING SYSTEM DESIGN PROJECT**

Concrete crossties are a dominant material choice for light rail, heavy rail, and commuter rail transit systems. However, methods for designing concrete crossties and fastening systems for rail transit applications are largely based on empirical results and practical experience, rather than considering actual loading conditions and service demands. Additionally, performance deficiencies have been noted on freight, passenger, and transit corridors using concrete crossties throughout the US (i.e. Amtrak, Metro-North, MBTA, Class I freight railroads, etc.). These deficiencies include chemical attack of the concrete, premature deterioration of the rail pad, and structural failures. Other extreme weather events, such as hurricane Sandy and its impact on New York City Transit (NYCT), emphasized the need for more resilient infrastructure components that can withstand abnormal situations and promptly be returned to safe revenue service [6]. One example of a proposed improvement would be corrosion-proof fastening systems.

To address this need for optimized, resilient crosstie and fastening systems for rail transit applications, UIUC will be conducting a multi-faceted applied research, development, and revenue-service demonstration project that consists of field experimentation, laboratory experimentation, and analytical modeling of light rail, heavy rail, and commuter rail infrastructure components. In addition to analysis, the project also includes development and installation of mode-specific prototype components.

### **Project Mission and Objectives**

The mission of this project is to use innovative technologies and methods to characterize the desired performance and resiliency requirements for concrete crossties and fastening systems, quantify their behavior under load, and develop resilient infrastructure component design solutions for concrete crossties and fastening systems for light rail, heavy rail, and commuter rail transit operators. The project will have a major focus on keeping public transportation safe and in a state of good repair, especially during and after natural disasters and other externally caused extreme events.

The objectives of the project are to;

1. Conduct a comprehensive field investigation of the performance demands on concrete crossties and fastening systems on light rail, heavy rail, and commuter rail transit systems.
2. Conduct focused laboratory instrumentation to validate analytical modeling and further the knowledge gained during field experimentation.
3. Using field and laboratory loading data, develop an analytical finite element (FE) model for concrete

crossties and fastening systems on light rail, heavy rail, and commuter rail transit systems.

4. Develop mechanistic design recommendations for resilient transit applications of concrete crossties and fastening system design.
5. Manufacture and install resilient prototype crossties and fastening systems in revenue service on two of the three rail transit modes.

The objectives listed previously will result in rail transit concrete crosstie and fastening systems with increased robustness, adaptiveness, and readiness for the myriad of loading conditions faced in a rail transit environment.

The project addresses one of the primary strategic goals of US DOT – State of Good Repair [7]. Increased resiliency and lower life cycle costs will result in lengthened maintenance intervals, in turn increasing capital and operating costs available for other infrastructure improvements, and increasing the track capacity available to operate during and after extreme events, and under normal operating conditions.

### **Methods and Technologies**

Many technologies will be employed by UIUC to instrument and subsequently model rail transit infrastructure. Types of instrumentation to be used include weldable and concrete surface strain gauges, linear potentiometers, rail seat pressure transducers, and lateral load evaluation devices. These devices will be employed in both field and laboratory settings to understand the loads experienced at various interfaces within the combined crosstie and fastener system.

Laboratory experimentation will be used to replicate and field conditions, as well as investigate system performance under various other loading conditions, environmental conditions, and states of fastening system deterioration (i.e. removal of specific fastening system components) to understand the effect of these parameters on the performance of the individual components and the track infrastructure as a whole.

## **INTRODUCTION TO MECHANISTIC DESIGN**

As was previously mentioned this project will apply mechanistic design principles to the field rail transit infrastructure component design. Mechanistic design is a process derived from analytical and scientific principles, in which component design considers loading and performance requirements of the environment in which the component will be placed. In a rail transportation application, mechanistic design would use vertical, lateral, and longitudinal loads measured in the track structure and the properties of each material to design components that can withstand or transfer the loads [5] to the ballast, subballast, and ultimately the subgrade.

Since mechanistic design requires a thorough understanding of the loads present in a system, a critical first step of the project is to investigate theoretical rail transit wheel loads found in North America. Another early phase of the project will involve instrumentation of track operated by multiple rail transit

providers to quantify the variation in loads within a system under normal operating conditions. Once loads entering the system are understood, designers and researchers then investigate how these loads are transferred through the concrete crosstie and fastening system.

### Overview of Mechanistic Design Process

Researchers at UIUC are developing a mechanistic design process that uses existing heavy-haul freight loading environment data to optimize the design of concrete crossties and fastening systems for North American freight railroad applications [5]. While the loading environment used is specific to North American heavy-haul freight applications, the design process is applicable to practically any other kind of rail transportation, including rail transit. The steps of the mechanistic design process are as follows:

1. Define input loads
2. Qualitative establishment of load path
3. Define design criteria
4. Design process
  - a. Material verification
  - b. Component verification
  - c. Assembly level verification
5. System level verification

The first step of the mechanistic design process is to characterize the wheel loads that are applied to the track structure. This step is important to ensure that appropriate design strengths are selected for the system and its components. The magnitude and distribution of vertical, lateral, and longitudinal wheel loads vary depending on train speed, track geometry requirements and condition, vehicle health, and vehicle type. In the passenger rail environment, car loads can have large variation due to loading due to ridership at different times and on different lines. Thus, it is important to capture comprehensive data that accurately depicts this variation, so it can be considered in the subsequent design steps.

### LOAD ENVIRONMENT

Rail transit loading conditions can differ greatly from those observed on North American heavy-haul freight railroads. These differences can be attributed in part to the large variety of vehicles in use on transit systems nationwide, and even on specific systems. Other transit characteristics that may affect the load environment include ridership for a particular line (i.e. how many passengers per vehicle), and characteristics of the line or system itself.

For the purpose of this discussion, rail transit will be divided into three types of operation: light rail, heavy rail, and commuter rail. These types are defined based on the characteristics of vehicles operated, characteristics of the system (i.e. distance between stations), and infrastructure [8]. Commuter rail transit often shares corridors and infrastructure with freight railroads,

thus their track is often designed to meet the needs of the heavier freight trains consisting of railcars that are in unrestricted interchange in North America [9]. The load environment varies greatly between the three types, with commuter rail having the heaviest axle loads of the three.

In preparation for the project, an extensive literature review was undertaken to generally characterize the load environments for light rail, heavy rail, and commuter rail transit. The literature review included numerous design sheets and data plans for different rail transit vehicles throughout North America.

Axle loads for light rail, heavy rail, and commuter rail vehicles used in North American transit operations have been quantified in Tables 1, 2, and 3, respectively. These values represent the AW0 and AW3 loads, which are defined as the empty load and the crush load for the vehicles, respectively. The AW3 load considers maximum vehicle capacity for seated and standing passengers and will likely be used to develop wheel loads and rail seat loads for the aforementioned design process [10]. The following data is compiled from a large collection of resources across multiple subject-related websites and databases. These data represent 100% of light rail, 85% of heavy rail, and 47% of all commuter rail vehicles in the United States.

Table 1. Light rail transit axle loads

Axle Load Category (kips)	AW0 Loads		AW3 Loads	
	Percent	Cumulative	Percent	Cumulative
$P_A < 10$	0.1%	0.1%	0.0%	0.0%
$10 < P_A < 15$	38.6%	38.7%	0.1%	0.1%
$15 < P_A < 20$	61.3%	100.0%	5.7%	5.8%
$20 < P_A < 25$	0.0%	100.0%	92.5%	98.3%
$25 < P_A < 30$	0.0%	100.0%	1.7%	100.0%
$30 < P_A < 35$	0.0%	100.0%	0.0%	100.0%
$35 < P_A < 40$	0.0%	100.0%	0.0%	100.0%
$40 < P_A < 45$	0.0%	100.0%	0.0%	100.0%
$45 < P_A$	0.0%	100.0%	0.0%	100.0%

Table 2. Heavy rail transit axle loads

Axle Load Category (kips)	AW0 Loads		AW3 Loads	
	Percent	Cumulative	Percent	Cumulative
$P_A < 10$	0.0%	0.0%	0.0%	0.0%
$10 < P_A < 15$	18.2%	18.2%	0.0%	0.0%
$15 < P_A < 20$	40.3%	58.5%	10.0%	10.0%
$20 < P_A < 25$	41.5%	100.0%	43.0%	53.0%
$25 < P_A < 30$	0.0%	100.0%	38.5%	91.5%
$30 < P_A < 35$	0.0%	100.0%	8.5%	100.0%
$35 < P_A < 40$	0.0%	100.0%	0.0%	100.0%
$40 < P_A < 45$	0.0%	100.0%	0.0%	100.0%
$45 < P_A$	0.0%	100.0%	0.0%	100.0%

Table 3. Commuter rail transit axle loads

Axle Load Category (kips)	AW0 Loads		AW3 Loads	
	Percent	Cumulative	Percent	Cumulative
$P_A < 10$	0.0%	0.0%	0.0%	0.0%
$10 < P_A < 15$	0.0%	0.0%	0.0%	0.0%
$15 < P_A < 20$	0.0%	0.0%	0.0%	0.0%
$20 < P_A < 25$	0.0%	0.0%	0.0%	0.0%
$25 < P_A < 30$	16.0%	16.0%	0.0%	0.0%
$30 < P_A < 35$	79.5%	95.5%	8.7%	8.7%
$35 < P_A < 40$	4.5%	100.0%	31.5%	40.2%
$40 < P_A < 45$	0.0%	100.0%	46.1%	83.6%
$45 < P_A$	0.0%	100.0%	13.7%	100.0%

Values for the percent of loads that fall within each category are provided, as well as the cumulative percentage of loads that fall below a certain loading category. The values presented in these tables will be expanded upon through field experimentation on rail transit infrastructure during the field experimentation phases of the project. Load environment data collected during field experimentation will be used throughout the laboratory analysis and design phases of the project. Wheel loads of maintenance-of-way equipment will also be considered in the mechanistic design process.

One of the key objectives for collecting accurate axle and wheel loads is for the determination of rail seat loads. Rail seat loads are critical inputs in the flexural design of concrete crossties and fastening systems. The remainder of this paper provides a preliminary discussion relating to a transit application of current and proposed concrete crosstie flexural analysis procedures.

**FLEXURAL ANALYSIS**

In concrete crossties, the two critical flexural regions are rail seat positive bending and center negative bending (see Figure 1) [3]. Rail seat positive bending results in tension occurring along the bottom of the crosstie, while center negative bending results in tension occurring along the top. Since these are the two critical methods of flexure, they will be the focus of the following flexural analysis. The main objective of flexural analysis is to determine the maximum expected bending moments that a crosstie is expected to experience in service.

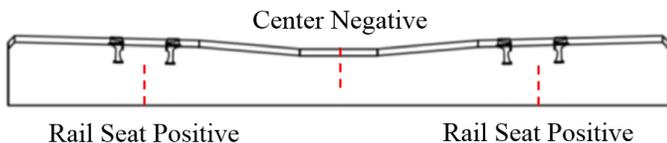


Figure 1. Critical concrete crosstie flexural regions

Currently, much work is being done in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Committee 30 (Ties), Subcommittee 4 (Concrete Tie

Technology), which is responsible for the flexural design of prestressed concrete monoblock crossties to update the analysis practices. The following section will outline the current AREMA practice and the proposed practice. Since most transit crossties are 8'-3" in length and spaced at 30", these dimensions will be used for this analysis. Additionally, the analysis will be performed the highest specified transit axle load, 33 kip, which is the design axle load for NYCT.

**Rail Seat Positive Bending (Current Method)**

In the current methodology, Figure 30-4-3 in Chapter 30 (Ties) of the 2014 AREMA Manual on Railway Engineering [11] (hereafter referred to as the "AREMA Manual") is used to determine the unfactored rail seat positive bending moment. Using the dimensional parameters defined previously, the unfactored rail seat positive bending moment ( $B_{RS+}$ ) is 320 in-kips.

Per AREMA Chapter 30, Article 4.4.1.3, the factored design rail seat positive bending moment ( $M_{RS+}$ ) can be found using Equation 1.

$$M_{RS+} = B_{RS+} \times A \times V \tag{1}$$

- Where:
- $M_{RS+}$  = factored rail seat positive bending moment (in\_kips)
  - $B_{RS+}$  = unfactored rail seat positive bending moment (in\_kips)
  - $A$  = transit axle reduction factor (AL/82)
  - $V$  = speed factor (AREMA Figure 30-4-4) [11]

It is important to note that the reduction factor "A" is found by dividing the design axle load (AL, in kips) by 82. This is because Figure 30-4-3 of the AREMA Manual [11] was derived based on an 82 kip axle load [5]. Thus, for a 33 kip design axle load, A is 0.40. Using a design speed of 55 mph, Figure 30-4-4 of the AREMA Manual [11] suggests a V of 0.88. However, the AREMA Manual states that the speed factor (V) shall not be less than 1.0 [11]. Thus, V is 1.0. Multiplying these factors as given in Equation 1,  $M_{RS+}$  is found to be 128 in-kips.

**Center Negative Bending (Current Method)**

In the current methodology, the center negative bending moment is found by multiplying the  $M_{RS+}$  value found above by a center negative reduction factor ( $F_C$ ) determined from Table 30-4-1 (Equation 2) [11].

$$M_{C-} = F_C \cdot M_{RS+} \tag{2}$$

- Where:
- $M_{C-}$  = factored center negative bending moment (in-kips)
  - $F_C$  = center negative reduction factor
  - $M_{RS+}$  = factored rail seat positive bending moment (in-kips)

The center negative reduction factors (F) are based on crosstie length. For an 8'-3" crosstie, a factor of 0.77 is

recommended by the AREMA Manual [11]. Multiplying  $M_{RS+}$  by F as given in Equation 2,  $M_{C-}$  is found to be 99 in-kips.

### Rail Seat Positive Bending (Proposed Method)

In the proposed methodology, the design rail seat must first be determined. This value can be determined using Equation 3.

$$R = 0.5AL \times DF \times IF \quad (3)$$

Where: R = design rail seat load (kips)  
 AL = axle load (kips)  
 DF = distribution factor  
 (defined in Figure 30-4-1)  
 IF = impact factor

The distribution factor (DF) is used to determine the percentage of the wheel load (one-half the axle load) that acts on the rail seat. This percentage is found in AREMA Figure 30-4-1 and is a function of crosstie spacing [11]. Chapter 30, Article 4.1.2.4 of the AREMA Manual recommends an impact factor of 3 [11].

For crossties spaced at 30", DF is found to be 0.59. Thus, using Equation 3, the design rail seat load (R) is found to be 29.2 kips.

Once the design rail seat load has been determined, the next step is to compute the rail seat positive bending moment. This can be found using Equation 4. This equation is based on Figure 2, which assumes a newly-tamped support condition. The rail-center spacing (g) is taken as 60" for standard gauge track.

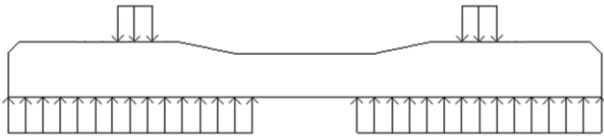


Figure 2. Support assumption for rail seat positive bending

$$M_{RS+} = \frac{R(L - g - s)}{8} \quad (4)$$

Where:  $M_{RS+}$  = rail seat positive bending moment (in\_kips)  
 R = rail seat load (kips)  
 L = crosstie length (in)  
 g = rail-center spacing (in)  
 s = rail foot width (in)

Thus, using Equation 4,  $M_{RS+}$  is found to be 120.5 in-kips.

### Center Negative Bending (Proposed Method)

In the current methodology, the center negative bending moment is found by multiplying the  $M_{RS+}$  value found above by a center negative reduction factor (F) determined from Table 30-4-1 (Equation 2).

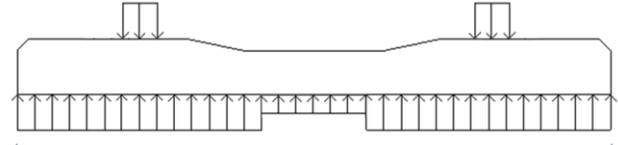


Figure 3. Support assumption for center negative bending

$$M_{C-} = \frac{R}{2} \left( \frac{L^2 - (1 - \alpha)c^2}{2(L - (1 - \alpha)c)} - g \right) \quad (5)$$

Where:  $M_{C-}$  = rail seat positive bending moment (in\_kips)  
 R = rail seat load (kips)  
 L = crosstie length (in)  
 $\alpha$  = center support factor  
 c = center support region = 2g-L (in)  
 g = rail-center spacing (in)

The center support factor is a proposed factor that can be modified to the level of maintenance that the transit agency will uphold. In order to achieve the  $M_{C-}$  specified in the current AREMA manual, this  $\alpha$ -factor should be 0.42. At this time, current transit-focused concrete crosstie designs are being analyzed to provide final recommendations for the  $\alpha$ -factor, which will be discussed and balloted for inclusion in Chapter 30 (Ties) of the AREMA Manual.

## CONCLUSION

Light rail, heavy rail, and commuter rail transit infrastructure is subject to a wide variety of loading conditions that must be considered in the design of track infrastructure and its components. Both internal and external factors must be considered to design an optimized crosstie and fastening system for any particular rail transit system.

Mechanistic design is a proposed process for rail transit infrastructure design which would take into consideration the load and external environments when designing infrastructure components. Extreme events must also be considered, and rail transit infrastructure should not restrict the recovery process from such events.

Through funding from the Federal Transit Administration (FTA), UIUC will be investigating the load environments of light rail, heavy rail, and commuter rail transit and using mechanistic design principles to develop optimized, resilient railway crossties and fastening systems for these respective applications. These optimized systems will have lower life cycle costs, thus increasing replacement intervals and improving safety and performance during normal operating conditions, and following extreme events.

Concrete crosstie flexural capacity is a key design consideration for the track system. Concrete crosstie bending is highly dependent on the ballast support conditions. As such, the assumed support conditions used in the flexural analysis of the crosstie are very important in determining the design of the

crosstie. Two general equations, currently proposed for inclusion in the 2016 AREMA Manual for Railway Engineering, are given in this paper. The proposed equation for rail seat positive bending assumed a newly tamped support condition with no reaction at the center. The proposed center negative equation uses a center support factor,  $\alpha$ , to modify the assumed reaction at the crosstie center. This  $\alpha$ -factor can be adjusted by the infrastructure owner or operator to reflect a desired level of track maintenance. Ultimately, these analyses should provide more efficient designs for concrete crossties produced for the rail transit applications.

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- New York City Transit (NYCT)
- MetroLink
- Metra
- CXT Concrete Ties, Inc.
- GIC
- Pandrol USA
- Amsted RPS
- Hanson Professional Services, Inc.

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