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Mechanistic Design of Concrete Crossties and Fastening Systems – Phase 1

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TECHNICAL SUMMARY

Title

Mechanistic Design of Concrete Crossties and Fastening Systems – Phase 1

Introduction

The objective of this project is the development and deployment of resilient concrete crossties and fastening systems for heavy haul freight, intercity passenger, and rail transit applications.

For a variety of reasons, concrete crossties are a dominant material choice for heavy haul freight, intercity passenger, and rail transit operators at demanding territories. The methods of designing concrete crossties and fastening systems for the aforementioned railroad systems are not developed based on mechanistic design practices considering actual field loadings and service demands, and they are largely based on empirical results and practical experience. The need for mechanistic design practices and resilient component designs is recognized by the manufactures of the crossties, fastening systems, and operators (end users). Additionally, deficiencies in concrete crosstie performance have been noted in the US that include: premature deterioration of concrete due to chemical attack, premature deterioration of the rail pad, and some structural failures. This project maps directly to the US DOT strategic goal of "State of Good Repair". Focus on the goal of "state of good repair" will result in concrete crossties and fastening systems with increased robustness, adaptiveness, and improved service.

Approach and Methodology

The method for accomplishing this objective is through the use of mechanistic design principles aimed at keeping freight and public transportation safe and in a state of good repair. The specific approaches of the project are:

1) Conduct a comprehensive field investigation of the performance demands on concrete crossties and fastening systems on various types of rail infrastructure (e.g. freight, rail transit, etc.).

2) Conduct focused laboratory instrumentation to validate analytical modeling and further the knowledge gained during field experimentation.

3) Develop an analytical finite element model (using field and laboratory loading data) for concrete crosstie and fastening systems on light rail, heavy rail, and commuter rail transit systems.

Findings

This project provides a review of the existing design process for concrete crosstie and fastening systems, and the method by which a mechanistic design process can be achieved. A mechanistic design process will provide many benefits that are not currently achieved by the iterative design process outlined in AREMA.

Conclusions

The primary difference between the empirical and mechanistic design processes is that while mechanistic design will provide more accurate predictions of the load experienced by components, it will require a large amount of capital and time in order to develop the process. Also, even if both processes were fully developed, designing a system using mechanistic design will take more time as the full load path will need to be determined. As finite element models become more robust, it should be possible to determine the load path and distributed forces more quickly, but currently this is a time consuming process. Once a mechanistic design is developed it will provide much more flexibility than the iterative design process, allowing for variable factors of safety for each failure mode, as well as allowing multiple types of fastening systems while still producing reliable predictions of performance.

Recommendations

The end goal of this study is to provide a framework for a mechanistic design process that can provide some immediate changes to the design process outlined in the AREMA Recommended Practices. However, the more important purpose is to highlight the areas that need the most improvement, so that future research projects will have clear goals that can positively impact the rail industry.

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SECTION 1 INTRODUCTION

1.1 Background and Motivation

Historically, North American concrete crosstie and fastening systems 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 of concrete crossties and fastening systems, inefficiencies in component design may exist, negatively impacting the economies of using concrete crossties and fastening systems. Improvements in the design of these systems will provide a more robust railway superstructure, where the loading environment is more fully considered, failures are reduced, and the possibility of predicting performance metrics (e.g. wear rates) exists. Based on a survey that polled railroads and fastening system manufacturers, both domestic and international, a list of the primary failures experienced in the field was developed (Van Dyk 2013). Table 1 provides a list of the survey results for critical concrete crosstie and fastening system problems in the United States.

Table 1.1 Concrete Crosstie Critical Failures.

Most Critical Concrete Tie Problems
Rail seat deterioration (RSD)
Shoulder/fastener wear or fatigue
Derailment damage
Cracking from center binding
Cracking from dynamic loads
Tamping damage
Other (ex: manufactured defect)
Cracking from environmental or chemical degradation

The problems listed in bold in Table 1 are issues that can potentially be mitigated by improving the design process for concrete crossties and fastening systems. These failures occur due to problems with the infrastructure or rolling stock, or result from severe loading conditions. Some failures may exist due to incorrect design assumptions and procedures, or a lack of understanding of the failure modes. A mechanistic design process will reduce the occurrence of these failures by understanding how and why they are occurring and then altering the design of the system to prevent occurrences of similar situations. There will still be cases where damage and failures will occur, but a mechanistic design process can minimize this risk and allow railroads to understand the capacity of their infrastructure and its components.

1.2 *Study 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 heavy haul freight, intercity passenger, and rail transit applications. The project will have a major focus on keeping railroad 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 various types of rail infrastructure (e.g. freight, rail transit, etc.).
2) Conduct focused laboratory instrumentation to validate analytical modeling and further the knowledge gained during field experimentation.
3) Develop an analytical finite element model (using field and laboratory loading data) for concrete crosstie and fastening systems on light rail, heavy rail, and commuter rail transit systems.

The objectives listed previously will result in concrete crosstie and fastening systems with increased robustness, adaptiveness, and readiness for the myriad of loading conditions faced in realistic rail environment. The project addresses one of the primary strategic goals of US DOT – State of Good Repair. 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.

1.3 *Mechanistic Design Principles*

The mechanistic design process is one derived from analytical and scientific principles, considering field loading conditions and performance requirements. Representative input loads and load distribution factors are used in order to determine the required component, geometric and material properties. This approach is based on loads measured in the track structure and the properties of the materials to withstand or transfer them. Responses such as contact pressure or relative displacement of components are evaluated in order to optimize component geometry and material requirements. Since mechanistic design requires a thorough understanding of the load path and distribution, this improved understanding allows for the development of load factors. By understanding exactly how loads transfer through the system, it can be determined at what point these loads have the possibility to cause failures in the system. A load factor can be developed to ensure that these levels of loading will never be reached. The load factor can change based on location and traffic composition.

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 (Applied Research Associates (ARA) Inc. 2004). The University of Illinois at Urbana-Champaign (UIUC) is developing a mechanistic design process that uses the existing loading environment to optimize the design of the concrete crosstie and fastening system. The approach chosen by UIUC begins by defining the vertical, lateral, and longitudinal input loads, and noting how these loads are passed through the system. The next step is defining load thresholds, which are limits of critical properties for the materials used to build the components, the components themselves (i.e. considering their geometry in addition to material properties), and the fully assembled fastening system. After the criteria for loading thresholds are defined, the components are designed using a set of pre-defined criteria. The last step is to verify that the system as a whole is performing according to expectations, primarily by installing the system in the field and measuring critical performance properties. The overall design process that will be followed can be seen in Figure 1 and will be discussed in detail in the next section of this chapter.

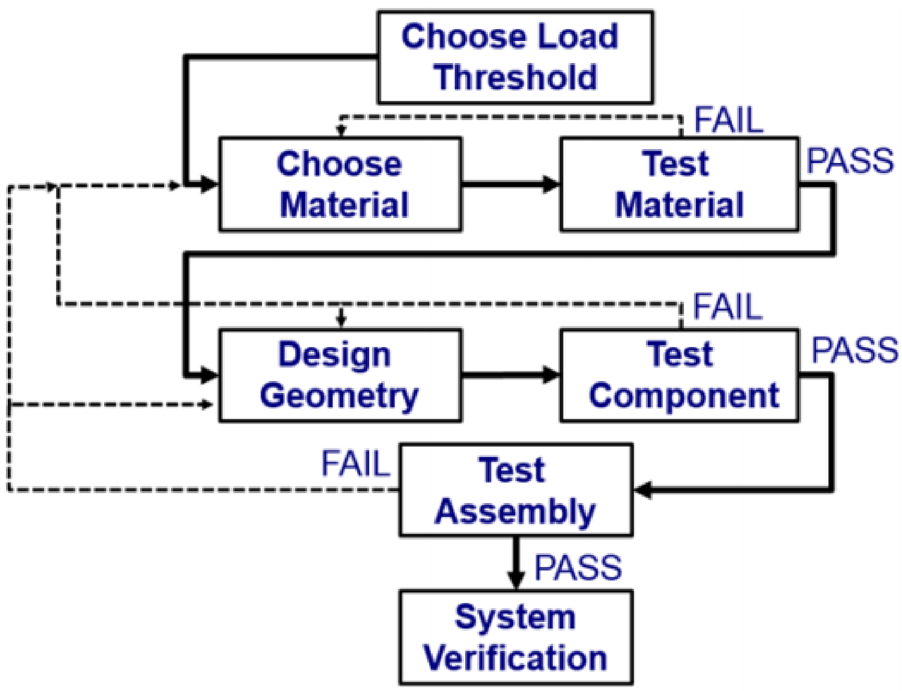

Figure 1.1 Mechanistic Design Process Flow Chart

SECTION 2 OVERVIEW OF DESIGN PROCESS FOR CONCRETE CROSSTIE AND FASTENING SYSTEMS

2.1 Define Load Inputs

The first step in the mechanistic design process is to characterize the wheel loads that are applied to the track structure to ensure that appropriate design strengths for the system and its components can be selected. The wheel load can be divided into vertical, lateral, and longitudinal components. The magnitude and distribution of loading is primarily determined by traffic type, train speed, track geometry requirements and condition, and vehicle health. The railway operating environment in North America has a wide variety of train types sharing the same infrastructure. The most apparent difference is the diverging characteristics of passenger trains and freight trains. Passenger trains have much lower axle loads than typical freight trains, but they tend to run at much higher speeds. Even within each train type, there are large distributions of wheel loads that can be expected (e.g. loaded and empty freight cars). Based on the prevalence of different traffic types and track strength requirements, the input loads used for the design of a system are quite variable. Train speed affects the magnitude of wheel loads, with the greatest effect of speed noticed in conjunction with impact loads occurring at high speeds. Impact loads are typically caused by characteristics of the vehicle or wheels, or due to certain infrastructure components (e.g. joints) or geometric defects. Track geometry also plays a large role in the magnitude of wheel loads, particularly in the significance of lateral versus vertical loads. In curves, the lateral wheel loads are much higher than in tangents. The final factor is vehicle and track health. Poor health of vehicles, particularly variations in the wheel profile, can cause high impact loads that may result in fracture and wear of components. Poor track health can lead to similar problems, but with different root causes. Track warp, cross-level deviations, and any other deviation or combination of deviators can result in a different distribution of loads.

Due to the high variability in axle loads, it is important to be able to accurately characterize the range of loading conditions that should be used in the design process. The wheel loads selected for design will determine the loading demands on the system and its components. Given that there is a distribution of axle loads, it is not reasonable to use the maximum load for design, since it may not be indicative of the overall distribution. Instead, loads are used that capture a desired percentage of the loading conditions, bounding the loads that should be expected for a given traffic type. For example, a railroad may choose to use a 99.5% design approach. This results in selecting a wheel load representing a value that is equal to or greater than 99.5% of wheel loads. In other words, 0.5% of wheel loads will exceed the design value, which could result in excessive wear or component failure. This approach will allow railroads to weigh the tradeoffs between first costs and operating (maintenance) costs with respect to the design of their components. Using a conservative threshold will result in a more durable system, and will lower the risk of damage to the system based on the expected wheel load environment. However, it can also be expected that designing a system based on a conservative threshold will have a greater initial cost for components. A less-conservative approach will have a higher percentage of loads that exceed the design value, which could result in an increased number of component failures and wear to the system. Several choices in threshold levels are proposed, as the final choice will vary depending on the preference of the company performing or paying for the design. The three percentile loads that are provided are 99.5%, 97.5%, and 95%. The reason that these percentiles are so high is due to the quantity of wheel loads that occur. Consider a typical freight train with 100 or more cars. Each car typically has eight wheel loads, so even at the most conservative threshold level (99.5%) a single train will have an average of four wheel loads that exceed the design value. Due to the high quantity of wheel load repetitions that will be experienced by the crosstie and fastening system over the course of its service life, high percentile load thresholds should be used.

In order to develop load thresholds that fully describe the wheel load distribution, the wheel loads are decomposed into three categories. These categories include vertical, lateral, and longitudinal wheel loads.

2.1.1 Vertical Wheel Loads

To better understand the range of vertical loads applied to the track 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. Vertical wheel loads can depend on a variety of factors. Some of the factors that are believed to have the greatest effect on their magnitude are train speed, track geometry, vehicle characteristics, curvature, grade, position of the wheel within the train, geographic location, and temperature. WILD site data can be used to determine the effect of many of these factors, most importantly looking at the effect of train speed and vehicle characteristics.

WILD sites are typically constructed on well-maintained tangent track with concrete crossties, premium ballast, and well compacted subgrade (possibly with hot mix asphalt underlayment) to reduce sources of load variation within the track structure. 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 2.1.

As Figure 2.1 shows, at Amtrak's Edgewood, MD WILD site, locomotives, freight cars, and passenger coaches all impart different magnitudes of vertical load into 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 Survey provide a comparison of the North American and international loading environments and are summarized in Table 2.1. 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 crosstie 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 2.1).

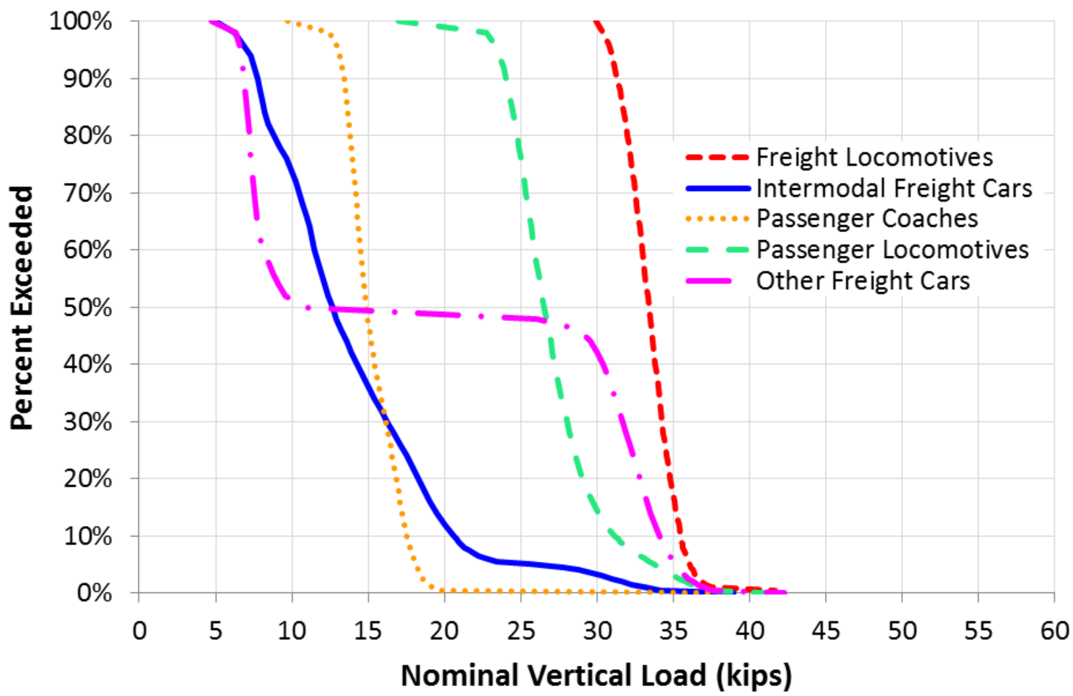

Figure 2.1 Percent exceeding particular nominal vertical loads on Amtrak at Edgewood, Maryland (WILD data from November 2010) (Van Dyk 2013).

Table 2.1 Loading Environment Summary (Average of Responses) (Van Dyk 2013).

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

*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 crossties and elastic fastening systems. The load's attenuation and progression through the track provides information critical to the design of the superstructure components.

Before designing the individual components, the vertical wheel loads must be quantified in order to determine the magnitude of the loads that will be distributed to the rest of the system. The loads a track structure will experience will be different in every location, as freight cars have variable weights, and the traffic density and make-up will not be the same. In order to quantify these loads, WILD data was used to examine average and peak loads imparted by different types of cars, and then use knowledge of the specific route to determine what vehicles are expected. As discussed earlier, several load thresholds were quantified to allow the choice of what design load to utilize. Tables 2.2, 2.3, and 2.4 describe the loads gathered from WILD sites, which were used to determine the threshold values for vertical loads based on different traffic types.

Table 2.2 Distribution of Static Vertical Wheel Loads (Van Dyk 2013).

	Nominal Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car[1]	7	10	11	14	15
Loaded Freight Car[1]	34	40	41	42	46
Intermodal Freight Car[1]	21	36	37	40	51
Freight Locomotive[1]	34	37	38	39	44
Passenger Locomotive[2]	27	36	38	40	43
Passenger Coach[2]	15	19	19	21	46

Table 2.3 Distribution of Peak Vertical Wheel Loads (Van Dyk 2013).

	Peak Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car[1]	11	21	27	40	101
Loaded Freight Car[1]	43	57	66	85	157
Intermodal Freight Car[1]	28	47	55	75	142
Freight Locomotive[1]	43	54	58	69	110
Passenger Locomotive[2]	39	50	54	64	94
Passenger Coach[2]	24	36	43	59	109

Table 2.4 Peak Vertical Load to Nominal Vertical Load Ratio.

	Peak Load / Nominal Load				
Car Type	Mean	95%	97.5%	99.5%	100%
Unloaded Freight Car[1]	1.6	2.1	2.5	2.9	6.7
Loaded Freight Car[1]	1.3	1.4	1.6	2.0	3.4
Intermodal Freight Car[1]	1.3	1.3	1.5	1.9	2.8
Freight Locomotive[1]	1.3	1.5	1.5	1.8	2.5
Passenger Locomotive[2]	1.4	1.4	1.4	1.6	2.2
Passenger Coach[2]	1.6	1.9	2.3	2.8	2.4

1 Source of data: Union Pacific Railroad; Gothenburg, Nebraska; January 2010
2 Source of data: Amtrak; Edgewood, Maryland, Hook, Pennsylvania, and Mansfield, Massachusetts; November 2010

A key factor in design is the ratio that represents the difference between peak and static wheel loads. The majority of peak wheel loads are between 1.3 and 3 times larger than the static load for the respective vehicle type. Since WILD sites are built on well-maintained track, the impact loads recorded at these locations are largely due to problems with the shape of the wheels or other rolling stock conditions. By developing more stringent requirements for wheel geometry, the loads experienced by the track can be greatly diminished. Instead of requiring a design that considers peak loads, the lower magnitude static loads can be used. Some consideration should also be given to impact forces that are generated due to track irregularities.

Another major difference between nominal and peak loads is the amount of variability. For example, the nominal load imposed by a loaded freight car differs by only 2 kips from the 95% load threshold to the 99.5% threshold. However, when considering the peak load this difference increases to 28 kips. This greater variability suggests that when choosing a load threshold, the peak load will be more important for the design of infrastructure, as the nominal load will not change very much depending on which load threshold is chosen.

It should be noted that these data represent best-case loading scenarios. Specifically, due to the aforementioned well-maintained track at discretely located WILD sites, this data only accounts for variation in vehicle wheel health, and not track health. The effect of track health on the magnitude of vertical wheel loads should be studied in order to determine the final vertical load thresholds to be used in design. However it is likely the overall distribution of the loads will remain the same, and track health variability can be considered through the use of an additional load factor. For example, poor track health may result in 10% higher impact loads. This could be accounted for by multiplying the peak load determined from WILD sites by 1.1. Additional research needs to be undertaken in order to quantify the magnitude of this load factor.

2.1.2 Lateral Wheel Loads

In order to quantify the magnitude and distribution of lateral wheel loads, truck performance detector (TPD) data was utilized. TPD's are similar to WILD sites, but use strain gauges located in curves instead of tangent track. However, they provide less detailed information, particularly by not differentiating between static and peak wheel loads. Instead of using strain gauges to collect data for the full rotation of the wheel, TPD sites only have two instrumented cribs per curve. Despite this limitation, the data collected can still provide the magnitudes of typical lateral wheel loads. Some of the factors that are believed to have the greatest effect on their magnitude are train speed, track geometry, vehicle characteristics, curvature, grade, position of the wheel within the train, geographic location, temperature, low vs. high rail, and rail surface condition. TPD site data can be used to determine the effect of many of these factors, in particular, examining the effect of train speed, curvature, and superelevation. These three factors can be combined into a property known as cant deficiency. Cant deficiency is a measure of how much additional superelevation would be required for a train running at a given speed to be at the balance speed. The balance speed is the train speed at which an equal amount of force would be imparted on both rails.

For locations in curves, the lateral wheel load can exceed 50 percent of the vertical wheel load. The lateral load will not only affect the design of components such as the shoulder or insulator, it also can change the load distribution in the entire crosstie and fastening system. The lateral load will have more variability than vertical load, due to the difference between load magnitudes in tangent track and curves. Lateral loading is typically very low on tangent track, and as a result, it has very little effect on the design of components for those sections. Figure 2.2 gives an example of the distribution of lateral loads measured by TPDs, categorized according to car type.

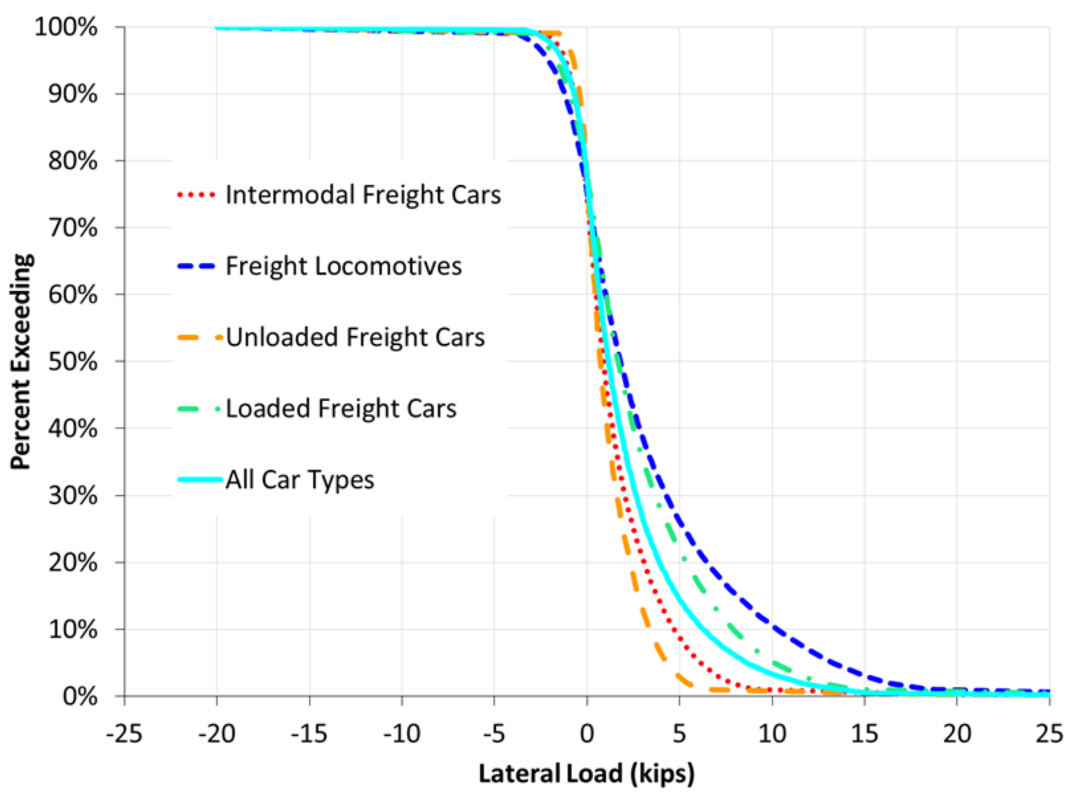

Figure 2.2 Lateral load variation with car type (Scheppe 2014).

As Figure 2.2 shows, different car types impart different magnitude of lateral loads. The TPD sites that collected these data were located all over the United States, with curves of varying degree of curvature and superelevation. Many of the factors that were believed to affect the magnitude of lateral wheel load were analyzed, with car weight having the most significant impact.

In order to determine the demands on the components within the concrete crosstie and fastening system, lateral wheel loads need to be quantified. Table 2.5 and Table 2.6 describe the wheel loads as measured by TPD sites. The categories are the same as used previously for quantifying vertical wheel loads.

Table 2.5 Distribution of Peak Lateral Wheel Loads (Scheppe 2014).

	Lateral Load (kips)				
Car Type	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	1.1	4.4	5.2	6.9	22.4
Loaded Freight Car	2.7	10.1	12.1	15.9	33.5
Intermodal Freight Car	1.9	6.2	7.4	10.1	22.8
Freight Locomotive	3.9	13.3	15.6	20.5	34.4

Table 2.6 Distribution of Lateral/Vertical Load Ratios (Scheppe 2014).

	L/V				
Car Type	Mean	95%	97.5%	99.5%	100% (Max)
Unloaded Freight Car	0.15	0.44	0.50	0.64	4.00
Loaded Freight Car	0.11	0.35	0.41	0.52	1.46
Intermodal Freight Car	0.12	0.39	0.46	0.59	1.61
Freight Locomotive	0.11	0.38	0.44	0.56	0.81

As shown in Table 2.5, as static vertical wheel load increases, lateral wheel load also increases. One exception is loads from freight locomotives compared to loaded freight cars. Even though freight locomotives have slightly lower static vertical wheel loads than loaded freight cars, they tend to have significantly higher lateral wheel loads. Based on TPD data, locomotives at the front of a freight consist show no difference in lateral wheel load distribution from locomotives at the middle or end of the consist. This suggests that the increased loading is solely due to the curving characteristics of the locomotives.

Table 2.6 contains the distribution of L/V ratio collected at TPD sites. At high values of L/V, the wheel can climb over the rail, causing a derailment. Instability of the rail can start to occur at L/V ratios of 0.68, and at 1.29 rollover is nearly assured (Hay 1953). From the analysis of the data it can be seen that empty cars are the most prone to high L/V ratios.

As with WILD data discussed in the vertical wheel load section, this data represents a best-case scenario. TPD sites tend to be well maintained and free from issues that may occur elsewhere on the network, such as geometric defects or poor support conditions. These issues could result in higher magnitude lateral wheel loads than quantified here.

In the future, data will be collected from curves with higher degrees of curvature. The degree of curvature studied in this report only reached up to 6 degrees, which is not the maximum for mainline tracks in the US. It is possible that more severe curves could cause lateral loads to increase, and change the way lateral wheel loads should be estimated. Additionally, TPD data from passenger trains will be measured and added to the lateral loading table for use as input loads for design.

2.1.3 Longitudinal Wheel Loads

The magnitude and distribution of longitudinal loads is not well understood compared to the other two loading types. This is partially due to the fact that there are no wayside detectors that quantify the magnitude of longitudinal loads from passing trains. One technology that could be used to measure these loads is an Instrumented Wheel Set (IWS). An IWS is a wheel set that has strain gauges on the axle and wheel. An IWS can be deployed on any vehicle type and will provide vertical, lateral, and longitudinal forces on the wheel set as well as at the contact patch between the wheel and the rail (Van Dyk 2013). Since this technology is on the rail car rather than at a discrete wayside location, the nature of the data that is collected is different from TPD and WILD sites and represents the continuous nature of rail infrastructure. An IWS gives an in-depth (i.e. continuous) understanding of the forces on a single wheel as it moves over a given route. However, in order to develop an understanding of a variety of car types, the number of wheel sets and the volume of data would be prohibitively large. Given how longitudinal load is transferred, use of an IWS may be the appropriate approach to quantifying loads, as longitudinal load might not be as closely tied to car weight as vertical and lateral load are Longitudinal load cannot be classified according to wheel loads like vertical and lateral loads were. Longitudinal loads will vary according to the tractive effort of the locomotive and the braking characteristics of the train (e.g. condition of brakes, length of train, etc.). Longitudinal loads are also present without train-induced forces, due to thermal stress in the rail.

Because of these characteristics, simply examining the distribution of wheel loads and determining the appropriate threshold is not an appropriate method to determine the input load for design. It is also not completely understood how the longitudinal load is transferred through the fastening system and into the crosstie. Most previous research within the realm of longitudinal forces has focused on bridge approaches, examining what magnitude of load is induced from braking. Some of the factors that are believed to have the greatest effect on longitudinal load magnitude are train speed, track geometry, vehicle characteristics, curvature, grade, position of the wheel within the train, geographic location, and temperature. Of particular interest is the relationship between longitudinal load and track geometry (tangent vs. curve) as well as gradient. In the future, research should be conducted to investigate typical values of longitudinal load in tangent and curved track, varying the acceleration and braking characteristics of the train as well as the clamping force of the fastening system.

Absent other data, the values provided in Table 2.7 from AREMA (Table 30-1-1 in manual) can provide an estimate for longitudinal load magnitude.

Table 2.7 Longitudinal Wheel Loads

	Mainline Freight	Light Density Freight	High Speed Passenger
Longitudinal Load (kips)	50	30	25

2.1.4 Load Distribution

After establishing the distribution of the wheel load environment, the next step in the mechanistic design process is to determine how these wheel loads are transferred through the system. As the wheel loads from trains are transferred through the concrete crosstie and fastening system, each component attenuates and distributes the load to the next component in the system.

2.1.4.1 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 static load path was conducted at UIUC. This analysis underwent several iterations with increasingly complex assumptions. This static analysis of interface loads and component deflections, described in the following sections, 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 is developing a software program (I-TRACK) that accepts particular input parameters, such as material and geometrical component properties, and calculates forces at interfaces and deflections of components and the system as a whole. Using I-TRACK, the spectra of loads such as those shown in Figure 2.1 can be traced throughout the remainder of the fastening system (and the crosstie, ballast, and subgrade), providing estimates of the magnitudes of forces to be measured at each interface given a particular traffic type.

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 should be considered as estimates, providing feasible values to be compared with other load quantification efforts. To evaluate the loads within the system more accurately, laboratory and field instrumentation and finite element (FE) modeling techniques were employed. The detailed load path discussion and analysis culminated in the result shown in Figure 2.3.

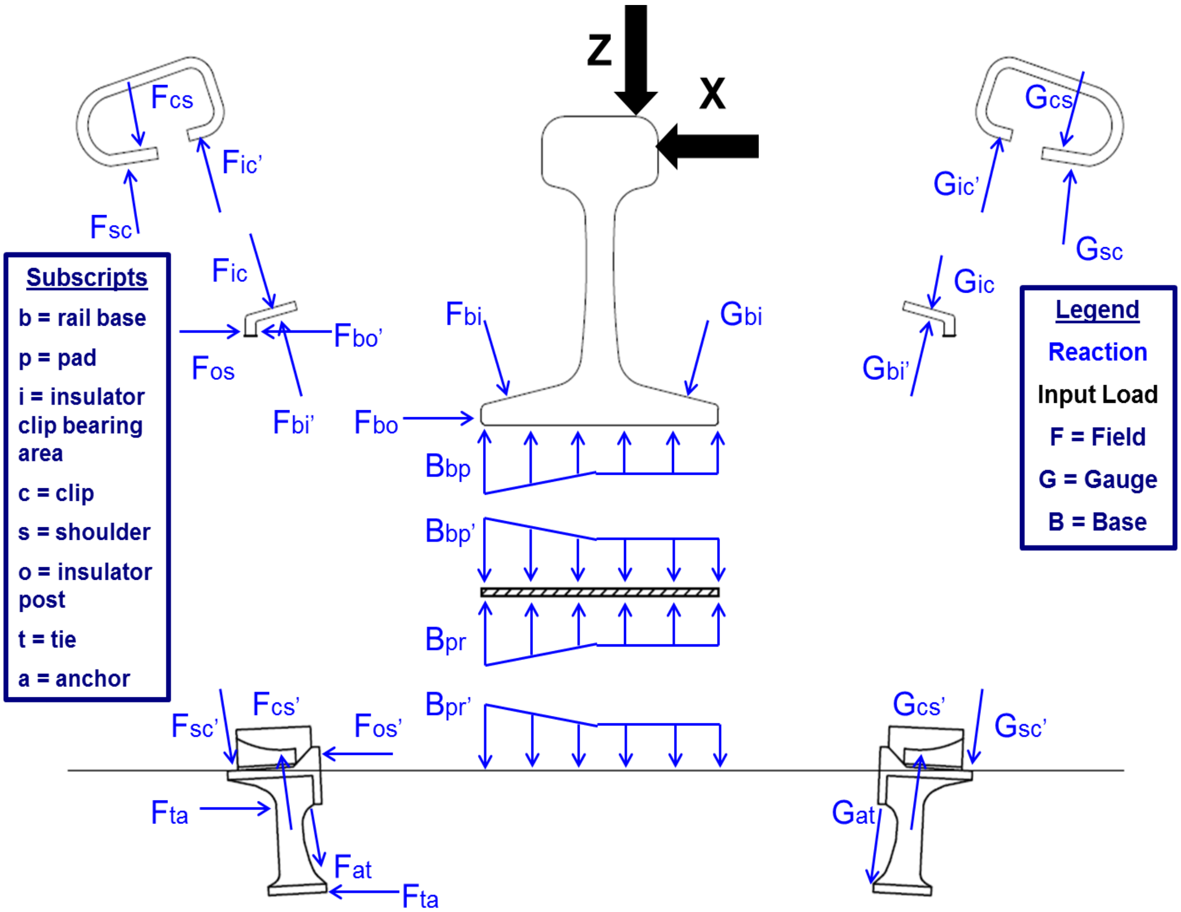

Figure 2.3 Concrete crosstie fastening system load path map and component free body diagram, case (d) (deformable bodies)

2.1.4.2 Laboratory Experimentation, Field Instrumentation, and Analytical Modeling

After identifying locations where the load is transferred throughout the system, it is necessary to quantify the loads that were previously derived through a qualitative method. This quantification process defines the demands on each component, focusing primarily on determining the magnitude of forces that are transferred at component interfaces.

In order to determine the demands on each component, the magnitude of forces that are distributed must be quantified. Given the continuous and elastic nature of the track structure, each component in the system will not be subjected to the full wheel load. As the wheel load is distributed throughout the system it will be transferred to multiple components longitudinally and will be attenuated as it transfers through components. Thus, each component will have its own input load that will be some percentage of the initial wheel load that is measured at the wheel-rail interface. The challenge with determining what portion of the input wheel load is imparted on each component is that this particular number is highly variable due to many factors such as track stiffness. As the component geometry varies, either due to design changes or wear, the load path will also change. A change in the load path could result in the magnitude of the force on each component changing, thus changing the requirements for the strength. This creates a challenging circular relationship within component design. The load distribution will guide the design of a component, but as the design (e.g. geometry) changes the load distribution will further change.

Given these conditions, determining what load is actually imparted on each component of the crosstie and fastening system is not as simple as quantifying the initial distribution. In order to quantify the input loads on each component laboratory experimentation, field experimentation, and FE modeling can be used.

2.2 Define Design Criteria

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

The proposed design process is referred to as a limit state design. In limit state design, the design of each component is based on load-related failure modes. Each type of failure can be tied to how the component was loaded and the specific properties that were exceeded. A failure is defined as a change in the behavior of an object such that it can no longer perform its intended function. For example, failure of a rail clip would be any condition that causes the rail clip to no longer provide the desired amount of clamping force.

In order to prevent failures from occurring, certain design criteria must be developed. These design criteria will be defined for various material properties, such as tensile strength or compressive strength. The appropriate value of the criteria will be determined based on safe system operation. Safe system operation refers to the process of reducing the probability of a failure in order to minimize the chance of an accident. Each component will have an associated probability of failure. Depending on the severity of a failure occurring, the acceptable probability of failure may change, with a severe failure requiring a lower probability of failure.

Limit states can be divided into two primary categories; ultimate and fatigue. An ultimate limit state is defined by a failure that can be caused by a single loading event that exceeds a certain threshold. For example, a very high impact load could result in the cracking of a crosstie. This category of failure would require a low probability of failure, to ensure that this type of failure is unlikely to occur during the design life of a component. For example, if a concrete crosstie has a 50 year design life, the chance of a load occurring that would cause that crosstie to crack should be less than once in 50 years. Fatigue limit states are related time-dependent failures, in which repeated loading over a period of time can result in the failure of a component through wearing or other mechanisms. For example, a concrete crosstie rail seat could gradually abrade over time until it reaches a level that causes the rail to roll. This would require an estimation of the amount of tonnage that the track will experience during the component's lifetime in order to determine the total fatigue demands (Kaewunruen 2011).

In order to test that the various design criteria are met, an approach using both nominal and required strength will be used. The nominal strength is an approximation of the actual strength of a component. This can be determined by performing laboratory tests and stressing the component until failure occurs. In this stage, a reduction factor should be included to account for the acceptable probability of failure of the failure mode type as discussed earlier. A more critical failure will have a higher reduction factor, which reduces the estimated strength of the object. This reduction factor should also consider the variability of test results, which are largely a function of the type of material being tested or variation of component geometry.

In order to determine if the nominal strength is adequate, the required strength needs to be determined. The required strength refers to the amount of strength required to resist demands due to the input load and the resulting load distribution. This required strength depends on the input wheel load, and is a function of different load thresholds. The input load used will also depend on the type of limit state that is being tested. Ultimate limits will require a high percentile load, while fatigue limits will require a load closer to the average, as it is based on a failure that occurs over a longer time scale. Based on the load imparted on the object, the required strength can be determined. This required strength must be less than or equal to nominal strength multiplied by the reduction factor. This will ensure that the tested strength of the object meets the predicted demands and will be unlikely to fail given the operating conditions. This approach is similar to the Load and Resistance Factor Design (LRFD) process used in structural design.

The proposed design criteria will be split into categories based on where the design fits into the overall process of designing a concrete crosstie and fastening system. There will be different critical properties and acceptable limit states based on what aspect of the component and system is being designed. The design criteria can be split into three categories: material, geometric, and assembly.

2.2.1 Material Design Criteria

Material design criteria are design properties that are based solely on the material that is used to in the fabrication of components. The critical material properties in need of specified criteria are compressive strength, tensile strength, flexural strength, shear strength, stiffness, wear resistance, and fatigue strength. These tests should be the same for all types of fastening systems, as they don't depend on the geometry of the components or the load path in the system. These material criteria will depend on a variety of factors, such as the environment and the tonnage. The environment can affect required wear resistance based on the prevalence of moisture and fines. For instance, environments with a high likelihood of intrusion of moisture and fines will require more strict wear resistance requirements. Tonnage (e.g. both axle load and number of load applications) will help determine how critical fatigue is, as it will determine the number of cycles per year that the components experience. Higher traffic levels will increase the likelihood of fatigue failure occurring before the design life of the component is reached.

2.2.2 Geometric Design Criteria

Geometric design criteria are design properties based on the geometry of the components. The critical properties are the same as the material design criteria, and include compressive strength, tensile strength, flexural strength, shear strength, stiffness, wear resistance, and fatigue strength. However, the acceptable limits of the design criteria will change, as the strength will depend on both the material properties and geometry of the component. This stage of design criteria will consider the load distribution and what percentage of a typical wheel load will be imparted on each component. This can be used to calculate the input load and therefore determine the stresses and strains on each component. These stresses and strains can then be used to determine the required strength for each property.

2.2.3 Assembly Design Criteria

Assembly design criteria are design properties that are based on the performance of the fully assembled crosstie and fastening system. This system design testing should be conducted in a laboratory setting, to avoid variation due to support conditions. Critical properties to develop design criteria for include contact pressure, relative displacement, and wear resistance. These should be measured at interfaces between components, to determine whether the system is behaving in a way that encourages good long-term performance. For example, high pressures between two interfaces can result in damage to the components and require that they be replaced. These design criteria will limit the contact pressure to a level that will not cause excessive damage for the design life of the component. As different types of fastening systems will have different components, the interfaces will also vary, thus these criteria are fastening system dependent.

2.3 Design Process

After the aforementioned design criteria are selected, the component design process can begin (Figure 2.1). The first step is to select the desired load threshold. This will determine the value for the required strength. The required strength is then compared to nominal strength. A material (e.g. steel) should be selected, and then tested according to the defined material design criteria. If all material-level design criteria are not met, then a new material will need to be chosen or the existing material modified until all material design criteria are met. After the material passes, the geometry of the component should be designed. The component will then be tested for all geometric design criteria. If any criteria are not met, either a new material should be chosen, or the geometry should be modified. If a new material is chosen, the material criteria will need to be checked again before continuing. After passing the geometric criteria, the assembly criteria will need to be tested. If any assembly criteria are not met, a new material or geometry should be chosen, retesting material or geometric criteria if changes occur. Following successful completion of all assembly design criteria, the crosstie and fastening system can move to the system verification process.

2.4 System Level Verification

The system verification stage of the design process confirms that the design is adequate and will perform as expected in revenue service. In this stage, representative support conditions are included to account for all possible forms of variability that could affect the performance of the system. Critical properties to consider include maximum ballast pressure, maximum subgrade pressure, total track deflection, and track modulus. Historically, this is accomplished by installing the fastening system in a section of revenue service track, to test whether the system will perform well over time. Another way to test this would be using an analytical model, such as the FE model developed by UIUC, which would have the capability of checking the values of critical system properties. This approach would be more cost effective than field testing as the physical components would not need to be manufactured. It also would be faster, as producing the components requires more time as compared to a simulated setting. If the critical properties were exceeded then the fastening system could be further modified until it exceeds the required system level design thresholds. The system will still need to be tested in the field, but this approach should avoid the costly process of physical design iterations. Once the system passes all the tests in a simulated setting it can be deemed ready for revenue service.

SECTION 3 DESIGN PROCESS EXAMPLES

In order to illustrate the mechanistic design process that was introduced, several examples are presented. These examples will demonstrate how the new design approach will work, and describe the ways in which this new process will improve the performance of the concrete crosstie and the fastening system. These examples are not meant to be a comprehensive set of all possible applications of mechanistic design for concrete crossties and fastening systems, but are intended to provide examples of potential ways to mechanistically design select components. Each component design section will follow a general outline as described below:

1. Description of the current design process
2. Design example using the current design process
3. Discussion of potential improvements to the current design process
4. Design example using the revised current design process
5. Discussion of future work in order to meet a fully mechanistic design

The design examples are the insulator in the fastening system and the concrete crosstie.

3.1 Insulator in Fastening system

3.1.1 Current Status

3.1.1.1 Overview of Current Design Process - General Case

There are no component-specific tests for the insulator provided in AREMA Chapter 30. Instead, system-level tests are specified to ensure reasonable wear characteristics of the system. Electrical properties of the entire crosstie and fastening system are also tested and limited to a specified threshold. Tests for wearing properties (i.e. AREMA Test 6, Tie and Fastener System Wear/Deterioration Test) include visual inspection and measurements of each component before and after the test while tests for electrical properties (i.e. AREMA Test 7, Fastener Electrical Impedance Test) involve determining the ability of the tie and fastening system to resist conducting electrical current under wet conditions.

Under AREMA, the only "design" requirement for a new insulator involves running ASTM D257 to measure the material's electrical resistivity. Otherwise, no geometric parameters are specified nor are load-related specifications. As long as thresholds for AREMA Tests 6 and 7 are met (i.e. displacements do not exceed a maximum specified value and impedance values are above a specified minimum value), the insulator is considered acceptable.

3.1.1.2 Overview of current design - general case and current design process using Safelok I

Under the current AREMA recommended practices, the first test that would be run would be ASTM D257. This test is run on the insulator material to ensure the component has necessary electrical properties. This test has no threshold values, and is used to provide general information of the electrical resistance properties of the material and the resulting component.

AREMA Test 7 is the next step in testing the insulator in a Safelok I fastening system. In this test, minimum electrical impedance values would be measured by applying a known electrical current between the two rails. Electrically isolating the rail from the shoulder and crosstie is a primary function of insulator, and this test is run to ensure proper electrical isolation is achieved.

This is an appropriate test to run considering the most important function of the insulator is to electrically isolate the rail from the shoulder and crosstie. The component-level test that is run to ensure adequate electrical resistivity of the insulator (as well as the tie pad) should provide a good indication of whether this test will pass or fail. Regardless, this test should still be run to provide traceability through the entire mechanistic design process.

AREMA Test 6 is the next step in testing the Safelok I fastening system after the geometric design of the system is complete. In this test, maximum lateral rail head displacements are measured. In addition to protecting the cast shoulder and electrically isolating the rail from the shoulder and crosstie, lateral rail restraint is also a primary function of the insulator. Thus, lateral rail displacements are an indicator of insulator performance, yet they are not specified in AREMA. Lateral displacements are a system performance indicator.

As a sample calculation, if the lateral rail head displacement is less than 0.25 inches, the insulator would pass the test and be considered an adequate component design, assuming allowable wear of the component is determined through visual inspection of the insulator. Missing from this test is a measurement of the lateral rail base displacement. Given the insulator is in direct contact with the rail base, this measurement would give valuable insight into the demands placed on the insulator. A maximum value would be the limiting factor with this measurement. This test is not rooted in mechanistic design due to the fact that it is a wear and deterioration test of a fastening system that has already been designed. AREMA Test 6 is very much used in an empirical approach to designing fastening systems.

The combination of these tests is used for validation and comparison. The values for allowable wear and rail displacements as measured during Test 6 appear to be empirically derived from industry experience and not from a calculated, mechanistic approach.

If a true mechanistic component design approach were to be used for the insulator, the electrical properties of the insulator material would be determined before any geometric design aspects were considered. However, because there should be an applied load test to test the ability of the insulator to withstand a specified load for a specified duration, material selection must be carefully considered. A proper balance of electrical resistivity and ability to withstand an applied load must be determined for insulator mechanistic design.

3.1.2 New Design Methodology

3.1.2.1 Overview of new design process - general case

A mechanistic component design process for the fastening system insulator has four steps: selecting load thresholds; selecting component material; designing component geometry; and verifying component performance at the system level.

Load threshold selection
Using lateral fastening system force measurement data obtained from both field and laboratory experiments and FE modeling results, load thresholds (i.e. low, medium, high) should be designated. Applied wheel loads should also be designated for system level verification tests. Load threshold selection includes designating the magnitudes of applied forces on the component and system that a given percentage of all applied forces will statistically fall below (i.e. confidence level) the load as described in section 2.

Material selection
Material selection should be made based on specific material properties. For an insulator, relevant material properties include electrical resistivity, compressive strength, tensile strength, flexural strength, shear strength, stiffness, wear resistance, and fatigue characteristics. The material properties should take into consideration the lateral force data described earlier. Tests for material properties should be conducted on samples of the material to ensure the material withstands applied stresses and displacements up to maximum values defined by either the fastening system manufacturer or end user (i.e. railroads).

Geometric design
Once the material is selected, the geometry of the component can be designed. The geometric characteristics should take into consideration the applied forces and optimize necessary bearing areas to stay below maximum limits of the material (e.g. compressive strength, tensile strength, etc.). Although the component material has already been tested, component tests should be run to ensure proper bearing areas and stresses are as designed now that geometry has been selected.

System level component verification
Once material selection and component geometry design are complete, verification of the component through system level testing can be conducted. The verification test should be conducted on a fastening system installed on a concrete crosstie. The applied loads should be based on the selection of the load threshold from step one.

<u>*3.1.2.2 Overview of new design process using Safelok I – sample calculations*</u>

Load threshold selection
The design load for the component should be based on lateral fastening system (FS) force data selected from Table 3.1 that was obtained through field experimentation. A threshold should be chosen using the field data and based on the probability that a certain percent of anticipated loads will fall under a specific load.

Table 3.1 Lateral fastening system forces – Peaks

	Peak Load (lbf)				
	Mean	95%	97.50%	99.50%	100%
Force on Shoulder[1]	2,020	5,501	6,414	7,408	7,883

1 Source of data: Transportation Technology Center; Pueblo, Colorado; May 2013

Sample selection:

Choose 95% confidence threshold
95% of lateral FS forces fall below 5,500 lbf (based on field data)
Design FS force → 8,000 lbf

The design load for the system level verification tests should be based on lateral wheel load data obtained in the field (Table 3.1). A threshold should be chosen using the field data and based on the probability that a certain percent of loads will fall under a specific load magnitude.

Sample selection:

Choose 95% confidence threshold
95% of lateral wheel loads fall below 26,000 lbf (based on field data)
Design wheel load → 26,000 lbf

Material selection
A sample of the material used in the insulator should be tested to meet necessary electrical resistivity. Apply 10 volts AC 60 Hz potential between each end of the sample piece of material. After measuring the current flow between the two points, the calculated resistance of the material should be greater than or equal to 10,000 Ω.

As a sample calculation, if the electrical impedance between the two rails is measured to be greater than 10,000 Ω, the insulator would pass the test and be considered an adequate component design.

Sample calculation:

$$\frac{\text{Applied Voltage (V)}}{\text{Current Flow (A)}} = R$$

$$\frac{10{,}000\ \text{V}}{0.00094\ \text{A}} = 10{,}638\ \Omega \rightarrow \text{Pass}$$

Applied Load

A sample of the material used in the insulator should be tested to meet necessary load vs. deflection requirements. Apply 10,000 lbf to a 0.5" x 4" x 0.25" (L x W x H) sample piece of material and measure displacement in direction of applied load. After applying load 10 times for one second each, generate a load versus displacement curve. The slope of the linear trend line should be less than 150,000 lb/in (defined by either the fastening system manufacturer or end user (e.g. railroads)).

Sample calculation:

$$\frac{\text{Applied Load (lbf)}}{\text{Displacement (in)}} = S$$

$$\frac{10{,}000 \text{ lbf}}{0.0714 \text{ in}} = 140{,}000 \text{ lbf/in} \rightarrow \text{Pass}$$

Geometric design

The insulator bearing area on the shoulder should be designed in a way to ensure stress limits are not exceeded. Based on the design applied load (8,000 lbf) and the material's compressive strength (e.g. 25,000 psi), the bearing area of the applied load should be designed to ensure stresses fall under the material's limits. A safety factor could be used in the process to add an additional assurance to ensure stress limits are not exceeded.

Sample calculation:

$$\frac{\text{Applied Load (lbf)}}{\text{Compressive Strength (psi)}}(\text{S.F.}) = A$$

$$\frac{8{,}000 \text{ lbf}}{25{,}000 \text{ psi}}(2) = 0.64 \text{ in}^2$$

System level component verification

Methods of measuring bearing areas and forces on the insulator should be developed to ensure the design values and actual values are equivalent. The measurements could be implemented on tests such as AREMA Test 6 to evaluate insulator design and actual performance in parallel with wear and abrasion testing.

Sample calculation:

$$\frac{\text{Measured Force (lbf)}}{\text{Bearing Area (in}^2\text{)}} = \sigma$$

$$\frac{7{,}250 \text{ lbf}}{0.68 \text{ in}^2} = 10{,}662 \text{ psi} > 25{,}000 \text{ psi} \rightarrow \text{Pass}$$

Path Forward for insulator

More validation data from the field as well as from the FE model should be used and analyzed to make the revised design process a reality. An in-depth understanding of solid materials is necessary to finish the design process given that material selection is such an important factor in the design of fastening system components. Further full-scale testing on lateral loads and load distribution must be conducted to obtain more data that can be used for validation. Likewise, field full-scale testing should be conducted in parallel with FE modeling to expedite data analysis.

3.2 Concrete Crosstie

3.2.1 Current Concrete Crosstie Design Practices

Chapter 30 of AREMA 2014 (AREMA 2014) contains the current recommended design practices for concrete crossties. Section 4 of Chapter 30 provides considerations for materials, physical dimensions, flexural strength, longitudinal rail restraint, lateral rail restraint, electrical properties, testing, ballast, special track, and repair. Section 4 also includes recommended practices for shipping, handling, application and use of concrete crossties. Flexural strength and testing are separated by type of concrete crosstie, prestressed monoblock, and two-block. The following text will focus exclusively on the current methods of determining flexural strength of standard prestressed monoblock concrete crossties, found in Section 4.4. Section 4 starts with general considerations and assumptions, these will be explained further below.

Crosstie Spacing

Crosstie spacing affects rail and crosstie flexural stresses and the bearing stress on ballast (or other support). If crosstie dimensions and ballast conditions are held constant, an increase in crosstie spacing results in a decrease in track modulus (larger track deflection upon loading). Recommended crosstie spacing in Chapter 30 of AREMA is between 20 and 30 inches.

Crosstie Dimensions

Section 4 specifies minimum dimensions for crossties. Length increase generally increases track modulus and provides larger distance for prestressing force to transfer from steel to concrete within the rail seat. Width increase also serves to increase track modulus and also provides larger bearing area on ballast, thereby reducing ballast bearing stress. An increase in depth often increases the flexural strength of the crosstie and the frictional area of ballast. The design criteria contained in Section 4 are valid for crossties between the minimum and maximum requirements shown below in Table 3.2. This report only focuses on the design of concrete crossties when the requirements in Table 3.2 are met.

Table 3.2 Dimensional requirements for pre-tensioned concrete crossties (AREMA)

	Minimum	Maximum
Length	* 7'-9"	9'-0"
Width	6" (top) / 8" (bearing)	13"
Depth	6"	10"
Rail Cant	1/45"	1/35"

* 8'-0" if no additional provisions to ensure adequate prestress transfer

Load Distribution

AREMA Chapter 30 states that wheel loads applied to the rail will be distributed to several crossties. Field investigations have been used to develop a conservative estimate of load distribution to a single crosstie. This is shown in Figure 3.1 below.

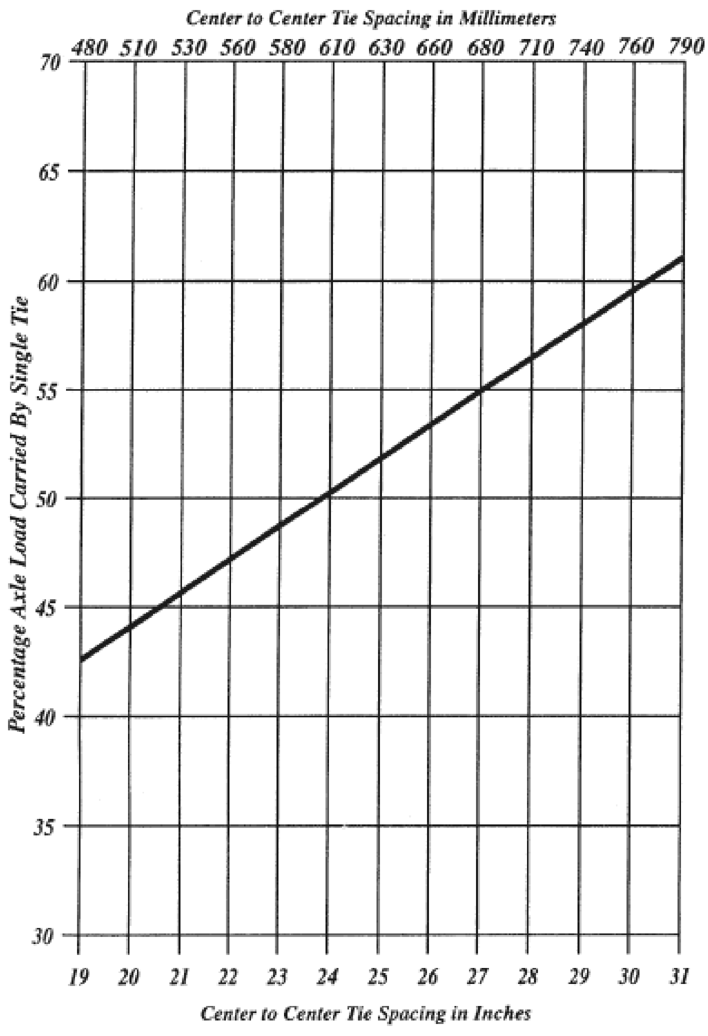

Figure 3.1 Estimated Distribution of Loads (AREMA 2014 Fig. 30-4-1)

Impact Factors
AREMA bases the design specifications listed in Chapter 30 on an assumed impact factor of 200%. In the calculation of rail seat load, this impact factor is added to 1, making the total impact factor 300% (Static load multiplied by 3). The impact factor accounts for the increased loadings caused by track dynamics and wheel imperfections.

Flexural Strength/Design for Flexure
The mechanistic design of prestressed monoblock crossties for flexure is the main focus of the mechanistic design practices that are contained within this report. The design of any structure must begin with a structural analysis to determine the loadings that the structure will experience. In AREMA Chapter 30, this analysis takes the form of the empirically-derived factored design flexural strength values. There are four key locations on the crosstie: the rail seat positive bending moment, the rail seat negative bending moment, the center positive bending moment, and the center negative bending moment. These positions are shown below in Figure 3.2.

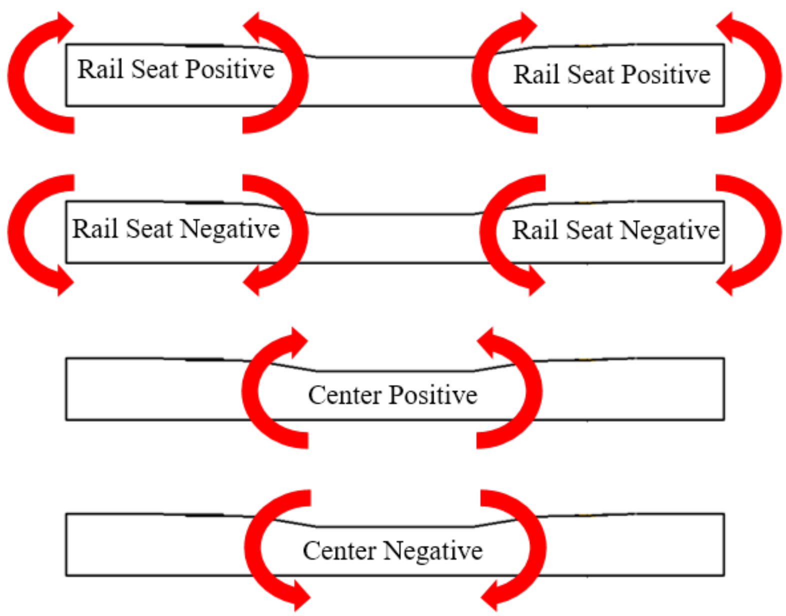

Figure 3.2 Critical Moment Locations

First, to determine the factored design bending moment for a given loading condition, Figure 3.3 is used. By specifying the crosstie spacing and the crosstie length, an unfactored rail seat positive bending moment can be found from Figure 3.3. Figure 3.4 is then used to determine the speed and tonnage factors, which are based on expected track speed and tonnage, respectively. These three values are then multiplied together according to Equation 1. For each figure linear interpolation can be performed between two specified points.

$$M = B \cdot V \cdot T \tag{1}$$

where:

M = factored rail seat positive bending moment (kip · in)
B = unfactored rail seat positive bending moment (kip · in)
V = speed factor
T = tonnage factor

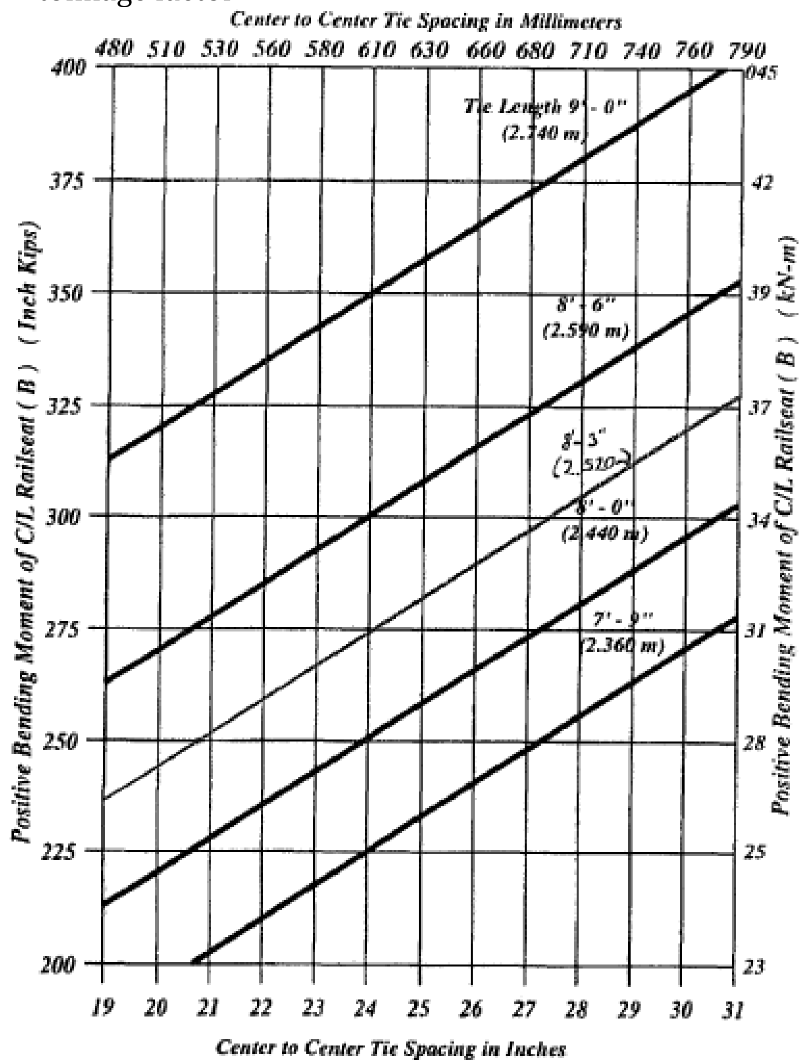

Figure 3.3 Unfactored Bending Moment at Rail Seat Center (AREMA 2014 Figure 30-4-3)

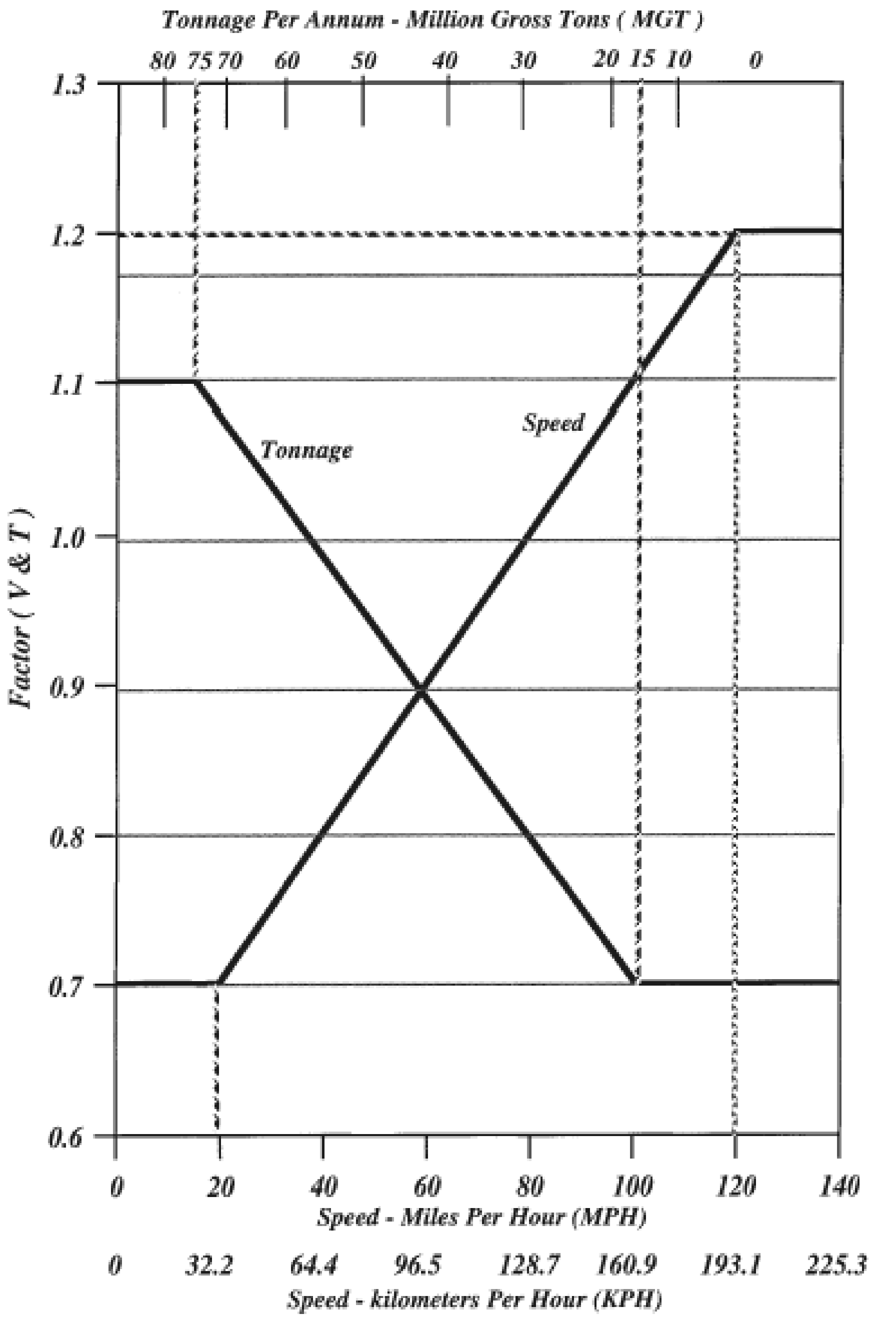

Figure 3.4 Tonnage and Speed Factors (AREMA 2014 Figure 30-4-4)

Once the factored rail seat positive bending moment is determined, it is further factored to determine factored bending moments at the other key locations. The factors are based on crosstie length and can be linearly interpreted, and are shown in Table 3.3 below.

Table 3.3 Bending Moment Factors (AREMA 2014 Table 30-4-1)

Tie Length	Rail Seat Negative	Center Negative	Center Positive
7′-9″ (2.360 m)	0.72M	1.13M	0.61M
8′-0″ (2.440 m)	0.64M	0.92M	0.56M
8′-3″ (2.520 m)	0.58M	0.77M	0.51M
8′-6″ (2.590 m)	0.53M	0.67M	0.47M
9′-0″ (2.740 m)	0.46M	0.57M	0.40M

Throughout Section 4.4 there are notes that allow for some freedom in crosstie design. AREMA allows for the factored design positive bending moment to be reduced due to the use of attenuating crosstie pads, which have been shown to reduce crosstie bending moment. AREMA also states that crossties with a larger bottom width at the rail seat than at the center (wasted section) will experience higher moments at the rail seat and lower moments at the center compared to constant bottom width crossties, which must be either considered in analysis or by increasing bending moment requirement by 10% at the rail seat positive and reducing by 10% at the center negative. AREMA recommends a maximum prestress after losses of 2,500 psi at all points in the tie. Furthermore, AREMA specifies a minimum prestress after losses and without any applied load of 500 psi.

In the design section, AREMA defines failure for two-block designs as cracks exceeding AREMA-specified allowable crack widths in Table 30-4-3. However, there are no explicit recommendations or specifications for failure of prestressed monoblock crossties. Instead, AREMA states that prestressed monoblock crossties must comply with ACI 318, “Building Code Requirements for Structural Concrete” specifications (ACI 2011). In ACI 318-11 prestressed concrete design requirements are included in Chapter 18. Serviceability design requirements for prestressed concrete for ACI 318-11 are shown in Table 3.4 below. From the table, it is assumed that prestressed concrete monoblock crossties are considered as Class U. Design of Class U prestressed concrete assumes uncracked behavior, allowing the gross section of the concrete to be used in calculation of the flexural strength capacity. Considering this, failure of a prestressed monoblock crosstie must be defined as cracking. In the testing methods section AREMA defines failure of the crosstie to be cracking extending to the first layer of reinforcement.

Table 3.4 Serviceability Design Requirements (ACI 318-11 Table R18.3.3)

	Prestressed			
	Class U	Class T	Class C	Nonprestressed
Assumed behavior	Uncracked	Transition between uncracked and cracked	Cracked	Cracked
Section properties for stress calculation at service loads	Gross section 18.3.4	Gross section 18.3.4	Cracked section 18.3.4	No requirement
Allowable stress at transfer	18.4.1	18.4.1	18.4.1	No requirement
Allowable compressive stress based on uncracked section properties	18.4.2	18.4.2	No requirement	No requirement
Tensile stress at service loads 18.3.3	$\leq 7.5\sqrt{f_c'}$	$7.5\sqrt{f_c'} < f_t \leq 12\sqrt{f_c'}$	No requirement	No requirement
Deflection calculation basis	9.5.4.1 Gross section	9.5.4.2 Cracked section, bilinear	9.5.4.2 Cracked section, bilinear	9.5.2, 9.5.3 Effective moment of inertia
Crack control	No requirement	No requirement	10.6.4 Modified by 18.4.4.1	10.6.4
Computation of Δf_{ps} or f_s for crack control	—	—	Cracked section analysis	$M/(A_s \times$ lever arm), or $0.6f_y$
Side skin reinforcement	No requirement	No requirement	10.6.7	10.6.7

Testing of Flexural Strength

For a prestressed concrete monoblock crosstie design to be approved, there are a series of design validation tests that the crosstie must pass. These tests are explained extensively in AREMA Chapter 30, Section 4.9, "Testing of Monoblock Ties".

3.2.2 Numerical Example of Current Concrete Crosstie Design Process

The following section includes a sample calculation demonstrating the current design process specified by AREMA 2014 and explained in detail in the previous section. This system will be designed for a prestressed concrete monoblock crosstie 8'-6" in length, spaced at 24" on center for a corridor with an annual tonnage of 55 MGT and average train speed of 80 mph. This scenario is solely for example purposes.

1. Use pre-determined crosstie length of 8'-6" and spacing of 24" to determine the unfactored positive bending moment at the rail seat. This value can be determined from Figure 3.3. Figure 3.5 shows how this value is found. In this example, the rail seat positive bending moment is found to be 300 kip-in.

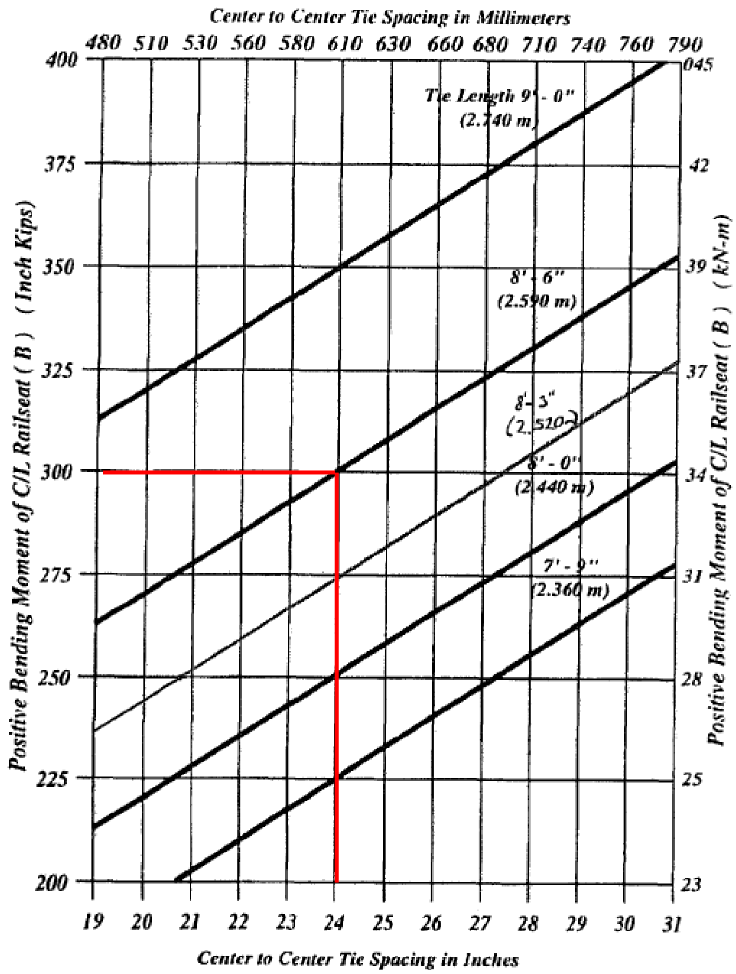

Figure 3.5 Determination of Unfactored Rail Seat Bending Moment

2. Next, the velocity (V) and tonnage (T) factors are determined using Figure 3.3. This determination is illustrated in Figure 3.6 below. In this example, the velocity factor (for 80 mph) is found to be 1.0 and the tonnage factor (for 55 MGT) is found to be 1.0.

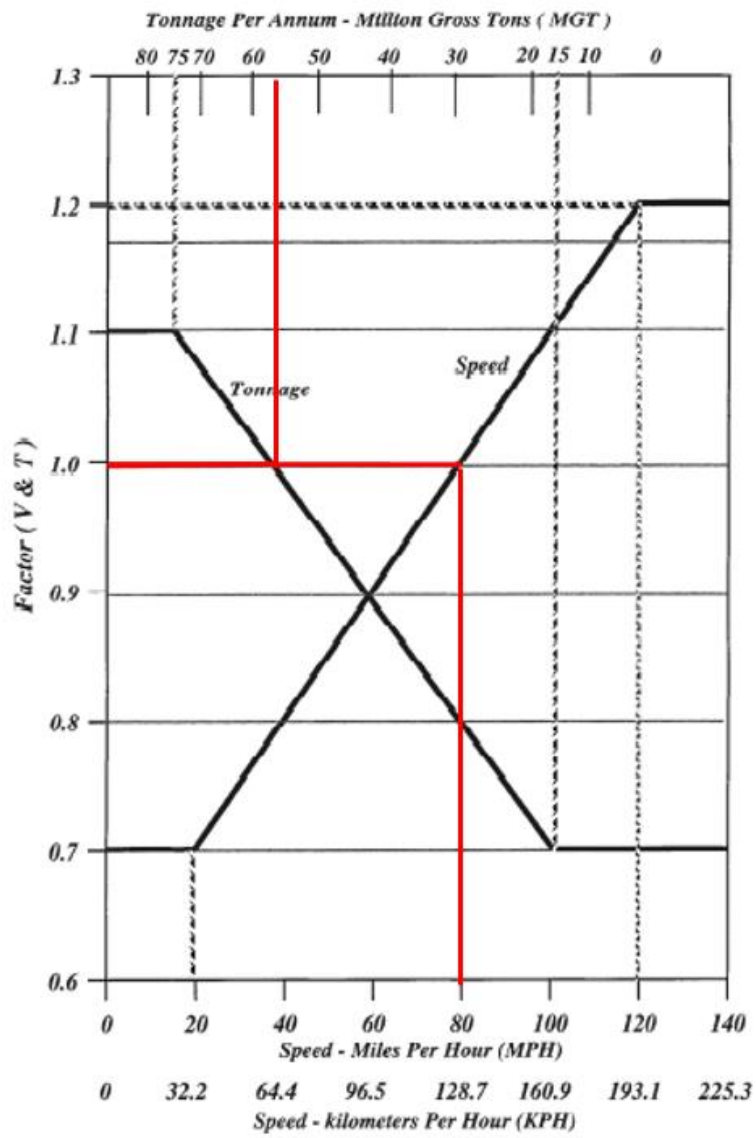

Figure 3.6 Determination of Velocity and Tonnage Factors

3. Next, factored design rail seat positive moment can be calculated. Using Equation 2, this value can be computed.

$$\mathrm{M} = B \cdot V \cdot T \tag{2}$$

$$\mathrm{M} = (300\ \mathrm{kip} \cdot \mathrm{in})(1.0)(1.0) = \mathbf{300\ kip \cdot in}$$

4. Next, the factored design bending moments can be determined using the crosstie length and the computed factored design rail seat positive moment (M) following **Table 3.3**. The sample calculations and results are shown in **Table 3.5** below.

Table 3.5 Factored Design Bending Moment Calculations

	Positive	Negative
Rail seat	1.00M = 300 kip-in	0.53M = 159 kip-in
Crosstie center	0.47M = 141 kip-in	0.67M = 201 kip-in

5. The factored design moments listed in Table 3.5 can now be used to design a prestressed concrete monoblock crosstie. AREMA does not provide any recommendations on this process, other than specifying the minimum and maximum dimensions (shown in Table 3.2) and setting a minimum and maximum amount of prestress after losses. Instead, AREMA relies on empirical tests to validate the design. Thus, a crosstie designer must go through the design process unaided to design a crosstie that will pass the tests explained earlier in this report. Using the CXT 505S crosstie specifications as an example, the flexural strength values are given as applied loads, shown in Table 3.6 below. Below, these applied loads are converted to bending moments per AREMA to check that they exceed the factored design bending moments. CXT did not provide flexural strengths for rail seat negative or center positive, likely because rail seat positive and center negative are the most critical cases and often limit the design.

Table 3.6 CXT Test Loads

Section	Rail Set Load
Rail Seat Positive	61 kips
Center Negative	15 kips

Rail Seat Positive Flexural Capacity

The CXT-specified test load for rail seat positive bending is 61 kips. In the below equation, this is denoted as P, where M is the factored rail seat positive flexural strength, and x is the distance from the end of the crosstie to the center of the rail seat (for the CXT 505S, this distance is 21.16 inches).

$$\mathrm{P} = \frac{2M}{\frac{2X}{3} - 2.25''} \tag{3}$$

Solving the above equation for M,

$$\mathrm{M} = \frac{\mathrm{P}\left(\frac{2X}{3} - 2.25''\right)}{2} \tag{4}$$

Solving this equation for a CXT 505S, rail seat positive bending moment capacity can be found.

$$\mathrm{M} = \frac{61\left(\frac{2(21.16'')}{3} - 2.25''\right)}{2} = \mathbf{362\ kip \cdot in}$$

This capacity exceeds the required bending moment found in Table 3.5, and theoretically should pass all tests related to flexural strength prescribed by AREMA.

Center Negative Flexural Capacity

A similar process is followed to compute the factored center negative flexural capacity. The CXT-specified test load for center negative bending is 15 kips. In the below equation, this is denoted as P and M is the factored center negative flexural strength.

$$P = \frac{2M}{27"} \tag{5}$$

Solving the above equation for M,

$$M = \frac{27P}{2} \tag{6}$$

Solving this equation for a CXT 505S, rail seat positive bending moment capacity can be found.

$$M = \frac{27(15)}{2} = \mathbf{203\ kip \cdot in}$$

This capacity exceeds the required bending moment found in Table 3.5, and theoretically should be pass all tests related to flexural strength prescribed by AREMA.

6. Finally, after the crosstie is designed, it must pass all tests specified by AREMA Section 4.9

3.2.3 Comments on Current Concrete Crosstie Design Process

The design process specified by AREMA does not follow a mechanistic framework. There are also a number of very important factors that are either not considered or not specified. Below is a list of factors with a brief explanation of the factor and its importance.

- *No modifiable or justified dynamic amplification factor*

  In Chapter 30, Section 4.1.2.4, a constant 200% impact factor is assumed. This value could change based on vehicle dynamics and track structure. As train tonnage and speed increase, this dynamic amplification factor could prove to be even greater (for example, see Table 2.4). This amplification factor needs to be adjustable so that designers and railroads can determine the factor of safety they want to include in the system. To consider the wheel load and wheel-rail dynamic interaction into design, AREMA uses another design chart (Figure 3.3) to scale the calculated unfactored bending moment. In this chart, AREMA uses train speed and annual tonnage as the two parameters to scale the design crosstie bending capacity; however this is based more on statistics than dynamics and predicts a more general case. Wheel-rail dynamic interaction depends on more factors than just train speed and annual tonnage. For example, wheel profile, contact condition, and railcar suspension system all play a factor in dynamic and impact loading cases. In short, there needs to be more inputs in calculating dynamic amplification factor. The current design methodology may reach the requirement of the common case, but it neglects the destructive force of extreme impact loading, which could cause the failure of the track system.

- *Origin and assumptions for determination of bending moments is unclear*

Bending moments determined by AREMA 2014 Figure 30-4-3, speed and tonnage factors from Figure 30-4-4, and bending moment scaling factors found in Table 30-4-1 are all presented without explanation of origin. There is no indication of how these moments or factors were derived and what they are based on. After much review it was found that the values in Figure 30-4-3 are likely found according to a 1983 P.J. McQueen paper titled "Introduction to Concrete Tie Systems" for an 82 kip axle load and uniform ballast reaction (McQueen 1983). However, the origins of Figure 30-4-4 and Table 30-4-1 remain unknown.

- *There is no consideration of the pad attenuation or the ballast support conditions*

  Quantifying or assigning values to reflect these factors is very difficult, but not including them at all or even providing an assumption is unacceptable. Pad attenuation has been shown to significantly affect the loadings experienced by the crosstie along with its dynamic response. Ballast conditions, such as rail seat bound and center bound are not considered, instead opting for the improbable assumption of perfect ballast contact with the bottom of the crosstie.

- *There are no equations, recommendations, methods, or even defined limit states for crosstie design*

  AREMA has put all of the design responsibility on crosstie manufacturers. Chapter 30 does not suggest an equation or a method for determining the theoretical flexural strength of a crosstie, only providing a method of analysis. A limit state (i.e. cracking) is not explicitly stated in the design section.

3.2.4 New Design Methodology

Examples of design methodologies that are based in mechanics are seen in many other design codes worldwide. The two best examples of these mechanistic design methodologies are the International Union of Railways specification 713R (UIC 713) and the Australian Standard 1085, Part 14 (Standards Australia 2003). As discussed previously, the AREMA determination of bending moments is empirically driven and difficult to follow and modify. As previously stated, the unfactored positive rail seat bending moment values shown in Figure 3.3 are likely based on the calculations found in McQueen's 1983 paper "Introduction to Concrete Tie Systems" (McQueen 1983). The origin of the speed and tonnage factors found in Figure 3.4 is unknown. Additionally, the origin of the factors presented in Table 3.3 is not officially stated, but they could be based on empirical data presented in McQueen's 2006 paper "Flexural Performance Requirements for Prestressed Concrete Ties by Factoring" (McQueen 2006).

To move toward a more mechanistic design framework, the AREMA analysis must shift from the current factored method to a mechanically-based analysis. UIC 713 and AS 1085.14 provided good examples for this, and both methods served as a template for the following proposed methodology. It is important to note that no current railroad design standard provides any recommendation for crosstie design, instead presenting only a recommendation for analysis. Thus, this proposed method only includes analysis.

Step 1: Determine rail seat load

Following the current AREMA methodology for determining rail seat load, use Figure 3.1 to determine the distribution factor. The end user can define the unfactored wheel-rail load and impact factor or the designer can use the wheel-rail loads given in Table 2.3. It is important to note that the wheel-rail loads given in Table 2.3 already account for impacts, thus an impact factor of 0% should be used with these values. The design rail seat load (R) can be calculated using Equation 7.

$$\mathrm{R} = \mathrm{WL} \times \mathrm{DF} \times (1 + \mathrm{IF}) \tag{7}$$

where:

$$\mathrm{R} = \text{design rail seat load (kip)}$$
$$\mathrm{WL} = \text{unfactored wheel-rail load (kip)}$$
$$\mathrm{DF} = \text{distribution factor}$$
$$\mathrm{IF} = \text{impact factor}$$

Step 2: Calculate design rail seat positive bending moment

For the rail seat positive bending moment, it is assumed that the crosstie is supported only at the rail seats, as seen in Figure 11. This represents a feasible worst-case scenario for rail seat positive bending and approximates the ballast reaction seen for newly-tamped track. These are the same support conditions used in Part 14 of the 2003 AS (Standards Australia 2003).

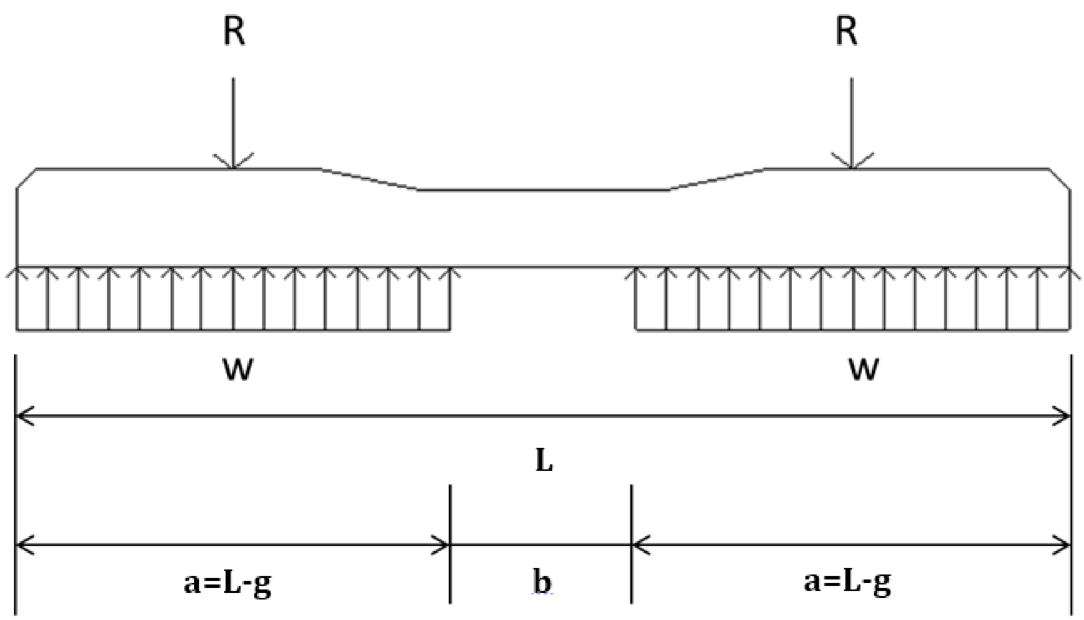

Figure 3.7 Support Conditions for Rail Seat Positive Bending Moment

To calculate the design rail seat positive bending moment, the rail seat section shown in Figure 3.7 can be modeled as a beam with a uniform distributed load bending about a centered point load (shown in Figure 3.8). The equation for the rail seat positive bending moment is given by Equation 8.

$$M_{RS+} = \frac{Ra}{8} \tag{8}$$

where:

$$M_{RS+} = \text{design rail seat posititve bending moment (kip} \cdot \text{in)}$$
$$R = \text{design rail seat load (kips)}$$
$$a = \text{rail seat support reaction (in)}$$

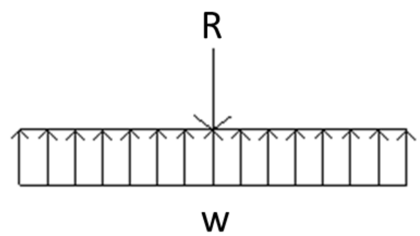

Figure 3.8 Simplified Beam Model for Rail Seat Positive Bending Moment

Step 3: Calculate design center negative bending moment

For the center negative bending moment analysis, it is assumed that the crosstie is uniformly supported, as shown in Figure 3.9. This uniform ballast reaction can be found by dividing the design axle load (2R) by the crosstie length (L). This approximates the ballast reaction after heavy train traffic and ballast fouling. The equation for the center negative bending moment is given in Equation 9.

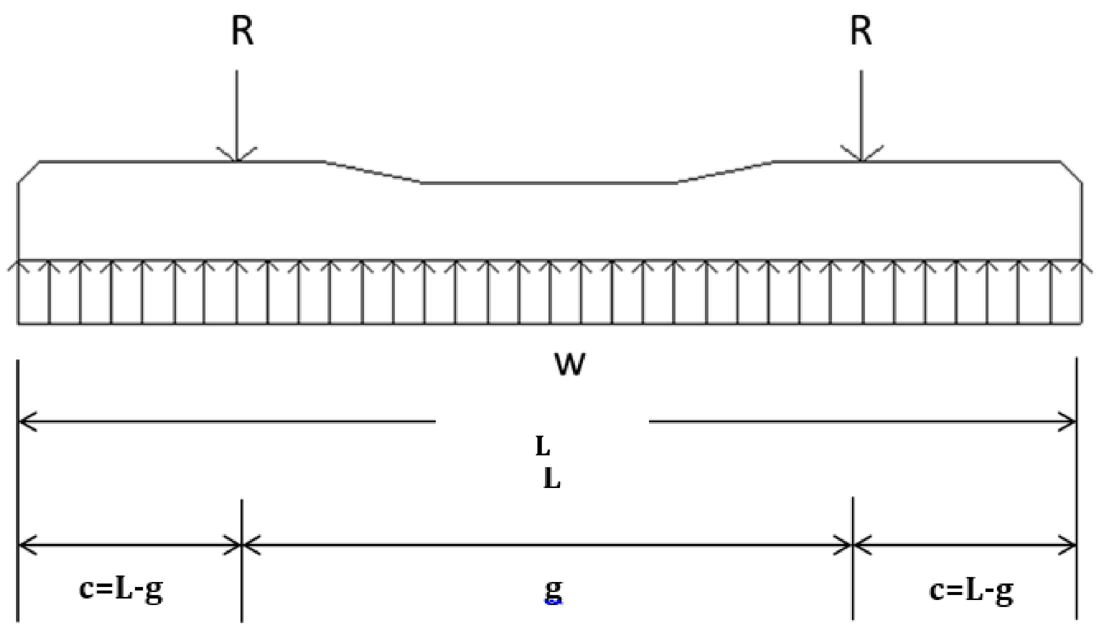

Figure 3.9 Support Conditions for Center Negative Bending Moment

$$M_{C-} = \frac{w(0.5L)^2}{2} - \frac{Rg}{2} \tag{9}$$

where:

M_{C-} = design center negative bending moment (kip · in)
w = distributed ballast reaction (kips/in)
L = crosstie length (in)
R = design rail seat load (kips)
g = rail center spacing (in)

This equation is found by modeling the crosstie as a beam cantilevered at the center, as shown in **Figure 3.10**.

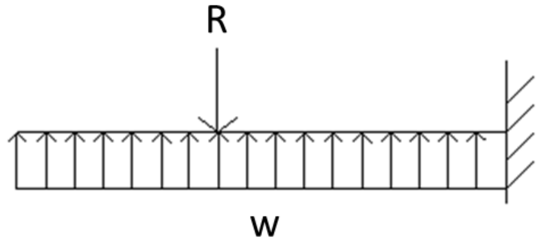

Figure 3.10 Simplified Beam Model for Center Negative Bending Moment

After speaking with many concrete crosstie manufacturers and designers, it became clear that they design only for rail seat positive and center negative bending. This is due to the eccentricity of the prestressing steel. If the crosstie is designed to withstand the positive flexural demand at the rail seat, then the crosstie should also be sufficient for center positive bending. The same philosophy holds true for negative bending; if the crosstie is designed to satisfy the center negative bending, it too should be adequate for rail seat negative bending. Therefore, no mechanics-based analysis is proposed to calculate the rail seat negative or center positive bending moments.

AREMA, UIC 713, and AS 1085.14 are similar in that they both stop after the analysis of the crosstie. It must be remembered that this is only half of the design process, and a methodology for the physical design of the crosstie must also be included. There are many parameters that affect both the cracking and ultimate flexural strength of a crosstie. Some examples are provided below but not limited to:

- Prestress jacking force
- Number of prestressing wires or strands
- Arrangement of prestressing wires or strands
- Concrete strength
- Concrete cross section at rail seat and center

There must be some method or equation to give crosstie manufacturers an idea of what parameters can be changed and how these changes will affect the crosstie flexural strength.

3.2.5 Numerical Example of New Design Process

For this example, flexural analysis will be performed for a prestressed concrete crosstie that is 8'-6" long, has a 60" gauge length, is spaced at 24", and must withstand an 82 kip axle load.

Step 1: Determine rail seat load

Using Figure 2.1, for 24" crosstie spacing, 50% of the wheel load is carried by a single rail seat immediately under the point of load application. Using Equation 10, and the AREMA-specified 200% impact factor, the design rail seat load can be calculated.

$$\mathrm{R} = \mathrm{WL} \times \mathrm{DF} \times (1 + \mathrm{IF}) \tag{10}$$

$$\mathrm{R} = \left(\frac{82\ \mathrm{k}}{2}\right) \times 0.50 \times (1 + 2.00) = \mathbf{61.5\ kips}$$

Step 2: Calculate design rail seat positive bending moment

From the assumptions stated in the previous section and illustrated in Figure 3.8, Equation 11 can be used to calculate the rail seat positive bending moment.

$$\mathrm{M_{RS+}} = \frac{\mathrm{Ra}}{8} \tag{11}$$

$$\mathrm{M_{RS+}} = \frac{(61.5\ \mathrm{k})(102" - 60")}{8} = \mathbf{323\ kip \cdot in}$$

Step 3: Calculate design center negative bending moment

From the assumptions stated in the previous section and illustrated in Figure 3.10, Equation 12 can be used to calculate the center negative bending moment.

$$\mathrm{M_{C-}} = \frac{\mathrm{w}(0.5\mathrm{L})^2}{2} - \frac{\mathrm{Rg}}{2} \tag{12}$$

$$\mathrm{M_{C-}} = \frac{\left(\frac{2 \cdot 61.5\ \mathrm{k}}{102"}\right)(0.5 \cdot 102")^2}{2} - \frac{(61.5\ \mathrm{k})(60")}{2} = \mathbf{277\ kip \cdot in}$$

This completes the proposed procedure for performing flexural analysis on a prestressed concrete crosstie. These moments are compared with the numerical AREMA example in Table 3.7 below.

Table 3.7 Comparison Between Current AREMA and Proposed Flexural Analysis Methods

Method	AREMA	Proposed	Difference
M_{RS+} (kip-in)	300 kip-in	323 kip-in	+8%
M_{C-} (kip-in)	201 kip-in	277 kip-in	+38%

3.2.6 Future Work for Concrete Crosstie Mechanistic Design

For this methodology to be implemented agreement must be reached between crosstie manufacturers, railroads, researchers, and AREMA. The new analyses discussed in the previous section require higher flexural strength of crossties, which will result in designs that while currently acceptable according to AREMA standards will become inadequate. A large part of this discussion is related to limit states and dynamic amplification factors. If these parameters are accepted, the design process can be revised.

Listed below are the next steps necessary to continue refining this process and the methods for testing them:

- All assumptions and factors made in the new design procedure need to be verified (from field and laboratory experiments as well as FE modeling results). This can be accomplished by conducting more tests in the field and more iterations of the FE model. The factor of greatest concern and need of review is the dynamic amplification factor associated with extreme loading. Further investigation into WILD data can shed light on probabilistic loadings that incorporate dynamic amplification effects.
- Bending moment distribution of the crosstie under different ballast conditions needs to be further investigated. Currently, even with the proposed changes, the ballast conditions are almost completely neglected when determining the required bending moments at the critical sections of the crosstie. Changes to support conditions including ballast consolidation and ballast stiffness are factors that significantly affect the forces and moments experienced by the crosstie. This can be further investigated by calculating the bending moments under changing ballast reactions using linear-elastic analysis as shown in the proposed section.
- The acceptable prestressing transfer length must be considered in the crosstie design process. It is not currently mentioned in the proposed new method, but should be considered by crosstie manufacturers. Researchers at Kansas State University have done extensive research in the required transfer length of different prestressing wires and strands (Haynes 2013, Bodapati 2013). Findings from their work could be used to provide crosstie manufacturers guidance on this issue. The same researchers have also developed a non-contact method of measuring the prestressing forces in a crosstie, which could be implemented by manufacturers as a method of quality control (Zhao 2013).

SECTION 4 CONCLUSIONS

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

4.1 Summary

This project provides a review of the existing design process for concrete crosstie and fastening systems, and the method by which a mechanistic design process can be achieved. A mechanistic design process will provide many benefits that are not currently achieved by the iterative design process outlined in AREMA. Table 4.1 compares the two methods to highlight the areas where a mechanistic design process would provide the greatest benefit.

Table 4.1 Qualitative Comparison of Iterative and Mechanistic Design Processes

Category	Iterative Design (Current)	Mechanistic Design (Proposed)
Ease of development	Already developed	Will require large amounts of capital investment and time
Time required to run analysis	Relatively quick	Requires lengthy analysis process
Accuracy of demand estimates	Variable, could be inaccurate	Highly accurate, based on system specific analysis
Ability to account for specific failure modes	Limited, mostly focused on crosstie failure modes	Design specifically accounts for each failure mode of every component
Potential for design of new systems	Low, may not be accurate	High, very flexible for material or geometry chosen for the system
Safety factor of design	Relatively conservative	More variable according to choice of designer

The primary difference between the two design processes is that while mechanistic design will provide more accurate predictions of the load experienced by components, it will require a large amount of capital and time in order to develop the process. Also, even if both processes were fully developed, designing a system using mechanistic design will take more time as the full load path will need to be determined. As finite element models become more robust, it should be possible to determine the load path and distributed forces more quickly, but currently this is a time consuming process. Once a mechanistic design is developed it will provide much more flexibility than the iterative design process, allowing for variable factors of safety for each failure mode, as well as allowing multiple types of fastening systems while still producing reliable predictions of performance.

The end goal of this study is to provide a framework for a mechanistic design process that can provide some immediate changes to the design process outlined in the AREMA Recommended Practices. However, the more important purpose is to highlight the areas that need the most improvement, so that future research projects will have clear goals that can positively impact the rail industry.

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