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Laboratory analysis of track gauge restraining capacity of center-cracked railway concrete sleepers with various support conditions

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ABSTRACT

As the number of concrete railway sleepers has steadily grown in North America, the importance of understanding the performance and failure of these components has also increased. Concrete sleepers typically perform better than timber sleepers to maintain track geometry and have a longer expected service life. Nevertheless, there have been derailments that were caused by excessive increase of track gauge due to deteriorated concrete sleepers and fastening systems. As ballast support conditions are closely related to sleeper performance, there is a need to fully understand the behavior of poorly supported sleepers. To quantify the influence of support conditions on sleeper deflection and gauge widening, laboratory experiments were performed. Using a static structural loading frame, new and center-cracked concrete sleepers were subjected to different support conditions, engineered using rubber pads. Simulated conditions included center bound sleepers, newly tamped track, and track under high impact loads. This paper presents a correlation between ballast support conditions and their effect on concrete sleeper health and track gauge. Using statistical tools to analyze the experimental results, it is shown that there is no significant difference between new sleepers and lightly center-cracked sleepers. Even extreme deterioration at the sleeper center has little influence on the gauge widening effect due to sleeper bending. Moreover, the gauge widening effect due to pure concrete sleeper bending seemed to be minimal, but not insignificant when compared to the amount of track gauge increase due to other track infrastructure conditions. Therefore, railway accidents where damaged concrete sleepers fail to restrain track gauge are more likely to be related to the rail seat, fastening system, or other production problems rather than center cracking.

1. Introduction

In the United States, the use of concrete railway sleepers has increased steadily over the past decade as concrete sleepers have emerged as an economic alternative to timber sleepers to accommodate heavy axle freight train loads [1]. As the number of concrete railway sleepers has grown, the importance of understanding the performance and failure of these components has also increased.

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Although not as frequent as the accidents caused by defective timber sleepers, derailments have been related to deteriorated concrete sleepers and fastening systems leading to wide track gauge [2]. Further, an analysis of the U.S. Federal Railroad Administration (FRA) accident database, an industry survey, and additional literature review indicate the need to better understand the gauge restraining capacity of deteriorated concrete sleepers, especially when associated with poor track support conditions [2]. Using laboratory data, this paper focuses on correlating sleeper center cracks and various track support conditions with the potential track gauge widening.

1.1. Functions, design, and failure of concrete sleepers

To further comprehend the problems of concrete sleepers, it is useful to understand their functions within the railroad track. Any condition that results in sleepers being unable to serve these functions are considered a defective condition. According to Zeman [3], the roles of railroad sleepers are:

- Supporting the rails under load;
- Distributing the stresses at the rail seat to acceptable levels for the ballast layer;
- Maintaining proper geometry of the track structure.

Maintaining proper geometry of the track structure is not an exclusive role of sleepers, but a shared responsibility with other track elements and components [3]. Nevertheless, even though sleepers restrict the lateral and vertical movements of the track, perhaps their most relevant contribution to maintaining track geometry is to maintain the track gauge with the assistance of rail fastening systems. Various research efforts focus on reporting the failure mechanisms of concrete sleepers [4–6], but do not necessarily map them to a failure of fulfilling the basic functions of these components. Therefore, this work focuses on answering the question of when the studied defects would lead to a train derailment or pose some other tangible risk.

Since the actual fulfillment of the concrete sleeper's function is closely related to their structural design process, it is pertinent to understand the common practices of concrete sleeper design. In addition, even though concrete sleepers can be monoblock or twin-block, the latter are outside the scope of this study as they are not commonly used in North America [7]. There are two prominent methods of designing concrete sleepers: the maximum allowable stress approach and the limit states approach. The allowable stress method “ensures that all stresses within the sleeper do not exceed predetermined values” [8], which could lead to an uneconomical scenario by over-designing sleepers [9]. The limit state methods also require that the design resistance must be greater than the “effect of design loads” [10]. The main difference, however, lies in using maximum probable loads believed to occur in a given time period [10] (as opposed to factoring input loads), often leading to more economical designs. There can be many simultaneous limit states, such as serviceability limits of tolerable deformations, acceptable cracking, and maximum vibration. For instance, Murray recommends four limit state categories for concrete sleepers, namely: strength, operations, serviceability, and fatigue [8]. One advantage of the limit states methods is the fact that mapping the failure modes is a key factor considered from the beginning of the design process. When developing limit states for concrete sleepers, Leong provides one of the most complete lists of defective conditions that would cause these components to fail [9]. A modified version of this list is shown below:

Bottom abrasion that allows for excessive gauge widening due to bending deformation;

Rail seat deterioration (RSD) that allows for excessive gauge widening due to rail rotation;

Cracking that allows for the movement of the fastening systems, increasing in track gauge (e.g. severe rail seat or longitudinal cracking);

Cracking that allows for excessive gauge widening due to bending deformation (e.g. severe center or longitudinal cracking);

Chemical degradation (e.g. alkali silica reactivity (ASR)).

Therefore, it seems that most failures of concrete sleepers are not related to their functions of supporting the rails or transmitting the loads to the ballast, but with its role of restraining track gauge. However, to successfully restrain track gauge, effective rail fastening systems are also required. Even though fastening systems are not the focus of this work, it is important to highlight that defective conditions fastening systems rarely require the removal of sleepers. An exception to this statement are worn or broken fastening system parts that are cast in the concrete sleeper. For example, a sleeper with worn shoulders may no longer be able to restrain gauge, which could lead to the replacement of the complete sleeper given most shoulder designs cannot be easily replaced or repaired.

1.2. Background on gauge widening in railroad track

Gauge widening is typically caused by rail wear, rail roll, worn fastening systems, rail cant deficiency, or broken or bent sleepers, and it contributes to wheel-drop derailments, especially in the presence of worn wheels [11]. For a wheel-drop derailment to occur, the track gauge must be greater than some gauge equivalent dimension of the wheelset. Therefore, some basic wheelset dimensions need to be understood to determine what this gauge equivalent dimension is. Fig. 1 shows the standard wheel dimensions as defined by the Association of American Railroads (AAR) [12]. The two most relevant measurements for this analysis are the flange thickness and the rim width, which are respectively called “B” and “L” in this figure. The distance between two wheels on the same axle, measured at the back of the wheel flanges, is commonly referred as “back-to-back” dimension and will be abbreviated as “BB” in this study.

Therefore, a wheel-drop derailment could happen in less severe conditions where the track gauge is greater than the sum of the thickness of one wheel, the back-to-back distance, and the flange thickness of the other wheel (L + BB + B dimension), as shown in