



Effect of track conditions on the flexural performance of concrete sleepers on heavy-haul freight railroads

Z. Gao, M. S. Dersch, Y. Qian, & J. R. Edwards
University of Illinois at Urbana-Champaign, Urbana, IL, USA

ABSTRACT: Concrete sleepers have been widely used throughout the world as an alternative for timber sleepers. In North America, heavy-haul railroads have increased their use of concrete sleepers in recent years for a variety of factors. According to an international survey conducted by researchers at the University of Illinois at Urbana-Champaign (UIUC), railroad industry representatives consider center cracking to be one of the most common concrete sleeper failure mechanisms. Having a better understanding of sleepers' flexural behaviour can potentially reduce the occurrences of center cracking by ensuring both designs and maintenance practices are adequate for the field conditions. To measure the bending moments experienced in North American heavy-haul freight service, field experiments were conducted at three Class I railroad sites in North America under different track conditions. Concrete surface strain gauges were installed on concrete sleepers at each location to record bending strains experienced by the sleepers under the passage of trains. These strains were converted into moments using calibration factors determined either by calculations based on the sleepers' cross-sectional and material properties or by laboratory experimentation. This paper compares the measured moments from three test sites to analyse the effect of track conditions on the flexural performance of concrete sleepers.

1 INTRODUCTION

Throughout the world, the majority of railroad track infrastructure is supported by ballast. A ballasted track system typically consists of rail, fastening systems, sleepers, ballast, sub-ballast, and subgrade. The most commonly used material for sleepers in the United States is timber, which is used for approximately 90-95% of the sleepers in revenue service (Anonymous 2008). Concrete is the second most common material for sleepers, making up most of the remaining 5-10%. Typically, concrete sleepers are used in the most demanding service conditions (e.g. high curvature, steep grades, heavy tonnage, high speed passenger traffic, etc.).

The primary purpose of the sleeper in the overall track infrastructure system is to maintain track geometry (e.g. gauge, cross level, etc.) and to transfer applied wheel loads to the track substructure (Hay 1982). When a concrete sleeper supported on ballast is loaded vertically, the load is transferred from the wheel to the rail, fastening system, sleeper, ballast, sub-ballast, and subgrade, sequentially. The ballast support conditions play a critical role in the type and severity of bending that the sleeper will experience under loading from a passing train (Wolf et al. 2014). The ballast support is affected by a vari-

ety of factors that include loading during train operations, maintenance activities (i.e. tamping), fouling (i.e. intrusion of fine particles), and voids or gaps between the sleeper and ballast (Kaewunruen & Remennikov 2007).

Railroad operators, concrete sleeper manufacturers, and researchers from around the world participated in a survey and rated sleeper cracking from centre binding as the third most critical problem facing concrete sleepers (Van Dyk 2013). North American respondents considered centre cracking to be slightly less critical than their international counterparts, ranking it as the fifth most critical issue associated with concrete sleepers. However, North American respondents ranked cracking from dynamic loads as the third most critical issue, one place ahead of international respondents. This survey shows that sleeper cracking is a challenge experienced both domestically and internationally and thus an important issue and for research.

2 FIELD EXPERIMENTATION PLAN

To measure the bending moments and support conditions experienced in North American heavy-haul freight service, field experimentation was conducted

at three different locations of Class I heavy-haul freight railroads in the United States. The first field site was located on a tangent track in Ogallala, Nebraska (NE), on the Union Pacific Railroad's South Morrill Subdivision. The annual tonnage recorded in 2014 on this line was approximately 200 million gross tonnes (MGT). The second field site was located on a curved track in Norden, California (CA), on the Union Pacific Railroad's Roseville Subdivision. The location chosen consists of a curve with a $5^{\circ}52'$ curvature on a 1.8% grade. Annual tonnage on this line was approximately 14 MGT at the time of installation (Holder et al. 2016). The final site was chosen on a curved track near Crawford, NE on the BNSF Railway's Butte Subdivision. This line is considered as one of the most demanding railroad lines in the United States due to its high curvature and high tonnage (Holder et al. 2016). The annual tonnage recorded in 2015 on this line was nearly 161 MGT. The field testing site consists of a 8° curvature on a 1.31% grade. Figure 1 shows the locations of the three field sites.



Figure 1. Field experimentation site locations

Researchers in the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (UIUC) have selected surface-mounted strain gauges to measure the bending strains experienced by concrete sleepers under revenue service heavy-haul freight train loads. Since centre cracking is considered as one of the most important issues with concrete sleepers, concrete surface strain gauges were installed at the centre of the sleepers within the field testing sites (Fig. 2a). For the Ogallala, NE and Norden, CA sites, the instrumentation was divided into two zones, with each zone consisted of five adjacent instrumented sleepers. For the Crawford, NE site, strain gauges were only installed on a total of five adjacent sleepers. Calibration factors, determined either by calculations based on the sleepers' cross-sectional and material properties or by laboratory experimentation, were applied to the recorded bending strains which converted the strains into bending moments. Loading configurations used for calibration tests were adapted from tests specified in Chapter 30, Section

4.9 in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering (MRE) (AREMA 2016).

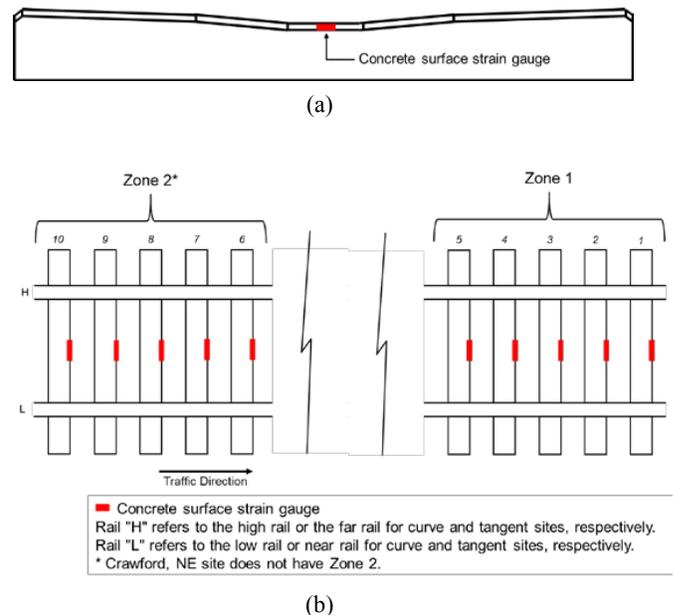


Figure 2. (a) Illustration of an instrumented sleeper (profile view), (b) experimentation layout for the Ogallala, NE and Norden, CA sites (Zone 1 was used at the Crawford, NE site)

3 PRILIMINARY RESULTS

The installation in Ogallala, NE occurred on March 27th, 2015. Since, 10 visits to the site were made with approximately 6 to 8 weeks between each visit. In total, 78 unit coal trains consisting of 43,284 loaded axles were collected. The installation in Norden, NE occurred on September 23rd, 2015 and data from 20 trains and 6,394 axles were collected between September 23rd and September 26th. Intermodal trains, passenger trains, mixed manifest trains, and empty trains were among the recorded data. The installation in Crawford, NE occurred on March 22nd, 2016, and similar to the Norden, NE site, only one site visit was made in which time a total of 11 train passes and 4,584 axles were collected. Among those train passes, there were 5 unit coal freight trains, 3 mixed manifest trains, and 3 empty trains. Overall, the instrumentation of all three sites were proven to be robust, as no surface strain gauge was damaged over the data collection period.

3.1 Variations among three sites

Measured bending moments were plotted versus their percentile exceeding (Figs. 3-5). For a given curve shown in these figures, each point represents the percentage of loaded axles that would cause a bending moment greater than or equal to a certain magnitude.

Figure 3 shows the bending moment distributions for different types of trains that were collected at the Norden, CA site. Intermodal trains and manifest trains shared comparable distributions, as at any magnitude of percent exceeding, the bending moment difference between those two train types was less than 1.0 kNm (8.9 kip-in). Since the majority of train axles passing through the site during the data collection period were from the manifest trains, the bending moment distribution of all the collected train passes was similar to that of the manifest trains. Overall, the measured bending moments never exceeded 22.7 kNm (201.0 kip-in), the AREMA recommended design limit for the centre of a concrete sleeper, which is shown as the vertical dash line on the graph.

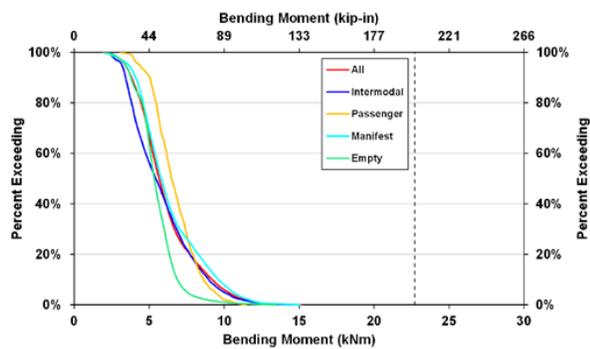


Figure 3. Bending moment variation with train type at the Norden, CA site

Bending moment distributions for all train types at the Crawford, NE site can be seen in Figure 4. Due to the limited amount of trains recorded at this site, the curves shown in Figure 4 are not as smooth as the curves shown in Figure 3. Among all train types, unit coal trains had the highest bending moment at any percent exceeding level, given that the axle load of a coal unit freight car was greater than that of a manifest or an empty car. In total, 4.5% of the measured bending moments exceeded the AREMA recommended design limit.

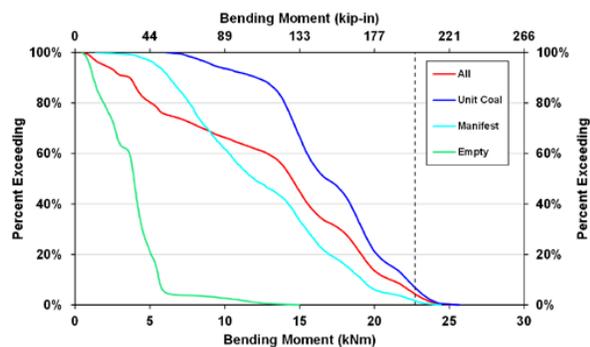


Figure 4. Bending moment variation with train type at the Crawford, NE site

Figure 5 shows the distributions of all the measured bending moments from all three sites. Bending moments experienced by sleepers at the Norden, CA site was the lowest among all three sites, indicating that the substructure (i.e. ballast, subballast, subgrade) of this site led to improved contact at the sleeper-ballast interface and thus lowered the bending moments. However, this indication might not be accurate considering the fact that the sleeper's bending moment is affected not only by the support condition, but also by the axle loads imposed onto the sleeper. Therefore, the low magnitude of bending moments recorded at the Norden, CA site could also be contributed by the low axle loads of the manifest trains that constituted the majority of trains passing through the site. In addition, the train speed at the Norden, CA site was considerably lower than those recorded at the other two sites; a few trains even stopped on top of the instrumented sleepers (Holder et al. 2016). This lower speed could potentially reduce the occurrence of high impact loads due to wheel defects, which would ultimately lead to sleepers experiencing lower bending moments.

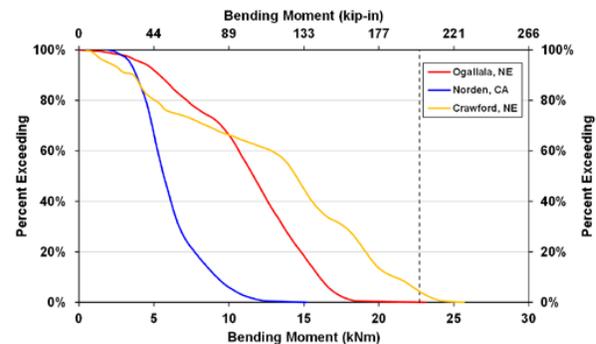


Figure 5. Bending moment variation with field experimentation site location

The bending moments measured at the Ogallala, NE site were lower than those measured at the Crawford, NE site between 0 and 65 percent exceeding. This is interesting to note given all trains recorded at the Ogallala, NE site and the majority of trains recorded at the Crawford, NE site were unit coal trains, with a consistent nominal axle load of 320 kN (72 kips). The bending moment difference between these two sites under the same train type might suggest that the Ogallala, NE site had a more evenly distributed ballast at the sleeper-ballast interface. One possible explanation for the difference in the bending moments is that the high curvature at the Crawford, NE site could likely cause ballast underneath the sleepers to migrate towards the low rail. This redistribution of ballast would create an asymmetric centre-binding support condition for the sleepers, where the ballast was concentrated underneath the centre portion of the sleepers as well as the



intermediate portion between the sleeper centre and the low rail.

Table 1 summarizes the key magnitudes of measured sleeper bending moments of all train types from all three sites. The maximum bending moment recorded from the unit coal trains at the Crawford, NE site was 2.6 kNm (23.0 kip-in) greater than the maximum recorded moment at the Ogallala, NE site, and the average bending moment was 5.7 kNm (50.4 kip-in) greater. Whether the high curvature characteristic of a railroad track could lead to these amounts of change in sleeper centre bending moment needs to be further investigated.

Table 1. Distribution of measured sleeper bending moments

Experimentation Site	Train Type	Sleeper Bending Moment kNm (kip-in)		
		Min	Mean	Max
Ogallala, NE	Unit Coal	0.5 (4.4)	11.2 (99.1)	23.1 (204.5)
Norden, CA	Intermodal	2.0 (17.7)	5.1 (45.1)	12.6 (111.5)
	Passenger	2.6 (23.0)	5.8 (51.3)	10.0 (88.5)
	Manifest	1.7 (15.0)	5.5 (48.7)	13.1 (115.9)
	Empty	1.7 (15.0)	4.7 (41.6)	11.7 (103.6)
Crawford, NE	Unit Coal	6.1 (54.0)	16.9 (149.6)	25.7 (227.5)
	Manifest	1.4 (12.4)	12.4 (109.7)	24.4 (216.0)
	Empty	0.5 (4.4)	3.8 (33.6)	15.0 (132.8)

3.2 Variations with each site

It is hypothesized that the varying ballast support conditions lead to the primary source of difference in the bending strains between adjacent sleepers. Therefore, bending moments among adjacent sleepers could be used to understand the variations in support conditions along the longitudinal direction of a railroad line. To visualize the distribution of measured bending moments of each sleeper within each site, box-and-whisker plots were developed (Figs. 6-8). The top line of the box represents the 75th percentile bending moment (Q3). The middle line is the median bending moment. The bottom line of the box represents the 25th percentile bending moment (Q1). The interquartile range (IQR), found as Q3 minus Q1, can provide an estimate of the variability of the data set – the greater the IQR, the higher the variability. The upper whisker shown on the graphs is the limit for upper outliers, which are defined as data points greater than Q3 plus 1.5 times

the IQR (or $(Q3 + 1.5 \cdot IQR)$) (Ott & Longnecker 2001).

Figure 6 demonstrates the bending moment distribution for each of the ten instrumented sleepers at the Norden, CA site. In general, each sleeper exhibited a different distribution, but the differences among them were insignificant. On average, the mean bending moment difference between adjacent sleepers was 0.6 kNm (5.3 kip-in), while the maximum bending moment difference was 1.1 kNm (9.7 kip-in). The consistent moment distributions for all instrumented sleepers indicate that the ballast support condition along the longitudinal direction of the Norden, CA site was consistent as well. This uniform ballast distribution would allow the axle loads to be transmitted down into the substructure evenly along the longitudinal direction.

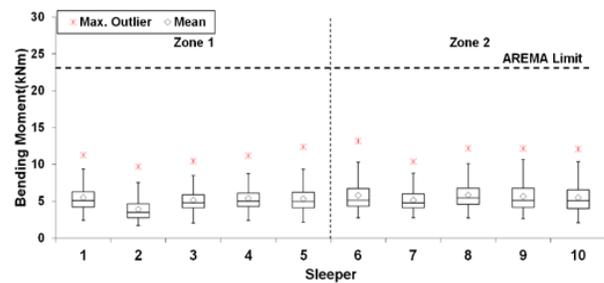


Figure 6. Box-and-whisker plot of measured bending moments at the Norden, CA site

Figure 7 illustrates the bending moment distribution for each instrumented sleeper at the Crawford, NE site. Unlike the Norden, CA site, the IQRs of bending moments at this site were more widely spread out, possibly due to the fact that there were fewer trains recorded at the site and 27% of the collected data were from empty trains. As mentioned in the previous sub-section, 4.5% of the total measured bending moments exceeded the AREMA limit, but based on Figure 7, it could be confirmed that all those exceedances occurred on a single sleeper (Sleeper #5), meaning that this sleeper was experiencing greater support at the centre. If no proper maintenance activity (e.g. tamping) was conducted around this sleeper, centre cracking might happen to the sleeper which would eventually endanger the railroad safe operations.

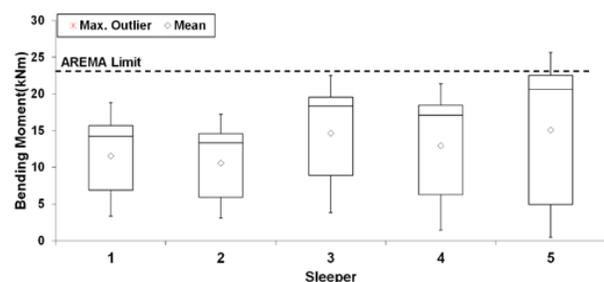


Figure 7. Box-and-whisker plot of measured bending moments at the Crawford, NE site

The support condition variations among instrumented sleepers at the Ogallala, NE site can be seen in Figure 8. The variability at this site was more significant than the other two sites. For instance, although Sleeper #9 and #10 were adjacent to one another, the centre support varied to the extent that Sleeper #9 experienced a bending moment that was nearly 6 kNm (53 kip-in) higher than Sleeper #10. The magnitude of the variation was over 26% of the AREMA recommended design capacity for the centre of concrete sleepers. It should be noted that Sleeper #4's bending moment outliers exceeded the AREMA recommended design limit value 3 times over the data collection period. That is, of the 43,284 loaded axles that passed over the sleeper, only 3 axles induced centre bending moments over the AREMA recommendation of 22.7 kNm (201.0 kip-in). The probability of exceedance was calculated to be 0.007% for Sleeper #4 and 0.0007% for all ten instrumented sleepers. Both of the probabilities were considered to be insignificant, thus indicating that the bending of the sleepers at this location would only cause centre moments to exceed the recommended values under very rare circumstances or if the support conditions were to vary more.

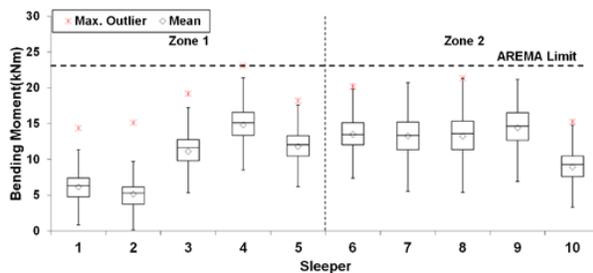


Figure 8. Box-and-whisker plot of measured bending moments at the Ogallala, NE site

4 CONCLUSIONS

Overall, bending strains, and subsequent moments, were successfully measured at three Class I heavy-haul freight railroad lines in North America. The effectiveness of surface-mounted concrete strain gauges in measuring sleeper bending behaviour was demonstrated. From this work, several conclusions were drawn relating to the flexural behaviour as well as support conditions of concrete sleepers at three field experimentation sites under revenue heavy-haul freight services:

- Measured center bending moments were highly variable among all three sites.
- Traffic differences at each site could partially account for the variations in bending moments. For the Norden, CA site, the majority of the recorded trains were manifest trains. The smaller magnitude of bending moments meas-

ured from this site could be caused by the axle loads of manifest trains being lower than those experienced from the other two sites.

- The bending moment variations among the three sites could also be a result of track conditions. The high tonnage and high curvature characteristics of the Crawford, NE site probably led to 4.5% of the measured bending moments exceeding the AREMA recommended design limit, posing a potential for increased deterioration of the concrete sleepers and the track substructure.
- Variations of support conditions existed along the longitudinal direction at each site. The Ogallala, NE site experienced significant variation in the bending moments along the longitudinal direction of track, in that the variation could be as much as 6 kNm (53 kip-in), or 26% of the AREMA recommended design capacity, between adjacent sleepers.

5 ACKNOWLEDGMENTS

Portions of this research effort were funded by U.S. National University Rail Center (NURail Center). Portions of the field experimentation were funded by Vossloh Fastening Systems. The authors would like to acknowledge the following industry partners: Union Pacific Railroad; BNSF Railway; National Railway Passenger Corporation (Amtrak); Progress Rail Services Corporation, a Caterpillar company; GIC; Hanson Professional Services, Inc.; CXT Concrete Ties, Inc., and LB Foster Company. The authors would also like to formally thank Steve Mattson of voestalpine Nortrak, Prof. Bill Spencer and Dr. Sihang Wei of UIUC, Prof. Dan Kuchma of Tufts University, and Prof. Fernando Moreu of the University of New Mexico for their knowledge in instrumentation, and Matt Csenge, Phanuwat Kaewpanya, and Álamo DiTarso for their assistance in the collection and processing of this data. The authors are also grateful for the advice and assistance provided by students and staff from RailTEC. J. Riley Edwards has been supported in part by grants to the UIUC Railroad Engineering Program from CN and Hanson Professional Services.

REFERENCES

- American Railway Engineering and Maintenance-of-Way Association (AREMA). 2014. Manual for Railway Engineering. Lancaster, MD.
- Anonymous. 2008. M/W Budgets to Climb in 2008. Railway Track & Structures 104(1): 18–25.
- Hay, W.W. 1982. Railroad Engineering, 2nd ed., John Wiley and Sons, New York, NY.
- Holder, D.E., X. Lin, M.V. Csenge, Y. Qian, M.S. Dersch, and J.R. Edwards. 2016. Lateral Load Performance of SkI-Style



- Fastening System: Laboratory and Field Results. *Presentation at 2016 International Crosstie and Fastening System Symposium*, Urbana, IL, USA.
- Holder, D.E., Y. Qian, M.V. Csenge, J.R. Edwards, M.S. Dersch, and B.J. Van Dyk. 2016. Comparison of Lateral Load Performance of Concrete Crosstie Heavy Haul Fastening Systems. *Presentation at 2016 AREMA Annual Conference and Exposition*, Orlando, FL, USA.
- Kaewunruen, S. and A.M. Remennikov. 2007. Investigation of free vibrations of voided concrete sleepers in railway track system. *Journal of Rail and Rapid Transit* 221: 495-507.
- Ott, R.L. and M. Longnecker. 2001. *An Introduction to Statistical Methods and Data Analysis*, 5th ed., Duxbury Press, Pacific Grove, CA.
- Van Dyk, B. J. 2013. Characterization of Loading Environment for Shared-Use Railway Superstructure in North America. M.S. Thesis. University of Illinois at Urbana-Champaign, Urbana, IL, USA.
- Wolf, H.E., S. Mattson, J.R. Edwards, M.S. Dersch, and C.P.L. Barkan. 2014. Flexural Analysis of Prestressed Concrete Monoblock Crossties: Comparison of Current Methodologies and Sensitivity to Support Conditions. In: *Proceedings of the Transportation Research Board 94th Annual Meeting*. Washington, DC, USA.