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Proposed Test Method for Center Bound Risk Assessment: A Case Study

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The center bound condition in railway sleepers results from loss of support at the ends and concentration of reactions in the central region, altering stress distribution and generating a characteristic cracking pattern, with direct impact on structural safety margins. A case in Brazil, associated with lateral ballast insufficiency, motivated the need for a methodology capable of reproducing, in a controlled and traceable manner, the support uncertainty observed in the track and enabling comparison of damage signatures under different scenarios. This study proposes an experimental methodology to evaluate the sensitivity of damage to variations in the effective central support length. A dedicated test setup was developed to reproduce centralized support and to allow controlled variation of support width in four configurations: 5 cm, 20 cm and 60 cm. Nine prestressed concrete sleepers were tested, with three specimens per configuration, up to failure. At each 15 kN load increment, the cracking pattern was mapped and the opening of the first crack was measured, enabling tracking of damage progression and establishing experimental indicators comparable across support conditions. The results show variations in first-crack load, crack pattern evolution, and ultimate load as a function of effective support length. The developed setup and associated procedure establish an experimental basis linking support condition to damage signature, enabling inference of the presence and progression of center bound in the investigated case and characterization of structural vulnerability to support variability. As an outcome, a methodological tool for risk assessment was delivered to the railway operator, consisting of a reproducible test protocol, damage indicators, and a comparative reference database to support inspection, diagnosis, and maintenance decisions when the occurrence of center bound is uncertain.

Keywords: Center bound, Prestressed concrete sleepers, Experimental test setup.

1. Introduction

Concrete sleepers play a fundamental role in railway infrastructure by maintaining track gauge and transferring the forces and vibrations generated by train passages to the ballast layer. This sector has shown significant growth in recent years, with global market projections indicating that its value may reach approximately 21.33 billion dollars by 2034 (FACT, 2024). Beyond their structural importance within the track system, the performance of sleepers is strongly influenced by the support conditions provided by the ballast, which govern the distribution of stresses along the element.

Although ballast ideally provides relatively uniform support, field conditions frequently involve localized voids, uneven compaction, or loss of contact between the sleeper and the ballast. These discontinuities alter the load transfer mechanism and may lead to stress concentrations either at the sleeper ends or in its central region. Li *et al*. (2022) highlighted the variability of sleeper–ballast contact conditions and demonstrated that localized loss of support can significantly modify the stress distribution along the sleeper.

The structural implications of these support variations have been investigated in previous studies. Bastos (2016), for instance, evaluated six different ballast support configurations beneath concrete sleepers in order to quantify their influence on sleeper deflection. The results showed that bending moments in the central region of the sleeper are more sensitive to variations in ballast support than those occurring under the rail seats. This observation is particularly relevant because the central section of the sleeper is susceptible to the development of transverse cracks on its upper surface due to high negative bending moments (You *et al*., 2022).

The occurrence of these cracks is commonly associated with inadequate ballast support beneath sleepers (Chen *et al*., 2014). When combined with track geometric irregularities, such conditions may generate significant dynamic loads that further intensify stress concentrations. In railway engineering practice, this phenomenon is commonly referred to as center bound (Clark *et al*., 2017). Ballast degradation resulting from insufficient compaction, void formation, or inadequate maintenance may aggravate this condition by increasing the concentration of reactions in the central region of the sleeper and consequently amplifying bending moments (Montalbán-Domingo *et al*.,2014).

In the Brazilian context, a recent case investigated by the research group at the Federal University of Uberlandia highlighted the uncertainty associated with identifying this phenomenon in the field. Because the analyzed sleepers were prestressed concrete elements, cracks generated during center bound conditions tended to close after load relief due to the prestressing force, causing the sleeper to visually appear intact even after experiencing a potentially critical stress state. This characteristic introduces uncertainty in field diagnosis and reinforces the need for experimental methodologies capable of reproducing the support conditions observed in track environments in a controlled and traceable manner.

Following reports of this phenomenon in a railway line under construction, experimental investigations became necessary in order to reproduce this condition and better understand the structural behavior of sleepers subjected to it. To address this need, a dedicated test setup was developed with an effective central support base and inclined support surfaces designed to simulate the loss of ballast support at the sleeper ends. Within this context, the objective of this study is to present an experimental testing technique capable of reproducing center bound conditions and to report the experimental response of concrete sleepers tested under three different effective support widths.

2. Mechanical basis of the center-bound condition

The structural response of concrete sleepers is influenced by the distribution of ballast reactions along their length. Under ideal conditions, the ballast provides relatively uniform support, allowing loads applied at the rail seats to be transferred to the ballast bed. In this configuration, the bending moment distribution typically presents positive moments near the rail seats and smaller negative moments in the central region of the sleeper (Kaewunruen and Remennikov, 2009).

However, field conditions rarely reproduce this scenario. Localized ballast degradation, insufficient compaction, and void formation may alter the contact conditions between the sleeper and the ballast layer. When support near the sleeper ends is reduced or lost, reactions may become concentrated in the central region of the element. This configuration, commonly referred to as center bound, modifies the internal force distribution and increases negative bending moments at the sleeper center (Clark *et al*., 2017). The increase in negative bending moments generates tensile stresses at the upper fiber of the central section, which may lead to the development of transverse cracks on the top surface of the sleeper. Such cracking patterns have been frequently associated with inadequate ballast support conditions and are considered a characteristic indicator of central reaction concentration (You *et al*., 2022). The mechanical implications of this support configuration are therefore directly related to the redistribution of reactions along the sleeper and the resulting changes in the bending moment diagram.

Despite the relevance of this phenomenon in railway track performance, conventional laboratory procedures used for sleeper qualification do not explicitly consider center bound conditions. Standard testing methods typically evaluate sleepers under simplified flexural configurations in which the element is supported at two points and loaded at the rail seats, reproducing bending behaviour associated with conventional ballast support conditions. While these procedures are suitable for assessing structural capacity and compliance with design requirements, they do not reproduce the stress redistribution associated with localized loss of ballast support.

As a consequence, the structural response of sleepers subjected to central support concentration remains insufficiently represented in standardized testing procedures. In order to investigate the influence of this support condition on sleeper behaviour and cracking development, experimental configurations capable of controlling the effective width of the central support are required. Such an approach enables the systematic evaluation of the structural response under center bound scenarios and the identification of damage signatures associated with different support configurations.

Within this context, the experimental program presented in this study was designed to reproduce centralized support conditions with controlled variations in effective support width, allowing the assessment of cracking development and structural response of prestressed concrete sleepers subjected to center bound conditions.

3. Experimental Program

3.1. *Specimens*

The experimental program was conducted using prestressed concrete sleepers designed for broad-gauge railway lines. The sleepers had an overall length of 2.80 m and a trapezoidal cross-section with approximate dimensions of 25 cm × 30 cm as Fig.1. The prestressed concrete sleepers belonging to the same production family and design series, in order to minimize variability associated with geometry, materials, and prestressing configuration.

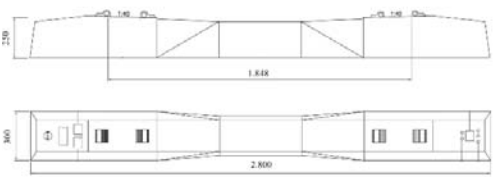

Fig. 1. Geometry of the sleepers

Before testing, the specimens were visually inspected to confirm the absence of pre-existing visible defects that could interfere with the interpretation of cracking initiation and propagation. The sleepers were grouped according to the selected support configurations, and each group was tested under the same loading and monitoring procedure.

3.2. *Test setup and support configuration*

The tests were carried out at the Structural Laboratory of the School of Civil Engineering of the Federal University of Uberlandia. A dedicated steel box-type support device was developed to reproduce the center-bound condition under controlled laboratory conditions. The support structure was built with a 3% downward slope from the center toward both ends, so that the sleeper remained effectively supported in the central region while support near the ends was relieved as Fig.2.

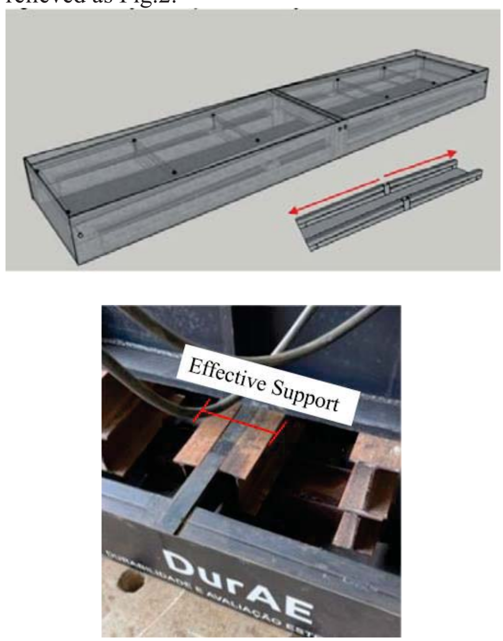

Fig.2. Steel box-type support device

The actuator was fixed to a rigid steel beam designed to distribute the applied load to the rail-seat regions. Loading was applied monotonically in increments of 15 kN until failure. The use of discrete load steps enabled the progressive evaluation of structural response and damage development throughout the test. At each load level, the test was temporarily interrupted to inspect the sleeper surface, mark newly formed cracks, and measure crack opening. Crack development was monitored throughout the entire test. Whenever a crack appeared, its position was marked directly on the sleeper surface and the corresponding load level was recorded. At each load increment, crack opening was measured using a crack width gauge, allowing the progression of the first visible crack.

The loading system was instrumented with three load cells, including two positioned at the rail-seat loading points and one located at the central loading point of the rigid steel beam used to distribute the applied force. Five linear variable differential transformers (LVDTs) were used to monitor sleeper displacements. The instrumentation arrangement included one vertical LVDT at the sleeper center, two vertical LVDTs positioned near the sleeper ends, and two horizontal LVDTs also placed near the ends (Fig 3a and Fig 3b.

Three effective central support widths were considered in the present study, namely 5 cm, 20 cm, and 60 cm. These configurations were selected to represent different levels of support concentration and to evaluate their influence on cracking initiation, crack propagation, displacement response, and ultimate load.

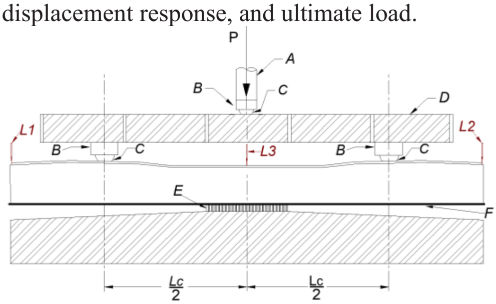

Fig. 3a. Test configuration

A – Hydraulic actuator for the application of the specified load
B – Load cell with measurement capacity compatible with the specified load
C – Spherical hinge
D – Load transfer beam designed to withstand the specified load
E – Effective sleeper support during testing
F – Rubber pad
L1, L2, L3 – Linear Variable Differential Transformer (LVDT) displacement transducers

Fig. 3b. Assembled experimental setup

4. Results and discussion

Table 1 shows the ultimate load and the maximum displacement for each sleeper tested and Fig.4. presents the load–displacement curves obtained for the sleepers tested under the three investigated effective central support widths (5 cm, 20 cm, and 60 cm).

Table 1. Ultimate Load and Maximum displacement for each sleeper tested.

Sample	Ultimate Load (kN)	Maximum displacement (mm)
5 cm -1	182.13	17.29
5 cm -2	181.21	14.72
5 cm -3	183.23	15.92
20 cm -1	173.88	24.28
20 cm -2	154.44	27.71
20 cm -3	199.49	26.62
60 cm -1	210.79	30.62
60 cm -2	182.79	28.68
60 cm -3	203.53	30.21

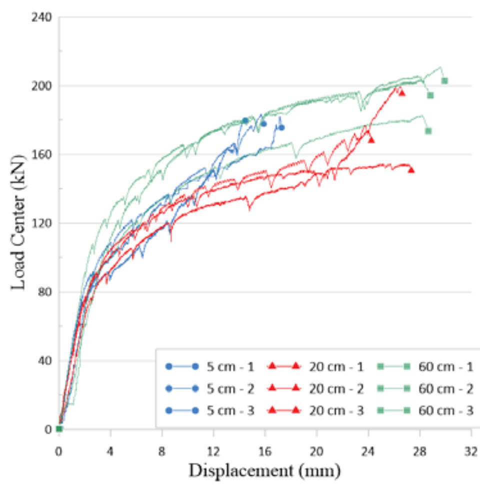

Fig. 4. Load–displacement response of prestressed concrete sleepers tested under different effective central support widths (5 cm, 20 cm, and 60 cm).

For all configurations, the initial portion of the curves shows a steep load increase for relatively small displacements, indicating a high initial stiffness associated with the prestressed concrete section and the elastic behaviour of the system. As loading progresses, the slope of the curves gradually decreases due to the onset of cracking and the progressive redistribution of internal stresses within the sleeper.

Differences in structural response are observed among the support configurations. The sleepers tested with the smallest effective support width (5 cm) exhibit lower load capacity and lower displacement before rupture. This behaviour reflects a higher concentration of reactions in the central region of the sleeper, which increases negative bending moments and accelerates cracking and ruptura

In contrast, sleepers tested with the largest support width (60 cm) show higher load levels and greater structural stiffness. In these specimens, loads exceeding 200 kN were reached and a greater displacement development occurred, suggesting that the larger support area promotes a more distributed transfer of reactions beneath the sleeper.

The intermediate configuration (20 cm) shows behaviour between these two conditions, with moderate stiffness and load capacity. Although some variability exists among specimens within the same group, the overall response trends remain consistent.

Fig.5. illustrates the crack patterns observed in sleepers tested under the three investigated effective central support widths: (a) 5 cm, (b) 20 cm, and (c) 60 cm. The numbers shown along each crack correspond to the load level (kN) at which the crack was first observed during the loading process.

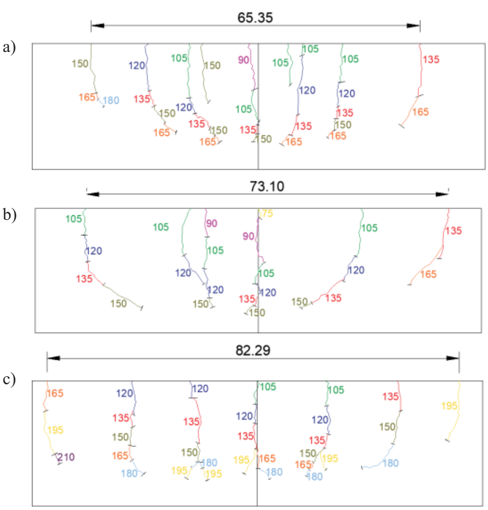

Fig. 5. Crack patterns observed in sleepers tested under different effective central support widths: (a) 5 cm, (b) 20 cm, and (c) 60 cm.*

For the configuration with the smallest support width (5 cm), cracks were predominantly concentrated near the central region of the sleeper with a crack map extending approximately 65.35 cm.

For the intermediate support width (20 cm), the crack pattern becomes less concentrated in the central region and shows a slightly wider distribution along the sleeper length (73.10 cm).

In the case of the largest support width (60 cm), the crack pattern exhibits a more distributed configuration along the sleeper length with 82.29 cm. Cracks appear more widely spaced, suggesting that the increase in effective support area reduces the severity of stress concentration in the central region.

A comparison of the three configurations demonstrates a relationship between the effective central support width and the resulting crack pattern. Narrow support conditions promote a higher concentration of cracks in the central region, while wider support conditions lead more distributed damage pattern.

The proposed test configuration allows the reproduction of crack signatures associated with center-bound conditions under controlled laboratory conditions, providing a useful experimental reference for interpreting sleeper damage observed in railway tracks.

An additional aspect relevant to field diagnosis is the tendency of cracks in prestressed concrete sleepers to partially close after load removal due to the prestressing force, shows in Fig 6a and 6b.

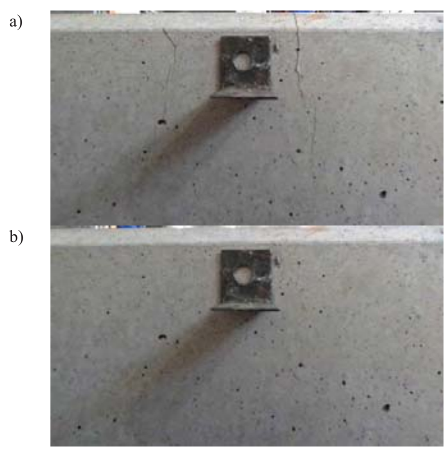

Fig. 6. Crack opening under load (a) and partial closure after unloading (b) in a prestressed concrete sleeper subjected to center-bound simulation

This behaviour may visually mask prior damage and make routine inspection less reliable when used as the sole assessment approach. Within this context, the proposed experimental methodology contributes by establishing a controlled relationship between support condition, global structural response, and crack signature, thereby providing a reference framework to support diagnosis when the occurrence of center bound is uncertain.

5. Conclusions

- The proposed setup was able to reproduce center-bound support conditions in a controlled and repeatable manner.
- Reducing the effective central support width intensified damage in the middle region of the sleeper, leading to earlier cracking, greater displacement development, and a more concentrated crack pattern.
- The experimental results established comparative damage signatures associated with different support widths, providing a useful basis for the diagnosis of uncertain support conditions in track.
- The methodology provided experimental evidence supporting the identification of the cracking phenomenon observed in the Brazilian railway case as a center-bound condition, including situations in which crack closure after unloading may have visually masked prior damage.
- Conventional sleeper qualification tests do not explicitly reproduce this type of support condition and therefore do not directly address damage associated with track support defects or ballast maintenance deficiencies.

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