Comparison of the Structural Performance of Ballasted and Non-Ballasted Pavement of the Railway with the Help of Beam Models on Elastic Bed and Finite Element Model

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Abstract:
Today, many countries are opting for ballast less paving of railways using concrete line slabs as an alternative. Ballast paving is particularly prevalent in high-speed lines, urban railways, as well as bridges and tunnels designed for high loads and speeds. The priority lies in ensuring that these lines are paved with proper structural performance, especially considering the mechanics of the line and the choice between ballast pavement and line slabs. This article delves into the structural modeling and analysis process of ballast and slabs for railway lines. Models for both ballast and slab lines under passage have been developed. The study investigates the train wheel load and the impact of bed conditions. Theoretical solutions, including the beam model on an elastic bed for ballast lines and the two-beam model for line slabs, have been presented. Multiple finite element models were explored using ABAQUS software, confirming the accuracy of the theoretical results with acceptable precision. This work establishes a suitable model for calculating the effects of vertical force on the line pavement structure and provides applications for comparing design performance between ballast and slab lines. The results highlight the optimal performance of the modeling and the superiority of the line slabs.

Keywords: Ballast paving, ballast less pavement, structural function, finite element, ABAQUS.

Introduction
Although several centuries have passed since the birth of the railway, the anticipated growth in this industry has not materialized. Numerous factors, including world wars, the evolution of the aviation industry, and various political influences, have played pivotal roles in shaping the industry’s progress. These factors have significantly impacted its scientific and theoretical development (Guan et al., 2007; Törnquist, 2007). The absence of regulations and standardized guidelines for designing railway elements and components, coupled with a simplistic and non-specialized perspective in certain scientific fields, has hindered the advancement of this industry. The lack of synchronized progress with other sciences has resulted in the neglect of analysis and design for these structures. Considering the priorities of the country’s rail transport vision, the development of customer-oriented transportation through scheduled cargo trains, combined transportation, and high-speed passenger trains
stands out as a crucial focus (Button et al., 2004; Crozet, 2004; Donato et al., 2004). Achieving this vision necessitates the establishment of a solid foundation for high-performance structured pavements. Without creating a robust framework to support the use of high-performance structured pavements, the objectives of the country’s rail transport vision will remain unattainable.

Introduction of Railway Lines

The primary function of a railway line is to establish a durable and level surface for the smooth passage of trains and rail fleets. It has the task of distributing and diminishing the substantial stresses generated by the wheel's passage to a manageable level for various components of the road surface, including the bed. Therefore, the railway line and pavement are evaluated in terms of structural adequacy and performance. The structure of railway lines can be generally classified into two categories: ballasted and non-ballasted. The ballasted pavement of the railway comprises a set of rails, sleepers, and their connecting devices, all placed on the top layer. To enhance the structure’s performance, it is constructed on a layer of carefully shaped ballast and a compact substrate. This configuration facilitates the transfer and distribution of the load, operating on the principle of stress dispersion layer by layer (Ishikawa et al., 2014; Koike et al., 2014; Woodward et al., 2014).

Since the beginning of the 20th century, with the increase in operating speed and axle loads on railway lines, the Yalas T line ceased to meet the structural requirements of some lines. Consequently, there was a serious consideration to replace it with high-durability materials, and this plan gained momentum in the years following 1990. Despite the extensive advantages and competition in terms of life cycle costs, nowadays, overhead lines are not only used for high-speed lines but also for other rail systems, including Intercity and intracity systems, in various locations such as technical buildings, bridges, and tunnels (Chai et al., 2018; Kaewunruen et al., 2019). Line slabs, also known as ballast less pavements, are connected by rail binding, forming a continuous concrete slab placed under the fixed base on the prepared bed. Often, a continuous rail is welded within them. These structures are categorized into different types, including in-situ and prefabricated. In this research, various parameters of both ballasted and non-ballasted pavement structures are studied to compare their performance (Kistanov, 2017; X. Yang et al., 2019).

Comparison of the Structure of Ballasted and Non-Ballasted Railway Pavements

Creating a solid bed to withstand the heavy loads of the rail fleet is a necessity in railway lines. This not only supports the heavy loads but also fulfills other functions of the line, such as stabilizing width and geometrical specifications and controlling vibrations. In comparison with ballasted pavement, some structural advantages of lines without ballast are as follows:

- High resistance against incoming loads and more uniform distribution of stress.
- Controlling the change of shapes and making them uniform,
- Absence of upward pulling force on the line when the high-speed train passes.
- Better ability to bear the longitudinal and transverse forces of the line,
- Better lateral stability and reduced risk of buckling.
- Higher shear resistance of concrete slabs in lateral movement against lateral acceleration in screws compared to ballast bed.
- Increasing the life span of the line (weaknesses in the structure’s operating criteria, especially cracks and fatigue are less visible),
- Reducing plastic damage that changes the geometry of the line,
- Less construction depth, reducing the height and weight of the structure, and
- Reaching higher speeds and improving safety in walking and moving.

Construction, repair, and maintenance: Approximately 60 percent of maintenance activities are directly influenced by the use of
high-quality materials, highlighting the impact of these materials in the repair and maintenance processes. Research indicates that the cost and time required for repair and maintenance in ballast less lines are significantly lower than those in ballasted pavements. Technically and economically conducted studies in passenger lines support this conclusion (Serdelová & Vičan, 2015; Y. Yang, Wu, Wu, Jiang, et al., 2015; Y. Yang, Wu, Wu, Zhang, et al., 2015). The capital cost for laying is nearly three times that of a ballast bed. On the other hand, considering the costs over the operational period and the reduced need for maintenance, the difference in investment cost can be recouped in approximately 10 years. Proper distribution of load to minimize pressure on the bed is illustrated in Figure (1). The figure depicts the base and substrate in two types of pavements, with and without ballast. Following the principle of stress distribution for a constant axial load in both systems, the stress decreases through various pavement layers until reaching the tolerable limit for each layer, concluding at the substrate layer. A comparison of stress values in each layer allows us to discern the superior performance of the line slab.

Changes in the formed shapes can be compared using Table (1) for both binding and line slab configurations. The table provides valuable data for both types of ballast lines and line slabs.

<table>
<thead>
<tr>
<th></th>
<th>Changing the shape in the ballast line (mm)</th>
<th>Change of shape in paving the line slab (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fastening</td>
<td>0.05-0.35 mm</td>
<td>Fastening 0.8-1.5</td>
</tr>
<tr>
<td>Ballast</td>
<td>0.3-0.7 mm</td>
<td>Slab 0.05-0.2</td>
</tr>
</tbody>
</table>

It is evident that the change in the shape of the bindings in the slab lines is more pronounced than in the ballast lines. This emphasizes the necessity of designing specific bindings for this type of lines to minimize shape alterations (Galvín et al., 2010). To mitigate changes in the shape of the ballast lines and enhance rigidity in such cases, solutions have been implemented. Figure (2) illustrates the use of special sleepers as one such solution. Each of these methods has its own advantages and disadvantages, preventing their widespread use and restricting their application to specific lines (Alves Costa et al., 2012; Di Mino et al., 2012).

![Figure 1. Comparison of Stress Distribution in Ballast Lines and Line Slab (Budisa)](image)

(a)

![Figure 2. Use of Special Sleepers](image)

(b)
Providing and fixing the geometric parameters of the line in line slab configurations, along with the increase in operating speed, can be significant. Durability during the operational period: Examination of a sample of continuous armored lines, after handling a tonnage exceeding 750 million since their construction, indicates that these lines remained free of cracks throughout the service period (Guerrieri et al., 2012).

Materials and Methods

Material Selection

The innovative approach to analyzing and designing the slab structure of railway lines necessitates a comprehensive examination of the structure and various models as crucial tools in shaping the theory of analysis. In this research, theoretical analyses and numerous computer simulations have been investigated and planned for comparison based on them. Achievement of suitability for the performance of the structure of lines without concrete ballast and with ballast was attained (Paiva et al., 2015; Sol-Sánchez et al., 2015). However, specific information, such as features and characteristics of geometry, materials, loading, and design parameters, was selected and utilized (Wang et al., 2015).

The model of the beam on the elastic bed for ballast pavement, considering values pertinent to its structure, especially for the intermittent support module of the bed, and the two-beam model on the elastic bed, is regarded as the slab model for railway lines. The theory of these two models was then solved. While the use of beam theory on an elastic platform has been considered for ballast pavement for many years, the use of the two-beam theory on an elastic bed is a novel aspect. To validate the results of these theories, several finite element models were created using ABAQUS software, and the results were confirmed with appropriate accuracy.

To account for the dynamic effects of train movement and apply quasi-static loads (Pd) for utilizing legal relations in pavement design, the dimensionless dynamic impact coefficient is consistently greater than one for the vertical wheel load (Ps). Relation (1) is employed as the necessary equation in the research process.

\[
P_d = \varphi P_s \quad [\varphi = 1 + 5.21 \frac{V}{D}] \tag{1}
\]

In this relationship, V represents the speed, and D stands for the diameter of the wagon or locomotive. To calculate the dynamic impact coefficient, various regulations and research results provide relationships, primarily of an experimental nature. Each of these relationships takes into account the effect of various parameters.

Model of the Structure of Railway Lines

The primary task of line models is to establish the relationship between the components of the
superstructures and substructures of the line, ensuring accurate interactions. The complexity lies in determining the impact of traffic loads on the stresses, strains, and deformations of the system. Generally, railway lines are subjected to loads applied in three directions: vertical, lateral, and longitudinal. However, some models only consider the vertical components of the load. Various models, such as the beam on continuous elastic bed, beam on discrete and separate support cases, two-beam model on a continuous elastic bed, two-dimensional beam and plate models, and three-dimensional finite element models, can be considered (Morelli et al., 2014; Podworna, 2014). Kamyab Moghaddam has conducted research on recent developments in ballast less versus ballasted tracks, focusing on high-speed and urban lines. His investigation unveiled that flexible fastening systems can offer reliable track support and present a favorable life cycle cost for a slab track system. The outcomes of the direct fixation fastening model, concerning lateral deflection and longitudinal resistance of fasteners in this study, were compared against the criteria reviewed by Kamyab Moghaddam, confirming the validity of the model (Moghaddam, 2017).

One of the crucial components of the railway line is the rail, which is modeled as a continuous beam structure on an elastic support. The dynamic displacement of the rail under passing loads is primarily based on two theories: the first being Euler-Bernoulli’s theory. However, this theory falls short in accounting for the effects of shear deformation and torsional inertia of the beam under vibrations. For this purpose, Tymoshenko’s theory is employed.

In recent years, the continuous beam model on elastic supports has been applied to ballasted pavements. A more detailed model, as depicted in Figure (3), is introduced, encompassing two layers of rails and sleepers, as well as the top and bottom layers. In this model, the rail takes the form of continuous beams on separate supports, while the sleepers are represented as masses. The concentric binders and ballast are modeled as spring and damper elements, and the bed is considered rigid (Cheng & Xue, 2014).

Models, developed based on the multiplicity of layers and spring-damper elements representing various pavement components, are presented in Figure (4). These models have been simplified according to the structural condition for both ballast pavement and slab lines.

Various two-dimensional and three-dimensional models can be considered for the vehicle, with the simplest and most suitable model for research purposes being the concentrated load model or a set of loads on the rail influenced by the dynamic impact factor in the concentrated load. The result is obtained by dividing the
The Parameters and Limits of the Required Values of the Research

In the research process, specific values are necessary, and the limits and specifications of these parameters are outlined in Table 3. The predominant use of rail in railway lines, particularly in the country, can be traced back to the UIC60 section. Due to the unique shape of this section and the limitations of software modeling, it has been represented in the research process as section I, as illustrated in Figure (5) within the software. The error associated with this approximation is negligible, given the significance of the moment of inertia of the rail in the analysis.

<table>
<thead>
<tr>
<th>Amount</th>
<th>Unit</th>
<th>Concrete Slab</th>
<th>Amount</th>
<th>Unit</th>
<th>UIC60 Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>m</td>
<td>4</td>
<td>172</td>
<td>mm</td>
<td>Section Height</td>
</tr>
<tr>
<td>250</td>
<td>m</td>
<td>3</td>
<td>150</td>
<td>mm</td>
<td>Heel width</td>
</tr>
<tr>
<td>300</td>
<td>cm</td>
<td>3</td>
<td>72</td>
<td>mm</td>
<td>Hat width</td>
</tr>
<tr>
<td>400</td>
<td>cm4</td>
<td>2</td>
<td>37.5</td>
<td>mm</td>
<td>The thickness of the cap</td>
</tr>
<tr>
<td>400</td>
<td>GPa</td>
<td>4</td>
<td>16.5</td>
<td>mm</td>
<td>Web thickness</td>
</tr>
<tr>
<td>350</td>
<td>No Unit</td>
<td>2</td>
<td>16.9</td>
<td>mm</td>
<td>The equivalent thickness of the heel</td>
</tr>
<tr>
<td>2500</td>
<td>Kg/m3</td>
<td>Special Weight</td>
<td>81</td>
<td>mm</td>
<td>The distance of the neutral axis from the bottom</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3055</td>
<td>cm4</td>
<td>Moment of inertia of strong axis</td>
</tr>
<tr>
<td>644</td>
<td>MPa</td>
<td>The reaction module of the rail support (u1)</td>
<td>200</td>
<td>GPa</td>
<td>Modulus of elasticity of rail steel</td>
</tr>
<tr>
<td>225</td>
<td>MPa</td>
<td>The reaction module of the rail support (u2)</td>
<td>0.3</td>
<td>-</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>31</td>
<td>MPa</td>
<td>Modulus of the response of the bed sometimes supported top line</td>
<td>60</td>
<td>Kg/m</td>
<td>Weight per unit of rail length</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7850</td>
<td>Kg/m3</td>
<td>Special Weight</td>
</tr>
</tbody>
</table>

Figure 5. UIC60 Rail Section. Section I, Equivalent Shape for UIC60 Rail in Section Builder Software
Beam Model on the Elastic Bed

The most common analysis model for the railway structure is the beam on the elastic bed, wherein torsion and shear effects are considered negligible, and the Euler-Bernoulli beam theory is typically chosen. As an illustration, a theoretical example of a ballast line with a beam designed on an elastic base is compared with software modeling, and the results are presented (Gil & Im, 2014; Remennikov & Kaewunruen, 2014).

By utilizing the relations and values from the theoretical solution and taking into account the effect of only one spur wheel, the maximum displacement is calculated. (The impact of other wheels of the train can be calculated within the range of interaction, following the principle of superposition.) Understanding the change in positions allows for the determination of other parameters related to the structure’s response. The governing differential equation for this model is described in relation (2):

\[ E_I I_c \frac{d^4y}{dx^4} + uy(x) = 0 \]  

(2)

Figure 6. Diagram of Displacement and Maximum Rail Anchor in Beam Model on Elastic Bed

Figure 7. Rail Displacement Diagram in Solving Theory and Software

The finite element model validates the shape change diagram and explores the impact of various parameters, such as bed modulus, rail type, and rail steel. The results indicate the limited effect of these parameters compared to the substantial impact of the bed modulus.
Notably, the structural design of the rail and its interaction force with the pavement significantly influence the design results (Hudson et al., 2016).

Table 2. The results for Investigating the Effect of the Modulus of the Support of the Bed

<table>
<thead>
<tr>
<th>Abaqus Model</th>
<th>Theory results</th>
<th>Modulus of reaction</th>
<th>Rail moment of inertia</th>
<th>Modulus of elasticity</th>
<th>Wheel load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaqus Model</td>
<td>Change the location of the rail</td>
<td>Sometimes the bed rest</td>
<td>Rail moment of inertia</td>
<td>Modulus of elasticity</td>
<td>Wheel load</td>
</tr>
<tr>
<td>mm</td>
<td>mm</td>
<td>MPa</td>
<td>Cm4</td>
<td>GPa</td>
<td>kN</td>
</tr>
<tr>
<td>3.8176</td>
<td>4.1920</td>
<td>20</td>
<td>3055</td>
<td>200</td>
<td>176.3</td>
</tr>
<tr>
<td>2.7700</td>
<td>3.0177</td>
<td>31</td>
<td>3055</td>
<td>200</td>
<td>176.3</td>
</tr>
<tr>
<td>1.9488</td>
<td>2.1085</td>
<td>50</td>
<td>3055</td>
<td>200</td>
<td>176.3</td>
</tr>
<tr>
<td>1.4488</td>
<td>1.5556</td>
<td>75</td>
<td>3055</td>
<td>200</td>
<td>176.3</td>
</tr>
<tr>
<td>1.0951</td>
<td>1.1672</td>
<td>110</td>
<td>3055</td>
<td>200</td>
<td>176.3</td>
</tr>
</tbody>
</table>

Figure 8. Diagram of the Study of the Effect of the Modulus of the Support of the Bed on the Displacement of the Rail

To investigate the impact of intermittent support conditions at both ends of the beam (simple beam and clamped beam), beam length, and element size, various models were considered. The results indicated that within a reasonable length in the range of load interaction and depending on the substrate modulus, the conditions of the final support will not significantly affect the results. The effect of load arrangement on the results of location changes in each theory and ABAQUS finite element modeling method, as shown in Figure (9) and Table (4), indicates that the effect of lateral axles within a maximum range of up to three wheels can influence the results of location change and serve as an effective anchor. The impact of this range on location change, within the range of two wheels, yields acceptable results.

Figure 9. The Effect of the Arrangement of the Wheels of a Passing Wagon on the Rail Displacement Diagram in ABAQUS

Table 2. The Results for Investigating the Effect of the Modulus of the Support of the Bed
Two-Beam Model on Elastic Bed

The dynamic conditions governing the slab structure of the lines are highly similar to those of ballast pavement and railway bridges. A comprehensive investigation was conducted on a wide range of sources, leading to the development of a specific structural dynamic model for pavement without ballast. Equations (3) and (4) in Raitah present the differential equations that govern this model:

\[ E_s I_s \frac{d^4 y_1}{d x^4} + u_1 (y_1 - y_2) = 0 \]  \hspace{1cm} (3)

\[ E_c I_c \frac{d^4 y}{d x^4} + u_1 (y_1 - y_2) + u_2 y_2 = 0 \]  \hspace{1cm} (4)

The variables \( y_1 \) and \( y_2 \) represent the displacement of the rail and slab, while \( u_1 \) and \( u_2 \) denote the elastic modulus of the intermittent support for the rail and slab, respectively. Additionally, \( E_s \) and \( E_c \) represent the elasticity modulus of the rail and the concrete slab, and \( I_c \) and \( I_s \) are the moments of inertia of the rail and the concrete slab (D’Angelo et al., 2016; Lamas-Lopez et al., 2016). This model aims to solve the theory and present formulas or calculations through software. The results obtained with the help of various component models have certain limitations. To facilitate a more accurate comparison, and considering the specific tasks and type of line intended for the slab pavement, the wheel load in the calculations and disturbances has been calculated and set equal to 195.83.

Effect of Single Axial Load: In this study, the responses of the structure under the influence of a single axle load of 3, 5, 8, 10, 17, 20, 25, 30, and 39 tons are examined with the following fixed values. (The value of the elastic modulus of the slab support, denoted as \( u_2 \), is set to 408.).
Comparison of Beam Model on Elastic Bed and Two Beam Model on Elastic Bed

Based on the modelling performed, the results of the maximum displacement and rail anchor, two crucial parameters in the structure’s response, are presented in Figure (12). The primary objective is to compare the structural performance of two types of pavements, namely ballast pavement and line slab.

Figure 13. Comparison Diagram of Rail Displacement in Two Beam Models and Two Beams on Elastic Bed

Conclusion

In a broader perspective, the following results can be highlighted: the performance of the slab structure of the lines surpasses that of ballast pavement in handling incoming loads and addressing structural weaknesses. This superiority is attributed to the system’s inherent high rigidity, complemented by targeted measures. According to the discussed models, the bed modulus and its accurate determination, along with dynamic axial load values, emerge as the most influential parameters. The impact of increasing the axial load on slab lines induces more substantial differences in displacements in the rail and the slab, particularly concerning the maximum anchor. The theories of beams on an elastic bed for ballast pavement and the theory of two beams on an elastic bed for slab lines can be employed with sufficient accuracy for modeling these structures. Investigating the behavior of slab lines using the theory of two beams on an elastic bed allows for a thorough examination, enabling the establishment of appropriate design limits derived from this theory. The exact solutions of the differential equations governing the discussed beam models, with results noteworthy enough to mention, can be employed in a codified and algorithmic manner, contributing to legal considerations and the development of computing software. Additionally, in this research, automatic calculations have been executed using Excel software with the aforementioned algorithmic approach, enhancing the practical applicability of the findings.

Above all, the discussion should explain how your research has moved the body of scientific knowledge forward.

Conflict of Interests

No conflict of interest.

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