Finite element modelling of jointed plain concrete pavements under rolling forklift tire

Jagadeesh, A.; Premarathna, W. A.A.S.; Kumar, A.; Kasbergen, C.; Erkens, S.

DOI
10.1016/j.engstruct.2025.119705

Publication date
2025

Document Version
Final published version

Published in
Engineering Structures

Citation (APA)
Jagadeesh, A., Premarathna, W. A. A. S., Kumar, A., Kasbergen, C., & Erkens, S. (2025). Finite element modelling of jointed plain concrete pavements under rolling forklift tire. *Engineering Structures*, *328*, Article 119705. https://doi.org/10.1016/j.engstruct.2025.119705

Engineering Structures 328 (2025) 119705

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Finite element modelling of jointed plain concrete pavements under rolling forklift tire

A. Jagadeesh, W.A.A.S. Premarathna, A. Kumar *, C. Kasbergen, S. Erkens

Department of Engineering Structures, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Stevinweg 1, Delft, CN 2628, the Netherlands

A R T I C L E I N F O

Keywords:
Concrete pavements
Dowel bars
Rolling forklift tire
Tire-pavement interaction
Load transfer efficiency

A B S T R A C T

This research addresses the critical issue of load transfer efficiency (LTE) in jointed plain concrete pavements (JPCP), with a specific focus on the role of dowel bars in ensuring optimal load transfer and providing a comfortable ride for vehicles. While experimental studies have investigated factors like joint width, slab thickness, concrete strength, and dowel bar size that influence LTE, they are limited in their ability to accurately replicate real-world conditions and can be time-consuming. To overcome these limitations, finite element modelling (FEM) is employed as a powerful tool for simulating complex loading conditions and analyzing stress and strain distributions in pavements. The primary objective of this research is to develop an advanced FE model that incorporates the forklift tire-pavement interaction, enabling precise analysis of complex loading conditions in industrial pavements and the impact of various rigid pavement parameters on load transfer. By explicitly considering the interaction between the tire and pavement, the proposed model will provide an extensive and robust numerical tool for designers and engineers. Additionally, this study represents a novel framework to integrate concrete pavement dowel bars and complex tire modelling using FEM. The developed methodology holds significant promise in optimizing the design of dowel bar systems and back-calculating the pavement parameters for rolling weight deflectometers.

1. Introduction

Load transfer efficiency (LTE) of dowel bars is a critical factor in the design and construction of concrete pavements. The effectiveness of dowel bars in transferring loads between concrete slabs and ensuring a smooth ride for vehicles has been a subject of extensive research over the years. Past experimental studies have shown that the LTE of dowel bars can be influenced by various factors, such as joint width, slab thickness, concrete strength, and dowel bar size [1–3]. These studies have also shown that the LTE of dowel bars can be improved by optimizing the design of the dowel bar system, including the size and spacing of the dowel bars, the size and type of joints, and the quality of the concrete. However the understanding of LTE under heavy vehicle loads expected in the field has not improved much.

Experimental studies often involve complex and time-consuming procedures, and they are also limited by the availability of test equipment and the size of specimens that can be tested [1–3]. Additionally, it is challenging to accurately recreate realistic loading conditions in the laboratory, making it difficult to obtain accurate results that reflect actual field conditions. To overcome these challenges, finite element modelling (FEM) has emerged as a powerful tool for evaluating the LTE of dowel bars in concrete pavements [4–9]. The use of FEM allows for the simulation of complex loading conditions and the evaluation of the stress and strain distributions in concrete pavements under various conditions. These models also provide the opportunity to evaluate the effect of different design parameters on the LTE of dowel bars and to optimize the design of concrete pavements.

In the field of jointed plain concrete pavements (JPCP), several numerical studies have been conducted to evaluate the impact of various factors on load transfer efficiency and stress distribution. Saxena et al. [4] developed a 3D FE model of concrete slabs with dowel bars and investigated the effect of dowel bar misalignment and dowel-concrete friction parameters on pullout force of dowel bars. Inspired by this pioneering work, Sii et al. [5] utilized 3D-FE analyses to investigate the effect of dowel looseness on jointed concrete pavements. Their findings revealed that small gaps between the dowels and slabs led to a significant reduction in load transfer efficiency. Sadeghi and Hesami [6] employed a 3D FEM to evaluate load transfer efficiency in jointed

* Corresponding author.
E-mail address: k.anupam@tudelft.nl (A. Kumar).

https://doi.org/10.1016/j.engstruct.2025.119705
Received 2 July 2024; Received in revised form 17 December 2024; Accepted 13 January 2025
Available online 17 January 2025

concrete pavements, identifying that increasing elastic modulus and slab thickness improved load transfer efficiency. Similarly, Liu et al. [7] studied the mechanical behavior of concrete pavements, specifically considering the presence of voids beneath slabs and joints. Their research concluded that the size of the voids and the stiffness of the joints influenced the stress distribution in loaded slabs. Singh and Chandrappa [8] developed a 3D FEM, focusing on the effects of uniform vertical and longitudinal dowel misalignment, which resulted in excessive tensile and compressive stresses, leading to reduced load transfer efficiency. Recently Xie and Wang [9] compared the mitigation methods for traffic-induced reflective cracking in airport composite pavement, highlighting the effectiveness of increased overlay thickness and dowel bar retrofit.

Despite the valuable insights provided by the studies [4–9], they share several common limitations. The analyses are based on simplified 3D FE models which do not fully capture the complexities and variations present in the field [4–8]. They cannot encompass all the intricacies of actual pavement and tire structures. It is logical that the interaction between the tire and pavement can significantly affect the LTE of dowel bars, and therefore it is important to model this interaction in FEM. There are few studies [10,11] conducted in the past on the interaction between rolling tire and asphalt pavement, yet none on the concrete pavements. Such models can be developed by taking advantage of recent developments in dowel bar modelling and tire modelling through rolling the tires on pavement surfaces [10–12].

Moreover the existing studies do not investigate the spatiotemporal dynamic analysis of JPCP's, which could have significant influence on the dowel bar durability. The existing studies are limited to typical highway loads and do not investigate the industrial pavements under forklift tires [4–9]. In summary, none of the existing studies on concrete pavement modelling employ tire-pavement interaction in their analysis considering a realistic rolling tire. Such analyses will provide deeper insights into underlying mechanisms of dowel bar load transfer.

The novelty of this study lies in the detailed integration of dynamic tire modeling with jointed plain concrete pavements (JPCP), which goes beyond the typical static load application methods used in previous research. While FEM tools are widely used, our work addresses a gap in existing literature by simulating the effects of rolling tires, providing a more accurate representation of load distribution on concrete pavements. Hence, the research objective is to provide a framework to model the complex tire-rigid pavement interaction using FEM techniques to understand the load transfer analysis. It is expected that the proposed framework will become a useful tool for bridging the gap between JPCP modeling and practical applications.

1.1. Motivation of the research study

The motivation behind this research study is two fold: (1) The application of tire-rigid pavement FE model in the analysis and design of industrial pavements to investigate the influencing factors such as material properties and load transfer capabilities. (2) Additionally, considering the gain in popularity of rolling weight deflectometers, this study could help in developing transfer functions between falling weight and rolling weight deflectometers for JPCP's.

1.1.1. Analysis and design of industrial pavements

The current research aims to enhance the long-term performance and durability of concrete pavements for industrial applications. Previous experimental and field studies [13–17] have addressed the design and evaluation of road surfaces for industrial pavements, focusing on durable construction methods and efficient load transfer mechanisms. Recently, Hasheminasab and Kashi [18] have utilized FEM to explore pavement designs for industrial pavements subjected to loads from container storage. However, previous studies primarily focused on static loads from storage, neglecting the dynamic effects caused by moving forklift vehicles. By integrating rolling tires with previous research, this study aims to enhance our understanding of pavement design and evaluation in industrial environments, addressing load impacts, innovative techniques, and performance assessments.

1.1.2. Application to rolling weight deflectometers

Recently, the use of rolling weight deflectometers (RWD) has increased in field applications. These devices use experimental data for back calculation to determine material properties and layer thicknesses, but studies on RWDs for concrete pavements are limited [19]. A key research area has emerged in integrating FEM with RWD results [19–23]. This integration is beneficial, especially when field data is scarce, and it reduces analysis time. Advances in computational technology enable a comprehensive understanding of concrete pavement behavior using FEM.

The ongoing development of RWDs will help create transfer functions from falling/heavy weight deflectometers to RWDs for JPCPs, particularly for industrial pavements. This integrated approach improves the evaluation of JPCP behavior, enhancing load transfer efficiency and providing a smoother ride for vehicles.

2. Proposed framework

The primary focus of this research is to address the critical issue of load transfer in JPCPs subjected to heavy forklift traffic, particularly in industrial areas. The goal is to develop an advanced FEM framework that considers the interaction between solid forklift tires and rigid pavements. This framework, depicted in Fig. 1, involves four major steps: developing the JPCP model, creating the rolling tire-JPCP model, validating the model, and conducting analysis. This systematic approach evaluates deflection and load transfer in concrete pavements, providing valuable insights into dowel bar performance under various loading conditions and times. The research specifically analyzes load transfer and deformation in two-slab JPCPs under solid tire rolling, with conditions including a tire speed of 10 km/h, a load of 20 kN, and a dry friction coefficient of 0.35. This study will facilitate detailed analysis of factors influencing JPCP performance.

2.1. Development of JPCP model

A finite element model of the concrete pavement is developed, which includes the representation of the concrete slabs, joints, and dowel bars. The model was developed in the commercial package ABAQUS 2021 [25]. It has four pavement layers (3.5 m x 4.5 m) and dowel bars as shown in Fig. 2**.** Linear elastic material properties are used for each pavement layer and dowel bars and are given in Table 1 [5,6,24]. To ensure appropriate constraints and boundary conditions, the following measures are applied:

a) Tie constraints are applied between the fixed ends of the dowel bars and the adjacent fixed slab, ensuring a rigid connection.
b) Surface-to-surface interaction is employed for the free ends of the dowel bars and the free slab, with a friction coefficient of 0.05 to represent the frictional resistance between these surfaces [24].
c) The contact between the slabs and the base layer is modeled using surface-to-surface interaction, with a friction coefficient of 1 to reflect the higher friction between these layers.
d) Fixed boundary conditions are imposed on the bottom of the subgrade and the sides of all layers.

A JPCP model with 11,200 elements for dowel bars, 16,120 elements for both the fixed and free slabs, and 23,184 elements for the other layers was found to be computationally efficient and consistent with prior studies [10–12,26,36].

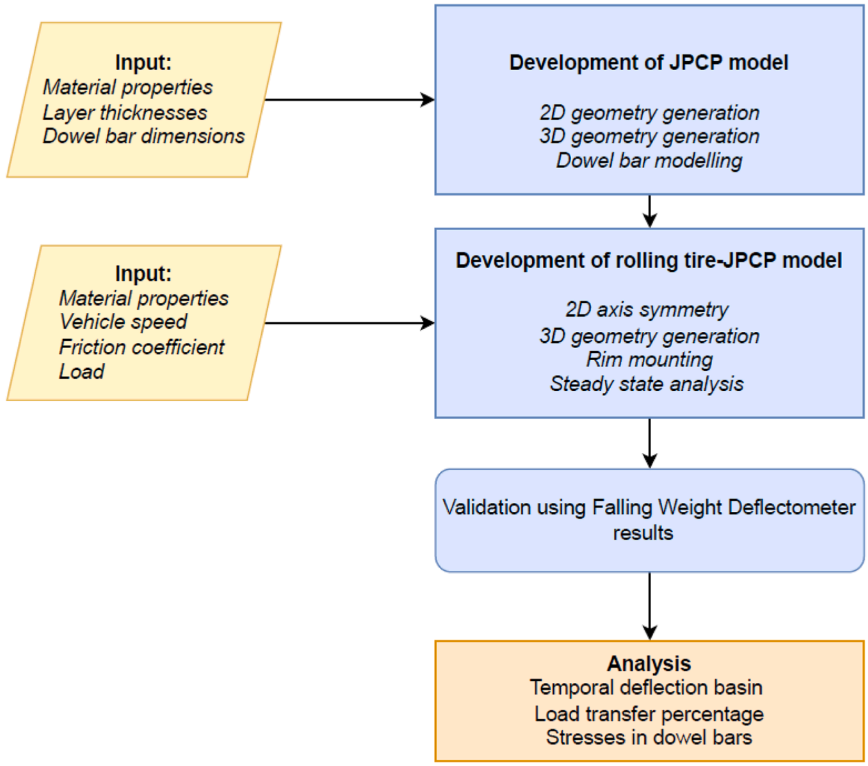


Fig. 1. Framework to develop tire-rigid pavement interaction model.

2.2. Development of rolling tire – JPCP model

The development of an FE model for rolling tires on concrete pavements involves a systematic approach to accurately simulate tire behavior. Instead of a linear elastic single layered shell tire model [26], the authors used a more detailed solid tire with hyper-elastic material properties. The initial FE model consisting of a tire with a smooth single layered pavement surface was developed with the tire comprising of three rubber layers, namely the base layer, cushion layer, and tread layer, along with reinforcements as shown in Fig. 3. The governing equation of the dynamics of the tire model is shown below:

$$\{f\} = [k]\{x\} + [c]\{\dot{x}\} + [m]\{\ddot{x}\} \tag{1}$$

where;

f is time dependent force if both damping ($[c]\{\dot{x}\}$) component and inertia component ($[m]\{\ddot{x}\}$) exist. Otherwise, the event is a static.

$[m]$ is mass matrix, $[c]$ is damping matrix, and $[k]$ is stiffness matrix

x is displacement, $\dot{x}$ is velocity and $\ddot{x}$ is acceleration

The following are the constraints and boundary conditions for the developed tire model:

(a) Tie constraints are employed to connect the element nodes between the base/cushion and cushion/tread layers.
(b) Reinforcements are embedded within the base layer, while the inner surface of the base layer is defined as a rigid body representing the tire rim.
(c) Surface-to-surface contact is established between the tire tread and a rigid surface representing the tire contact.
(d) For static analysis, only the vertical load was applied on the tire rim.
(e) For dynamic analysis, the tire model is further enhanced with angular velocity (ω) and translational velocity (v).
(f) The frictional coefficient between the tire and the concrete pavement surface was assumed to be 0.35
(g) The damping effect in the above equation will be taken care of using the viscoelasticity of the rubber components.
(h) The load representing the forklift's total weight is applied at the center of the tire and directly distributed to the rim of the tire.

Hyper-elastic material models such as Mooney Rivlin, Yeoh and Ogden (as shown in Table 2) are utilized to represent the behavior of the rubber layers [12]. The relaxation properties of the rubber layers (as shown in Table 3) are incorporated to account for material relaxation during tire rolling, enabling a comprehensive analysis of the dynamic behavior of rolling tires on concrete pavements.

The constitutive equations of Mooney Rivlin, Yeoh and Ogden hyper-elastic material models are presented as follows:

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{D_1}(J_{el} - 1)^2 \tag{2}$$

$$U = \sum_{i=1}^{3} C_{i0}(\bar{I}_1 - 3)^i + \sum_{i=1}^{3} \frac{1}{D_i}(J_{el} - 1)^{2i} \tag{3}$$

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{i=1}^{N} \frac{1}{D_i}(J_{el} - 1)^{2i} \tag{4}$$

where U is the strain energy, N is the polynomial order, λ_i is the deviatoric principal stretch, $\bar{I}_1$, $\bar{I}_2$ and $\bar{I}_3$ are first, second and third invariants, C_{ij} and D_i are temperature-dependent material properties, α_1 and μ_1 are temperature-dependent material coefficients, J_{el} is the elastic volume ratio.

The simulations were performed using the Abaqus/Standard solver with implicit time integration, specifically the Backward Euler Method, which is appropriate for quasi-static and steady-state analyses. The time increment used in the simulations was set to 0.0001 seconds and a total time of 1.3 seconds.

It was found that the tire model with 65000 hexahedral elements is enough to obtain a computationally efficient solution and is in line with

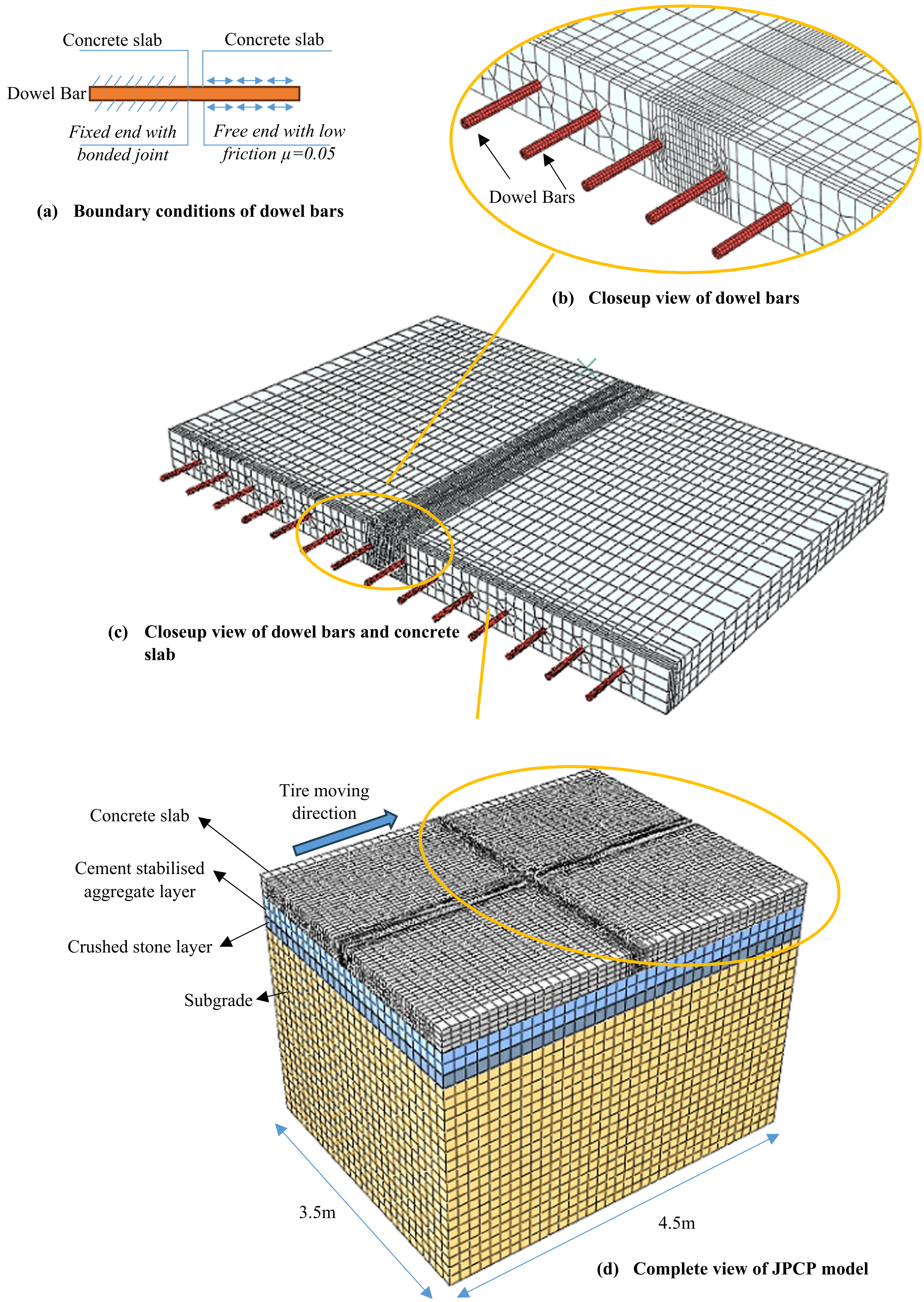


Fig. 2. FE model of Jointed Plain Concrete Pavement.

Table 1
Material properties and dimensions of JPCP model.

Material	Young's modulus (MPa)	Poisson ratio	Density (kg/m^3)	Dimensions (mm)
Concrete slab	35000	0.2	2440	Thickness = 250 Spacing between slabs = 2
Cement stabilized aggregate layer	2900	0.3	2170	Thickness = 250
Crushed stone layer	193	0.35	1920	Thickness = 150
Subgrade	143	0.35	1700	Thickness = 2500
Dowel bars	210000	0.3	7830	Diameter = 30 Spacing = 230 Length = 500

the past relevant studies [10–12,26,36]. When executing the computations on a high-performance computing (HPC) LINUX system, the process required 48 cores and approximately 26 hours of running time for each simulation. From the above modelling, the deflection on the unloaded and loaded slabs can be obtained.

2.3. Validation of FE model

Model validation of concrete pavement involves comparing experimental data obtained from Falling Weight Deflectometer (FWD) tests with the predictions generated by numerical models. FWD experiments provide valuable information on the response of concrete pavements to the dynamic load of 57.5 kN exerted by a simulated tire load. By measuring the deflection response at various locations, FWD tests help assess pavement performance and structural integrity. In the current study, FWD experimental results and modelling procedure from Mackiewicz [24] were used as a benchmark for comparison. Fig. 4 shows the comparison of experimental results with the numerical modelling results. It was observed that the deformation trend of the concrete pavement and dowel bars follows a similar trend to the experimental results. More details about the FWD experiments and modelling procedures could be found in Mackiewicz [24].

Although numerical models have shown promising results in predicting pavement response to tire loading, there are a few limitations to consider. Factors such as modelling of falling weight, material heterogeneity, moisture effects, and temperature variations can impact the accuracy of the models. Furthermore, the complexity of the tire-pavement interaction introduces challenges in capturing all relevant phenomena in the numerical simulations.

In addition to the above validation, Fig. 5 shows the results of stresses in the tire model and the contact stresses at the interface and is in line with the past numerical studies [12]. More detailed validation on the tire-pavement interaction models could be found in the past studies made by the authors [10–12].

2.4. Load transfer efficiency and percentage

Load Transfer Efficiency (LTE), a critical parameter in JPCP design, is defined as the ratio of deflection on the unloaded slab to the loaded slab, expressed as a percentage [1–3], when the load is applied on the concrete slab with fixed dowel bars. It is calculated as:

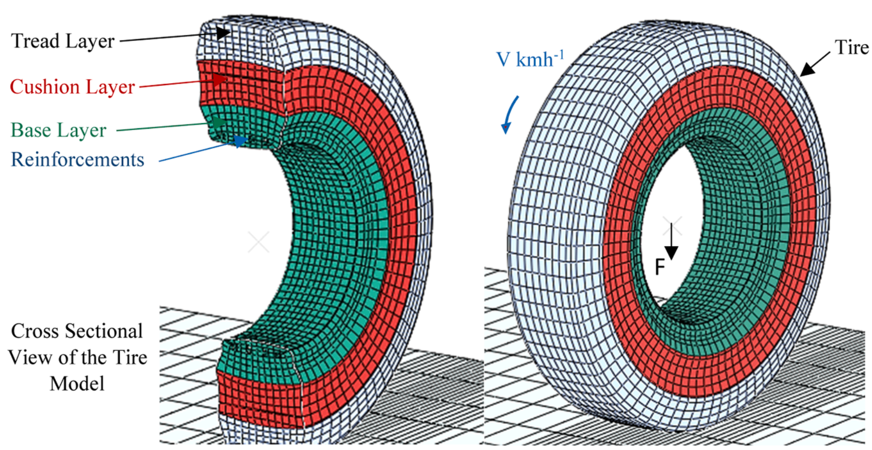


Fig. 3. Model of rolling forklift tire on JPCP.

Table 2
Coefficients of Mooney-Rivlin, Ogden and Yeoh material models for tire elements [12,36].

Rubber layer of the tire model	Base (Mooney-Rivlin)		Cushion (Ogden)						Tread (Yeoh)		
Coefficients	C_{10} (MPa)	C_{01} (MPa)	μ_1 (MPa)	μ_2 (MPa)	μ_3 (MPa)	α_1 -	α_2 -	α_3 -	C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
	0.6	2.5	−9.3	8.9	0.9	1.5	2.1	−3.7	0.7	−0.1	0.1

Table 3
Viscoelastic relaxation parameters for tire elements [36].

Rubber layer	g_1 -	τ_1 (S)	g_2 -	τ_2 (S)	g_3 -	τ_3 (S)	Density (kg/m^3)
Base	0.2208	0.0003	0.1208	0.0146	0.0993	0.1890	1150
Cushion	0.0016	0.0001	0.1099	0.0173	0.0603	0.2198	975
Tread	0.1545	0.0032	0.1223	0.0377	0.1253	1.8288	1280

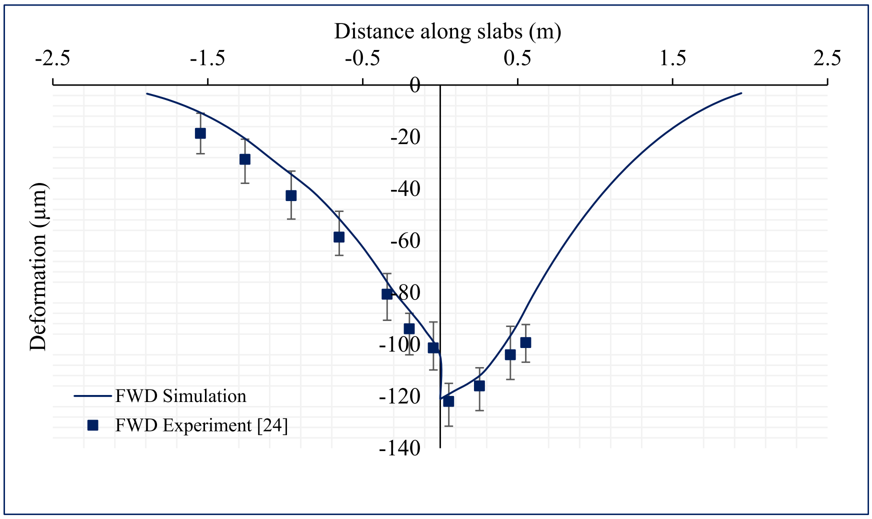
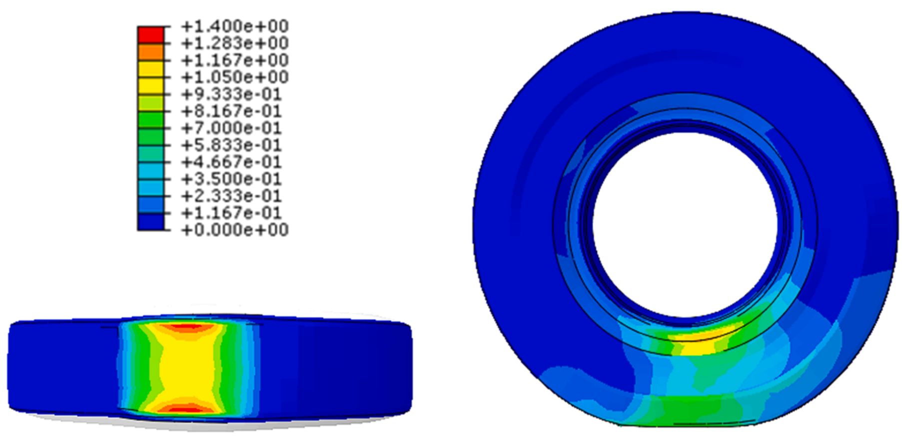


Fig. 4. Validation of Jointed Plain Concrete Pavement (JPCP) model.



a) Contact pressure at pavement interface (MPa)

b) von Mises stress (MPa)

Fig. 5. Contact and von Mises stresses in tire model.

$$LTE = \left(\frac{\textit{Deflection of unloaded concrete slab}}{\textit{Deflection of loaded concrete slab}}\right) \times 100\%$$

An LTE of 100% implies perfect load transfer across the joint, with dowel bars effectively distributing the load between adjacent slabs. While LTE measures load transfer at specific points, a new terminology Load Transfer Percentage (LTP) was introduced in this study which provides a more comprehensive assessment by accounting for variations in load transfer along the entire joint. LTP evaluates LTE when load is applied at different locations along the length of the slab, offering a holistic understanding of joint performance. A generalized formula for LTP is:

$$LTP = \left(\frac{\textit{Deflection of unloaded concrete slab at various locations}}{\textit{Deflection of loaded concrete slab at various locations}}\right) \times 100\%$$

By considering multiple locations rather than just a single measurement point, LTP accounts for spatial variability in load transfer. This approach reduces potential errors and misinterpretations that could arise from using only LTE, which focuses on isolated points. Consequently, LTP provides a more robust and reliable measure of joint performance, particularly in scenarios where dowel bars might perform inconsistently along the length of the joint.

3. Results and analysis

This section presents the discussions regarding the analysis of deflection basins and load transfer mechanisms. A comprehensive comparison is presented, focusing on the influence of static and rolling tire effects on deflection basins and stresses in the dowel bars followed by a parametric analysis.

3.1. Analysis of deflection basin under rolling tire

Fig. 6 presents a comparison of concrete slab deformation at different time intervals for the load of 20 kN, vehicle speed of 10 km/hr and friction coefficient of 0.35. Rolling of the tire model was started on the fixed slab at the distance of 1.7 m from the joint and the model reached the steady state at the distance of 1 m from the joint. Fig. 7 shows the three-dimensional deformation of the slabs at different times. The following observations are made from the plots of Figs. 6 and 7.

- At first, the trend of deformation results aligns with previous experimental and numerical findings made by Mackiewicz [24]

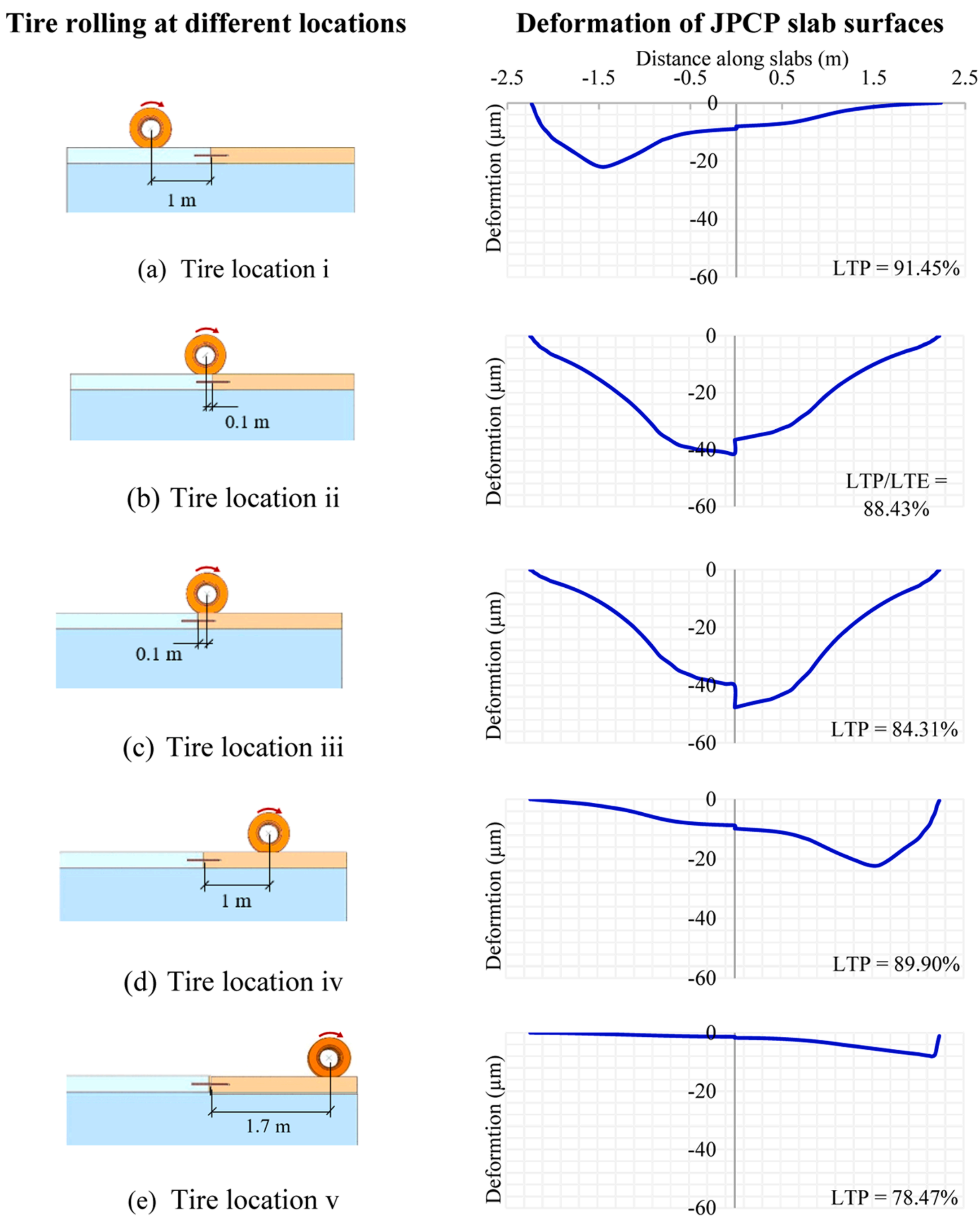


Fig. 6. Variation of slab deformation and load transfer at different tire locations.

using FWD testing, demonstrating that the deformation patterns of the concrete pavement and dowel bars are consistent. This shows that the developed model is consistent with the findings made in the past studies and could be used for further detailed analysis.

- The maximum deformation in the pavement surfaces is observed directly under the tire location, indicating a correlation between tire position and deformation. Notably, there is an asymmetrical deformation basin occurring in the pavements. This is in line with the past numerical studies [10,11,21].
- Upon comparing the peak deformation basins depicted in Fig. 6b (tire located at 0.1 m from the joint on fixed slab) and Fig. 6c (tire located at 0.1 m from the joint on free slab), it becomes apparent that the peak deformation in Fig. 6c is higher than that of Fig. 6b. This discrepancy can be attributed to the contrasting behavior of the dowel bar connections, leading to an asymmetrical deformation basin within the pavements, as observed in Figs. 7b and 7c. Specifically, the peak deformation occurs in the left slab (Fig. 6b) where the dowel bars are fixed, while the right slab (Fig. 6c) allows the dowel bars to move freely.

3.2. Analysis of load transfer percentage in JPCP under rolling tire

This sub-section compares the load transfer of JPCP slabs using the deformation basin results. The following observations are made from the plots of Fig. 6.

- Currently in practice, LTE is measured when the load is applied to the concrete slab at a fixed dowel end (location ii), yielding an LTE value

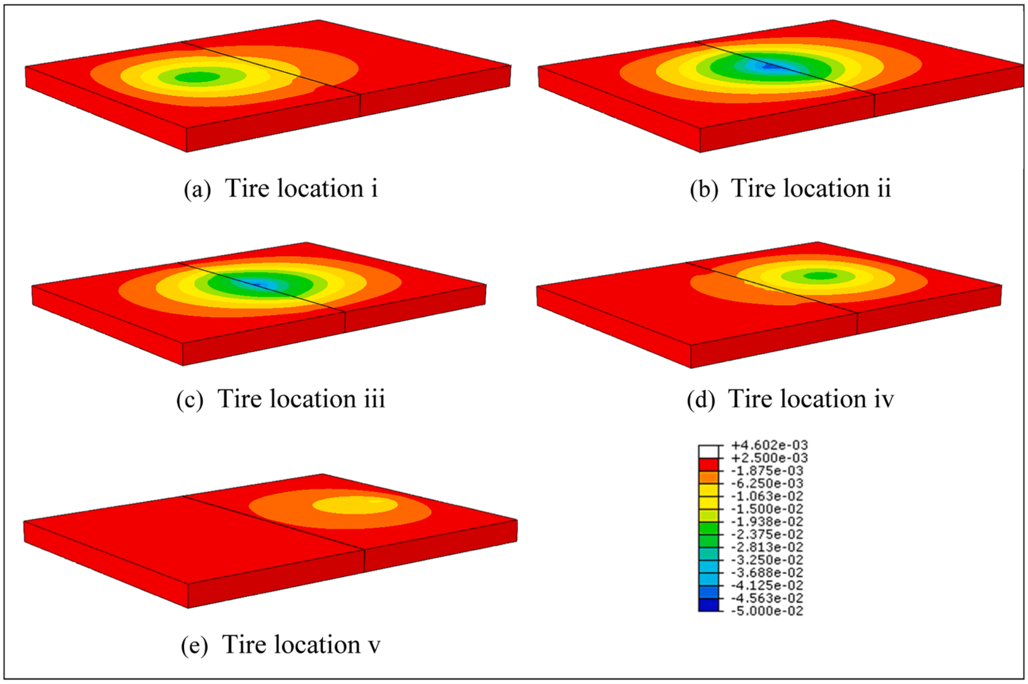


Fig. 7. Deformation of JPCP model under rolling tire (Units are in mm).

of 88.43 %. However, using the new measurement approach, LTP can be assessed at various locations, as demonstrated in Fig. 6. This method reveals that LTP values can vary significantly based on the tire's position.

- When the tire model commenced rolling on the left slab from a distance of 1 m from the joint, a higher LTP value of 91.45 % was observed, with a gradual decline in the LTP values as it continued to move.
- During the tire's movement from the left slab to the right slab, the LTP value decreases from 88.43 % to 84.31 %, resulting in a notable difference of 4.66 % between these two tire positions. This unique finding helps in understanding the efficacy of current dowel joints and the extent of freedom allowed for the dowel bar on the free end.
- When the tire moves away from the joint at the distance of 1.7 m from the joint, LTP reduced to 78.47 %. A minor boundary effect is evident at the end of the concrete slab.

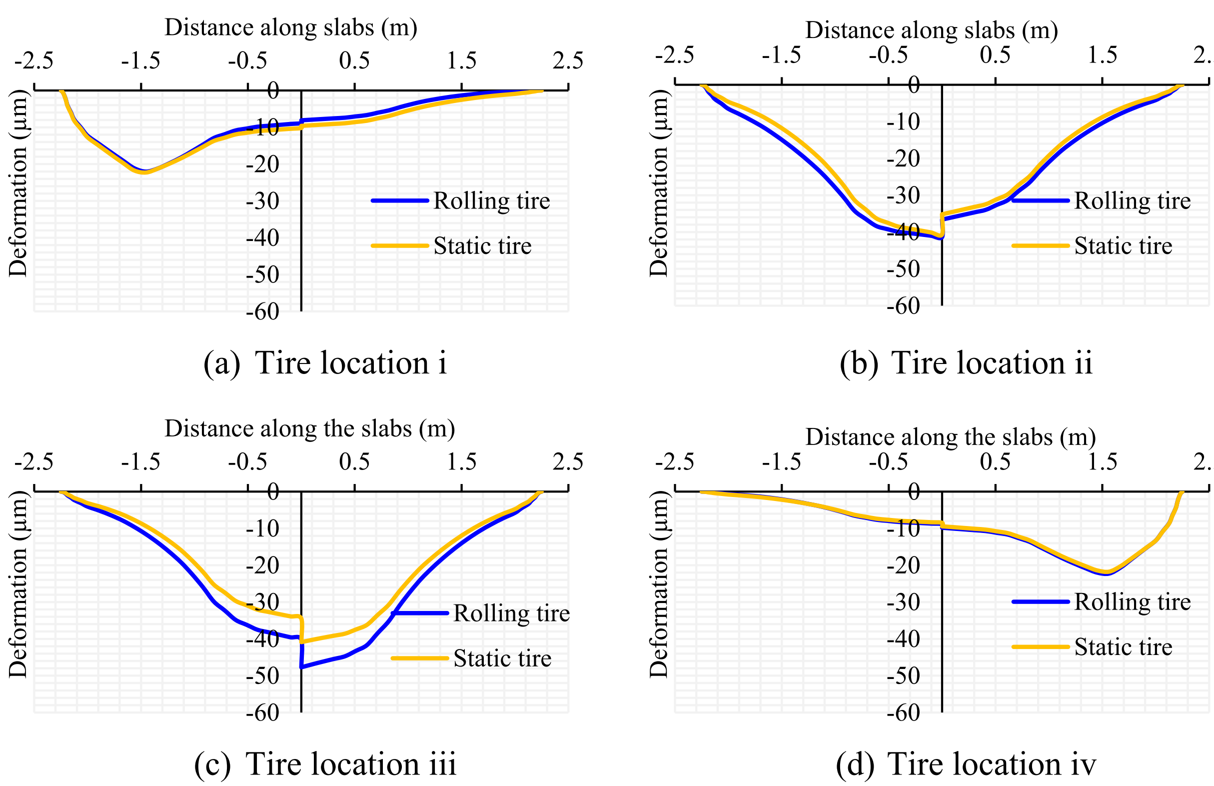


Fig. 8. Comparison of slab deformation for static and rolling tire conditions.

However, it is important to recognize that when the load is close to the fixed edges of the slab, significant boundary effects can occur. These effects may greatly influence the deflections observed, including the LTP values, as the constraints at the fixed edges alter the load transfer behavior. This consideration should be carefully accounted for when interpreting results near fixed boundaries.

Despite this, the above boundary effect can be disregarded in Fig. 7b and c, as it has minimal impact on the dowel bars. Consequently, we can conclude that a two slab model is sufficient for assessing the effectiveness of dowel bars at critical locations, especially when computational resources are limited. This consideration will be crucial as we advance from a 2 slab model to 3, 5 or 9 slab models as suggested in the past analytical studies [27–30].

3.3. Comparison of static and rolling tire effects on deflection basins

Fig. 8 provides a comprehensive comparison of the deformation patterns observed in the concrete slab at various locations under both static and rolling tire loading conditions. The analysis focused on a tire speed of 0 and 10 km/hr.

At first, it was observed that the deflection basin exhibited similarities between the static tire and the rolling tire. However, upon closer examination, differences were identified at various tire locations (i, ii, iii, and iv) between the static and rolling tire responses. Specifically, these differences were found to be −1.51 μm (18.66 %), 1.44 μm (-3.93 %), 6.83 μm (-14.32 %), and 0.39 μm (-3.96 %), respectively at various tire locations (i, ii, iii, and iv).

Notably, tire locations ii to iv displayed higher levels of deformation when subjected to rolling tire loading compared to static tire loading. This observation suggested that the dynamic nature of the rolling tire, as it traverses the concrete slab, induces slightly higher deflections in JPCPs due to the viscous nature of tire and inertial effects.

These findings reinforce previous research conducted by Yousefi Darestani [31], which similarly reported that rolling tire loading produces higher deformations in the structural response when compared to static tire loading. Overall, the results from this study provide valuable insights into the behavior of concrete slabs under static and rolling tire loading scenarios.

3.4. Comparison of static and rolling tire effects on dowel bar stresses

Fig. 9 showcases the stress distribution within an individual dowel bar beneath the tire, considering both static and rolling tire conditions. In this representation, negative values indicate compression of the dowel bar. In particular, the principal stress in the vertical direction was measured at the center node along the mid-length of the dowel bar (shown in Fig. 9), as this location typically experiences the highest stress concentration under loading. The vertical stress component is critical because it directly correlates with the effectiveness of the load transfer mechanism between adjacent concrete pavement slabs and is a key failure criterion [11,37]. Several observations can be made based on the findings from Fig. 9:

- The static stress in the dowel bar at the critical tire location (iii) is notably higher when compared to the stress levels at other tire locations (i, ii, and iv). Traditionally, in current practice, static stresses are typically calculated only at the critical location, specifically when the tire is placed on the free end of the dowel bar. The obtained results align with this standard practice of stress measurement at the critical location.
- For the rolling tire results, a distinctive sudden spike in the stress levels is evident, indicating the moment when the tire rolls over the dowel bar (the arrows in Fig. 9 shows the location of rolling tire with respect to time). This observation highlights that the rolling tire condition provides more valuable information compared to the static tire condition. The results obtained in this study corroborate past experimental and small-scale numerical studies [32–35], validating the importance of considering rolling tire effects for accurate stress analysis.
- The stresses obtained through the static method lead to a maximum underestimation of approximately −4.61 %. This is due to the fact that rolling tires introduce additional factors such as momentum, tire deformation, and dynamic loading, which are not captured by static models. This omission of dynamic effects in the static method results in lower stress estimations and is in line with the past studies [31]. This underestimation suggests that the static approach fails to capture the actual stresses induced in the dowel bars. As a consequence, the selection of material properties based on static results could lead to inaccuracies, potentially compromising the durability of the dowel bars and JPCP systems.

The insights gained from these results hold significance for evaluating potential innovative materials for future replacements of dowel bars. By understanding the true stress distribution under rolling tire conditions, researchers and engineers can make more informed decisions when exploring and adopting alternative materials that enhance

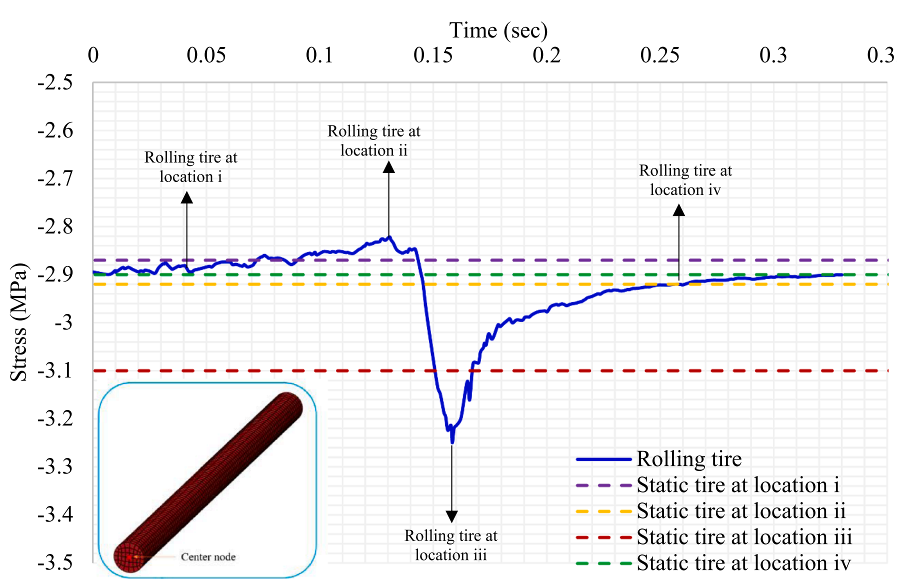


Fig. 9. Stresses in an individual dowel bar under the rolling tire (inner figure shows the mid-cross section of dowel bar and stress measurement location).

the longevity and performance of dowel bars and JPCPs.

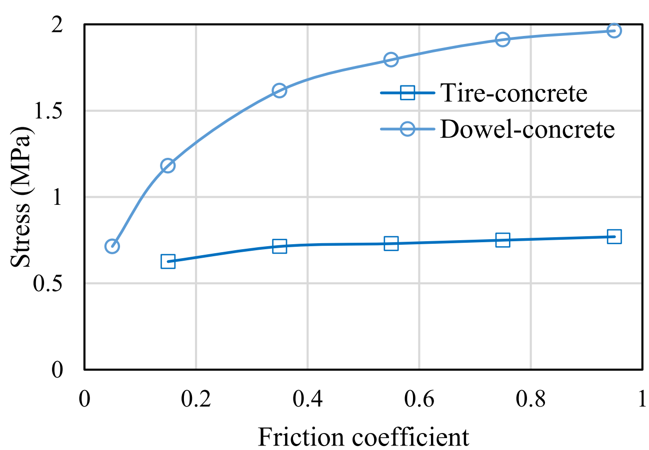
3.5. Parametric study on dowel bar stresses

A thorough investigation was carried out to evaluate the principal vertical stresses in the middle of the dowel bar as shown in Fig. 10, incorporating various parameters such as vehicle speed (ranging from 10 to 20 km/hr), load (5–30 kN), and friction coefficients between tire-concrete and dowel bar-concrete (varying from 0.05 to 0.95). The baseline values for the study were established at a vehicle speed of 40 km/hr, a load of 20 kN, and friction coefficients of 0.35 and 0.05 for tire-pavement and dowel bar-concrete, respectively. It was found that the overall impact of vehicle speed (-3.76 %) and friction coefficient between tire and pavement (7.30 %) on dowel bar stresses is minimal, while the impact of friction coefficient between dowel bar and concrete (63.63 %) and load (25.76 %) is substantial. Specifically, the results show an ascending trend for friction coefficients and load, while speed exhibited no significant difference. Further exploration and in-depth dynamic analyses for multiple slabs are needed to delve more profoundly into this aspect and comprehend the intricate mechanics influencing this phenomenon.

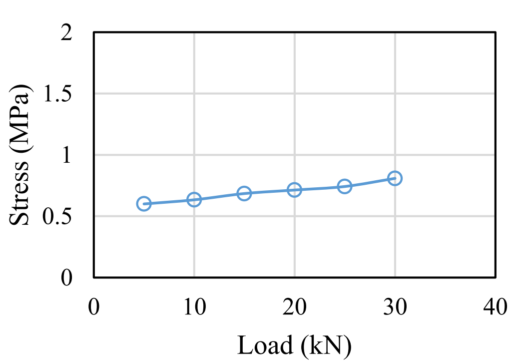
4. Conclusions

This research has focused on addressing the issue of load transfer in concrete pavements, specifically examining the role of dowel bars in achieving optimal load transfer and ensuring a comfortable ride for vehicles. The main objective of this ongoing research was to develop an advanced FEM framework that incorporates the interaction between tires and concrete pavements, enabling precise analysis of complex loading conditions and evaluating the impact of various rigid pavement parameters on load transfer. Based on the results and analysis presented in the paper, the following five highlights can be made:

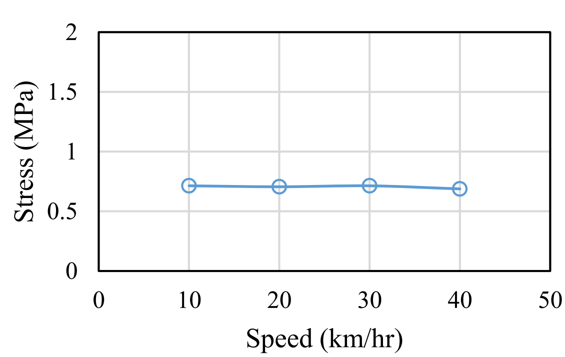
1. *Deflection Basin Analysis:* The analysis of deflection basins under rolling tires confirms that the developed model aligns with previous experimental findings, showing consistent deformation patterns. The asymmetry in deformation basins is influenced by the dowel bar's fixed or free behavior, with higher peak deformation observed on free slabs compared to fixed ones.
2. *Load Transfer Percentage:* The study reveals that load transfer percentages (LTP) vary significantly with tire position, with LTP decreasing as the tire moves away from the joint. Understanding these variations is essential in assessing the effectiveness of current dowel joints and the freedom allowed for dowel bars on the free end.
3. *Static versus. Rolling Tire Effects on Deflection:* Rolling tire loading results in slightly higher deflections compared to static loading due to dynamic factors like tire viscosity and inertial effects. This reinforces that rolling tire conditions should be considered for more accurate deflection analysis in concrete pavements.
4. *Static versus Rolling Tire Effects on Dowel Bar Stresses:* Rolling tires induce higher stress levels in dowel bars compared to static conditions, highlighting the importance of incorporating dynamic effects for accurate stress assessments and material selections.
5. *Parametric Study on Dowel Bar Stresses:* Vehicle speed and tire friction coefficients have a minimal impact on dowel bar stresses, while friction between the dowel bar and concrete, and load, significantly influence stress levels. This underscores the need for further dynamic



(a) Stress vs friction coefficients



(b) Stress vs tire loads



(c) Stress vs vehicle speed

Fig. 10. Stresses in an individual dowel bar for varying parameters.

analysis to understand the complex mechanics affecting dowel performance.

While the findings provide valuable insights into JPCP behavior under dynamic loading, further research and validation are required before these results can be directly applied in practice. This study lays the groundwork for future investigations that may eventually lead to practical improvements in rigid pavement design, dowel bar selection, and maintenance strategies.

Future works

This ongoing research will progress from the initial 2 slab model to more comprehensive 9 slab models. This expansion will lead to greater accuracy in simulating complex pavement systems, enabling the utilization of higher computational power and additional resources. Overall, the combination of refined meshing, sensitivity analysis for different pavements and tires, validation with rolling weight deflectometers, and the expansion to more sophisticated multi-slab models will contribute to a comprehensive and reliable FE model. This endeavor will ultimately enhance our understanding of rigid pavement behavior under various conditions, leading to improved JPCP design and maintenance practices.

CRediT authorship contribution statement

Ajayshankar Jagadeesh: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **WAAS Premarathna:** Writing – original draft, Validation, Software, Investigation, Formal analysis, Data curation. **Anupam Kumar:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization. **Cor Kasbergen:** Validation, Software, Resources, Formal analysis. **Sandra Erkens:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Prabhu M, Varma AH, Buch N. Experimental and analytical investigations of mechanistic effects of dowel misalignment in jointed concrete pavements. Transp Res Rec 2007;2037(1):12–29.
[2] Al-Humeidawi BH, Mandal P. Experimental investigation on the combined effect of dowel misalignment and cyclic wheel loading on dowel bar performance in JPCP. Eng Struct 2018;174:256–66.
[3] Yin W, Lu H, Yuan J, Huang B. Mechanical characteristics of dowel bar-concrete interaction: based on substructure experiment. Int J Pavement Eng 2022;23(7):2392–404.
[4] Saxena P, Hoegh K, Khazanovich L, Gotlif A. Laboratory and finite element evaluation of joint lockup. Transp Res Rec 2009;2095(1):34–42.
[5] Sii, H.B., Chai, G.W., van Staden, R. and Guan, H., 2014. Evaluation of doweled joints in concrete pavements using three-dimensional finite element analysis. In Design, analysis, and asphalt material characterization for road and airfield pavements (pp. 115-129).
[6] Sadeghi V, Hesami S. Investigation of load transfer efficiency in jointed plain concrete pavements (JPCP) using FEM. Int J Pavement Res Technol 2018;11(3):245–52.
[7] Liu B, Zhou Y, Gu L, Wang D, Huang X. Mechanical behavior of concrete pavement considering void beneath slabs and joints LTE. Adv Civ Eng 2020;2020:1–13.
[8] Singh A, Chandrappa AK. Effect of uniform vertical and longitudinal dowel misalignment in jointed plain concrete pavement. Int J Pavement Res Technol 2022:1–12.
[9] Xie P, Wang H. Comparative evaluation of mitigation methods for traffic-induced reflective cracking in airport composite pavement. Constr Build Mater 2023;390:131787.
[10] Srirangam SK, Anupam K, Scarpas A, Kasbergen C, Kane M. Safety aspects of wet asphalt pavement surfaces through field and numerical modeling investigations. Transp Res Rec 2014;2446(1):37–51.
[11] Srirangam SK, Anupam K, Casey D, Liu X, Kasbergen C, Scarpas A. Evaluation of structural performance of poroelastic road surfacing pavement subjected to rolling–truck tire loads. Transp Res Rec 2016;2591(1):42–56.
[12] Premarathna WAAS, Jayasinghe JASC, Wijesundara KK, Gamage P, Ranatunga RRMSK, Senanayake CD. Investigation of design and performance improvements on solid resilient tires through numerical simulation. Eng Fail Anal 2021;128:105618.
[13] Luhr, D.R., 2004. Design and construction of roller-compacted concrete pavements for container terminals. In Ports 2004: Port Development in the Changing World (pp. 1-10).
[14] Majer S, Budziński B, Gardas P. Loads and road design for intermodal container terminals with untypical heavy load traffic. Logist Transp 2020;45:103–10.
[15] Sullivan, B. and Leader, B., 2020. Development of an Improved Rutting Performance Model for Port and Container Terminal Pavements. DOI: 0.13140/RG, 2(13158.45126).
[16] Syed A, Sonparote RS. Development and early-age performance of an innovative prestressed precast concrete pavement. J Constr Eng Manag 2020;146(2):05019018.
[17] Sengun E, Kim S, Ceylan H. A comparative study on structural design of plain and roller-compacted concrete for heavy-duty pavements. Road Mater Pavement Des 2023.
[18] Hasheminasab S, Kashi E. Finite element analysis of ports pavement under container loading. J Eng, Des Technol 2021;19(2):497–508.
[19] Scavone M, Katicha SW, Flintsch GW, Amarh E. Estimating load transfer efficiency for jointed pavements from TSD deflection velocity measurements. Transp Res Rec 2023. 03611981231171923.
[20] Li M, Wang H, Xu G, Xie P. Finite element modeling and parametric analysis of viscoelastic and nonlinear pavement responses under dynamic FWD loading. Constr Build Mater 2017;141:23–35.
[21] Sun Z, Kasbergen C, van Dalen KN, Anupam K, Skarpas A, Erkens SM. A parameter identification technique for traffic speed deflectometer tests of pavements. Road Mater Pavement Des 2023;24(4):1065–87.
[22] Mabrouk GM, Elbagalati OS, Dessouky S, Fuentes L, Walubita LF. 3D-finite element pavement structural model for using with traffic speed deflectometers. Int J Pavement Eng 2022;23(12):4065–79.
[23] Scavone M, Katicha SW, Flintsch GW, Amarh E. On the TSD deflection velocity measurements: a revision to the current state of the art and discussion over its applicability for concrete pavement assessment. Int J Pavement Eng 2022:1–13.
[24] Mackiewicz P. Analysis of stresses in concrete pavement under a dowel according to its diameter and load transfer efficiency. Can J Civ Eng 2015;42(11):845–53.
[25] Manual, A.S.U.S., 2012. Abaqus 6.11. http://130.149, 89(2080), p.v6.
[26] Jagadeesh A, Ong GP. Skid resistance evaluation of pervious pavement mixtures using XRCT-based modelling. Asian Transp Stud 2021;7:100041.
[27] Shi XP, Fwa TF, Tan SA. Three-slab model for concrete pavements. J Transp Eng 1999;125(5):449–55.
[28] Zhang J, Fwa TF, Tan KH, Shi XP. Five-slab thick-plate model for concrete pavement. Road Mater Pavement Des 2000;1(1-2):9–34.
[29] Wei L, Fwa TF. Closed-form, six-slab, thick-plate solution for analysis of edge slab of concrete pavement. Transp Res Rec 2005;1919(1):2–15.
[30] Liu W, Fwa TF. Nine-slab model for jointed concrete pavements. Int J Pavement Eng 2007;8(4):277–306.
[31] Yousefi Darestani, M., Thambiratnam, D., Baweja, D. and Nata-Atmadja, A., 2006. Dynamic response of concrete pavements under vehicular loads. In Responding to Tomorrow's Challenges in Structural Engineering. International Association for Bridge and Structural Engineering Symposium-Budapest 2006 (pp. 104-107). IABSE.
[32] Guo J, Chan TM. Characteristics of compressive stress around dowel joint in concrete pavement system. Int J Pavement Eng 2022:1–17.
[33] Mackiewicz P, Szydło A. The analysis of stress concentration around dowel bars in concrete pavement. Mag Concr Res 2020;72(2):97–107.
[34] Mackiewicz P. Finite-element analysis of stress concentration around dowel bars in jointed plain concrete pavement. J Transp Eng 2015;141(6):06015001.
[35] Shoukry, S.N., William, G.W. and Riad, M., 2011. Application of LS-DYNA in Identifying Critical Stresses Around Dowel Bars. In 8th Int. LS-DYNA Users Conference.
[36] Premarathna WAAS, Jayasinghe JASC, Gamage P, Senanayake CD, Wijesundara KK, Ranatunga RRMSK. Analysis of factors influencing on performance of solid tires: combined approach of design of experiments and thermo-mechanical numerical simulation. Eur J Mech-A/Solids 2022;96:104680.
[37] Anupam K, Srirangam SK, Varveri A, Kasbergen C, Scarpas A. Microstructural analysis of porous asphalt concrete mix subjected to rolling truck tire loads. Transp Res Rec 2016;2575(1):113–22.