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The Role of Dowel Geometric Properties in Load Transfer: A Shear Force Perspective for Jointed Plain Concrete Pavements

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Abstract

This paper explores the influence of dowel geometric properties on dowel engagement and load transfer performance in Jointed Plain Concrete Pavement (JPCP). Dowels are essential components for engaging adjacent slabs and transferring loads across joints, directly affecting the pavement's mechanical behavior and service life. A three-dimensional finite element model was developed using EverFE to simulate the dowel–concrete interaction under load. Additionally, statistical analysis, including ANOVA performed in SPSS, was used to evaluate the significance of various geometric parameters: dowel length (45 and 55 cm), diameter (2 and 2.5 cm), vertical placement (top, middle, bottom), arrangement (even vs. wheel path), and vertical misalignment (0° and 5°). The results reveal that dowel length minimally influences shear engagement, while larger dowel diameters substantially enhance the system's ability to carry shear loads. Vertical misalignment reduces dowel participation and compromises joint performance. Dowels arranged evenly across the slab width and positioned at mid-depth show greater engagement and improved structural response. By analyzing the shear forces taken by dowels, this study highlights the critical role of geometry in dowel effectiveness, guiding optimized dowel design to ensure long-term pavement performance.

Keywords: Dowel bar engagement; Dowel geometry optimization; Finite Element Simulation; Jointed Plain Concrete Pavement (JPCP); Load transfer performance.

1. Introduction

Jointed Plain Concrete Pavement (JPCP) is one of the most widely used types of concrete pavement due to its relatively simple construction and cost-effectiveness. It consists of unreinforced concrete slabs, typically ranging from

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3.7 to 6.1 meters in length. Joints are introduced between the slabs to manage thermal expansion, shrinkage, and loading effects. Transverse joints are equipped with dowels, and the longitudinal joints with tie bars play a crucial role in maintaining slab alignment and ensuring efficient load transfer across the joints, according to Pavement Interactive (2024). When traffic moves across a joint, the load applied by the vehicle induces stresses in the concrete slabs. If not properly managed, these stresses can lead to differential settlement, cracking, and premature pavement failure, according to Bautista and Basheer (2008). Dowels embedded in the concrete at the joints transfer a portion of the load from the loaded slab to the adjacent one, thereby improving the structural response and extending the pavement's service life by We Are SDG (2025). This research focuses on analyzing how various geometric parameters of dowels affect load transfer efficiency (LTE). Load transfer is a complex interaction influenced by several factors, including the concrete type, jointing technique, the friction coefficient at the dowel-concrete interface, and dowel properties such as diameter, spacing, and material. In this study, special attention is given to the concept of dowel engagement, which refers to how effectively a dowel participates in resisting shear forces. The shear force in each dowel is analyzed as a key indicator of its engagement. According to Keymanesh et al. (2018), a higher shear force suggests more active participation in load transfer, thus indicating higher efficiency. By understanding how geometric characteristics influence this mechanism, the study aims to provide insights that can lead to more durable and efficient pavement designs.

2. Methods and Materials

A parametric study will be conducted to evaluate the influence of various geometric properties of dowels on LTE, and different combinations of these parameters will be systematically investigated.

2.1. Used software

For this study, EverFE was used as the primary software tool. EverFE is a three-dimensional Finite Element Analysis (FEA) program specifically designed to analyze JPCP. This software allows for the detailed simulation of stresses, displacements, and load transfer behavior across joints, making it particularly effective for evaluating the performance of dowel bars under various configurations. By accurately modeling the interactions between slabs, joints, and embedded dowels, EverFE provided valuable insights into the mechanical behavior of JPCP under different loading and environmental conditions, as demonstrated in prior research by Gu et al. (2019). A univariate variance analysis (ANOVA) was conducted using SPSS to verify the results. ANOVA assessed whether the means of different groups differ significantly, allowing the identification of which factors have a statistically meaningful impact on the outcome. This method strengthens the validity of the findings by confirming that observed differences are not due to random variation, as Pallant (2020) stated.

2.2. Input parameters

Based on a literature review, the input values for the EverFE software were determined. First, the parameters of the concrete slab were determined. This gave a width of 4,000 mm, a length of 5,000 mm, and a thickness of 200 mm by Agentschap Wegen & Verkeer (2021). The temperature coefficient is 0.0000099 per °C by Sahib and Tarefder (2016). According to Agentschap Wegen & Verkeer (2023), the parameters of the underlying layers were determined. Three layers were modelled: a 50 mm-thick asphalt base layer and two subgrade layers with 200 mm and 400 mm thickness, respectively. Further details on the properties of these layers are given in Fig. 1. For this study, the temperature was assumed to be constant. The slab's bottom and top temperature difference was at a fixed value of 0°C. For the dowels and tie bars, an E-modulus of 200,000 MPa and a nu coefficient (Poisson's ratio) of 0.3 were used, according to Pirdavani (2023). During this study, only the parameters of the dowels are adjusted. The parameters of the tie bars remain constant in all cases. A length of 80 cm, a diameter of 16 mm, and a spacing of 1 m were used, Agentschap Wegen & Verkeer (2021). The tie-slab support modulus was 1,000 MPa, the tie-slab restraint modulus was set to 10,000 MPa, according to Shaban et al. (2020). The boundary conditions in EverFE were defined to prevent rigid-body motion by restraining translational movement at the model base. The slab–base interface was modeled as unbonded, allowing for realistic horizontal movement of the slab relative to the supporting layer.

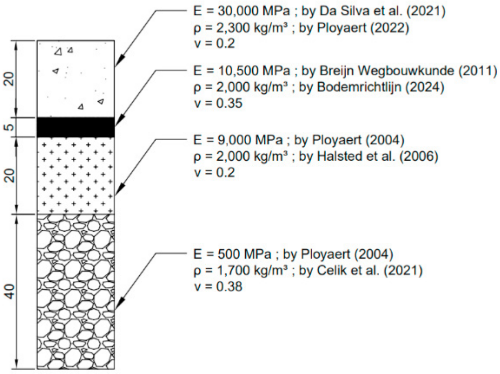
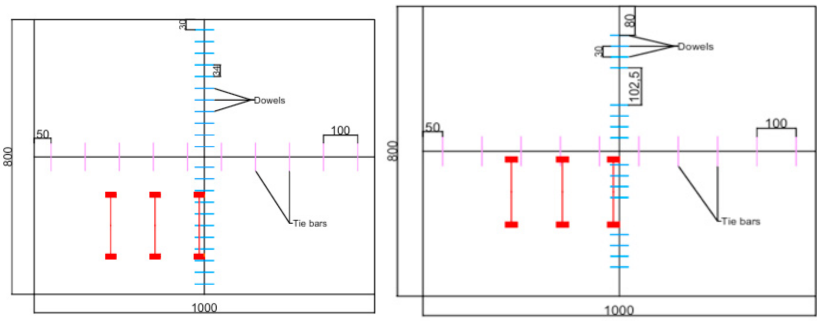


Fig. 1. Concrete road configuration with properties.

In this study, the longitudinal contact length of the tire with the ground was 30 cm, while the width of the lateral contact of the wheel with the ground was equal to 15 cm. The axle distance between the centers of the 2 wheels on the same axle was 180 cm. This study incorporated 2 distinct loading scenarios, both tridem axles with 40 kN load per tire, illustrated in Fig. 2. These scenarios accounted for the fact that vehicles do not always follow the same path. When defining the loading positions, potential vehicle swerving was taken into consideration. According to research by Kim et al. (2018) at the University of Florida, dowel bars can be installed in various configurations. Therefore, this study will evaluate two specific arrangements. The first is the even dowel configuration, in which dowels are evenly distributed across the entire slab width with a consistent spacing of 34 cm. The second is the wheel path configuration, where dowels are placed only beneath the expected wheel paths of vehicles. Given the potential for lateral movement within a lane, dowels in this setup were spaced at 30 cm to allow for slight deviations.



a b

Fig. 2. a) Loading place 1 and even dowel configuration, and b) Loading place 2 and wheel path dowel configuration.

For the vertical dowel placement in this study, the dowels were placed at different heights to test their impact on performance. In the first setup, the dowel was positioned 5 cm from the top of the slab. In the second setup, the dowel was located in the middle of the slab, while in the third setup, the dowel was placed 15 cm from the top. By testing these variations, we aimed to better understand the effect of dowel positioning on overall performance. In light of previous research by Da Silva et al. (2021) indicating potential misalignment of dowel bars within JPCP, this study aimed to examine the impact of such misalignment on dowel performance. Specifically, the investigation focuses on the effect of vertical tilt on LTE. To this end, various configurations were tested to assess the influence of dowel bar characteristics on structural performance. Two key setups were compared: one with aligned dowels (0° angle) and another with tilted dowels (5° upward angle), simulating potential misalignment. The study varied several parameters, including dowel length (45 cm and 55 cm), dowel diameter (2 cm and 2.5 cm), dowel placement within the slab (top, middle, bottom), dowel arrangement (even spacing versus wheel path), and loading location (positions 1 and 2). Based on these parameters, multiple combinations of input values were generated, resulting in 48 distinct scenarios per loading location. These combinations will be systematically tested using EverFE simulations to identify the optimal settings that maximize structural performance. By analyzing these variations, the study aimed to quantify the effects of dowel misalignment and geometry on pavement behavior, contributing to improved design and construction practices.

2.3. Simulated scenarios

The next step involved testing all scenarios using the EverFE software. It is essential to know which output parameters apply to this study. Based on research, 3 output parameters have been chosen that are relevant to this study. Research showed that dowels' geometric parameters influence LTE. This influence can be determined by determining the deflection and stress-based LTE for each scenario, Yaqoob et al. (2024). To determine the stress-based LTE, the maximum stress at the bottom of the slab was determined from both the loaded and unloaded slab at a distance of 100 mm from the joint. For the deflection-based LTE, the deflection of both the loaded and unloaded slab was determined at a distance of 50 mm from the joint. The magnitude of the shear forces in the dowels can also represent LTE. Research by Keymanesh et al. (2018) shows that the dowel's shear force reflects how actively a dowel participates in load transfer through the joint. The shear force was measured in the dowels both to the left and right of the joint and at the joint.

3. Results

The results will show which parameters will most impact shear forces and, consequently, LTE. The results showed that LTE coming from deflection and stress remains approximately the same for all different scenarios. This striking result was also the reason for looking at the shear forces, from which conclusions can also be drawn for LTE. Shear forces were collected for all dowels in each configuration, and the maximum shear force observed among them was used as the representative value for the entire system, given that the forces on the other dowels were found to be proportional to this maximum. A statistical analysis was conducted using SPSS Univariate ANOVA to identify which factors significantly influence the shear forces. The results of this analysis are presented in Table 1, indicating which parameters have a statistically significant effect on LTE.

Table 1. Results of the Univariate ANOVA analysis.

Parameter	β	Std. Error	t	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Intercept	-24.78	2.693	-9.2	<0.001	-30.14	-19.43
Loading 1	4.477	1.905	2.40	0.021	0.692	8.26
Loading 2	0[a]					
Dowel length: 45cm	0.077	1.905	0.04	0.968	-3.71	3.86
Dowel length: 55 cm	0[a]					
Dowel height: top	-22.64	2.333	-9.70	<0.001	-27.27	-18,0
Dowel height: middle	-23.47	2.333	-10.1	<0.001	-28.08	-18.81
Dowel height: bottom	0[a]					
Arrangement: even	-13.70	1.905	-7.19	<0.001	-17.48	-9.91
Arrangement: wheel path	0[a]					
Misalignment: 0°	.-9.503	1.905	-4.99	<0.001	-13.29	-5.72
Misalignment: 5°	0[a]					
Diameter: 2 cm	10.435	1.905	5.479	<0.001	6.65	14.22
Diameter: 2.5 cm	0[a]					

[a]: reference parameter value.

The analysis showed that the length of the dowels has no direct influence on shear forces and, consequently, on LTE, as its significance level is substantially high. The other parameters had significance values lower than 0.001, i.e., they substantially influence LTE. Thus, when comparing the values within a parameter, this can be done as a function of length since it has no influence. The loading places were not compared with each other because this study is about the dowels' geometric parameters, and the load's location can also not be predicted precisely because not every vehicle will drive at this exact location.

3.1. Diameter

Fig. 3 compares shear forces by dowels with a diameter of 2 cm and a diameter of 2.5 cm. This shows that a dowel of 2.5 cm has a higher absolute value of shear force and, therefore, will contribute more to LTE.

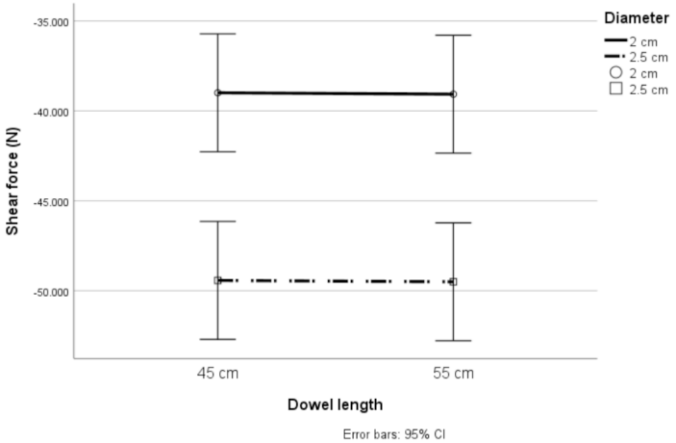


Fig. 3. Maximum shear forces for different dowel diameters as a function of the length.

3.2. Misalignment

When a dowel without misalignment is compared with a dowel with a vertical misalignment of 5°, it can be concluded that misalignment negatively impacts LTE. This is because the absolute value of the maximum shear force is lower for the misaligned dowels than for the straight-aligned dowels. This analysis is also shown in Fig. 4.

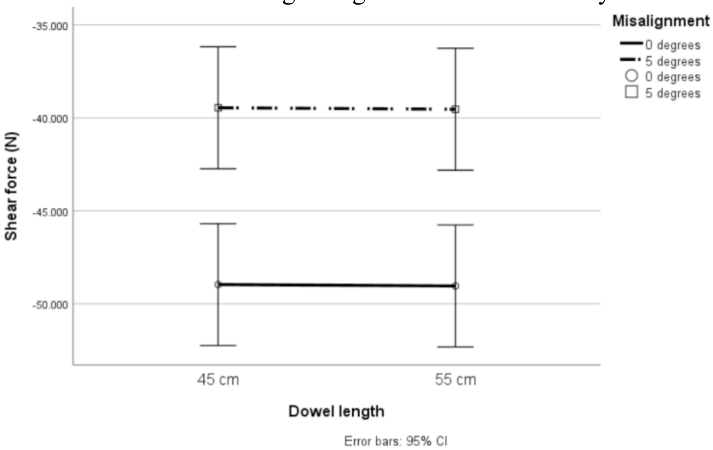


Fig. 4. Maximum shear forces for different dowel misalignments as a function of the length.

3.3. Dowel arrangement

Fig. 5 shows the difference in maximum shear force between an even path dowel configuration and a wheel path dowel configuration. It can be seen that the dowels contribute more to LTE in the even path configuration.

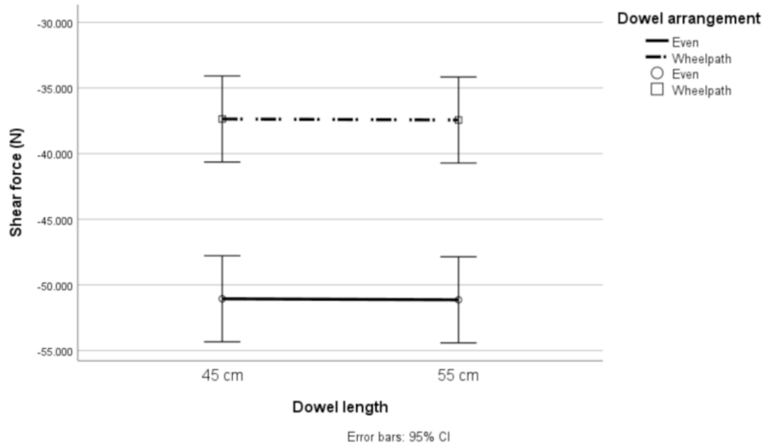


Fig. 5. Maximum shear forces for different dowel arrangements as a function of the length.

3.4. Dowel place in height

The difference in the height of the dowel is shown in Fig. 6. It is clear that dowels placed at the bottom of the slab contribute less to LTE than those placed in the middle or at the top. The dowel in the middle has a slightly higher absolute value in shear force than the dowel at the top, but this difference is minimal.

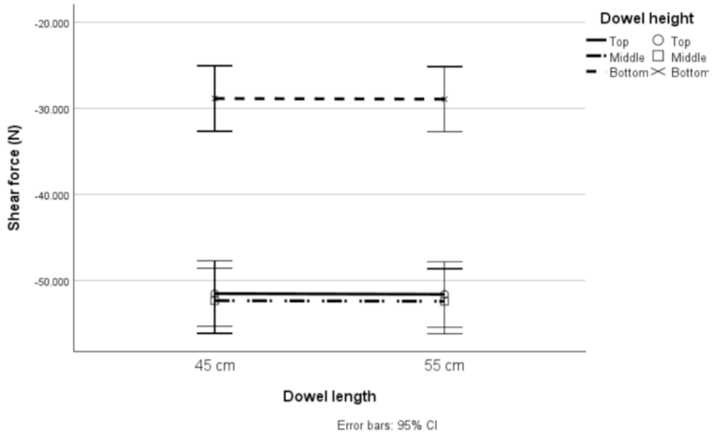


Fig. 6. Maximum shear forces for different dowel heights as a function of the length.

4. Discussions

Given the uniformly high stiffness of all pavement layers, traditional LTE metrics based on deflection and stress showed minimal variation across different configurations. We focused on analyzing the dowel shear forces (Fs) at the joints to capture more meaningful differences in system behavior. Since the Fs trends were consistent across all dowels within each configuration, the maximum Fs value at the joint was selected as a representative performance indicator. Higher maximum Fs values are interpreted as evidence of stronger mechanical engagement of the dowel system, reflecting a greater portion of the applied load being transferred through the dowels rather than substructure deformation. This approach aligns with established literature by Lorenz (2014), Hu et al. (2017), and Lorenz (2015), which identifies dowel shear force as a critical parameter in assessing the performance of load transfer systems in jointed concrete pavements. Consequently, configurations exhibiting higher maximum Fs values demonstrate superior structural participation of the mechanical load transfer components.

4.1. Dowel length

The results showed that length has almost no effect on LTE. This is due to the fact that the bending and shear stresses are concentrated in the part of the joint opening and the surrounding concrete immediately near the joint. The stresses decrease rapidly as one moves farther from the joint, stated by Hammons (1997). Therefore, because the stresses decrease dramatically further from the joint, there will be minimal LTE difference between 45 and 55 centimeters dowels.

4.2. Diameter

Based on the statistical analysis, it can be concluded that the dowel diameter significantly influences LTE. A larger diameter has a positive influence on LTE. This is because a larger diameter is associated with a larger cross-section of the dowel. This causes the dowel to experience smaller shear stress than a dowel with a smaller diameter but equally large shear force. A larger diameter also provides a more rigid joint, as highlighted by Yaqoob and Silfwerbrand (2025).

4.3. Misalignment

Vertical misalignment of dowel bars in JPCP reduces LTE, leading to uneven stress distribution along the contact surface between the dowel and concrete. This creates increased bending stresses and point loads, which reduce the effectiveness of the dowels. In return, this results in less efficient load transfer between adjacent slabs, according to Yaqoob et al. (2024). When a dowel is vertically misaligned, it only partially touches the concrete or is at the wrong angle. This causes a concentration of forces on small surfaces, which more quickly leads to less efficient load transfer between concrete slabs.

4.4. Dowel arrangement

The more dowels are present in the slab, the more they will effectively participate in transferring shear forces. As a result, the load is distributed more evenly across the joint, leading to improved LTE. In other words, more dowels enhance the slab's ability to transfer loads smoothly and reduce differential deflection between adjacent slabs.

4.5. Dowel place in height

The results show that the vertical position of dowels in the slab influences the LTE significantly. This confirms a prior study that concluded that a dowel placed at the top of the slab provides additional tensile stresses in the loaded slab. This would increase the probability of tensile fatigue, which in turn could eventually lead to the loosening of the dowel, which would then reduce LTE. Conversely, when a dowel gets placed at the bottom of the slab, the shear force carried by the dowels tends to decrease. In this position, the dowel is misaligned with the critical shear zone, reducing its engagement in the load transfer mechanism. This leads to a more pronounced differential deflection between adjacent slabs and a decline in overall LTE. The optimal position for a dowel is at the mid-depth of the slab. This ensures effective shear transfer, balanced stress distribution, and maximized LTE while minimizing the risk of joint damage, Singh and Chandrappa (2023).

5. Conclusion

This study aimed to determine the influence of different geometric parameters of dowels on Load Transfer Efficiency (LTE) using a series of scenarios modeled in EverFE. The findings lead to the following conclusions:

- Dowel length minimally influences LTE, as stresses are concentrated near the joint and decrease with distance, so dowel length's impact on shear forces is minimal.
- Larger dowel diameters enhance LTE by providing a stiffer connection and greater capacity to resist shear forces.
- Vertical misalignment reduces LTE; precise dowel alignment is critical for long-term pavement performance.

- Evenly spaced dowels across the full lane width yield higher LTE since more dowels share the load.
- Dowels placed in the mid-height of the slab result in the most balanced load distribution and the highest LTE.

While these insights are valuable, several limitations should be noted. The simulations were conducted under idealized boundary conditions in EverFE and did not capture real-world variability such as construction tolerances, material inconsistencies, or environmental effects. Time-dependent behaviors like creep, shrinkage, fatigue, and wear were also excluded, though they can influence LTE over time. Furthermore, the study focused solely on geometric parameters, leaving out factors like dowel–concrete bond behavior and sublayer stiffness.

Future research should consider these additional factors and include experimental validation or probabilistic approaches to strengthen the applicability of the findings. By quantifying how dowel geometry impacts LTE, this study provides a basis for optimizing dowel design in JPCP, ultimately contributing to longer-lasting, safer, and more cost-effective concrete pavements.

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