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Modeling of Dowel Jointed Rigid Airfield Pavement under Thermal Gradients and Dynamic Loads

Ahmed Ebrahim Abu El-Maaty[a*], Ghada Mousa Hekal[a] and Eman M.Salah El-Din[a]

Faculty of Engineering, Civil Engineering Department, Menoufia University, Shibin Elkom City, Egypt.

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Abstract

Concrete pavements have been widely used for constructing runways, taxiways, and apron areas at airports. The aviation industry has responded to increased demand for air travel by developing longer, wider, and heavier aircraft with increasing numbers of wheels to support the aircraft while in ground operation. Many researchers developed their models based on the finite element method (FEM) for the analysis of jointed concrete pavement. Despite the notable improvement, important considerations were overlooked. These simplifications may affect the results of the developed models and make them unrealistic. Sensitivity studies were conducted in this study to investigate the effect of the loading parameters on the load transfer efficiency (LTE) indictors where concept of LTE is fundamental in airfield design procedures. Development of the three-dimensional computational model was guided by a set of technical requirements, all of which were met in the final model with using the finite element code ABAQUS (6.13). The effect of main gear loading magnitudes in different wheel configurations combined with positive and negative thermal gradients was investigated. The verification process was presented to increases the confidence in the model results. Understanding the response of rigid airfield pavement under such circumstances is important developing a new pavement design procedure, as well as implementing a suitable remedial measure for existing pavements. The results obtained that utilizing a dynamic load allows studying the fatigue cycles that pavement can be subjected under different wheel configurations. This allows examining the cycles of tension-compression due to wheel loading which may reduce the strength of the concrete and develop more fatigue damage than considering a static load imposed only in one direction, i.e. no stress reversal is involved. Moreover, the change in the thermal gradient from positive to negative significantly changed the slab curvature shape. The critical case in the stress was found in the combination of the wheel load and the positive thermal gradient.

Key words: Finite Element Modeling; Dynamic Loads; Thermal Gradients; Airfield; Jointed Concrete Pavement; Load Transfer Efficiency.

1. Introduction

The function of airport pavements is to provide a firm support to accommodate satisfactorily trafficking aircraft loads throughout its operational life. Pavement design procedures are developed to fulfill the above criteria (AC 150/5320-6E, 2009). Rigid pavements are complex structural systems that consist of numerous different concrete slabs where longitudinal and transverse joints are supplied between them, which may or may not include dowel bars. Dowel bars connect the slabs also transfer the applied loading across the joint mainly by shear. The concept of load transfer is straightforward: when the load is applied to a concrete slab, stresses and deflections are decreased if a fraction of this load is transmitted to an adjoining slab. Load transfer is essential to the FAA pavement design procedure. Load transfer is a complicated phenomenon that varies with concrete material, age, environmental conditions, as thermal gradient, shrinkage and moisture content, quality of construction, magnitude and configuration of the wheel load, and the way of jointing [1, 2]. In 1926, Westergaard developed a response model for rigid pavement of a slabs-on-grade applied by wheel loading and simulating the paving layer as a thin, infinite or semi-infinite plate based on a bed of springs [3]. It was suggested that a 25 % of the load transfers to the adjacent slab was an appropriate design value for

* Corresponding author: maaty5000@yahoo.com

load transfer [4]. The federal aviation administration (FAA) developed a new design procedure program called (FAARFIELD). However, it continues to consider the 25 % of the load transfers to the adjacent slab through the joint. The field stress based LTE values for CC2 test items at NAPTF was found considerably higher than 0.25 [5]. Moreover, the design procedure is based on static analysis assuming that the speed of the wheel is zero. However, load transfer takes place mainly under moving vehicles. The stress-based load transfer efficiency may not remain constant at 0.25 as it depends on aforementioned external factors. The finite element has become an advanced method, which is used for rigid pavement analysis since the early 1970s. Despite the notable improvement, some serious sides of the pavement modeling have been overlooked. Previously developed models either have ignored modeling the dowel bar or modeled their action by a beam or spring elements and, consequently, the interface between the dowel and the surrounding concrete is not modeled. Such simplifications may disturb the results obtained at the joint and make it unrealistic. The foundation representation usually as Winkler foundation, the effect interaction with the slab or base was not accounted in the modeling. Also, simulation of the lift-off of the pavements, especially when curling or warping due to thermal gradients was not accounted for [6, 7].

The moving-axle load is applied on the slab as a static load or as a short duration pulse applied at a particular position on the slab. Although these methods represented pavement response due to dynamic loads, they could not capture some significant details in analyzing the modes of failure of concrete pavements such as the effect of dowel bar vibration on the stiffness of the surrounding concrete. Most of the previous studies used low-grade meshing element, using poor grade element without a suitable type of formulation and integration affect the accuracy of the obtained results and the time which the model take until it converges. Load transferred across the transverse joints which was through aggregate interlock has been modeled by shear spring elements; this approximation does not simulate the actual behavior of aggregate interlock [8, 9].

This research focuses on the effect of loading parameters on load transfer efficiency of indicators of jointed rigid airfield pavement. These loading parameters include the main gear loading magnitudes in different wheel configurations combined with positive and negative thermal gradients. The 3D, nonlinear, dynamic, finite elements (FE) model was established to study the pavement response with dowelled joints. ABAQUS is a general-purpose finite element code, which is used in this research. This software provides numerous interactions, constraints, mesh generators, and different loading conditions, which make it suitable to carry out a complicated dynamic analysis.

2. Literature Review

The finite element analysis (FEA) methods offer a solid basis for understanding rigid pavement behavior. Recent FEA methods have been proven as reliable tools for prediction of pavement responses such as stresses, strains, deflections under traffic and environmental loading. These finite element programs make use of various foundation models as well as joint models and the predicted data such as stresses due to edge and interior loading, strain distribution, deflections has been proven to be valid by experimentally measured data. Brill et al. 2001 [10] presented a correction in dowel-concrete interaction stiffness to account for bearing of dowel on both loaded as well as unloaded slab. 2D -FE program JSLAB was used to compute the load transfer efficiencies and compared it with dimensionless parameter comprising of ratio of equivalent joint stiffness and product of radius of relative stiffness and subgrade modulus. The results of this analysis also demonstrated that load transfer efficiency based on deflection was insensitive to slab size. Moreover, doweled joints transfer load more uniformly than interlock joints but they did not necessarily increase the load transfer efficiency.

Jeffery et al., 2007 [11] study's objective was to identify key slab loading locations on airfield rigid pavements. Five individual aircraft gear geometries (e.g., dual, dual tandems, triple dual tandems) and four main landing gear (e.g., B-777, A-380, MD-11, and B-747) analyses were conducted for a given slab configuration, pavement geometry, and materials. The numerical results show that the ratio between the top of the slab and bottom tensile stresses were significantly higher for the main landing gear analysis relative to the individual gear analysis. Furthermore, this initial finite element analysis has shown consideration of the entire main landing gear of the aircraft is necessary if the top tensile stresses are going to be accurately predicted. The 2-D finite element analysis program ILLISLAB was used for the initial analyses, but NIKE3D (3-D finite element analysis program) would be used for future numerical simulations and verification of the 2-D analyses. Maitra et al. 2009 [12] examined the effects of different parameters on load transfer efficiency of a joint with the help of a three-dimensional finite-element model for the analysis of a dowel-jointed concrete pavement. The model was compared using experimental data. The group action of the dowel bar system was also examined and useful relationships have been developed for estimation of the relative load shared by the individual dowel bars. These relationships will be useful in the design and evaluation of dowel jointed concrete pavements by ANSYS.

Caliendo et al. 2010 [13] investigated two specific three-dimensional finite-element models for making an evaluation of the maximum stresses at critical locations in concrete slabs. Concrete airport pavements with square-shaped slabs were studied. A homogeneous, isotropic elastic half-space was assumed as a subgrade model so that the influence of variation in young's modulus was examined in contrast with Winkler's reaction modulus. The effects of two aircrafts A380 and B747, different subgrade bearing capabilities and temperature gradients were investigated. Combined stresses due to aircraft load and temperature gradient were accurately estimated by means of a finite-element software "ABAQUS" and compared to their separate actions. Therefore, the incorrect applicability of the principle of effects superposition, which was due to the support soil that was nonresistant to tensile stress, is quantified. Moreover, the difference in the values of the stresses due to the two different aforementioned aircrafts was calculated. Load-transfer efficiency (LTE) of jointed concrete pavement is typically measured by the ratio of unloaded and loaded slab deflection. However, the maximum tensile stress in a slab is one of the critical mechanical responses that influence the performance of the jointed concrete pavement. Therefore, stress-based load-transfer efficiency is often considered an appropriate way to quantify LTE. Strain gauge data from full-scale tests collected by the federal aviation administration were analyzed by Wadkar et.al, 2011 [14] to compute the stress-based LTE of joints under moving loads. The effect of static aircraft gear loads and slab size on the LTE of joints was analyzed by using a two-dimensional finite-element program JSLAB. Fem-calculated stress-based LTE under static aircraft loading on average was 38% lower than that measured under moving loads. LTE values were similar under various gear positions, gear configurations, and different slab sizes.

Finite element models of Jointed concrete pavement were developed by Youngguk et al. 2013 [15] using ABAQUS considering very detailed modeling of dowel bars and their contact characteristic to concrete. Using the models, transverse stresses at joints that could induce longitudinal cracking were comprehensively analyzed. The results showed that primary causes of longitudinal cracks at joints were found related to the vertical translation of dowel bar and the curling of the JCP slab due to environmental loading. Other factors affecting those cracks included concrete elastic modulus, concrete thermal expansion coefficient, foundation stiffness, vertical temperature gradient, and bond characteristic between concrete and dowel bar. To mitigate longitudinal cracking at joints, dowel bars should be installed at the mid-depth of the slab and cares must be taken when installing dowel bars to prevent their vertical translation.

3. Finite Element Model

A 3D nonlinear, dynamic, finite element model was developed to study the pavement response with doweled joints. Several researchers used over time ABAQUS to model joints for a comprehensive analysis of joints in jointed plain concrete pavements (JPCP). This software provides numerous interactions, constraints, mesh generators, and different loading conditions, which make it suitable to carry out a complicated dynamic analysis. Creating a realistic model and calibration of model parameters is necessary for obtaining accurate dynamic and damping behavior of rigid pavements. To obtain correct model parameters such as element type, mesh size, interactions between foundation layers, boundary conditions, joint stiffness value and damping parameters, a series of steps were performed.

The pavement system was selected based on a typical rigid pavement designed for usage in Egypt. The developed model contains two dowels-jointed concrete slabs resting on base, subbase and subgrade layers as shown in Figure1. For dodging difficulties related to boundary conditions, the pavement slabs were represented by their full widths of 5.0 m with full lengths of 5.0 m. The base, subbase, and subgrade shaped slightly wider than the slab to enable a better distribution of the stresses and widened by 0.5 m for each edge of the slab. The two adjacent slabs were connected with 14 dowel bars placed at 350 mm spacing center to center, at mid-height of the slab. The dowel bars were 32 mm in diameter and 500 mm in length, the slab thickness is 340 mm. The slabs lay on top of a 150 mm-thick of the base layer. Extension of the subbase is 250 mm. The extension of the subgrade is 2.5 m to ensure better simulation of subgrade responses as an approximation of the infinite foundation. The primary model had zero gaps between the two adjacent slabs to take combined effect of aggregate interlock and dowel bar as load transfer efficiencies devices [16].

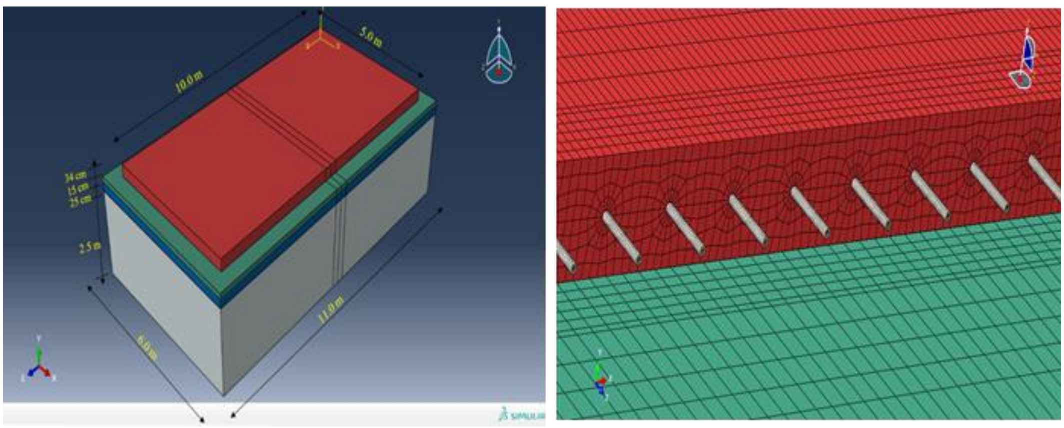


Figure 1. Three-Dimensional Model Assembly and the Detailed the X-Y View of the Assembly

3.1. Material Modelling

In ABAQUS, many constitutive models have been established to define the nonlinearity actions of concrete such the smeared crack concrete, the brittle cracking, and the concrete damaged plasticity model. In this study, concrete damaged plasticity model is used as it is set for applications where concrete is applied to arbitrary loading conditions, as cyclic, and/or dynamic loading. The concrete model of damaged plasticity can be incorporation with material damping based on ABAQUS User's guide, 2013 [17]. The main parameters required for defining the plastic-damage model were Dilation angle, Eccentricity, Fb/fc, K, Viscosity parameter. These parameters are assumed 38^{o}, 0.1, 1.16, 2/3 and zero respectively. Also concrete compression hardening and damage was defined as well concrete tension damage and stiffening [18, 19].

Federal Aviation Administration functions a state-of-the-art; full-scale pavement test facility concerned with airfield pavement only at research National Airport Pavement Test Facility (NAPTF). A construction cycle 6 includes test pavement and instrumentation layout and materials testing data. Items used in the test are set by the 3-letter sign of MRS (medium-strength subgrade, rigid pavement, stabilized base), then a number and a letter. The number (1, 2, and 3) corresponds to the goal strength of the concrete (500, 750 and 1000 psi respectively) (NAPTF-Databases). In this study, CC6 data is used as concrete model input for the elastic behavior. The density is used to apply the self-weight loading on the concrete.

FAARFIELD program includes three items usually used in designing rigid pavement thickness, Item P-306 of Econocrete Subbase, P-304 of Cement-Treated Base and P-301 of Soil-Cement Base [16]. The base materials were represented as elastic isotropic models. Subbase and subgrade layers were modeled by using solid brick elements. The supporting soil was modeled as a homogeneous, isotropic elastic material. Data obtained from FAA report on developing FEDFAA program for rigid pavement model evaluation [20]. The usage of the solid brick elements to model dowel bars correctly mimics the interaction between dowel bars and the surrounding concrete. Dowel bars were represented using elastic isotropic material models [21]. The properties constants used are listed in Table 1.

Table 1. Concrete, Base, Steel Properties Used for the Finite Element Model

Cases	Parameter	Value
PCC slab (MRS-1)	Modulus of elasticity	**3,800,000 psi**
	Poisson’s ratio	**0.15**
	Density	**2400 kg/m^3**
(MRS-2)	Modulus of elasticity	**5,700,000 psi**
(MRS-3)	Modulus of elasticity	**7,600,000 psi**
Item P-306	Modulus of elasticity	**700,000 psi**
	Poisson’s ratio	**0.2**

Cases	Parameter	Value
P-304	Modulus of elasticity	500,000 psi
P-301	Modulus of elasticity	250,000 psi
Steel bar	Modulus of elasticity	210,000 MPa
	Poisson’s ratio	0.3
p-209 subbase	Modulus of elasticity	14,474
	Poisson’s ratio	0.35
Very low-subgrade	Modulus of elasticity	4,500
	Poisson’s ratio	0.4

3.2. Modelling of Interfaces

The interface between half of the dowel bar in a slab and concrete modeled as a perfect bond and the other half in the neighboring slab could move along the dowel bar’s axial direction. The tangential behavior of the dowel modeled using Coulomb frictional contact between the surfaces. Gravity load applied to activate the Coulomb friction model and generate the appropriate contact forces. The different friction coefficients were taken as 0.3 for the perfectly bonded side and 0.05 for the free side of the dowel. Separation was allowed between the surfaces [22]. The normal behaviour of the load transfer device modeled using hard contact pressure definition between the two surfaces. For this purpose, special surface-to-surface elements were used to model hard contact behavior. The tangential behaviour of surface between the slab and base was modelled as Isotropic Coulomb friction. No shear stress limit is included. According to 1993 AASHTO pavement design guide, a range of 0.9 and 2.2 of the friction coefficient between the slab and base interface and its variance rely on the base type. For this study, it was assumed as 1.5. Loss of contact between slab and base modeled using normal hard contact that allows the surfaces to separate after coming in contact [23]. No separation was permitted between foundation layers. The interaction between the top of the subbase and the bottom of the base, the interaction between the lower surface of the subbase and the upper surface of subgrade were simulated by the use of hard contact interface elements and isotropic Coulomb friction model, the coefficient of friction was assumed 1.5. The sides between the two neighboring slabs at the joint were considered to have a zero gap with a Coulomb friction of 1.5 mimicking a restricted aggregate interlocking [24].

3.3. Meshing of the Model

Meshing irregularities in the model in a non-uniform way can create stresses does not exist in real structures. Wedge elements with very fine meshing were selected for the dowel bars to ensure the regular distribution of mesh element around dowel bar; the fine mesh permits precise calculation of the interaction stresses that progress around the dowels. Second-order elements naturally perform better than First-Order elements in models with stress concentrations. However, in contact problems, convergence difficulties may arise with these elements. So first order 6-node linear triangular prism elements are used for the dowel bars meshing [17]. Reduced-integration elements lean to be in some way more capable. At lower computational cost, outputs are frequent as efficient as or better than full integration. Hourglassing can also be reduced by distributing point loads and boundary conditions over some adjacent nodes. So, eight-node linear continuum three-dimensional brick element (C3D8R), reduced integration, and hourglass control available in ABAQUS (6.13) are used for discretizing the concrete slabs. Realizing the fact that the joints, the area around the dowels and loading path are critical stress zones that can initiate pavement failure, a refined mesh was developed in these areas, to capture the flow of stresses accurately around the dowel bars. This element has the capability of simulation of large deformation, geometric and material nonlinearity. All layers under the pavement (base, subbase and subgrade) were simulated with the same element type to preserve the continuity of nodes between consecutive layers. Figure 2 demonstrations the cross section at the pavement joint and its meshing details.

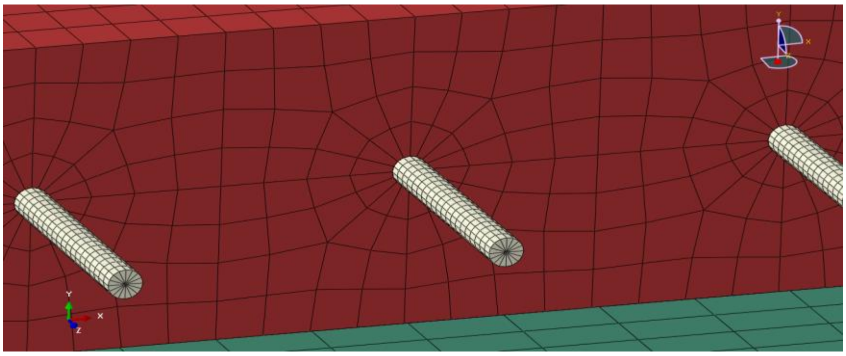


Figure 2. Meshing Details across the Dowelled Pavement Joint

3.4. Boundary Conditions

The bedrock was assumed deep enough to simulate semi-infinite boundaries, which mimic the natural extension of layers. All translational degrees of freedom were restricted at the lower surface of the subgrade layer. The sides of subgrade boundaries were constrained in their Y-direction and were applied to the sides of the base as well as all side surfaces of the subbase. As portions of the concrete slab may lose contact with the base. Therefore, No exterior restrictions are used at the slabs whose stability is preserved by its interaction with the base and starting the slab own-weight. The dowel bars were connected to the slab by the interaction properties and stabilized by their weight; no further boundary conditions were applied.

4. Analysis Method

The starting point for each general step is the deformed state at the end of the last general step. Therefore, the state of the model evolves in a sequence of general steps as it responds to the loads defined in each step. Any initial conditions define the starting point for the first general step in the simulation. All general analysis procedures share the same concepts for applying loads and defining “time.” In all cases of analysis, ABAQUS/CAE creates a special initial step at the beginning of the model's step sequence and names it initial. The initial step allows defining boundary conditions, predefined fields, and interactions that are applicable at the very beginning of the analysis. The initial step is followed by one or more analysis steps. Each analysis step is associated with a specific procedure that defines the type of analysis to be performed during the step, the second step in all cases in this study is set for applying gravity loads and stabilization of the model, the step type is general/ static. The following steps are dedicated for application of the case parameters and conditions. The nonlinear effects are expected, such as large displacements, material nonlinearities, boundary nonlinearities, contact or friction, the NLGEOM command is be used to accounts for geometric nonlinearities. Once the NLGEOM option is set for a step, setting remains in effect for all subsequent steps [17].

4.1. Aircraft Loading

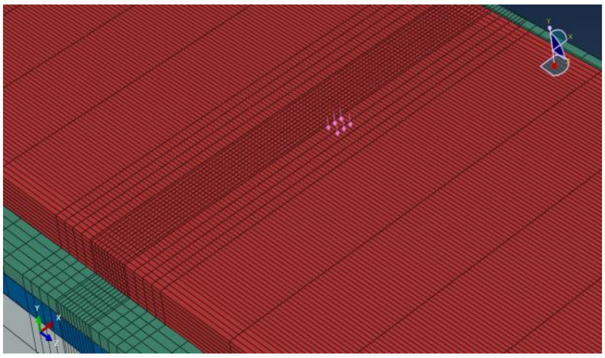
The moving tire is to be modeled as tire imprint area to represent a smooth pavement surface. Traditionally, the contact stresses at the wheel–pavement interface is assumed to equal to the tire pressure and is distributed on a regular basis in a rectangular contact area. The contact area used in this research was designed using the Portland Cement Association method [23]. This technique assumes that the wheel-pavement contact area "Ac", that calculated by dividing the load on each tire by the tire pressure, to be a rectangular figure with 0.8712 L length and 0.6 L width. The following equation calculates the length of the contact area (L):

$$L = \sqrt{\frac{A_c}{0.5227}} \tag{1}$$

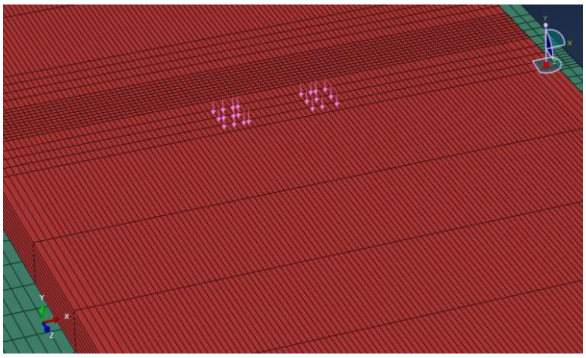
Wheel loading was applied using a pressure on the top surface of the concrete slab over a footprint. Four types of aircraft, F-16C, B737-500, B777-200ER and A330-200STD were investigated in studying the loading gear configurations effect on the airfield rigid pavement analysis. This choice based on their extent use in Egyptian's commercial and military fleet. The F-15 was used for the parametric cases in this study. Table 2 shows the main characteristics of airplanes considered in this study. Figure 3 shows the loading gear configurations for each aircraft type. Dynamic vertical wheel loading at the joint was investigated in the finite element analysis. The effects of tire friction and velocity of the wheel moving across the surface were not considered according to FAA, 2010 [25].

Table 2. Main Characteristics of the Airplanes (FARFIELD)

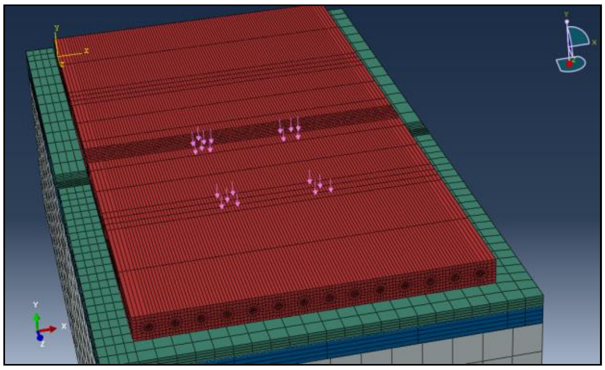
Aircraft	Tire pressure (MPa)	Footprint area (mm^2)	Tire contact length (mm)	Tire contact width (mm)	Dual spacing (mm)	Tandem spacing (mm)
F-15	2.344	61290	353.4	220.8	0.0	0.0
F-16C	1.482	60292.4	350.5	219	0.0	0.0
B737-500	1.338	105836.2	464.3	290.2	774.7	0.0
B777-200ER	1.413	163938.8	577.9	361.2	1397	1447.8
A330-200STD	1.420	189364	621.1	388.2	1397	1981.2



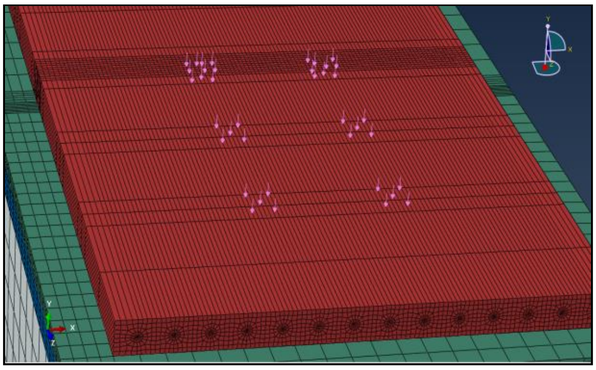
(a) Single load of F-16 and F-15 aircrafts



(b) Dual load of B737-500 aircraft



(c) Dual tandem of A330-200STD aircraft



(d) Three duals in tandem of B777-200ER aircraft

Figure 3. Loading Gear Configurations for Each Aircraft Type

4.2. Dynamic Implicit Analysis

Typical dynamic applications fall into three categories: transient fidelity applications, moderate dissipation applications and quasi-static applications. The analysis product default depends on the presence of contact in the model: analyses involving contact are treated as moderate dissipation applications; analyses without contact are treated as transient fidelity applications. In this study, the quasi-static and analysis product default approaches, which based on the concept of moving the load at subsequent positions along the pavement for each new time step, were used. Damping effect was considered in both analysis types.

4.3. Damping

The phenomenon of dissipation of energy in the system through various mechanisms is called damping. ABAQUS provides “Rayleigh” damping for this purpose. It provides a convenient abstraction to damp lower (mass dependent) and higher (stiffness-dependent) frequency range behavior. Rayleigh damping is proportional to the stiffness and mass of the structure and can be defined using equation 2.

$$[c]= \alpha\ [m] + \beta\ [k] \tag{2}$$

Where,

[c]: damping matrix of the physical system, [m]: mass matrix of the physical

[k]: stiffness matrix of the system, α: mass proportional damping coefficient (1/s) and β: stiffness proportional damping coefficient (s).

To define material Rayleigh damping, it has required specifying two Rayleigh damping factors: αR for mass proportional damping and βR for stiffness proportional damping. The pavement damping is mainly stiffness proportional and hence the first term in the equation is neglected. Implicit dynamic procedure and damping factor (β) is used for simulation the dynamic effect of the load drop. The β value is calibrated to the actual field measured unloaded and loaded HWD deflections. Damping value of 0.2 is used for loads of 35000, 35500, 36000, 36650 and 37500 lbs., respectively to match the FEM predicted deflections with the HWD result data [5]. Previous studies show that dynamic LTE (s) is not sensitive foundation damping ‘Ck’ and hence not used in this model [26].

4.4. Thermal Loading

There are two main types of thermal strains are usually exhibited in a concrete pavement slab: thermal gradient strains and uniform thermal strains. Thermal gradient strains happen because of the daily temperature changes and cause curling of the slab. Uniform thermal strains happen because of the seasonal temperature changes that cause the entire slab to expand or contract evenly. The solution’s accuracy depends on the proper simulation of a three-dimensional dowel-concrete interface that models friction contact and separation along the full length of the dowel-concrete interface for each dowel along the transverse joint. The 3D FE model developed in this study was designed with these requirements in consideration.

Slab curling caused by thermal stress gradients generates stress concentrations at the dowel bar locations as the dowels restrain the slab from moving. Upwards curling on the slab occurs at night when the top of the slab cools and contracts. During the daytime, the top of the slab heats and causes downward curling. The input of thermal gradient considered as a linear distribution. The main concern of this study is thermal gradient strains. To predict the time-dependent variations of slab temperature, a three-dimensional steady-state heat transfer analysis was conducted.

Temperature profiles implemented in ABAQUS in current study as in two successive steps; first by application of gravity load in a separate timing step, then the application of the thermal gradient profile accompanied with the propagated gravitational load effect. The two-cycle procedure was found to lead to an almost steady strain state. Thermal loading was applied to the model by specifying a temperature gradient profile through the slab thickness as boundary conditions. Boundary conditions were used to prescribe both temperatures (degree of freedom 11) and displacements/rotations (degrees of freedom 1–6) at nodes in fully coupled thermal-stress analysis. A thermal gradient profile of +10 C̊ of 40 C̊ and 30 C̊ was considered in order to account for severe weather conditions. A negative thermal gradient profile of -10 C̊ was also considered.

4.5. Load Combinations

The 3D FE model of JPCP was analyzed for a combination of thermal and traffic loads. A fully coupled thermal-stress analysis was performed as the mechanical and thermal solutions affect each other strongly and therefore, must be obtained simultaneously and this requires the existence of elements with both temperature and displacement degrees of freedom in the model. Coupled temperature-displacement elements were provided for this purpose in ABAQUS/standard. In ABAQUS/standard, the temperatures are integrated using a backward-difference scheme, and the nonlinear coupled system is solved using newton's method. ABAQUS/standard offers an exact as well as an approximate implementation of newton's method for fully coupled temperature-displacement analysis. Steady-state coupled temperature-displacement analysis is performed in this analysis. In steady-state cases, an arbitrary “time” scale is assigned to the step. This time scale is convenient for changing loads and boundary conditions through the step and for obtaining solutions to highly nonlinear (but steady state) cases. The concrete does not display significant changes in its properties. Therefore, a linear thermos-elastic material model was assumed for concrete. The materials in a fully coupled thermal-stress analysis must have both thermal properties, such as conductivity, and mechanical properties, such as elasticity, defined. The thermal expansion, conductivity and specific heat of the concrete slab are assumed 1×10-5 /OC, 1.37×10-3 J/S/Mm/OC and 880 J/Kg/OC, respectively.

5. Model Results

Contour plots are used to show the value of attributes such as loads or predefined fields variables at a particular step of a model in the certain model database. Output requests in this study mainly focus on showing stresses around deformed dowel hole at the location of maximum stresses at end and beginning of load application for each step of the entire analysis history. They also focus on showing stresses and deformation at the critical edge of the loaded and unloaded slab. The history of a certain variable has plotted versus the time of the moving axle (the change in loading position) from a certain point to the joint. Figures 4 to 6 show different general pavement deformation and stresses results obtained using the developed model.

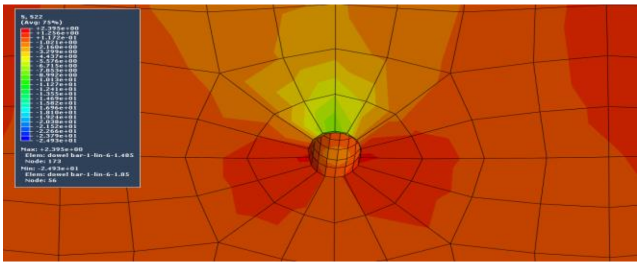


Figure 4. Stresses Distribution at the Surrounding of the Dowel Bar across the Joint

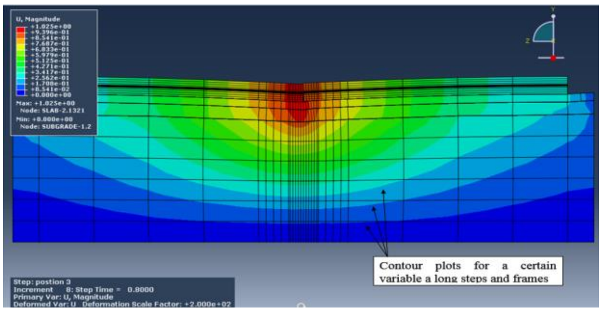


Figure 5. Y-Z Plane of the Model Deformation

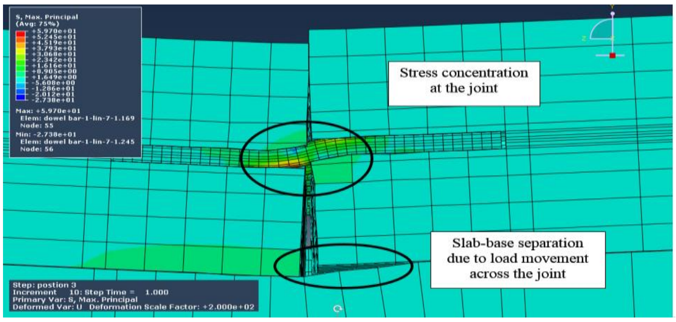


Figure 6. Maximum Principle Stresses at the Joint

6. Verification of the Model

Most finite element codes can be used as a "black box" by researchers without extensive knowledge of Finite element method. Therefore, FEM packages could be misused resulting in what is termed "garbage in, garbage out" simulations [27]. The most efficient process of examining the precision of the developed model is to match its results with field test measurements for the same arrangement under the same loading circumstances. Due to the limited resources and absence of the ability to perform a specialized test procedure, the verification process is done by using the results from using the HWD test on NAPTF sections by comparison of its results to the developed model. Periodic heavyweight Deflectometer (HWD) testing was conducted at the NAPTF using KUAB 240 model in 2004. This verification is limited to calculation of deflection based LTE for MRS test sections using the loaded and unloaded deflections obtained from HWD sensors across the longitudinal joints (dowelled). Implicit dynamic procedure and Damping factor (β) is used for simulation the dynamic effect of the load drop. The damping value of 0.2 is used for loads of 35000, 35500, 36000, 36650 and 37500 lbs., respectively to match the FEM predicted deflections with the HWD result data [12].

The deflection readings are only for slab deflection due to the HWD, not the gravitational force as in the developed FE model. The deflection of the gravity phase is subtracted from total deflection, called (unloaded1), and (loaded 1). The gravitational deflection is found to be 0.11651 mm. Then the sum of two deflections (SD) on two sides of joints was calculated. According to Wadkar, 2010 [5] the average LTE (δ) for longitudinal joints was computed to be 0.92 respectively. The average SD was 23.02 mils (0.5755 mm.). The unloaded deflection ranged between 9.78 and 11.77 mils (0.2445 and 0.29425 mm.). The loaded deflections ranged between 10.86 and 12.73 mils (0.2715 and 0.31825). Table 3 shows that unloaded and loaded deflection was in the previously mentioned range ,which obtained from HWD data analysis. The comparison of calculated deflection LTE from 3D FE analysis with field test results is within the acceptable range. The overall agreement was promising and easily to be improved for further studies. Because of the flexibility of the developed model, it can be easily rehabilitated in a manner that considers other features affect pavements responses.

Table 3. Results of HWD Data Analysis for Test Item MRS

Loading case (Ib.)	FEM unloaded (mm.)	FEM loaded (mm.)	LTE (δ)	FEM Unloaded1(mm)	FEM Loaded1(mm.)	SD (mm)
35000	0.390784	0.436249	89.6%	0.225648	0.271149	0.496797
35500	0.394716	0.44096	89.51%	0.229616	0.27586	0.505476
36000	0.400612	0.448025	89.42%	0.235512	0.281925	0.518437
36500	0.404541	0.452733	89.35%	0.239441	0.287633	0.527074
37500	0.410434	0.459792	89.26%	0.245334	0.294692	0.540026
			AVERAGE			
36100	0.4002174	0.4475518	89.43%	0.2351102	0.2822518	0.517562
Ranges			92%	0.2445&	0.2715 &	0.5755
Accuracy%			97.2	0.29425	0.31825	89.93

7. Analysis of Results

Sensitivity studies were made to evaluate the effect of loading parameters on the response of rigid airfield pavement. These effects were mainly assessed using load transfer indicators.

7.1. Main Gear Loading in Different Wheel Configuration

The representation of the main gear is the main concern for this study that involves multiple loads and complex gear configurations. Four sets of main landing gear with different wheels configuration was used to apply loading on the runway pavement to take account for every landing gear's type influence. All wheel configurations are set in the same speed and dynamic properties. Four types of aircraft F-16C, B737-500, B777-200ER and A330-200STD were investigated. This choice bases on their extent use in Egyptian's commercial and military fleet. Wheel loads are applied on one side of the joint at the edge of the slab in a straight wheel path. MRS1 was used for modeling the pavement slabs, the base layer used for this case was Item P-306 and the foundation setting was the "very low" case, which allows the responses of pavement to appear more visible and easier to observe and analysis.

Compared to a single F-15 load is used and its tire pressure is higher than F-16 single load with about 75%. It was found that stress based LTE is insensitive to this increase of aircraft load. On other hand, the deflection based LTE is decreased with this increase in aircraft load. Figures 7 and 8 illustrate the sensitivity of load transfer indicators to a particular pavement structure, which varies in the airplane wheel configuration. The single wheel-loading configuration was expanded to dual wheel configuration and three duals in tandem wheel configuration to study the effect of variation wheel configuration on LTEs. The observations of the stresses and strains histories at the transverse joint and the middle of the slab are noticed and showed that stress based load transfer efficiency is significantly increased as the wheel configuration changes from single wheel to three dual wheel in tandem. From above, it is obvious that stress LTE is insensitive to aircraft load but sensitive to wheel configuration. The results show that the deflection based LTE increases as the wheel configuration changes from single wheel to three duals in tandem (6-wheel).

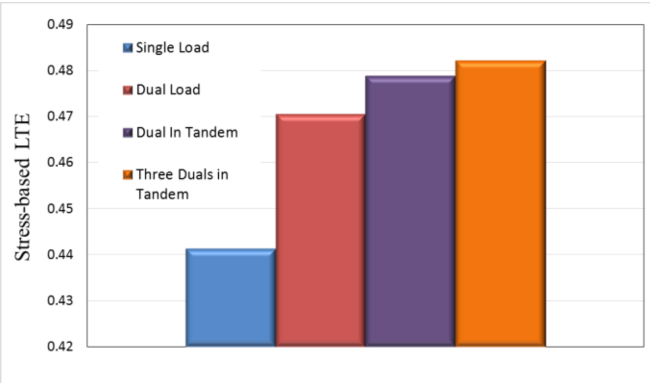


Figure 7. Stress Based Load Transfer Efficiency across the Joint

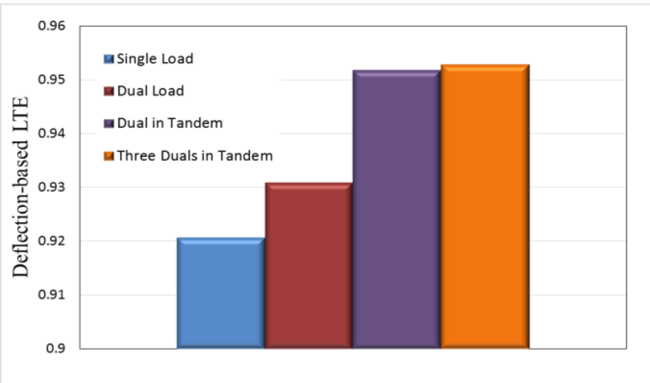


Figure 8. Deflection Based Load Transfer Efficiency across the Joint

7.2. Thermal Loading

Pavement response is significantly changed when the wheel loads are combined with thermal gradients. Ignoring the thermal stresses during design can underestimate the design stresses. A 3D finite element analysis is performed for the model under the combined effect of dynamic wheel loads and thermal gradient through the slab thickness. Specific gradients and loading conditions examined in this study; negative gradient of -10 C̊ to study night time curling and positive gradient of + 10 C̊ to study daytime curling. Four types of aircraft F-16C, B737-500, B777-200ER and A330-200STD were investigated as wheel loads, which combined with the thermal effect. All wheel configurations are set in the same speed and dynamic properties. Wheel loads are applied on one side of the joint at the edge of the slab in the wheel path. MRS1 was used for modeling the pavement slabs, the base layer used for this case was Item P-306 and the foundation setting was the "very low" case, which allows the responses of pavement to appear more visible and easier to observe and analysis. Figures 9 to 12 summarize the behavior indictor observed in this model.

The results obtained from this case demonstrate that the change in the thermal gradient from positive to negative significantly changes the slab curvature shape as shown in Figures 13 and 14. This curvature affects the slab response especially when the pavement is subjected to positive thermal gradient. If a pavement slab is subjected to a temperature gradient through its depth, its surface will tend to warp, the tendency of the slab edges to curl downward during the day and upward during the night because of temperature gradients is resisted by the weight of the slab itself. This resistance tends to keep the slab in its original position, resulting in compressive and tensile stresses being induced at the top and bottom of the slab. Pavement curling due to thermal gradient affects the differential displacement between the highest and the lowest point along the slab length, which affect the deflection due to the passage of the traffic load.

The slab edge deflection decreases significantly compared to the "wheel load only" case under positive gradient. While the slab edge deflection increases compared to the "wheel load only" case under negative thermal gradient. The results show that the deflection based LTE increases as the wheel configuration changes from single wheel to three duals in tandem (6-wheel) and slightly higher from "wheel load only" case. The stresses developed in rigid pavement result from the change in the thermal gradient from positive to negative under the loading conditions are located across the joint is examined. The stress also increases as the thermal gradient increases. The critical case in the stress was found at combination of wheel load and positive thermal gradient. The use of complex gears provides the ability to control the stresses and curvature observed at mid-slab especially with a negative gradient. The stress based load transfer efficiency significantly increases as the wheel configuration changes from single wheel to three dual wheels in tandem combined with either negative or positive gradient. On other hand, both negative and positive gradients are found to be lower than them in "wheel load only" case.

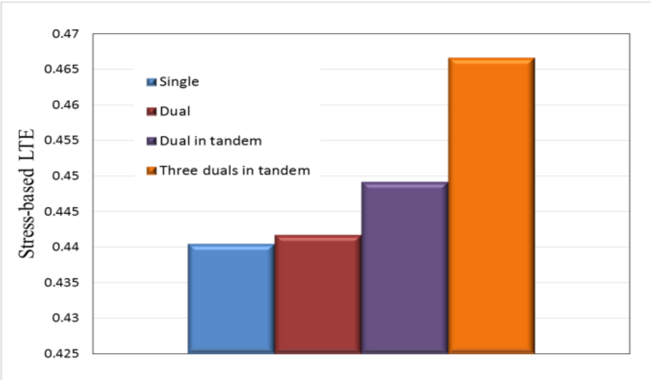


Figure 9. Stress based load transfer efficiency for positive gradient

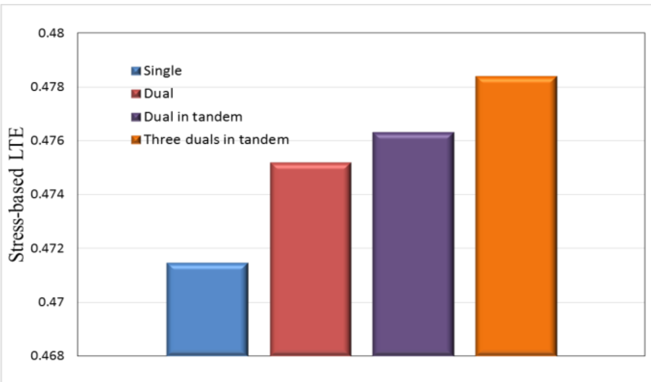


Figure 10. Stress based load transfer efficiency for negative gradient

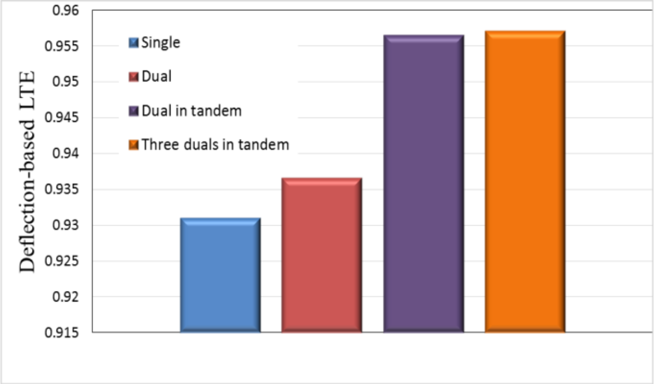


Figure 11. Deflection based load transfer efficiency for positive gradient

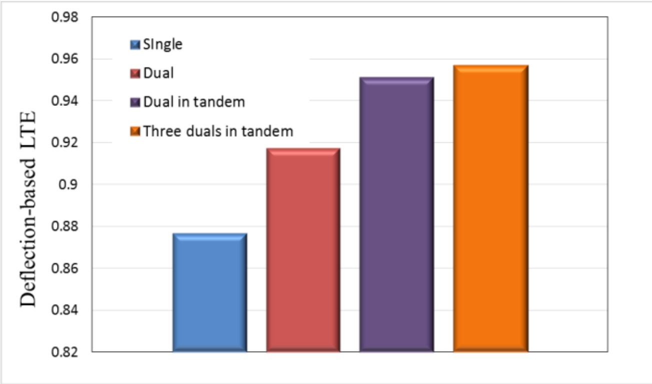


Figure 12. Deflection based load transfer efficiency for negative gradient

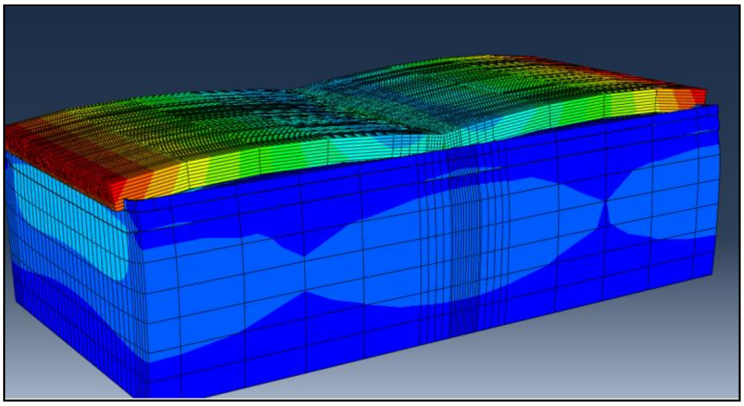


Figure 13. Downward curling of slab due to temperature gradient

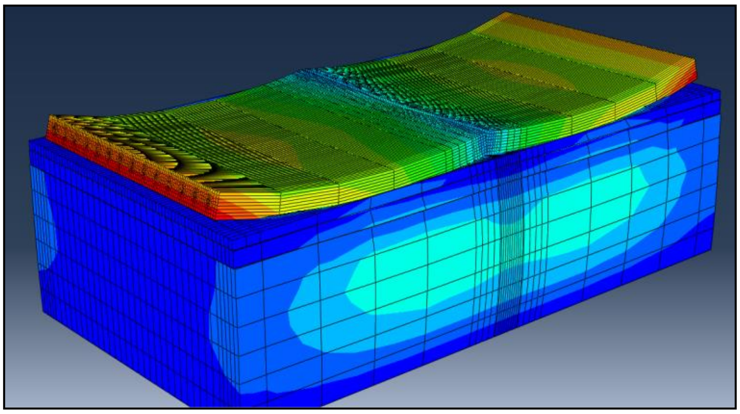


Figure 14. Upward curling of slab due to temperature gradient

8. Conclusions

The following conclusions were made based on the analysis and observations of 3D finite element model representing valuable insight on the behavior of the slab-dowel system when subjected to loading. Conclusions from the numerical investigations are summarized below:

1- Results obtained from the developed model show that constraining the lateral sides of the slab, where the tie bars are usually loaded, did not affect the slab response under wheel loads. Therefore modeling the tie bars in this case was not essential. However, it was important for modeling the pavement subjected to thermal loading.

2- The stress based load transfer variation is likely attributed to formation of cracks at the joint. Modeling the dowel bars using hexahedron solid brick elements had several advantages especially in locating the areas of high stresses in the concrete surrounding the bars. Modeling aggregate interlock along the transverse joint using surface to surface contact allowed the simulation of load transfer, relative motion and gap formulation between the slabs along the transverse joint.

3- It was found that stress based LTE was insensitive to aircraft load increase but very sensitive to wheel configuration where it significantly increased as the wheel configuration changed from single wheel to three dual wheels in tandem. On the other hand, deflection based LTE decreased with aircraft load increase and increased as wheel configuration changed from single wheel to three duals in tandem (6-wheel) slightly higher than “wheel load only” case. The distribution of the developed stresses in the pavement along the straight wheel path showed that the stress was constant along the slab length and changed significantly at the joint especially around the dowel holes.

4- The change in the thermal gradient from positive to negative significantly changed the slab curvature shape. The critical case in the stress was found in the combination of the wheel load and the positive thermal gradient. The slab edge deflection decreased significantly compared to the “wheel load only” case under positive gradient and significantly increased under negative thermal gradient.

5- The use of complex gears found to have the ability to control the stresses and curvature observed at mid-slab especially with a negative gradient. The stress based load transfer efficiency significantly increased as the wheel configuration changed from single wheel to three dual wheels in tandem combined with negative or positive gradient where negative or positive gradient was found to be lower than them in “wheel load only” case.

6- Changing the axle load configuration was preferred than increasing its magnitude which significantly increased the stresses induced in the slab. Utilizing a dynamic load allowed studying the fatigue cycles that pavement can be subjected under different wheel configurations. This allowed examining the cycles of tension-compression due to wheel loading which may reduce the strength of the concrete and develop more fatigue damage than considering a static load imposed only in one direction, i.e. no stress reversal is involved.

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