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Development of Domain Analysis for Determining Potential Pavement Damage

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Abstract

A new approach for quantifying flexible pavement damage potential is proposed. The new method, domain analysis, utilizes multiaxial results from advanced finite element models to calculate the response of flexible pavements to tire loading. The output is a single scalar value, which is unique to a given pavement structure and loading configuration. The ability of the domain analysis to quantify bulk damage potential and overcome flaws of conventional approaches based on point responses is demonstrated by testing three case studies: (1) comparison of typical loading conditions of dual-tire assembly (DTA), new-generation wide-base tire (NG-WBT), and steer tire; (2) effect of tire-inflation pressures; and (3) influence of differential tire-inflation pressure for DTA. The proposed method provides a direct link between three-dimensional contact stresses at the tire-pavement interface and three-dimensional responses of a loaded pavement structure. Also, the applicability of the domain analysis method could easily extend to other pavement structures, tire types and configurations, and loading conditions, along with considering other failure criteria.

Introduction and Background

Damage prediction in conventional pavement analysis is handled through empirically derived transfer functions. AASHTOWare Pavement Mechanistic-Empirical Pavement Design Guide (MEPDG) program is a useful tool for pavement engineers that utilizes critical mechanistic responses (i.e., strains) at predefined points as inputs for transfer functions (AASHTO 2008). Based on an extensive effort of field testing, transfer functions evolve pavement damage by quantifying the number of repetitions to failure. For example, by using the maximum tensile strain at the bottom of the asphalt concrete (AC) layer, the number of repetitions for bottom-up fatigue cracking is predicted.

Two key drawbacks of this approach include the reliance of predicting pavement damage on a single strain value and lack of transfer functions that appropriately represents near-surface damage. Minor differences in strain inputs (e.g., for fatigue cracking or rutting) would inherently lead to the same damage prediction, thereby unable to contrast distinct loading scenarios. Furthermore, the multilayered elastic analysis (MLEA) scheme embedded within the AASHTOWare framework inaccurately accounts for the moving tire load and viscoelastic nature of AC layers. Instead, the load excitation is assumed as a pressure in the vertical direction only and distributed over a circular contact area (ARA 2004; Gungor et al. 2017).

Realistic implications of actual tire-pavement contact stresses lie within the near-surface region, where the contact stress influence is highest. For instance, interstate highways experience top-down cracking due to the high level of near-surface shear strains (Myers et al. 1998; Drakos et al. 2001; Wang and Al-Qadi 2009; Yoo and Al-Qadi 2008). In the current state of pavement design methodologies, transfer functions relating shear strains to near-surface cracking do not exist. Like fatigue cracking and rutting predictions, significant field testing efforts would be required to generate corresponding transfer functions. To address these shortcomings, several numerical methods exist that aim to evaluate the impact of tire loading on pavement damage at the near-surface region. Currently established methods include finite element (FE) modeling of critical structural responses, combination of FE analysis with limit failure criteria, and fully coupled damage models within the material domain.

FE analysis is an effective technique to simulate tire-pavement interaction. A robust modeling platform to generate a three-dimensional (3D) flexible pavement model has been implemented by Al-Qadi and his co-workers (Al-Qadi and Yoo 2007; Elseifi et al. 2006; Wang and Al-Qadi 2011; Yoo et al. 2006; Yoo and Al-Qadi 2007). Several advancements over two decades of work include linear viscoelastic material characterization for AC layers, dynamic implicit analysis, layer interaction, continuous moving load, 3D and nonuniform contact stresses, infinite boundary element, and temperature profile along the AC layer depth. Moreover, nonlinear material characterization was appended to account for stress-dependency of granular base layers (Al-Qadi et al. 2010; Kim et al. 2009). Although limitations of MLEA from the mechanistic-empirical approach are addressed using FE analysis, quantifying pavement damage still relies on strains at point locations without appropriately quantifying near-surface damage. As aforementioned, regardless of the difference in contact stress distribution at the tire-pavement interface, similar resulting strains would generate the same level of damage. This clearly indicates the limited capability of point strains to represent the full influence of 3D and nonuniform contact stresses.

As an alternative for analysis, past studies presented the use of shear stress ratio to estimate potential damage, without evolving to a fully-damaged state. Using a failure criteria, for example, Mohr-Coulomb failure surface, the octahedral shear stress ratio at a specific point location is calculated to compare the critical octahedral shear stress to the material shear strength (Freeman and Carpenter 1986; Ameri-Gaznon and Little 1988; Ameri-Gaznon et al. 1989; Button and Perdomo 1991; Wang and Al-Qadi 2010, among others). The rationale is that as the shear stress ratio tends to unity, the potential of rapid deformation increases accordingly. However, appending a failure surface does not resolve reducing the comparison of pavement structural responses to a single analysis point, thereby still ignoring the influence of multiaxial contact stresses at the near-surface region.

In a different perspective, advanced constitutive models and failure theories have been implemented to analyze damage evolution within pavement layers. Continuum damage theories have been commonly used in predicting fatigue cracking damage in pavements (Lee et al. 2000; Daniel and Kim 2002; Gibson et al. 2003; Chehab et al. 2003; Park 2004; Dai et al. 2006; Kim et al. 2007; among others), whereas viscoplasticity theories were used for modeling plastic deformations at relatively high temperatures (Perl et al. 1983; Lu and Wright 1998; Collop et al. 2003; Krishnan and Rajagopal 2004; Tashman et al. 2004; Kim et al. 2006; Underwood et al. 2009; Al-Rub et al. 2011; Darabi et al. 2012a, b, among others). However, due to the complexity of constitutive models and the required computational effort, the analysis is either maintained within the material domain or significant simplifications of the pavement structural model is required. Hence, there exists a need to quantify pavement damage potential at the near-surface region, while accounting for multiaxial structural responses.

Research Objective

Alternative to analyzing pavement responses via critical strains at point locations, the main objective of the presented research is to quantify the bulk behavior of a loaded pavement structure using a new post-processing method, coined, domain analysis. The proposed method not only provides a means to comprehensively evaluate the realistic impact of 3D tire-pavement contact stresses, but it also assesses the damage potential of the weakened area within a pavement structure. The development and testing of the method are presented, analyzing two distinct pavement structures along with various tire loading conditions and configurations.

Domain Analysis

The proposed approach, domain analysis, allows for the prediction of the damage potential by considering volumetric domains in lieu of a single-point response. This paper details the development and implementation of the domain analysis on several case studies. The procedure is composed of four main steps:

1. Calculate multiaxial stress and strain states using a pavement model;
2. Discretize the pavement domain to identify critical zones;
3. Compare stress and strain states with respect to a failure criteria; and
4. Combine the failure potential of critical regions to obtain a scalar that indicates the level of demand on the pavement structure (which includes the calculation of weight factors and cumulative ratio).

Pavement Model and Multiaxial Stress and Strain States

Stresses and strains are calculated using a baseline finite element model (FEM) of the loaded pavement structure. From the pavement FEM, a subdomain that covers an area of 1 m21 m2 in the xz-plane centered on the middle of the wheel path and extended 0.75 m into the subgrade layer is extracted (Fig. 1). As the stresses and strains tend to zero at the boundaries of the full pavement FEM, the domain for the multiaxial stress state analysis could be limited to the selected subdomain. Furthermore, the critical loading step is selected when the tire is at the middle of the wheel path.

In general, an element stress state can be represented by normal and tangential stresses. If a material element is rotated in a manner that leads to zero shear stresses, the element stress state can then be characterized using principal stresses, or the normal stresses acting on the element. Using the principal stresses, the hydrostatic stress, p_σ, and shear stress indicator, q_σ, can be defined using the following equations:

(1)

$$p_\sigma = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)$$

(2)

$$q_\sigma = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]}$$

where σ_1, σ_2, and σ_3 = maximum, intermediate, and minimum principal stresses, respectively. Below, the same form of equations represent the hydrostatic strain, p_ϵ, and shear strain indicator, q_ϵ:

(3)

$$p_\epsilon = \frac{1}{3}(\epsilon_1 + \epsilon_2 + \epsilon_3)$$

(4)

$$q_\epsilon = \sqrt{\frac{2}{9}[(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_1 - \epsilon_3)^2]}$$

where ϵ_1, ϵ_2, and ϵ_3 = maximum, intermediate, and minimum principal strains, respectively.

Initially, a two-dimensional (2D) plane was held at the midlength of the pavement model; however, the variation of the given plane along the traffic direction indicated that the maximum stress and strain states occur just behind the middle of the tire footprint. This behavior is due to the viscoelastic nature of AC layers, wherein strain response follows the loading with a delay. Therefore, maximum stresses and maximum strains may not occur at the same location for varying load simulations. As each loading case generated a different plane of the maximum values, volume averaging was implemented to include all values within the 3D subdomain.

Domain Discretization

Quantifying the bulk behavior was focused on critical zones that coincide with locations where distresses often occur and that are considered in pavement design. The analysis was focused on the near-surface region and bottom of the layer. At each 2D plane along yz (recall coordinate system from Fig. 1), a zoning process is introduced to differentiate response magnitudes throughout the layer depth (Fig. 2).

The horizontal boundary, defined by a given depth v, is a function of the pavement layer thickness, and the vertical boundary is defined by the tire width of a specific load case with an addition of $h = 50\ \text{mm}$ to the left and right of the tire edges. This addition corresponded to previous observations wherein high shear values localized near the tire edges (Hernandez et al. 2016, Wang and Al-Qadi 2010). Moreover, the horizontal boundary was confined within 100 mm from the surface, where near-surface cracking is generally observed (Yoo and Al-Qadi 2008).

Partitioning each 2D slice with the vertical and horizontal limits that enveloped the two regions of interest (near-surface and bottom of the layer) generated nine zones ($Z1 - Z9$), as illustrated in Fig. 2. It is worth noting that the zoning process exhibits domain dependency, that is, the user-defined limits influence the range of values considered per zone. In addition, as the zoning limits were fixed per pavement structure, they do not significantly influence the ratios of the loading cases considered relative to a reference case. Furthermore, along the longitudinal direction, the cloud of points varied within the nine zones, which is another strong motivation for the domain analysis to be implemented three-dimensionally.

Using the centroid of each finite element within the subdomain, principal values were obtained, and the hydrostatic stress and strain and shear stress and strain indicators were calculated and plotted in the Cartesian plane using Eqs. (1)–(4). Fig. 3 illustrates a typical pq diagram in the stress domain. One could observe that the zone directly underneath the tire ($Z2$) experienced the highest level of compression and shear. Particularly, the triangle-up markers are scattered over the negative hydrostatic stress and had the greatest shear stress values within the pq diagram.

Other near-surface regions ($Z1$ and $Z3$) remained to exhibit shear and compression but at smaller magnitudes. As the zones transition into a greater depth, $Z5$ (middle zone) still exhibited high levels of shear, but normal stresses were slowly transitioning from compression into tension. As the bottom of the layer was bounded by $Z7$, $Z8$, and $Z9$, high shear was still observed, but the normal stresses fully transitioned into tension. This observation was mostly predominant within $Z8$, represented by the triangle-right markers on the positive p regime (Fig. 3).

From the zoning process of each major pavement layer, four critical zones were identified: (1) $Z2$ within the AC relating to near-surface cracking and rutting; (2) $Z8$ within the AC relating to bottom-up fatigue cracking; (3) $Z2$ within the base; and (4) $Z2$ within the subgrade both related to rutting.

Failure Criteria

The modified Drucker-Prager/Cap model was adopted as the failure criteria to relate a given stress/strain state to its damage potential, although other failure theories could be easily implemented. To accomplish this, a pq coordinate is characterized using its proximity relative to a failure surface. From plasticity theories, the modified Drucker-Prager/Cap model is used to account for tension cut-off, compression, and shear. Within the failure surface, the material remains elastic but reaches failure as soon as the material point state coincides with the failure plane.

The yield surface consists of (1) the Drucker-Prager shear failure surface; (2) an elliptical cap to limit the hydrostatic pressure; and (3) a smooth transition zone between the failure surface and the cap. The Drucker-Prager shear failure surface is defined by

(5)

$$F_s = q - p\tan\beta - d = 0$$

where β and d = angle of friction and cohesion, respectively.

Moreover, the cap and transition yield surfaces are calculated by

(6)

$$F_c = \sqrt{(p - p_a)^2 + \left[\frac{Rt}{1 + \alpha + \frac{\alpha}{\cos\beta}}\right]^2} - R(d + p_a\tan\beta) = 0$$

(7)

$$F_t = \sqrt{(p - p_a)^2 + \left[t - \left(1 - \frac{\alpha}{\cos\beta}\right)(d + p_a\tan\beta)\right]^2} - R(d + p_a\tan\beta) = 0$$

(8)

$$p_a = \frac{p_b - Rd}{1 + R\tan\beta}$$

where R = material parameter that controls the shape of the cap; α = smooth transition surface between the Drucker-Prager shear failure surface cap; and p_b = mean effective yield stress and defines the position of the cap (Helwany 2007).

The baseline values characterizing the Drucker-Prager failure plane, in the stress domain, were obtained from Gokhale et al. (2005); however these model inputs were modified to encase the worst loading case (i.e., one that generates the highest values of p and q). It is noteworthy that the parameters assumed for each major pavement layer were kept constant for all loading conditions (per case study) to eliminate the influence of material damage capacity as a variable. Moreover, given that the FE analysis solely simulates one load pass, it was deemed appropriate to modify the failure surface parameters to envelope the entire pq point cloud.

The currently assumed failure surface values may not represent material failure most accurately with respect to temperature and rate effects; however, a sensitivity analysis revealed that maintaining the failure surface consistently for all simulations being compared does not adversely affect the results relative to the reference case. This is a clear shortcoming of the domain analysis method; however, accurate material failure characterization can be included in the future as a potential solution.

Polar Coordinate Transformation and Weight Factor Calculation

To effectively relate the pq diagram values and failure envelope, the values in the Cartesian coordinate were transformed into polar coordinates. Two important parameters can be extracted from the pq diagram in the Cartesian plane: (1) the magnitude of the vector connecting the origin to a specific pq coordinate, and (2) the angle θ between the vector and the positive horizontal axis. Additionally, the failure plane was also transformed (Fig. 4).

This coordinate transformation allowed the relative comparison of the cloud of stress and strain states to the failure plane. Depending on the proximity of the point to the failure plane, the material may fail in compression and/or shear. Therefore, a weight factor was created to adequately penalize the stress/strain state point based on its location relative to the failure envelope. However, as the coverage of the pq coordinates varied depending on the load case and pavement structure combination, a constant weighting scheme was implemented on an empty polar coordinate system to prevent an inconsistent definition of weight factors.

Weight factors (independent of the load case) were defined by regionalizing the polar coordinate system into 30 sectors, which stemmed from defining six radii boundaries and seven angle boundaries (0, $\pi/6$, 3, 2, $2\pi/3$, $5\pi/6$, and π). Using the midpoint of each sector, its shortest distance to the failure surface was calculated. The weights are defined by the stress/strain ratio; that is, current stress/strain state of the sector midpoint divided by the allowable stress/strain state. A weight of 1.0 indicates that the midpoint sector coincides with the yield surface, and failure is reached. From Fig. 4, the weight assigned to location 1 is greater than that of location 2; therefore, the highest weight factor defines the sector closest to the failure envelope. It must be noted that this process is only implemented in the sectors within the failure envelope as absolute failure is assumed for the sectors beyond. As the pq cloud is also transformed into the same polar coordinate system, each coordinate is weighted depending on its enveloping sector.

Cumulative Ratio

The next step in the domain analysis method is to quantify the cumulative impact of the 3D and nonuniform contact stresses. Using the vector magnitude and weight factors, the pq point cloud can be combined into one cumulative scalar value, coined as the cumulative stress, $C\sigma$, or cumulative strain, $C\epsilon$. However, a direct comparison between various loading cases is deemed relatively unfair given that their corresponding mesh geometries differ. For instance, the DTA would generate a higher number of points in the pq diagram than the NG-WBT case. Therefore, a homogenizing factor is defined to account for the geometric difference between load cases along the cross-sectional area (yz-plane). The homogenizing factor, a_{jl}/A_l, is calculated by considering the elemental area relative to the total area covered by a specific zone. Note that a_{jl} is the area of element j within zone l, and A_l is the total area of the zone l.

Furthermore, a volumetric factor, l_{elem}/L_{sub}, is also introduced to consider the variation of the stress/strain state along the longitudinal direction, x. It is implemented similarly to the homogenizing factor, except that the extent of the volumetric factor is along the traveling direction of the subdomain. At this point, the presented method captures all stress and strain responses within the 3D subdomain. The resulting scalar is the cumulative ratio, CR, which is calculated by normalizing the cumulative value with respect to the reference load case:

(9)

$$C\sigma, C\epsilon = \frac{\sum_{l=1}^{z} \sum_{j=1}^{e} \sum_{i=1}^{s} |(pq)_{\sigma,\epsilon}|_{jl} \times a_{jl} \times l_{elem} \times w_i}{A_l \times L_{sub}}$$

(10)

$$CRS = \frac{C\sigma}{C\sigma_{ref}}$$

(11)

$$CRE = \frac{C\epsilon}{C\epsilon_{ref}}$$

where $C\sigma$ = cumulative stress of the specific load case; Cϵ = cumulative strain of the specific load case; $|(pq)_{\sigma,\epsilon}|_{jl}$ = vector magnitude of the element j for a total of e elements within the zone l for a total of z zones; $l_{e\,l\,e\,m}$ = element length along the travel direction; w_i = weight of the specific sector i for a total of s sectors; L_{sub} = total length of the subdomain; CRS = unitless cumulative ratio in the stress domain; CRE = unitless cumulative ratio in the strain domain; $C\sigma_{ref}$ = cumulative stress of the reference load case; and $C\epsilon_{ref}$ = cumulative strain of a reference load case.

Each of the four critical zones: (1) $Z2$ within the AC relating to near-surface cracking and rutting; (2) $Z8$ within the AC relating to bottom-up fatigue cracking; (3) $Z2$ within the base; and (4) $Z2$ within the subgrade both related to rutting, can be analyzed to determine the governing zone that may lead to the highest damage potential, for example, a load case may fail in subgrade rutting if $Z2$ within the subgrade has significantly high cumulative ratios.

A secondary partition at the middle of the tire width ($Z = 0 \text{ mm}$) was introduced to capture the near-surface influence of an asymmetric load distribution. For example, asymmetric pavement responses are encased by the two boxes in Fig. 5. The combined $Z2$ and $Z5$ on the right is termed *ACD1*, whereas the one on the left is termed *ACD2*. It is noteworthy that this new zoning process was implemented only within the near-surface region of the AC layer.

Another approach comparing the cumulative stress/strain state is to analyze the bulk behavior of the entire pavement structure by combining the four critical zones using a weighted sum. Note that the domain analysis equations are interchangeable, depending on whether the analysis considers the stress or strain domain. One advantage of this method is that the same computational engine is used, but the input parameters are altered.

Numerical Simulation Inputs

Using Abaqus/CAE, the pavement FEM considered dynamic implicit analysis, 3D and nonuniform contact stresses, continuous moving load, infinite boundary elements to simulate far-field region behavior, and appropriate layer interaction properties between pavement layers. Additional details of the model generation scheme could be found elsewhere (Al-Qadi et al. 2008; Yoo and Al-Qadi 2008; Wang and Al-Qadi 2009; Al-Qadi et al. 2010; Hernandez et al. 2016). Limitations of the modeling approach include AC material homogeneity and isotropy; single moving load pass; pavement analysis without crack initiation, healing, or propagation; and assumption of a fixed elasto-plastic limit to define the domain analysis weight factors.

Combinations of applied load and tire-inflation pressure on the DTA and NG-WBT are considered (Table 1) to simulate typical tire configurations of the current freight traffic. Additionally, the steer tire (inherently one of the DTA tires) was considered to quantify the impact from the cab of freight trucks; although the load is lower than the half-axle trailer configuration, the tire load could be significantly localized. Given these three tires, various scenarios from the cab and trailer axles were considered. Three distinct case studies were investigated to test the capabilities of the domain analysis:

1. Comparison of typical loading condition of DTA, NG-WBT, and steer tire;
2. Effect of tire-inflation pressures; and
3. Influence of differential tire-inflation pressure for DTA.

Table 1. Loading cases used in finite element analysis

Case study	Tire	Load (kN)	Inflation pressure (kPa)
Case I	NG-WBT	44.0	758
	DTA	44.0	758
	Steer tire	29.7	690
Case II	NG-WBT	37.8	480
	NG-WBT	37.8	690
	NG-WBT	37.8	830
	DTA	37.8	480

	DTA	37.8	690
	DTA	37.8	830
Case III	DTA (uniform)	44.0	758/758
	DTA (differential)	44.0	552/758

A simplified diagram comparing vertical contact stress distributions for each of the three cases is presented in Fig. 6. It is noteworthy that the contact stresses were obtained from measurements by a third party as contractual work for the Illinois Center for Transportation. In addition, the x-axis presents the normalized contact width, wherein the actual width is normalized to the nominal width for comparison purposes. The analysis of the contact stress database was completed by Hernandez et al. (2013).

The analysis matrix of the loading conditions was combined with two pavement structures. Low-volume and interstate roadways were simulated to cover the extremes of pavement structure configurations, which are referred to as thin and thick pavements in the following sections, respectively. It is worth noting that the thick pavement included three AC layers over a granular base layer, whereas the thin pavement only considered one AC layer. Table 2 describes the various layers and corresponding thicknesses considered for the case studies. Cases I and III considered the same thick pavement structure with three AC layers, whereas Case II considered thin and thick pavement structures.

Table 2. Pavement structure configurations

Pavement layer	Layer thickness (mm)		
	Case I/III	Case II	
Wearing surface	62.5	100[a]	50
Intermediate	100	—	50
Binder	250	—	250
Granular base	150	200	300

[a] Considers only one AC Layer.

The AC layers were assumed linear viscoelastic, wherein the Prony series were computed using the dynamic modulus data from the Long-Term Pavement Performance (LTPP) database. From 1,000 data sets, material characterization was narrowed to six data sets based on confidence levels and nominal maximum aggregate sizes (Fig. 7). The thin and thick pavement structures considered a combination of the *strong* and *weak* AC material properties.

Granular layers were characterized as nonlinear, stress-dependent, and anisotropic only for the thin pavement structure, as it is assumed that the stress magnitudes were significantly reduced for thick pavements. Instead, the interstate pavement cases assumed the granular layer as linear elastic. Material constants for the nonlinear anisotropic granular materials were obtained from a database. Further details of the material characterization can be found elsewhere (Hernandez et al. 2016).

Implementation

Three scenarios were considered to test the capabilities of the domain analysis method by evaluating the impact of tire type, configuration, and inflation pressures. Implementing the pavement modeling scheme and material characterization by Hernandez et al. (2016), the output database of the FE simulations was utilized as inputs of the domain analysis method. It is worth noting that DTA with uniform tire-inflation pressure was selected as reference for all three cases. The following analysis includes the two main outputs of the domain analysis: CRS and CRE, which are the cumulative ratio in the stress and strain domains, respectively.

Case I: Tire Type and Configuration

Three tire configurations are loaded onto a perpetual pavement structure, consisting of AC and granular base layers with thicknesses of 412.5 and 150 mm, respectively (Table 2). Details of the loading conditions may be referred to in Table 1. Moreover, NG-WBT and DTA load inputs for the FE model were extracted from a database of experimentally measured contact loads (Hernandez et al. 2013, 2014), whereas the load input for the steer tire (placed onto the front-cab axle) was obtained from a FE tire model by a third-party from a work collaboration with the Illinois Center for Transportation.

Prior to presenting the resulting stress/strain ratios, maximum strains at six-point locations are shown. Extracting the strain values plays an importance related to the conventional mechanistic-empirical pavement design method, wherein the critical strain is utilized as an input in the transfer function to predict damage. It is noteworthy that the x, y, and z directions correspond to 1, 2, and 3 directions. The variables are $\epsilon_{33,AC}$, $\epsilon_{33,surf}$, $\epsilon_{22,AC}$, $\epsilon_{22,base}$, $\epsilon_{22,sg}$, and $\epsilon_{23,AC}$, which correspond to the critical transverse tensile strains at the bottom of the AC and surface; vertical compressive strain within the AC, base, and subgrade; and vertical shear strain within the AC, respectively. These strain outputs are selected as they are conventional inputs into transfer functions to estimate damage, except for $\epsilon_{23,AC}$, which was previously introduced by Yoo and Al-Qadi (2008) to be a major factor for near-surface cracking.

Fig. 8 illustrates the variation of the critical strains, normalized to the DTA case. One could observe that the strains within the AC layer were significantly higher than those of the base and subgrade layers. Additionally, at the depth of 23.3 mm, the NG-WBT and steer tire cases generated AC shear strain increments of 70 and 33%, respectively, due to higher contact stress magnitudes relative to DTA. As this response is excluded from the conventional MEPDG approach to estimate damage, near-surface behavior would be inaccurately predicted.

On the other hand, Fig. 9 illustrates the 3D pavement response via pq diagrams at the critical 2D plane (yz-plane). Clearly, a comparison of the pq diagrams depicts the significant complexity of pavement responses relative to single-point critical strains. High levels of compression and shear were induced at the near-surface region ($Z2$) directly underneath the tire, although one could clearly observe that the NG-WBT generated significantly greater compression and shear as the spread of triangle-up markers are tending towards the negative horizontal and positive vertical scales [Fig. 9(a)]. Moreover, Fig. 9(c) shows that the steer tire with a 9% decrement in the tire-inflation pressure but 32.5% increment in the applied load generated more concentrated values than those of the DTA [Fig. 9(b)].

Plotting NG-WBT p- and q-values along the layer width and depth, Fig. 10(a) highlights high-shear concentrations at tire edges. As expected, high-compression stresses were found directly underneath the tire [Fig. 10(b)]. Throughout the remainder of the 2D slices along the contact length, the same trend is observed at varying magnitudes. Another key point of the provided contour plots is the undeniable influence of tire-pavement contact stresses at the near-surface region.

Using the domain analysis method, five distinct zones were compared in Fig. 11, namely: $ACD1$; $ACD2$; $Z2$ and $Z8$ within the AC; $Z2$ within the base; and $Z2$ within the subgrade. All ratios for the DTA case remained equal to unity as DTA was the reference case. On one hand, the NG-WBT case resulted in CRS values within the AC layer to be over 1.0, which suggested higher damage potential relative to the DTA. In addition, the secondary partitioning resulted in a higher $ACD1$ value than that of $ACD2$. This difference was attributed to the asymmetric contact stress distribution based on experimental measurements (recall Fig. 10). Note that only the *CRS* values for the critical zones are presented as they have the similar trends in the strain domain.

On the other hand, the steer tire generated CRS increments up to 12% within the AC layer. Conventionally, MEPDG accounts for the front-cab axle based on load distribution; however, under the given tire-inflation pressure and applied load combination, the steer tire induced a higher damage potential relative to the DTA. Near-surface damage due to shear strain cannot be analyzed using MEPDG, although it clearly governs damage potential as illustrated on Fig. 8. Additionally, the proposed method captured the reduced influence of contact stresses within the granular layers, as the CRS values for the NG-WBT remained close to 1.0, whereas the ones for the steer tire were significantly less than 1.0 due to the decreased applied load.

Case II: Uniform Tire-Inflation Pressure

In the second case study, the influence of tire-inflation pressure was analyzed while maintaining an applied load of 37.8 kN. The DTA with tire-inflation pressure of 690 kPa was selected as the reference case. The structures containing AC layers of 100 and 350 mm are referred to as thick and thin pavements, respectively (Table 2), which represent low-volume and interstate highway pavements.

Like Case I, critical point responses due to NG-WBT loading are illustrated in Fig. 12 as a link to MEPDG damage evaluation (via transfer functions). Using the conventional method of determining single-point critical strains, one could observe that most of the responses from NG-WBT cases were minimally influenced by varying tire-inflation pressures, except for the shear strain within the thick pavement. Under NG-WBT loading, a high level of AC near-surface behavior was captured by the shear strain; however, the differences may not be realistic as it cannot fully capture the 3D influence of the contact stress distribution. It is worth noting that although a difference was observed for $\epsilon_{33,surf}$ and $\epsilon_{22,AC}$ for the thick pavement, the absolute strain difference was within 6 $\mu\epsilon$. Given the minute difference in strain, the anticipated number of repetitions to failure for these cases would result to similar values despite significant differences in the contact stresses at the tire-pavement interface.

Using the proposed method, domain analysis, Figs. 13 and 14 present the effect of tire-inflation pressure on *CRE* and *CRS* for both NG-WBT and DTA. The filled and hollow markers correspond to the thick and thin pavements, respectively. As illustrated, the increase in tire-inflation pressure leads to an increase in pavement response, more evidently for NG-WBT than DTA cases. Due to the symmetry of the applied contact stresses, $ACD1$ and $ACD2$ are not included in the following analysis.

The thick pavement, loaded by NG-WBT, was clearly governed by the near-surface zone ($Z2$ within the AC), whereas the highest *CRS* value of the thin pavement structure was found within the bottom of the AC, followed by the stress-dependent granular base [Fig. 13(a)]. The highest difference with respect to DTA at 690 kPa was observed for NG-WBT at 830 kPa on the thin pavement model, where *CRE* was 1.36 [Fig. 13(b)]. On the other hand, the DTA cases were marginally influenced by the tire-inflation pressures as the ratios within the critical zones and weighted sum remained close to unity (Fig. 14).

Although the lowest tire-inflation pressure generated the lowest bulk stress and strain ratios, the contour plots of the corresponding cases revealed higher stress and strain values within the tire edges at near-surface. As shown in Fig. 6, NG-WBT with tire-inflation pressure of 480 kPa generated significantly high tire-edge contact stresses. Localizing the domain analysis results to tire edges revealed that the NG-WBT with lowest tire-inflation pressure could lead to the highest near-surface damage potential. As shown, the domain analysis effectively captured the 3D stress/strain state of pavement responses, while point strain inputs for MEPDG transfer functions could not adequately quantify the influence of varying tire-inflation pressures.

Case III: Differential Tire-Inflation Pressure

DTA with differential tire-inflation pressures represent the typical operating conditions of heavy truck tires due to the difficulty of maintaining the inner tire pressure. The pavement structure considered AC and base layer thicknesses of 412.5 and 150 mm, respectively (Table 2).

The loading condition included a differential tire-inflation pressure of 552 and 758 kPa, while maintaining the applied load at 44 kN (Table 1). In contrast to the pq diagram of the DTA with uniform inflation pressure of 758 kPa in Fig. 9(b), the differentially inflated DTA resulted to higher magnitudes and wider distribution [Fig. 15(a)]. Particularly as illustrated in Fig. 15(b), the tire inflated to 758 kPa generated higher states of shear and compression at near-surface (*ACD2*, which is the left-hand combination of $Z2$ and $Z5$).

Contrasting the point strain and domain analysis outputs, Fig. 16(a) showcases that the differential tire-inflation pressure has minimal influence on the maximum strains. For fatigue cracking and rutting evaluation using MEPDG, the resulting number of repetitions to failure would be nearly similar, whereas the potential damage could lead up to a 20% increase for the tire with higher tire-inflation pressure based on the domain analysis.

On one hand, the *CRS* increment for $ACD2$ of the DTA with differential tire-inflation pressure was 14% greater than the reference DTA [Fig. 16(b)]. On the other hand, $ACD1$ *CRS* for the differentially inflated DTA was less than 1.0 due to the decrease of tire-inflation by 27%. Additionally, combining the critical zones into the weighted sum dilutes the localization of stresses and strains [Fig. 16(c)]. Therefore, secondary partitioning of the domain analysis ($ACD1$ and $ACD2$) allows to distinguish the influence of each tire on multiaxial pavement responses.

Summary and Conclusions

Domain analysis is proposed to assess the pavement structure in three dimensions and to provide a more comprehensive assessment of the stresses and strains imposed by tires on pavements. Given that a pavement fails due to bulk weakening rather than damage at one point, in the case of fatigue cracking and rutting, this new approach considers the bulk pavement damage potential induced by 3D and nonuniform contact stresses. The implementation of the proposed method comprises of four major steps: calculation of multiaxial responses using advanced FEM, identification of critical zones in the pavement, comparison of responses with respect to failure criteria, and computation of a scalar to represent the load demand on a given pavement structure.

This study provided an opportunity to test the capabilities of the domain analysis through three loading scenarios. First, after analyzing a thick pavement subjected to experimentally measured contact loads of NG-WBT and DTA, the new method was able to capture the complex and asymmetric pavement response distribution. The steer tire, typically accounted with a lower load distribution factor relative to trailer axles, resulted to a higher damage potential in comparison to the DTA at near-surface due to higher contact stresses. Second, using numerically generated contact stresses, it was observed that many of the critical point responses of typical thin and thick pavements were not significantly influenced by the tire-inflation pressure, while the domain analysis estimated an increment of approximately 17% in the damage potential when tire-inflation pressure was increased from 480 to 830 kPa. Finally, based on loading a thick pavement structure with differentially inflated DTA (from experimental measurements), the domain analysis captured the greater propensity of the higher inflated tire to potentially lead to higher damage, whereas, single-point responses cannot effectively capture this multiaxial difference. A direct implication of similar single-point strains is the inability to properly predict damage—in the MEPDG scheme, the resulting number of repetitions to failure via transfer functions would be indistinguishable. Moreover, near-surface behavior is unaccounted for by the currently established transfer functions.

Domain analysis can serve as a computationally efficient method to analyze the impact of multiaxial tire-pavement contact stresses on pavement responses. Particularly, complex details at the near-surface region, which is predominantly governed by contact stress distribution, was effectively quantified. The applicability of the domain analysis method could easily extend to other pavement structures, tire types and configurations, and loading conditions, along with considering other failure criteria.

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