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Interface stress state in the most common shear tests

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HIGHLIGHTS

- Stress histories at AC interface during wheel passage and in shear testing devices.
- Stress histories at AC interface strongly depend on the alignment the wheel runs.
- Some existing devices mimic only one of in situ stress histories, others none at all.

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ABSTRACT

The finite element model (FEM) results of a pavement structure are used to evaluate how stress state at the layer interface varies during the passage of a wheel over the road surface and to qualify the reasonability of existing dynamic tests used to characterize interface shear behavior. FEM interface stress states, inside and outside the tire track, are compared with stress histories undergone by specimens tested with the most common devices, such as guillotine or inclined. The outcomes clearly highlight that none of the existing devices can mimic the typical stress histories of the different alignments, merely approximating more or less some of these. In fact, in certain conditions, the inclined test configuration is quite good for alignments close to the rim of the wheel. This is no longer true if the traffic wander is considered. The real stress state may only be reproduced with a device that can independently manage normal pressure and shear.

1. Introduction

Interface shear strength between asphalt layers is increasingly focused on in view of the role played by the bond between layers and the capacity of the whole structure to withstand the traffic load. Poor bond causes reduced bearing capacity and consequent premature failures due to the concentration of the maximum stress at the bottom of each layer rather than at the bottom of the base layers. Slippage failure are typically caused by the debonding at the first interface, between wearing and binder courses. Efforts have been made to improve the bond, taking into consideration tack coat and emulsion as well as materials, application rate, surface conditions and curing time. Following the visual evidence that associates interface failures with slippage cracking and the related shear separation modality, the direct shear test has become the most widespread testing device to assess interface shear strength [1]. However, to achieve a significant characterization of the interface shear behavior, understanding the state of stress and strain at the contact between the layers represents a major step.

Many theoretical studies document researchers' interest in modeling the pavement structure. Generally, stresses and strains can be computed following three different approaches. One is the layered elastic method, a simple procedure based on the assumption of homogeneous and linear elastic materials behavior. Real field conditions with non-linear materials and complex tire contact pressure configurations are hard to reproduce with this [2,3]. The 2D FE model assumes a plain strain condition hence it is not appropriate to analyze non-uniformities as happens with actual tire contact pressure distribution. The last approach is more complete, developed to overcome the limitations of the previous methods, and uses 3D FEM analysis.

Early solutions for stress, strain and displacement calculations were presented by Burmister [4]. His model was based on the assumption of uniform and infinite layers composed of homogeneous isotropic and linear elastic materials. In 1945 the solutions were extended to three-layer systems. Following the Burmister approach, many researchers [5–7] also further contributed to the development of analytic theories for the determination of the state of stress and strain.

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To date, the most popular procedure to compute stresses, strains, and deflections at any point in relation to wheel loading and material properties is the multi-layered approach. Moreover, the rational design of the multilayer system must tackle interface characterization, in many cases restricted to two extreme conditions of either perfect bond or full slip. On the other hand, there is no widely accepted test method to measure the degree of bond, thus compromising the accuracy of the modeled pavement response.

In the research developed by Romain [8], a four-layered structure was modeled and the state of stress was analyzed at different interface conditions. They observed that tensile strain increases at the bottom of the layer adjacent to the interface with poor compared with full bonding. This increase is more pronounced when the moduli of adjacent materials are similar.

Uzan et al. [9] introduced the horizontal interface reaction modulus, assumed constant according to the linear elastic theory. Both strains computed by the BItumen Stress Analysis in Roads (BISAR) program and measured strains resulting from trial tests were compared in terms of distribution within pavement depth. Results showed that field conditions could be associated with partial adherence; the strain values are strongly related with the interface properties and the behavior of non-linear materials.

Al Hakim et al. [10] considered four typical theoretical structures and observed an average 20% decrease in pavement life when the value of the shear reaction modulus approaches 104 MN/m^3. A further reduction, up to 50%, was reported when complete debonding occurred.

Hachiya and Sato [11] used BISAR to compute stress and strain in the pavement structure in the two extreme cases of full bond or full slip. They observed an increase in shear stress when a higher horizontal load was applied and five times higher horizontal tensile stresses in the case of full slip. The BISAR program was also used by Brown and Brunton [12]. They evaluated up to a 75% reduction of the pavement life when the interface changes from full bond to full slip, both unrealistic conditions. A model similar to that by Uzan [9] was considered, assuming a 0.7 interface friction coefficient.

A 50% increase of the maximum horizontal tensile strain when the interface changes from full bond to full slip was also stated by Shahin et al. [13]. They assumed a magnitude of the horizontal load equal to half of the vertical load and focused their investigation on the tensile strain distribution. The results demonstrated that the largest tensile strain is located just outside the loading area with a 180° direction from the horizontal load direction.

Romanoschi and Metcalf [14] introduced a new constitutive model to represent the interface behavior, derived from the experimental shear strength vs shear displacement curves. Shear stress and displacement are proportional until the shear stress equals the shear strength and the interface fails. After this point, a friction model can be used to represent the debonding state. The experimental values of the computed interface shear stiffness modulus were compared with the results achieved by Uzan [9]. They also stated that, under traffic, the pavement structure is subjected to a repetitive load of different magnitudes depending on the vehicle. Vehicle's type influences vertical and horizontal pressures acting on the pavement surface and then on the stress field at the interface. Moreover, the ratio of shear to normal stresses at a point at the interface changes as the vehicle approaches and recedes from that point.

Kruntcheva et al. [15] using the BISAR program estimated up to an 80% reduction of the pavement life in the case of poor bond due to the greater sensitivity of the entire structure to horizontal stresses.

Luo and Prozzi [16] estimated horizontal strains in the longitudinal transverse direction using the multilayer linear elastic computer program CIRCLY. The results revealed compressive strains in the loading area and tensile strains at the edge or outside the wheel.

Ziari and Khabiri [17] used the program KENLAYER to implement an interface constitutive model and to compute critical stress and strains. It was found that the state of strain dramatically changes between the two conditions of full bond and full slip.

Su et al. [18] investigated these two extreme conditions comparing the shear stress contour on the vertical plane at the edge of the tire. The computed stress distribution demonstrated high shear stresses in terms of range and magnitude when the bond is lost, increasing the rutting potential. A correlation between shear and horizontal stresses was found.

Pasquini et al. [19] calculated the stress field at the interface of a typical flexible pavement through a layered elastic theory (LET) model. The stress results at different depths of the pavement were reported on the Mohr's plane and compared with the experimental envelopes derived from ASTRA tests.

Wang and Al-Qadi [20] inserted the measured 3D tire contact stresses in an ABAQUS model, assuming full bond at the interface. The results highlighted an increase in transverse tensile strength at the bottom of the hot mix asphalt and an outward shear flow from the tire center with a shear strain concentration under the tire ribs.

Baek et al. [21] investigated the effects of interface conditions on reflective cracking. The hyperbolic Mohr–Coulomb friction model proposed by Ozer et al. [22] was implemented in ABAQUS to characterize interface behavior. The model uses three parameters: shear strength, interface reaction modulus and friction. A strong relation between global fracture behavior and interface strength was demonstrated.

Liu and Hao [23] also developed a mechanical model in ABAQUS to analyze the U-shaped cracking mechanism. The distribution on longitudinal tensile and shear stress showed that the bottom cracks of the investigated failures are caused by high tensile strain while bilateral cracks refer to shear stresses.

Ozer et al. [24] using ABAQUS 3D introduced zero thickness interface elements and formulated behavior in terms of tangential and normal fraction applying basic friction in the framework of plasticity theory. Normal pressure and equivalent shear traction were considered at different stages of moving wheel loads as well as the in-depth distribution of shear stresses.

Alongside the evolution of new and more accurate models for the interface representation in FE models, researchers have begun to focus on the comparison between stress conditions at the interface computed from the model and shear strength outcomes from the experimental tests.

Jia et al. [25] analyzed the scatter plot of shear and normal stress from an ABAQUS model. They noticed an asymmetric distribution towards normal stress with a maximum shear stress around half of the maximum normal stress. The outline of the scatter plot was assumed as the stress maximum boundary and was compared with the shear strength envelope, resulting from monotonic tests. They assumed that interface failure is not expected if there is no intersection of the two curves. A similar comparison between FEM results and interface shear strength was presented by Ozer et al. [22] through the introduction of the stress ratio. This parameter was computed as the ratio between predicted interface stress from a FEM and interface shear strength at the corresponding normal stress. It was identified as a useful approach to estimate critical interface conditions for different pavement structures and materials.

The main issue related to the use of such a parameter is the identification of the interface failure criteria from the results of the monotonic shear tests where the shear strength is evaluated at different levels of normal pressure. As confirmed by recent dynamic models, a pavement structure undergoes repetitive