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A Finite Element Investigation of the Superelevated Horizontal Curve

Murat BOSTANCIOĞLU [1,*]

[1]*Sivas Cumhuriyet University, Faculty of Engineering, Civil Engineering Department, Sivas, Turkey*

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Abstract. Stress-strain analyses are studied under the bottom of the pavement layer, and pavement life values are calculated depending on the cross-section variation because of the superelevation in horizontal curves. For this purpose, 1st principal total mechanical strain values are analyzed with the superelevation values changing between 0-8 (%) and the different positions of wheel contact pressure. Finite element method is used for analysis. According to results of the study, it is obtained that pavement life decreases with the increasing superelevation, in the case of 8% superelevation and decreasing the distance to pavement edge, pavement life decreasing gets to 34%.

***Keywords*:**Fatigue, finite element method, tensile strain, pavement life.

Dever Uygulaması Yapılmış Bir Yatay Kurbanın Sonlu Elemanlar Yöntemi ile İncelenmesi

Özet. Bu çalışmada dever uygulaması yapılmış bir yatay kurbanın kaplama tabakası altındaki gerilme-birim şekil değiştirme ve kaplama ömrü değerleri dever sebebiyle değişen kesitlere bağlı olarak analiz edilmiştir. Bu amaçla deverin 0-8 (%) değerleri arasında değişimine bağlı olarak ve ayrıca tekerlek temas gerilmesinin pozisyonu değiştirilerek birim şekil değiştirme değerleri sonlu elemanlar yöntemi ile analiz edilmiştir. Çalışmadan elde edilen sonuçlara göre dever değerinin artmasına bağlı olarak kaplama ömrü azalmıştır. Bu azalma değeri deverin 8% olması ve yükleme noktasının kaplama kenarına olan mesafesinin azalması ile 34% seviyesinde hesaplanmıştır.

***AnahtarKelimeler*:**Yorulma ömrü, sonlu elemanlar yöntemi, çekme birim şekil değişimi, kaplama ömrü

1. INTRODUCTION

Roadways have vital importance for the living and development of society since they are responsible for large portion of the transportation of goods and people [1]. As a result of frequent road failure in most developing countries, the need for stronger, long-lasting and all-weather pavements has become a priority in pavement engineering as a result of rapid growth in the automobile traffic and the development of modern civilization.

In Pavement Engineering, it is known that the major causes of failure of asphalt pavement are fatigue cracking, caused by excessive horizontal tensile strain at the bottom of the asphalt layer due to repeated traffic loading and rutting deformation caused by densification and shear deformation of subgrade [2].

The fatigue resistance of asphalt concrete (AC) mixtures is its ability to withstand repeated bending

* Corresponding author. *Email address: bostancioglu@cumhuriyet.edu.tr*

without fracture. Most analyses utilize flexure stresses or strains on the underside of the AC pavement layers to assess the pavement lives [3].

Asphalt pavements consist of four main layers as the surface layer (AC layer), base layer, subbase layer and subgrade layer (soil layer). Since these layers have a complex structure consisting a number of materials (bitumen and fine or coarse aggregates) with different properties, mathematical description of these layers may not be possible [4,5].

Mechanistic methods used in the analysis of layered pavement systems work reasonably well. These methods analyze stresses and strains that occur depending on the traffic loads and environmental factors with mechanical theories [6,7].

Finite element method (FEM) can be successfully used for analyzing pavement structures with complex geometry, boundary conditions and material properties and to investigate the effects of static and cyclic loading combined with linear and non-linear material characteristics [6,8-11].

Turkish General Directory of Highways considers the geometric characteristics of roads that are effective in pavement failure as the slopes, ramp length and the radius of horizontal curves while recommending the bitumen performance grade according to Superpave design method [12].

In this study, the effect of cross-section variation (due to superelevation) on the horizontal curves that is necessary for pavement engineering, on the pavement life is investigated by the FEM technique through these important geometric characteristics. For this reason, mechanical strain values under the bottom of pavement and pavement life are analysed depend on the superelevation and loading position change in a determined cross-section.

Paper becomes different from the other studies that consider the cross-section effect on the pavement thickness calculations.

Metal corrosion is a very important problem in various industrial processes which is widely used water, alcohol and acid. The acid solutions used cause too much corrosion in the metal that is an iron, copper, aluminum. Corrosion inhibitors that are containing nitrogen, oxygen, Sulphur and aromatic ring, are used to prevent corrosion caused by acid solutions.

As it is well known that experimental studies have been used to understand the corrosion inhibition mechanism of molecules and to explain corrosion inhibition efficiencies. Quantum chemical calculations provide preliminary information on the activities of molecules. In quantum chemical calculations, parameters related to the activity of molecules are calculated using density functional theory (DFT) that are calculated HOMO (highest occupied molecular orbital), LUMO (lowest unoccupied molecular orbital), electrophilicity, electronegativity, chemical potential, chemical hardness and nucleophilicity.
In this study, we can be seen that activity of studied molecules whose names are 2-(4-nitrophenyl) benzimidazole (4NPBI), 2-(4-aminophenyl) benzimidazole (4APBI), 2-(2-nitrophenyl) benzimidazole (2NPBI), 2-(2-aminophenyl) benzimidazole (2APBI), 2-phenyl benzimidazole (PBI), 2-(4-chlorophenyl) benzimidazole (4CPBI), 2-(4-metilphenyl) benzimidazole (4MPBI), 2-(4-bromophenyl) benzimidazole (4BPBI) in Figure 1 [1].

2. FINITE ELEMENT MODEL AND METHOD

2.1. Model geometry and material defining

Three-layered conventional flexible pavement structure is selected for this study consists of a 250 mm thick surface layer, 500 mm thick base and subbase layer and 2000 mm thick subgrade layer. The pavement configuration is shown in Figure 1. This configuration is obtained from the field work of Karadeiz Technical University on Trabzon-Arsin highway (Turkey) [7] and the values are used as the same as this work.

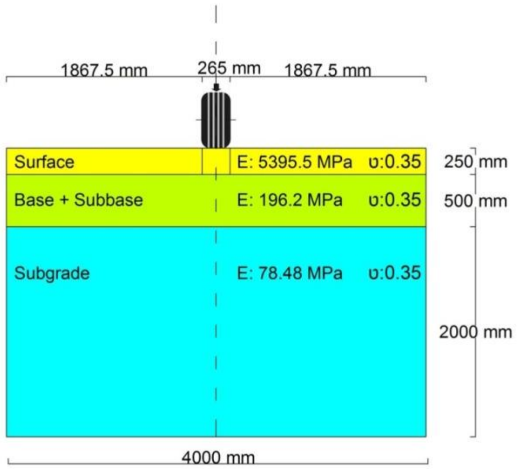

Figure 1. Pavement configuration.

Since asphaltic-pavement is a complex structure consisting of a number of materials with different properties, perfect mathematical description of the structure may not be possible. Most structural response models based on layered theory do not consider the heterogeneity of the asphalt concrete material. They are mostly based on linear elastic or linear viscoelastic theory. In the linear elastic theory, the material in each layer is assumed to be homogenous, isotropic, and linear elastic. Such material can be fully characterized by two elastic parameters such as the modulus of elasticity and Poisson's ratio [4]. In studies investigating the effect of parametric changes on the pavement performance, such as the strengthening of flexible pavements with geogrid, crack propagation modeling, the flexible pavement layers were identified by a fixed modulus of elasticity and Poisson's ratio, or they were added to the calculations by varying these values in a certain range [10,11,13].

In this study, which is particularly emphasized by the change effect at the cross-section, it is considered sufficient to define the layers as linear elastic. As can be seen in Figure 1, three different materials and their elastic material properties were used on the pavement modelling.

In the modelling of the problem, ANSYS 13.0 finite element program is used. 2 dimensional, 8 node structural solid element (PLANE183) was selected for use in the analysis [14]. The problem is considered under the plane strain condition. A plane strain model assumes that the thickness in the horizontal plane is infinite [8].

2.2. Boundary conditions, loading and failure criteria

The bottom surface of the subgrade is assumed to be fixed which means that nodes at the bottom of the subgrade can't move horizontally or vertically. The boundary nodes along the pavement edges are horizontally constrained but are free to move in the vertical direction [8].

The size of contact area between tyre and pavement depends on the contact pressure and can be represented by two semicircles and a rectangle as shown in Figure 2 (a). This shape is converted to a rectangle which's sizes are 0.8712Lx0.6L and area is 0.5227L^2 as suggested by Huang [15] (Figure 2 (b)).

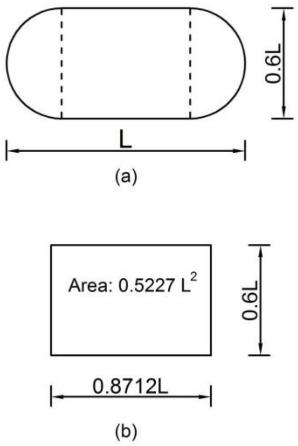

Figure 2. Contact area.

In this study the 5225 kg (51 kN) wheel load is assumed to be uniformly distributed over the contact area (26.5x29 cm^2) between tyre and pavement according to field work studied by Özcanan and Akpınar [7]. The contact pressure is assumed as equal to the tyre pressure [6] and selected as 0.667 MPa for this study. According to equivalent rectangle area suggested by Huang, contact area sizes are calculated as 23x33 cm^2 and the field measurements are in accordance with this calculation.

Due to symmetry, the pavement under a half wheel load is considered in the analysis [6]. Figure 3 shows the finite elements mesh of the model and load distribution on the surface.

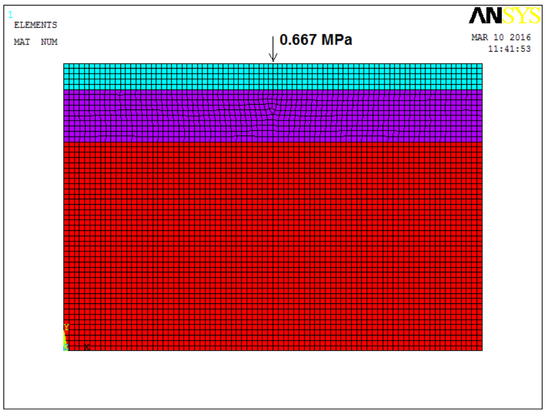

Figure 3. Finite element mesh model

According to elastic layer theory, the maximum strain is at the bottom of the asphalt surfacing layer. Most pavement design models are therefore based on straining at the bottom of the asphalt layer to predict performance with respect to fatigue cracking [14].

The failure criterion for fatigue cracking of the asphalt surfacing layer may be evaluated from the following equation;

$$\log(N_f) = 16.664\text{-}3.291\log\left(\frac{\varepsilon_t}{10^{-6}}\right)\text{-}0.854\log(E) \quad (1)$$

Where N_f is the number of load applications to induce fatigue cracking over 10% of the wheel path area, ε_t is the horizontal tensile strain repeatedly applied at the bottom of the asphalt surfacing layer and E is the stiffness modulus for asphalt surfacing layer [16].

3. RESULTS AND DISCUSSION

3.1. Verification of the model

Compressive stress values measured on and under 250 mm thick asphalt surface layer of Trabzon-Arsin highway from Turkey with 20 cm diameter pressure gauge are determined as 0.68 and 0.1 MPa respectively [7]. Stress values are compared with the values obtained from finite element model and the model results are given in Figure 4. According to Figure 4, model results are compatible with the field work. Furthermore, results obtained from the study of Walutiba and Ven [17] indicating that the vertical stress under 200 mm thick surface layer decreases 75% with regard to under wheel stress, in this study, vertical stress decreases 78% but thickness of surfacing layer is 250 mm and the results are in acceptable level.

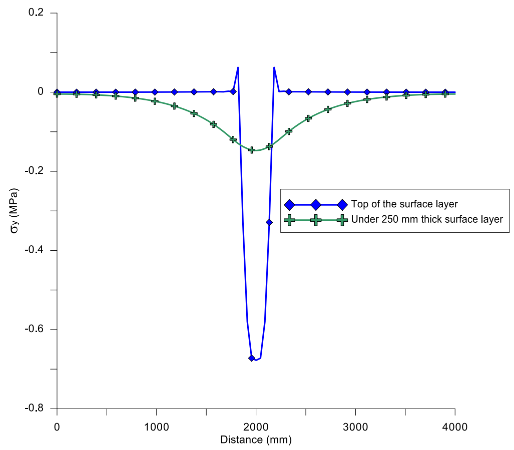

Figure 4. Compressive stress values obtained from FEM model.

3.2. Stress-strain analysis of the bottom of asphalt surfacing layer

For stress and strain analysis of the bottom of asphalt surfacing layer, the loading condition in which the contact pressure is performed in the middle of the traffic lane (4000 mm) is considered. 1st principal total mechanical tensile strain values at the bottom of the surfacing layer are obtained through the cross-section while the loading value and position are constant, and superelevation (d) is changing between 0 and 8%. Strain values are shown in Figure 5.

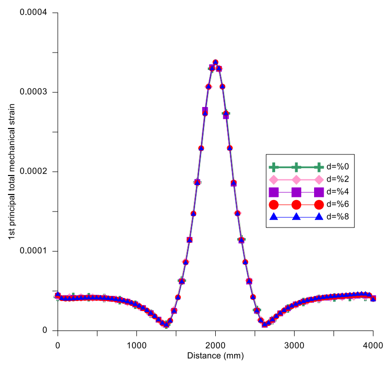

Figure 5. 1st principal total mechanical tensile strain values at the bottom of the surfacing layer

As can be seen in Figure 5, tensile strains for all superelevation values are adjacent to each other. From these results, it can be concluded that superelevation change has no significant effect on the tensile strains and pavement life while the loading is in the middle of the traffic lane (lateral supports of layers and pavement edges are strong enough).

While the loading is in the middle of the traffic lane, maximum vertical pressure stresses at the bottom of the surfacing layer are obtained as illustrated in Figure 6. According to Figure 6, increasing superelevation increases the compressive stresses. The decrease of the vertical component and the increase of the horizontal component of the loading with the steeper cross-section explain this situation.

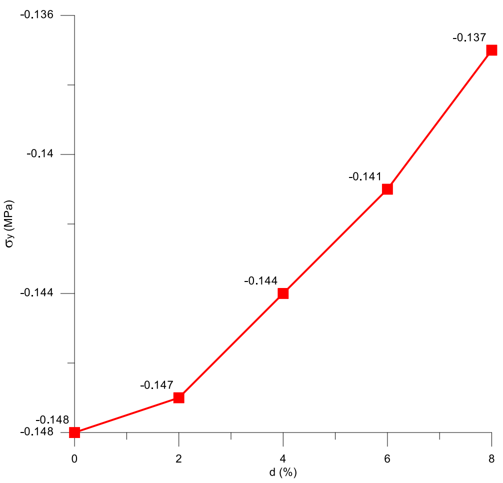

Figure 6. Maximum vertical pressure stress values at the bottom of the surfacing layer

3.3. Strain analysis depends on the loading position and superelevation change

It is explained in the previous section that superelevation has no significant effect on the tensile strain values in the case of loading is in the middle of the cross section. But, in concern with the positioning of a standard width (2380 mm) heavy vehicle [14] on a traffic lane, Figure 7-b represents a more realistic placement than Figure 7-a.

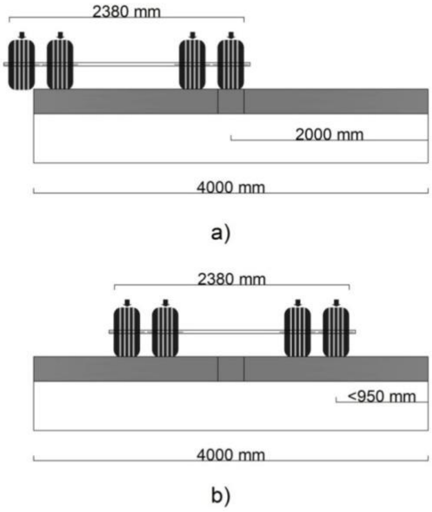

Figure 7. Positioning of a heavy vehicle on a traffic lane

The positioning of a heavy vehicle towards to horizontal curve centre and superelevation change are considered together. Hence, the contact pressure is placed in the distance of 1500 mm, 1000 mm and 500 mm from the pavement edge and strain analysis are performed with varied superelevation values (Figure 8).

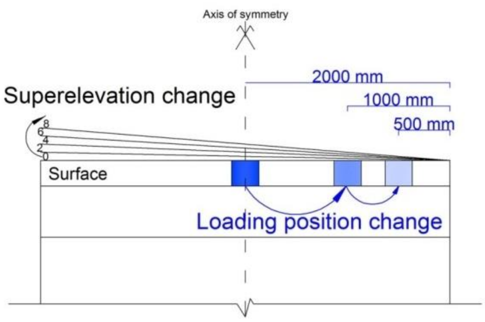

Figure 8. Illustration of loading position and superelevation change

When analyzing the tensile strain values at the bottom of the asphalt surfacing layer (under the wheel placement horizontally) for changing load position and changing superelevation, it can be seen that decreasing distance of loading to pavement edge makes superelevation-strain curves steeper (Figure 9). It means that pavement becomes more sensitive to superelevation change with decreasing distance to the edge. As a result of there is no lateral support in the horizontal direction of wheel-surfacing layer contact point and decreasing lateral support of layers, superelevation effect on the tensile strains is more noticeable.

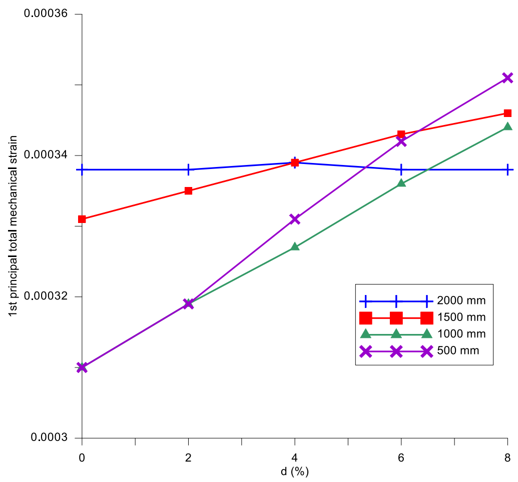

Figure 9. 1st principal total mechanical tensile strain values depend on the loading position and superelevation change

N_f values are calculated with obtained tensile strain values and stiffness modulus of surfacing layer for to evaluate the effect of superelevation to pavement life for the more sensitive loading conditions as stated above (1000 and 500 mm distance from the pavement edge) and presented in Figure 10. Nf results show that increasing superelevation decreases the pavement life. While the distance from the edge is 1000 mm, pavement life decreases 29% in comparison with 0% superelevation, and this ratio reaches to 34% for 500 mm distance.

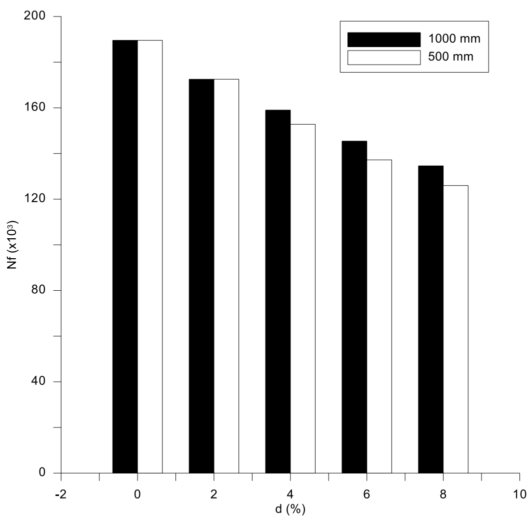

Figure 10. N_f values depend on the superelevation changing.

3.4. Precautions for increasing the pavement life of superelevated horizontal curves

Increasing the stiffness modulus or thickness of asphalt surfacing layer can be the solution of deteriorating effect of superelevation. In this study the most damaging conditions that are the 8% superelevation and loading at 500 mm distance from the pavement edge are considered. In this loading and cross-section condition, stiffness modulus and thickness values are calculated that equates the Nf value of 8% superelevated cross-section to Nf value of 0% superelevated cross-section (flat cross-section). Results are presented in Figure 11 and 12.

According to Figure 11, stiffness modulus value that ensures to Nf value of 0% superelevated cross-section (Nf=189572) is calculated as 10693 MPa from the curve equation so the stiffness modulus of superelevated surfacing layer must be increased just about two times.

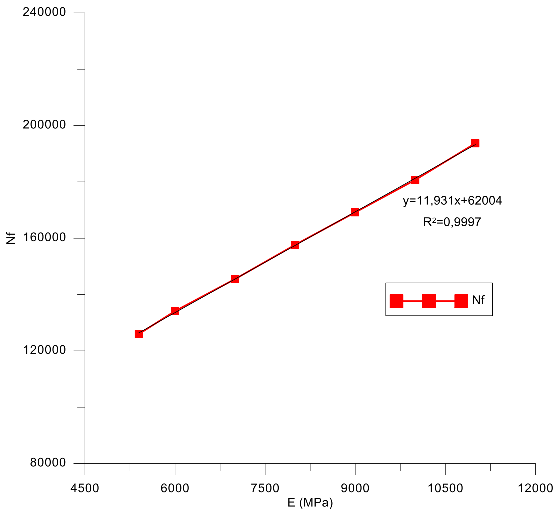

Figure 11. N_f values depend on the stiffness modulus.

While the stiffness modulus is constant, the 1st principal total mechanical strain value was calculated for different layer thickness values for obtaining the 189572 Nf value. The thickness that equates the 1st principal total mechanical strain value of 8% superelevated cross-section to flat cross-section determined from the curve equation as 296 mm (Figure 12). According to this result, surfacing layer thickness must be increased 46 mm.

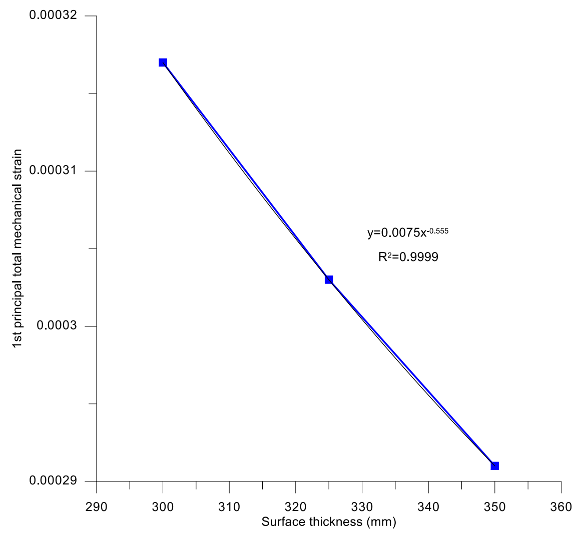

Figure 12. 1st principal total mechanical tensile strain values depend on the surfacing layer thickness.

4. CONCLUSION

The following results can be drawn from the analysis of this study;

* FEM is an applicable method for the modelling of multilayered pavement structures

* While the contact pressure is in the middle of the traffic lane, superelevation change has no remarkable effect on the 1st principal total mechanical strain and pavement life, but compressive stress values increase 7.4% with the increasing superelevation.

* The effect of superelevation becomes more distinctive when the loading gets closer to pavement edge. Decreasing distance to pavement edge decreases the pavement life 34%.

* The deteriorating effect of superelevation can be more efficient in the fill cross-sections that their lateral support is less than the cut one.

* For increasing the pavement life in superelevated horizontal curves, stiffness modulus of pavement must be increased approximately two times, or pavement thickness must be increased dramatically.

* According to results of this study, cross-section geometry that doesn't consider in pavement thickness analysis but has an effect on it must be taken into consideration.

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