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The Application of Micromechanical Modeling to Study the Non-Linear Behavior of Flexible Pavement under Truck Loading in Pakistan

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Abstract: This report presents the work done to create a 3D model of a pavement structure, which incorporates in a most accurately way non damaging effects of asphalt layer considering the different layers that compose the pavement structure. A series of approaches have been considered from linear viscoelastic modelling using Maxwell model via UMAT subroutine to integrated viscoelastic response using Prony series available in the built in ABAQUS material library. During this work also other effects have been considered including the viscoelastic behaviour caused by creep, which is included via a separate CREEP subroutine. In order to predict also the non-linear effect of viscous elastic response the well-known Schapery's nonlinear viscoelastic constitutive model was considered. Implementing 3D Schapery's model can be done by using again user material subroutine UMAT. It was found that the use of a nonlinear viscoelastic model substantially transformed the pavement response. A series of python scripts have been developed to create a multi-step analysis to simulate a cyclic loading application.
Keywords: Viscoelasticity, Abaqus. Asphalt, Damage, Simulation, Modelling, Pavement design

I. INTRODUCTION

Trucking is an important part of freight transportation in the Pakistan. Sustainable socioeconomic growth in Pakistan is heavily reliant on communication infrastructure such as roads, airports, railways, and seaports (Chaudry and Memon, 2013). Highway in Pakistan, public transport is the predominant means of passenger and freight transit just as it is in other developing countries across the world. Pakistan has a total road network of around 264,401 kilometres (Assessment and the, 2018). The proportion of goods transported by road is estimated to be 90%, while the percentages of cargo transported by rail and air are 8% and 2%, respectively (Co et al., 2006).

Heavy-duty vehicles wreak havoc on the flexible pavement. As a result, maintaining current transportation infrastructure and conduct a thorough structural and design study of new asphaltic pavements is essential. The frequency and magnitude of the applied wheel load govern the exact truck load impact on a pavement structure. This load is applied to the pavement by the tyres of the vehicle.

As a result, a proper interpretation of the effect of this load on pavement is required in order to assess the stresses and strains that will be created in the pavement. In Pakistan, increasing vehicle traffic and a shift from railroads to highways have wreaked havoc on the pavement grid rapidly.

Throughout its design life, road pavement is subjected to a variety of axle load combinations. As a result, the damage impact on the road structure from different axle combinations varies over its life cycle (Crespo Márquez et al., 2012). The pavement engineer must make an accurate assessment of the pavement's responsiveness and features.

As a result, when asphalt pavement is exposed to because of the high stress (or strain) levels, pavement substances may show non-linear viscoelastic characteristics.

As a result, it's crucial to see if the linear material behavior of bitumen road is important so that more accurate designing of structural layers can be done when they're subjected to heavy vehicle loads. Hence, there is a need to develop a specific 3d micromechanical (finite element) model that can simulate truck load in the flexible pavement system and represent the complex nature of boundary conditions, layer interface, and material properties by combining certain laboratory determined viscoelastic properties, virtual microstructure, and an asphaltic pavement user subroutine in a finite element modeling software.

II. AIMS AND OBJECTIVE

The main objective of this study is to create a simulation effort to mechanically simulate asphalt pavement performance with a concentrate upon it influence of truck load on asphalt distress. Because bituminous materials have a viscous nature, components are non-linear under high stress intensities for even more accurate forecasts, it is important to account for the non-linear viscoelastic reactivity of flexible pavements being exposed to large truck loads. To describe the nonlinear elastic properties of bituminous pavement, this work uses Schapery's nonlinear viscoelastic theory. The system is adopted by linking UMAT (user materials) in the commercially used Simulation software ABAQUS 2017 that is based on the recurrent numerical analysis (2017). A series of deformation experiments at several stress intensities and temperatures have been taken into account and the load and isothermal viscoelasticity material characteristics of the asphalt mixtures are then evaluated.

Following are some specific goals:

A. Create a micromechanical (finite element) model that can represent the non-linear behavior of flexible pavement.
B. To include material characteristics established empirically into the finite element model capable of conducting non-linear viscoelastic damage analysis.
C. Create a user subroutine capable of doing non-linear viscoelastic analysis.
D. To determine how damage begins and spreads in the wearing course of pavement as a result of truck loading.
E. To detect early signs of deterioration in asphalt concrete pavement.
F. Improve road design while lowering maintenance costs.

III.SCOPE/SIGNIFICANCE OF THE STUDY

The creation of a fundamentally sound behavior and performance model for paving roads with truck loads will fulfil the following essential goals:

A. This model can offer precise information about the behavior of the pavement surface under varied dynamic loads and environmental circumstances for material designers as well as the link between material characteristics and model parameters, resulting in improved material and combination selection and, ultimately, the optimum road design.
B. This model may offer detailed information on the performance of asphalt under actual loading circumstances to pavement engineers, allowing them to better predict the service life of a new road structure or the remaining service life of an old roadway.
C. Detailed investigations of pavement reactions arising from non-linear viscoelastic constitutive relationships are intended to enhance the existing pavement analysis and design technique by providing a superior knowledge of effects from truck loads upon on deterioration of asphalt

IV. MODEL DESCRIPTION

A three dimensional FE (Finite Element) model of a traditional asphalt pavement has been created using a commercial software tool known as ABAQUS. The model has been subjected to the tire pressure of a double axle truck tire. The pavement is cyclically loaded using multi step analysis. The load cycle taken from literature has been decomposed in a series of steps. This has the major benefit of using larger time step for the no loading zone between two steps. The loading time is around 0.058 seconds and the no loading time is 30 seconds. For this reason, it was important to create a multistep analysis. This allowed the solver to use larger step for the longer time simulation saving in computational time and physical memory. Typical asphaltic pavement was modelled through the three dimensional FE method in order to review the mechanical performance behaviour of the pavement under the influence to heavy truck loading. This task is performed once the raw model that include all the required model part is create and only loadings and steps need to be defined.

The finite element model can be seen in Figure 1, where also the different materials are shown. The representative volume of the pavement structure has a base of 3460 by 3560 mm and a total height of 2600 mm. The asphalt course (green) has a thickness of 101.6 mm, the base course (grey) 203.2 mm, the sub base (red) 406.4 mm and the rest is the sub grade (blue). Except the asphalt course all the layers are considered perfectly elastic, only the top layer is capable of dissipating energy because of its viscoelastic nature. The mesh has been constructed with the cyclic analysis to be take place in a much localised area as shown in Figure 1.

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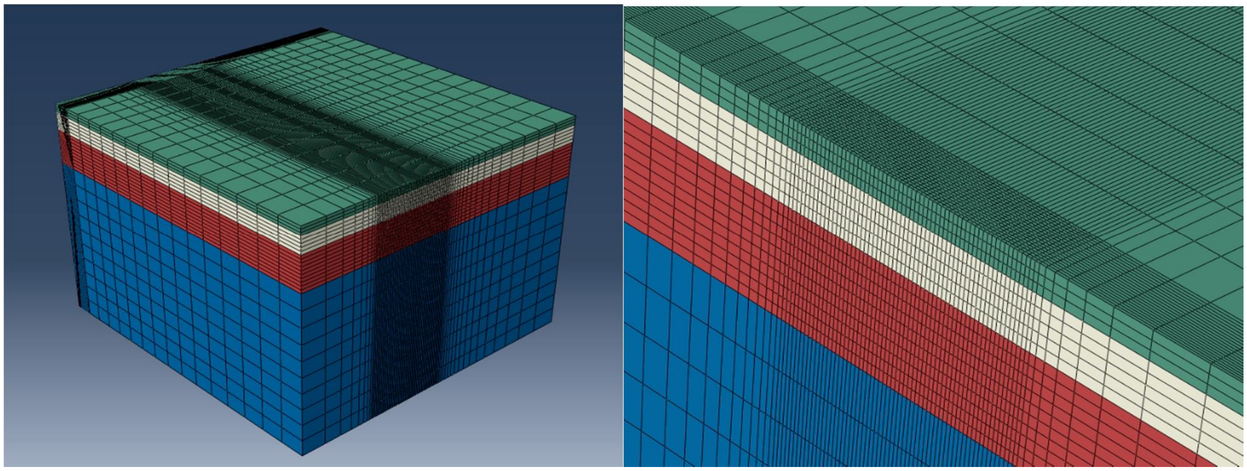

Figure 1: Finite element model of the pavment and mesh details

A total number of 82,320 C3D8R elements in ABAQUS (FE Tool) have been used. Due to the symmetry, only one quarter of the entire domain with a single axle loading in dual-tire is modelled. Several considerations have been done on boundary conditions. The base of the model has been constrained in vertical displacement. Initially symmetry conditions have been applied on the side of the model. However, this choice is not totally correct since it does not consider the constrain pressure applied by the surrounding material. For this reason a total pressure of 0.2 MPa, taken from literature (Khan, Grenfell and Collop, 2015), has been adopted. The main loading in this model is represented by the inflation pressure applied by the tire and the load produced by the truck weight distributed on one quarter of the contact surface. The total force generated by body force is calculated following the general assumption that on a 3 Axle Tandem truck the maximum weight of 27.5 tons only 39% is transferred to the back wheels. In the model only half of one row is represented by applying the pressure on the elements that represents the tire imprint on the asphalt, which is a commonly adopted strategy. The pressure applied is around 124 MPa and is applied uniformly on the tire imprint as shown in Figure 2. The iterative integration methodology established by Haj-Ali and Muliana (2004) has been used to statistically incorporate the 3-D non-linear viscoelastic equations formulated by (Ban, H., Im, S., and Kim, Y. R. (2013) into ABAQUS 2017 through user defined subroutine (UMAT).

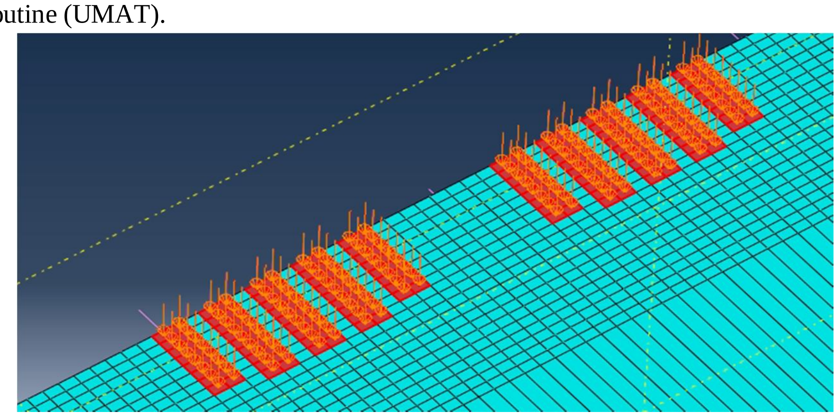

Figure 2: Half of one axle tire imprint

It can be noticed that squared mesh has been adopted in order to divide the imprint in a more efficient way and to allow better convergence. Traditionally meshes like this, with denser mesh in specifically selected areas are expected to work better because of the high stress intensity region, such as around the tyre loading area, and coarser elements for low-stress intensity zones. The tyre loading zone elements are 17 mm in size, which tiny enough to record mechanical responses caused by truck movements. Though, truck loading comprises a front steer axle and two tandem axles with dual tyres, the trapezoidal loading sequence was used to pick only the two tandem axles with dual tyres for saving time in the analysis. Because trapezoidal loading is so close to true loading, it is ideal for representing tandem axles. Two subsequent pressure states of 0.058 seconds are considered with another 0.058 seconds interval of no load then a gap of 30 seconds is considered before another truck passes through the same point. A total of 100 trucks passage was simulated.

V. CHARACTERIZATION OF VISCOELASTIC PROPERTIES

The uniaxial stress relaxation experimental test results of bituminous concrete were used to determine the viscoelastic parameters needed for the creation of FE model as well as the model validation. The Uniaxial Stress Relaxation Experiment for Asphaltic Concrete is concisely presented here. In this test, the specimen is subjected to an instantaneous strain that is maintained for a fixed interval of time. Relaxation time is the term for this period of time. The stress response is measured during relaxation time. Due to the non-linear characteristic of viscoelastic materials, stress relaxation is exhibited for continuous strain. The stress reaction is triggered when a sudden strain is imposed, and it progressively diminishes or relaxes during the relaxation interval.

The results of the Uniaxial Stress Relaxation Experiment are shown in the graphs below.

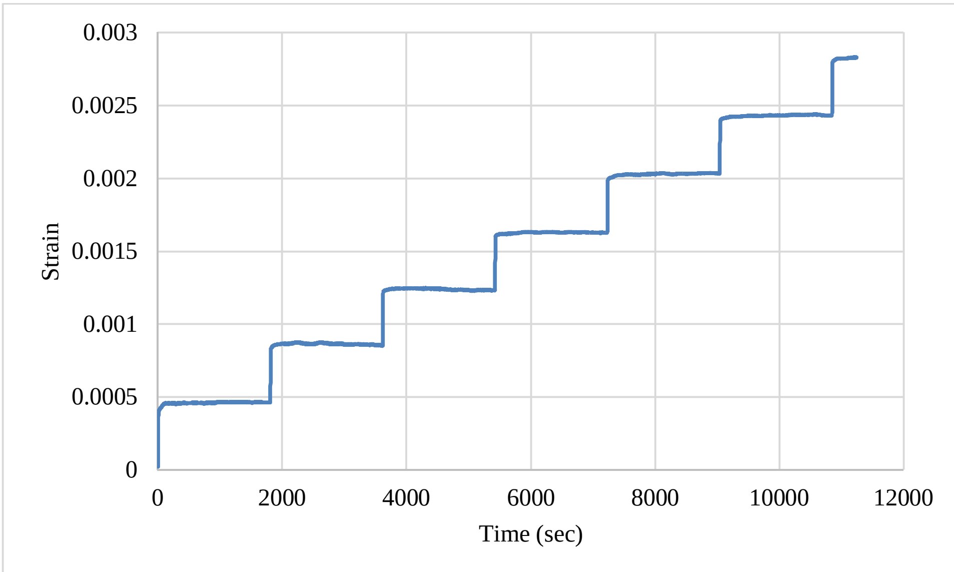

Figure 3: Application of instantaneous strain for 1800 seconds at a steady rate.

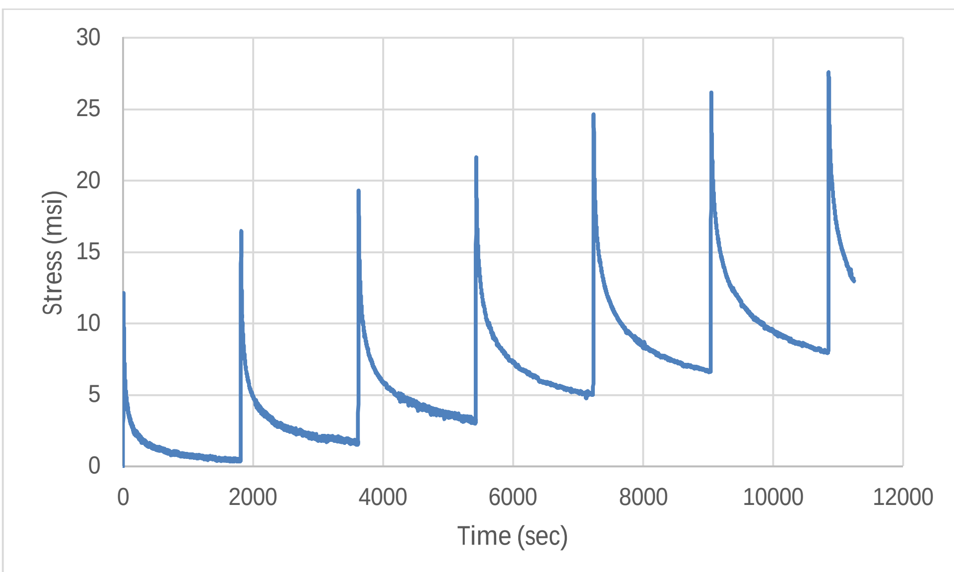

Figure 4: Uniaxial stress relaxation test stress-strain curves.

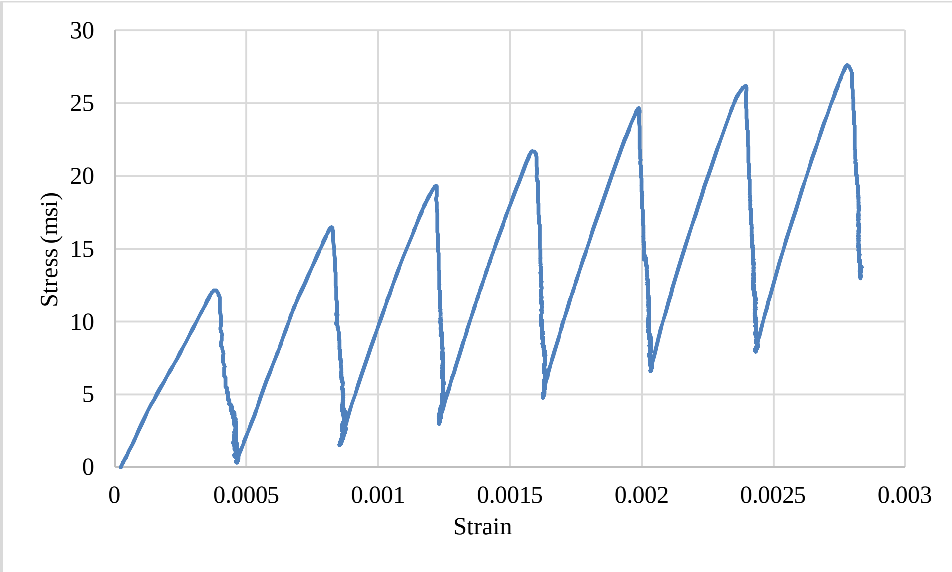

Figure 5: Stress relaxations under constant strain.

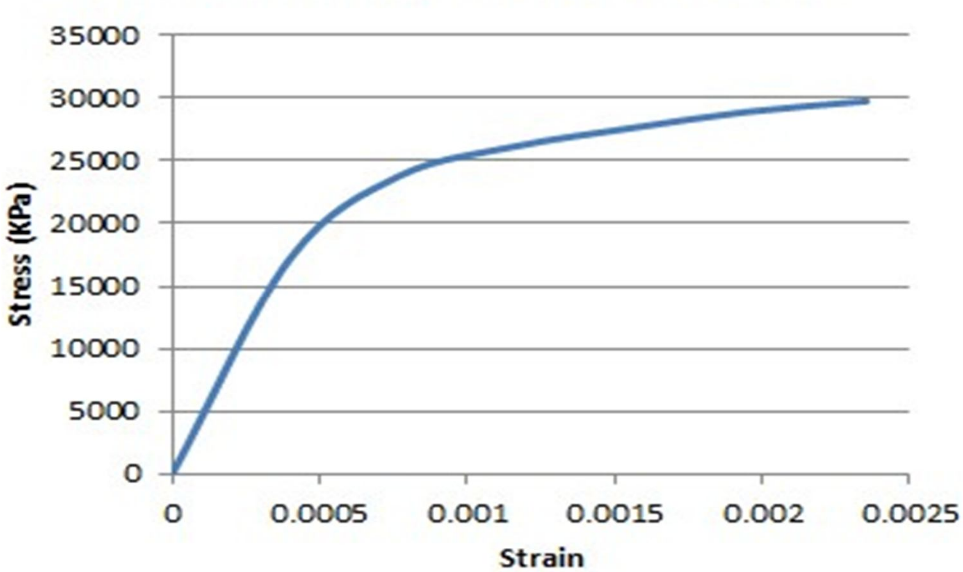

Figure 6: Stress vs Strain Graph

The behavior of asphalt concrete is not linear as the uniaxial stress relaxation test stress-strain graph shows that the non-linear behavior of Asphalt concrete becomes even more prominent at high temperatures.

Figure 7: Diagram showing preparation of specimen for stress relaxation test

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The results from this test were used to construct the shear relaxation curve. During the finite element modeling, the shear relaxation curve obtained from this test was fitted using prony series coefficients and the obtained stress-strain graph was also used to validate the finite element model.

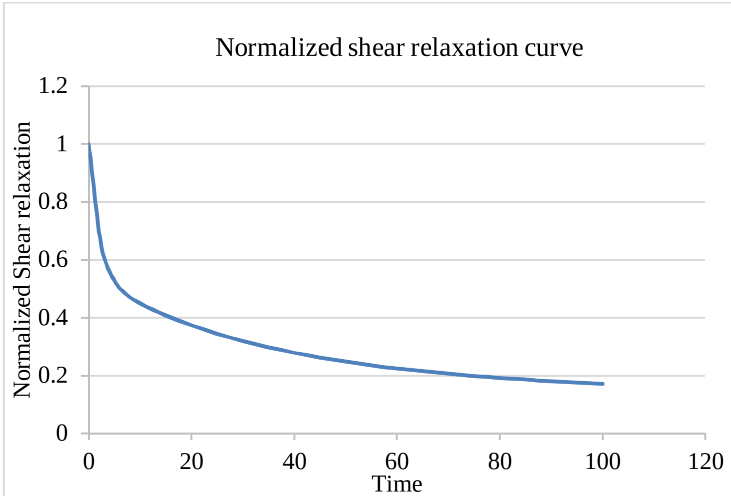

Figure 8: Relaxation curve obtained from Abaqus

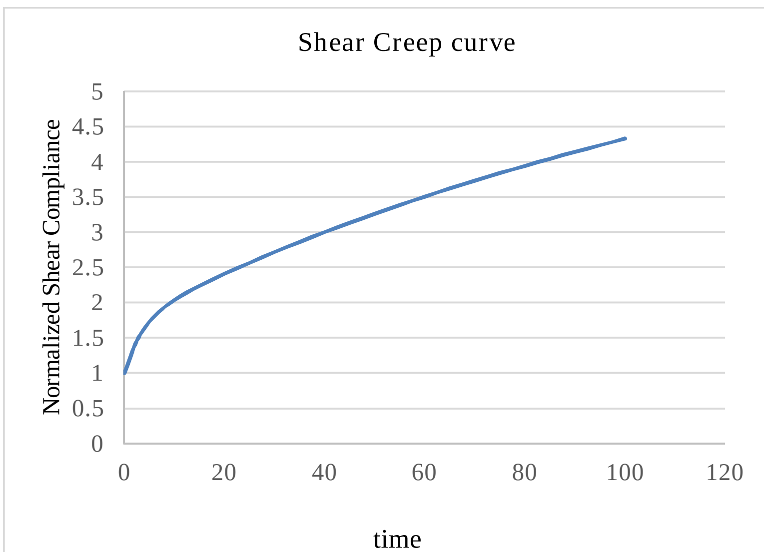

Figure 9: Shear creep curve obtained from Abaqus

VI. RESULTS

The initial results obtained with the Abaqus built in viscoelastic model are promising but also confirms the importance of considering non-linear visco-elasticity. In Figure the von Mises stress can be seen and it is evident that most of the load is located in the immediate vicinity (just in front) of the point of application of the pressure. Stresses after the top layer are greatly lower.

Figure 11 shows the stresses along z direction are depicted and a clear evidence of the imprints. The stress propagation across different layers is quite significant in this figure. Its magnitude is quite high in the location of the application of the loading and decreases with a progressive change from compressive to tensile stress in the layers. More interestingly the principal strain component shows how the strain response change drastically and how the layers behave when the load is applied. The mismatch in elastic properties is evident in the different elastic response that is clear due to the sudden change in contour. Figure 12 and Figure 13, further confirm how the behaviour of the layer immediately below the asphalt course is influenced by the top one. The viscous behaviour of the top layer however, tends to stabilise after few cycle, with no further increase in deformation as shown in Figure 14, and this is a well-known behavior forecasted for visco-elastic models.

The visco-elastic strain reaches a peak and then relax as soon as the load in removed and left redistributing. This lead to a progressive “hardening” that has its peak at around 200 seconds after which the increase in strain in nearly zero. Figure 15 shows the effect of the imprint by plotting along the cross section, the vertical component of total strain.

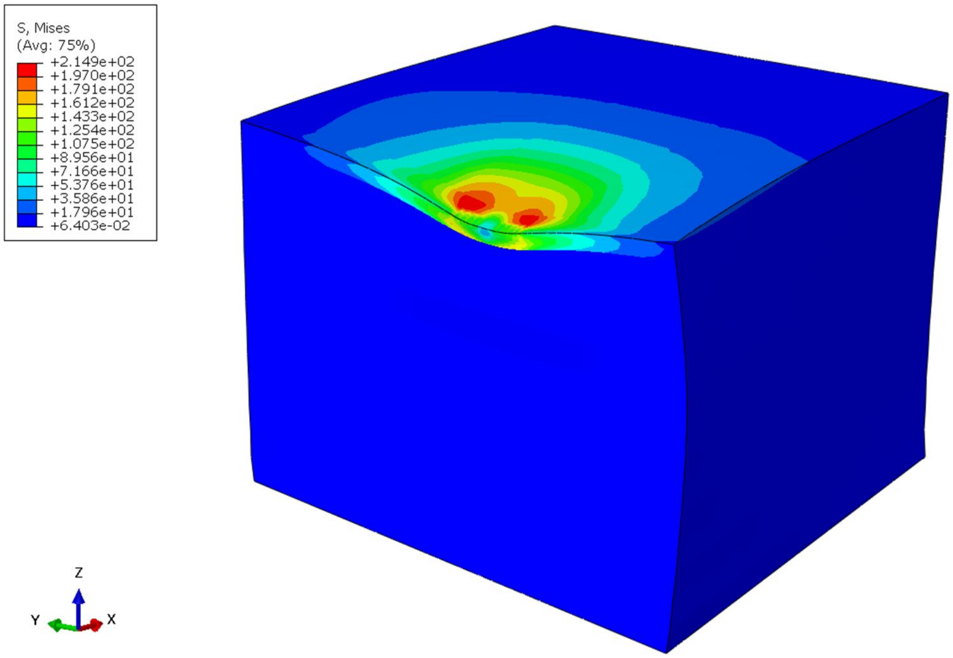

Figure 10: Von Mises stress in MPa

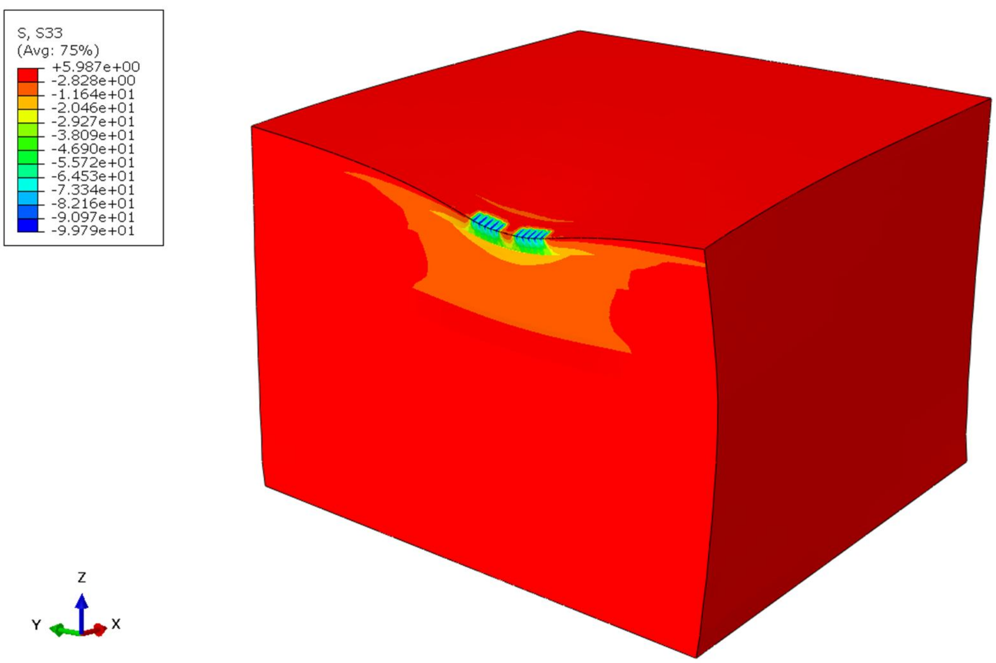

Figure 11: Stress on zz component [MPa]

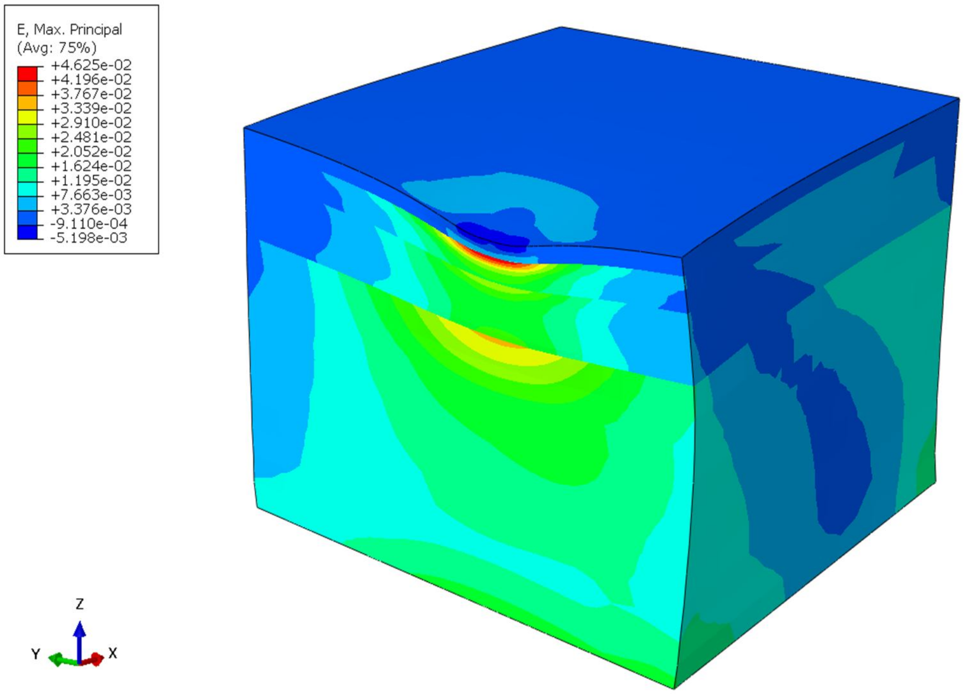

Figure 12: Pricipal strain component

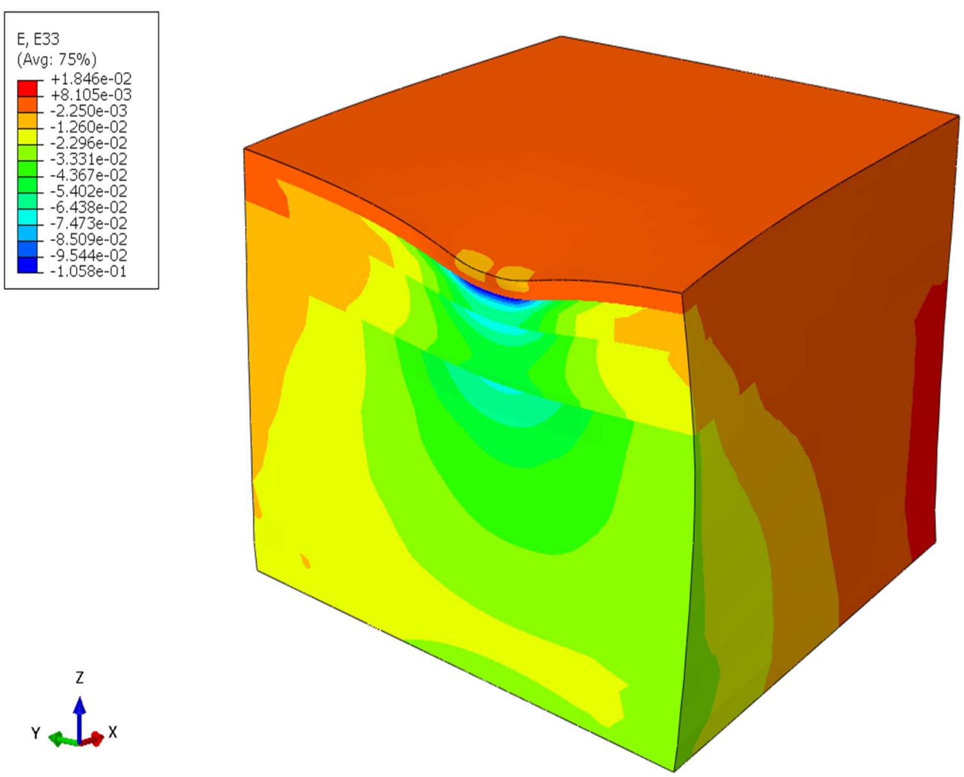

Figure 13: Strain over zz component.

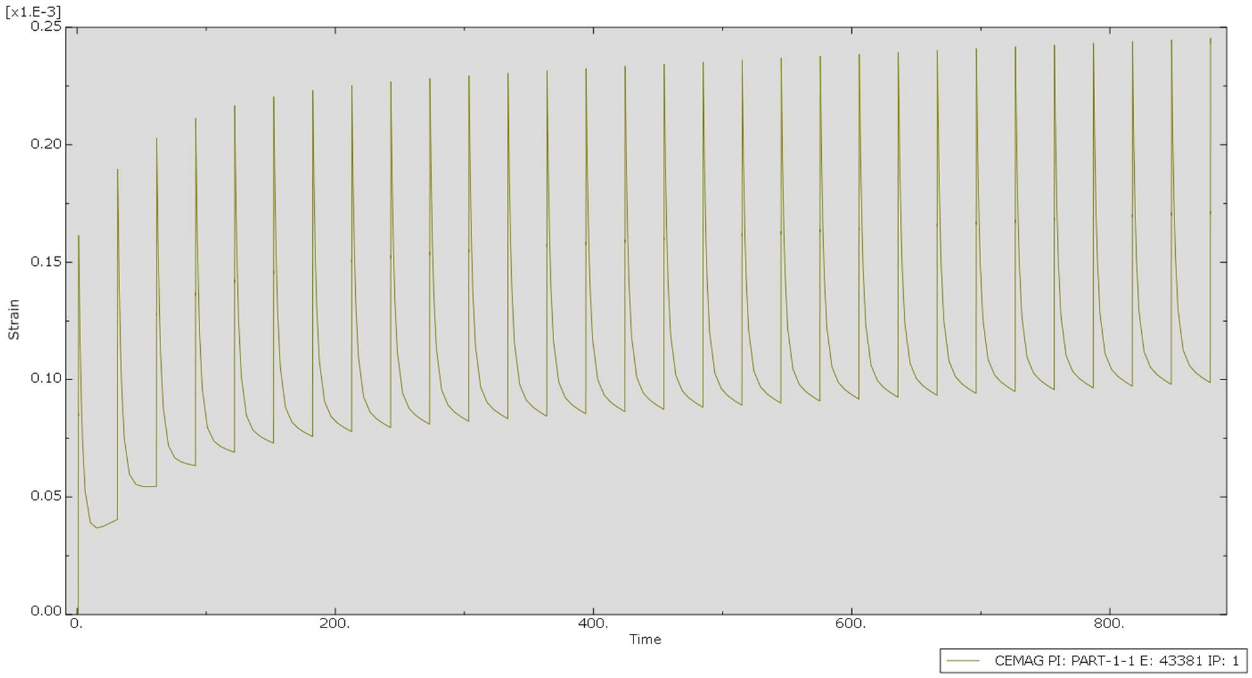

Figure 14: Viscous strain response during cyclic behaviour, using visco-elastic model.

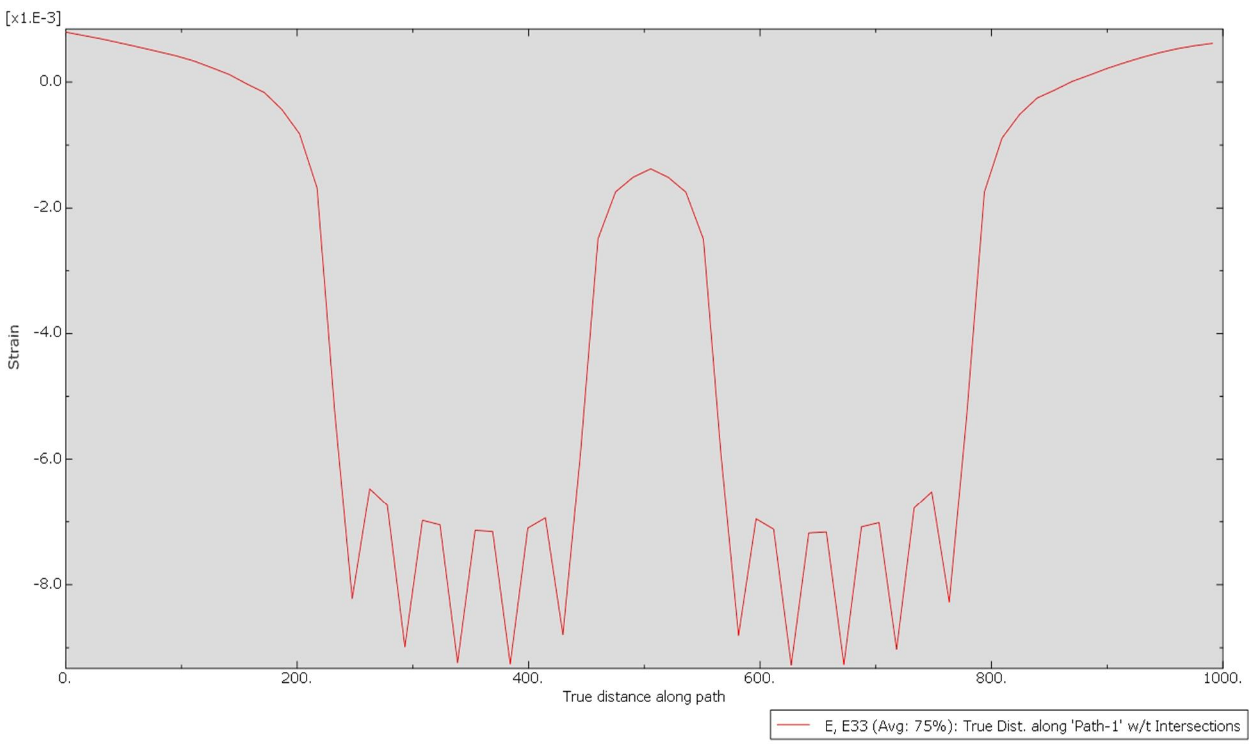

Figure 15: Vertical strain against a path over the cross section of the pavment

VII. CONCLUSIONS

The stress concentration in elastic analysis was not that high because asphalt concrete is viscoelastic material, so we have to design pavement structures on the basis viscoelastic analysis. The stress concentration in the material was considerably affected by the viscoelastic material specification. The stress intensity was amplified significantly after incorporation of the viscoelastic material parameters in the analysis.

It is important to incorporate the viscoelastic material behavior into the pavement designing practice. Because of the stress concentration and complex damage propagation caused due to the viscoelastic material nature, it is critical to be considered in the analysis. This is significant in most regions of Pakistan because climate is very hot in summer, hence the viscoelastic behavior of bituminous concrete becomes more observable and tempting. This is an important issue and it needs careful consideration so that the damages and distresses caused to the flexible pavements as a result of viscoelastic behavior of wearing course can be reduced.

It is obvious that we can model complex materials (like asphalt concrete in our case) that cannot be modeled by available Abaqus material models using UMAT subroutine. Advantage of UMAT subroutine is that only we have to define specified mechanical constants that are already available/known for materials in most of the cases. It avoids trials of the laboratory experiments. For example we cannot go all the time for laboratory tests of asphalt concrete to model and simulate it in FE software like Abaqus in our case, that require prony series coefficients, determination of which is not an easy job. For UMAT once we write the code script there is no need of these coefficients like prony, creep/ relaxation test data to be found via laboratory experiments every time.

The UMAT subroutine, like the viscoelastic UMAT in this study, can be used to develop a reliable performance prediction model for asphalt concrete by simply updating the subroutine. The load is not applied as a moving load in FE model for computational reason, this can be done with a DLOAD subroutine but this will mean that the pressure will have to travel across the entire model requiring a denser mesh along the moving path, due to a lack of time and resources at this time, this has been avoided; nonetheless, it is advised for future work for a more enhanced and realistic pavement study.

VIII. ACKNOWLEDGMENT

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