Development of a 3-D Simulation Model of Flexible Pavement Responses Reinforced with Glass Fiber Geogrid Under Moving Load

V. P. Sreenaja and Priya R.

Abstract In this work a numerical simulation model for computing mechanical responses of a pavement inserted with geogrid at positions- interface of bituminous layer and base course, middle of base course and interface between subgrade and base course was developed by considering viscoelastic nature of bituminous layers. The model is developed in ANSYS software using Finite Element method. Such an analysis plays a vital role in explaining pavement distress and its failure mechanism of a multilayered pavement system. The responses simulated are stress, strain and deformation under dynamic load. Viscoelastic property of bituminous pavement layers and the heterogeneity existed between different pavement layers in terms of material characterization are taken into account for the development of the model. The validation of the model is done by comparing the deflection and stress variation published in articles using ABAQUS software (4 and 6). From the analysis it is found that stress and deformation showed a significant reduction when the viscoelastic property was considered for single and tandem axle configuration; whereas the micro-strain value shows some percentage increment. When the glass fiber geogrid was placed at the middle of WMM layer, a significant reduction of 16.25, 14.9 and 6% on the mechanical responses, deformation, stress and micro-strain respectively is obtained.

Keywords Numerical simulation · Dynamic load · Viscoelasticity · Glass fiber geogrid

V. P. Sreenaja (✉)
Research Scholar, Department of Civil Engineering, College of Engineering Trivandrum, APJ Abdul Kalam Technological University, Thiruvananthapuram, India
e-mail: sreenaja97@gmail.com

P. R.
Department of Civil Engineering, College of Engineering Trivandrum, Trivandrum, India

A. Veeraragavan et al. (eds.), *Cognizant Transportation Systems: Challenges and Opportunities*, Lecture Notes in Civil Engineering 263,
https://doi.org/10.1007/978-981-97-7300-8_18

1 Introduction

Pavement distress and its failure mechanism can be explained by using mechanical response analysis in a multi-layered pavement system. The magnitude and frequency of dynamic loads produced by moving vehicles have an impact on the pavement responses. The dynamic loads exerted on the pavement due to wheel loads depends on axle load configuration, tyre pressure, pavement surface roughness and vehicle speed. Pavement mechanical response vary significantly under various loading condition, which depends on material heterogeneity and pavement structure composition of a multi-layered system.

Pavement response under actual field condition can be simulated using numerical methods, which provide an accurate and reliable mechanics-based approach of result interpretation. Due to their low costs, great efficiency and ideal matches with existing pavements, Finite Element (FE) models are commonly used. FE codes and software integrated a variety of methodologies for the simulation of loading geometry and material characterization. In order to simulate uncracked pavements under moving loads, Zaghloul and White [18] and Uddin et al. [16] developed a three-dimensional (3D) elastic multilayer pavement system in the FE software, ABAQUS by defining a step function with a duration, which is defined by the moving speed.

Fast-growing infrastructure development in pavement sector alarms that there needs a periodical pavement maintenance strategy. In order to do so, it is utmost important to aware about the mechanical response of pavement under static as well as dynamic load condition. Although the pavement structure is subjected to static as well as moving loads, majority of current pavement designs are based on time independent and linear elastic approach. Since the effect of stress–strain relationship of bituminous mixture on pavement responses are time dependent, it is utmost important to simulate the mechanical pavement responses such as stress, strain and deformation under dynamic wheel load application by taking into account the time dependent behaviour of bitumen for more durable pavement design.

Abd Alla [1] investigated the rational application of the FE method for the analysis of flexible pavements by accounting traffic loads with various characteristics, such as the effect of tyre pressure, axle load, asphalt layer rigidity and pavement layer properties, to estimate stresses and deformations through the pavement and found that as the depth from the surface increases, the deflection and stress caused by tyre pressure through the pavement reduces. Lin [11] used a quarter-truck vehicle model to simulate the dynamic vehicle load process and revealed that a four-fold increase in the road roughness coefficient causes a two-fold increase in the maximum dynamic vehicle load.

Lajcakova and Melcer [12] used MATLAB to numerically simulate the impact of moving loads on concrete pavements and they calculated the vertical deflection in the middle of the slab and time evolution of vertical tyre forces using Kirchoff theory. Numerical investigation on geogrid-reinforced flexible pavement under traffic loads using 3-D FE method and the effectiveness of glass fiber grid was analysed by Calvarano et al. in [4]. Dongliang and Cheng [7] investigated the mechanical behaviour of an asphalt pavement with a graded aggregate base using numerical simulation and they discovered that compressive stress was located on both sides of the wheel, while tensile stress was concentrated in the lower portion of the asphalt layer.

Geogrid-reinforced asphalt overlays on flexible pavements were evaluated using FE analysis by Correia et al. [5]. By comparing the numerical predictions with the experimental findings obtained from large-scale accelerated paved models, they were able to demonstrate a decrease in pavement stress in base course and the validation of the FE model. A 3D simulation model of the deflection basin of pavements under high-speed moving loads was developed by Deng et al. in [6] and they discovered a new parameter known as lag angle. Wu et al. [17] investigated the prediction of viscoelastic pavement responses under moving load and non-uniform tyre contact stresses using the 2.5-D Finite Element Method. They examined the effects of loading pattern and speed on pavement surface deflection and strain responses for asphalt pavements with four different layer thickness. From the study they disclosed that, for homogeneous contact stress in rectangular areas, the maximum tensile strains in the asphalt layer varied with the width/length ratio of the contact area.

Finite Element simulation model of instrumented asphalt pavement response under moving vehicular load was developed by Assogba et al. in [3]. They looked at the dynamic behaviour of a semi-rigid type of flexible pavement construction under a full-scale moving heavy vehicle load and found that longitudinal strain responses are tensile below the wheel load, but sensitive to compression in front of and behind the wheel load.

Jasim et al. [10] analysed the effects of geogrid (Tensar SS), when reinforcing conventional flexible pavements built on subgrade and investigated the suitable position for geogrid reinforcement under various tyre contact stress assumptions. They used a thick foundation pavement structure to run a 3D Finite Element model and found that adding a single geogrid layer to the upper third of the layer can increase pavement performance as well as provide structural stability. Qian et al. [14] evaluated the field and calculated mechanical responses with different moduli input using FE approach. Additionally, they used static flexural modulus for the Cement Stabilized Gravel (CSG) layer and dynamic resilience compressive modulus for the asphalt layer.

Numerous researchers have continuously worked on the development of 3D pavement simulation models using Finite Element approach and software such as ABAQUS and ANSYS as explained in the previous paragraphs. Recent researches are focused on analysing the dynamic behaviour of flexible pavements under the influence of moving traffic loads.

The study aims to develop a 3-D numerical simulation model for computing mechanical responses of a pavement reinforced with glass fiber geogrid was developed by considering the viscoelastic nature of bituminous layers. Thus, the specific objectives of the present study are;

1. To develop a 3-D FE simulation model considering viscoelastic behaviour of bituminous layers for different loading pattern on pavements under moving loads using ANSYS Software
2. To simulate the effect of providing glass fiber geogrids at positions - interface of bituminous layer and base course, middle of base course and interface between subgrade and base course on mechanical responses.

2 Methodology

The dynamic simulation study was carried out by using ANSYS Software, which is most suitable for advanced engineering simulation, specifically for dynamic load application. The study focuses on the development of 3-D FE model with reference to the material properties from Deng et al. [6]. Pavement layers considered are subgrade, base and surface layer. In order to reduce the layer thickness and aggregate consumption, base and sub base layer is provided as single WMM layer with 0.304 m thickness, which can perform the load bearing and drainage function of pavement in a satisfactory manner. The glass fiber geogrid insertion on various positions of base layer is selected based on the study results that, these positions of geogrid can increase pavement performance and provide structural stability [10]. The glass fiber geogrid is a biaxial planar structure (as shown in Fig. 1) with elastic modulus of reinforced base/sub base layer is equal to,

$$E_{\frac{reinforced\ base}{subbase}} = MIF \times E_{\frac{unreinforced\ base}{subbase}} \tag{1}$$

where, MIF–Modulus improvement factor, which is evaluated by conducting plate load tests on supporting layer. For glass fiber geogrid, MIF value ranges from 1.2 to 2.

The glass fibre geogrid with high tensile and elastic stiffness acts as stress relieving interlayer [9], which enables its role in pavement responses under loading condition. The properties of glass fiber geogrid considered for the model development are tabulated in Table 1 with reference from Calvarano et al. [4].

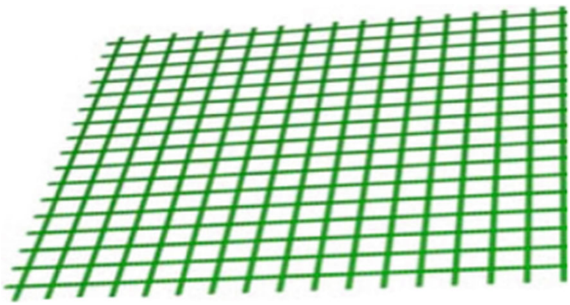


Fig. 1 Glass fiber geogrid model (*Source* Calvarano et al. [4])

Table 1 Properties of glass fiber geogrid (*Source* Calvarano et al. [4])

Property	Unit	Value
Poisson's ratio	–	0.3
Elastic axial stiffness	kN/m	213
Rib thickness	mm	3
Rib width	mm	1.2
Aperture size	mm	2.5

These properties of glass fiber geogrid are input to FE software in terms of elastic axial stiffness, Poisson's ratio and rib size. Since the consideration of viscoelastic property is involved in the model development, relaxation time and relative moduli at different temperatures are taking into account as the input parameters. Various axle configuration considered are single and tandem axles, for which the pavement responses are simulated. The development of 3-D FE model considering the viscoelastic property for various axle configuration and the effect of providing glass fiber geogrid at various positions are discussed in the subsequent section.

The dynamic simulation process is carried out by considering the viscoelasticity of bituminous mixture on a multilayered pavement system. The methodology followed for the simulation process is illustrated in Fig. 2.

As indicated in Fig. 2, the primary task is the conversion of vehicle speed into wheel load by using Eq. (2).

$$\textit{Vehicle speed} = \textit{wheel load} \; * 0.698 \tag{2}$$

The numeral in Eq. (2) indicates the value of tyre deformation factor, which depends on tyre pressure, axle configuration, etc. For each vehicle wheel load, corresponding load duration value can be computed as;

$$\textit{Load duration} = \frac{0.1905\, m}{\textit{speed in}\, m/s} \tag{3}$$

Model geometry and its material properties are selected according to Table 2 with reference from Deng et al. [6] which can be depicted in model geometry as shown in Fig. 3.

The upper layer which experiences the moving load impact on pavement structure is the bituminous layer. Thus, these layers are exempted from restrained conditions of rotations/displacements, which prevents the distortion of underlying pavement layers during loading condition, due to the low flexural strength.

Relaxation time and relative moduli are the parameters used to describe Prony-series and the relaxation time at various temperature was calculated using equation,

$$\text{Relaxation time}, T = \frac{\lambda_0}{E_0} = \frac{tan\varnothing}{2\pi f} \tag{4}$$

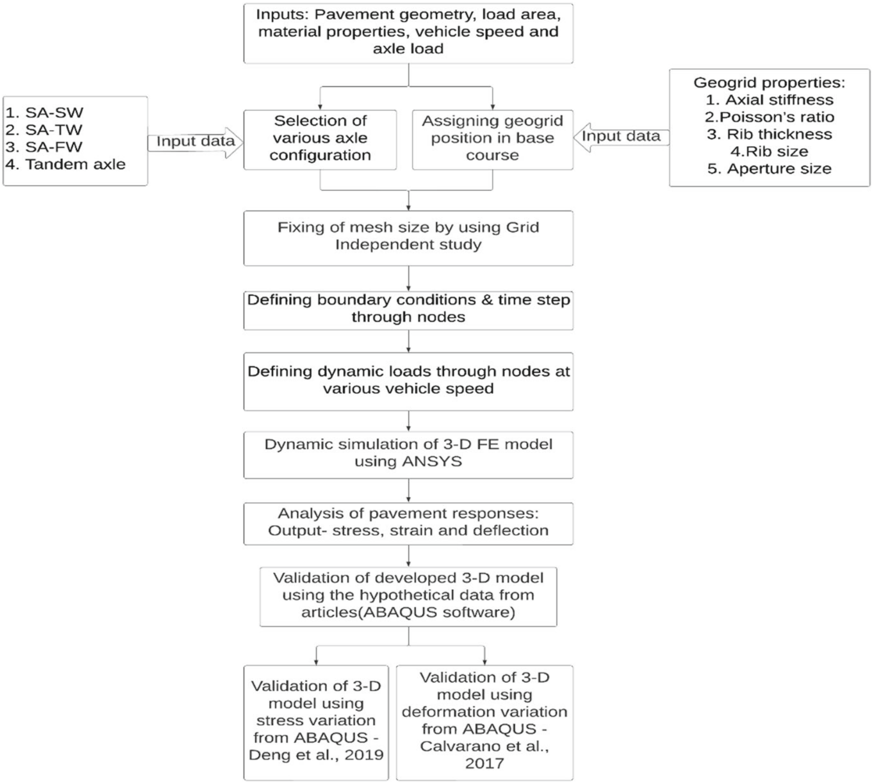


Fig. 2 Dynamic simulation methodology

Table 2 Material properties for dynamic simulation (*Source* Deng et al.) [6]

Model parameters	Surface layer	Base course	Subgrade
Thickness, m	0.152	0.304	1.778
Poisson's ratio	0.35	0.35	0.4
Density, Kg/m^3	2243	1922	1922
Materials used	Bituminous mixture	Aggregates	Soil
Dynamic complex modulus, MPa	428	–	–

where, $\varnothing$–Phase angle (degree)

f–frequency (f = 1/T)

λ_0–Viscosity coefficient (dashpot)

E_0–Elastic coefficient (spring).

Equivalent load contact area of elliptical shape is assumed for accurate simulation results. The equivalent area corresponding to 315/80R22.5 dual tyre vehicle is 0.1905 × 0.157.5 m (0.8712L × 0.6L), which was taken as node area, through which moving

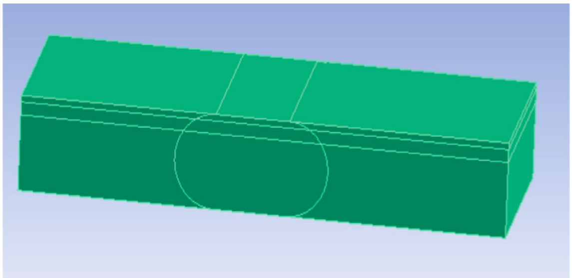


Fig. 3 Model geometry with load area

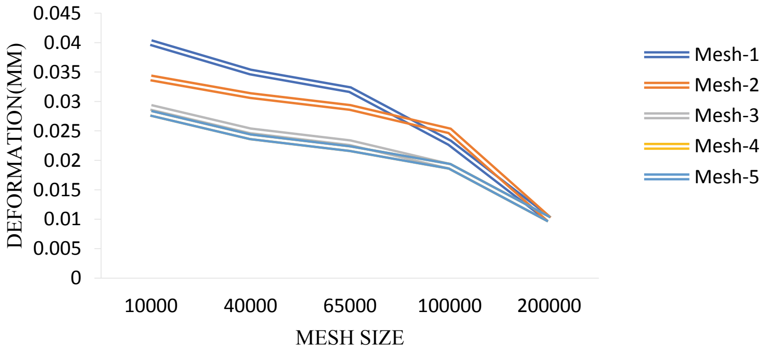


Fig. 4 Grid independent study

loads are applied. Grid independent study is utmost important to suitably select the grid size. It is an iterative process in which the simulation result converges to a constant value. Figure 4 depicted the converged deformation value of 0.01 mm, which corresponds to an applied mesh size of 200,000.

In order to study the influence of various axle configuration on pavement responses, dynamic load was applied along the load path in model geometry with appropriate load duration by defining time step. Time step is the input parameter which used to define the dynamic loading condition. Single and tandem axle configuration models are developed for various vehicle speed by inputting corresponding speed values of axle loads. For validation purpose of the model, same pavement cross section with 2 loading paths of 157.5 mm wide and 190.5 mm long are created symmetrically along the longitudinal direction with 193 mm space between the two-wheel paths. Contact load of 40 kN and tire inflation pressure of 689.5 kPa was applied along the loaded path and dynamic load was applied in each plane with a load magnitude of 40 kN at 28 kmph moving speed [6].

To analyse the influence of geogrid on mechanical response of pavement, a glass fiber geogrid of thickness 0.003 m is placed at positions- interface of surface and base course, middle of base course and interface of base and subgrade layer. The elastic modulus value of reinforced base/sub base layer is input by taking the corresponding MIF value of 1.62. Same model geometry (Fig. 3) was considered with reference

Table 3 Model parameters for validation (*Source* Calvarano et al. [4])

Layers	Thickness, m	Poisson's ratio	Modulus of elasticity, MPa	Materials used
HMA surface layer (BM)	0.08	0.35	1900	Bituminous mixture
Base layer (WMM)	0.20	0.35	300	Bituminous mixture
Subbase layer	0.27	0.3	41	Crushed stone
Subgrade	1.45	0.3	10	Sandy soil

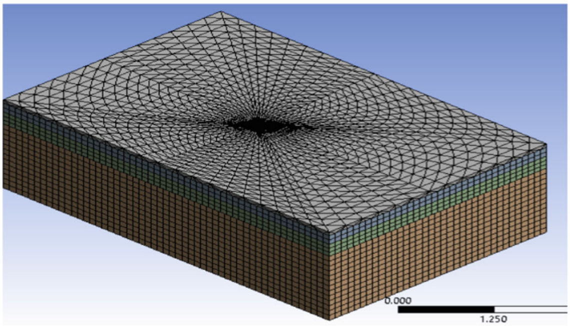


Fig. 5 Validation model geometry with geogrid and mesh

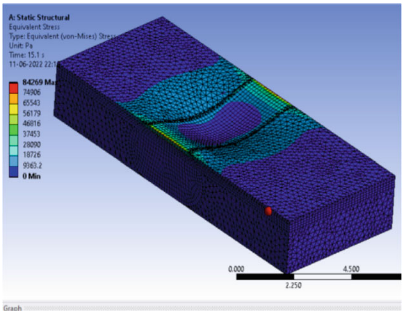
from dynamic simulation process, with the glass fiber geogrid insertion at above specified positions. For validation of the model, glass fiber geogrid was placed at HMA-base interface and a pressure of 550 kPa was applied on a circular area of radius 0.15 m. Model geometry considered for validation purpose can be sketched with the help of Table 3.

Loading of impulse type was assumed with 2000 number of load repetitions along with the applied axle load of 40 kN. A pressure of 550 kPa was applied in a circular area of radius 0.15 m with a frequency of 10 Hz at 0.1 s load duration, corresponding to an average speed of 70 kmph [4]. The model geometry with applied mesh is shown in Fig. 5.

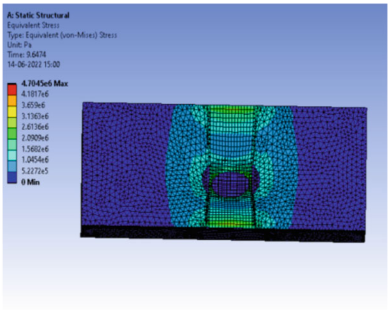
Then the stress variation from ANSYS and ABAQUS software [6] are compared and analysed to check the accuracy of simulated 3-D model.

3 Results and Discussions

Apart from static simulation process, dynamic simulation results can better reflect the field condition. So, as an illustration of real-world scenario, stress variation for pavement cross section with and without having viscoelastic properties, which is obtained from ANSYS are depicted in Fig. 6a and b.



(a) By considering viscoelasticity



(b) Without considering viscoelasticity

Fig. 6 **a** and **b** Stress variation for SA-SW: with & without considering viscoelasticity

For various axle configuration such as single axle-single wheel (SA-SW), single axle-two wheel (SA-TW), single axle-four wheel (SA-FW) and tandem axles, the mechanical responses are simulated and are tabulated in Table 4.

From Table 4, it can be seen that the stress and deformation value showed a considerable reduction, as the Viscoelastic property taking into account; whereas the micro-strain increased by a significant percentage due to the non-linear property of bituminous mixture. Validation results of stress variation from ANSYS is compared with the ABAQUS output from Deng et al. [6] and which is shown in Fig. 7.

Figure 7 depicted the stress variation with respect to tyre width and tyre pressure in a 3-D plane and the result comparison with ABAQUS [6] demonstrated that the stress variation follows the same pattern. The ABAQUS result variation is shown in Fig. 8.

From Figs. 7 and 8, it can be inferred that the developed 3-D simulation model fits with the ABAQUS model.

3.1 Effect of Geogrid Action in Pavement Deflection

The effect of viscoelastic property of bituminous layers on mechanical response was analysed and a significant reduction in corresponding response was observed, when the influence of viscoelastic property was taken into consideration. Thus, in order to simulate the effect of mechanical response of pavement inserted with glass fiber geogrid by considering the viscoelastic behaviour, glass fiber geogrid is placed at various positions- interface of surface and base layer, middle of base course and interface of base and subgrade layer. Corresponding stress, strain and deformation values are recorded. The deformation profile of geogrid reinforced pavement under moving load is shown in Fig. 9.

From Fig. 9, it can be seen that the deformation is 4.92 μm, which is less than the deflection value of 5.9012 μm (from Table 4), obtained for the pavement section

Table 4 Pavement responses for various axle configurations

Axle configuration	Stress variation, MPa			Deformation variation, μm			Micro-strain variation, μm/m		
	Without viscoelasticity	With viscoelasticity	% reduction	Without viscoelasticity	With viscoelasticity	% reduction	Without viscoelasticity	With viscoelasticity	% increment
SA-SW	0.08	0.013	83.75	0.069	0.03	99.4	0.164	0.174	5.74
SA-TW	0.094	0.032	65.96	0.082	0.079	3.6	0.164	2.67	93.86
SA-FW	0.462	0.0495	98.9	0.125	0.12	90.4	0.252	0.267	5.61
Tandem axle	6.7	3.2	52.2	337.9	0.231	99.9	0.94	176.56	99.47

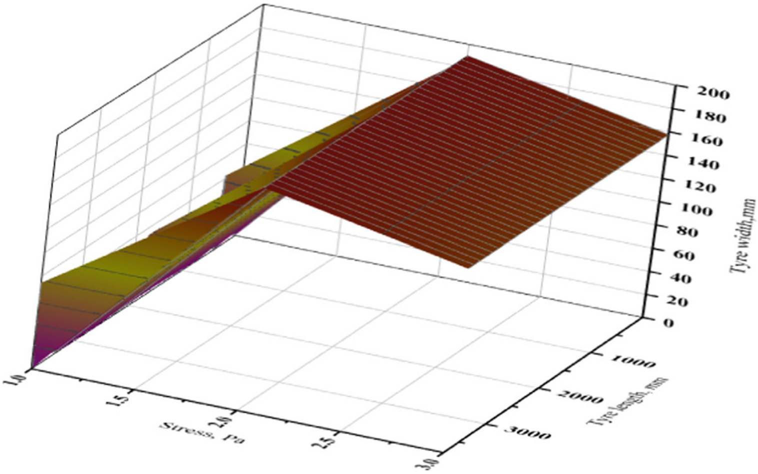


Fig. 7 Stress variation from ANSYS

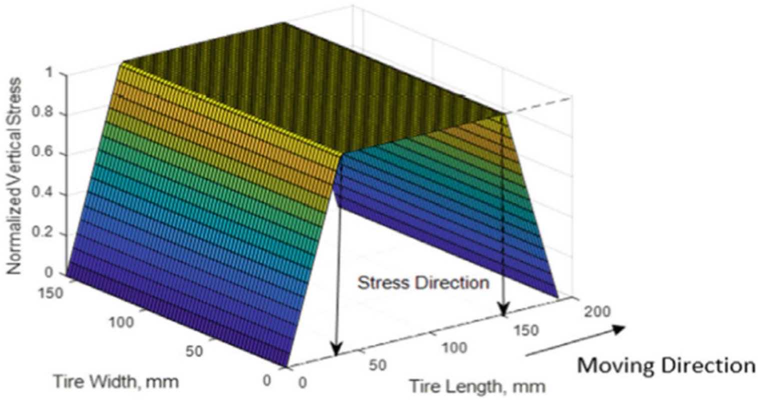


Fig. 8 Stress variation along moving direction from ABAQUS (*Source* Deng et al. [6])

Fig. 9 Deformation of geogrid-reinforced pavement

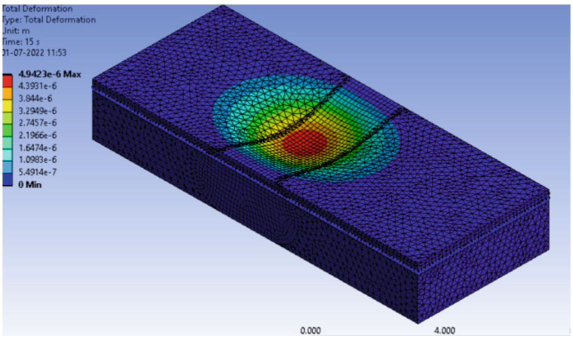
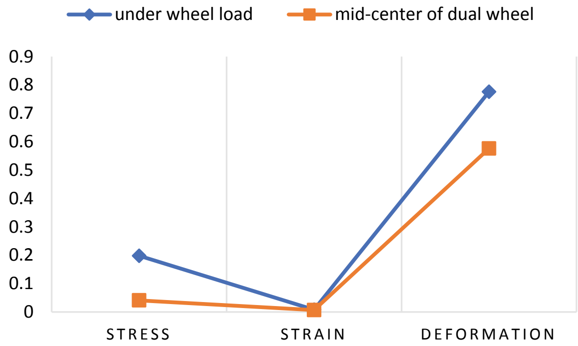
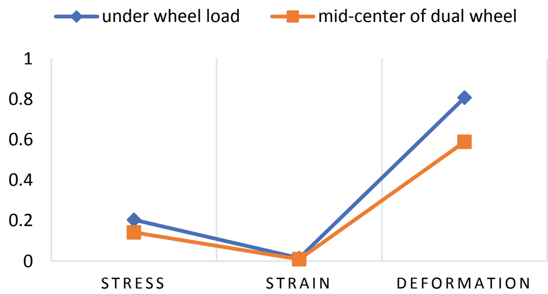


Fig. 10 **a** Variation of responses- HMA-Base interface **b** Variation of responses- middle of base course



a) Variation of respon ses- HMA-Base interface



b) Variation of responses - middle of base course

without incorporating geogrid under a moving load of 40 kN at 28 kmph. The variation of stress, strain and deformation at two analysis points- beneath the wheel load and centre of dual tyre is shown in Fig. 10, corresponding to the geogrid position- HMA-base interface and middle of base course.

Figure 10a and b indicates that the stress, deformation and strain values become smaller in magnitude, as the distance from load application increases. That means the response magnitude is more at wheel contact point, which reduces to approximately 31% of its initial magnitude when the analysis point changes to the center of dual tyre. The results of pavement reinforced with glass fiber geogrid showed that the stress intensity is optimum when geogrid is placed at the middle of WMM/base course, when compared to other locations HMA-base interface and base-subgrade interface. Even though the stress value is optimum at the middle of WMM, which decreases towards the bottom pavement layer. That means, pavement responses like stress, strain and deformation are reduced towards the lower pavement layers. Due to the incorporation of glass fiber geogrid, pavement deflection reduces from 5.9012 to 4.942 μm with 16.25% reduction and 14.29% change occurred in stress value from 0.094 MPa to 0.08 MPa and 6% reduction happened in micro-strain value.

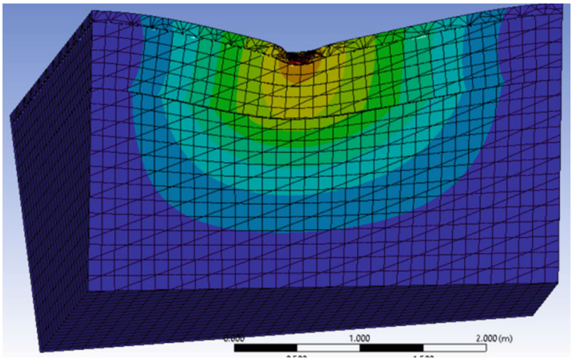


Fig. 11 Pavement deformation with geogrid at HMA-base interface

The study on pavement reinforced with glass fiber geogrid is validated by analysing the deformation profile obtained from ANSYS with the ABAQUS results [4]. The cross section of the deformation profile resulted from ANSYS is shown in Fig. 11.

The variation in deformation value was observed as 3%, which may due to the applied boundary conditions and higher result accuracy of ANSYS software when compared to ABAQUS. Hence it can be concluded that the developed geogrid model fits with the simulated model.

4 Conclusions

3-D Simulation of pavement response under moving load was analysed by inserting glass fiber geogrid at locations- interface of surface and base course, middle of base course and interface of base and subgrade with the consideration of viscoelastic property of bituminous pavement layers by using ANSYS. Following conclusions are deduced from the study.

1. Stress intensity resulted due to the application of viscoelasticity shows a reduction of 83.75, 65.96, 89.3 and 52.2% for SA-SW, SA-TW, SA-FW and tandem axles respectively
2. Deformation values resulted due to the influence of non-linear viscoelastic property on bituminous layer, decreases with 56.5, 3.6, 90.4 and 99.9% for SA-SW, SA-TW, SA-FW and tandem axles respectively, from linear bituminous property
3. Micro-strain magnitude increases with the application of non-linear property on bituminous layers, as it undergoes more elongation than linear structure due to creep action of pavement
4. Due to the incorporation of glass fiber geogrid, 16.25, 14.9 and 6% reduction occurred in deformation, stress and micro-strain values respectively
5. 31% reduction is observed in pavement responses when the analysis point changes from beneath the wheel load to center of dual tyre.

Thus, it can be inferred that the non-linear viscoelastic behaviour of bituminous layers influences the pavement responses like stress, strain and deformation with reduced stress and deformation magnitude and increased micro-strain value. Also, the presence of glass fiber geogrid in pavement layers resulted in further reduction of mechanical response magnitudes for pavement with viscoelastic behaviour under dynamic load application.

References

1. Abd Alla EM (2006) The Rational use of Finite Element method in the analysis of flexible pavements. J Eng Sci 34(4):1185–1211
2. Al-Qadi IL, Yoo PY (1990) Effect of transient dynamic loading o flexible pavement. Transp Res Rec
3. Assogba OC, Sun Z, Tan Y, Nonde L, Bin Z (2020) Finite-Element simulation of instrumented asphalt pavement response under moving vehicular load. ASCE 20(3):0402000
4. Calvarano LS, Palamara R, Leonardi G, Moraci N (2017) 3D-FEM analysis on geogrid reinforced flexible pavement roads. IOP Conference Series 022024
5. Correia NS, Esquivel ER, Zornberg JG (2018) Finite-element evaluations of geogrid-reinforced asphalt overlays over flexible pavements. ASCE
6. Deng Y, Luo X, Gu F, Zhang Y, Lytton RL (2019) 3D Simulation of deflection basin of pavements under high-speed moving loads. Constr Build Mater 226:868–878
7. He D, Cheng Y (2018) Numerical simulation for mechanical behavior of asphalt pavement with graded aggregate base. Adv Civ Eng
8. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj85p6z1df4AhXa2TgGHWZgAfEQFnoECBUQAw&url=https%3A%2F%2Fwww.tirerack.com%2Ftires%2Ftiretech%2Ftechpage.jsp%3Ftechid%3D72&usg=AOvVaw0B42fVO-mnWDFaPEY4iLgM
9. IRC: SP:59–2019 Guidelines for Use of Geosynthetics in Road Pavements and Associated Works
10. Jasim FA, Fattah YM, Al-Saadi IF, Abbas AS (2020) Geogrid reinforcement optimal location under different tire contact stress assumptions. Int J Pavement Res Technol, 14:357–365
11. Lin JH (2015) Simulation of dynamic vehicle load on road pavement. Vibroengineering Procedia, 5. ISSN 2345–0533
12. Lajčáková G, Melcer J (2015) Numerical simulation of moving load on concrete pavements. Transp Telecommun, 16(2):145–157
13. Ling M, Luo X, Hu S, Gu F, Lytton RL (2017) Numerical modeling and artificial neural network for predicting J-integral of top-down cracking in asphalt pavement. Transp Res Rec: J Transp Res Board 2631:83–95
14. Qian G, Shi C, Yu H, Yao D, Zhu X, Li X (2021) Evaluation of different modulus input on the mechanical responses of asphalt pavement based on field measurements. Constr Build Mater 312:125299
15. Suyabodha A (2017) A relationship between tyre pressure and rolling resistance under different moving load. MATEC Web of Conference 108:12004
16. Uddin W, Zhang D, Fernandez F (1994) Finite element simulation of pavement discontinuities and dynamic load response. Transp Res Rec: J Transp Res Board 1448
17. Wu C, Wang H, Zhao J, Jiang H, Yanjun Q, Yusupov B (2020) Prediction of viscoelastic pavement responses under moving load and non-uniform tire contact stresses using 2.5-D finite element method. Math Probl Eng, 2020. Article ID 1029089
18. Zaghloul SM, White T (1993) Use of a three-dimensional dynamic finite element program for analysis of flexible pavement. Transp Res Rec: J Transp Res Board, 1388