Numerical investigation of porous composite honeycomb track slab under point load

Fu, Hao; Kaewunruen, Sakdirat

DOI:
10.1016/j.matpr.2022.04.691

[Recent Advancements in Construction Materials & Structures, ICCMS-2021]

Numerical investigation of porous composite honeycomb track slab under point load

Hao Fu[a*], Sakdirat Kaewunruen[a]

[a]*Laboratory for Track Engineering and Operations for Future Uncertainties (TOFU Lab), Department of Civil Engineering, School of Engineering, The University of Birmingham, Edgbaston, Birmingham B15 2TT, UK; HXF992@student.bham.ac.uk*

Abstract

Traditional railway infrastructures include ballasted beds and concrete slab tracks. The additive manufacturing technology enables the application of porous structures in railway infrastructures. In this article, two types of porous supporting layers acting as the track supporting layer are designed. The nonlinear FEM simulations of composite porous track infrastructures are carried out to study the mechanical performance of the porous honeycomb track slab under point loads using nonlinear material properties. The track performance, including deflection and acceleration, of different track components, are compared with a conventional ballasted track to evaluate the feasibility of the 3D printed structures. This study can help the development of 3D printed porous composite honeycomb structures in railway engineering.

Keywords: track slab, FEM, railway, 3D printing, porous structure, honeycomb structure.

1. Introduction

Railway track systems can be classified into ballasted tracks and slab tracks according to the components of track supporting layers. The ballasted track system is the most adopted track system all over the world. A conventional ballasted track comprises rails, fastener system, sleepers, ballasted layer (including ballasted bed and sub-ballast layer) and subgrade. Ballasted tracks are utilized in normal-speed railway lines and heavy-haul railway lines for their relatively low construction cost and easiness of maintenance. In recent decades, slab tracks have been developed in high-speed railway systems for high ride comfort[1]. The slab track system comprises rails, fastener systems, track slabs (including concrete slab and hydraulically bonded layer) and subgrade layer. The two types of track infrastructures redistribute and disperse the dynamic moving train loads into sub-layers and keep the rail gauge and height to provide stable and reliable support for rolling stocks. Both the ballasted track and slab track systems are designed with a gradually decreasing material strength of components from top to bottom in accordance with the stress distribution inside the track infrastructures.

Due to the limitation of traditional manufacturing technology, the track structures with strong top and weak bottom layers are achieved by adopting different materials in each layer[2]. For example, the ballast beds are composed of ballast particles with higher material strength and particle size distribution (PSD), while the sub-ballast layers are made from crushed rock particles with poorer material properties and PSD[3, 4]. As for the slab track systems, the upper track slabs are made from reinforced concrete, and the sub-layers are hydraulically bonded layers without tendons[5].

3D printing technologies, also known as additive manufacturing technologies, make it possible to fabricate a structure with complex geometric shapes, which enable the structure with distinct mechanical properties by changing the structure's geometry in separate layers, as stated in Ref.[6]. Among all types of porous structures, the honeycomb structures have been identified with high specific strength and energy absorption capacity[7-10]. Thus, in this paper, the honeycomb structures are adopted in designing porous track slabs. Considering that the mechanical properties of porous structures are lower than that of the solid structure with the same material, the designed porous structures in this paper are only compared with the ballasted track used for normal-speed railways. The performance of the porous track slabs and traditional ballasted bed under point loads are analysed and compared using finite element methods. This research helps to expand the application of 3D printing in railway engineering.

2. FEM modelling

The porous honeycomb track slabs are designed with two main layers, a solid top layer for supporting rails and a porous honey sub-layer, according to the fact that the ballast layer of ballasted tracks and the ballastless track slab are both composed of two main layers. Considering that the stress in the track foundation is gradually reduced from top to bottom, the porous honeycomb structure at the bottom can be designed with a gradient density to better share and bear the load. Two kinds of honeycomb track slabs are designed, namely uniform honeycomb track slab and gradient honeycomb track slab. The dimensions of the designed two honeycomb track slabs and the traditional ballasted track are present in Fig. 1. The size of the honeycomb layer is 150mm in depth, 3000mm in length and 1400mm in width.

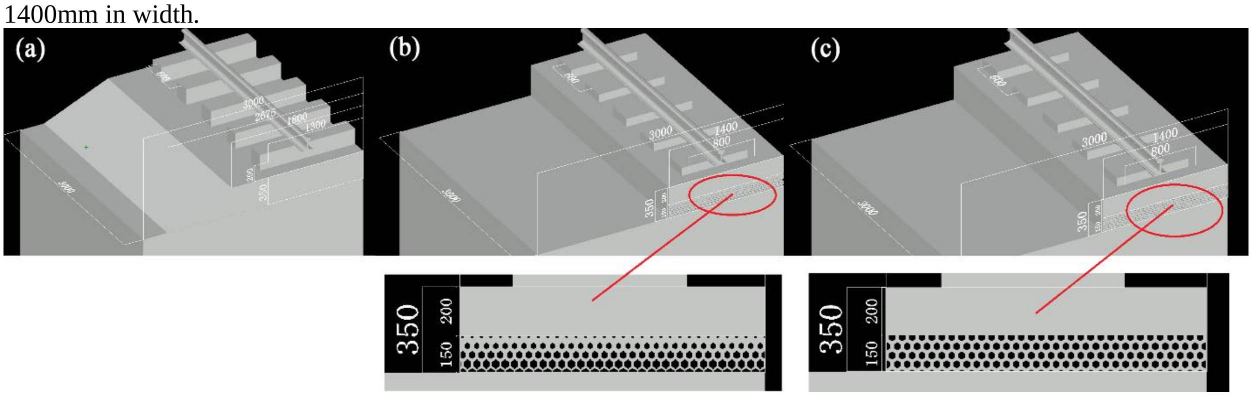


Fig. 1. Dimensions of the track models(a) ballasted track; (b) gradient honeycomb track support; (c) uniform honeycomb track support.

Ansys software has been used to establish the 3D finite element models. The parameters of FEM models are based on Ref.[11-13]. All FEM models comprise three parts: rails, supporting layers, and subgrade. In ballasted track model, the middle layers are composed of sleepers and ballasted beds. The middle layers are with solid tops and porous bottom structures in the two honeycomb structures. The rails are simulated using UIC 60 rail. The sleepers in ballasted bed are simulated with cuboid concrete sleepers with 230mm width, 180mm depth and 2600mm length. The fastener systems were modelled using dash springs with 17 MN/mm stiffness. The subgrades are simulated by soil. The fix constraints are set to the bottom surface of the subgrades. It should be noted that the models were simplified to half models with symmetry constraints on the symmetric surfaces to speed up the FEM simulation.

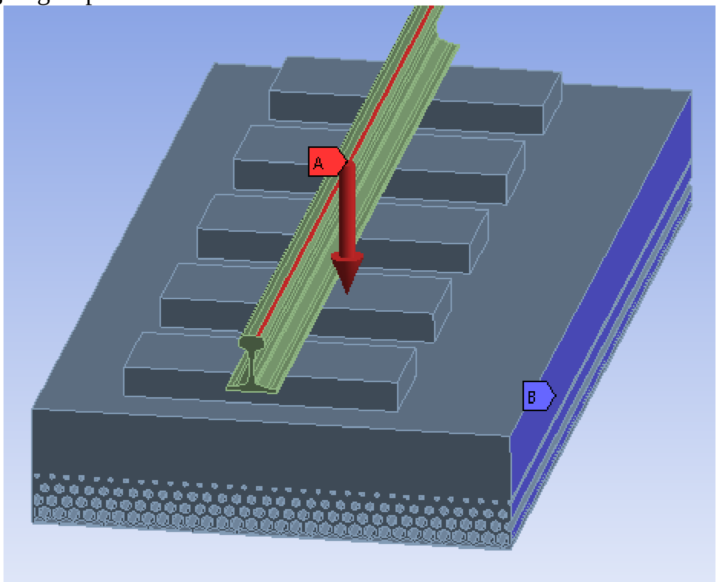
The material properties of the model components are present in Tab. 1. The steel was used for rails; The concrete was used for sleepers. The ballasted layer was considered a continuous solid structure with the bulk density of the ballasted bed and proper modulus. The honeycomb structures were simulated using a type of 3D printable photosensitive resin. The subgrades are simulated by a Mohr-Coulomb constitutive model with a 30-degree initial/residual inner friction angle and 2KPa initial/residual cohesion. The ballasted bed is simulated by a Mohr-Coulomb constitutive model with a 30-degree initial/residual inner friction angle and 50KPa initial/residual cohesion. The two honeycomb track supports are simulated using a bilinear isotropic hardening model with 60MPa yield strength and 150MPa tangent modulus. The ballasted bed and subgrade material properties have been calibrated and validated in Ref. [4].

Table 1. Material properties of the FEM model componemetns.

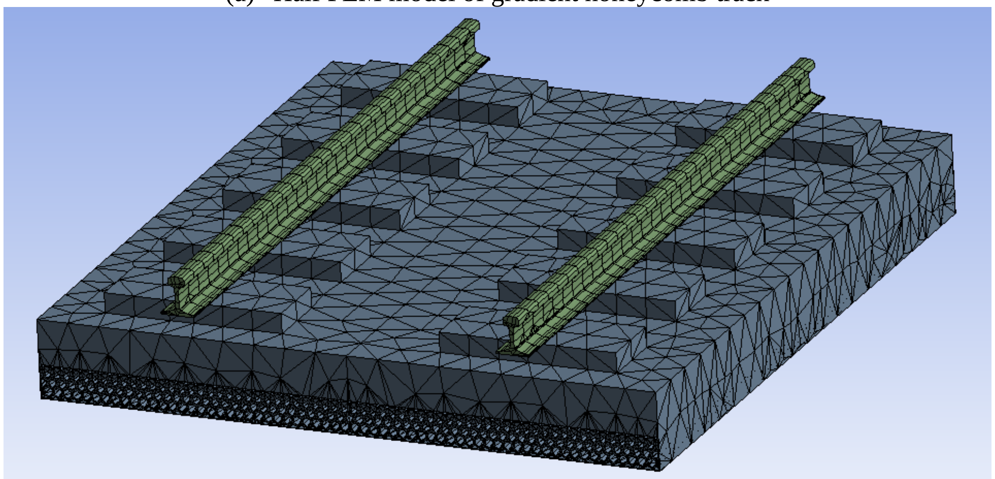
Type	Density	Young's Modulus	Poisson's Ratio
Rails	7.85 g/cm^3	210GPa	0.3

Sleepers	2.55 g/cm^3	36GPa	0.18
Ballasted bed	1.85 g/cm^3	15.7MPa	0.4
Honeycomb track supports	1.16 g/cm^3	2.69GPa	0.42
Subgrades	1.80 g/cm^3	45MPa	0.33

All the model components were meshed using hex-dominant method. The meshing sizes of the rails, sleepers, ballasted bed, composite honeycomb slabs and subgrade are 100mm, 100mm, 150mm, 150mm and 600mm, respectively. The meshing sizes are determined after meshing convergence tests. In order to compare the performance of the three types of track support layers, the sinusoidal time dependent point load with magnitude was applied on the top surface of the rail at the middle of the track models as suggested by [14]. The sinusoidal point load is with a maximum 170kN and minimum 110kN, and a period for 90km/h according to the wheel-rail contact force in Ref. [15]. An example of the half FEM model of gradient honeycomb track is present in Fig. 2(a), and the meshed model is displayed in Fig. 2(b). The point load is applied on point A, and the symmetric constraints are set to the surfaces belonging to group B.



(a) Half FEM model of gradient honeycomb track



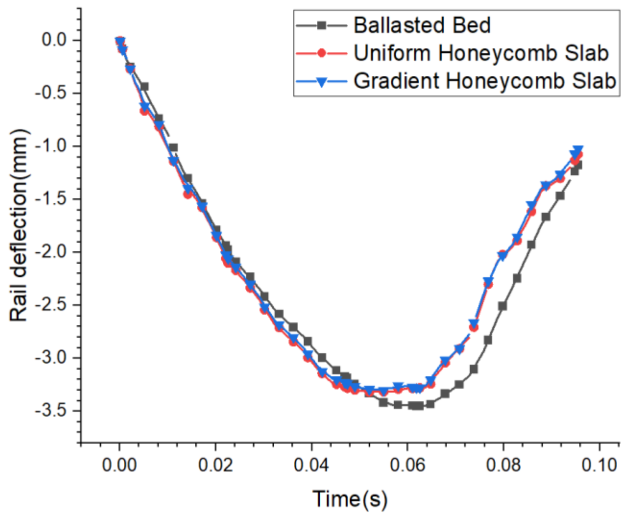
(b) Meshed FEM model of gradient honeycomb track

Fig. 2. Examples of FEM models: (a) Half FEM model of gradient honeycomb track; (b) Meshed FEM model of gradient honeycomb track.

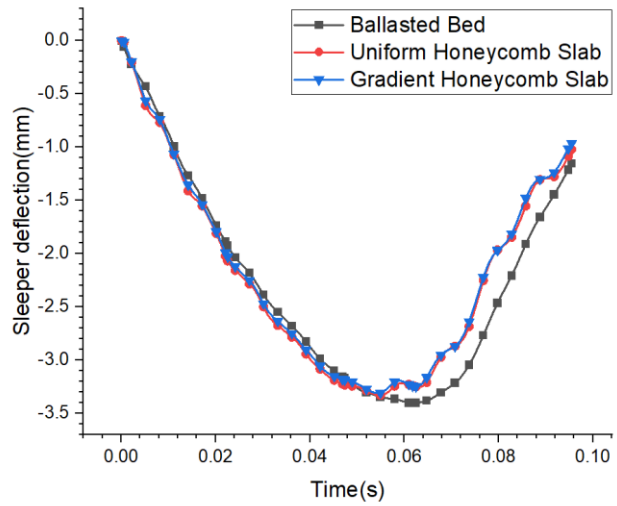
3. Results and discussions

In order to conduct a comprehensive comparison of three different track supporting layers with ballasted bed, uniform honeycomb slab and gradient honeycomb track slab, the deflection and acceleration of the track components are studied. It should be noted that the deflection is the maximum deflection inside each component; the acceleration of all components is measured at the middle section of the FEM models.

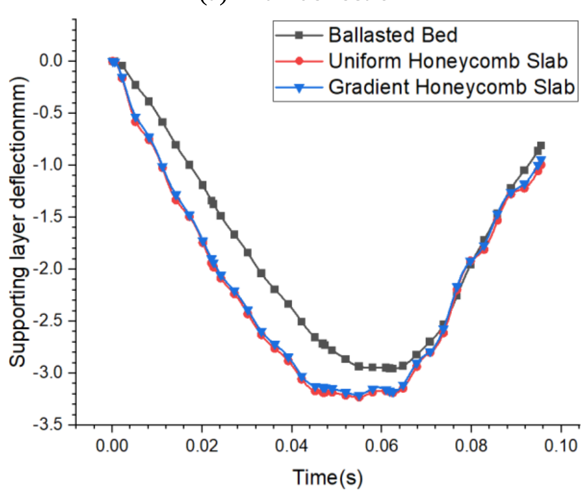
3.1. Track vertical deflection



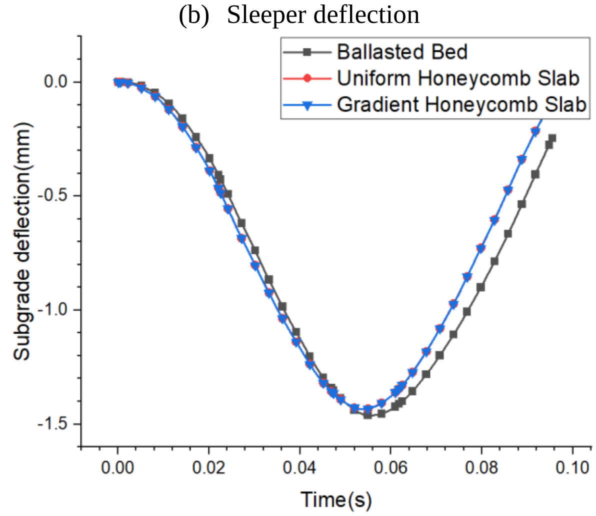
(a) Rail deflection



(b) Sleeper deflection



(c) Supporting layer deflection



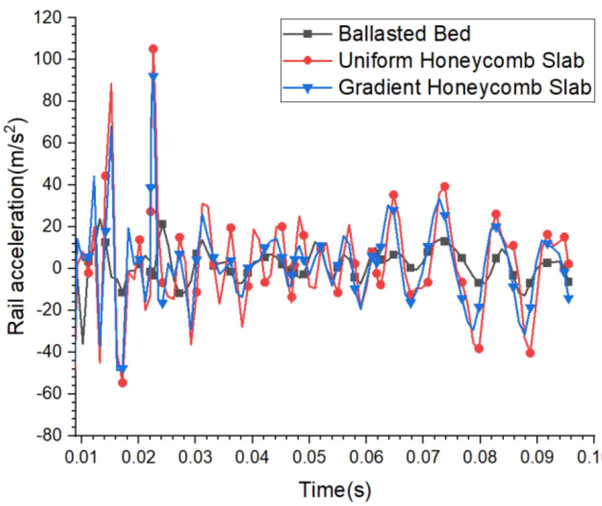
(d) Subgrade deflection

Fig. 3. Vertical deflection of track components for ballasted track, uniform honeycomb track and gradient honeycomb track: (a) Rail deflection; (b) sleeper deflection; (c) supporting layer deflection; (d) subgrade deflection.

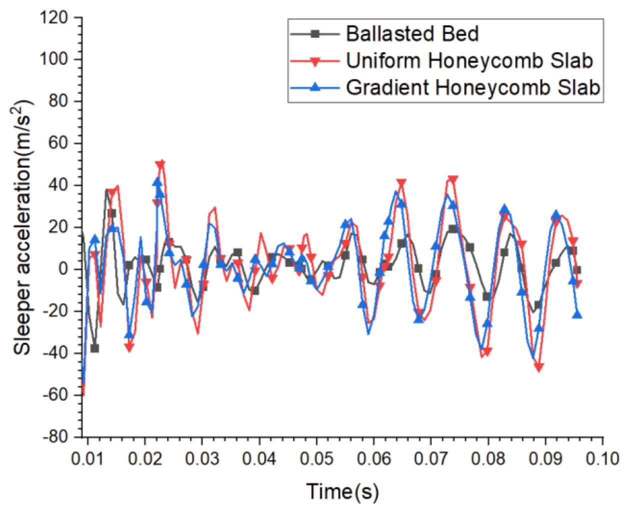
Fig. 3 presents the vertical deflection of rail, sleeper, supporting layer and subgrade of three type railway tracks in the middle section. As can be seen, the deflection of uniform honeycomb track slab and gradient honeycomb track slab has few differences in all track components. The composite uniform honeycomb and gradient honeycomb track slabs both can reduce the deflection of rail, sleeper and subgrade. However, the opposite effect is observed inside the supporting layers. The deflections of the subgrade of both honeycomb track slabs are almost the same. This may be due to the same material properties of the honeycomb track models and the same porosity of the two porous honeycomb structures.

The maximum rail deflection of ballasted track, uniform honeycomb track and gradient honeycomb track is 3.45mm, 3.30mm and 3.32 mm, respectively. The maximum sleeper deflection of ballasted track, uniform honeycomb track and gradient honeycomb track is 3.45mm, 3.30mm and 3.32 mm, respectively. The maximum rail deflection of ballasted track, uniform honeycomb track and gradient honeycomb track is 3.40mm, 3.30mm and 3.32 mm, respectively. The maximum supporting layer deflection of ballasted track, uniform honeycomb track and gradient honeycomb track is 2.96mm, 3.21mm and 3.23 mm, respectively. The maximum subgrade deflection of ballasted track, uniform honeycomb track and gradient honeycomb track is 1.46mm, 1.43mm and 1.44 mm, respectively. The results show that composite honeycomb track slabs have better stiffness than the conventional ballasted bed. However, the deflections of all components in the two honeycomb structures reach the peak value earlier than it in the two honeycomb structures. This indicates that ballasted beds have better ductility than honeycomb slabs.

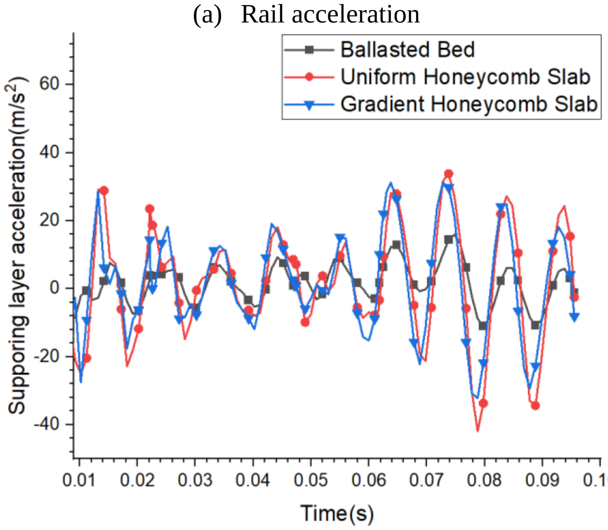
3.2. Track vertical acceleration



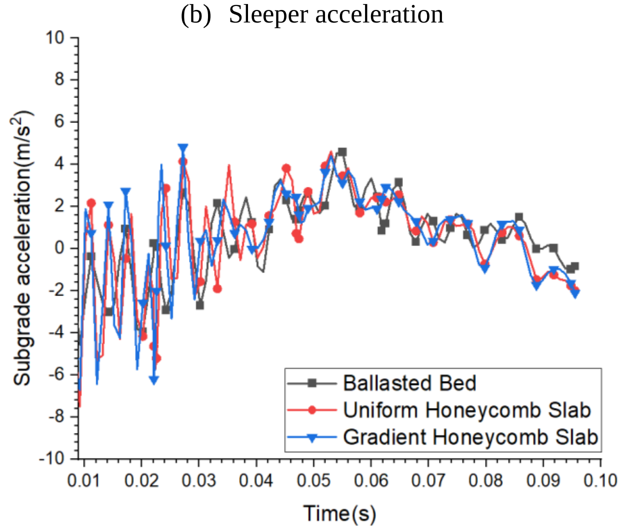
(a) Rail acceleration



(b) Sleeper acceleration



(c) Supporting layer acceleration



(d) Subgrade acceleration

Fig. 4. Vertical acceleration of track components for ballasted track, uniform honeycomb track and gradient honeycomb track: (a) Rail acceleration; (b) sleeper acceleration; (c) supporting layer acceleration and (d) subgrade acceleration.

Fig. 4 presents the average vertical acceleration of rail, sleeper, supporting layer and subgrade of three type railway tracks in the middle section. The figures show that the rail acceleration is the greatest in all track types, and the subgrade acceleration is the lowest. The reason may be that the force increases as the axle loads are transferred from the upper track structure (rails) to the bottom track structure (subgrade) via sleepers and supporting layers. The results indicate that the three track supporting layers can effectively redistribute dynamic train loads. The honeycomb structures have greater acceleration in all track components than the ballasted track, which indicates that honeycomb structures will induce higher acceleration. Also, it can be seen that the gradient honeycomb structure has a slightly lower acceleration in rail, sleeper, supporting layer and subgrade than the uniform honeycomb structures. This indicates that an optimization of the track support shape according to the stress distribution can help improve the track performance.

Tab. 2 shows the acceleration root mean square (RMS) of different track components in ballasted, uniform honeycomb and gradient honeycomb tracks. Considering the RMS value of rail acceleration, 8.39 m/s2(100%),in ballasted track, it increases to 26.66 m/s^2 (275%) and 23.09 m/s^2 (317%)for uniform honeycomb and gradient honeycomb tracks, respectively. Similar trends can be observed in all other track components, including sleeper, supporting layer and subgrade. The RMS acceleration of rail, sleeper and supporting layer in gradient honeycomb track is 13.4%, 8.2% and 11.4% lower than in the uniform honeycomb structure, respectively. The RMS acceleration of the subgrade in gradient honeycomb is slightly higher (6.0%) than in the uniform honeycomb track.

Table 1. Different Acceleration RMS of track components in different tracks.

Track components	Acceleration RMS in Ballasted track(m/s^2)	Acceleration RMS in Uniform Honeycomb(m/s^2)	Acceleration RMS in Gradient Honeycomb(m/s^2)
Rail	8.39	26.66	23.09
Sleeper	11.06	21.86	20.08
Supporting layer	5.76	16.16	14.32
Subgrade	1.88	2.35	2.49

4. Conclusion

The development of additive manufacturing technologies enables fabrication structures with porous patterns. This research aims to design porous track supporting layers and investigate the behaviour of the designed track supports using the finite element methods and compare their performance with the conventional ballasted track. In this regard, the honeycomb structures are adopted to design the composite porous track slabs. Three different tracks, including ballasted track, uniform honeycomb track and gradient honeycomb track, have been developed in FEM software Ansys. Finally, railway track behaviours, including deflection and acceleration, have been analysed and compared. The highlighted findings are presented as follows:

1. Honeycomb track structures can reduce the track deflection in rails, sleepers and subgrade. The performance of the uniform and gradient honeycomb track slabs in resisting track deflection has few differences.
2. The uniform and gradient honeycomb track slabs will result in greater track acceleration in all track components. The gradient honeycomb slab performs better than the uniform honeycomb slab in track acceleration. The results indicate that the composite honeycomb structures are not proper for high-speed railway lines or transition zones.
3. Gradient honeycomb track slab has overall better performance (8.2% to 13.4%) than uniform honeycomb track slab with the same mass in resisting the vibration of sinusoidal point load. This is because gradient structures can better adapt to the distribution of axial loads from the track top (rail) to the track bottom (subgrade).

Acknowledgements

The author Hao Fu thanks for the financial support from china scholorship council.

References

[1] Shi, S., L. Gao, H. Xiao, Y. Xu, and H. Yin, *Research on ballast breakage under tamping operation based on DEM–MBD coupling approach.* Construction and Building Materials, 2021. **272**: pp.

121810.DOI:https://doi.org/10.1016/j.conbuildmat.2020.121810
[2] Attaran, M., *The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing.* Business Horizons, 2017. **60**(5): pp. 677-688.DOI:https://doi.org/10.1016/j.bushor.2017.05.011
[3] Guo, Y., C. Zhao, V. Markine, G. Jing, and W. Zhai, *Calibration for discrete element modelling of railway ballast: A review.* Transportation Geotechnics, 2020. **23**: pp. 100341.DOI:https://doi.org/10.1016/j.trgeo.2020.100341
[4] Jing, G., J. Wang, H. Wang, and M. Siahkouhi, *Numerical investigation of the behavior of stone ballast mixed by steel slag in ballasted railway track.* Construction and Building Materials, 2020. **262**: pp. 120015.DOI:10.1016/j.conbuildmat.2020.120015
[5] Tayabji, S.D. and D. Bilow, *Concrete Slab Track State of the Practice.* Transportation Research Record, 2001. **1742**(1): pp. 87-96.DOI:10.3141/1742-11
[6] Fu, H. and S. Kaewunruen, *State-of-the-Art Review on Additive Manufacturing Technology in Railway Infrastructure Systems.* Journal of Composites Science, 2022. **6**(1): pp. 7
[7] Yin, H., Z. Liu, J. Dai, G. Wen, and C. Zhang, *Crushing behavior and optimization of sheet-based 3D periodic cellular structures.* Composites Part B: Engineering, 2020. **182**: pp. 107565.DOI:10.1016/j.compositesb.2019.107565
[8] Ma, Q., M.R.M. Rejab, A.P. Kumar, H. Fu, N.M. Kumar, and J. Tang, *Effect of infill pattern, density and material type of 3D printed cubic structure under quasi-static loading.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2020. **235**(19): pp. 4254-4272.DOI:10.1177/0954406220971667
[9] Ma, Q., M.R.M. Rejab, J.P. Siregar, and Z. Guan, *A review of the recent trends on core structures and impact response of sandwich panels.* Journal of Composite Materials, 2021. **55**(18): pp. 2513-2555.DOI:10.1177/0021998321990734
[10] Yap, Y.L. and W.Y. Yeong, *Shape recovery effect of 3D printed polymeric honeycomb.* Virtual and Physical Prototyping, 2015. **10**(2): pp. 91-99.DOI:10.1080/17452759.2015.1060350
[11] Kaewunruen, S., H. Fu, and C. Ye, *Numerical studies to evaluate crack propagation behaviour of prestressed concrete railway sleepers.* Engineering Failure Analysis, 2022. **131**: pp. 105888.DOI:https://doi.org/10.1016/j.engfailanal.2021.105888
[12] Mohamad Ali Ridho, B.K.A. and S. Kaewunruen, *Failure investigations into interspersed railway tracks exposed to flood and washaway conditions under moving train loads.* Engineering Failure Analysis, 2021. **129**: pp. 105726.DOI:10.1016/j.engfailanal.2021.105726
[13] Panda, B., M. Leite, B.B. Biswal, X. Niu, and A. Garg, *Experimental and numerical modelling of mechanical properties of 3D printed honeycomb structures.* Measurement, 2018. **116**: pp. 495-506.DOI:https://doi.org/10.1016/j.measurement.2017.11.037
[14] Steenbergen, M.J.M.M., A.V. Metrikine, and C. Esveld, *Assessment of design parameters of a slab track railway system from a dynamic viewpoint.* Journal of Sound and Vibration, 2007. **306**(1): pp. 361-371.DOI:https://doi.org/10.1016/j.jsv.2007.05.034
[15] Remennikov, A.M. and S. Kaewunruen, *A review of loading conditions for railway track structures due to train and track vertical interaction.* Structural Control and Health Monitoring, 2008. **15**(2): pp. 207-234.DOI:https://doi.org/10.1002/stc.227