Structural Engineering and Mechanics, Vol. 41, No. 2 (2012) 231-242
DOI: http://dx.doi.org/10.12989/sem.2012.41.2.231

Fibre composite railway sleeper design by using FE approach and optimization techniques

Ziad K. Awad* and Talal Yusaf

Faculty of Engineering and Surveying, University of Southern Queensland (USQ), Toowoomba, QLD4350, Australia

(Received March 17, 2010, Revised December 26, 2011, Accepted January 3, 2012)

Abstract. This research work aims to develop an optimal design using Finite Element (FE) and Genetic Algorithm (GA) methods to replace the traditional concrete and timber material by a Synthetic Polyurethane fibre glass composite material in railway sleepers. The conventional timber railway sleeper technology is associated with several technical problems related to its durability and ability to resist cutting and abrading action of the bearing plate. The use of pre-stress concrete sleeper in railway industry has many disadvantages related to the concrete material behaviour to resist dynamic stress that may lead to a significant mechanical damage with feasible fissures and cracks. Scientific researchers have recently developed a new composite material such as Glass Fibre Reinforced Polyurethane (GFRP) foam to replace the conventional one. The mechanical properties of these materials are reliable enough to help solving structural problems such as durability, light weight, long life span (50-60 years), less water absorption, provide electric insulation, excellent resistance of fatigue and ability to recycle. This paper suggests appropriate sleeper design to reduce the volume of the material. The design optimization shows that the sleeper length is more sensitive to the loading type than the other parameters.

Keywords: structural optimization; composite; dynamic stress analysis; railway engineering

1. Introduction

Fibre composite structure was used during the Second World War in the radar equipments and aircraft industry (Qiao *et al.* 1998). The fibre composite material has been attracted by many industrial sectors due to its robust characteristics such as; high strength, and high stiffness to weight ratio. During the last decades, many structural applications have been existed as a new invention of using FRP composite materials and the FRP railway sleeper is one of the new applications of fibre composite materials (Aravinthan 2008). The design requirement of the railway sleeper is relatively complex, and the designer needs to consider several parameters such as; the degree of comfort of the passengers and the cost of maintenance (Namura *et al.* 2005).

The traditional materials used for the sleeper constructions are; timber, concrete, and steel. These materials showed a high maintenance cost during the service life. Approximately, 12 million timber sleepers are replaced every year in the United States of America USA with an estimated cost of approximately 500 USD million (Qiao *et al.* 1998). The Australian railway industry paid approximately 25-35% of its annual budget on railway maintenance (Kaewunruen and Remennikov 2007). The

*Corresponding author, Ph.D. Strudent, E-mail: awad@usq.edu.au

major disadvantages of using the steel sleeper in railway industry are; material corrosion, high weight, and high cost. The conventional timber railway sleeper problems are related to its durability and ability to resist cutting and abrading action of the bearing plate. Moreover, the use of pre-stress concrete sleeper in railway industry has many disadvantages related to the concrete material behaviour to resist dynamic stresses that may lead to a significant mechanical damage with feasible fissures and cracks (González-Nicieza *et al.* 2008).

The railway structure consists of three main components: i) the upper part which called steel rail, ii) the middle part which called sleeper and iii) the ballast, as shown in Fig. 1. The major function of the sleeper is to transfers the load from the upper part (rail) to the lower part (ballast) with more homogenizations (Qiao *et al.* 1998). The behaviour of the railway is reported to be very complicated due to the behaviour of the granular ballast when it is subject to the dynamic loads and long duration (Anderson and Fair 2008). The differences in the ballast stress produce differential settlements under the railway sleepers with long term dynamic effects (González-Nicieza *et al.* 2008). Many numerical investigations have conducted to develop a simulation or mathematical models to evaluate the ballast behaviour. These simulations are generally focused on two categories: i) the movement of particles and ii) breaking particles under dynamic cyclic loads. The movement and breaking particles lead to increase the ballast stiffness with time (Suiker *et al.* 2005).

Recently, Manalo *et al.* (2010) presented a study on the alternative materials to replace the traditional timber railway sleeper. The conclusion was made that the FRP composite material is the most reliable choice to replace the timber sleeper. An initial study on the behaviour of Glass Fibre Reinforced Polyurethane (GFRP) foam sleeper was conducted by Nagafuji *et al.* (1988) to assess the resistance of the GFRP material against the environmental effect and repetitive bending fatigue tests. The composite material behaviour showed no significant change in the strength under environment and fatigue effects. In addition, the estimated life span of GFRP sleeper is 60 years (Nagafuji and Noritsugi 1988). Qiao *et al.* (1998) studied the optimum size of glass fibre reinforced plastic GFRP used to strengthen the rail-timber sleeper. The study investigated the ability of beam-elastic foundation to simulate the elastic behaviour of the timber cross tie. The conclusion was made that the optimum GFRP layer's thickness is 0.507 mm, and the orientation angle is $\pm 45^{\mathrm{o}}$.

Namura *et al.* (2005) studied the optimum design of GFRP sleeper by experimental investigation under the effect of the ballast settlement during long time cycles. The study showed that the sleeper dimensions have a major effect the settlement of ballast. The conclusion was made that the 2 m sleeper length has a middle ballast support, while the sleeper with 2.6 m long has end ballast supports. Sadeghi and Babaee (2006) presented the optimum design of B70 railway pre-stress concrete sleepers by using a parametric study. The procedure was made by dividing the sleeper shape into 11 parameters, and then creates 40 sleepers with different dimensions for analysis. The analysis of 40 sleepers showed that a few sleepers have homogenous stress distribution and less differential settlement. The rating procedure was used to select the optimum sleeper.

However, standard specification and codes for FRP in civil engineering are not available yet except British standard code for the design of composite BS4994 (Bank 2006) and the EUROCOMP design code (Clarke 1996). Many studies have made on the optimization of fibre composite material in order to find the optimum distribution of this material in terms of layer thickness and plies orientations. The common optimizations depend on the objective of minimizing the weight, cost and deflection of the structures (Walker and Smith 2003, Almeida and Awruch 2009). The Australian Rail Truck Corporation (ARTC) developed a new composite sleeper according to the AS5100 with dimensions, 2700 mm length, width = 250 mm, and depth = 190 mm. The expected load for this sleeper is 75 kN/rail (Prasad 2008).

This paper discusses the optimum design of the sleeper made from hard type GFRP foam as a new material. The synthetic sleeper is known by a relatively high initial cost. Therefore, this research tries to find the optimum design of the synthetic sleeper by minimizing the volume of GRFP material use. The design depends on the commercial FE software ABAQUS to analyse the structure. This approach requires a link between the FE analysis and optimization methods. The modeFRONTIER software is used to optimize the FE analysis data. The main objective leads to minimize the volume of material, which it means minimizing the cost of the sleeper. The final design should have the industry qualification's demands such as (Namura *et al.* 2005):

- Synthetic sleeper should be easy to install as the timber sleeper.
- It should be durable more than concrete sleeper.

Therefore, the new generation of a synthetic sleeper with modified characteristics is expected to be better than the timber and concrete sleepers.

2. Materials modelling

The railway sleeper model contains three parts; rail, sleeper, and ballast. Each part has a different material, and each material behaves differently. The ballast is generally considered as a linear elastic material in the railway structure when the analysis of the railway sleeper focuses on the type of loading and the behaviour of a sleeper unit (González-Nicieza *et al.* 2008). This assumption is valid if the dynamic load is assumed to run for the short duration. The sleeper is made of GFRP material, and this material is a composite from glass fibre and resin (matrix). It was found that the percentage of fibre to resin volume is very important because it controls the overall strength of the composite material (Bank 2006). Moreover, it affects the sleeper damping ratio. Any increase in the glass fibre ratio will decrease the damping ratio of the GFRP material (Berthelot and Sefrani 2007).

The mechanical properties of the present GFRP material is described by Namura *et al.* (2005) work as shown in Table 1. Table 1 shows that the GFRP material tensile strength and compressive strength are relatively acceptable compared to timber mechanical properties. In addition, Namura *et al.* (2005) investigated the fatigue behaviour of the GFRP material up to one million cycles in bending. It showed no significant change in adhesive strength and bending strength. It was also found that the sample has high retention power for screw pull-out test with 18 kN.

In the present work the ballast assumed to be a linear elastic material, and the sleeper was treated as a composite material. In addition, the ballast mechanical properties are shown in Table 1 (Kaewunruen and Remennikov 2007).

Table 1 Materials properties

Material	Elastic modules MPa	Poisson ratio	Tensile strength MPa	Comp. strength MPa	Shear strength MPa	Specific gravity
Sleeper	10600	0.3	163	63	10.6	0.75
Ballast	88	0.2	-	-	-	-

3. FE modelling of railway sleeper

Researchers have modelled the railway sleepers using computational methods such as the Finite Element FE and beam element on an elastic foundation as reported by Qiao *et al*. (1998). A 3D-FE was developed to simulate the railway sleeper as shown in Fig. 1. The model contains the rail, sleeper, and the ballast. The ballast is assumed to set on a rigid base. The sleeper is meshed into 1216 3D linear hexahedral elements of type C3D8R and the ballast to 4992 of the same type of elements. It was assumed a full interaction between the bottom of the sleeper and the top of ballast.

3.1 Model verification

In this study, two load cases are considered in the design optimization; the static and dynamic loads. The FE model simulation is verified with the experimental work done by Namura *et al.* (2005). The experimental work was done on the behaviour of the GFRP composite sleeper under cyclic load. This load is distributed on the top of the sleeper within the area of 100 mm width by 240 mm in length under the rail position. In the experimental test, the dynamic load is varying between 45 kN to 2 kN with 2 Hz frequency (Namura *et al.* 2005). The experimental work was conducted on the effect of sleeper geometry on its behaviour.

The numerical FE analysis was done for the first second of time to find the initial settlement of the FRP sleeper. The verification was made on the sleeper dimensions 2300 mm × 240 mm × 130

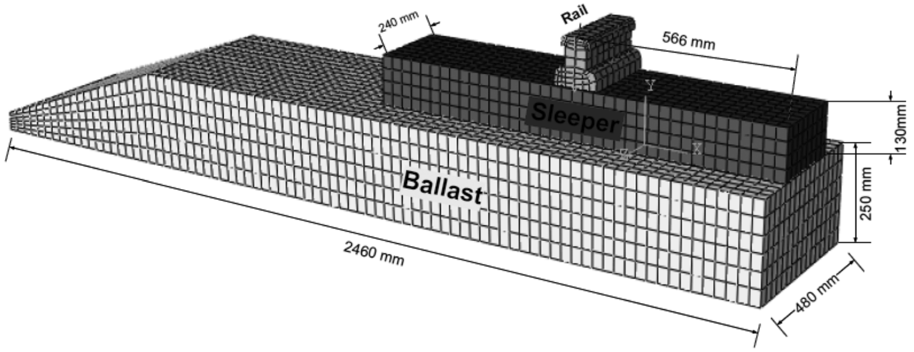

Fig. 1 Railway sleeper structure

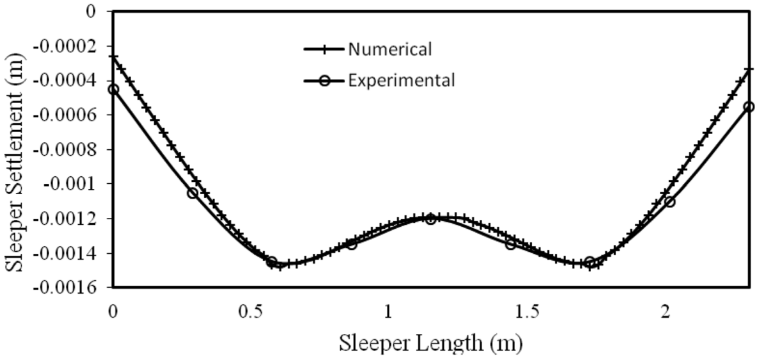

Fig. 2 Settlement of FRP sleeper

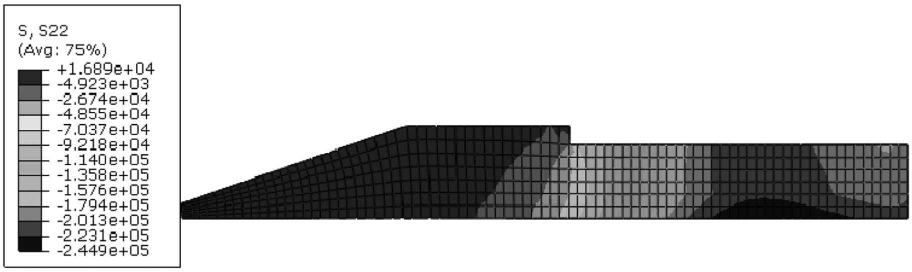

Fig. 3 Ballast vertical stresses

mm. The sleeper settlement under the maximum load 45 kN is shown in Fig. 2. The FE simulation shows a very close prediction compared to the experimental.

The initial ballast analysis described above shows that the maximum vertical stress is (2.44E+5 N/m^2) as shown in Fig. 3, which it is less than the allowable stress (8E+5 N/m^2) (Australia 2003). This means that there is a chance to reduce the sleeper width with the optimization methods. On the other hand, the shoulders of the ballast suffer from lateral forces due to the vertical load of the railway sleeper. The width of the ballast shoulder affects the settlement of the ballast because it plays an important role in the stability of the ballast (Kabo 2006).

4. Optimization technique

The advance fibre composite materials have several benefits, but it has high cost compared with some of the traditional materials. Design methods have to be very sophisticated to avoid the material wastage, and it is recommended to optimize any form of composite structure to reduce the GFRP material in the structures (Bank 2006). The minimizing of each dimension in the sleeper unit means cost saving. The main point of this research is to reduce the cost of material use in the production of the sleeper. The design of the GFRP composite sleeper requires more efforts on the investigation of different load cases. Dynamic design optimization is more important to find the required sleeper dimensions, and this design will be more economic and safe compared to the traditional design. Design constrains were developed by depending on the standards specification for the railway design. The Australian standard is recommended that the maximum stress under the railway sleeper is less than or equal to (8E+5 N/m^2) (Australia 2003).

The present sleeper design model is divided into two parts as shown in Fig. 4. The sleeper model is divided into design part and non-design part. The end and mid parts are considered as design parts. The section under the rail is considered as a non-design part due to the stress's concentration. Furthermore, this part will be in direct contact with steel rail, and this part will have few holes during the installation. Therefore, the design procedure will keep the part dimensions constant during the optimum design iterations. The variable length (L_1) is very important in the design according to the conclusion of Namura *et al.* (2005) work, where this parameter plays a crucial role by affecting the type of ballast support or effect the stress distribution through the ballast.

The Genetic Algorithm (GA) is one of the efficient design techniques which it is available in the modeFRONTIER (Bowness 2007). The objective function is minimizing the volume of material required in the sleeper. The number of the design variables is five as shown in Fig. 4. The selection of these variables depends on the idea to give a simple design sleeper for the industry. The objective function and design constraints are explained below

$$\text{Objective (volume of sleeper)} = \min\ (B_1, A_1, L_1, B_3, A_3) \tag{1}$$

$$\text{Variables} = \begin{cases} B_1 \\ A_1 \\ L_1 \\ B_3 \\ A_3 \end{cases}$$

Constraints: (part 1, part 2 and part 3)

$$\sigma_T \le \frac{\sigma_{ult}}{F.S} \tag{2}$$

$$\sigma_c \le \frac{\sigma_{ulc}}{F.S} \tag{3}$$

$$\delta_{rail} \le 1.7 \text{ mm} \tag{4}$$

$$\delta_{difference} \le 1.4 \text{ mm} \tag{5}$$

where, A_1 and B_1 are the dimensions of part – 1, A_3 and B_3 are the dimensions of part-3. L_1 is the sleeper ends length. σ_T and σ_c are the tensile and compressive stress of composite material respectively. σ_{ult} and σ_{ulc} are the ultimate strength in tension and compression as shown in Table 1. $F.S$ is the design factor of safety, which it is equal to 2. δ_{rail} and $\delta_{difference}$ are the total vertical displacement under rail and the differential displacement between the ballast under rail, mid span and end of rail respectively.

The constraint values in Eqs. (2)-(5) are usually conditioned and then added to the form of an

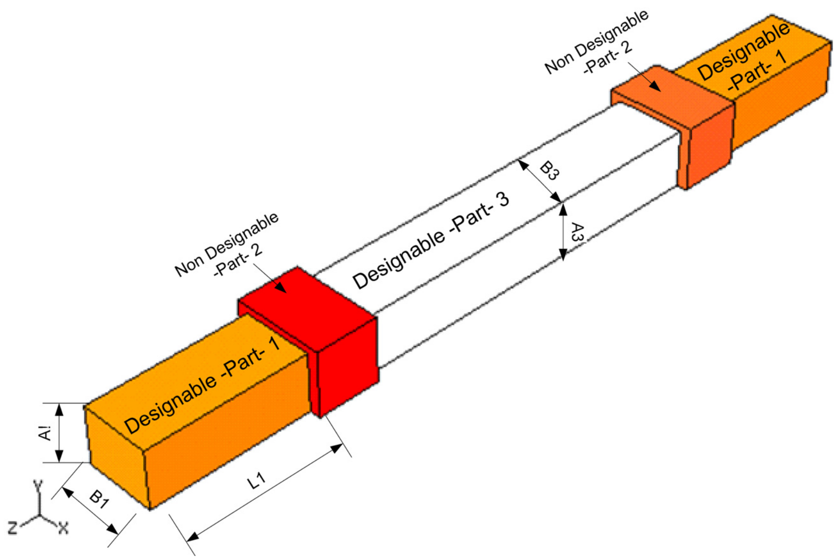

Fig. 4 Sleeper model design zones

individual fitness. These fitness values are the usual starting points for implementation of a genetic algorithm in the optimization problems. When individuals might have a stiffness problem, but are fitted with the other constraints, they should still be allowed to participate since there may be building blocks within individuals. The optimum design will be in two parts static design and dynamic design. The difference between two designs is the first one ramp load is applied, while the second one a sinusoidal load is applied.

5. Results and discussions

5.1 Static design

Initially, the design starts with the standard timber sleeper dimensions as shown previously in section (1), and 112.5 kN static loads. First, the model was created by the FE traditional software ABAQUS. The model is imported into modeFRONTIER workflow for the design, and the total number of constraints is five. The objective history of the design optimization is shown in Fig. 5, where the optimization iterations end with a minimum volume of material equal to 44% of the initial volume after 103 iterations. The design variables are optimized, and it is presented in Table 2. Iterations can be either visible or real with less volume than the optimum design such as (ID: 97, 98, 99 & 100) as shown in Fig. 5. These design points have deflection constraints higher than the allowable limit as shown in Fig. 6. The decision maker required to investigate the better design point between all points suggested by the program. The mid span cross section area is 2.5% greater

Table 2 Optimum design static variables

Variable	A1 (mm)	B1(mm)	L (mm)	A3 (mm)	B3 (mm)
Optimum value	141.6	167.6	254	178	136.7

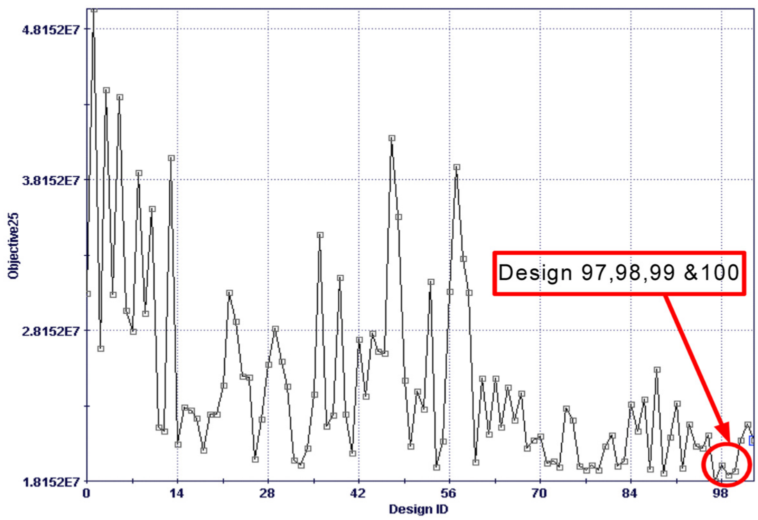

Fig. 5 Objective design history

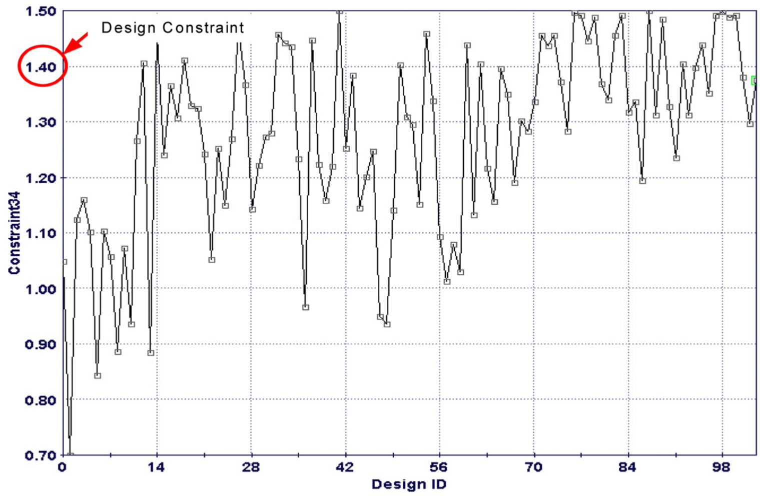

Fig. 6 Deferential settlement constraint history

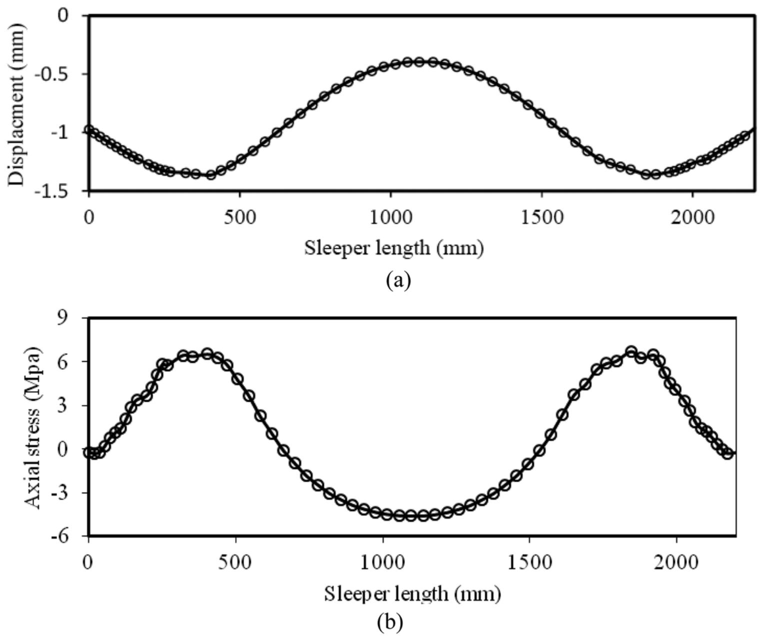

Fig. 7 (a) Axial stress, (b) Sleeper deflection

than the end cross section area. Fig. 7(a) shows the bottom sleeper stress distribution in the axial direction for the optimum static design. It shows that the maximum stress in compression and tension is about -4 MPa and 6 MPa respectively, which represents 13% and 7.5% of the allowable compression and tension stress of the GFRP materials. In contrast, the deflection constraint is expected to control the optimization process in the design iteration. The deflection of the optimum sleeper is shown in Fig. 7(b). This figure shows that the deflection under the sleeper can reach 1.4 mm, and the maximum deferential deflection is about 1 mm. On the other hand, the ballast stress is

Fig. 8 Vertical stress in the ballast

reaching the maximum allowable vertical stress under the rail as shown in Fig. 8. The static design was examined to find out its ability to withstand the dynamic load 112.5 kN and 2 Hz of frequency. The result of analysis shows that the deflection of the sleeper under the rail is 1.868 mm, and the vertical stress in the ballast is 0.91 MPa. It was also found that both stress and deflection are higher than the allowable limits, and therefore, it becomes very essential to consider the dynamic load in the design optimization.

5.2 Dynamic design

The existing recommended procedure for the dynamic design of the railway sleeper depends on the dynamic load factor. The Australian railway standard dynamic load factor is recommended that the minimum dynamic load factor is 150% of the static load (Australia 2003). The procedure of present design is the same procedure of the static design, and the aim of this design is to find the effect of the dynamic load on the final optimum design. The goal of dynamic design is to find out the flexibility of changing sleeper dimensions to enhance the sleeper dynamic behaviour. This means there is no need of using load factor or increase the volume to increase the mass. The dynamic rail load value is 112.5 kN and 2 Hz of frequency. The load applied on the sleeper and analysed to find the behaviour of the sleeper. In the dynamic system, the equation of motion can be written in general way (Qiao *et al.* 1998)

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\} = \{f\} \tag{6}$$

where, M is the mass matrix, C damping matrix, K is the stiffness matrix, f is the load vector, and x is the displacement vector.

The damping is assumed equal to zero and the external load applied in the form of sinusoidal load:

$$\{f\} = \sin w.t \tag{7}$$

where, w is the frequency and t is the time.

The initial analysis shows that the expected peak amplitude is about 1 sec time. The analysis results are used in the optimization design accounted for total time equal to 1.2 sec. The optimum dynamic design sleeper has volume 40% less than the initial design (standard sleeper dimensions). Furthermore, it shows only 5.5% increase of material volume compare to the static load. The

Table 3 dynamic design variables

Variable	A1 (mm)	B1(mm)	L (mm)	A3 (mm)	B3 (mm)
Optimum value	164	128	347.5	154	163.7

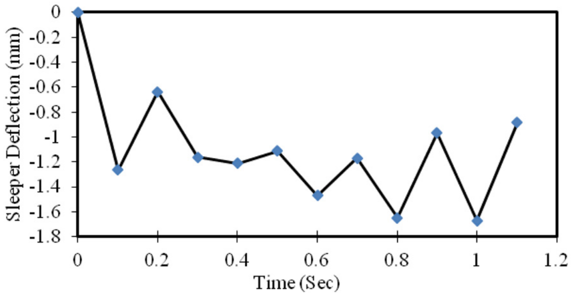

Fig. 9 Sleeper deflection history

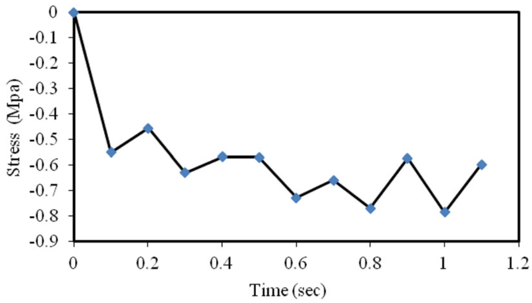

Fig. 10 Ballast stress history

optimum design result parameters are shown in Table 3. The optimum dynamic design time is 1 sec with respect to the initial design indication, which shows that the peak amplitude of the structure might happen in the first second time. The optimum sleeper under dynamic load is analysed to find the history of deflection under the rail, and it illustrates a good behaviour, which it is less than the allowable limit as shown in Fig. 9. In addition, The ballast stress diagram is shown in Fig. 10, and it is within the allowable limit.

5.3 Dynamic design for frequency verification

The dynamic design is verified through the frequency analysis. In this simulation, the interested frequency was assumed to be 1-10 Hz, while the usual train frequency is between 1-5 Hz (Bowness 2007, Anderson and Fair 2008). There are many important areas of structural analysis in which it is essential to be able to extract the Eigen-values of the system and, hence obtaining its natural frequencies of vibration is fundamental. The subspace method is used to find the natural frequency

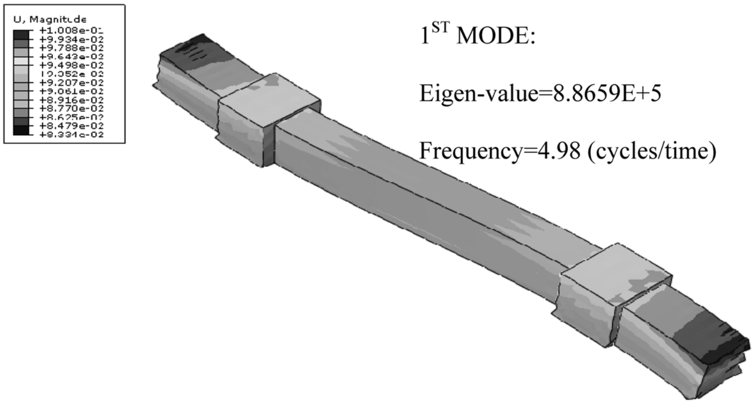

Fig. 11 First mode of dynamic design

of the design sleeper. The first mode and natural frequency are shown in Fig. 11, and the value of the natural frequency is 4.98 cycles/sec. Therefore, the design of the sleeper for dynamic load is saved against present external load. The sleeper should be re-designed for the higher range of frequency.

6. Conclusions

This paper demonstrates that both FE and optimization method are capable to developing a reliable and acceptable railway sleeper design. This optimum design will significantly contribute to reduce the cost of the sleeper as the amount of FRP material used in this design is far less than the standard timber sleeper. It was found that the dynamic load effect required only 5.5% greater than the total material that used during the static load design. This means that the average saving of the sleeper material by this design is approximately 50% in comparison to the standard design of the timber sleeper. It can be concluded that the optimum length of the sleeper studies in this paper under dynamic load is 2275 mm. The natural frequency of the structure was also evaluated in order to ensure that the safety of the structure against the external load frequency is within the design limit. This design is highly recommended to be adopted by the industry. The expected weight of the optimized sleeper is about 115 kgs, while the timber sleeper weighs is 100-150 kgs.

References

Almeida, F.S. and Awruch, A.M. (2009), "Design optimization of composite laminated structures using genetic algorithms and finite element analysis", *Compos. Struct.*, **88**(3), 443-454.

Anderson, W.F. and Fair, P. (2008), "Behavior of railroad ballast under monotonic and cyclic loading", *J. Geotech. Geoenviron. Eng.*, **134**(3), 316-327.

Aravinthan, T. (2008), *R&D on Engineering Fibre Composite-Past, Present and Future*, Toowoomba.

Australia, S. (2003), *Railway Track Material, Part 14:Prestressed Concrete Sleepers.*

Bank, L. (2006), *Composite for Construction: Structural Design with FRP Material*, JOHN WILEY & SONS, New Jersey.

Berthelot, J.M. and Sefrani, Y. (2007), "Longitudinal and transverse damping of unidirectional fibre composites", *Compos. Struct.*, **79**(3), 423-431.

Bowness, D., Lock, A.C., Powrie, W., Priest, J.A. and Richards, D.J. (2007), "Monitoring the dynamic displacements of railway track", *Proceedings of the Institution of Mechanical Engineers, Part F: J. Rail and Rapid Transit*.

Clarke, J.L. (1996), *Structural Design of Polymer Composite- EUROCOMP Design Code and Handbook*, E&FN Spon, UK.

González-Nicieza, C., Álvarez-Fernández, M.I., Menéndez-Díaz, A., Álvarez-Vigil, A.E. and Ariznavarreta-Fernández, F. (2008), "Failure analysis of concrete sleepers in heavy haul railway tracks", *Eng. Fail. Anal.*, **15**(1-2), 90-117.

Kabo, E. (2006), "A numerical study of the lateral ballast resistance in railway tracks", *Proceedings of the Institution of Mechanical Engineers, Part F: J. Rail and Rapid Transit*, **220**(4), 425-433.

Kaewunruen, S. and Remennikov, A. (2007), "Influence of voids and pockets on vibration characteristics of railway concrete sleepers", *Underground Coal Operators' Conference*, *Faculty of Eng.-Papers*, 360.

Manalo, A., Aravinthan, T., Karunasena, W. and Ticoalu, A. (2010), "A review of alternative materials for replacing existing timber sleepers", *Compos. Struct.*, **92**(3), 603-611.

Nagafuji, T. and Noritsugi, A. (1988), "Performance of synthetic sleepeer", *Railway Tech. Res. Inst., Quarterly Reports*, **29**(3), 107-113.

Namura, A., Yukihiro, K. and Seiichi, M. (2005), "Study on the optimum size of railway sleeper for ballasted truck", *Struct. Eng. Earthq. Eng.,* JSCE, **22**(2), 245S-255S

Prasad, P. (2008), *Fibre Composite Railway Transom*, Toowoomba.

Qiao, P., Davalos, J.F. and Zipfel, M.G. (1998), "Modeling and optimal design of composite-reinforced wood railroad crosstie", *Compos. Struct.*, **41**(1), 87-96.

Sadeghi, J.M. and Babaee, A. (2006), "Structural optimization of B70 railway prestressed concrete sleeper", *Iran. J. Sce. Tech.*, **30**(B4), 461-473.

Suiker, A.S.J., Selig, E.T. and Frenkel, R. (2005), "Static and cyclic triaxial testing of ballast and subballast", *J. Geotech. Geoenviron. Eng.*, **131**(6), 771-782.

Walker, M. and Smith, R.E. (2003), "A technique for the multiobjective optimisation of laminated composite structures using genetic algorithms and finite element analysis", *Compos. Struct.*, **62**(1), 123-128.