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Abstract. Recently, a new composite material, 'fibre-reinforced foamed urethane (FFU)' has gained a vital momentum for applications in the railway industry. As railway sleepers and bearers in crossings and switches, the FFU elements act as a beam which redistributes the train forces onto track support. This leads to considering as a necessary part in order to underpin the reliable and safe operations of railway crossings and switches. According to the application of FFU sleepers for structural purpose in the railway system, it is relevant to investigate the free vibration behaviours of FFU composite sleepers under free vibration. The responses of their behaviours provide modal parameters, for example, natural frequencies, damping loss factors, and mode shapes. One primary factor causing cracking of FFU composite sleeper and excessive railway track maintenance cost is the free vibration of FFU sleepers in a railway track structure. This paper presents a sensitivity analysis of free vibration behaviours of an FFU composite beam. Through finite element method (FEM), FFU-beam elements were used in the FFU composite beam modelling. The dynamic characteristics of a vibrating structure are also evaluated by FEM. It is vital to note that errors in FE model are inevitable, whilst the modal data extracted from the experimental test is generally accepted to be accurate. Hence, the correlation of data between FE modelling and experimental measurement leads to the research on this project. This model focuses on the influence of modal parameters of FFU composite sleepers on the free vibration properties. Furthermore, data on the vibration mode shapes indicates the dynamic performance of the railway track, as it plays a significant role in the cracking deterioration of FFU composite sleepers.

1. Introduction

It is clear that railway track support elements, for example, bearers, sleepers, and transoms are safety-critical and structural components in a ballasted railway system. Their major features are not only to resist static and dynamic loads imposed by the wheel and distribute them to the ballast and underlying formation, but also to secure the rail gauge to allow trains to travel safely [1-3]. Another vital function of the structural components in the ballasted railway track system is to help with providing lateral track resistance to improve the stiffness and stability of the track structure. Any structural damage of the elements could affect the reliability, safety, and quality of the railway track, resulting in impaired rail services. One practical issue in the railway industry now is the replacement of ageing, damaged and deteriorated railway (timber) sleepers in existing tracks [4-5]. Especially in particular areas, such as crossings, railway switches, railway bridges, transition zones, the need for alternative materials to substitute old timber elements is undoubtedly significant [6-7]. Railway crossings and switches are a distinctive track system as well known 'turnout system', that is utilized to divert a train from a specific direction or a particular track onto other directions or tracks [8-10]. In the past three decades, fibre reinforced urethane (FFU) composites have been used in the construction of the railway track systems. Sekisui Chemical & Co [11] is the principal producer of this material. A large number of studies using Japanese testing standards are conducted for this material in order to describe the limits of usage or validate them in particular and specific cases [11].

Due to the nature of experiencing various dynamic loadings on the railway track, free vibration characteristics of concrete composite beams as well-known concrete sleepers are vital in analysis and design processes. It is clear that the sleeper damage appears mostly at resonant frequencies of the sleepers, especially for the dominance in the first five modes of vibration. There have been a number of studies related to the determination of dynamic properties of concrete sleepers. Modal analysis is one of the widely used techniques to investigate the vibration parameters of concrete sleepers. Early modal analysis on a concrete sleeper in free-free condition utilizing an electrodynamic shaker [12]. In 1991, the development of an analytical model for analysing the dynamic behaviour of concrete sleepers in both free-free condition and in-situ conditions, based on the experimental results performed by Grassie [13], a two-dimensional dynamic modelling for vibration analysis of concrete sleepers. It was found that the Timoshenko beam element was the best approximation of the concrete sleepers. In the past few years, the two-dimensional finite element modelling and the modal testing of concrete sleepers in free-free condition were carried out by Gustavson [14] and Vincent [15]. The outcomes were accepted between numerical and experimental information. However, comprehensive modal testing of FFU sleepers in free-free condition has rarely been studied. This paper presents the results of a sensitivity analysis of free vibration characteristics of FFU composite beam. The beam model was analysed, based on the finite elements using a computer package, STRAND7. The two-dimensional beam element, considering shearing effects, was employed as the FFU beam to embrace the shear deformation and rotational inertia. Information on dynamic changes is of important benefit to the research on non-destructive testing and health monitoring of on-track FFU sleepers.

2. Analytical modal analysis

There are several books about analysis and design of beams on elastic foundation [16-17]. One would generally employ the finite element formulation, in case of partially supported beams under dynamic loading. To date, Timoshenko beam components are normally employed in the dynamic modelling of sleepers, in order to gain better agreement at higher frequencies with experimental data, since the rotatory inertia and shear deformation are included in the element formulation [18]. The equations of motion for free vibrations of the FFU beam can be written as follows [19-21].

In a dynamic system, the equation of motion of the system can generally be given by

$$[M]\{\ddot{r}\} + [C]\{\dot{r}\} + [K]\{r\} = \{p\} \tag{1}$$

Where [M] is the mass matrix, [C] is the damping matrix, and [K] is the stiffness matrix. The harmonic force applied to the system with magnitude P and loading frequency ω is shown by

$$\{p\} = Psin(\omega t) = Pe^{j\omega t} \tag{2}$$

As known, a non-trivial solution to Equation (1) is $\{r\} = \{R\}e^{j\omega t}$. Substituting this solution to Equation (1) and manipulating it with Equation (2), the equation of motion becomes

$$(-\omega^2[M] + j\omega[C] + [K])\{R\} = \{P\} \quad (3)$$

With some manipulations, transforming Equation (3) using modal coordinates by utilizing $\{R\} = [\Phi]\{W\}$ and the orthogonality principle, and it then yields

$$W_i = \frac{\{\phi_i{}^T\}}{\omega_i^2 - \omega^2 + 2\zeta_i\omega_i\omega j})\{P\} \quad (4)$$

Recalling $\{R\} = [\Phi]\{\mathrm{W}\} = W_1\emptyset_1 + \cdots + W_n\emptyset_n$, Equation (4) can be re-written as

$$\{R\} = \left(\sum_{i=1}^{n} \frac{\emptyset_i\emptyset_i^T}{\omega_i^2 - \omega^2 + 2\zeta_i\omega_i\omega j}\right)\{P\} \quad (5)$$

Then, the reacceptance of the system can be identified by

$$H_{ij}(\omega) = \frac{R_i(\omega)}{P_i(\omega)} = \sum_{i=1}^{n} \frac{\emptyset_i\emptyset_i^T}{\omega_i^2 - \omega^2 + 2\zeta_i\omega_i\omega j} \quad (6)$$

Thus, ω_i represents the resonant frequency, $\emptyset_i$ is the mass-normalized mode shape, and ζ_i denotes the modal damping ratio.

Note that for viscous damping (with critical dampingc_r), $\zeta_i = \frac{c_i}{c_r}$; for proportional damping ($[C] = a[M] + b[K]$), $\zeta_i = \frac{a}{2\omega_i} + \frac{b\omega_i}{2}$; and for hysteretic damping (η_i), $\zeta_i = \frac{\eta_i}{2}$

3. A finite-element model of FFU composite beam

The dynamic finite-element model of an FFU beam in free-free condition was developed to study its dynamic response. Generally, the Timoshenko beam model is the most acceptable alternative for modelling two-dimensional concrete sleepers [22-25]. However, this FE model was modelled using 40 Euler–Bernoulli beam components with 41 nodes, due to the model acting as a shallow beam. In addition, the numerical model added the beam elements, which take into account shear and flexural deformations, for modelling the FFU beam. Furthermore, the trapezoidal cross-section was assigned to the beam components. Figure 1 illustrates the two-dimensional finite element model for an FFU beam. Using a common-purpose finite element package STRAND7 [26-27]. The material and geometric characteristics of these elements were modified, based on the experimental test. Table 1 presents the geometrical and material properties of the finite element model. These characteristics were decided because they were identical to a special type of FFU sleepers manufactured in Japan. A series of natural frequency analyses was conducted in order to assess the quality of the finite element model. It is clear that 40 beam elements, denoting an FFU composite beam, can give a reasonable approximation of beam's vibration in free-free condition, compared with the existing experimental data.

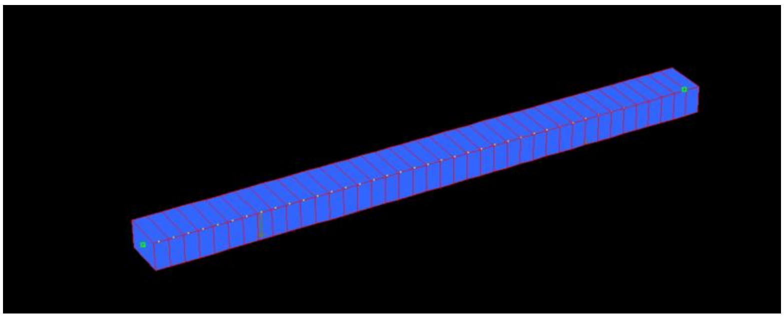


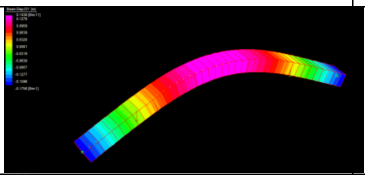
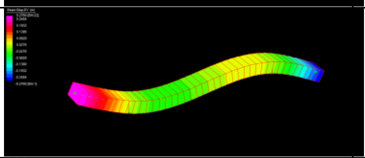
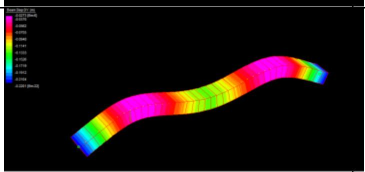
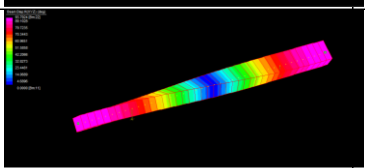
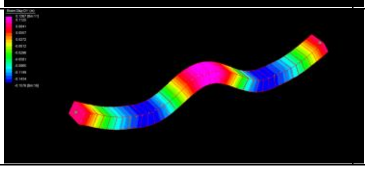
Figure 1. Finite element analysis for modelling of an FFU composite beam in the free-free condition

Table 1. Engineering properties utilized in the dynamic modelling [28]

Parameter lists		
Elastic modulus	15100	MPa
Poisson's ratio	0.35	-
Beam density	700	kg/m^3
Beam length	3.3	m
Beam cross-sectional area of a rectangle (0.16, depth * 0.26, width)	0.042	m^2

For the verification of the model, the natural frequencies of an FFU beam in the free-free condition were calibrated against the existing experimental testing. Table 2 shows the comparison between the finite-element analysis and experimental results. The outcomes are found to be in a very good agreement in the first two bending modes. The maximum difference of frequencies between the numerical and experimental results is less than 19.03 percent in the third bending mode. A good correlation between the numerical and experimental results is found for the shifts in natural frequencies for the free-free condition. Table 2 illustrates the first five mode shapes of an FFU beam model between the numerical modelling and experimental data in free-free condition.

Table 2. Natural frequencies of an ideal FFU composite beam (Hz) under the free-free condition

Mode no.	Mode shape	Numerical	Experimental	Difference (%)
1		68.59	68.23	0.52
2		144.20	143.61	0.41
3		200.77	247.96	19.03
4		356.78	N/A	N/A
5		608.17	N/A	N/A

4. Results

The results of vibration tests for the FFU composite beam model are given in Table 2. In the table, the first five modes of vibration are presented. Considering the results between the numerical modelling and experimental data, the lowest frequencies corresponded to the fundamental bending mode, the second frequencies to the second bending mode, the third frequencies to the third bending mode, the fourth frequencies to the lowest torsional mode, and the fifth modes to the fourth bending mode. It is clear that the values of frequencies of the first two mode shapes of the numerical modelling and experimental data are almost equal. However, there is a significant difference in the third bending mode between them, approximately 19 percent. Moreover, the last two mode shapes of the experimental data are not available. This is because there might be some environmental disturbance during the testing. It should be noted that these outcomes are focused on the sleeper behaviours due to a development in health monitoring of track components that one generally measures the dynamic behaviours on-track sleepers by placing accelerometers on the sleeper surface [29].

5. Conclusion

Vibration characteristics of Fibre-reinforced foamed urethane (FFU) are crucial for the development of a realistic dynamic model of railway track capable of predicting its dynamic response. The free vibration parameters of an FFU composite beam model in the railway system were examined using the finite element approach. The two-dimensional modelling based on the Euler–Bernoulli beam has been verified and found in very good agreements with the experimental modal test. An FFU beam used in the experimental test was carried out using an impact hammer excitation technique over the frequency range of interest: from 0 to 1600 Hz. It is clear that the resonant frequencies between the numerical modelling and the experimental data are satisfying in the first two modes. Anyway, the resonance of the second or third dynamic bending modes from the numerical modelling and the experimental data will expedite incurring cracks on the FFU beam model. According to what was mentioned, these vibration parameters of the numerical modelling and the experimental data are extremely vital for the development of dynamic health monitoring tool for FFU sleepers in the modern railway track at different periods: before and after maintenance. This model has been very valuable and has led to further research on structural behaviours of the railway FFU sleepers in the track structure system or as well known ‘the in-situ railway FFU sleepers'.

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