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Field test investigation and numerical analysis of ballasted track under moving locomotive[†]

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Abstract

This paper is devoted to investigating of dynamic behavior of a ballasted railway track by field tests and numerical analyses. In this regard, at first in a field test program, two different sections in a ballasted track including concrete and wooden sleepers with good quality are selected and their dynamic vertical deflections are measured due to moving locomotive. In continuation, the numerical model of vehicle track interaction is developed and its results are verified using the measured values in the field tests and the previous research studies. Finally, using the verified model, a series of sensitivity analyses are accomplished on effecting parameters including sleeper type and track modulus. Results indicate that the dynamic behavior of the ballasted track under moving locomotive is linear with concrete sleepers while non-linear with wooden sleepers.

Keywords: Concrete and wooden sleepers; Dynamic analysis; Field tests; Locomotive; Numerical models; Track dynamics

1. Introduction

The support condition of railway track can affect on its dynamic behavior under different railway vehicles. In ballasted track, the railway sleepers have the significant effects on the dynamic behavior of tracks.

In the available literatures, the researchers studied the dynamic behavior of railway tracks. For example, Kerr [1, 2] investigated the methods of measuring track modulus and dynamic behavior of tracks by considering the railway track as a beam on elastic foundation. Dahlberg [3, 4] studied the dynamic behavior and stiffness variations of railway track. In another work, Cai [5] investigated the track and train wheel interaction using numerical modeling. Oscarsson [6] studied the interaction between the train and ballasted railway track. Fryba [7] studied the railway behavior under the moving loads. Zhai and Cai [8] and also Sun and Dhanasekar [9] investigated the vehicle and track dynamic interaction in the ballasted railway. Zhai et al. [10] modeled the ballasted railway track under moving train loads and studied its dynamic behavior. Uzzal et al. [11] studied the influence of wheel flat by analysis of vehicle-track interaction. Cai et el. [12] investigated the effects of vehicle - track interaction on ground vibrations. Zakeri and Abbasi [13, 14] studied the rail support modulus and the loading pattern of concrete sleepers. Zakeri et al. [15] investigated the environmental vibrations of track due to loads of moving trains. Cao et al. [16] investigated the ground vibrations due to passing train. Real et al. [17] studied the effects of ballasted railway parameters on track deflection and stiffness. Sun et al. [18] determined the dynamic forces of railway track by numerical simulation of vehicle-track interaction. Reviewing the available technical literature indicates that the dynamic behavior of railway tracks including the concrete and wooden sleepers under moving locomotive has not been investigated and nor compared well as numerical studies and field tests. For this reason, this paper is devoted to this topic.

In this paper, firstly a series of field tests are done on the ballasted track sections with concrete and wooden sleepers due to a moving locomotive with three axle bogies. In continuation, the railway track and locomotive are modeled by using the finite element method, and then the track model is verified with the results of previous researchers. Afterwards, the track responses under the moving locomotive are calculated for concrete and wooden sleepers. Then the numerical results are compared with the field test studies and consequently good agreements are found between the field and numerical results for ballasted track with concrete and wooden sleepers. Finally a series of sensitivity analyses are accomplished on the ballasted track parameters under the moving locomotive.

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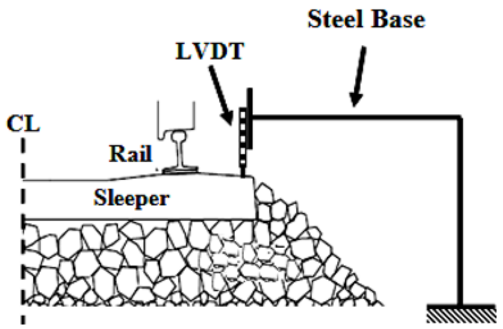


(a) A cross section of ballasted track

(b) A series of *LVDT* sensors

Fig. 1. Installed *LVDT* sensors on the steel bases in the ballasted railway track.

Fig. 2. The locomotive with three axle bogies.

(a) Track with concrete sleepers

(b) Track with wooden sleepers

Fig. 3. Passing locomotive over the track sections.

2. Field tests of railway track under moving locomotive

In this part, the dynamic behavior of railway track sections with wooden and concrete sleepers under moving locomotive is investigated as field works. In order to do the field tests, a series of sensors including Linear variable differential transformers (*LVDT*s) are utilized for determining the vertical track deflections. Fig. 1 indicates the *LVDT*s with steel bases installed on the ballasted railway track.

For applying the maximum train loads, a locomotive with three axle bogies is used, as shown in Fig. 2. The total weight of locomotive is 100 tons. The distance of wheel-axles in each bogie is 170 cm. Also, the distance between two bogie centers is 1080 cm.

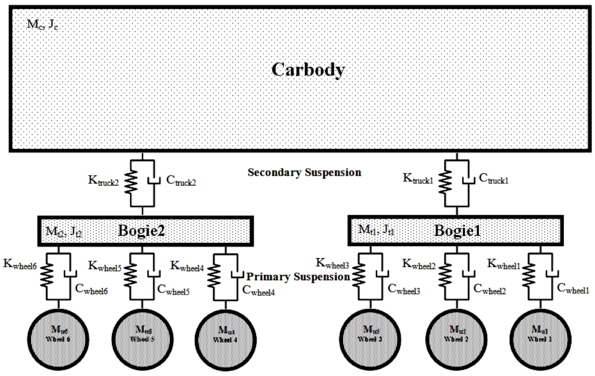
The locomotive is passed through two ballasted track sections with concrete and wooden sleepers, as shown in Fig. 3.

In continuation, the numerical model of ballasted railway track under the moving locomotive is presented.

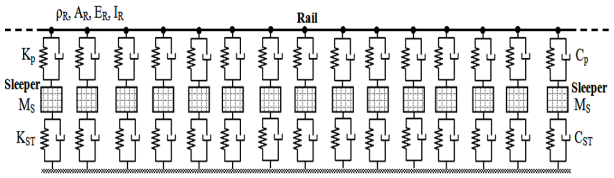
3. Numerical models of railway track and locomotive

For numerical analyses of ballasted track under moving train, the vehicle track interaction equations are developed and coupled based on the finite element method [19, 20]. In this matter, the mass, stiffness and damping matrices of ballasted railway track are formed. In the next stage, the motion equations of the locomotive are determined, and its mass, stiffness and damping matrices are derived. By assembling the matrices of all elements of railway track and vehicles, the numerical models for the track and the vehicle are established. Fig. 4 shows the overall model configuration.

As shown in Fig. 4, the vehicle model includes carbody and two bogies with three axle loads with K_{truck} and C_{truck} representing the stiffness and damping of bogies, and K_{wheel} and C_{wheel} of wheels. Also, M_c, J_c, M_t, J_t and M_w depict the mass of carbody, rotational inertia of carbody, mass of bogie, rotational inertia of bogie and mass of wheel respectively. Moreover, the railway track includes rail and sleepers with K_p and



(a) Railway vehicle model



(b) Railway track model

Fig. 4. Railway vehicle and track models.

C_p representing the stiffness and damping of fastening systems, and K_{ST} and C_{ST} of track supports. Also, ρ_R, A_R, E_R, I_R and M_S represent the density of rail, cross section area of rail, elasticity modulus of rail, inertia moment of rail and mass of sleeper respectively.

4. Verification of numerical models

In this section, the railway track model under loads of moving train is verified by comparing the similar results of Zakeri and Ghorbani [20] in which the train with four axle loads are considered, as illustrated in Fig. 5.

As it can be seen from Fig. 5, there are good agreements between the obtained results in the present study and works of Zakeri and Ghorbani [20].

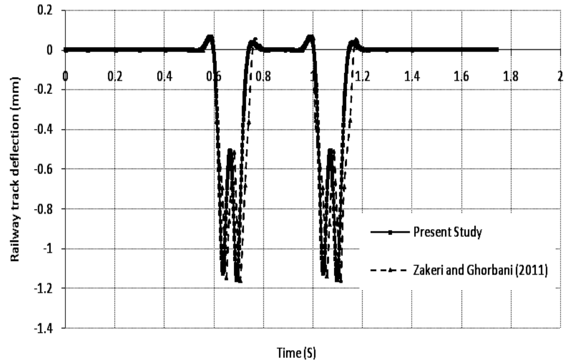
5. Field and numerical results

In this part, the results of numerical and field test studies for two track sections including concrete and wooden sleepers are presented and compared. Fig. 6 indicates the responses of track sections with the concrete and wooden sleepers due to moving locomotive.

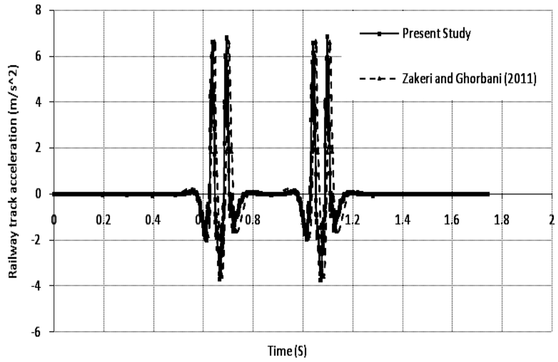
As it can be observed from Fig. 6, there are good agreements between the numerical and field test studies for both track sections.

6. Sensitivity analysis

Depending on the track support conditions, the mathematical relation between the applied train loads and the railway deflections and also the track support stiffness can be linear or

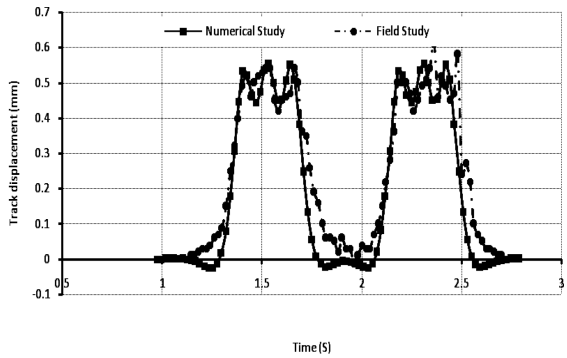


(a) Railway track deflection

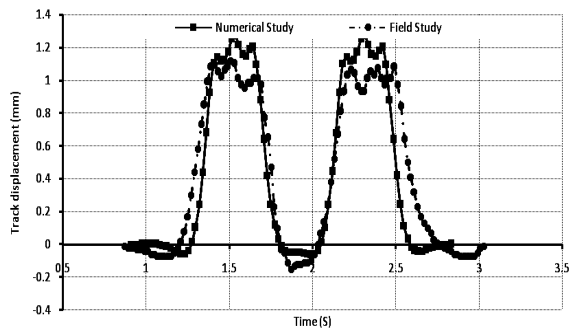


(b) Railway track acceleration

Fig. 5. Railway track responses in present study.



(a) Track with concrete sleepers



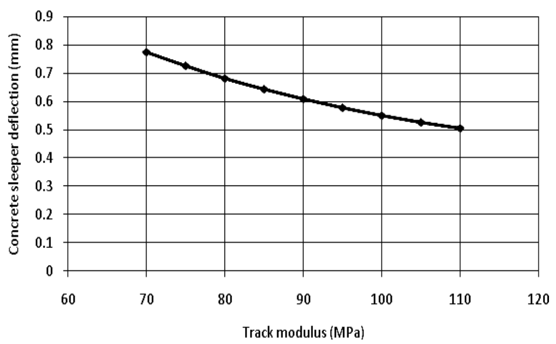
(b) Track with wooden sleepers

Fig. 6. Field and numerical results.

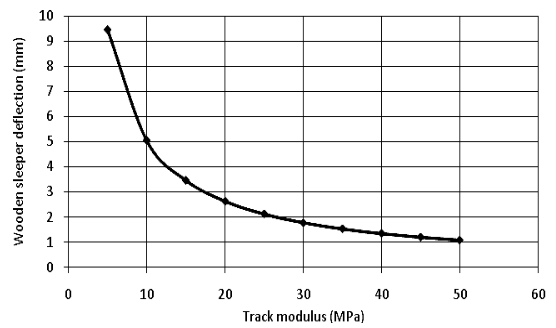
Table 1. The derived mathematical equations respect to concrete and wooden sleepers.

Sleeper type	Mathematical equation	Equation type
Concrete sleeper	$SD = -0.006 \times (TM) + 1.224$	Linear
Wooden sleeper	$SD = 44.47 \times (TM)^{-0.94}$	Non-linear

* Parameters of *SD* and *TM* are sleeper deflection (mm) and track modulus (MPa) respectively.



(a) Track with concrete sleepers



(b) Track with wooden sleepers

Fig. 7. The track sleeper responses for concrete and wooden sleepers.

nonlinear. For example, usually the relation between train loads and track stiffness is nonlinear because of the hardening of ballasted track due to compaction of substructure layers under heavy traffic loads [2, 21]. For this reason, a series of sensitivity analyses are performed on the ballasted track, in order to derive the mathematical relations of track responses for both concrete and wooden sleepers. Fig. 7 shows the responses of railway concrete and wooden sleepers under the moving locomotive.

As it can be observed from Fig. 7, the dynamic behavior of ballasted track with concrete sleepers is linear while that of track with wooden sleepers is non-linear. The reason of this issue results from the different rigidity and flexibility of the concrete and wooden sleepers. According to the mentioned explanations, the regression equations of the dynamic behavior of ballasted tracks with concrete and wooden sleepers under the moving locomotive are calculated based on Figs. 7(a) and (b), and they are illustrated in Table 1.

As it can be observed from Table 1, the mathematical relation between the sleeper deflection and track modulus is linear and nonlinear for concrete and wooden sleepers respectively.

7. Conclusion

In this paper, the dynamic behavior of railway ballasted track sections with concrete and wooden sleepers caused by the moving locomotive was investigated by numerical simulation and field test. The important findings of this paper are summarized as follows:

- The maximum vertical deflections of ballasted track with concrete and wooden sleepers under the moving locomotive were about 0.6 and 1.2 mm respectively in both numerical and field test studies. This shows that the track with concrete sleepers is heavy and stable and it has low displacement, whereas the track with wooden sleepers is light and it has more displacement and low stability.
- The dynamic behavior of track with concrete sleepers under the moving locomotive is linear with high stability. The mathematical relation between the concrete Sleeper deflection (*SD*) and Track modulus (*TM*) under the moving locomotive is based on $SD = -0.006 \times (TM) + 1.224$. In this equation, the units of *SD* and *TM* are mm and MPa, respectively.
- For the ballasted track with wooden sleepers with low stability, the dynamic behavior of this track under the moving locomotive is non-linear, and the mathematical equation between the wooden sleeper deflection (*SD*, in mm) and track modulus (*TM*, in MPa) is based on the power form $SD = 44.47 \times (TM)^{-0.94}$.

Nomenclature

LVDT : Linear variable differential transformer
K_{truck1} : Stiffness of bogie 1
C_{truck1} : Damping of bogie 1
K_{truck2} : Stiffness of bogie 2
C_{truck2} : Damping of bogie 2
K_{wheel1} : Stiffness of wheel 1
C_{wheel1} : Damping of wheel 1
K_{wheel2} : Stiffness of wheel 2
C_{wheel2} : Damping of wheel 2
K_{wheel3} : Stiffness of wheel 3
C_{wheel3} : Damping of wheel 3
K_{wheel4} : Stiffness of wheel 4
C_{wheel4} : Damping of wheel 4
K_{wheel5} : Stiffness of wheel 5
C_{wheel5} : Damping of wheel 5
K_{wheel6} : Stiffness of wheel 6
C_{wheel6} : Damping of wheel 6
M_c : Mass of carbody
J_c : Rotational inertia of carbody
M_{t1} : Mass of bogie 1
J_{t1} : Rotational inertia of bogie 1
M_{t2} : Mass of bogie 2

J_{t2} : Rotational inertia of bogie 2
M_{w1} : Mass of wheel 1
M_{w2} : Mass of wheel 2
M_{w3} : Mass of wheel 3
M_{w4} : Mass of wheel 4
M_{w5} : Mass of wheel 5
M_{w6} : Mass of wheel 6
ρ_R : Density of rail
A_R : Cross section area of rail
E_R : Elasticity modulus of rail
I_R : Inertia moment of rail
M_S : Mass of sleeper
K_p : Stiffness of fastening system
C_p : Damping of fastening system
K_{ST} : Stiffness of track support
C_{ST} : Damping of track support
SD : Sleeper deflection
TM : Track modulus

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