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The importance of 'dynamics' in the design and performance-based testing criteria for railway track components

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Abstract

It is unquestionable that track dynamics have caused various problems in railway operations and maintenance. Broken sleepers due to impacts at rail joints, switches and crossings, transition zones, bridge ends, and so on can result in failure of fastening systems and later lead to detrimental train derailments. Excessive ballast settlement and dilation from dynamic load conditions can weaken track lateral resistance and eventually track misalignment under extreme climate. These are a couple of clear evidences that railway industry faces daily. However, most railway practitioners still ignore the dynamics aspects when designing, testing, and manufacturing railway track components. The importance of 'dynamics' in the design, performance testing and manufacturing of track components have been highlighted with evidences in this paper. The thorough review of track load conditions is discussed. The proposed change from static or quasi-static design to a more rational dynamic design has been discussed. This implies the change from "*quasi-static load > static analysis and design > static and cyclic tests > quasi-static behaviors > individual component performance*" to "***realistic dynamic load > dynamic analysis > dynamic design and behavior > individual component performance > track performance***". Fundamental issues of dynamic testing of materials and structural components have been described to aid the understanding of inexperienced practitioners. The essential need to determine dynamic properties of materials and components, for dynamic design considerations will be highlighted. It is crucially important that such the dynamics aspects are highlighted so that the dynamic resistance of the components and railway tracks can be established for better public safety and operational reliability.

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Keywords: Dynamic properties; Dynamic load actions; Response spectra; Performance-based Design

1. Introduction

Nowadays, rail and track engineers have extensive practical experience in the operations of metro, urban, sub-urban, highspeed and freight railway networks. These railway networks can be designed and catered for either dedicated or mixed/dual traffic conditions. Despite the extensive experience, the public can often observe train delays, disruptions, and excessive unplanned maintenance due to either train or track problems. It is important to note that the most common and modern type of railway track systems for metro, urban, sub-urban and freight networks is the ballasted tracks, whilst the most adopted trackform for highspeed trains is the slab track system. These two common trackforms consist of similar structural layers: rail, resilient fasteners, track support structure, and substructure (i.e. foundation and structural fills). The key distinguish is the track support structure. For ballasted railway tracks, crosstie sleepers and ballast are used to assemble the track support structure. For slab tracks, the support structure consists of track slabs, shear keys, resilient layer (e.g. CA mortar, rubber, spring), and buried-structure (e.g. mass concrete, viaducts' slabs, tunnel floor, or cement-stabilised soil). Their railway track structures guide and facilitate the safe, cost-effective, and smooth ride of trains. Fig. 1 shows the main components of typical railway track systems, consisting superstructure and substructure (Kaewunruen and Remennikov, 2008; 2015; 2016). Its components can be idealised for modeling (such as by using spring-dashpots, lumped masses, or solid elements). The top components of the track systems such as the rails, elastic/resilent pads, fastening systems, under sleeper pads and ballast form a group that is referred to as the superstructure (Remennikov and Kaewunruen, 2005). On the other hand, the substructure is associated with a geotechnical system consisting of sub-ballast, ballast mat, and subgrade (formation) (Esveld, 2001; Indraratna et al., 2011). The sleepers are designed to transfer and distribute train loads from the rail foot to ballast bed; to hold and secure the rails at a correct gauge by using the rail fastening system; to maintain rail inclination; and to restrain longitudinal, lateral and vertical movements of the rails (Remennikov and Kaewunruen, 2008).

Nomenclature

E_d	the modulus of elasticity of concrete under dynamic loads
E_s	the modulus of elasticity of concrete under static loads
i	the sleeper number
N	a total number of sleeper
V	the moving speed of wheel
$\dot{\varepsilon}$	the strain rate of concrete under dynamic loads
$\dot{\varepsilon}_s$	the strain rate of concrete under static loads, and equals to 3×10^{-5}.
$w(x,t)$	the vertical deflection of rail
$\phi(x,t)$	the rotation angle of rail neutral axis
EI_r	the rail flexural rigidity
kAG_r	the rail shear distortion rigidity
m_r	the rail mass per unit length
r_r	the radius of gyration of rail cross-section
P_a	the rail axial force
$\bar{\mathrm{p}}(x,t)$	the generalized distribute force on the rail
$P(t)$	the moving wheel load
$f_i(t)$	the rail-sleeper reaction force (rail seat force)
l_p	the sleeper spacing
$\delta(x)$	Dirac delta function

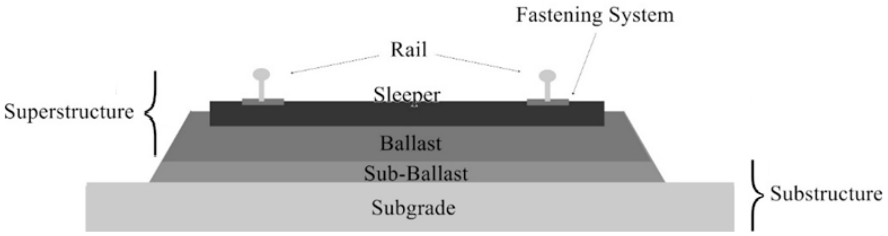


Fig. 1. Schematic railway track system.

The recently improved knowledge raises a concern in the design and manufacturing of railway track components such as prestressed concrete structures (sleepers or slabs), fastening system, ballast and supporting ground layers. In practice, most civil engineers and designers are well informed of the static structural design codes for prestressed concrete elements, which rely on allowable static stresses, material strength reductions, or partial limit state factors (Standards Australia, 2003; EN 13230). The static test apparatuses have been commonly used to obtain those static parameters (e.g. shear tests, flexural tests, compression tests, tensile tests, etc.). In particular, a railway track usually experience dynamic loading conditions (Remennikov and Kaewunruen, 2018). Track components will thus need to redistribute dynamic actions from train vehicles. This implies that the dynamic coupling vehicle-track interaction must be considered in the analysis and design (as illustrated in Fig. 2). For instance, a railway sleeper (or railroad tie), which is a safety-critical component of railway tracks, is commonly made of the prestressed concrete. The existing code for designing or manufacturing railway concrete sleepers makes use of the static stress design concepts (either allowable stresses or limit states) whereas the fibre stresses over cross sections at initial (at transfer) and final stages (under services) are limited (Kaewunruen et al., 2014; 2015a; 2015b). In addition, the fastening, the ballast and formation undergo similar dynamic effects. Under static analysis when the track components are considered under static loading, it is somewhat unclear whether the track components can support in terms of realistic capacity, or whether the components are over or under designed, or if there is a safety margin to cater heavier or faster train operations. This paper thus demonstrates the importance of dynamic effects, dynamic analysis, and the use of dynamic properties for railway track systems.

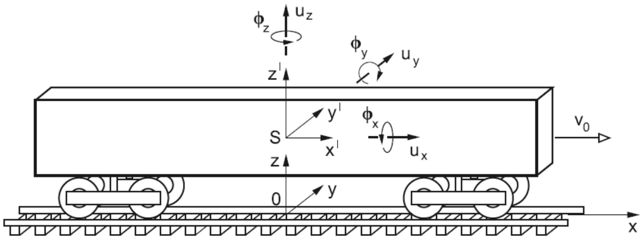


Fig. 2. A typical dynamic vehicle-track model (for ballasted railway tracks)

2. Dynamic vehicle-track modelling

In this study, the dynamic simulation concept by Cai (1992) has been adopted as shown in Fig. 2. The track model has included Timoshenko beam theory for both rails and sleepers, enabling more accurate behaviours of tracks. In reality, the irregularities or roughness of both wheel and rail will cause higher dynamic impact forces exceeding the design condition level or serviceability limit state. The exceeding magnitude of the force generated by wheel and rail irregularities will damage track components and impair ride quality (Kaewunruen and Remennikov, 2011; 2013; Griffin et al., 2014; Kaewunruen et al., 2015a; Setsobhonkul et al., 2017). This study is thus the first to demonstrate the influence of dynamic properties and modelling on the dynamic responses of track components. The dynamic amplification factor will be highlighted to identify the effect of train speeds. The scope of this study will be focused on ballasted railway tracks. A study on slab tracks has been presented elsewhere (Li et al., 2019). The commonly used passenger trains will be modeled and coupled with the discrete supported track model. The track model will be based on a standard rail gauge (1.435m). The outcome of this study will help railway organization in improving the test and design standards of railway track components. The ballasted track model (D-Track) is simulated on Winkler foundation principle and track dynamic responses are considered to be symmetrical. Rails and sleepers are represented by Timoshenko beams. The sleepers also support the rails and can be represented by discrete rigid masses. A free body diagram of track model is shown in the Fig. 3(a). P(t) represents a moving wheel force at constant speed (v). Fig. 3 (b) represents the force from rails to sleepers through the rail seat (i_{th}) and the reaction force $k_s z_i(y,t)$ per unit length. Equations of motion of the rail can be written as:

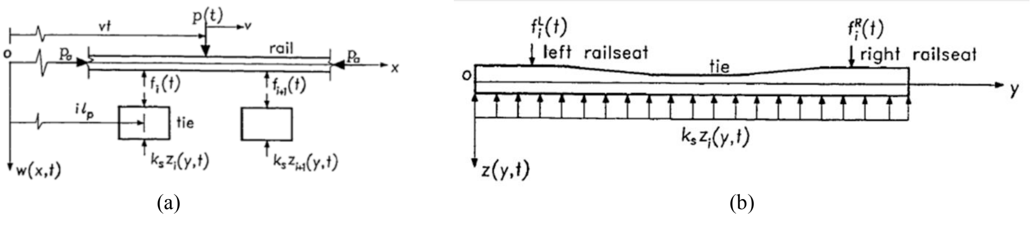
$$\frac{\partial}{\partial x}\left(kAG_r\left[\phi(x,t)-\frac{\partial w(x,t)}{\partial x}\right]\right)+m_r\frac{\partial^2 w(x,t)}{\partial t^2}=\bar{p}(x,t) \tag{1}$$

$$EI_r\frac{\partial^2 \phi(x,t)}{\partial x^2}-kAG_r\left[\phi(x,t)-\frac{\partial w(x,t)}{\partial x}\right]-m_r r_r^2\frac{\partial^2 \phi(x,t)}{\partial t^2}+P_a\phi(x,t)=0 \tag{2}$$

Moreover, $\bar{p}(x,t)$ are expressed as:

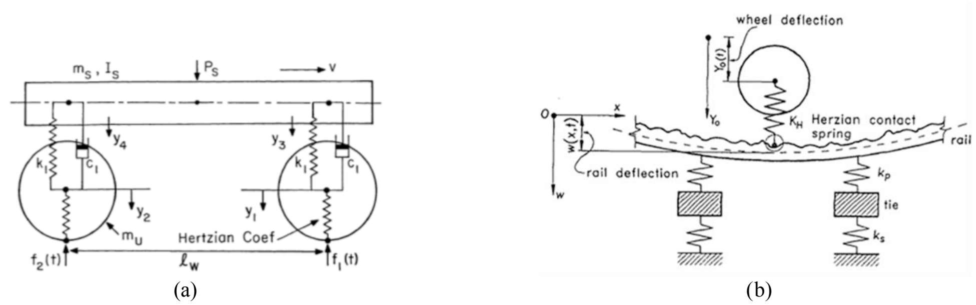
$$\bar{p}(x,t)=\sum_{i=1}^{N} f_i(t)\delta(x-il_p)+P(t)\delta(x-vt) \tag{3}$$

The wheelset model in this modelling consists of a four-degree of freedom, which includes of one bogie with two axles, rail and track. The wheelset model uses the unsprung masses (m_u) and the sideframe mass (m_s, I_s) to calculate the action on a rail through the primary suspension (k_1, c_1) as shown in Fig. 4(a). The components of vehicles are demonstrated as a spring load by using the Hertzian contact model. Moreover, the equations of motion in this model adopt the principles of Newton's law and beam vibration theory. The integration between wheelset and track equations can be calculated by the non-linear Hertzian wheel-rail interaction model as illustrated in Fig 4 (b). The D-Track model has been benchmarked by Kaewunruen and Remennikov (2006; 2016) in order to assess the accuracy and verify the precision of numerical results. D-Track is thus adopted for this study. The impact simulations at a rail joint (10 mm deep) will be used to demonstrate the effect of dynamic material properties on track components (Kaewunruen et al., 2015b; Kaewunruen and Chiengson, 2018).



(a) (b)

Fig. 3. Free-body diagram of ballasted track: (a) forces on the rail; (b) force on the sleeper.



(a) (b)

Fig. 4. Free-body diagram of a vehicle-track model: (a) wheelset; (b) Herzian wheel-rail contact.

The motion of wheelset system can calculate as the following equations where the reaction force on the two wheels are $\{f_1(t)\}\ and\ \{f_2(t)\}$:

$$\{f(t)\} = [M]\{\ddot{Y}(t)\} + [C]\{\dot{Y}(t)\} + [K]\{Y(t)\} \tag{4}$$

$$[M] = \begin{bmatrix} m_u & 0 & 0 & 0 \\ 0 & m_u & 0 & 0 \\ 0 & 0 & m_s/2 & m_s/2 \\ 0 & 0 & I_s/I_w & -I_s/I_w \end{bmatrix} \tag{5}$$

$$[C] = \begin{bmatrix} c_1 & 0 & -c_1 & 0 \\ 0 & c_1 & 0 & -c_1 \\ -c_1 & -c_1 & c_1 & c_1 \\ -c_1 I_w/2 & c_1 I_w/2 & c_1 I_w/2 & -c_1 I_w/2 \end{bmatrix} \tag{6}$$

$$[K] = \begin{bmatrix} k_1 & 0 & -k_1 & 0 \\ 0 & k_1 & 0 & -k_1 \\ -k_1 & -k_1 & k_1 & k_1 \\ -k_1 I_w/2 & k_1 I_w/2 & k_1 I_w/2 & -k_1 I_w/2 \end{bmatrix} \tag{7}$$

It can be noted that m_u is the unsprung mass; m_s is the side frame mass; I_s is the moment of inertia of side frame mass; I_w is the distance between axle, and $\boldsymbol{k_1}, \boldsymbol{c_1}$ are the stiffness and damping of primary suspension.

3. Dynamic vs static material properties

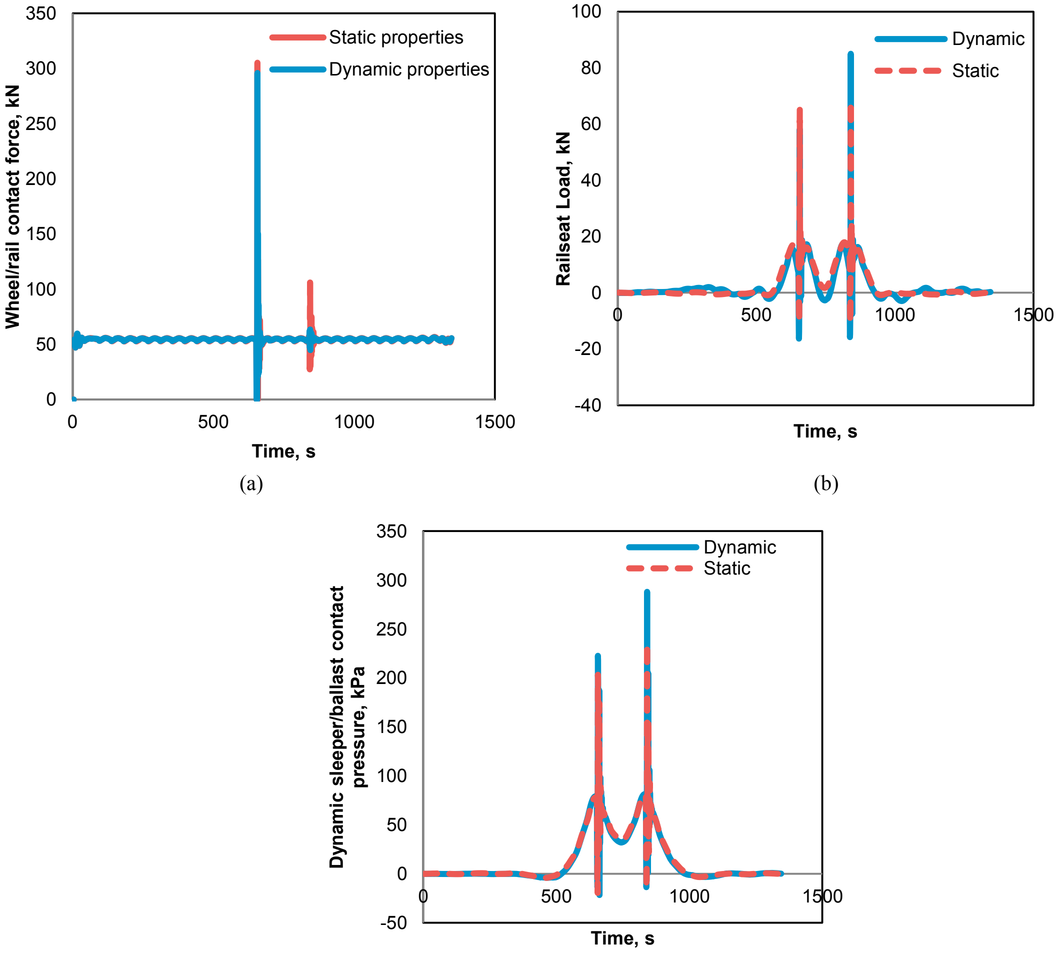
A train generally imposes dynamic loads to the track systems when a train is travelling over a certain level of track surface profile. As the dynamic modulus of elasticity of rail steel does not change much under dynamic loads, the dynamic modulus of elasticity is kept identical to the static modulus of elasticity for rail in this study. On the other hand, the rail pads play an important role in vibration attenuation in railway tracks. HDPE is a type of commonly used rail pads for ballasted rail tracks. According to the standard, the static stiffness of rail pads is around 200-300 kN/mm. When it is tested under dynamic impact loads at resonance, the dynamic stiffness of rail pads can be more than 2-3 times of static stiffness (Kaewunruen and Remennikov, 2008; 2010). In this study, the static stiffness of rail pads is chosen for 200 kN/mm, and the dynamic stiffness is chosen for 500 kN/mm. The dynamic modulus of elasticity of concrete structures will increase with strain rate. The CEB (Comité Euro-international du Béton, 1988) recommends an equation for determining the dynamic modulus of elasticity of concrete:

$$E_d / E_s = (\dot{\varepsilon} / \dot{\varepsilon}_s)^{0.026} \tag{8}$$

Since the damping of ballast is significant, the dynamic ballast stiffness remains relatively similar to the static stiffness (Indraratna et al., 2011; Kaewunruen et al., 2018; Li et al., 2019).

4. Results and discussions

The numerical simulations using a finite element approach (for a track system) and multi-body dynamics (for a train) have been carried out. The analytical model (as shown in Equations 1-7) adopts a passenger train wagon (Manchester type, 11.25 tone axle load) with wheel radius of 0.46m and Hertzian spring constant of 0.87 x 10^{11} N/m$^{3/2}$. When the train is operated at 100 km/h, the dynamic wheel/rail contact forces, railseat loads, and sleeper/ballast pressure can be seen in Fig. 5. These responses are incurred at the rail joint that induces the wheel fly and detrimental impact load conditions. It is clear that, under the dynamic loading condition, the dynamic load actions such as railseat loads and sleeper/ballast pressure are noticeably influenced by the dynamic material properties, despite the fact that the wheel/rail contact load may be rather identical. The adoption of static material properties can actually underestimate the dynamic railseat load and sleeper/ballast pressure by 25% and 22%, respectively. Although certain components may be able to withstand these load actions, the service lives are clearly reduced and premature damages of track components (i.e. sleepers, fasteners, ballast, subballast and ground formation) can be observed in a faster fashion. Note that the maximum wheel forces are about 5.5 times of the static axle load. Considering the railseat load, using static properties yields the amplification factor of 3.5 while the dynamic properties further enhance the factor up to 4.4. The dynamic amplification factors for sleeper/ballast pressure can be observed to be up to 3.0 for static properties and to 3.7 for dynamic properties. The dominant effect of the dynamic material properties can be clearly noticeable. On this ground, the dynamic material properties should be obtained as part of essential testing criteria so that the dynamic load actions can be appropriately determined. It is important to note that the additional effect of these dynamic material properties is additional to the effect of dynamic amplification, which is load-frequency-dependent. The dynamic amplification has been considered in the results by considering the inertia effects. The dynamic material properties have further enhanced additional effect (such as strain rate, frequency dependent).



(a) (b)

(c)

Fig. 5. Dynamic load actions: (a) wheel/rail contact force; (b) railseat load; (c) sleeper/ballast pressure.

Fig. 6 demonstrates the effect of the dynamic material properties on the structural responses of the track components. It is clear that the adoption of dynamic material properties will enhance the rail stresses but deteriorate the sleeper stresses. The dynamic amplification factors for the sleeper bending are 3.6 when using static properties and 4.8 when using dynamic properties. This implies that if engineers make use of static material properties obtained from standard test methods, they will overdesign the rails, whilst underdesign the rail sleepers by 24% and 33%, respectively. Note that the multi-body simulations have been conducted at 100 km/h over a dipped rail joint, creating impact loading conditions. In normal operations, the dynamic loading can either be milder or more severe, depending on the track maintenance levels. On this ground, the use of static material properties can no longer be considered as a conservative approach or conservative values as commonly accepted in industry. It is thus very important that the engineers and designers consider the importance of 'dynamics' in their analysis and design of railway track systems, which will enable safer and more reliable infrastructures.

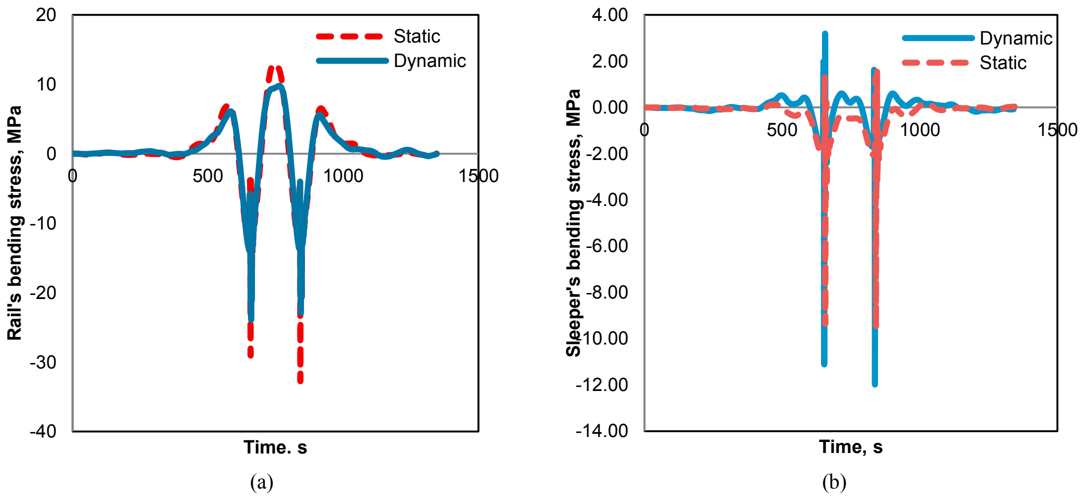


Fig. 6. Dynamic responses: (a) rail bending stress; (b) sleeper bending stress.

5. Conclusion

In Europe, there is no unified design method for railway track components. Current European standards (e.g. EN 13230) simply defines test methods (static, cyclic and high-cycle fatigue) based on static three-point load test of specimens over a simple support condition (roller-roller). This is clear evidence showing that most design concepts are still based on the analysis of static and quasi-static stresses resulting from static material properties obtained from simple static codified test methods. Such the design philosophy cannot address the issue of premature cracking of track components, which were detected in railway tracks. In fact, the scientific origin of the current standards for testing and design for track components is somewhat questionable. Accordingly, this paper addresses such important issues since the characteristics of actual forces applied to the railway tracks are rather dynamic. This paper highlights the incorporation of dynamic resistance (derived from dynamic behaviors of materials and component) as the essential part of dynamic analyses of railway tracks. The paper presents new findings demonstrating the effect of dynamic material properties on load action and structural responses. These are the key catalysts, which prove the need to shift from static to dynamic considerations in design and testing for track components. It is clear that by using dynamic design method, more rational, cost-effective railway track components can be appropriately designed and manufactured. This novel understanding will help track engineers to re-develop better and more rational engineering standards for design and testing of track infrastructure assets more effectively.

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