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6th European Conference on Computational Mechanics (ECCM 6)
7th European Conference on Computational Fluid Dynamics (ECFD 7)
11 – 15 June 2018, Glasgow, UK

EFFECT OF EXTREME CLIMATE ON WHEEL-RAIL INTERACTION OVER RAIL SQUATS

7TH EUROPEAN CONFERENCE ON COMPUTATIONAL FLUID DYNAMICS (ECFD 7)

(ECCM –ECFD 2018 CONFERENCE)

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Key words: Rail Squats, Extreme Climate, Track loading, Wheel-Rail, Dynamic Interaction.

Abstract. Globally, modern ballasted railway tracks have become the most efficient and effective type of infrastructure for railway industry operating below 250 km/h of train speed for over centuries. The ballasted tracks have been tailored and optimised over and over; and they are often used in light rail tracks, metro networks, suburban rail network and intercity rail lines since they are relatively inexpensive and quite superior in terms of maintainability and constructability. Rail squats are defined by the growth of any cracks that have grown longitudinally through the rail subsurface and some of the cracks propagating to the bottom of rails transversely have branched from initial longitudinal cracks with a depression of rail surface. The rail defects are commonly referred to as ‘squats’ when they were initiated from damage caused by rolling contact fatigue, and as ‘studs’ when they were associated with white etching layer caused by the transform from pearlitic steel due to friction heat generated by wheel sliding or excessive traction. Such rail surface defect induces wheel/rail impact and large amplitude vibration of track structure and poor ride quality. In Australia, Europe and Japan, rail squats/studs have occasionally turned into broken rails. The root cause and preventive solution to this defect are still under investigation from the fracture mechanical and material scientific point of view. The dynamic interactions between vehicle and track impose vibrations and acoustic radiations and become moving vibro-acoustic sources along the railway corridor. Especially when there is imperfection of either wheel or rail, the dynamic amplification of loading conditions and reflected vibration effects on infrastructure and rolling stocks is significantly higher. This study is the world first to evaluate the coupling dynamic vehicle-track interactions over rail squat defects considering the effect of extreme temperatures. The vehicle model has adopted multi degrees of freedom coupling with a discrete supported track model using Herzian contact theory. This paper highlights the dynamic load redistribution experienced by railway track components due to wheel/rail contacts. The insight into the dynamic amplification and track load distribution will enable predictive track maintenance and risk-based track inspection planning to enhance public safety and reduce unplanned maintenance costs.

1 INTRODUCTION

In global best practices, rail surface defects have been a critical safety concern and key maintenance priority of railway infrastructure owners and maintainers who operate either low, moderate or high speed trains including passenger suburban, metro, urban, mixed-traffic and freight rail systems. Rail surface defects can cause high risks and significant consequences such as train derailments, rail breaks, component failures, and so on. It has been estimated that the cost of rail renewal program (rail replacement) due to rail squats and studs has become a significant portion of the whole track maintenance cost, reportedly in Australia, Asia, and European countries e.g. Austria, Japan, Germany and France [1-6]. The rail squats and studs are typically classified as the growth of any cracks that has grown longitudinally through the subsurface due to repeated trainloads, which means both of squats and studs are typical rolling contact fatigue (RCF) defects but the mechanism of initiating cracks of those two defects are different. Also, the subsurface horizontal crack later results in a depression of rail surface sometimes called ‘dark spot’ [7] ‘Squats’ are defined as the crack initiated from rolling contact fatigue damage layer, and as ‘studs’ are defined as the crack initiated from white etching layer (WEL) due to wheel slides or excessive tractive effort [8-10].

In many countries, the rail defect has become a widespread problem in both passenger and freight rail networks. The rail squat/stud defects could be observed in all types of track structures, in all arrays of track geometries and gradients, and in all possible operational traffics as shown in Fig. 1. One exception where almost no squat could be observed is inside the dry tunnels [11]. However, recent collaborative research shows some rail studs appear in London Underground due to wheel traction issues [12]. The cracks of studs initiate in the WEL and grow horizontally at the depth of 3-6mm below the rail surface. The rail surface becomes depressed, giving rise to vibration impact and noise. The cracks of squats propagate from surface cracks initiated by rolling contact fatigue (RCF) and similarly grow at the depth of 3-6mm below the rail surface. Squats are often found in tangent tracks and in high rails of moderate radius curves, in particular squats caused in high rails of moderate radius curves are called gauge corner cracks, and in turnouts with vertical, unground rails. Accordingly, a number of research and development projects have been initiated around the world in order to investigate the root causes and feasible economical solutions to rail squat problem, which will have a significant impact on rail asset management strategy [13-14].

The rail squat/stud problem has largely been noticed when the ride quality of the passenger trains exceeds acceptable limits [13] Excessive noise and vibration have later increased complaints against rail operators. Most importantly, the impact forces due to the wheel/rail interaction have undermined the structural integrity and stability of track components [15-21]. In Japan and Europe, frequently the rail squats have transversely grown and turned into the broken rails, which could derail the trains and potentially result in a catastrophe [2]. An infamous example of the tragedy was the Hatfield accident in the UK. So far, there has no research into the effect of extreme climate variances on the squats and the wheel-rail interaction over the squat defects [22-26]. On this ground, this study is the world first to highlight such the critical imminent issue in railway industry.

a) WEL-related stud (multiple squats)

b) RCF-related squat (single squats)

Figure 1: Rail squats in railway tracks based on their initiation types

At present, with heavier and faster trains, the dynamic load transferring on to track and its components such rails, sleepers, ballast and formations is higher and amplified by the traffic speeds and rail surface defects. These dynamic impact loading conditions often damage the track support and cause initial differential settlement and plastic deformation. The track issue does not stop here. Such the plastic deformation and initial differential settlement further form and couple with short wavelength defects (if any) to exponentially aggravate the dynamic loading condition [27-29]. Therefore, it is very important to understand the coupled dynamic effect of rail defects on the rail infrastructure so that rail operators and maintainers can develop suitable cost-effective strategies for operations and maintenance. An example of strategies is to carry out preventative track maintenance (such as re-tamping, re-grinding and ballast cleaning when early sign of damage is inspected). In many regional railways (such as freight services), speed restrictions have been adopted to delay the maintenance regime when the rail defects exist. Note that these strategies are often called 'Base Operating Conditions (BOCs)' in railway industry practices. The BOCs have been developed from internal R&D activities and extensive empirical experience in the rail industry over the centuries.

The detailed modelling of rail track dynamic and wheel-rail interaction was studied in 1992 while D-track program for dynamic simulation also have been created by Cai for his PhD's thesis of Queen's University in Canada [30]. Afterward, Iwnick has done a benchmark, which was called Manchester Benchmarks in 1998 [31]. In 2005; Steffens [32] has adopted the parameter of Manchester Benchmarks to compare performance of vary dynamic simulation programs and also developed the user-interface of D-track. On the other hand, D-track had still an issue of lower result than others and then the owner has revised the program after this benchmark. Subsequently, Leong has done the Benchmark II with the revised version of D-Track in 2007 [28].

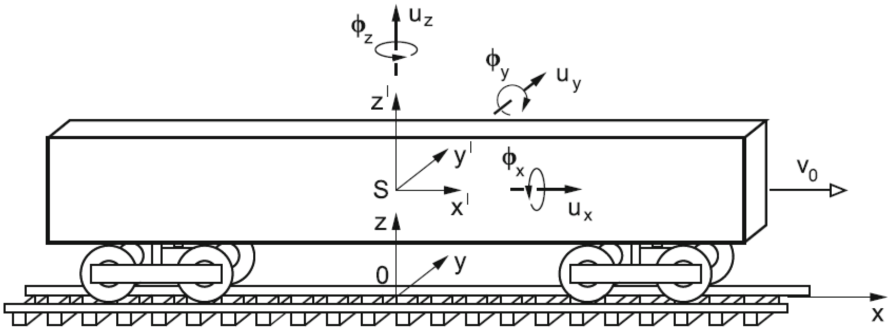
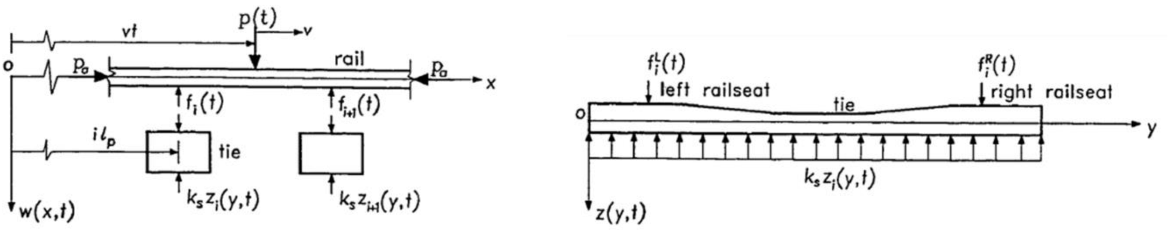


Figure 2: Coupling vehicle-track model

In this study, the dynamic simulation concept by Cai [30] has been adopted as seen in Figure 2 since the track model has included Timoshenko beam theory for rail and sleepers, which enable a more accurate behaviours of tracks. Note that rail cross section and sleeper pre-stressing are among the key influences on shear and rotational rigidities of Timoshenko beam behaviors in numerical modelling of railway tracks [33, 34]. The irregularity of wheel and rail will cause higher dynamic impact force that the design condition level or serviceability limit state. The exceeing magnitude of the force generated by wheel and rail irregularities will damage track components and impair ride quality [28]. This study thus is the first to present the wheel-rail dynamic forces over both rail squats exposed to extreme temperature variances. The scope of this study will be focused on ballasted railway tracks supporting a conventional passenger metro-style trains (Manchester Model). The track model will be based on a standard rail gauge (1.435m). The outcome of this study will help railway infrastructure managers improve the methods for monitoring, maintaining, adapting and retrofitting railway tracks subjected to imminent threats from climate change.

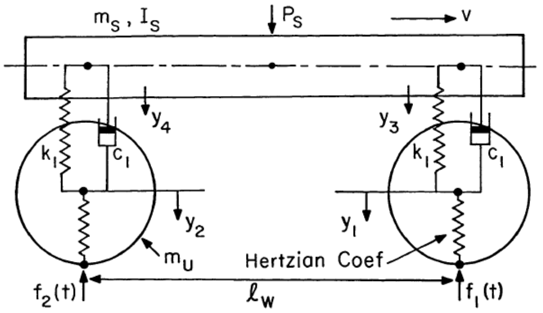
2 COUPLING VEHICLE-TRACK MODELLING

The track model (D-Track) is simulated on Winkler foundation principal which only cross-section of track dynamic responses is considered symmetrically. Rail and sleeper were represented on elastic beam of either the Timoshenko type. The sleepers also support the rail as discrete rigid masses. Free-body diagram of track model are shown in the Figure 3(a) where *P(t)* is a moving wheel force at constant speed (v). Figure 3 (b) represents the force from rail to sleeper through the rail seat (i^{th}) and reaction force $k_s z_i(y,t)$ per unit length.

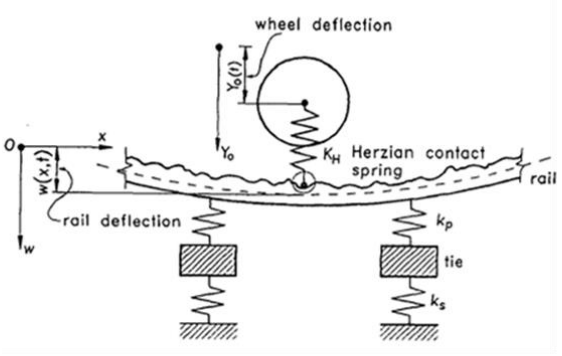


a) forces on the rail b) force on the sleeper

Figure 3: Free-body diagram of track model [30]



a) wheelset model



b) Herzian wheel-rail contact

Figure 4: Free-body diagram of vehicle-track model [30]

The wheelset model in this modelling consists of a four-degree of freedom which include of one bogie with two-axle, rail and track. The wheelset model uses the unsprung masses (m_u) and the sideframe mass (m_s, I_s) to calculate on one rail through the primary suspension (k_1, c_1) as shown in Figure 4(a). The components of vehicles are demonstrated as a spring load by using Hertzian contact model. Moreover, the equations of motion in this model used the principles of Newton's law and beam vibration to apply. Integration between wheelset and track equations can be calculated by the non-linear Hertzian wheel-rail interaction model as illustrated in Figure 4 (b). The D-Track model has been benchmarked by [28] in order to assess the accuracy and verify the precision of numerical results. D-Track is thus adopted for this study. The track structure used for analysis is based on UIC 60kg/m rail, HDPE rail pads (stiff), prestressed concrete sleepers with 600mm spacing, ballast with 300mm depth, and medium stiffness soil (compacted soil).

Rail squat profile irregularity can be esimated as inverse half-sinusoidal curve as shown in Figure 5. The dimension of moderate rail squats is around 50mm in length and 0.1mm indentation [5]. This rail squat dimension will be used for the track loading simulations. The train speed of 60 km/h will be used for benchmarking as it is a median speed of metro trains. Note that the longtitudinal force due to temperature can be obtained from F = AE x ΔT x 1.17 x 10^{-5} where F is the thermal force, A is the rail cross section area, E is the Young's modulus of rail, and is the rail temperature difference with respect to neutral temperature (or stress-free temperature). As the sensitivity of climate change is poised toward warmer temperature [35-37], the emplasis of this study is thus placed on the effect of extreme heat on the railway tracks.

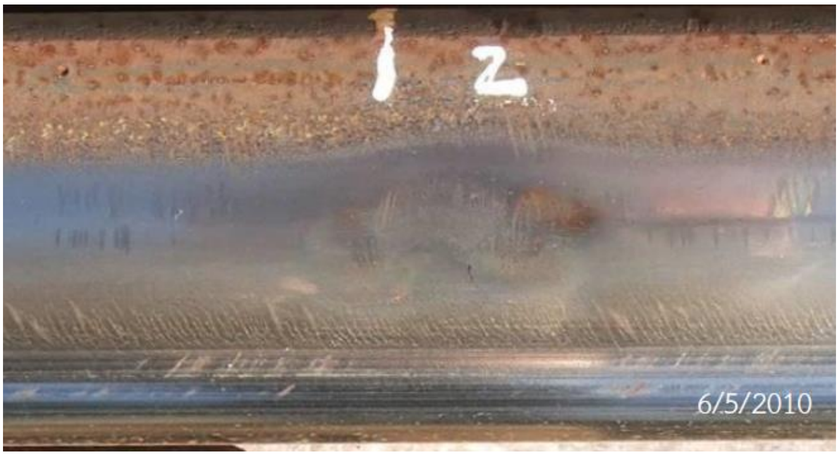


Figure 5: Moderate rail squat

3 RESULTS AND DISCUSSION

The numerical simulations have been carried out using 14.5t axle-load Manchester passenger train with wheel radius of 0.46m and Hertzian spring constant of 0.734 x 10^{11} N/$m^{3/2}$. The dynamic wheel/rail contact forces can be seen in Figure 6. It can be seen that moderate rail squats can induce dynamic impact loading up from 2 to 2.5 times of the static wheel load. This implies that more dynamic load will be transferred to fastening systems, sleepers, and ballast support.

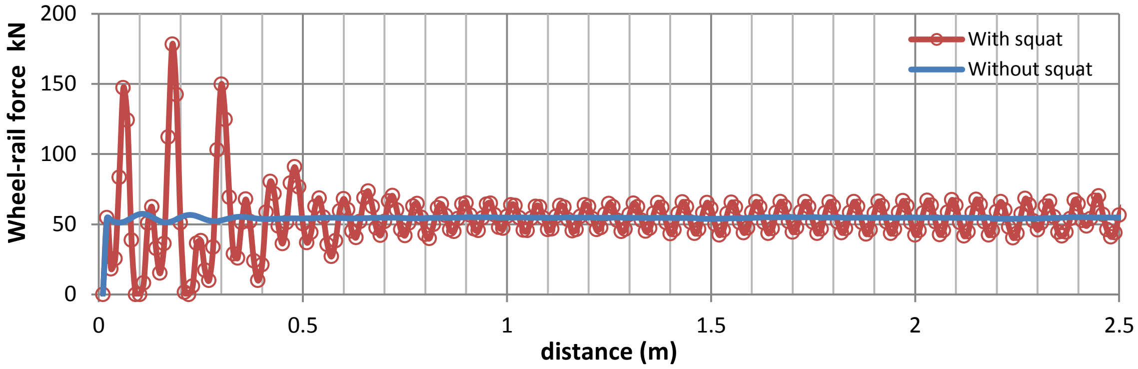


Figure 6: Dynamic wheel-rail force at the rail defect

3.1 Thermal effect on wheel-rail contact forces

Figure 7 shows the effect of extreme temperature on the wheel-rail contact forces. It is clear that the global extreme temperatures have negligible effects (less than 2% difference) on the wheel-rail contact forces.

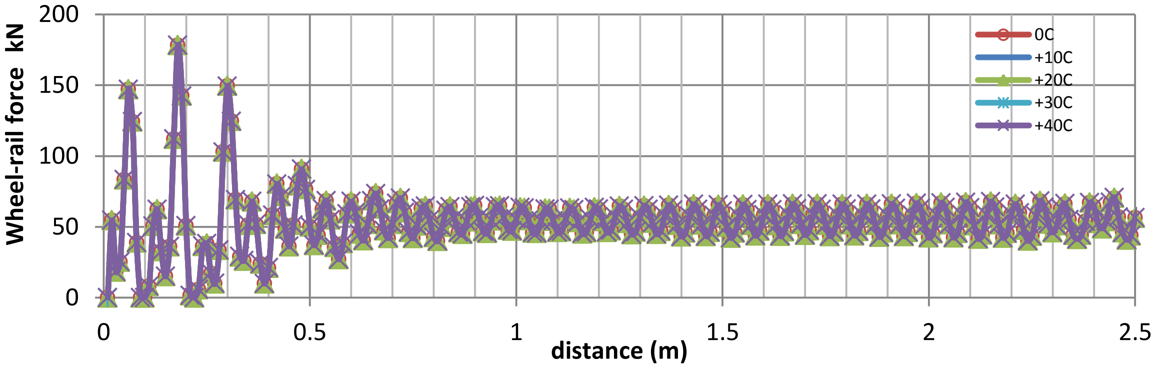


Figure 7: Thermal effect on dynamic wheel-rail force at the rail defect

3.2 Thermal effect of railseat forces

It is very clear from Figure 8 that the extreme temperature plays a significant role on the railseat forces redistributed from the wheel-rail forces at the top of running rails. The results exhibit that extreme heat will reduce downward force but will increase uplift force.

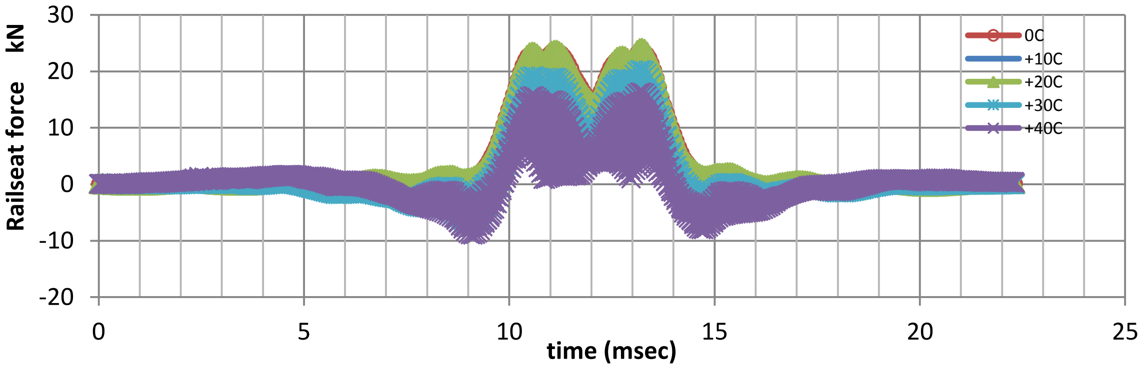


Figure 8: Thermal effect on dynamic railseat force

3.3 Thermal effect of sleeper-ballast pressure

Figure 9 demonstrates that the extreme heat does not much affect the sleeper-ballast pressures. The increase in heat tends to reduce the ballast pressure but a negligible rate (less than 2% on average). This is because the dynamic track load has been filtered by rail pads and sleepers, prior to transferring onto ballast. As such, quasi-static behavior of ballast pressure can be observed. The temperature that excites rail and sleeper vibrations does not induce observable dynamic content onto the ballast.

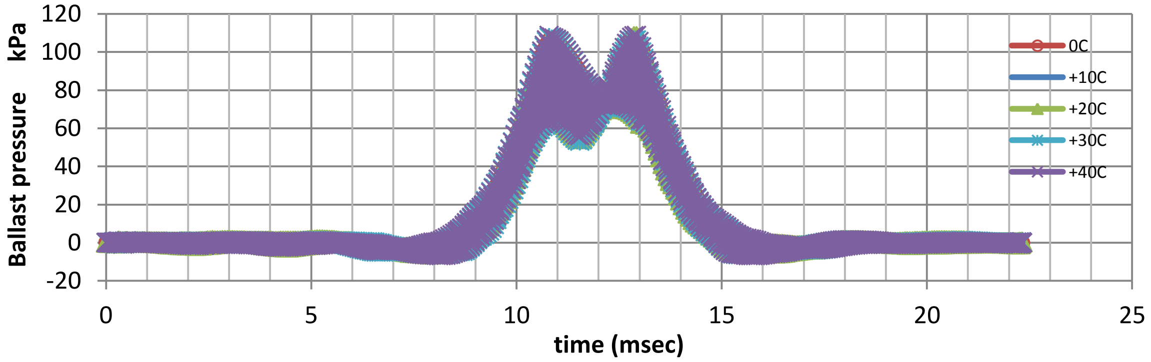


Figure 8: Thermal effect on ballast pressure

4 CONCLUSION

This paper presents the dynamic interactions between vehicle and track, which can cause vibrations and acoustic radiations to railway neighbourhood. The effects of extreme temperature on track loading conditions and load distribution have been highlighted. It is the first to evaluate the coupling dynamic vehicle-track interactions over rail defects under thermal variances. The results show that the thermal effect plays a key role on magnifying the rail/sleeper contact forces (railseat loads). However, such effect does not play a significant role for wheel-rail forces. Due to the loss of dynamic content, the ballast pressure remains static and quasi-static. The insight implies that sleepers will experience excessive dynamic uplift loads and the uplift can deteriorate and weaken ballast-sleeper friction and lateral track stiffness. More results on parametric effects of rail squats as well as the effect of adjacent track movement on track load distribution will be investigated in the near future. This understanding will help track engineers to manage and operate infrastructure assets more efficiently and effectively under climate variances. The insight is imperative to improve climate change adaptation strategy for rail infrastructure.

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