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Review of factors affecting stress-free temperature in the continuous welded rail track

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Abstract

Railways have a significant role to play in sustainable transportation. Rail travel is currently the only mode of rapid, large-scale, long-distance transport for both freight and passengers that offers zero carbon dioxide emissions at the point of use. However, our railway infrastructure needs to be more robust and resilient to the combined effects of climate change, traffic growth and increases in vehicle loads and speed. Rail buckling is of increasing concern as environmental temperatures rise and traffic loads, speed and intensity of use increase. A key indicator and control of the propensity for track buckling is the stress-free temperature of the rails. However, determining the actual stress-free temperature of a given section of track is challenging. Knowledge of the factors affecting stress-free temperature will help in the identification of vulnerable sections of track and the development of an appropriate maintenance regime. This paper reviews and discusses the factors affecting stress-free temperature in ballasted railway track with continuous welded rails (CWR).

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Keywords: Stress-free temperature; Continuous welded rail; Ballasted railway track; Climate change

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1. Introduction

Railways form an indispensable part of our social and economic infrastructure. They play a vital role in freight and passenger movement across the UK, connecting people and communities [1]. They also have an essential part to play in reducing traffic congestion, pollution and carbon emissions [2,3]. Rail travel is perhaps the only form of mass, rapid, long-distance transport realistically offering zero carbon dioxide emissions (on electrified lines) at the point of use. Further, railways utilise land more efficiently in terms of the number of people moved per hour per metre width than motorways, while offering a better travel experience in terms of comfort, reliability and safety [4]. A net-zero carbon transport strategy will require significant modal shift from air and road to rail. Thus maintaining

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and improving the railway infrastructure is at the core of any realistic sustainable transport policy, now and in the future.

Addressing the potential impacts of climate change is an essential aspect of current and future railway track management. Climate change increases the risk of heatwaves, floods and droughts [5–7]. It is also likely to result in higher maximum summer temperatures and a greater range in annual temperature [8]. Overall weather patterns will become more extreme, causing more disruption on the railway network [5,9–11]. Rail buckles can cause train derailments, which endanger life and cause damage that is costly to repair. High temperatures and heatwaves may cause overheating in tunnels, signal failures and bridge deformation [12]. Wetter winters will cause more floods, potentially damaging the track bed through ballast washout, damage to embankments and failure of drainage systems [4,12]. Low temperatures can result in increased numbers of rail breaks [13]. However, even the high temperatures that could potentially be reached with climate change are not on their own sufficient to cause buckles or breaks, for which at least one more factor is required; usually poor track condition (leading, for example, to a reduced resistance to lateral movement) or inappropriate pre-stressing of the rail [13,14]

To mitigate future risks, the resilience of the railway infrastructure to expected climate change needs to be improved. Continued safe operation of railways subjected to increasingly wide ranges of temperature, rainfall and wind will be a challenge. The potential for continuous welded rail (CWR) to buckle in extreme heat is a well-known example. In recent decades, much work has been done to improve our understanding and ability to manage rail stress, yet it continues to be a concern for many railway companies worldwide.

Steel rail sections were traditionally connected by bolted joints to form jointed rail track. For decades, bolted rail joints represented a major driver of track maintenance. The discontinuity of the rail surface at the joints between each bolted section produces high dynamic impact loads on the rail ends, undesirable train vibrations and increased stresses on the ballast and subgrade. This accelerates rail failure, sleeper wear and attrition of the ballast at the joint [15]. Continuous welded rail (CWR) was therefore introduced to eliminate the joints. CWR brought various advantages such as reduced wear on rolling stock, less damage to the subgrade, extended rail life and lower maintenance cost. Welding long sections of the rails together eliminates most of the joints, but leads to the potential for the build-up of high compressive stresses in the rails if the temperature rises.

Rails are made of steel, and tend to expand longitudinally when the surrounding temperature increases and contract when temperatures decrease. The change in length of the rail depends on the coefficient of thermal expansion, α, the length of rail L and the temperature rise ΔT (1):

$$\Delta L = \alpha L \Delta T \tag{1}$$

The coefficient of thermal expansion of rail steel is usually taken as $1.15 \times 10^{-5}\,^{\circ}\mathrm{C}^{-1}$ [16](see Fig. 1). .

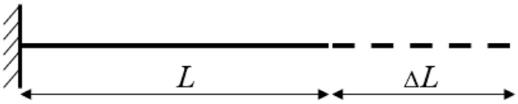

Fig. 1. Rail thermal expansion, fixed at one end.

Rearranging Eq. (1) in terms of the axial strain (ε), defined as the change in length (ΔL) divided by the initial length (L), gives:

$$e = \alpha \Delta T \tag{2}$$

In the case of CWR, longitudinal movement is restrained at both ends. Thus variations in temperature will generate an internal force (P), producing an axial stress (σ) in the rail. Using the definition of Young's modulus (E $= \frac{\sigma}{\varepsilon}$, where $\sigma = P/A$), the force, P, is calculated from the thermal strain prevented as:

$$P = EA\alpha\Delta T \tag{3}$$

Where, E is the Young's modulus of the rail steel, A is the cross-sectional area of the rail and ΔT is the rise in temperature above that at which the rail is stress-free.

A large temperature increase can generate high axial stresses in the rail, potentially leading to track buckling as illustrated in Fig. 2. A track buckle can cause a significant safety incident and requires the immediate closure of the affected section of the railway, resulting in costly delays and repairs.

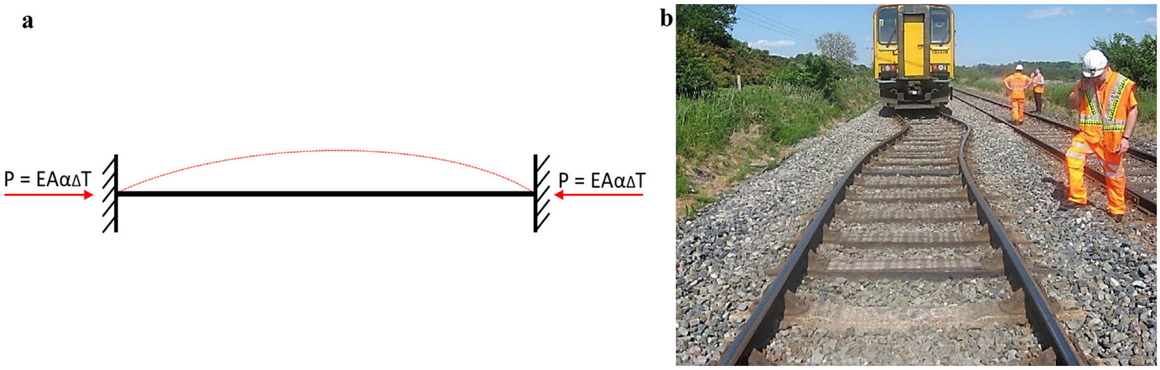

Fig. 2. (a) schematic rail thermal expansion, fixed on both ends; (b) buckled railway track due to thermal expansion.

The stability of CWR track at higher environmental conditions can be improved by appropriate management of rail stresses. In particular, the rails are laid in tension so that they only start to develop compressive stress above a certain temperature known as the stress-free temperature. Currently, the standard value for the stress-free temperature in the United Kingdom is 27 °C [17]. However, with trafficking and differential movement of the rails vertically, laterally, and potentially longitudinally relative to sleepers, it is known that the stress-free temperature may vary both over time and with distance along the track [18,19]. With climate change, the range of temperatures experienced by the track over an annual cycle is likely to increase; hence rail temperatures, including the stress-free temperature, may need to be managed differently to prevent buckling in the future. This could also improve the resilience of the railway network, enabling operation of faster, heavier and more frequent trains and reducing maintenance requirements and delays.

In this paper, factors affecting the changes in stress-free temperature along CWR track are reviewed. Knowing and being able to predict how the stress-free temperature can vary over time and along the track will help railway infrastructure owners and operators move from reactive or fixed-period preventative maintenance to a more targeted predictive approach. The findings of this study will inform future monitoring and research needs for achievement of this aim.

2. Stress-free temperature

The stress-free temperature plays a vital role in CWR track management. As its temperature rises, the rail will tend to expand. However, a railway track with CWR is designed to constrain thermal expansion or contraction of the rail [20], leading to the development of internal stresses. While the rail temperature remains below the stress-free temperature, the rail will be in tension; however, as the temperature rises above the stress-free temperature, internal compressive stresses begin to develop. Large internal tensile or compressive forces in CWR at temperatures significantly below or above the stress-free temperature can lead to rail breaks or track buckles respectively, when the internal forces are sufficient to overcome either the local tensile strength of the rail or the lateral restraint to buckling provided by the track system [17,21]. Rail breakage in tension is usually associated with a manufacturing fault (such as a tache ovale or a slag inclusion) or stress concentrations associated with cracking. The risk of rail breakage in cold weather means that laying the rails with a higher tension to increase the stress-free temperature is not necessarily a solution to the problem if there will be higher summer temperatures or extreme temperature fluctuations. With climate change, the range of temperature to which rails are subjected over the course of a year is likely to increase, hence it is important to manage the rail temperature and the stress-free temperature to prevent buckling.

The stress-free temperature is used to determine critical rail temperature values for CWR track [22]. The critical rail temperature is the temperature of CWR at which measures to protect traffic must be taken. It depends on the actual stress-free temperature, resistance to lateral movement offered by the ballast (ballast condition), track curvature and sleeper spacing. If the track has been disturbed, is not fully ballasted, or is not correctly supported or stressed, the critical rail temperature will be decreased [23]. Reducing the speed of trains reduces vehicle-induced lateral loads and mitigates the consequences of a derailment [24,25]. Implementing speed limits causes delays and cancellations on the railway network [13].

Although rails are laid to a uniform stress-free temperature of 27 °C, changes occur over time and along the length of the rail as small differences in permanent settlement and longitudinal rail creep develops due to trafficking. It might be thought that the actual stress-free temperature of the rails could be measured periodically and re-stressing carried out from time to time as required. Unfortunately, stress-free temperature measurement techniques are generally limited in their utility and difficult to deploy [26].

Stress-free temperature determination methods can be divided into classes based on (a) ultrasonic, (b) magnetic, (c) strain gauge, and (d) load–deflection measurement techniques. Residual stresses (which are difficult to separate from applied stresses) and the metallurgy of the rail significantly affect measurements using on ultrasonic and magnetic techniques. Strain gauges require a power supply, and thus are best suited to monitoring the stress-free temperature at specific locations only. The load–deflection method requires a reasonable length of rail to be unclipped, and can only be used when the rail temperature is lower than the stress-free temperature as it depends on measuring tension in the rail [21].

In the United Kingdom, the stress-free temperature is usually measured using Vertical Rail Stiffness Equipment (VERSE). An upward vertical force of 10 kN is applied to the unclipped 30 m section of the rail via hydraulic rams, and transducers measure both the applied pressure and the vertical displacement of the rail [27]. The relation between them enables the stress-free temperature to be calculated. The main advantages of VERSE are that a semi-skilled operator can use it, the rail does not need to be cut (but does need to be unclipped), and it is not especially time-consuming (the whole process takes around one hour). Stress-free temperature is measured in this way only in targeted problem areas of the track, owing to the direct and indirect (resulting from the temporary closure of revenue-earning lines) costs involved. Knowledge of the factors affecting the change in stress-free temperature along the track and over time would help in calculating the critical rail temperature more precisely, decreasing the risk of rail buckles and breaks as well as unnecessary speed restrictions. Changes in the stress-free temperature of CWR over time and along the length of the track would be expected to depend on (a) temperature changes; (b) differential settlements; (c) acceleration and braking forces; and (d) longitudinal restraints to rail movement, and variations thereof [16,17,21,22,28]. These factors are discussed in more detail in Section 3.

3. Factors affecting stress-free temperature

It is obvious that inadequate stress restoration following maintenance procedures will affect the stress-free temperature along the track. Everything that involves disturbance to the rails – rail replacement, the track being slewed or lifted, and track being re-sleepered or re-laid – will cause the stress-free temperature to deviate from its original installation value [22]. This paper will focus on factors whose occurrence and effect cannot be so easily predicted or avoided. The factors permanently affecting stress-free temperature can be considered in two groups. Factors such as differential resilient or elastic settlement, variations in actual rail temperature, and acceleration and braking forces would all have to act in association with variations in clamping force or stick–slip behaviour of the fasteners to permanently affect the rail stresses. However, differential plastic track settlement and the accumulation of lateral misalignment along the track is capable of permanently altering the stresses in the rail, and hence the stress-free temperature, even if the clamping forces and clip behaviour are all identical.

3.1. Longitudinal restraints to rail movement

Resistance to the longitudinal movement of the rail is provided by the clamping forces of the rail fastening and the restraining effect of the ballast. Longitudinal movement of the sleepers in the ballast or of the rails relative to the sleepers may alter the original stress-free temperature. The degree to which it will affect the stress-free temperature depends on the creep resistance of the fastenings and ballast conditions [16]. Poor condition of the fastenings or the ballast could reduce the longitudinal resistance, allowing the rail to move longitudinally. Undesired permanent longitudinal movement of the rail can affect the original stress-free temperature(see Fig. 3). .

Fig. 3. Rail fastenings and ballast provides longitudinal resistance.

3.2. Rail temperature change

Daily and seasonal variations in temperature influence the build-up of compressive and tensile forces in the rails. It is not only the variation in the ambient air temperature that affects the rail temperature; the location of the track may also have a significant impact on the development of longitudinal stresses in the rail. For example, a section of the track directly exposed to the sunlight will absorb much more solar energy than to a rail located in shadow, cutting or tunnel [29]. The rail colour and any coating may also have an influence on the rail temperature. A white reflective coating can decrease the rail temperature by up to 10 °C compared with an uncoated rail, reducing the tendency for undesired expansion [30–32]. Rails in transition zones between direct sunlight to shadow, or coated to uncoated rails, will experience differential maximum rail temperatures. If the overall rail geometry does not change and there is no slip at any of the clips, the stress-free temperature should not change. However, if there is slip at some clips but not others, and the amount of slip is different on cooling than on heating (owing, for example, to hysteretic slip–stick behaviour), the residual stress following multiple cycles of differential heating and cooling, and hence the stress-free temperature, could vary along the length of the rail.

3.3. Acceleration and braking forces

Longitudinal acceleration and braking forces generated by vehicles may result in local longitudinal rail movements (rail creep) and changes to the original stress-free temperature [16]. Rail creep can occur when thermal and dynamic forces exceed the longitudinal resistance to rail movement [26]. Changes in rail stress due to dynamic effects occur particularly on rising and falling gradients and in long continuous curves [16].

3.4. Differential track settlements

The original stress-free temperature of the rail may be disturbed as a result of the development of differential settlements along the track, which set up local variations in strain and hence internal stress (Fig. 4). This may be a particular issue at transition zones, for example from ballasted to slab track and onto or off under-line bridges [33].

Differential settlement along the track will result in an increase in rail tension because the length of the rail needs to increase, assuming that the track remains in contact with the ground. The increase in stress-free temperature associated with this increase in rail length and tension, assuming no slippage at rail clips, can be calculated for a sinusoidal deformed shape of given amplitude to wavelength ratio. This is shown in Fig. 5. If the track remains in contact with the ground, settlement would in theory increase the stress-free temperature. However, if the track

Fig. 4. Differential settlements in the trackbed, photograph courtesy of Graham Birch, Network Rail.

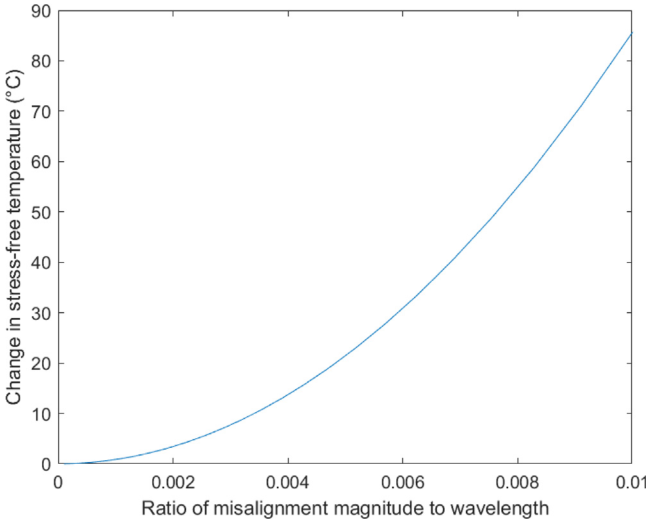

Fig. 5. Change in stress-free temperature against the ratio of misalignment magnitude to defect wavelength.

locally loses contact with the ground, resulting in some sleepers becoming unsupported or "hanging", substantial additional dynamic loads and rail stresses could result as the rail is pushed by the passing train into the gap created by the settlement.

4. Conclusion

The resilience of our railway infrastructure to the effects of climate change and traffic growth needs to be improved. In addition to the condition of the track, a key requirement for the management of CWR track is the stress-free temperature of the rail. This paper has presented an overview of the stress-free temperature and discussed the factors affecting its potential for variation along the track and over time. These include differential rail temperature changes, acceleration and braking forces, and differential track support stiffness, which - in combination with a variation in the degree of longitudinal restraint offered by the rail fasteners, can result in the redistribution of stress-free temperature along the track with trafficking or temperature cycling. A simple analysis of the effect of the strain associated with the development of permanent track settlements, which will change the stress-free temperature even if the longitudinal restraint to the rail is uniform, was also presented. Improved knowledge and understanding of these factors will help better identify vulnerable sections of track and designation of appropriate maintenance regimes. Further study will analyse the effect of variations in longitudinal restraint on the stress-free temperature distribution in the rail due to differential rail temperature change, acceleration and braking forces, and differential support stiffness and plastic settlement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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