XV

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I

CONGRESSO DE ENGENHARIA DE FACHADAS

TEMAS ESPECIAIS

INTELIGÊNCIA ARTIFICIAL
ENERGIA

Editores
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XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas

por Luís Simões da Silva, Paulo Vila Real, Filip Lubinković, Jorge Conde, Rohola Rahnavard, Luís Figueiredo Silva

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Prefácio

O XV Congresso de Construção Metálica e Mista e I Congresso de Engenharia de Fachadas representam um momento de grande relevância para o setor em Portugal, reunindo especialistas, investigadores e empresas num espaço comum de partilha de conhecimento. Nesta décima quinta edição, o Congresso de Construção Metálica e Mista reafirma a maturidade e solidez de um percurso iniciado há mais de duas décadas, consolidando-se como o principal evento técnico-científico nacional dedicado à construção metálica e mista. O crescimento contínuo do número de participantes, comunicações e empresas envolvidas testemunha o reconhecimento da sua importância e o papel que tem desempenhado na promoção da inovação, na disseminação prática do conhecimento e na aproximação entre a academia e a indústria.

Regista-se com satisfação o envolvimento excecional do setor empresarial. O Congresso conta com 80 patrocinadores e uma exposição técnica com 77 stands, números que revelam a confiança e o entusiasmo das empresas na valorização da construção metálica e mista e das fachadas, bem como no papel agregador que este evento desempenha no panorama nacional. No plano técnico-científico, foram submetidos 99 artigos e proferidas 28 palestras, refletindo a intensidade e qualidade da participação da comunidade académica e profissional. A todos expressamos o nosso reconhecimento.

É neste cenário de continuidade, progresso e consolidação que se integra, com especial significado, o I Congresso de Engenharia de Fachadas, que surge como resposta natural à evolução tecnológica do setor e à necessidade de um espaço próprio para discutir temas específicos associados à envolvente dos edifícios. Este novo congresso afirma definitivamente a Engenharia de Fachadas no panorama nacional, como área multidisciplinar, inovadora e essencial para a construção sustentável do futuro, refletindo o avanço das soluções construtivas, a crescente complexidade dos sistemas de fachada e o reconhecimento de que o desempenho do edifício depende, cada vez mais, da qualidade e integração destes elementos.

Num contexto em que a construção enfrenta novos desafios – desde a descarbonização e economia circular, até à necessidade de sistemas construtivos mais eficientes, industrializados e tecnologicamente avançados – este encontro conjunto mostra a capacidade do tecido técnico e industrial português para responder com soluções maduras, competitivas e orientadas para o futuro. A diversidade de comunicações recebidas e a forte participação académica e empresarial atestam o dinamismo do setor e reforçam a importância do diálogo contínuo entre investigação, projeto e indústria.

A fundação em 2025 da EdF – Associação Portuguesa de Engenharia de Fachadas, concretiza uma ambição longamente amadurecida por diversos profissionais e instituições. A EdF nasce para promover o conhecimento técnico, contribuir para a evolução normativa e potenciar a qualidade e visibilidade do trabalho português, dentro e fora do país. Este passo representa não apenas a criação de uma nova entidade, mas a consolidação de uma comunidade empenhada em reforçar competências e abrir novos horizontes à tecnologia de fachadas.

Por fim, a publicação de livro de atas testemunha a vitalidade técnica e científica do Congresso. Reúne trabalhos que refletem o que de mais recente se investiga e pratica, oferecendo um registo permanente do conhecimento aqui partilhado e convidando à reflexão sobre os caminhos que ainda temos por trilhar. Que estas páginas sirvam de referência, inspiração e instrumento de progresso para engenheiros, arquitetos, investigadores, estudantes e todos quantos contribuem para a evolução do setor.

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CRITICAL TEMPERATURE ON CURVED SUPERELEVATED RAILWAYS

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Abstract. Railways are essential for the efficient transport of people and cargo, but they face increasing risks due to temperature variations. This study analyses thermal instability in continuously welded rails located on curves with superelevation. The modelling, performed in ANSYS using the finite element method, evaluates factors such as rail profile, cant, fastener stiffness, ballast resistance, and geometric imperfections. The results show that loss of ballast resistance and increased imperfections reduce the critical buckling temperature. On the other hand, the use of cant can raise this temperature depending on the conditions. The research confirms that well-designed curves with superelevation reduce the risk of thermal buckling.

1. Introduction

Railway tracks, first introduced in the 16th century with wooden structures used in English mines, have evolved significantly over time to meet growing safety and efficiency requirements. At that time, wooden tracks with raised edges helped guide mining wagons with less friction [1]. With the Industrial Revolution, cast iron plates were incorporated, and later, rails with iron edges, which enabled the use of flanged wheels and higher speeds [2] [3].

The adoption of continuously welded rails (CWR) represented a significant advance, replacing expansion joints with a continuous rail connection. This system provides greater durability, less maintenance, noise reduction, and greater comfort for passengers [3] [4]. However, this configuration also requires greater control of internal stresses, as temperature variations can cause structural instability due to the inability to accommodate thermal expansion.

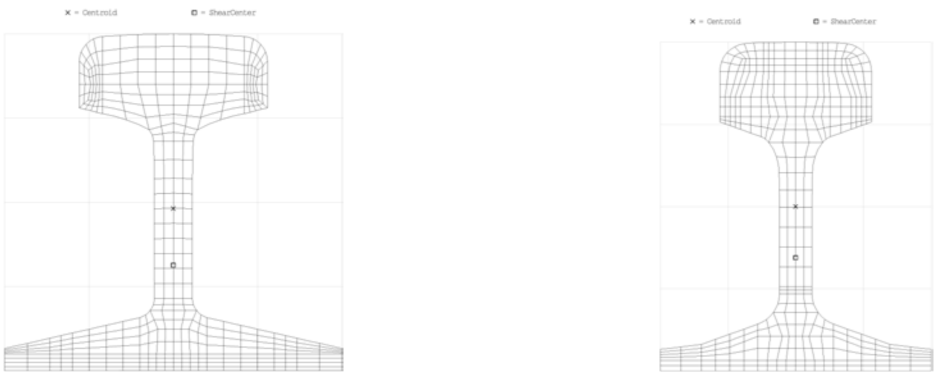
Lateral deformation caused by thermal expansion is one of the main concerns on CWR lines, especially in curved tracks. In these areas, cant is applied to compensate for lateral forces, such as centrifugal force and wind, contributing to safety and operational stability [1]. Temperature rises above the neutral rail temperature, inducing compressive forces which, when exceeding a critical limit, result in lateral buckling [5]. In addition, dynamic loads during braking and train movement reduce the critical deformation temperature, increasing the risk of instability [5].

In view of this, preventive strategies have been adopted, such as the use of safe operating limits, speed restrictions in extreme weather conditions, and the use of numerical models to predict critical behaviours. In countries such as UK or Australia, these measures are essential to mitigate risks [6].

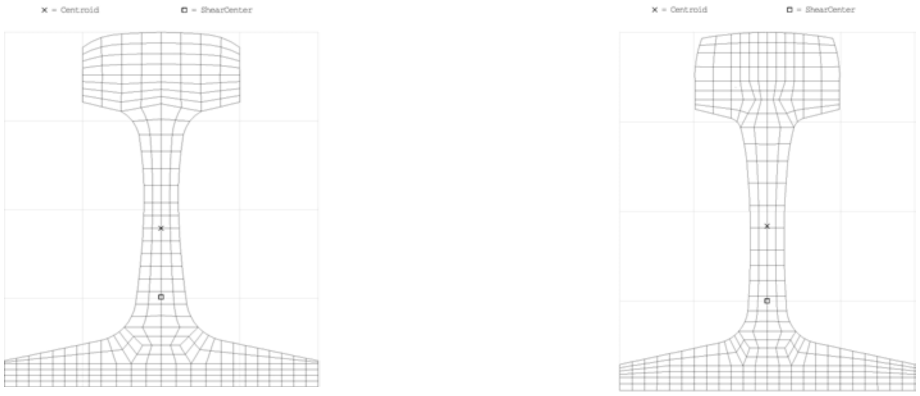
In this context, this study investigates the influence of thermal expansion on the stability of curved railways with superelevation, using Finite Element Analysis (FEA). The study considers factors such as rail profile, fastener stiffness, sleeper properties, ballast strength, cant magnitude, curve radius, and misalignments. The model is validated based on experimental data and analytical studies, allowing us to understand and predict the combined effects of these parameters on the thermal stability of the railway track.

2. Rail Components

The railroad can be subdivided into two major groups: the superstructure, consisting of rails, ties, fastenings, and ballast, and the infrastructure, which includes the subballast and subgrade [2]. The rails serve to guide and support the forces generated by wheel-rail contact. In this study, four different profiles were considered: S30, UIC50, 132RE, and 136RE, see Fig. 1. They are made of R260 steel in accordance with standard EN 13674-1 [7]. The geometric properties of these profiles have a direct impact on track stability, especially the cross-sectional area and second-order moments, which define axial and bending stiffness. Lighter profiles, such as S30, have lower buckling resistance, while robust profiles, such as 132RE and 136RE, provide greater resistance to thermal and dynamic stresses. This variation makes the choice of profile one of the determining factors in predicting the critical buckling temperature [4] [8].



a) S30 model b) UIC50 model



a) 132RE model b) 136RE model

Fig. 1: Representation of profiles

Wooden sleepers were included in the model with the function of distributing the loads applied by the rails, maintaining the track gauge, and ensuring geometric alignment. In addition, they contribute to the interaction with the ballast, influencing the lateral and longitudinal resistance of the track. The fastening system was modelled as responsible for ensuring the connection between the rail and the sleeper, ensuring longitudinal rigidity, torsional resistance, and displacement control [9]. These elements exhibit essentially elastic behaviour, but the loss of rigidity over time or due to fatigue can significantly compromise the stability of the system.

The ballast, in turn, was represented as a granular medium that provides lateral and longitudinal confinement to the rail. It is responsible for absorbing impacts, reducing vibrations, and ensuring drainage, in addition to actively participating in the buckling mechanism by resisting deformations imposed by heating [3].

Thermal buckling was defined as a global structural instability associated with the confined expansion of continuously welded rails. Unlike rails with joints, in which expansion is partially relieved, CWRs accumulate significant compressive stresses when the temperature rises above the so-called neutral temperature. The phenomenon can manifest itself in two main forms: progressive buckling, characterised by increasing displacements without sudden loss of resistance, and explosive buckling, in which sudden displacement and immediate instability of the track occur [10]. The definition of the collapse mode depends on the interaction between track stiffness, ballast resistance, torsional stiffness of the fastenings, and the amplitude of the initial imperfections.

Among the most relevant parameters are: the lateral and longitudinal resistance of the ballast, which depends on compaction, grain size, and shoulder height; torsional stiffness, which is essential for maintaining gauge and controlling relative displacements; the initial geometric imperfections, which act as a starting point for instability and significantly reduce the critical buckling temperature; the geometric properties of the rail profiles, which define the resistance to bending and compression; and the geometric parameters of the track, in particular curvature and superelevation, which were addressed in this study.

Track curvature introduces an asymmetric distribution of stresses, intensifying centrifugal forces on the outer rail and, consequently, improving the safety margin against thermal buckling [11] [12]. Reduced curvature radius is more prone to instability due to the accumulation of lateral stresses, becoming critical regions in terms of maintenance and monitoring. Superelevation, in turn, serves to balance dynamic forces in curves, distributing loads more evenly between the inner and outer rails. However, under the effect of temperature variations, superelevation alters stability conditions, changing the critical buckling temperature. In situations of excessive or deficient cant, the behaviour of the track becomes even more complex, requiring specific analyses for each geometric configuration.

Numerical modelling was performed using finite elements in ANSYS software, using the Geometric and Material Nonlinear Imperfection Analysis (GMNIA) approach. This technique allowed for the simultaneous consideration of geometric and material nonlinearities and initial imperfections. The rails and sleepers were discretised with Timoshenko BEAM188 beam elements, which have six degrees of freedom per node, allowing accurate representation of axial forces, bending, and torsion [13]. The ballast and fastening system were modelled using COMBIN39 spring elements, with nonlinear behaviour in lateral, longitudinal, and torsional resistance [14]. This choice made it possible to realistically reproduce the interaction between the tie, fastening, and ballast, which are determining factors in the buckling phenomenon.

This set of models allowed for a detailed analysis of the structural response of the track under temperature variations, considering different rail profiles, fastener stiffness, ballast resistance, initial imperfection levels, and the influence of superelevation. The model can reproduce both the pre-critical and post-critical regimes, providing a robust tool for assessing thermal stability in modern railways.

3. Numerical Model Description

The numerical model was developed with the objective of realistically representing the behaviour of the railway track under thermal effects, considering the different structural components and geometric parameters. The formulation adopted was based on the finite element method, implemented in ANSYS , allowing nonlinear analysis with the inclusion of initial imperfections.

The track geometry was constructed from the representation of continuously welded rails, modelled with a total length of 200 m. Four different rail profile sections were used, allowing comparison of the influence of the cross-sectional area and overall stability. The sleepers were inserted transversely, with uniform spacing of 500 mm, ensuring maintenance of the gauge (1435 mm) and transmission of forces between the rail and ballast.

The curvature of the track was implemented in order to assess the sensitivity of the system to increased lateral forces, see Fig. 2. The superelevation was introduced by tilting the track plane, creating a difference in height between the inner and outer rails. This configuration allowed the combined effect of curvature and the imbalance of loads applied to the system to be investigated.

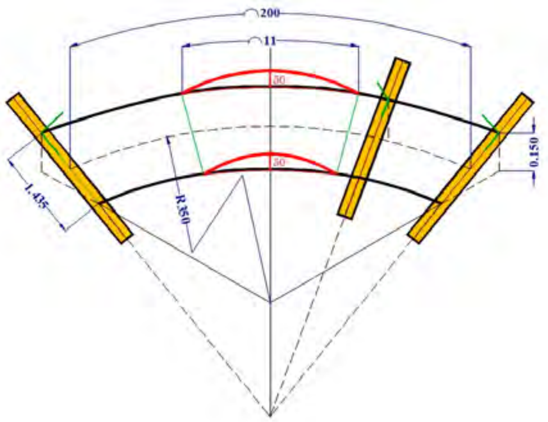


Fig. 2: Representation of the system with a radius of 350 meters

To reproduce the presence of initial geometric imperfections, sinusoidal deformations were applied to the rail, located at the centre point of the span. These imperfections had different amplitude parameters, ranging from 270 mm to 1000 mm, allowing their influence on the onset of buckling to be analysed. This procedure was essential to induce instability and enable the parametric study.

The boundary conditions were defined to represent the actual behaviour of continuously welded rails. The ends of the model were restricted in all degrees of translational freedom, preserving only rotation around the Z-axis, which ensures the necessary confinement for the simulation of thermal expansion, see Fig. 3. This arrangement ensures that the expansion is absorbed by the development of internal stresses and, subsequently, by the lateral displacement of the track.

The mesh was generated manually, ensuring sufficient refinement to capture the effects of thermal buckling. The average length of the rail finite elements was set at 0.085 m, while the elements representing the sleepers had dimensions of 0.11 m.

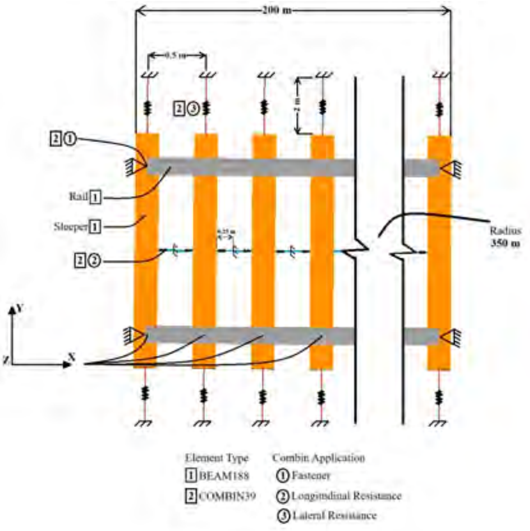


Fig. 3: Geometry of the model

This arrangement allowed for an accurate representation of the interactions between rail, sleeper, fastenings, and ballast, as well as enabling the analysis of different track geometry configurations under temperature variations. The incremental application of thermal loading, together with the introduction of initial imperfections, made it possible to capture the behaviour of the track from the pre-critical regime to the post-buckling regime.

4. Methodology

The investigation of the thermal stability of the railway track was conducted using computational modelling based on the finite element method, implemented in ANSYS. The model used GMNIA (Geometrically and Materially Nonlinear Imperfection Analysis), widely used in structural instability studies for the simultaneous representation of geometric nonlinearities, materials, and initial imperfections.

The rails and sleepers were discretised using the BEAM188 element, based on Timoshenko's beam theory, which considers six degrees of freedom per node and cubic interpolation functions. This element is suitable for analyses involving interaction between bending, compression, and torsion, in addition to allowing accurate calculation of stresses and deformations. The ballast and fastening system were modelled with the COMBIN39 element, which exhibits one-dimensional behaviour with the ability to simulate nonlinear forces as a function of displacement. This feature allowed the representation of the lateral and longitudinal resistance of the ballast, as well as the torsional stiffness of the fasteners, aspects already discussed in previous works on track stability [15].

Steel R260 grade was adopted to represent the rail material, in accordance with standard EN 13674-1 [7]. The stress-strain relationship under different temperatures was defined by the Ramberg-Osgood constitutive model, whose parameters were obtained from the study developed by Kamaya, from eq. (1) [16]. The reduction in the modulus of elasticity and yield stress as a function of temperature was considered according to correction factors available in the literature, ensuring the compatibility of the model with experimental results obtained under real conditions.

$$\varepsilon = \frac{\sigma}{E} + K\,(\frac{\sigma}{\sigma_y})^n \tag{1}$$

The sleepers were made of wood (Red Oak), using orthotropic elastic properties based on reference values, since the mechanical behaviour of this material depends heavily on the orientation of the fibres.

The initial geometric imperfections were modelled as sinusoidal displacements applied at the centre of the span to induce instability. The boundary conditions restricted all translational displacements at the ends, maintaining only freedom of rotation around the Z-axis. The thermal load was applied incrementally, from 20 °C to 300 °C, with maximum variations of 5 °C per step.

The solution procedures were performed incrementally and iteratively, using the Newton-Raphson method coupled with the reduced energy dissipation stabilisation technique (10^{-6}), as suggested in previous studies on structural instability [17] [18]. This method ensured convergence at critical points in the buckling process, where there are sudden changes in stiffness and structural response. The convergence criteria adopted tolerances of 0.001 for unitary displacement, internal force, and internal moment.

The rigidity of the fastenings and their lateral and torsional resistance are decisive factors for the thermal stability of continuously welded rails. Classic studies, such as those by Kish [9], show that greater lateral rigidity raises the critical buckling temperature by restricting transverse displacement. In curves with superelevation, the torsional resistance of the fastenings becomes even more relevant, see Fig. 4, as it limits rail rotation caused by asymmetrical loads, preventing loss of overall stability [12].

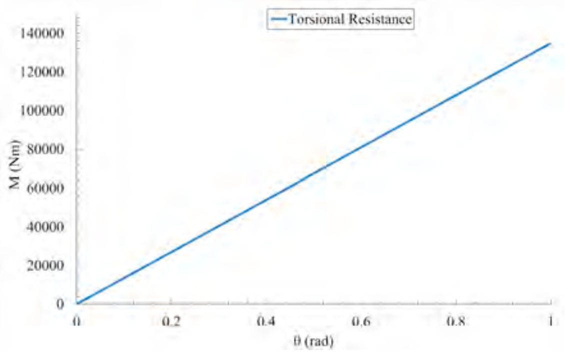
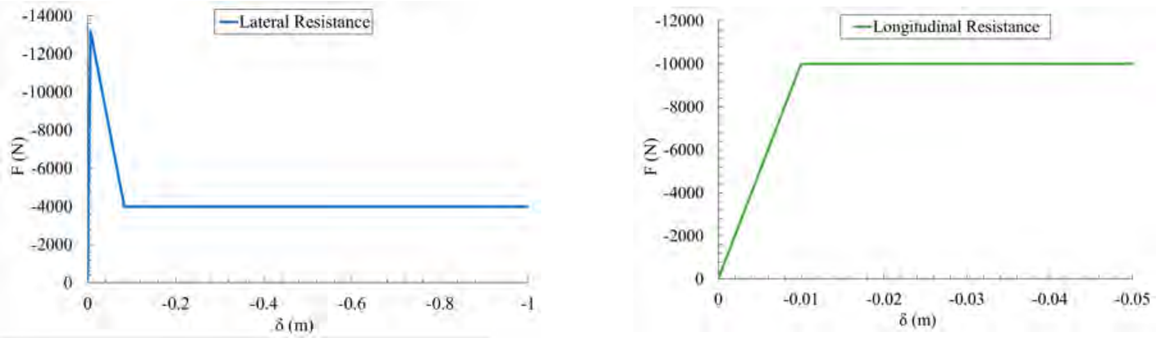


Fig. 4: Torsional resistance

The lateral and longitudinal resistance of the track depends mainly on the ballast, complemented by the fastenings and sleepers. Tests such as the Single Tie Push Test (STPT) indicate that much of the lateral resistance comes from the ballast [19,9]. Longitudinal resistance, responsible for absorbing thermal stresses and braking or acceleration loads, varies with the type of sleeper and ballast conditions. According to Dersch et al. [20], concrete sleepers have up to 20% more longitudinal resistance than wooden ones, with a minimum of 15 kN per complete fastener recommended to ensure structural safety [1]. Fig. 5 presents the lateral and longitudinal ballast resistance.



a) Lateral Resistance b) Longitudinal Resistance

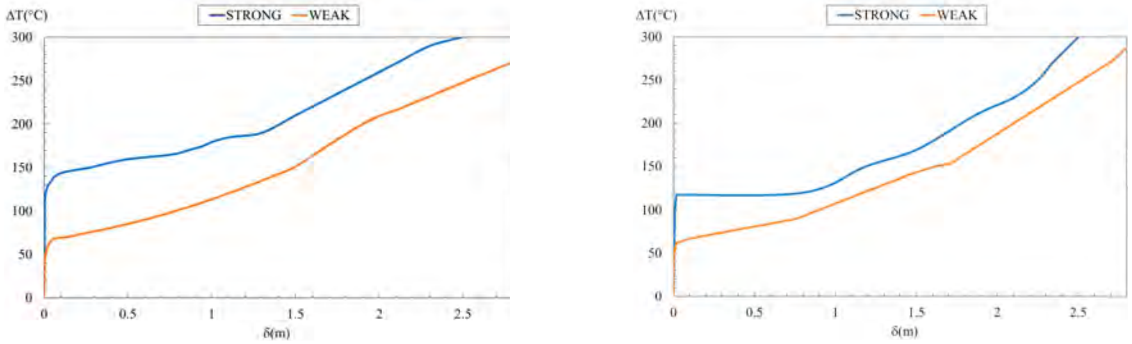
Fig. 5: Lateral and longitudinal resistances

5. Results

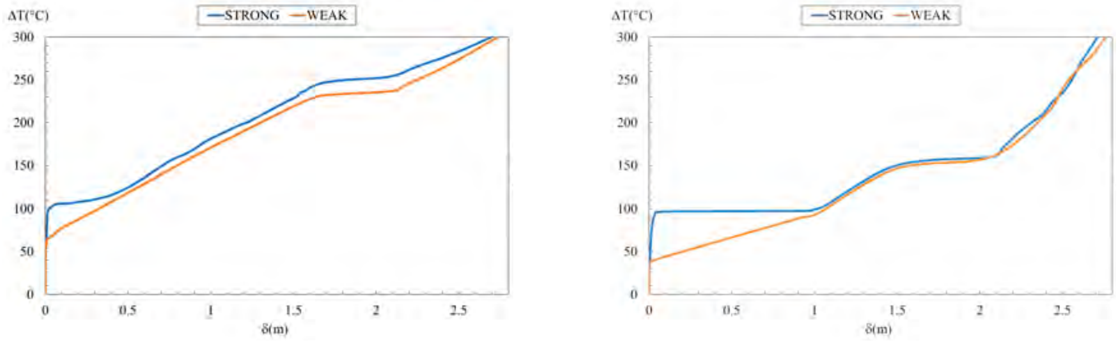
In total 24 numerical simulations were performed to evaluate the thermal stability of continuously welded rails, considering different rail profiles, ballast resistance conditions, and initial imperfection levels. The model disregarded vertical loads, focusing on the lateral response of the track due to temperature variations, with monitoring of displacements at the upper rail node in the middle of the span.

The results showed that three parameters were decisive in defining the critical buckling temperature: the amplitude of the initial imperfection, the lateral stiffness of the ballast, and the rail profile. When compacted ballast (strong conditions) applies, the critical temperature varied between 96 °C and 141 °C, depending on the profile considered. In situations of degraded ballast conditions (weak conditions), the values dropped to approximately 38 °C.

Analysis of the rail profiles (136RE, 132RE, UIC50, and S30) revealed counterintuitive behaviour: the lightest profile, S30, exhibited higher critical temperatures than the more robust profiles, such as 132RE and 136RE, this can be verified graphically in the Fig. 6. This result was attributed to the lower longitudinal stiffness of S30, which reduces the accumulation of compressive stresses. The American profiles 132RE and 136RE, although designed for high loads, showed greater vulnerability, with reductions of up to 78% compared to S30. The European profile UIC50 showed intermediate performance. These results reinforce that thermal buckling depends on the interaction between rail, fastenings, and ballast, and not only on the inertia of the section.



a) S30 buckling curves b) UIC50 buckling curves



a) 132RE buckling curves b) 136RE buckling curves

Fig. 6: Buckling curves for imperfection factor (a = 270)

The initial geometric imperfections, evaluated with maximum amplitudes (L/a), using (a) equal to 270, 500, and 1000, significantly reduced stability. In extreme scenarios, the increase in imperfection led to drops of up to 50% in critical temperature, while under favourable structural conditions, this effect was around 10%, confirming that sensitivity to imperfections is directly associated with the overall stiffness of the track.

Another aspect analysed was the superelevation in curved sections. The results, summarised in Table 1, showed that the presence of cant (150 mm) contributed to raising the critical temperature and reducing susceptibility to buckling. The appropriate track inclination not only increased the thermal safety margin, but also modified the mode of instability: without superelevation, progressive buckling predominated, while with superelevation, the rails exhibited more stable behavior, with explosive buckling occurring only at very high temperatures.

Table 1: Temperature change with Cant

Resistance	**Imperfection (a)**	**Profile**	**Previous Studies (°C) [15]**	**Present Study (°C)**	**Variation (%)**
Strong	270	132RE	68	103	+51.47%
	270	136RE	66	97	+46.97%
	500	132RE	98	114	+16.33%
	500	136RE	95	107	+12.63%
	1000	132RE	118	131	+11.02%
	1000	136RE	119	128	+7.56%
Weak	270	132RE	28	62	+121.43%
	270	136RE	28	38	+35.71%
	500	132RE	37	71	+91.89%
	500	136RE	37	43	+16.22%
	1000	132RE	46	83	+80.43%
	1000	136RE	48	57	+18.75%

In summary, the analysis showed that thermal buckling is a phenomenon that is highly sensitive to the combination of ballast conditions, rail profile, initial imperfections, and superelevation. An integrated understanding of these factors is essential for design and maintenance strategies that ensure track stability in scenarios of increasing thermal variations.

6. Conclusion

The main conclusions are:

1. The critical buckling temperature of continuously welded rails is highly sensitive to three main parameters: the initial geometric imperfection, the lateral stiffness of the ballast, and the rail profile, with variations above 340% between scenarios;
2. Among the analysed rail profiles, the lighter section S30 presented the best thermal performance due to its lower longitudinal stiffness, while the heavier profiles 132RE and 136RE showed higher vulnerability under unfavourable support conditions, with reductions of up to 78% in relation to the S30;
3. The superelevation (cant) proved to be an effective stabilising element, especially in curved tracks, increasing the critical buckling temperature and providing a more predictable structural response, while geometric imperfections significantly reduced stability, particularly in tracks with degraded ballast.

Notation

ε	Strain
σ	Stress
σ_y	Yield stress
n	Hardening exponent
K	Tensile strength
E	Young's Module
α	Variable to define imperfections

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