Influence of Pier Stiffness on Track-Bridge Interaction

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Abstract

The bridge is a common engineering structure over which a rail track is often laid. With the introduction of continuous welded rail (CWR), major rail tracks have shifted worldwide from jointed rail to continuous welded rail. CWR eliminates fish plates and overcomes many of the drawbacks of the jointed rail, resulting in a long, smooth track with no joints. Track-bridge interaction (TBI) is important when a continuous welded rail is provided over a bridge structure. Since numerous parameters influence the phenomenon, a numerical model has been developed in SAP2000. Longitudinal pier/abutment stiffness is an important structural property of bridge substructure, and its magnitude changes significantly from one bridge to another. Due to the coupling between CWR track and the bridge, the bridge pier stiffness affects the rail stress developed in addition to pre-existing stress. Pier stiffness has been identified as an important parameter affecting the track-bridge interaction phenomenon as its value changes with the site conditions. The developed numerical model has been utilized to study the influence of pier stiffness on support reaction and additional rail stress in CWR subjected to thermal loading. Both the support reaction and rail stress have been found to be considerably influenced by pier stiffness. Additional rail stress in CWR is a source of concern because the track is a long, slender member that can buckle if excessive compressive stress develops in the track.

Keywords: Track-bridge interaction; Continuous Welded Rail; Pier stiffness; Additional Rail Stress; Horizontal Support Reaction

1. Introduction

Rail tracks are an essential engineering structure generally supported on an embankment and very often by a bridge structure. Continuous welded rail (CWR) is progressively replacing conventional jointed rail because of its inherent advantages over the latter. A seamless track system without intermittent joints is the main benefit of deploying CWR. The other benefits of CWR over a jointed rail track include better ride quality, lower noise pollution, decreased track maintenance requirements, and better track structural longevity (IRICEN, 1996). Also, the elimination of fishplate joints considerably reduces the dynamic effects of the vehicle load on the track, especially when the vehicle wheel passes from one rail segment to another over the joint (Cai, et al., 2007). The special expansion joints (SEJs), which are undesirable on a high-speed track, are eliminated by CWR over the bridge (Sanchez et al., 2021). However, the track-bridge system provided by CWR needs special attention as additional rail stress and support reactions are developed due to the interaction between the two inter-coupled systems.

The interaction between track and bridge systems arises due to the inter-coupling between the two structures through the support medium of the track and various fastening elements. Forces are developed at the track-bridge interface due to various load effects. For steel bridges, temperature variation significantly contributes to the track-bridge interaction (TBI) effects. Several studies have highlighted the influence of TBI in the presence of thermal loading (Fryba, 1985; Mubarack & Upadhyay, 2021; Yun et al., 2019). The development of high rail stress is not desirable, especially in the transition zone to the bridge (Strauss et al., 2015). To calculate the final reaction at the support, these additional horizontal support reactions must be added to the conventional support forces (UIC, 2001). Ballasted tracks are advantageous in both the dynamic and economic aspects of the bridge design (Quesada et al., 2021). The accurate estimation of rail stresses, displacements, and support reactions is essential during the design stage of the bridge. UIC Leaflet has been the pioneer in developing a codal provision in Europe based on earlier research on track-bridge interaction phenomena (UIC, 2001). The UIC code outlines criteria and methodology for conducting track-bridge interaction studies, and it provides rail stress and displacement limits to define track failure criteria. In addition, to account for the non-linear nature of the ballast, the code allows the bi-linear approximation of the track stiffness in the longitudinal direction.

Dutoit identified the role of pier stiffness as an important parameter for high-speed rail bridge design criteria (Dutoit, 2009). A detailed investigation of the influence of pier stiffness on the development of track stress and rail displacement is missing in the present literature. This paper will investigate the influence of pier stiffness on support reaction and additional rail stresses for a single-span simply supported steel bridge subjected to thermal loading. The well-maintained ballasted track is considered for the present study.

2. Track-bridge Interaction

As the CWR track is directly exposed to the environment, and the rail is a slender metallic structure with low thermal inertia, the track absorbs and emits heat rapidly and undergoes large temperature variations on a day-to-day basis. Any change in track temperature with respect to neutral temperature (the temperature at which the track develops no thermal stress) induces thermal strains in the track, and the track will tend to move longitudinally. Figure 1 shows the development of track forces due to the restrainment of these thermal movements. In Figure 1, F is the track force, the parameter α is the coefficient of thermal expansion for steel, ΔT_R is the rail temperature change relative to laying temperature, E is Young's modulus (steel), and A is the cross-sectional area of two rails combined. In Figure 1, the track movements occur in the end zone or the expansion zone in CWR, where the thermal strain is gradually relieved. However, the immovable central zone of CWR develops the full track force.

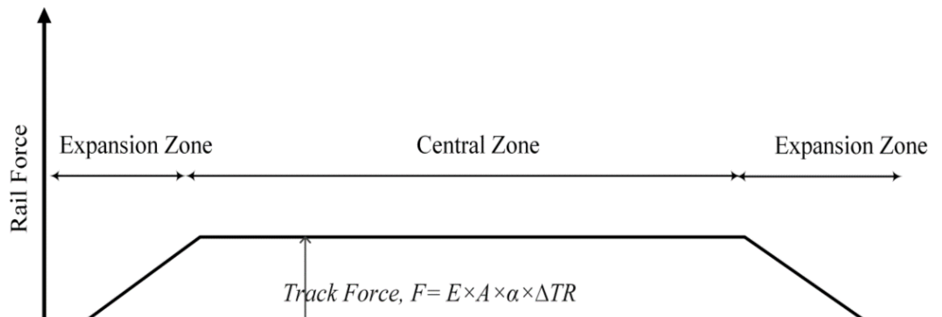

Fig. 1: Variation of longitudinal rail force in CWR

When the CWR track is allowed to pass over a bridge, the track is made to rest on a surface that is subjected to movement, and additional rail stresses are induced in CWR due to the coupling between them (Kumar & Upadhyay, 2012). The above phenomenon is called track-bridge interaction. In the case of a ballasted track, track and bridge are coupled through rail, sleeper ballast, and fastening. In the case of a ballast-less track or a slab track, the rail, fastenings, and concrete slab are supported directly on the bridge superstructure. The TBI phenomenon causes the creation of additional rail stress as well as additional horizontal support reactions at the bridge support. The interaction between the track and bridge is caused by temperature changes, horizontal braking and acceleration, traffic-induced bridge deck end rotations, and deformations and settlements due to creep and shrinkage. For steel bridges, temperature changes are a major source of TBI effects. This paper considers the temperature loading effects for a single span simply supported steel bridge.

3. Numerical Modelling of TBI

As numerous parameters affect the TBI phenomenon, the evaluation of various forces and stresses are computationally intensive. For the purpose of this study, the authors' previously developed and validated numerical model for the track bridge interaction has been used (Mubarack & Upadhyay, 2021). The numerical model was developed in SAP2000 (Computers and Structures Inc., 2016). Figure 2 shows the model for the track bridge system for a single span bridge, where CWR passes over a bridge that is located in the central zone of CWR track. The single span bridge has been modeled with fixed support at one end and movable/roller support at the other. The special expansion joint (SEJ) is not provided. Rail and deck elements were modeled with linear elastic beam elements.

In Figure 2, K_s, the resistance of the deck to horizontal displacement represents the longitudinal stiffness provided to the bridge deck by the bridge substructure. The support stiffness (K_s) was incorporated in the present model through linear spring elements in SAP2000. K considers the combined stiffness of the pier, bearing, base, foundation, and the subgrade on which the foundation rests. The stiffness of the movable bearing is ignored. The rail is modeled by combining two UIC rail sections. The bridge deck is modeled with linear beam elements. Only the effect of the uniform temperature load on the bridge deck has been considered.

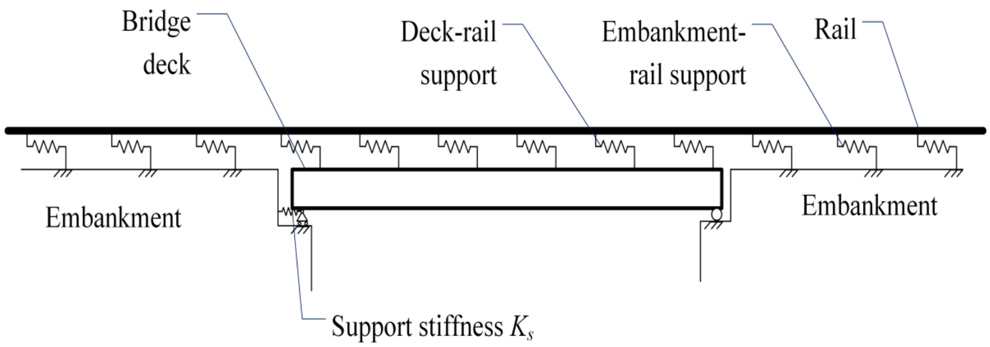

Fig. 2: Model for track-bridge interaction

Track stiffness is an important parameter that affects the phenomenon. Ballast behavior is essentially non-linear in nature. Figure 3 shows the track stiffness in the longitudinal direction for a well-maintained ballast under frozen and normal conditions. The deck-rail support and embankment rail support are modeled with two-noded connection elements called link elements, which simulates ballast stiffnesses. In the present model, well-maintained ballast under normal condition is considered. For investigating the influence of thermal loading, track is considered vertically unloaded with vehicle traffic. The longitudinal track stiffness has been incorporated by employing nonlinear link elements in SAP2000.

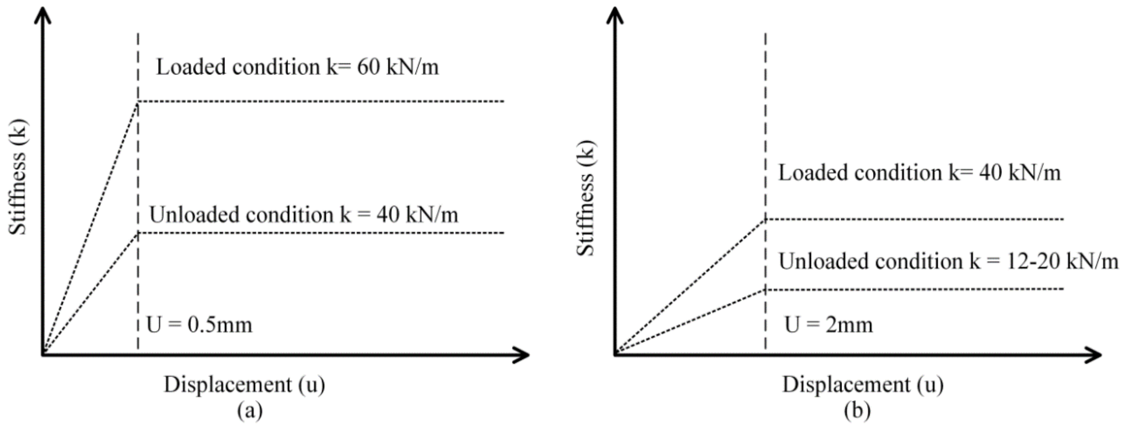

Fig. 3: Longitudinal track stiffness **(a)** frozen ballast **(b)** normal ballast

4. **Numerical Studies**

The model described in the previous section has been used to find the effects of the stiffness variation of the bridge deck support. A normal ballasted track having horizontal ballast stiffness 20 kN/m of the track with a yield displacement of 2mm is considered. The horizontal support stiffness variation of 0 kN.mm to 1000 kN.mm has been considered to investigate the influence of pier stiffness on additional rail stresses in CWR and the corresponding pier reactions. The length of the bridge deck considered is 75m. The UIC 60 rail section is used, and the combined cross-sectional area of the two rails is 1,540 mm^2. The bridge deck has the following specifications: Young's modulus, E=2.1x10^5 N/mm^2, coefficient of thermal expansion α = 1.0 x 10^{-05} °C^{-1}, cross-section area = 0.71 m^2, moment of inertia I = 3.84 m^4. The temperature increment applied to the bridge deck is 35 °C. The application of thermal loading caused the development of additional rail stress at the fixed and moveable ends of the bridge, as well as the support reaction.

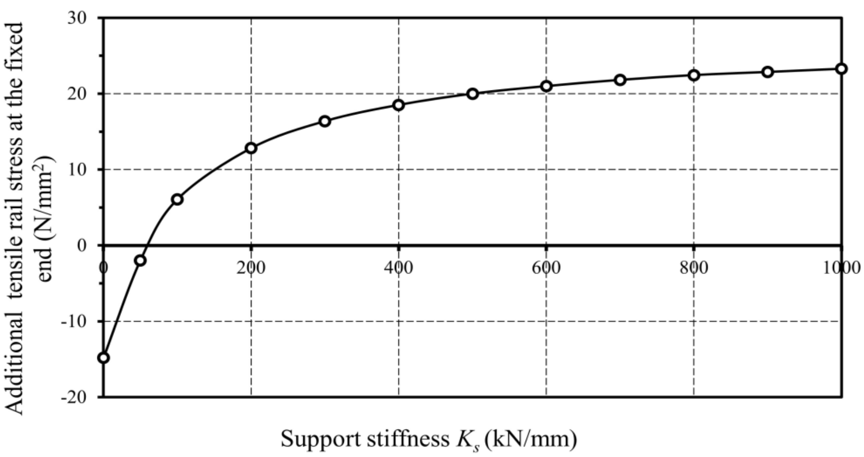

Fig. 4: Variation of additional rail stress at the fixed end with support stiffness

Figure 4 shows the variation of additional rail stress at the fixed end of the bridge corresponding to different support stiffness values. Initially, the track develops a stress equal to -14.8MPa (compressive) under zero-support stiffness, which is a floating-deck condition (represents an extremely flexible support condition). The nature of the track stress at the fixed end was reversed by slightly increasing the support stiffness. From Figure 4, higher support stiffness results in larger tensile stress at the fixed-elastic end, but the increase in rail stress tends to decrease.

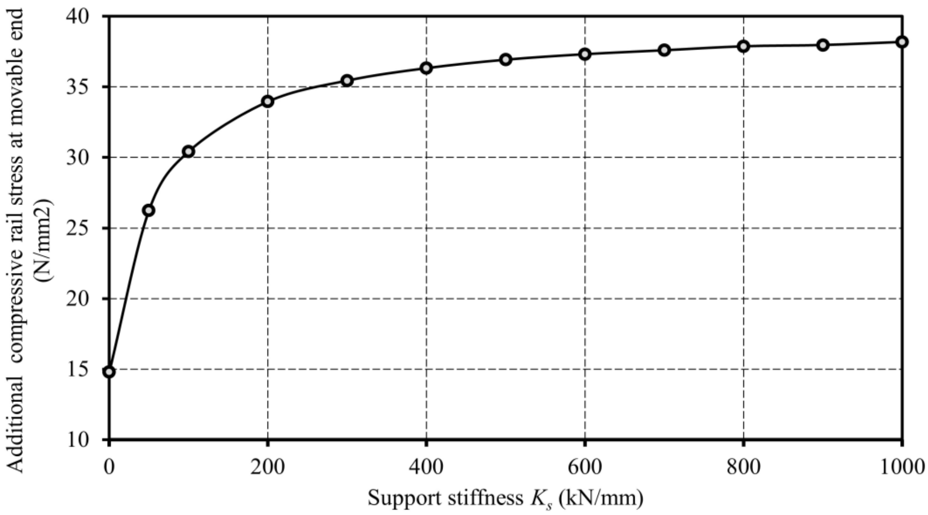

Fig. 5: Variation of additional rail stress at the movable end with support stiffness

Figure 5 shows the additional compressive rail stress variation at the movable end corresponding to various support stiffness values. Initially, for K_s =0, compressive rail stress at the movable end = 14.8 N/mm^2, matching the value at the fixed end. For all stiffness instances, CWR at the movable end of the bridge develops compressive stress. A higher support stiffness increases additional compressive stress at the movable end. Figure 6 shows the variation of rail stress along the track length as viewed in the present model.

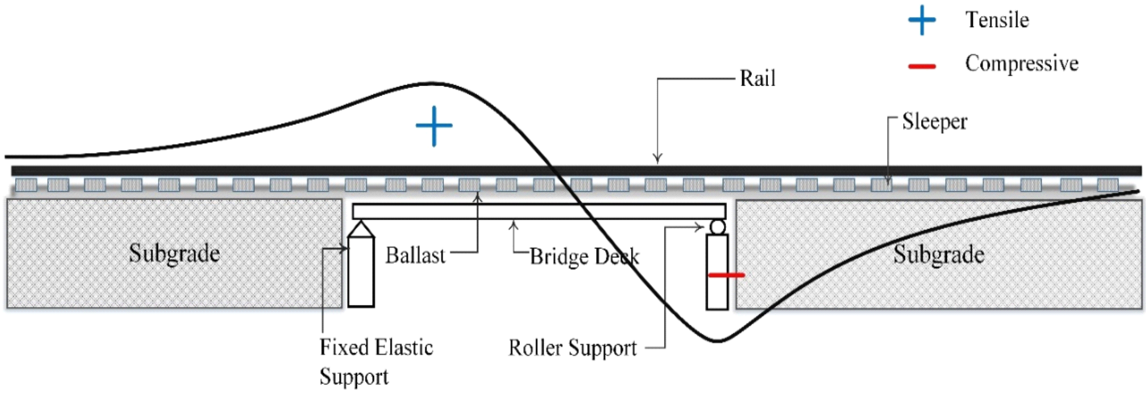

Fig. 6: Variation of additional rail stress along the length of CWR due to TBI as realized in the present model

Figure 7 shows the variation of horizontal bridge support reactions at the fixed end with support stiffness. The bridge support reaction is increasing considerably with an increase in support stiffness. A higher support stiffness increases the support reaction. However, at higher support stiffness, due to the nonlinear nature of the phenomenon, the increase in support reaction tends to decrease. From Figure 7, a significant amount of force is observed to be developed by the bridge pier even at a moderate value of pier stiffness. This reaction is in addition to the reaction due to existing loads. The development of such large horizontal forces is not desirable for long, slender piers due to the possibility of developing high overturning moments in the pier foundation, which highlights the importance of the present study.

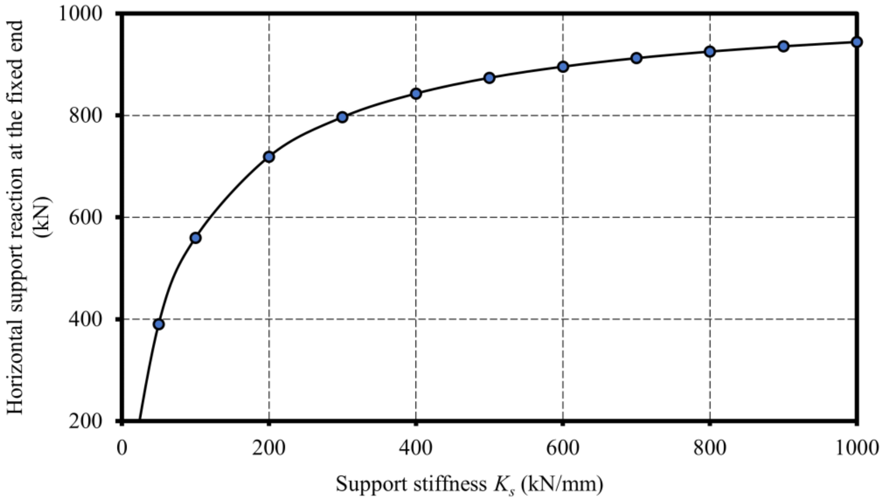

Fig. 7: Variation of horizontal support reactions at the fixed end with the change in support stiffness

5. **Conclusion**

CWR is gaining popularity over jointed rail because of its inherent advantages. However, the designer should have a good understanding of the TBI-related issues for the safe and efficient design of the track-bridge system. This paper studied the effect of pier stiffness on the TBI phenomenon considering thermal loading for single-span simply-supported bridges. The simplified numerical model, which handles the non-linearity associated with the ballast, has been utilized to find additional rail axial stresses and support reactions. In the present study, it has been observed that in a steel bridge with simply-supported decks, due to thermal loading, stiff piers develop more rail stress and support reaction because of the continuity of the CWR track passing over it. With an increase in support stiffness, both the maximum compressive and tensile rail stresses increase; however, the increase in both stresses tends to decline with higher support stiffness. At lower support stiffness, changes in interaction effects were more sensitive. Measuring rail stress at the fixed and movable ends of the bridge as well as estimating support responses are essential during the bridge design stage. The present study contributes to the knowledge of the behavior of CWR over bridges, especially under thermal loading. The designer may assess the final bridge forces considering the effect of other load cases on the interaction and the local stiffness variations of the ballast.

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