International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-10 Issue-6, March 2022

Study of Integral Structure behaviour for Rail Structure Interaction in the Proposed Metro Viaduct

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Abstract: ***Long welded rails (LWR) are preferred in metro rail systems because they provide a smooth ride. They are extremely sturdy, require less maintenance and safe to travel at higher speeds. Rail structure interaction (RSI), especially additional longitudinal stresses in rail, is the major concern in the LWR. UIC standards provide the limitations of additional rail in longitudinal stresses. This paper studies the characteristics of additional forces in long welded rail used in one of the Metro Railway systems in India. The LWR is placed on five spans with integral intermediate piers of balanced cantilever superstructure (BCM). A nonlinear finite element analysis is performed using the analytical tool MIDAS CIVIL 2021 to study the interaction mechanism. For this study, rail and deck (unballasted) are linked with a multilinear elastic spring, as recommended in UIC 774-3R. The study was conducted in accordance with the International Union of Railways and Indian standards. This paper shows a comparison of the rail stresses along the rail due to combined thermal and live loading for both balanced cantilever span and conventional simply supported spans. The results show that rail stresses have significant variation due to bearing articulation, adjacent spans and integral BCM system.***

Keywords: ***Integral Structure, Long Span Bridges, Metro Rail System, Long Welded Rail (LWR), Rail Structure Interaction.***

I. INTRODUCTION

The growing population worldwide makes road transport unviable inside the highly populated urban and suburban areas. High-population countries like India are moving towards an elevated or underground tunnel rail transport system called the Metro rail system to ease off the severe stress laid by the hasty growth of the vehicular population. Metro rail systems provide high-speed and traffic-less transport in heavily populated urban areas. In many urban areas, a fully underground rail system is not possible. Because the existing underground sewage systems and the type of terrain in particular areas are constraining tunnel constructions. These constraints force the engineers to opt for elevated structures where tunnel construction is not possible. Due to existing buildings, the elevated structures happen to be longer and taller than the bridges used for road transports. The long-elevated structures, that are supported by a series of spans over tall pillars or towers, are called viaducts. Nowadays long welded rails are predominantly used in metro rail systems, especially where the viaducts are required. They provide a smooth ride, less maintenance of tracks and that makes the train travel safer even at high speed transports [1]. The LWR and the bridge structure are connected using fasteners over the track plinth. So, stress or deformation in one element induces stress or deformation in another element.

This is called the Rail Structure Interaction (RSI) effect. Deformations in bridge/track are induced due to thermal actions, braking/traction, and vertical loads from the train live load. Additional stress in the rail and relative/absolute displacement at the ends of the deck, and forces transmitted to substructure bridge elements are studied with respect to above mentioned loads. The UIC 774-3R [2] and RDSO guidelines [3] include the basic methodology for analysis of track-bridge interaction and describe the actions to be considered and the limit values to be complied with as regards both stresses and displacements of the rails. The RSI effect has been studied by many researchers [4], [5], [6], [7] and [8]. Donald R Ahlbeck et al [7] discusses the structural performance of LWR. Ruge et al [9] addressed the influence of load history on the analysis of track–bridge interaction and studied the longitudinal forces in CWRs due to nonlinear track–bridge interaction. Petrageli et al [4] stated that application of the long-welded rail can be extended to longer bridges as the stresses in the rail can be controlled easily. Bharat J [5] shah et al developed the finite element model for calculating the amount of additional rail stresses generated with and without Rail Expansion Joint (REJ). The REJ is often suggested in the viaduct to take care of rail structure interaction effect [10]. But it requires more maintenance and cost.

So REJ is recommended in unavoidable situations where additional rail stresses and relative displacement exceed the recommended limits UIC774-3R [2]. The response due to RSI effect depends on the stiffness of bridge elements (such as foundation, column, bearings), resistance offered by the track structure to deformation, the boundary condition of rails and the effect of soil structure interaction [11]. Ahammed Ali Asif et al [12], A.J.Reis et al [13] and R. Simões et [14] al concluded that it will be necessary to model the approach spans/embankments to analysis the actual behavior of track bridge interaction [12], [13] and [14].

Manuscript received on January 24, 2022.
Revised Manuscript received on February 12, 2022.
Manuscript published on March 30, 2022.
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In recent years with the continuous improvement of the bridge and construction techniques, many special types of structures are used in railway bridges due to site and construction constraints. The special type of superstructures are such as skewed steel bridge [15], arch bridge [16], extra dosed cable stayed bridge [17], integral railway rigid frame [18] and sliding slab track on bridge [19] and recent trend of high speed railway bridges [20], [21].

The balanced cantilever bridge with segmental box girder is an innovative bridge structure that is being used in many viaducts. Bearings are not used throughout the intermediate spans. The superstructure and substructure are integrally connected. Piers are given with free bearing. The following are some advantages of this type of bridge:

- Less maintenance is required due to the absence of bearings and expansion joints.
- During the construction stage, traffic can be allowed beneath the superstructure.
- Due to integral behavior, the lateral forces are distributed evenly. So that bending moment is reduced at the bottom of the pier and provides good performance against seismic loads.
- Since it is a statically indeterminate structure, the sudden failure of structure is prevented due to integrity.
- Temporary bridge supports are not required during construction to counteract the unbalanced load.

The balanced cantilever bridge has been widely used in Indian metro railways in recent years. For this balanced cantilever structure different bearing articulation and structural arrangement, RSI still remains unclear and the main influencing factors have not been fully studied. In this paper the attempt has been made to understand the effect of RSI in the balance cantilever bridge.

The detailed objectives of this study are listed in below

1. Develop a finite element model of the BCM bridge by considering the soil structure interaction, long welded rail, approach span and track structure fastener's multilinear spring.
2. Analyze the effect of RSI for different fastener nonlinear stiffness with and without live load case.
3. Effect of additional rail stress due to temperature variation, tractive/ braking force, and vertical live load throughout the spans, especially at the integral portion.
4. Study the result with the limitations given in recommendation of UIC 774 3R [2].
5. Compare the results with conventional simply supported span with the same geometrical and span arrangement.

II. METHODOLOY

A.Geometry

In the proposed CMRL project at kathipara location over the existing road flyover due to site constraints, a long-span viaduct is proposed. The viaduct structure is proposed with five spans integral structure with a span arrangement of 58*m*+100*m*+100*m*+95*m*+60*m* with a curvature of 125*m* radius. The superstructure is an insitu box girder with a balanced cantilever structure to carry a double track. The maximum depth of the box girder is 4.475*m* at the pier location and the minimum depth is 2.855*m* at the end of the balanced cantilever portion. The general arrangement and typical cross-sections are shown in Figure 1 to Figure 4. Track structure comprises of two rails in parallel are placed at standard gauge distance with guard rails. The rails are connected to fasteners at distance of 0.650*m* along the track length over the track plinth and the track plinth is casted over the deck slab connected with shear connectors.

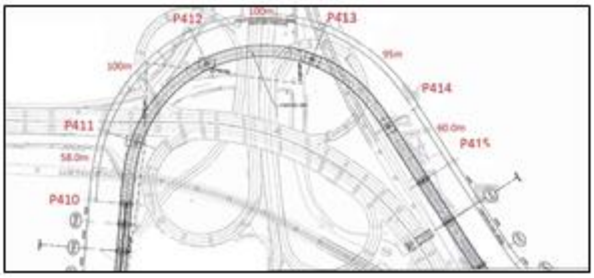


Figure 1: Plan of proposed integral structure

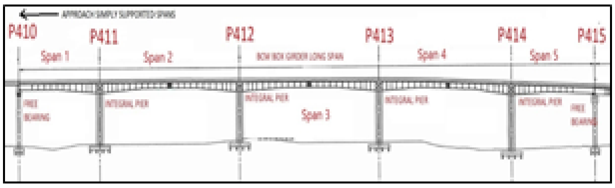
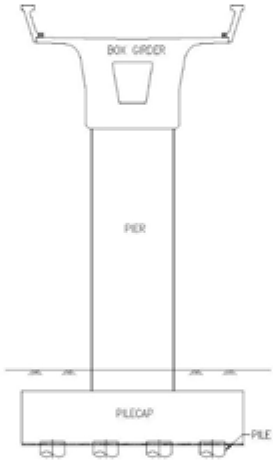
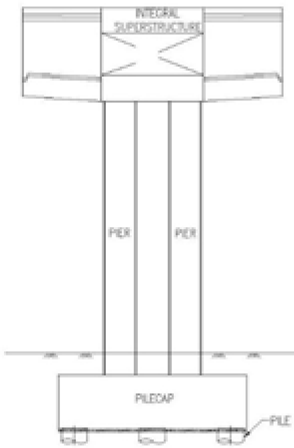


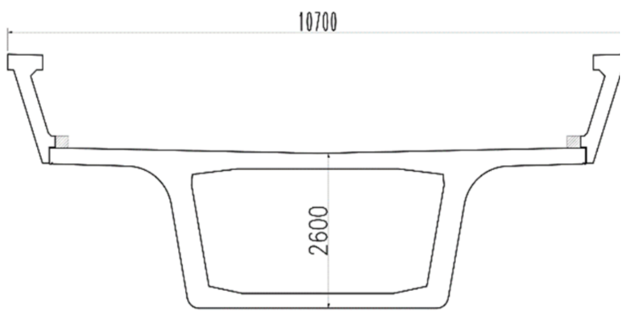
Figure 2: Elevation of the proposed integral structure



(a) Cross section View



(b) Longitudinal View



***(c*) Box Girder Superstructure at mid span**

Figure 3: Structural Arrangements

The substructures are with four intermediate piers as integrated (monolithically constructed) along superstructures and the two end piers of long-span are connected with superstructure through metallic guided free bearing.

The adjacent span of this superstructure structure is continuing with the U girder superstructure. Intermediate piers are of twin column system with rectangle-shaped 4.1*m* in transverse and 1.5*m* in longitudinal, connected monolithically at the top with the superstructure. The height of piers varies from 23.510*m* to 25.500*m*. The end piers consist of single rectangle-shaped columns 3.2*m* in transverse and 2.0*m* in longitudinal connected at the top with a transverse cap beam with free bearing connected to the superstructure. The substructures are supported with a pile foundation and the depth of the pile cap is proposed with 2.5*m* thickness. The foundations of intermediate piers are provided with 12 nos of piles of 1.20*m* diameter. These structural elements are specified as per IRS standards [22] [23].

B. Modelling

For the purpose of nonlinear analysis, finite element method (FEM) software MIDAS CIVIL [24] have been used. The complete viaduct structure of integral long span of 58*m*+100*m*+100*m*+95*m*+60*m* is modelled in the MIDAS CIVIL [24]. In modelling the rail, box girder superstructure, pier columns and piles are modelled as linear element. Pile cap is modelled as two-dimensional plate element. These structural elements are connected using boundary conditions as described in clause II-C. The sectional & material properties of the structural components assigned in the model are presented in Table 1 as follows:

Table 1: Material and sectional properties

Component	Material Properties	Sectional Properties
Rail	E = 2.1 x10^5 N/mm^2 α = 1.2 x10^{-5}	UIC - 60 rail
Box Girder	f_{ck} = 55 N/mm^2 E=3.50 x10^4 N/mm^2 α = 1.17 x10^{-5}	Depth = 2.855m at mid and 4.475m at end / support.
Intermediate Pier	f_{ck} = 35 N/mm^2 E=3.40 x10^4 N/mm^2 α = 1.17 x10^{-5}	Pier size = 4.10*m* x 1.50*m*- twin piers
End Pier	f_{ck} = 35 N/mm^2 E=3.40 x10^4 N/mm^2 α = 1.17 x10^{-5}	Pier size = 3.20*m* x 2.00*m*
Pile & Pile cap	f_{ck} = 35 N/mm^2 E=2.95 x10^4 N/mm^2 α = 1.17 x10^{-5}	Pilecap size = 15.0m x 9.50*m* x 2.80*m* Pile dia = 1.5*m* No of piles = 12 Nos
Pile & Pile cap	f_{ck} = 35 N/mm^2 E=2.95 x10^4 N/mm^2 α = 1.17 x10^{-5}	Pilecap size = 6.60m x 6.60*m* x 1.80*m* Pile dia = 1.5*m* No of piles = 5 Nos

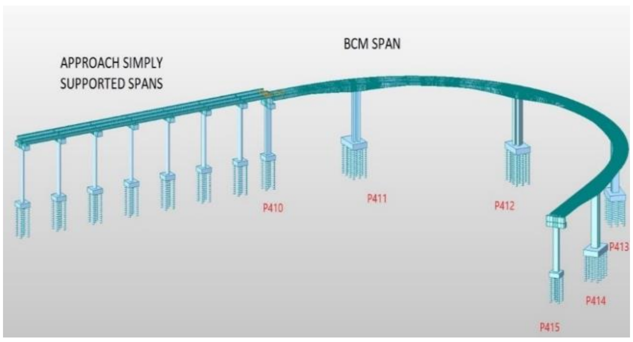


Figure 4: 3D FEM Model

C. Boundary Conditions

The structural components are connected to each other with different boundary conditions based on the behavior of the components. To predict the exact behavior of the components, the proper definition of boundary conditions like an elastic link or rigid link is more important. The boundary conditions of different elements defined in the analysis are shown below Figure 5 to Figure 9.

The details of the track to deck connectivity and superstructure to foundation connectivity are detailed in the following subtopics.

C1) Track- Deck Connections

In metro rail system ballast less track system is adopted with rails connected to track plinth through fasteners spaced at every 0.65m. Since the track is directly connected to the plinth through the fastening system, the stiffness of rail is considered as per UIC 774-3R [2] clause 1.2.2 to represent the bilinear behavior of rail fastening. The fastener stiffness of loaded and unloaded track is shown in Figure 5. And the model has done in the software as shown in Figure 6, Figure 7, Figure 8 and Figure 9.

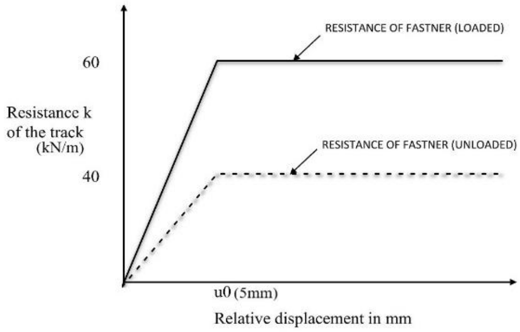


Figure 5: Stiffness of fasteners

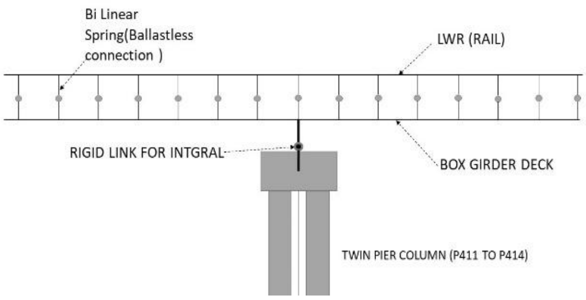


Figure 6: FE link at integral pier & deck

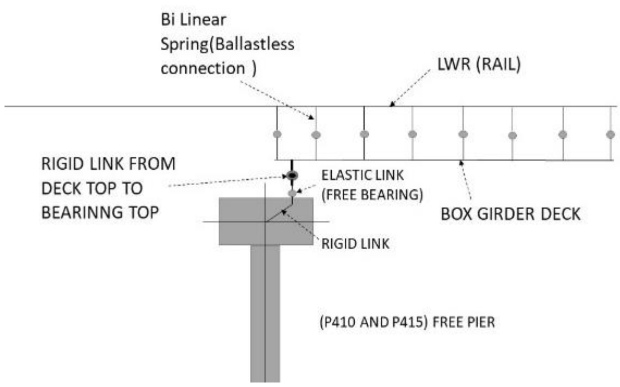


Figure 7: FE link at free pier & deck

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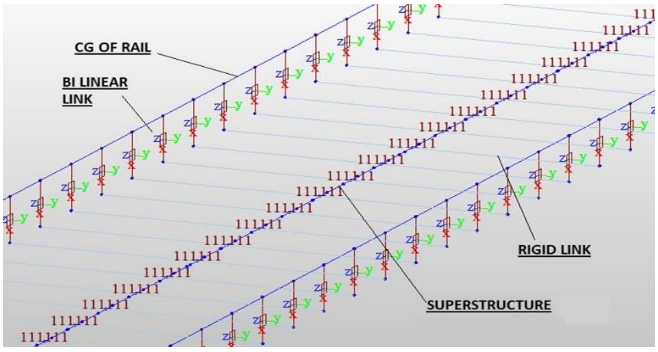


Figure 8: FE model track and deck boundary condition

C2) Structural Connections

The intermediate girder at P411, P412, P413, and P414 are connected to the pier as rigid connection since it is an integrated connection. The end pier P410 & P415 are connected by free metallic guided bearing, and it is defined elastic link with rotations and movements allowed.

The pier to pile cap & piles to pile cap are rigidly connected at center of mass as shown in Figure 9. The pile is modelled with rigid support at the bottom at founding level and lateral point soil springs at unit meter interval based on the subgrade modulus of soil refer to IS 2911 [25] as per bore hole soil strata

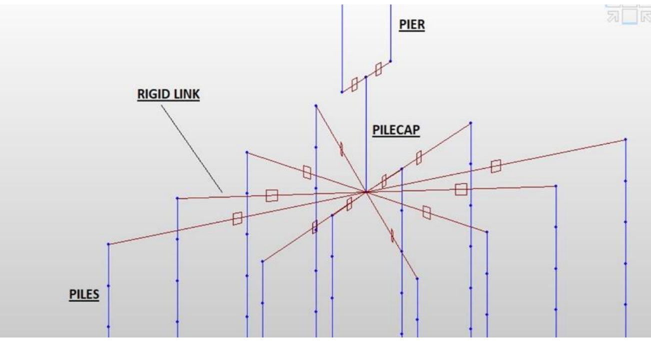


Figure 9: Pile, Pilecap & Pier connections

D.The Applied Loading

The rail structure interaction is induced by temperature effect, braking/traction and vertical load on the superstructure, all these forces are applied for this study. The analysis is carried out by applying a uniform temperature variation increase/decrease of $\Delta T = 26.25^0$C at the Chennai region as per IRC 6 [26]. The temperature load is applied in the deck and modelled in Figure 10 as per UIC specifications. The train live load is applied as Modern Rolling Stock type with 16 Mton axle load as per Chennai metro standard. The UDL 37.00kN/m is applied with considering the dynamic augment for 126.4m length of six successive cars. To achieve the critical effect of longitudinal force, the tractive force and the braking force are applied in same direction.

Traction force is considered as 18% of un factored vertical live load. And the braking force is considered as 15% of the unfactored vertical live load. The live loads are applied as per Chennai metro railway standard. Curvature load is also applied as transverse force along with vertical load as per IRS bridge rule [23]. The analysis is carried out for loaded and unloaded condition with relevant track stiffness as per UIC standards [2].

Under live load combinations, single track and two track loaded conditions are studied to get the worst effect. The live loads are positioned at 5 locations which creates a critical load effect on the 5 spans of integral structure. The loading position and combinations are shown in Figure 11 and Table 2.

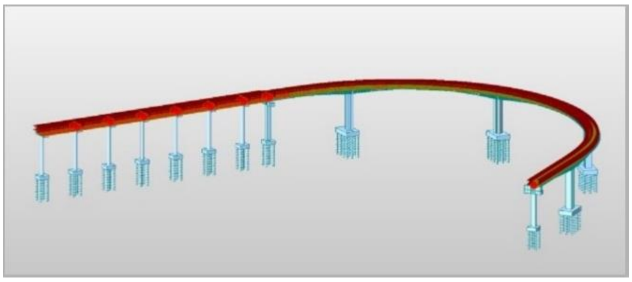
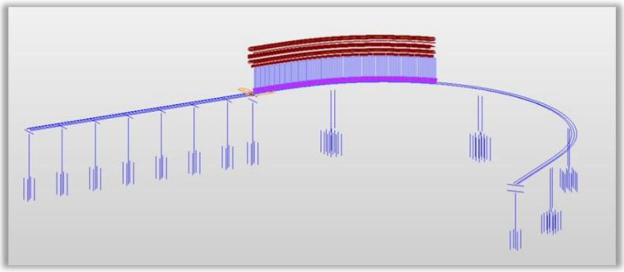
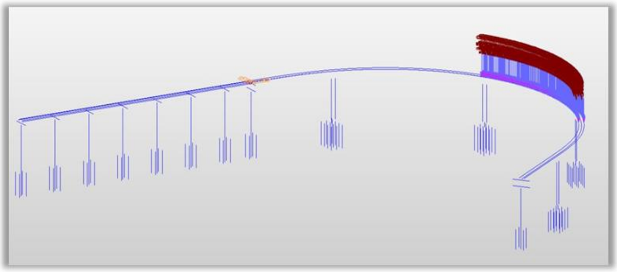


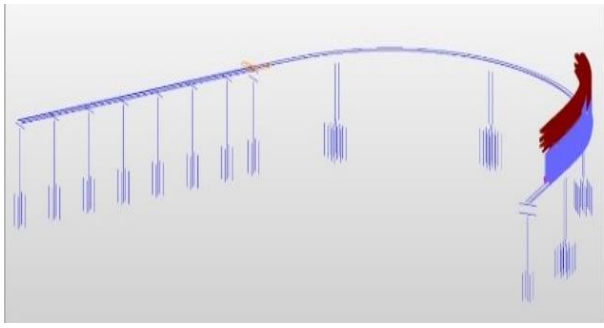
Figure 10: Temperature Load In Deck Positive and Negative Variation



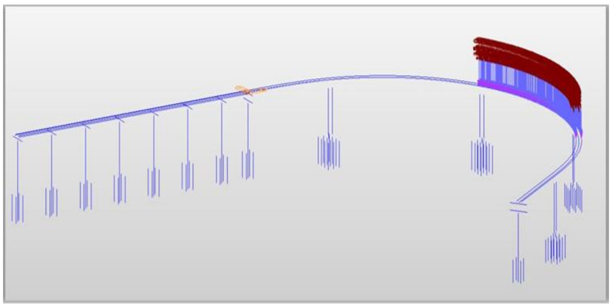
Live Load position 1 (Critical at span 1)



Live Load position 2 (Critical at span 2)



Live Load position 3 (Critical at span 3)



Live Load position 4(Critical at span 4)

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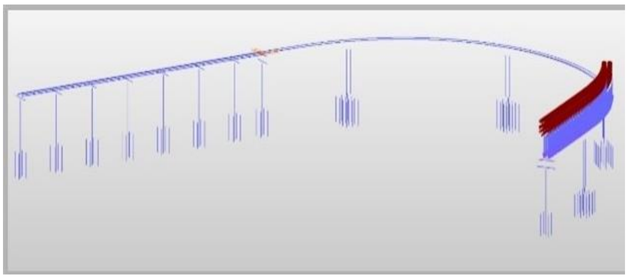


Live Load position 5 (Critical at span 5)

Figure 11: Live load positions

III. RESULTS AND DISCUSSION

Rail structure interaction of the long span integral structure is analyzed with the above said parameters. It is observed that the rail stress pattern for the integral structure under temperature and live load cases varies from typical simply supported structures. The rail stress and forces for the integral and simply supported structure for the same span arrangement is studied and compared. The variations of the results for this change in boundary conditions are tabulated and shown in graphs. Also, maximum additional tensile/compressive stress in rails are verified with permissible stress of 92 N/mm^2 for the unballasted track as per clause 1.5.2 of UIC 774-3R [2]. The difference in rail stress for various load cases is described in the following topics. The rail stress results of the RSI analysis for the integral BCM spans (58m+100m+100m+95m+60m) for various load cases are in Table 3.

Table 3: Resultant Summary

Kathipara Long Span	Unloaded case	Loaded case	
	Axial temperature case in N/mm^2	Vertical LL + Braking/Traction + Centrifugal + Temperature in N/mm^2	Allowable Stress as per UIC 774-3R in N/mm^2
Maximum Compressive Stress	14	+21.5(Case 2)	+92
Maximum Tensile Stress	-14	-26.6(Case 1)	-92

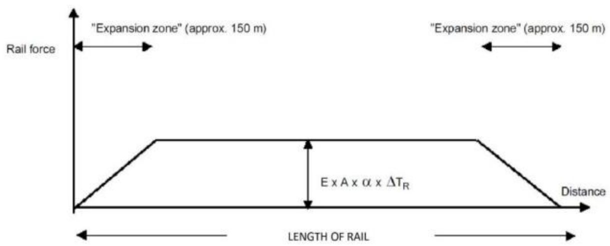
* The live loads are applied at five positions for worst case as shown in Figure 11

Table 2: Load combinations

COMBINATIONS	TEMPERATURE	VERTICAL LIVE LOAD WITH IMPACT*	TRACTIVE*	BRARKING*	FASTNER STIFFNESS
COMB 1	+ IN DECK				Unloaded
COMB 2	- IN DECK				
COMB 3	+ IN DECK	Position 1 to 5	Positive direction at track 1	Positive direction at track 2	Loaded
COMB 4	+ IN DECK	Position 1 to 5	Opposite direction at track 1	Opposite direction at track 2	
COMB 5	+ IN DECK	Position 1 to 5	Positive direction at track 2	Positive direction at track 1	
COMB 6	- IN DECK	Position 1 to 5	Opposite direction at track 2	Opposite direction at track 1	
COMB 7	- IN DECK	Position 1 to 5	Positive direction at track 1	Positive direction at track 2	
COMB 8	- IN DECK	Position 1 to 5	Opposite direction at track 1	Opposite direction at track 2	
COMB 9	- IN DECK	Position 1 to 5	Positive direction at track 2	Positive direction at track 1	
COMB 10	- IN DECK	Position 1 to 5	Opposite direction at track 2	Opposite direction at track 1	

A.Rail Stress Due To Temperature Variations

For the LWR track, the stress diagram in the rail due to the temperature variation in rail is shown in Figure 12 as per UIC standard [2]. As per clause 1.4.2 of UIC 774-3R [2], it is understood that change in temperature in the rail does not influence the interaction effect and only stress will be developed in the rail.



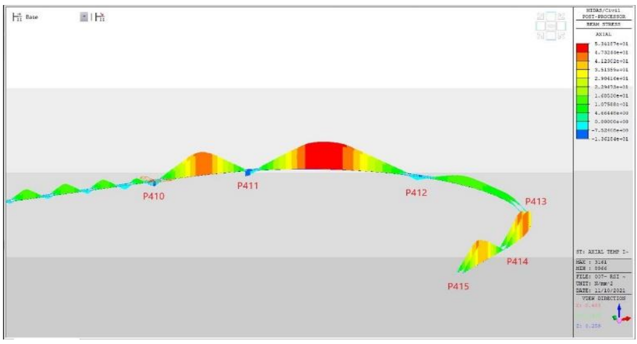


Figure 12: Rail Stresses Due to Temperature Variations in Rail

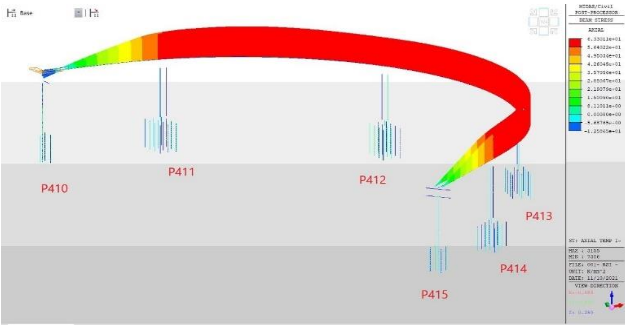


Figure 12: Rail stresses due to temperature variations in the deck at BCM span.

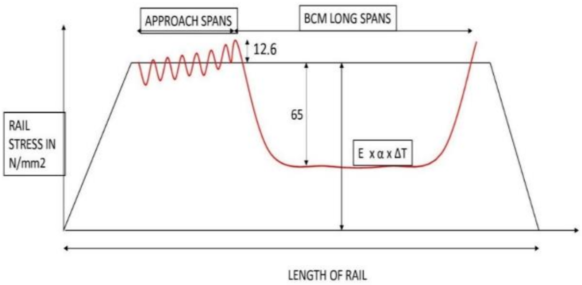


Figure 13: Rail stresses due to temperature variations in the deck at BCM long span with combined effect

As per analysis, it is noted that due to increase in deck temperature, the tensile stress in rail is obtained as 63.1 N/mm^2 due to the interaction effect. However, the rail is subjected to compressive stress during temperature increases. Thus, temperature variation in integral structure is not generating the addictive stress in the rail due to the interaction effect. The rail stress pattern due to temperature increase by the interaction effect is shown in red color in the Figure 13 and Figure 14. For the same span arrangement, the simply supported boundary condition is applied and analyzed. The additional rail stress due to deck temperature variation is 13.6 N/mm^2 at simply supported locations as shown at expansion joint as in the Figure 15 Figure 16. It is observed from the analysis, the integral behavior of structure does not generate additional stress in rail due to temperature increase by the interaction effect. The above-said stress is vice versa for the temperature decrement case and no additional stress is generated for the integral portion of the structure.

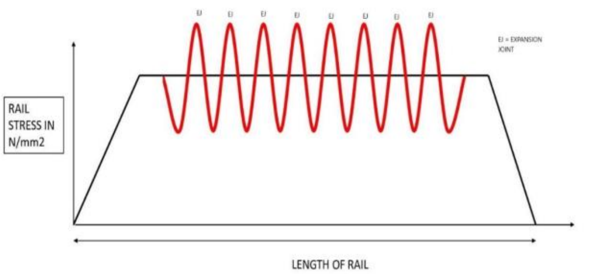


Figure 14: Rail Stresses Due to Deck's Temperature Variations for Simply Supported & Results From MIDAS.

B. Rail Stress Due To Live Load

Among all the live load cases, Load case 1&2 gives the maximum rail stress. The stress pattern for the same is presented in figure 16. The maximum tensile and compressive stress due to live load at integral span is +22.12N/mm^2 and -21.5N/mm^2 respectively.

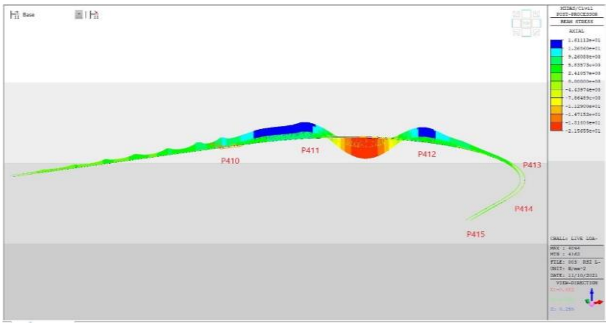


Figure 15: Rail Stresses Due To Live Load For Integral Span

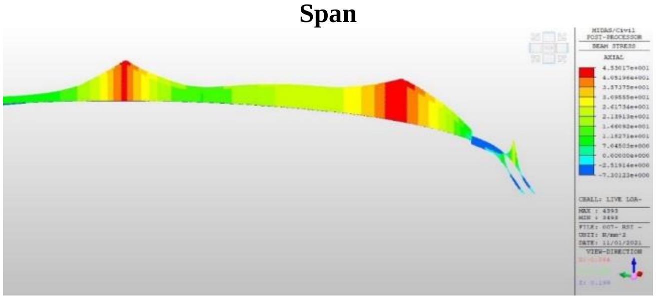


Figure 16: Rail Stresses Due To Live Load For Simply Supported Span.

For the comparison purpose, simply supported span boundary condition with same live load case is analyzed. The maximum compressive and tensile stress are obtained as +7.3N/mm^2 and -45.3N/mm^2. The stress pattern for the same is shown in the above Figure 17.

C. Additional rail stress for combined effect (envelope).

The envelope of rail stress in integral span for combined effect of temperature & live load is shown in figure. The maximum additional stress for considering all combination as per Table 3 is -26.6 N/mm^2 at integral portion which is lesser than -52 N/mm^2 the simply supported spans.

As per stress envelope from MIDAS CIVIL [24] for the combined effect, the critical additional stress location for integral bridge due to live load only. The maximum additional stress at these locations is -26.6 N/mm^2. It is also verified with the permissible value of 92 N/mm^2 as recommended in UIC 774-3R [2].

IV. SUMMARY AND CONCLUSION

This paper presents the RSI analysis of integral balanced cantilever bridge using FEM based analytical tool. The study aimed on the analysis of the rail axial stresses and forces to the substructure due to RSI. The RSI analysis carried out for the three separate load cases such as temperature variation in deck, tractive/braking force, and vertical bending of deck due to live load as per UIC standards. From the analysis results, the change in rail stress due to integral behavior are presented graphically along the bridge. The following conclusions can be drawn from the obtained results.

- Due to temperature variation in the deck, the RSI effect is not creating additional stress in the rail at the integral portion of the structure since it is counteracting the rail stresses developed due to temperature change in rail.
- If the structure is integral, the additional stress in rail will be generated only due to live load.

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DOI: 10.35940/ijrte.F6786.0310622
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• The interaction effect will create the worst effect in case simply supported bridges than integral structure at intermediate piers.
• In case of rail stress are exceeding in long-span structure under simply supported conditions, instead of Switch Expansion Joint proposal at rail can be checked with integral structure as an alternative option without altering the span arrangement.

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