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Study of Rail Structure Interaction on Double-Decker integrated bridge with Metro and Highway Structure

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Abstract: ***In the metro rail system, Long Welded Rails (LWR) have been used for less maintenance, smooth & safe ride at higher speeds. The arrangement of connecting rail and deck system causes an interaction effect in force transfer. The study of this effect in the structure is Rail Structure Interaction (RSI) analysis. In this study, the behavior of double-decker integrated structure, rail stresses and relative deformation are studied due to the bending behavior of the deck, bearing articulation & support stiffness with the proposed geometrical arrangement of the bridge and applicable loading as per standards. The effect of RSI analysis and limitations of additional stresses are referred with the guidance of UIC standards & RDSO guidelines. The double-decker elevated viaduct structure is proposed with a first level highway deck carrying highway loading and second level metro system carrying metro loading. In highway bridge deck, the decks are proposed with four span continuous to avoid discomfort due to more number of expansion joints and thereby provide smooth riding for passengers. The effect of RSI is studied in this paper by considering the above complexity of two-level superstructure with a different type of superstructure at the metro level due to the track requirement like U girder deck system at each track, I girder deck system as a single deck for both the tracks at the cross over / pocket track locations and I girder deck system at highway level with deck continuity. A finite element analysis is performed using the analytical tool MIDAS CIVIL software to study the interaction mechanism for this double-decker bridge structure. For this study, rail and deck (unballasted) are linked with a multilinear elastic spring as recommended in UIC 774-3R and other boundary conditions as per IRS & IRC standards. This paper discusses the behavior of structure from the results of the rail stresses and forces to the substructure due to thermal and live load effects at both level Metro Rail system and Highway Road systems.***

Index Terms: ***Double-decker bridge, Rail structure interaction (RSI), Metro Rail system, Highway bridge, Long welded rail (LWR), Integrated structure.***

I. INTRODUCTION

Highly populated countries like India are getting developed with urban transportation with integrated metro bridges in cities.

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A large volume of people are transported quickly using this metro system. The metro structure is generally either an underground structure or an elevated metro viaduct system. Due to constraints on land in highly populated areas & demolition of monumental structures in metro cities, the requirement of underground structures may get mandatory. But the overall cost of underground metro structures is high comparatively with elevated metro structures. The elevated metro structures are limiting the development of infrastructure of other transportation in metro cities. Hence the option of an integrated multilevel bridge is an optimum with cost-effective, construction easiness and provides parallel development of urban transportation. In this study, the integrated double-decker bridge proposed with a first level of structure carrying road traffic and a second level of structure carrying rail traffic proposed in Chennai Metro corridor 2 is considered. In this integrated structure, at the first level of highway traffic, it is a four-span deck continuous system and at the second level of the metro, the rail is continuous to facilitate the smooth and fast riding quality. In general metro rail, the longitudinal welded rail (LWR) has been used for riding comfort and enhance less maintenance & safety. The interaction between connecting rail and bridge has been studied by various researchers in railway bridges. Normally the LWR and the bridge structure are connected using fasteners over the track plinth for the metro system. So, stress or deformation in one element induces stress or deformation in another element. This is called the Rail Structure Interaction (RSI) effect. Displacements in bridges/tracks are developed due to temperature changes, braking/traction due to train & road vehicles and corresponding vertical loads. Additional stress in the rail, relative 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 [1], LWR manual [2] and RDSO guidelines [3] guide the 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 property of rail of UIC 60 in the IRS Track Manual in page 1 of 6 of IRS track manual [4] is considered. The RSI effect has been studied by many researchers [5]-[20] and considered as reference. Ó. Ramos Gutiérrez, F. Schanack, G. Carreras and J. Retuerto[5] discuss the structural response due to length of bridge and number of expansion joint as per European standard.

They stated that the rail stresses are higher on embankment compared to bridge portion since the deformation is fully restrained at the embankment. M. Touati, N. Lamdouar and L. Bouhlal [6] explain the methodology of RSI analysis to control the stability of the track. R. Okelo and A. Olabimtan [7] explained that the effect of lateral forces transferred to the substructure is negligible. And they state that acceleration and braking of training moving in opposite directions gives the worst effect. R. Kumar and A. Upadhyay [8] explain the effect of temperature gradient on track-bridge interaction. B. J. Shah and S. K. Surti [9] 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 the rail structure interaction effect. 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 in UIC 774-3R [1].

Ahammed Ali ,Ramesh. K.Y and Sisir.P [10] concluded that the effect of actual bearing articulation along with stiffness affects the response of RSI analysis.

The response due to the RSI effect depends on the behavior of the deck, support stiffness, bearing articulation & and stiffness, static arrangement of the bridge and applied loading like temperature, creep & shrinkage, and live load [11] – [14].

In recent years with the advancement of bridge construction, special types of structures have been used in railway bridges. The special type of superstructures are such as skewed steel bridges [7], extra-dosed/ cable-stayed bridges [15], arch bridges [16], integral railway rigid frames [17], sliding slab track on bridges [18] and the recent trend of high-speed railway bridges [19],[20],[21].

The double-decker superstructure with train and road traffic integrated with substructure is proposed as per the requirement of the project and modernization in urban transportation. The study of RSI on this integrated bridge is challenging for modeling and analyzing its behavior. The effect RSI is one of the important influencing factors in controlling the horizontal force on the substructure and deciding the geometry of the structure to make the structure safe for rail stresses. In this paper, an attempt has been made to understand the effect of RSI in the double-level integrated bridge.

The detailed objectives of this study are listed below.

1. Develop a finite element model of the integrated bridge by considering the soil structure interaction parameter for the foundation, conventional bridge elements, long welded rail, approach span and track structure fasteners as multilinear springs.
2. Analyze the effect of RSI for different nonlinear stiffness of the track in both unloaded and loaded conditions.
3. Effect of additional rail stress due to temperature variation, tractive/ braking force, and vertical live load throughout the spans for both level metro and road loading.
4. Study the behavior of integral structure with the results of rail stress against the limitations given in the recommendation in page 17 of RSI guideline [3] and force on substructure due to RSI.

II. ANALYSIS

A. Geometry

In this study, the integrated double-decker viaduct proposed in the CMRL project -corridor 2 for a length of 3.0km with the first level carrying a highway structure over the existing road and the second level carrying a metro structure is considered. For analysis, a critical stretch of length 500m with typical spans of 20 Numbers x 25m is considered with a Prestressed I girder deck system at a first level above the existing road for highway structure and I girder at pocket tracks, U girder deck system at normal tracks at the second level metro system. The general arrangement and typical cross-sections of the integrated bridge are shown in Figure 1 to Figure 4. The track structure comprises two rails in parallel are placed at standard gauge distance. The rails are connected to fasteners at a distance of 1.0m along the track length over the track plinth and the track plinth is casted over the deck slab connected with shear connectors.

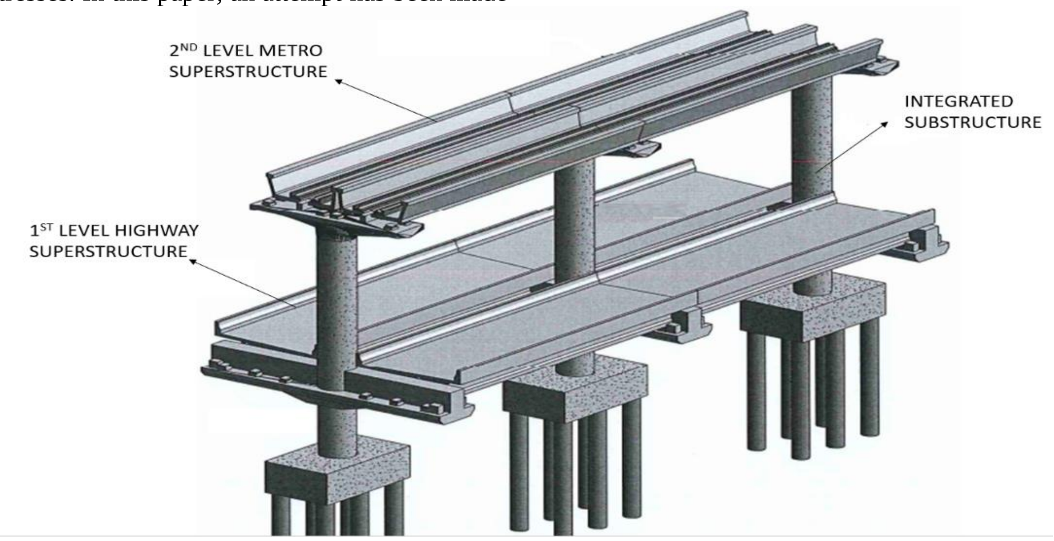

Figure 1: 3D isometric view of double-decker integrated bridge structure

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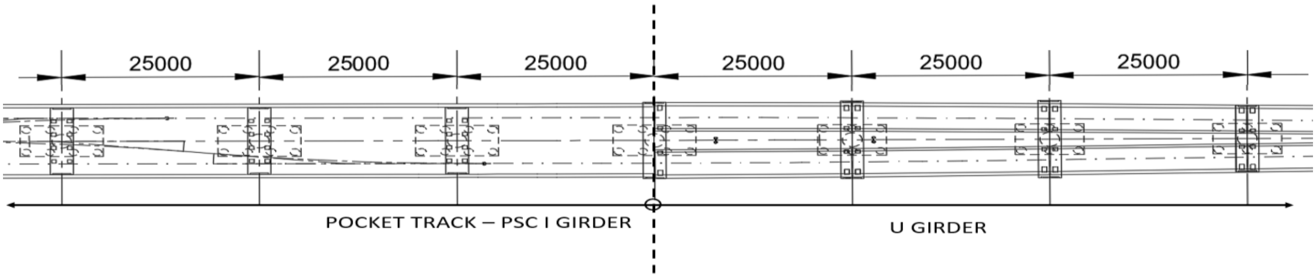

Figure 2: Plan of proposed structure

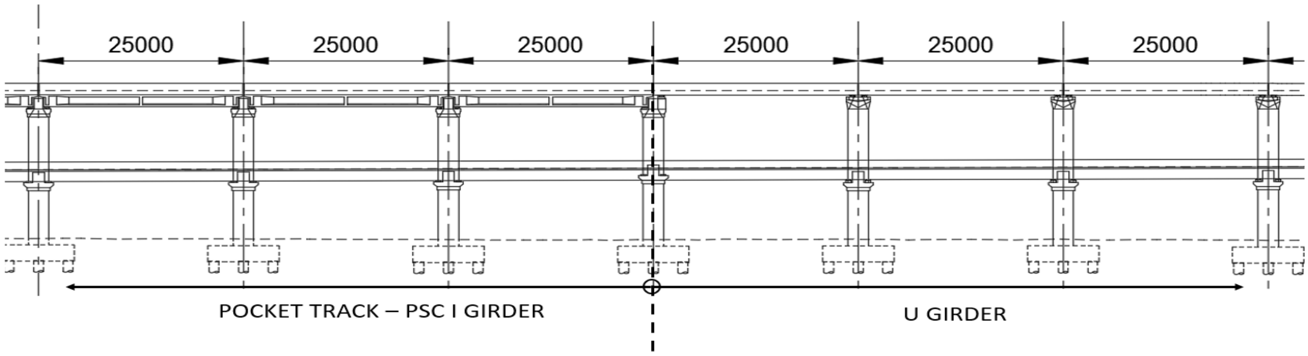

Figure 3: Elevation of the structure

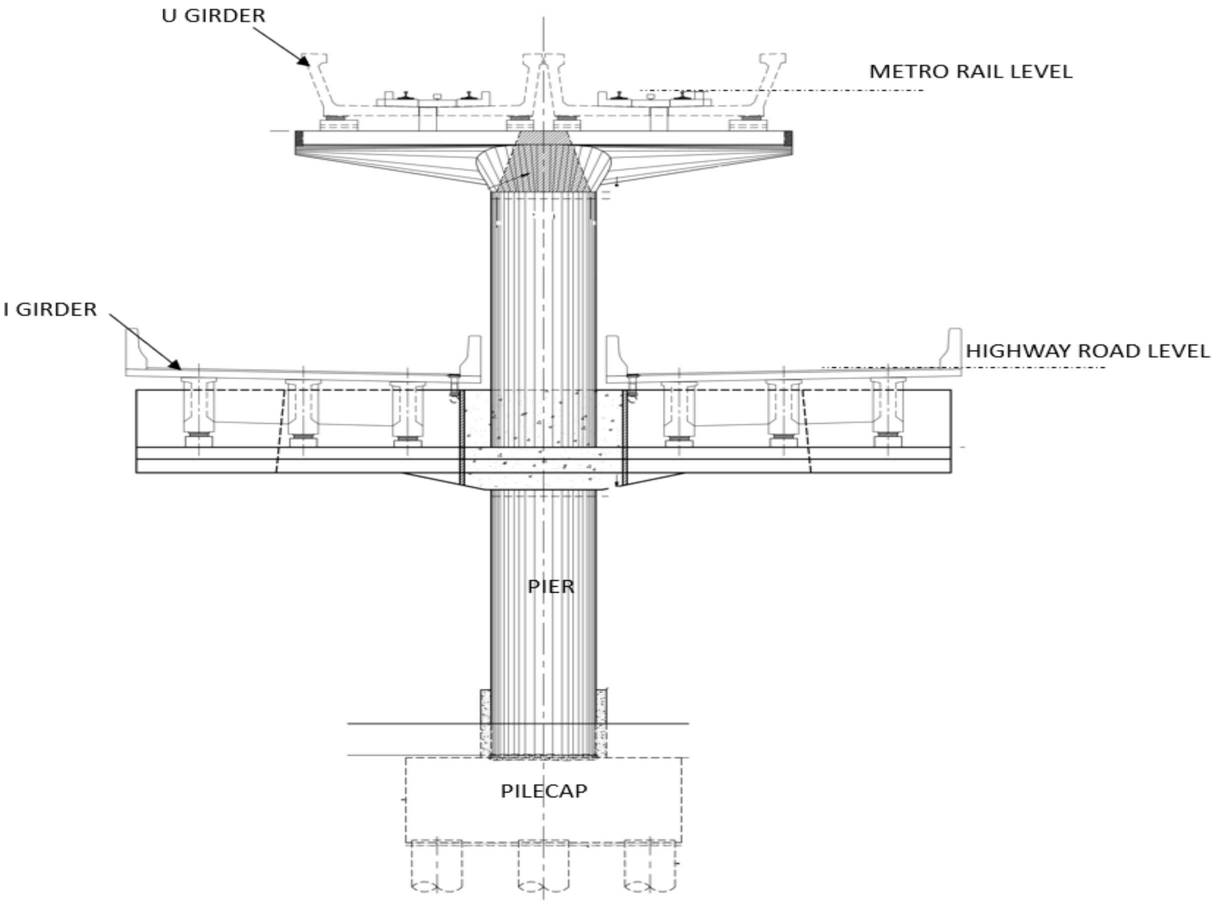

Figure 4: Cross section View

The depth of the I girder is 1.8m including the deck thickness. The substructure piers are proposed with circular and rectangle shape. The superstructures at both levels are rested over the pier cap with bearing articulation of elastomeric bearings and RCC restrainer is proposed for transfer of longitudinal forces. The height of piers varies from 18.0m to 23.0m from existing ground/road to rail level to accommodate the vertical clearance of existing road traffic and first-level highway traffic. These structural elements are following the specifications as per IRS standards [22] [23]. The deck continuity at highway level superstructure is followed as per the guideline of IRC SP66 [27].

B. Modelling

For this analysis, the finite element method (FEM) software MIDAS CIVIL [24] has been used. The viaduct structure of a span of 500m is modeled in the software [24]. The rail as per UIC 60[4], I girder superstructure, U girder superstructure, piercap, pier columns and piles are modeled as per geometry. Pile cap is modeled as rigid connecting elements per IS 2911 [25] and IRC 78 [28] specifications. These structural elements are connected using boundary conditions as described in chapter II-C. The sectional and material properties of the structural components assigned in the model are presented in Table 1 as follows:

I. 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
I girder-Highway level	f_{ck} = 50 N/mm^2 E=3.40 x10^4 N/mm^2 α = 1.17 x10^{-5}	Depth = 1.6m
I girder-Metro level	f_{ck} = 50 N/mm^2 E=3.40 x10^4 N/mm^2 α = 1.17 x10^{-5}	Depth = 1.6m
U girder	f_{ck} = 55 N/mm^2 E=3.50 x10^4 N/mm^2 α = 1.17 x10^{-5}	Depth = 1.820m
Pier	f_{ck} = 50 N/mm^2 E=2.95 x10^4 N/mm^2 α = 1.17 x10^{-5}	Pier size = 2.5m diameter
Pile & Pile cap at Pocket track location	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 = 1.2*m* No of piles = 8 Nos
Pile & Pile cap at standard pier location	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 = 1.2*m* No of piles = 6 Nos

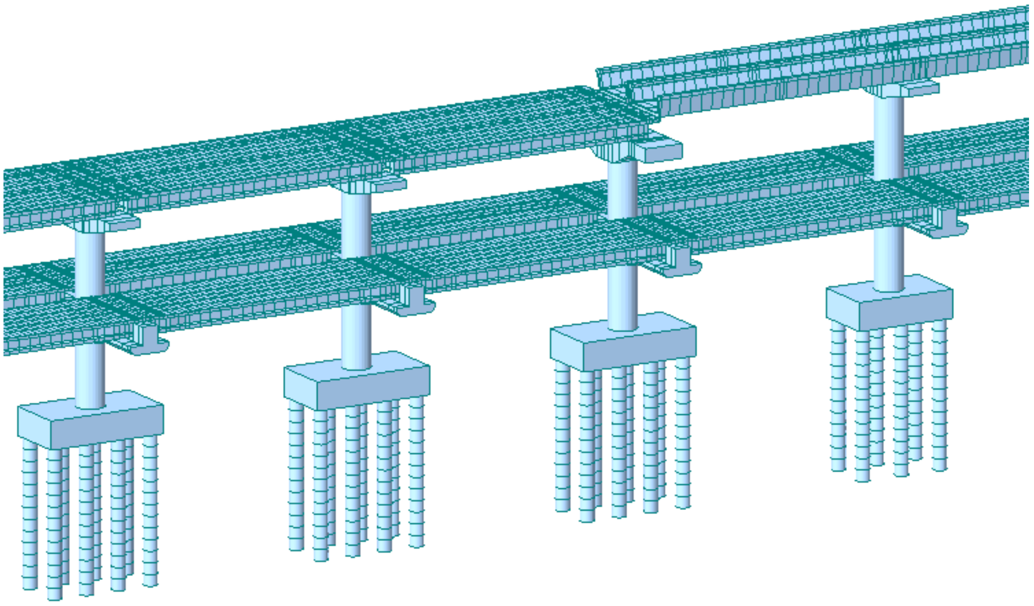

Figure 5: 3D FEM Model -Integrated Double decker

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C. Boundary Conditions

The structural components are connected to each other with different boundary conditions as per the actual conditions of the bridge components. To predict the exact behavior of the complete structure, the proper definition of boundary conditions is more important. The various boundary conditions of different elements defined in the analysis are shown below from Figure 6 to Figure 11.

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

C1) Track- Deck Connections

In the metro rail system, a ballast less track with rails connected to the track plinth through fasteners spaced at every 1.0m is considered. Since the track is directly connected to the plinth through the fastening system, the stiffness of the rail is considered as per UIC 774-3R [1] clause 1.2.2 to represent the bilinear behavior of rail fastening. The fastener stiffness of the loaded and unloaded track is shown in Figure 6. and the software model of the same considered in the analysis is shown in Figure 7 to Figure 9.

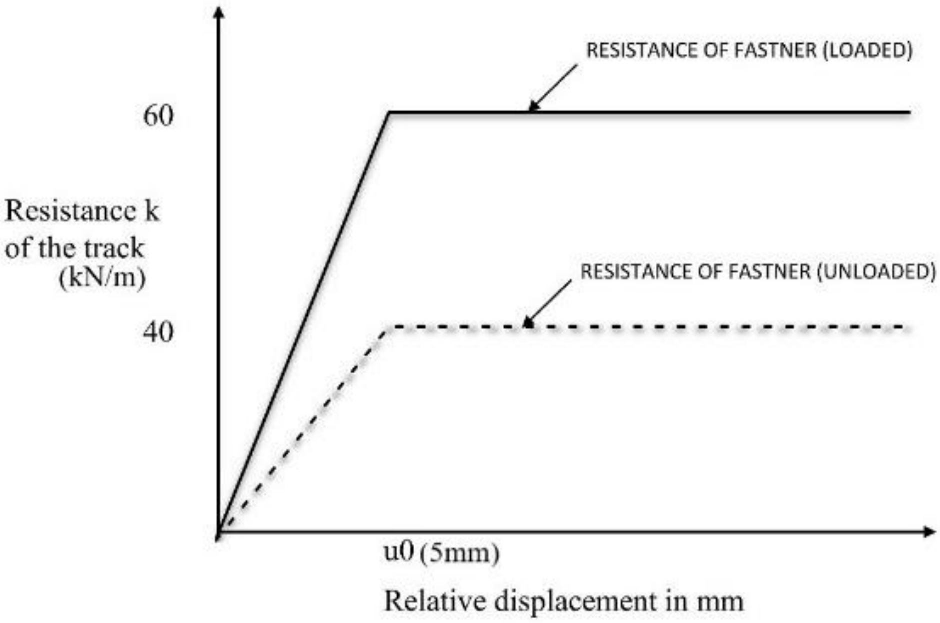

Figure 6: Stiffness of fasteners as per UIC 774 3R

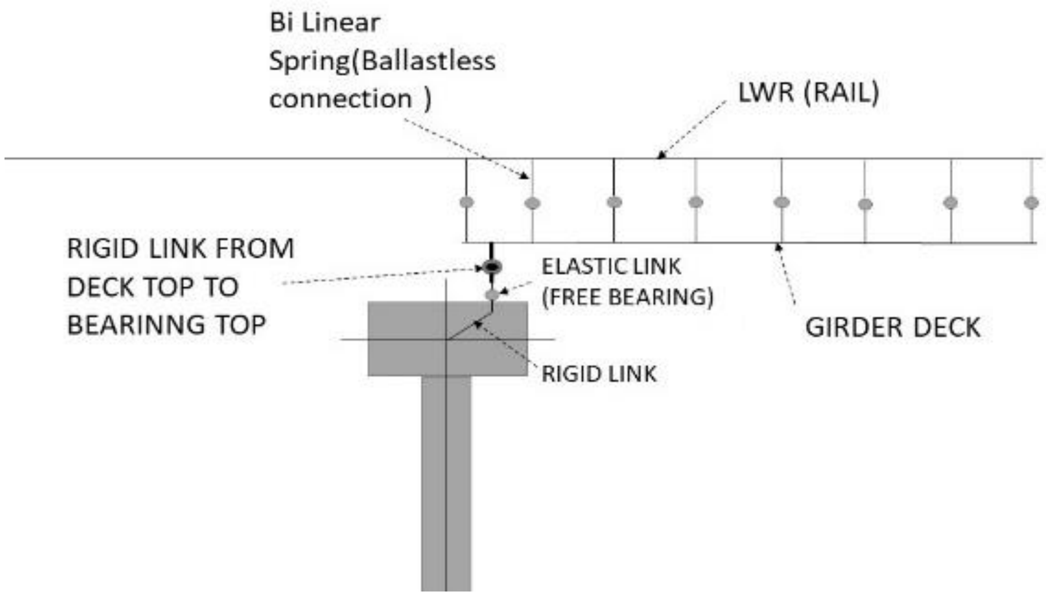

Figure 7: Link pier & deck

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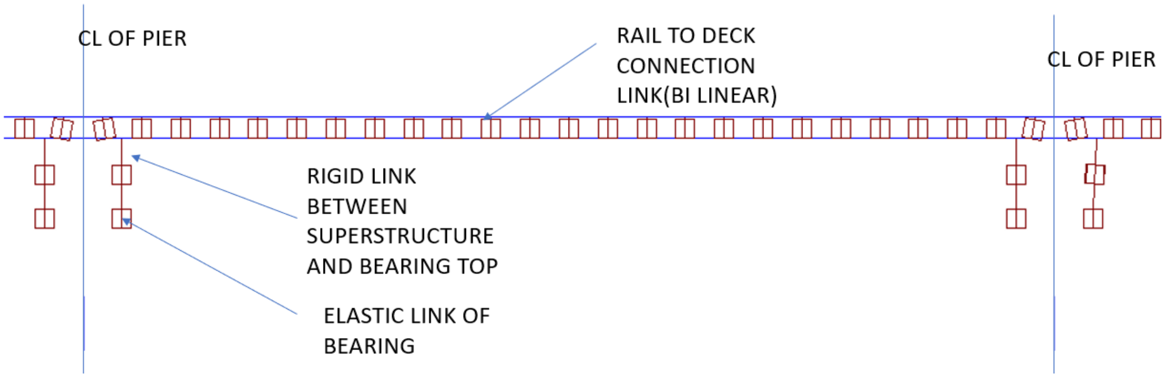


Figure 8: FE model track and deck connection

C2) Structural Connections

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 at lateral with soil springs at unit meter height interval based on the subgrade modulus of soil in reference with IS 2911 [25] as per actual borehole soil strata.

The pier cap is connected to the pier using a rigid link since the pier cap to the pier is monolithically connected. The superstructure resting over the pier cap through an elastomeric bearing, an elastic link with calculated stiffness of elastomeric bearing is connected from the soffit of the superstructure to the pier cap at both the levels of the superstructure as shown in Figure 10.

In highway level superstructure, since four-span deck continuity is proposed, a moment released elastic connection is considered between the decks as per proposed deck continuity to account for this effect. The rotation is allowed at the deck connecting slab as per IRC SP 66 [27] as shown in Figure 11.

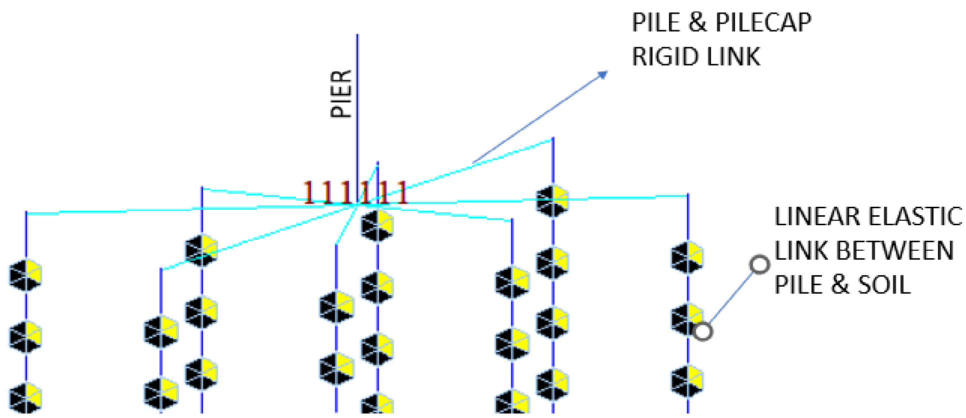
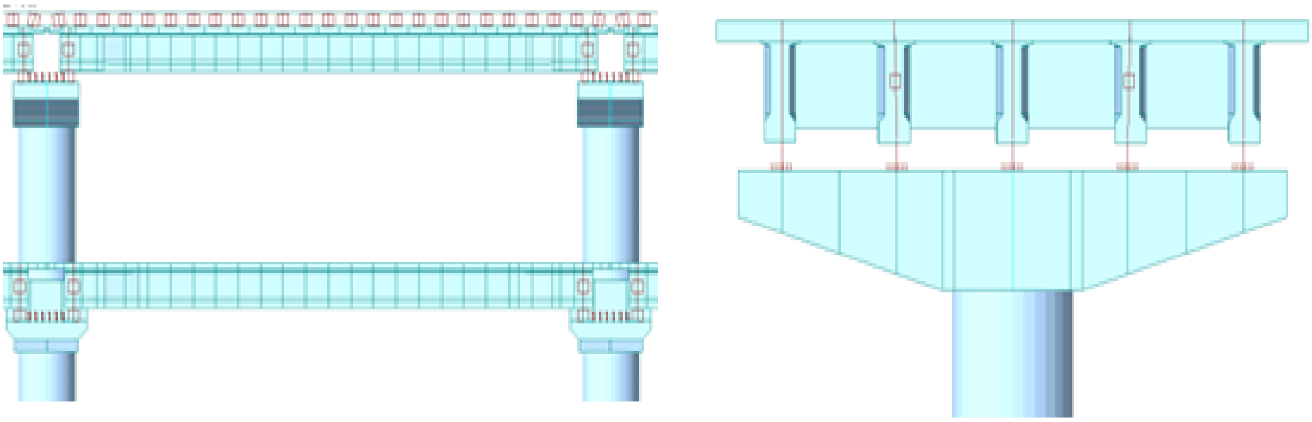


Figure 9: Pile, Pilecap & Pier connections



a) Longitudinal view of connections at both levels

b) View at Metro level connection

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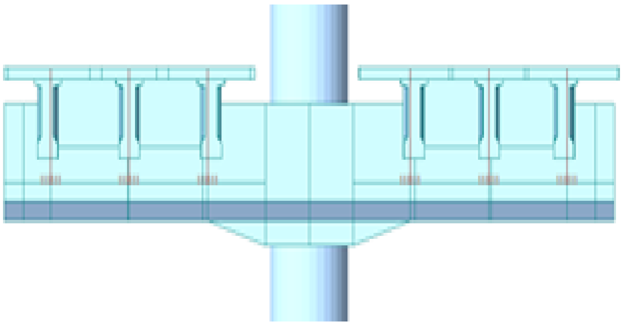


c) View at Highway level connection.

Figure 10: Deck & substructure Connections

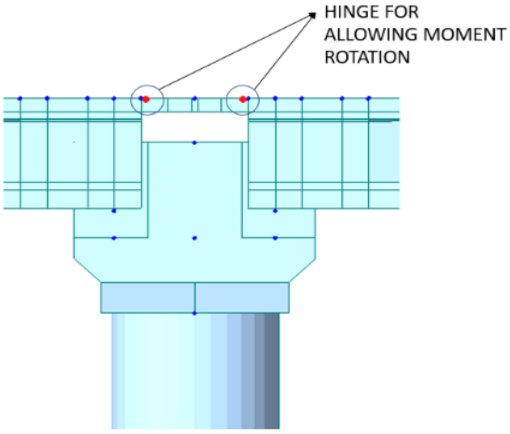


Figure 11: Deck continuity connection

D. The Applied Loading

As stated in UIC 774-3R [1], the rail structure interaction is induced by temperature effect, braking/traction and vertical load on the superstructure, all these forces are applied on the structure for this study. The analysis is carried out by applying an uniform temperature variation increase of ΔT = 13.125^{0}C and a decrease of ΔT = 26.0^{0}C including shrinkage effect for the Chennai, India region as per clause 215 of IRC 6 [26]. The temperature load is applied in the deck in the model.

At the second level, the train vertical live load of 16 Mton axle load is applied as UDL of 37.00kN/m with the dynamic augment for a length 126.4m of six successive cars as per metro specifications.

The train longitudinal traction force of 18% of un factored vertical live load and the braking force of 15% of the unfactored vertical live load is applied as per metro specifications. To achieve the worst effect of longitudinal force, the tractive force and the braking force are applied in the same direction for both track loaded conditions corresponding to vertical live load. The analysis is carried out for loaded and unloaded conditions with relevant track stiffness as per clause 1.2.2 of UIC standard [1]. The live loads are applied at various critical positions

Case 1. At the pocket track on PSC, I girder superstructure, Case 2. At partially on pocket track on PSC I girder and partially on U girder superstructure next to pocket track, Case 3 at completely on U girder superstructure.

At the first level, highway live loads are applied as per IRC 6 specifications[26]. Two class A vehicle loads are applied as critical cases with 20% of vertical load as longitudinal load (braking load) as per IRC 6.

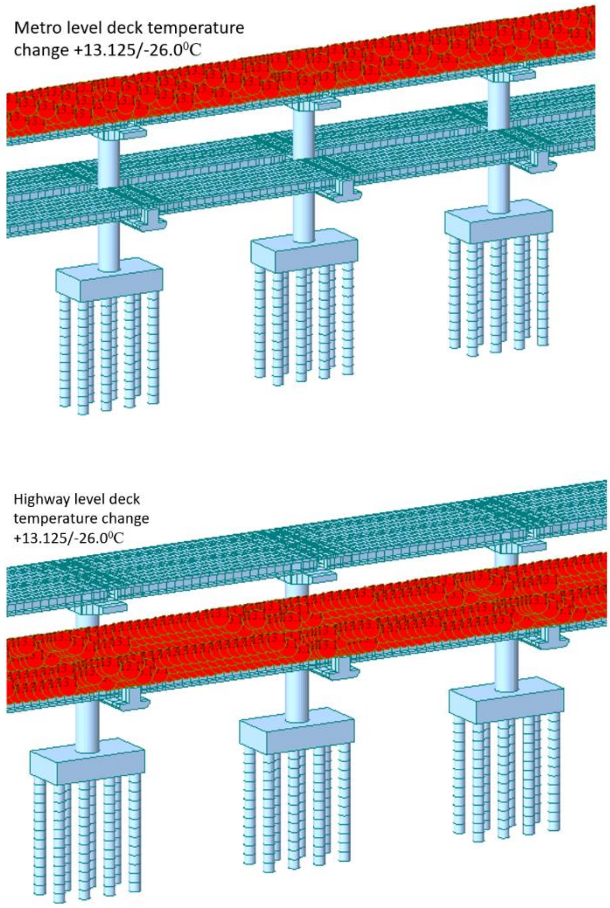
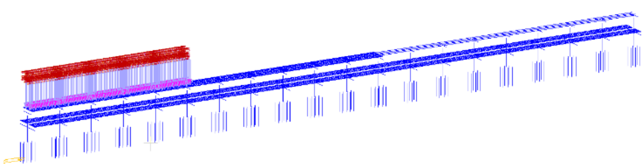
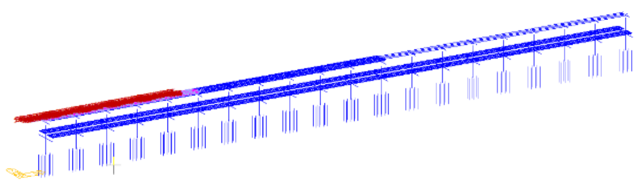


Figure 12: Temperature load in deck positive and negative variation



a) Metro level -vertical live load (Case 1)



b) Metro level – Longitudinal Tractive/braking load. (Case 2)

Figure 13. Typical Metro level live load at pocket track location

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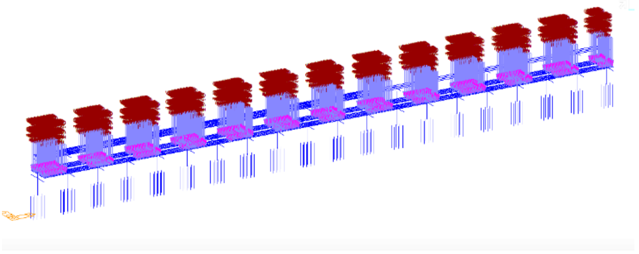
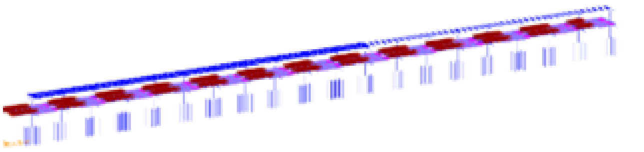


a) Highway level vertical live load



b) Highway level – Longitudinal Tractive/braking load.

Figure 14: Highway load applied on the model.

III. RESULTS AND DISCUSSION

From the Rail structure interaction analysis of the double decker integral structure with the above said parameters, it is observed that the behavior under rail stress is not having any difference in stress pattern when compared with a typical metro structure without any integrated superstructure. However, the magnitude of rail stress is increased due to the integrated double deck structure under temperature and live load application. The rail stress pattern of alternate tension is changed to compression at pocket track location with deck continuous at metro level in temperature increase and vice versa in temperature decrease. The maximum rail stress and forces at the substructure from the analysis for the considered geometry is summarized in below table II and III.

From the summary, the maximum additional tensile/compressive stress in rails are obtained as 64.3 N/mm^2 and 77.6 N/mm^2 respectively due to the interaction effect and found within the permissible stress value of 92 N/mm^2 for the unballasted track as per page 17 of RSI of guideline[3]. The differences in rail stress for various load cases are presented in the following topics.

A. Rail Stress Due to Temperature Variations

For the LWR track, the stress diagram in the rail due to the temperature variation in the rail is shown in Figure 15 as per Figure 1 of UIC standard [1]. As per clause 1.4.2 of UIC 774-3R [1], a change in temperature at the structure will impact in the additional stresses in the rail and forces developed in the structure.

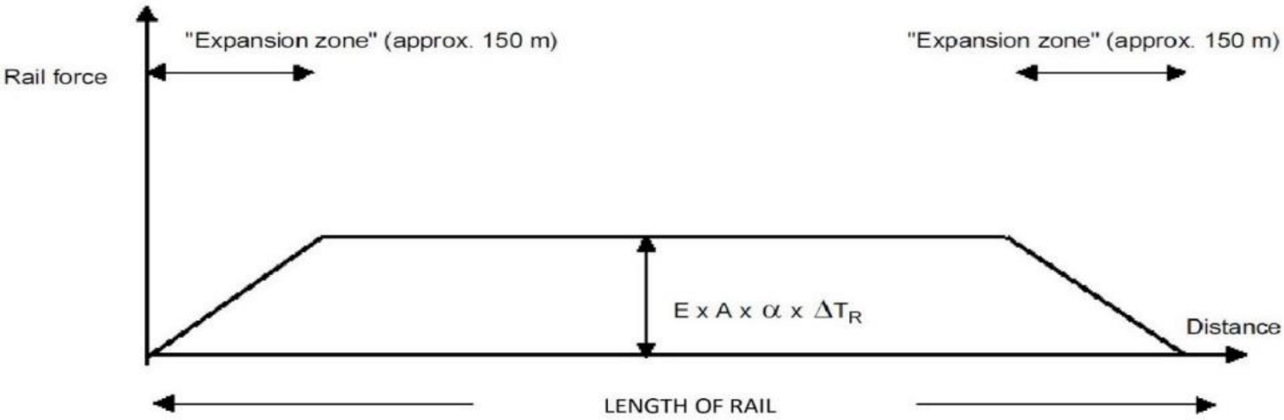


Figure 15: Rail stresses due to temperature variations in rail

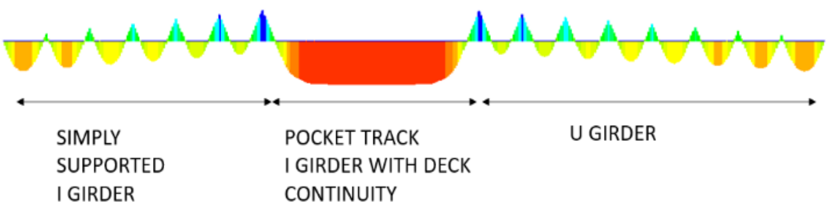


Figure 16: Rail stresses due to temperature variations in the Metro level superstructure deck (Second level)

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Figure 17: Rail stresses due to temperature variations in the Highway level superstructure deck (First level)

As per analysis, it is noted that due to the change in deck temperature, the additional tensile stress/compressive in rail is maximum at deck continuity at pocket track locations. The rail stress pattern due to temperature change in metro deck superstructure by the interaction effect is shown in Figure 12 and Figure 15 to Figure 17. In quantitatively, the magnitude of rail stresses due to temperature variation at the metro deck is higher compared to temperature variation at the highway deck superstructure. Also, it is observed that deck movement in the highway structure will also have a significant impact on the stresses in the rail.

B. Rail Stress Due to Live Load

Figure 18: Rail stresses due to Metro live load for loading at left end

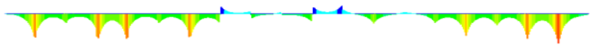

Figure 19: Rail stresses due to Metro Longitudinal load corresponding to vertical load

Figure 20: Rail stresses due to Highway level vertical load

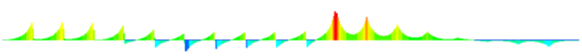

Figure 21: Rail stresses due to highway level longitudinal load corresponding to vertical load

The rail stress due to vertical live load on integrated superstructures shows similar behavior of tension and compression pattern. However, the stress pattern due to longitudinal force on the metro level and highway level shows a difference in the pattern due to deck continuity at the highway level. The summary of maximum tensile/compressive stresses is presented in Table II.

C. Additional Rail Stress for Combined Effect (Envelope).

The envelope of rail stresses for the combined effect of live load vertical and longitudinal is shown in the below Figure 22. The maximum additional stress considering all combinations as per Table II is 77.6N/mm^2 under compression which is lesser than the limitation of 92 N/mm^2 as specified in page 17 of RSI of guideline[3].

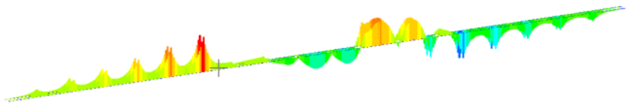

Figure 22: Rail stresses due to live load envelope

The summary of maximum rail stresses are tabulated as follows:

II. Summary of maximum Rail stresses

Description	Rail stress (N/mm^2)	
	Compression	Tension
Increase in deck temperature	19.5	28.3
Decrease in deck temperature	56.0	38.9
Maximum of above (a)	56.0	38.9
Live Load (b) Vertical + Horizontal (Combination of both level loading)	21.6	25.4
Summation (a + b)	77.6	64.3
Limitation	92	92

The longitudinal force on integrated substructure due to metro and highway loading are tabulated as follows:

III. Summary of maximum force on the substructure

Force per pier (in kN)	Unloaded Case	Loaded Case
	Axial temperature case	Traction /Braking force at Metro level
Integrated pier with U girder at Metro level and I girder system at Highway level	338	420
Integrated pier at Pocket track location with I girder system at both Metro and Highway level with deck continuity	329	479

From the above the integrated system shows higher longitudinal force on pier due to double-level loading and also with deck continuous. The substructure has to be designed for this force along with other applicable force on substructure.

IV. SUMMARY AND CONCLUSION

This paper presents the RSI analysis of double-decker bridge using FEM based MIDAS software tool. The study aimed at analyze of rail structure interaction on integrated double-decker bridge structures from the behavior of rail stresses and forces to the substructure. The RSI analysis is carried out for the three separate load cases such as temperature variation in the deck, tractive/braking force, and vertical bending of the deck due to live load as per UIC standards.

From the analysis results, the change in rail stress due to two level superstructure loading are presented graphically along the bridge with various type of superstructure. The following conclusions can be drawn from the obtained results.

- There is no change in the behavior of integrated structure from the stress patterns due to multi-level superstructure loading.
- Due to temperature variation the magnitude of stress increases due to integrated superstructure. However, the maximum stresses are within permissible limits.
- The maximum stress on rail is observed at the deck continuity location at a metro level in temperature variation case.
- Since the deck structure at highway level is not directly connected with the rail, the loading on the superstructure will have a significant impact on rail stresses and deformation.
- The force on the substructure is increased significantly due to two level loading.
- From RSI analysis, it is understood that due to integrated bridge structure with additional highway superstructure over conventional metro structure has nominal increase in rail stress which can be controlled with structure geometry and stiffness.
- Hence proposing integrated bridges with metro cum highway is an optimum structure which can reduce the cost and land acquisition by avoiding two individual bridges for two different modes of transportations at highly populated metro cities.

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