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Dynamic amplifications in railway transition zones: investigation of key phenomena

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Abstract. The railway transition zone where the track transitions from a ballasted track to a slab track, is a crucial area that can experience amplified dynamic responses. This work aims to develop a deeper insight into the mechanisms leading to the amplified dynamic response in railway transition zones. The study employs a finite element model to investigate the amplification of total strain energy due to the phenomena of reflection and redistribution of energy close to the transition interface. The results of the study are obtained for three case studies involving non-reflecting boundary (representing an energy sink) and homogeneous material along the vertical direction of the track, and the responses are studied for individual and combined effects in comparison to a benchmark case. The findings of the study show that eliminating the phenomena results in no dynamic amplification in total strain energy in railway transition zones. The conclusion highlights the importance of understanding these phenomena in order to design an efficient railway transition structure.

1. Introduction

Railway transition zones are subjected to increased degradation due to amplification of dynamic responses compared to the open tracks. The literature suggests that the dynamic amplification in transition zones can be associated mainly to stiffness variation and differential settlement [1], [2], [3]. However there is a lack of understanding of phenomena that initiates and governs the processes leading to these amplifications. The authors in this paper show that the phenomena of reflection and redistribution of energies close to the transition interface play a major role in defining the behavior of railway transition zones (RTZs) described above. A vertical rigid boundary at the interface of a ballasted track and a concrete structure and an in-homogeneity in mechanical properties of materials in longitudinal and vertical directions are two inherent characteristics of a typical RTZs. Over the years several mitigation measures have been adopted that aim to gradually minimize the material in-homogeneity in longitudinal direction but they have proved to be either inefficient or marginally effective in reducing the degradation

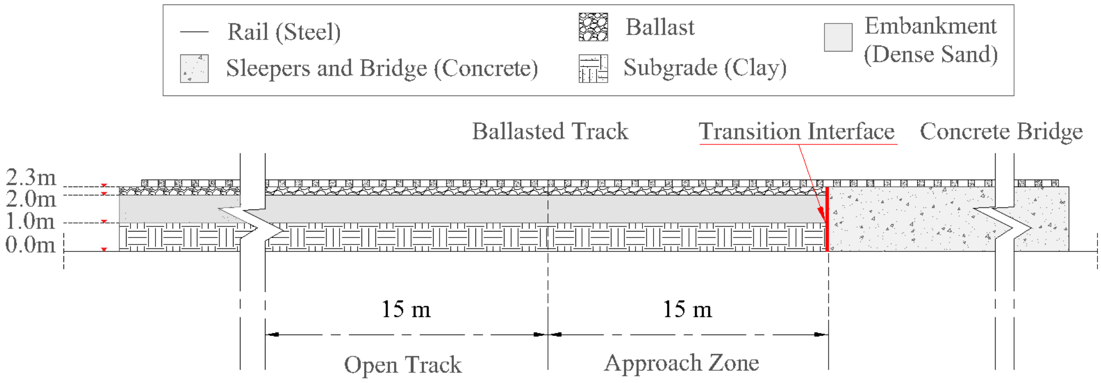


Figure 1. Geometric and cross-sectional details of the embankment-bridge transition under study.

in RTZs. In [4] authors proposed an energy based criterion to design and evaluate the performance of railway transition zones. Hence, in this work the phenomena of reflection and redistribution of energy will be studied in the proximity of the transition interface in terms of total strain energy, and its importance will be highlighted in order to design an effective solution aimed at minimizing the dynamic response in RTZs. It is to be noted that the system under study is simplified in terms of geometry and material behaviour as the purpose of this work is to investigate the phenomena described above. The geometry of RTZs obviously is more complex and the material behaviour may be non-linear, but for the purpose of this study the simplified model is deemed sufficient.

2. Method

A two dimensional (2-D) plane strain finite element (FE) model with linear elastic materials for the rail, concrete sleepers, ballast, embankment and sub-grade was used in this study. The properties of materials used are tabulated in Table 1 [5]. The system under study consists of the ballasted track (soft side), a concrete bridge (stiff side) and the interface between these two parts, referred in this paper as transition interface. The geometric details of the system are shown in Figure 1 including the two zones under study. The first zone under study is open track (OT) which is far away from transition effects and the second zone is approach zone on ballasted track next to transition interface. For the purpose of this study 4 different cases were simulated as described below. A single axle load of 90 kN and velocity 144 km/h was used as dynamic loading for all the cases studied in this paper.

Case 1 - Base model: A standard bridge embankment transition was simulated in this case with cross-section details shown in Figure 1 with three track-bed layers namely ballast, embankment and sub-grade. The vertical interface of ballasted track and the concrete bridge allows frictional sliding in tangential direction based on Coulomb friction law and the concrete bridge acts as a rigid boundary in normal direction.

Table 1. Mechanical properties of the track components

Material	Elasticity modulus E [N/m^2]	Density ρ [kg/m^3]	Poisson's ratio ν	Rayleigh damping α	β
Steel (rail)	21 x 10^{10}	7850	0.3	-	-
Concrete (sleepers)	3.5 x 10^{10}	2400	0.15	-	-
Ballast	1.5 x 10^8	1560	0.2	0.0439	0.0091
Sand (embankment)	8 x 10^7	1810	0.3	8.52	0.0004
Clay (subgrade)	2.55 x 10^7	1730	0.3	8.52	0.0029
USP	1 x 10^6	500	0.1	-	-

Case 2 - Homogeneous foundation: The base model described above is studied with a different foundation for the ballasted part of the track. In this case instead of a three layered track-bed system, a homogeneous foundation (same mechanical properties as ballast) was used under the sleepers. The transition interface properties are the same as case 1. This case is representative of a condition with no redistribution of energy due to in-homogeneity of materials in vertical direction. The only material in-homogeneity in case 2 is along the longitudinal direction of the track.

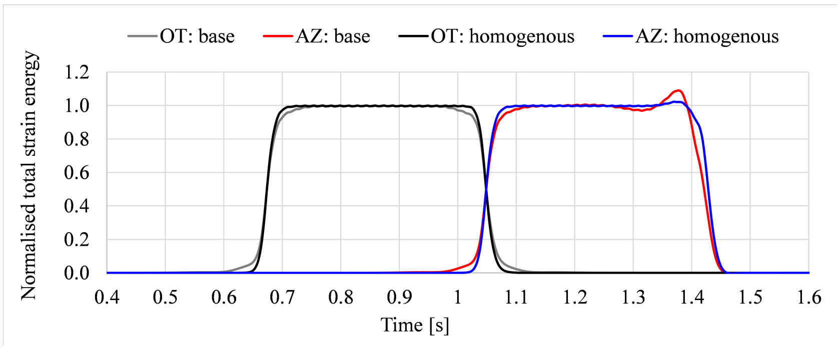
Case 3 - Non-reflective boundary: In this case the base model is modified where the mesh elements at the vertical boundary of the ballasted track at the transition interface were replaced by infinite elements. These elements (CINPE4) are continuum infinite, plane strain and 4-node elements [6]. This case is representative of a system where we limit the reflections from the vertical rigid boundary of the concrete bridge.

Case 4 - Homogeneous foundation and non-reflective boundary: This case is a combination of case 2 and case 3, where the response will be studied for combined effects of no reflection and no redistribution of energies in the proximity of the transition interface. The above mentioned cases will be analyzed in terms of total strain energy variation in top most layer (ballast) and the bottom most layer (sub-grade) for open track and approach zone. Case 1 will be compared with cases 2, 3 and 4.

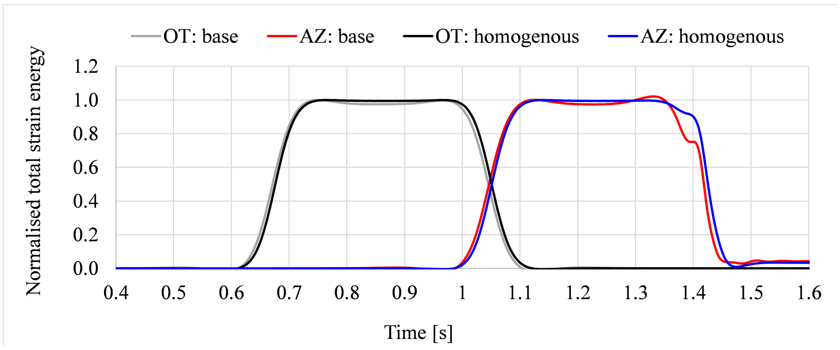
3. Results

In this section, a comparison of total strain energy graphs are presented for ballast and sub-grade layer in open track and approach zone. It is to be noted that this a study of the phenomena and the focus is mainly on studying the amplifications in the railway transition zones with respect to the open tracks due to phenomena of reflection and redistribution of energy. Hence, the results presented in this section are normalized against the maximum values of total strain energy in the open tracks.

Case 1 versus Case 2: Comparison of case 1 and case 2 is performed such that the effects of the phenomenon of energy redistribution due to non-uniformity of materials in the vertical direction is studied. This phenomenon is studied in the proximity (AZ: approach zone) of the transition interface and far (OT: open track) from the transition effects. The results obtained from the base model with non-homogeneous foundation are compared against the results obtained by simulation of a homogeneous foundation. Figure 2 shows the comparison of normalized total strain energy (OT, AZ) in ballast (a) and sub-grade (b) for case 1 and case 2.



(a)

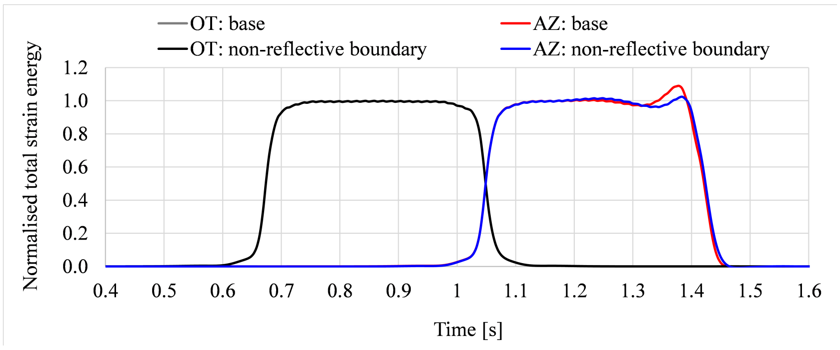


(b)

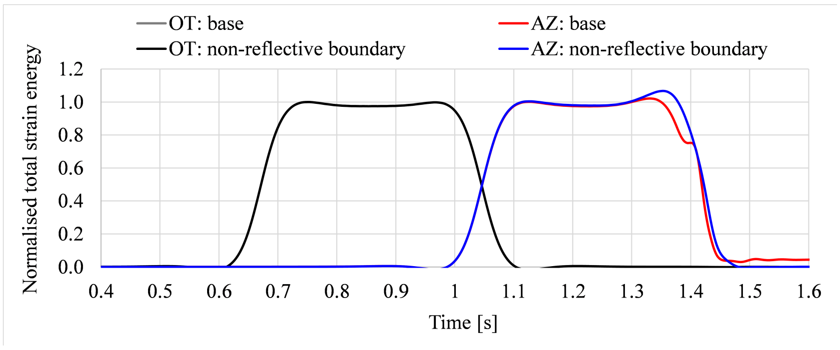
Figure 2. Comparison of normalized total strain energy in the layers of (a) ballast and (b) sub-grade for case 1 and case 2

As seen in Figure 2, case 2 shows an increase of 2.21% in normalized total strain energy for the layer of ballast in approach zone relative to open track compared to case 1 where this increase is much higher (9%). This implies that in-homogeneity in foundation contributes significantly to the dynamic amplifications in railway transition zones. It is to be noted that the smaller amplification in total strain energy in case 2 could also be due to the fact that overall stiffness of the foundation is increased and the stiffness jump is lower than that in case 1. However, the effects of this difference in stiffness jump are negligible as ballast and subgrade both are approximately 230 times softer than the concrete bridge; this was verified in a simulation with a softer foundation. In any case, although the distribution of total strain energy in the approach zone for case 2 is not as uniform as in the open tracks, there is no significant increase in the magnitude of energy neither in ballast nor in sub-grade. Hence, the non-uniformity in strain energy distribution in case 2 is solely due to reflection of energy from the vertical boundary at the interface of ballasted track and the ballastless track.

Case 1 versus case 3: Comparison of case 1 and case 3 is performed such that the effects of the phenomenon of reflection at the vertical rigid boundary (concrete bridge) is studied. This phenomenon is studied in the proximity (AZ) of the transition interface and far (OT) from the transition effects. The results obtained from the base model with rigid boundary and frictional sliding at transition interface is compared against the results obtained by simulation of a non-reflective boundary at the transition interface. Figure 3 shows the comparison of normalized total strain energy (OT, AZ) in ballast (a) and sub-grade (b) for case 1 and case 3.



(a)

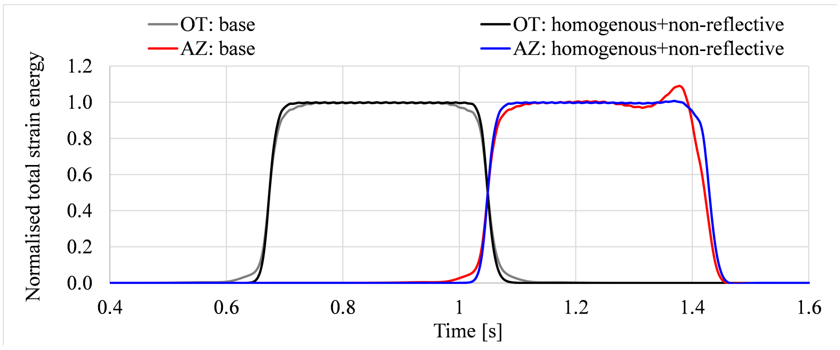


(b)

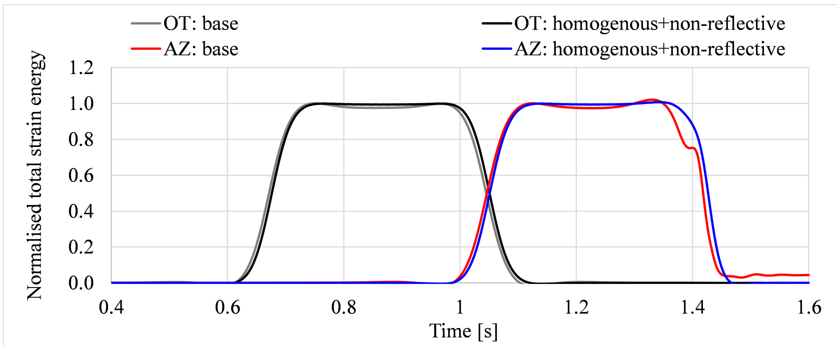
Figure 3. Comparison of normalized total strain energy in the layers of (a) ballast and (b) subgrade for case 1 and case 3

As seen in Figure 3, case 3 shows an increase of 2.43% in normalized total strain energy for the layer of ballast in approach zone relative to open track compared to case 1 where this increase was much higher (9%). This shows that reflection from the vertical boundary at the interface of ballasted track and the concrete structure contributes significantly to the dynamic amplifications in railway transition zones. In addition to this, an increase can be seen for the sub-grade layer which can be due to redistribution of energy between the three elastic layers of ballast, embankment and sub-grade. Moreover, the distribution of total strain energy in the proximity of transition interface is not uniform similar to case 1, 2 and 3. In this particular case the non-uniformity is expected due to redistribution of energy between track-bed layers.

Case 1 versus case 4: Comparison of case 1 and case 4 is performed such that the effects of the phenomenon of both energy redistribution and reflection is studied. This phenomenon is studied in the proximity (AZ) of the transition interface and far (OT) from the transition effects. The results obtained from the base model with non-homogeneous foundation and rigid vertical boundary with friction sliding at the transition interface is compared against the results obtained by adopting a homogeneous foundation and a non-reflective boundary. Figure 4 shows the comparison of normalized total strain energy (OT, AZ) in ballast (a) and sub-grade (b) for case 1 and case 4.



(a)



(b)

Figure 4. Comparison of normalized total strain energy in the layers of (a) ballast and (b) sub-grade for case 1 and case 4

As seen in Figure 4, case 4 shows no increase at all in normalized total strain energy for the layer of ballast in approach zone relative to open track compared to all the other cases studied above. Moreover, there is no non-uniformity in the distribution of strain energy in approach zone and the energy variation curve is exactly the same as for open track

4. Conclusion

This work highlights the need to mitigate the phenomena of reflection and redistribution of energies in the proximity of a transition interface. It is clearly seen in the results presented above that eliminating either of these two phenomena can lead to a significant reduction in energy amplifications in approach zones relative to open tracks. It was also shown that if a transition structure is designed such that the combined effects of reflection and redistribution of energies are mitigated, there will be no increase in the strain energy for any track-bed layer. Amplifications due to redistribution of energy can be dealt with by making the foundation as homogeneous as possible or gradually decreasing the inhomogeneity. Transition wedges are effective to some extent in achieving this but the problem due to reflection of energy still remains. The energy reflection could be managed by trapping and dampening the energy in these zones using absorbing materials.

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