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28–30 April 2014, Split, Croatia

Road and Rail Infrastructure III

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TRACK-STRUCTURE INTERACTION ANALYSIS USING FE MODELLING TECHNIQUES

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Abstract

With the growth in both High Speed and Light Rail infrastructure projects worldwide there is a general requirement for accurate modelling of the interaction of the track with respect to any supporting bridge structures, and in particular, to ensure that any interaction between the track and the bridge as a result of temperature and train loading is within specified design limits. To accurately assess track-structure interaction effects nonlinear analyses are required to investigate thermal loading on the bridge deck, thermal loading on the rail if any rail expansion devices are fitted, and vertical and longitudinal braking and/or acceleration loads associated with the trainsets. For a complete rail track assessment, dynamic effects caused by the passage of trains that affect the structure itself must also be considered. The paper will describe how rail track analysis for both high speed and general trainsets can be carried out according to the Union Internationale des Chemins de fer (International Union of Railways) UIC774-3 Code of Practice [1] and Eurocode 1 [2] with particular reference to LUSAS [3] Rail Track-Structure Interaction and Interactive Modal Dynamics analysis software applications. Automated modelling techniques and results and graphing capabilities will be described. Projects either built or under construction and on which the software has been used to good effect are described and cited.

Keywords: track-structure interaction, bridge, train, rail, UIC774-3

1 UIC774-3 Code of Practice / Eurocode 1

According to the UIC774-3 Code of Practice and its incorporation into the Eurocodes [2], the track-structure interaction effects should be evaluated in terms of the longitudinal reactions at supports, rail stresses induced by the temperature and train loading effects in addition to the absolute and relative displacements of the rails and deck. To accurately assess the behaviour these interaction effects should be evaluated through the use of a series of nonlinear analyses where all thermal and train loads are taken into account. Loading to consider will include:

- thermal loading on the bridge deck;
- thermal loading on the rail if any rail expansion devices are fitted;
- vertical loads associated with the trainsets;
- longitudinal braking and/or acceleration loads associated with the trainsets.

The interaction between the track and the bridge is approximated in the UIC774-3 Code of Practice by a bilinear relationship. The resistance of the track to the longitudinal displacements for a particular track type is a function of both the relative displacement of the rail to the supporting structure and the loading applied to the track. Application of train loads increases the resistance of the track to the relative displacements where these train loads are present but is unchanged for all other locations.

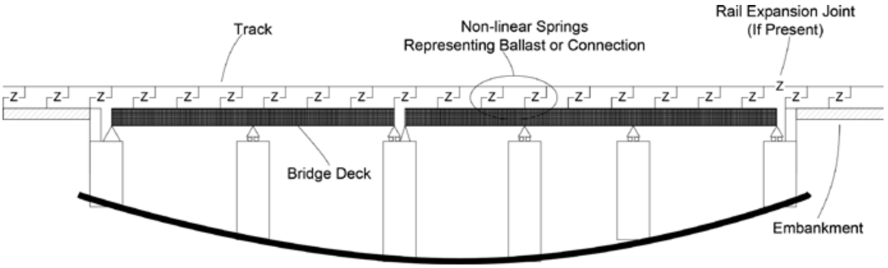

Figure 1 Representation of structural system for evaluation of interaction effects to UIC-774-3

The values of displacement and resistance to use in these bilinear curves are governed by the track structure and maintenance procedures adopted and will be specified in the design specifications for the structure. Typical values are listed in the Code of Practice for ballast, frozen ballast and track without ballast for moderate to good maintenance.

Figure 1 illustrates the structural system that needs to be considered for the interaction analysis. According to the UIC774-3 Code of Practice there is no requirement to consider a detailed model of the substructure (bearing-pier-foundation and bearing-abutment-foundation systems) when 'standard' bridges are considered, instead this can be modelled simply through constraints and/or spring supports that approximate the horizontal flexibility due to pier translational, bending and rotational movement. However, Rail Track-Structure Interaction analysis software does allow analyses to be carried out where the bearing and the pier/abutment-foundation are explicitly modelled.

2 Modelling with Rail Track Analysis Software

Rail Track-Structure Interaction analysis software provides the means to create a finite element model, analyse it, and conduct a bridge/track interaction check in accordance with the UIC774-3 Code of Practice. It can be used for single deck structures as well as for long, multi-decked, multiple span viaduct structures typical of the Gyeongbu high speed railway in South Korea, and on which it has been widely used.

Rail track and bridge interaction models are built automatically from data defined in a Microsoft Excel spreadsheet. This spreadsheet comprises a number of worksheets that relate to particular aspects of the modelling and cover: Number of Decks, Tracks and Embankment Lengths, Structure Definition, Geometric Properties, Material Properties, Interaction and Expansion Joint Properties, and Loading to be used. The number of decks that can be analysed is effectively unlimited. Either one or two tracks can be modelled and for two tracks, one will take the braking load of a trainset and the other will take the acceleration load of a separate trainset. Lengths of the embankments to either side of the structure need to be sufficiently long to allow the trainset loading to be placed within the model and, according to the UIC774-3 Code of Practice, should be at least 100 m.

For each deck the modelling spreadsheet allows the definition of the left pier/abutment, up to eight internal piers and the right pier/abutment, each with their own support / bearing characteristics. These can include the physical modelling of the piers if specified. The geometric and material properties for the rail and deck components are defined on separate worksheets. Mass density is not used in the analysis but is provided to allow the separate solution with self-weight and for it to be combined with the thermal/train loading effects covered in these types of analyses. The main bilinear interaction effects for the track/bridge interaction are defined in the Interaction and Expansion Joints worksheet along with additional properties associated with the rail/track. These include the eccentricity between the rail/slab and the presence of any rail expansion joints.

The temperature effects in the rails for a continuously welded rail (CWR) track do not cause a displacement of the track and do not need to be considered (UIC774-3 Clause 1.4.2). For all other tracks the change in temperature of the bridge deck and rails relative to the reference temperature of the deck when the rail was fixed needs to be considered in accordance to the code of practice and design specifications. To achieve this, temperature values for the deck and for the rails are defined along with as many rail/train loads as required to completely describe the loading regime.
Train loading is defined in terms of the type (braking, acceleration or vertical loading), track, position and magnitude. Complex loading patterns and parametric loading can be defined to investigate multiple positions of the trainsets with minimum effort. At model creation time a user-specified element length (in accordance with the limitations in UIC774-3) is used to define the embankment and bridge features of the model with all of the analyses generated automatically.

3 Analysis

When running an analysis, deck and rail track temperature loading can be considered in isolation for subsequent analysis of multiple rail configurations, or a full analysis can be carried out considering the combined temperature in the deck and rail track plus trainset loading. Because the response of the ballast and/or track restraining clips is nonlinear a nonlinear analysis is always needed. During an analysis the Track-Structure Interaction analysis software automatically updates the material properties associated with the track/structure interface based upon the position of the train or trains – a key requirement to get accurate results. For a 'total' rail track/interaction assessment, dynamic effects caused by the passage of trains that affect the structure itself could also be considered.

4 Results viewing / processing

Results are produced in Microsoft Excel spreadsheet format or a propriety software results format. Separate worksheets within the results spreadsheet contain results for specific areas of interest. These worksheets include:
- raw results data in summary, graph and tabular form for each track and deck component;
- envelopes of raw track and deck data in summary, graph and tabular form for combinations of temperature and trainset rail loading;
- tables of railbed and bridge displacements;
- tables of longitudinal reactions;
- tables of rail stress values.

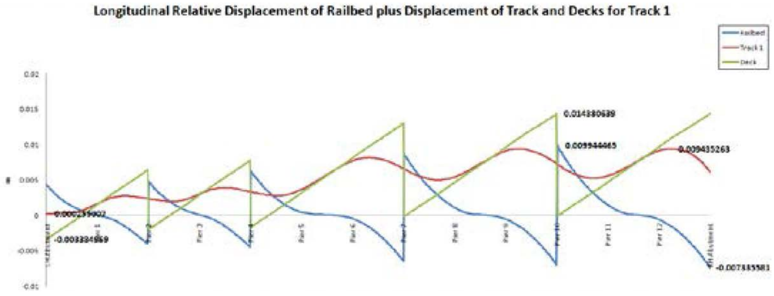

Figure 2 Envelope of axial stresses in a rail track from temperature loading

The tabular results provide summaries to allow the quick determination of which analysis is causing the worst effects for each of the checks that need to be carried out to the UIC774-3

Code of Practice which include: Relative Displacement between Rails and Deck; Longitudinal Relative Displacement between Ends of Decks (axial, end rotation and total effects); Vertical Relative Displacement between Ends of Decks; Longitudinal Reactions; and Axial Rail Stress. A sample results summary table and envelope of relative railbed plus track / deck longitudinal displacements in a rail track is shown in Figure 2.

5 Key values for checking to UIC774-3

5.1 Peak relative railbed displacement

For a continuously welded rail (CWR) track the typical criteria to be met for the relative railbed displacements is quoted in Clause 1.5.3 of UIC774-3 which states that: “The maximum permissible displacement between rail and deck or embankment under braking and/or acceleration forces is 4mm.”. To permit checking of these criteria railbed displacements are included in a Track results worksheet. These are output in the form of the maximum and minimum values which are reported in the summaries at the top of the sets of results, the values over the structure graphed in the top chart and the individual values along the length of the track in tabular form. Summary tables are also created which indicate which track and location is associated with the peak value.

5.2 Peak longitudinal reactions at the abutments

These are provided in a Longitudinal Reactions Check worksheet and show both the position at which the trainset(s) is/are when the peak longitudinal reaction occurred as well as the peak reaction and where it occurs.

5.3 Peak axial rail stresses

For a continuously welded rail track with UIC 60 rails the typical criteria to be met for the rail stress are quoted in Clause 1.5.2 of UIC774-3 which states that “The maximum permissible additional compressive rail stress is 72 N/mm^2” and “The maximum permissible additional tensile rail stress is 92 N/mm^2.” These criteria rail axial stress values are also included in the Track results and summary worksheets and are of the same form as presented for the relative railbed displacements.

6 ‘Simplified’ and ‘Complete’ UIC 774-3 analysis methods

For a computer analysis, according to UIC 774-3 (Clause 1.7) two different methods of analysis can be used, each giving a different level of accuracy. These are termed ‘simplified’ analysis and ‘complete’ analysis. Simplified analysis considers the temperature, and the longitudinal and vertical train effects separately and permits them to be combined to get a total effect. Simplified analysis is actually quite conservative because it assumes that superposition of results is valid for sets of nonlinear analyses when it is not – it is only really valid for linear analysis. As a result combining ‘simplified’ analysis results can lead to an over-estimate of the rail stresses. Complete simultaneous analysis considers the temperature and longitudinal and vertical train effects simultaneously. As a result there are accuracy benefits in using Rail Track-Structure Interaction analysis software to carry out a complete simultaneous analysis, rather than using software that combines results from simplified analyses.

To illustrate the differences obtained, rail stress results due to braking and acceleration on the two tracks crossing Hwashil viaduct on the Gyeongbu line in South Korea are shown in Table 1. A simplified analysis carried out in LUSAS considered the temperature and the longitudinal and vertical train effects separately before combining them to get a total effect. Then, a 'complete' simultaneous analysis was carried out for the same viaduct using the Rail Track-Structure Interaction analysis software option. The ratio of the 'Simplified' to the 'Complete' analysis shows the over-estimate involved. The key issue with the separate analysis approach is the ability for the track resistance to be overestimated by the combination of the two nonlinear analyses and potentially cause the rail stresses to be overestimated also. A study of the Hwasil viaduct by Lee et al [4] showed similar results.

Table 1 Comparison of peak compressive rail stresses for Hwashil viaduct for 'Simplified' and 'Complete' UIC774-3 analysis methods

Trainset Loading Type	'Simplified' : Separate Nonlinear Analysis Of Thermal And Train Loading [N/mm²]	'Complete': Nonlinear Thermal And Train Loading With Material Change [N/mm²]	Over-Prediction Ratio 'Simplified' / 'Complete'
Track 1 (Braking)	94.99	79.08	1.2
Track 2 (Accelerating)	103.66	92.58	1.12

Comparison of the results for the separate and complete analyses shows that the peak compressive stress for the separate analysis is 1.2 times that of the complete analysis for track 1 and 1.12 times that for track 2. It should be noted however that from other studies undertaken (that are outside the scope of this paper) the separate analysis method can give an apparent increase in track resistance of up to 1.6 times that of the loaded track due to the combination of the nonlinear results. One overall conclusion is obvious from the analyses: when a combined thermal and train loading from a separate analysis gives interaction forces that exceed the stated yield resistance then the separate analysis method will potentially over predict the rail stresses unless the loaded track yield surface is reduced by the mobilised track resistance over the extent of the train loading.

7 Rail Track Analysis in practice

7.1 High speed rail

In addition to reported uses on all bridges on the Gyeongbu High Speed Railway 2nd phase (between Daegu and Busan), Saman Engineering Corporation used Rail Track Analysis software for preliminary design work on the Honam High Speed Railway on behalf of its client the Korea Rail Network Authority. This high speed railway, when complete, will link South Korea's capital city, Seoul, with Mokpo, a southern port city in South Jeolla Province.

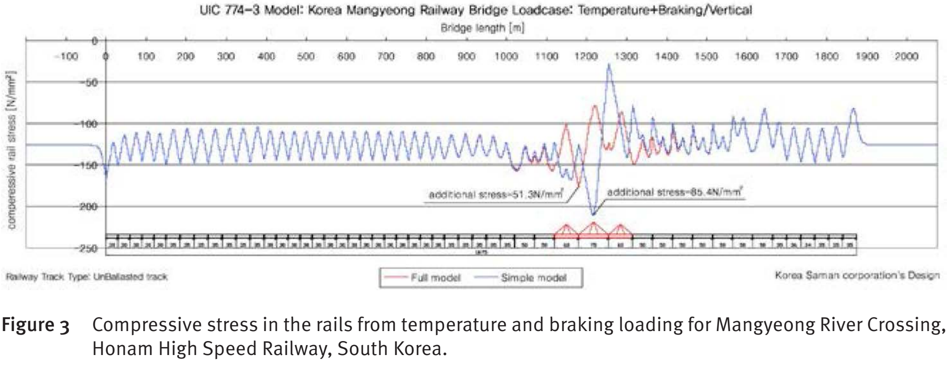

Figure 3 Compressive stress in the rails from temperature and braking loading for Mangyeong River Crossing, Honam High Speed Railway, South Korea.

The Mangyeong River crossing, one of many structures on the new route, has a length of 1,875 m and comprises a total of 50 spans of varying length and construction type. Three steel box framed spans of 60/75/60 metres over the river are flanked by steel girders of 50 m span, and then by various numbers of 35 m and 30 m pre-stressed concrete box section spans for the remainder of the crossing's length. Saman carried out a rail track/structure interaction analysis to evaluate axial stresses in the rails due to acceleration and braking forces caused by passing trains. Induced track displacements relative to the bridge deck were checked and found to be within the specified design limits.

7.2 Light rail

The Dallas Area Rapid Transit (DART) light rail system in the United States is a good example of the use of Rail Track Analysis on a light rail project. DART, as a whole, currently comprises 85 miles (137 km) between its four lines – Red, Blue, Green and Orange. US Consultant Gannett Fleming was responsible for the design of 7 new structures along a 4.75 mile (8 km) extension to the Blue route, which was completed in December 2012. The longest of these, a causeway bridge over Rowlett Creek, is a 28 span, 2,565 foot (782 m) long, pre-cast concrete beam structure. This, and the 11 span, 1054 foot (321 m) long KCS bridge consisting of both precast concrete beams and a long-span steel through girder were both analysed using Rail Track Analysis software to assess track-structure interaction effects and verify key values were within acceptable limits.

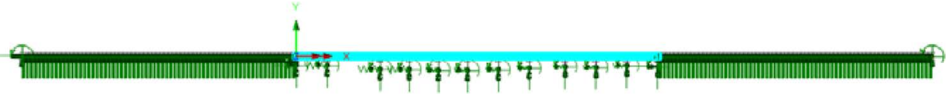

Figure 4 Rail Track Analysis Model for KCS Bridge, DART Blue Line extension, USA.

8 Dynamic analysis

For a 'total' rail track/structure analysis assessment, and depending upon the requirements of a design code, dynamic effects caused by the passage of trains across a structure may also need to be considered. This could take the form of analysing the response of the structure over time based on contributions of a number of natural frequencies (time response) or the response of the structure to dynamic loading at known frequencies (forced response). Using linear Interactive Modal Dynamic superposition techniques, rapid solutions to moving load analyses of trainsets over time at varying speeds can be achieved with output such as time histories and peak summaries, secondary response spectra, and animated visualisations being obtained. Alternatively step-by-step dynamics (full transient analysis) could be done to examine the response of the complete structure over time taking all effects (including nonlinear effects) into account. Eurocode EN 1991-2:2003 Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges [2] provides good guidance via a flowchart for determining when a static or dynamic analysis should be undertaken.

9 Conclusion

The use of Rail Track-Structure Interaction analysis software has many benefits over manual methods. Automated model building guarantees correctly-built models compared to manual model creation that may require extensive checking along with the project time savings associated with this. The material properties associated with the track/structure interface are automatically updated according to the position of the passing train or trains for all analyses.

Results are automatically provided in summary, tabular or graphical formats for all or selected parts of the track/bridge model. Overall it provides a faster assessment of thermal and / or train loading track interaction effects on multi-span structures to the UIC774-3 Code of Practice than all other known methods.
Eurocode EN 1991-2:2003 Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges encompasses significant elements of the UIC 774-3 modelling approach when evaluating the combined response of the structure and track to variable actions. For a UIC60 rail, the limiting design criteria are the same as those specified in the International Union of Railways Code UIC 774-3 meaning that Rail Track-Structure Interaction analysis software can be directly employed to meet Eurocode requirements.

References

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