지반운동을 공간변화를 고려한 고속철도 장대레일의 응력해석

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Rail-Stress of High-Speed Railway Bridges using Long Rails and subjected to Spatial Variation of Ground Motion Excitations

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Abstract : The use of long rails in high-speed railway bridges causes additional stresses due to nonlinear behaviours between the rail and bridge decks in the neighbourhood of the deck joints. In the seismic response analysis of high-speed railway bridges, since structural response is highly sensitive to properties of the ground motion, spatial variation of the ground excitation affects responses of the bridges, which in turn affect stresses in the rails. In addition, it is shown that high-speed trains need very long distances to stop when braking under seismic occurrence corresponding to operational earthquake performance level so that verification of the safe stoppage of the train is also required. In view of such additional stresses due to long rails, sensibility of structural response to the properties of the ground motion and braking distance needed by the train to stop safely, this paper proposes and establishes a time domain nonlinear dynamic analysis method that accounts for braking loads, spatial variation of the ground motion and material nonlinearities of rails to analyze long rail stresses in high-speed railway bridges subjected to seismic event. The accuracy of the proposed method is demonstrated through an application on a typical site of the Korean high-speed railway.

초록 : 고속철도교량에서 장대레일의 사용은 연결부 근처에서 레일과 교량상판사이의 비선형 거동으로 인하여 부가적인 응력을 유발한다. 고속철도 교량의 지진응답해석에서, 구조물응답은 지반운동특성에 매우 영향을 많이 받으므로, 지반운동의 위치에 따른 변화가 구조물의 응답에 영향을 미치게 되고, 그 결과는 레일에 응력을 유발하게 된다. 또한 고속철도에서 사용지진 수준의 지진발생시에 열차의 긴 제동거리가 필요하므로 열차의 안전한 정지를 확보하는 것이 요구된다. 이러한 관점에서 장대레일에 의해 부가적으로 발생하는 응력, 지반운동의 공간변화에 대한 구조물 응답의 영향, 그리고 안전하게 정지하기 위해 필요한 열차의 제동거리 등의 사항이 레일의 응력해석에 고려될 필요가 있다. 본 논문에서는 지진하중을 받는 고속철도교량의 장대레일 응력해석을 위하여 제동하중, 지반운동의 공간적변화, 그리고 레일의 재료 비선형을 고려한 시간영역에서의 비선형 동적해석방법을 개발하고 적용하였다. 제시된 방법을 한국고속철도의 특정부지에 적용하여 지반운동의 공간변화에 따른 응답의 타당성을 보였다.

Key Words : long rail; dynamic nonlinear analysis; relative displacement of decks; stresses in rail; spatial variation of ground motion; high-speed railway bridge.

1. Introduction

Long rails have been introduced in railway and high-speed railway to mitigate dynamic shocks and offer optimal riding comfort to the passengers. The use of such long rails in high-speed railway bridges causes additional stresses due to nonlinear behaviours between the rail and bridge decks in the neighbourhood of the deck joints. As excessive stresses and displacements may cause trains to derail, safety should be secured in

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rails and railway constructions so that trains can run safely when accelerating or braking. Even if bridges of the Korean high-speed railway (KTX) have been seismically designed to avoid collapse of the piers or unseating of the superstructure during earthquakes[1,2], damage of the rails under seismic events that can cause derailment of trains has been disregarded. However, high-speed trains running at operational speeds need long distances, up to several kilometres, to stop. Therefore, safe stoppage of trains under seismic occurrence appears to be a very important aspect that cannot be ignored. Considering such nonlinear behaviours between the rail and bridge decks and, safety of the braking train during seismic events, an analysis that takes into account simultaneously both the safety of rails during acceleration or braking and braking loads during earthquake occurrence considering seismic loading corresponding to operational earthquake performance level is required.

Design criteria in several countries[4-8] limit stresses in rails by restricting the relative displacements between contiguous bridge decks using seismic analyses which model the bridges without rails. However, such approach seems inadequate to limit stresses in rails since stiffness of long rails increases with the length of the train and, rails and decks interact. Hence, a method analysing rail stresses through nonlinear time domain analysis, which models not only the bridges and rails but also the rail-bridge interaction, must be used to analyse adequately stresses in railway bridge rails. In addition, spatial variation of ground motion (i.e., wave passage effect resulting from the difference in arrival times of seismic waves at multi-supports) must be considered in such nonlinear time domain analysis. As stresses in long rails involve very long railway track lengths and structural response is highly sensitive to properties of the ground motion, a procedure that performs dynamic analysis considering the spatial variation of the input ground motion is proposed for the seismic analysis of bridges[9,10], introducing material nonlinearities in rail-structure interaction to reflect the characteristics of the elements connecting the rail and bridge superstructure (ballast and fastening).

Table 1. Seismic risk factor of high-speed railway bridges according to performance levels[3]

Return period (years)	Performance level	Seismic risk factor
100	Operational	0.57
500	-	1.0
1000	Collapse prevention	1.4

Table 2. Soil type and site coefficient[3]

Soil profile type	Shear wave velocity (m/s)	Soil profile name	Site coefficient
I	> 760	Hard rock. Rock	1.0
II	360 to 760	Soft rock. Very dense soil	1.2
III	180 to 360	Stiff soil profile	1.5
IV	< 180	Soft soil profile	2.0

Table 3. Seismic zone factor (return period of 500 years)[3]

Seismic zone	Seismic zone factor
I	0.11
II	0.07

2. Design Ground Motion

As the accuracy of the proposed method will be demonstrated through an application on a typical site of the KTX, artificial ground motion must be generated and used as input ground motion to overcome the lack of real earthquakes records in Korea.

Tables 1, 2 and 3 summarized the criteria and features necessary for the generation of design ground motion in Korea. Considering operational performance level, the corresponding seismic risk factor is 0.57 (Table 1). The magnitude of the ground acceleration determined by the acceleration and site coefficients should be calculated at first. The site coefficient is calculated as the harmonic mean of shear wave velocities of layers located at a depth of 30m from the surface (Table 2). The region where the KTX is constructed pertains to a seismic zone factor of 0.11 (Table 3).

3. Modelling of the Bridge System

As mentioned above, limitation of stresses in rails by restricting the relative displacements between contiguous bridge decks using seismic analyses which model the bridges without rails may be inadequate to limit stresses in rails since stiffness of long rails increases with the length of the train and, rails and decks interact. Therefore, a rail-stress analysis using nonlinear time domain analysis, which models not only the bridges and rails but also the rail-bridge interaction, should be used to analyse adequately stresses in railway bridge rails.

The bridges used in the analysis are two 3-span continuous bridges of 100m (B and C in Fig. 2). To consider the length of the train load and the characteristics of the long rails, simple bridges of 450m at both extremities of the continuous bridges have been included in the model. The elements connecting the rails to the bridge superstructure (ballast and fastening) are assumed to show perfect plastic behaviour according to the presence or not of vertical loading (Fig. 1). The rails are constituted by two tracks. The rails and the bridge superstructure are modelled so as to have 1 node each 5m(Fig. 2).

4. Analysis Procedure

As structural response is sensible to the properties of the ground excitation and long rails involve very long railway track lengths, spatial variation of ground motion resulting from the difference in arrival times of seismic waves at multi-supports must be considered in nonlinear time domain analysis.

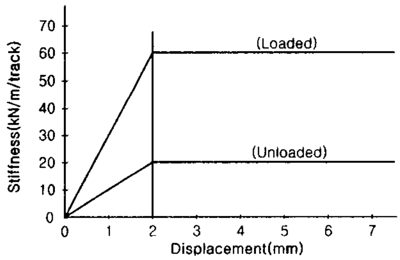


Fig. 1. Model of ballast and fastening

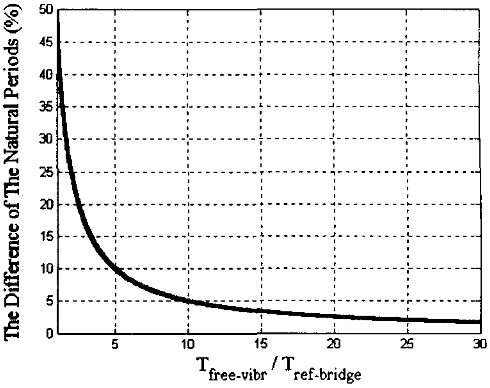


Fig. 3. Comparison of two contiguous 3-span bridges with different natural periods according to the duration of free vibration

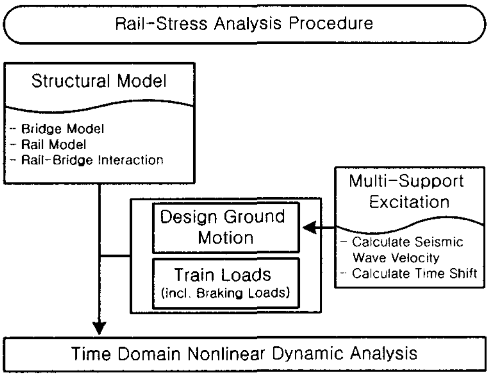


Fig. 4. The proposed rail-stress analysis procedure

The phase difference or time shift of the input seismic wave, determined by the velocity of the ground motion and the separation distance between the structural support points, may affect the relative displacement of contiguous bridge decks and the joint rail stresses. Assuming that contiguous bridges show linear behaviour independently, Fig. 3 compares two contiguous 3-span bridges with different natural periods according to the duration of free vibration. In view of Fig. 3, it can be affirmed that, when the duration of strong earthquakes remains between 2 and 10 seconds, and both bridges show close natural periods, spatial varia-

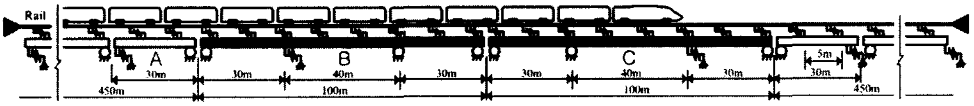


Fig. 2. Model of the bridge system

tion of the ground motion resulting from the multi-support excitation has to be accounted. Such feature becomes clearer as bridges show nonlinear behaviours. Following, in the case continuous bridges are contiguous in a section of the high-speed railway seismic wave passage effect must be considered for rail-stress analysis if the natural periods of the bridges are similar because time shift increases as the separation distance between the input points of the seismic wave.

Fig. 4 depicts the proposed analysis procedure. Structural modelling considering the bridges, the rails and rail-bridge interactions is performed at first. Analysis is performed for seismic and braking loads by means of a direct integration method (in time domain) considering material nonlinearities of long rails. As mentioned above, the difference between the natural periods of contiguous bridges determines the consideration or not of wave passage effect. In the case wave passage effect is considered, the velocity and time shift of the seismic wave must be computed before performing the time domain dynamic analysis.

5. Analysis Results

The accuracy of the proposed method will be demonstrated through an application on a typical site of the KTX, the boring data adopted in the analysis correspond to usual satisfactory soil and are summarized in Table 4. The fourth layer can be regarded as the base layer. According to the boring data, the mean of shear wave velocities at 30m depth being 553.5m/s, the soil is relevant to a soil profile type II corresponding to a site coefficient of 1.2(Table 2). The peak ground acceleration (PGA) is calculated as the product of the seismic zone factor, seismic risk factor and site coefficient. In this case, the PGA is 0.0752 and, multiplied by the gravitational acceleration, gives the artificial ground motion used in the analysis(Fig. 5).

Table 4. Boring data

Layer, i	Thickness, H_i (m)	Soil type	Shear wave velocity, $\underline{V_{si}}$ (m/s)
1	4.0	Sand	254.2
2	3.5	Sand	278.1
3	4.5	Soft rock	535.5
4	18.0	Rock	1007.9

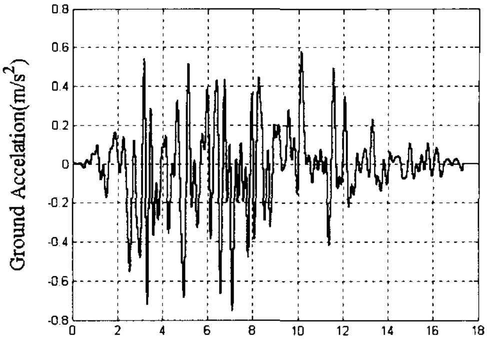


Fig. 5. Input ground motion

The propagation velocity of the seismic wave is the harmonic mean of the shear wave velocities at the base layer and at the surface, and can be expressed as follows,

$$\overline{V}=\frac{2V_sV_0}{V_s+V_0}=493.4\ m/s \tag{1}$$

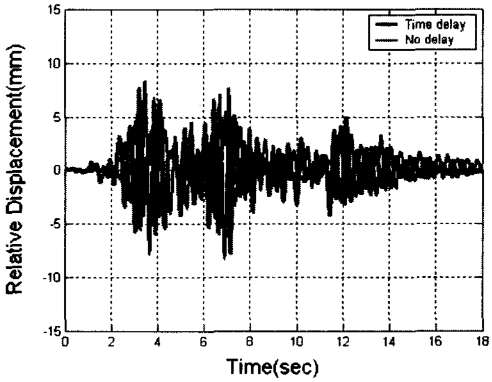
where $V_s=\sum_{i=1}^{n-1}H_i\div\sum_{i=1}^{n-1}\frac{H_i}{V_{s_i}}$ is the mean of shear wave velocities above the base layer, V_s and H_i are the wave velocity and thickness of the i^{th} subsoil layer in Table 4, V_0 = V_{s_n} is the shear wave velocity of the base layer, and n represents the number of layers before the base layer is met.

The difference in arrival times of the seismic waves between two points is calculated by the following expression,

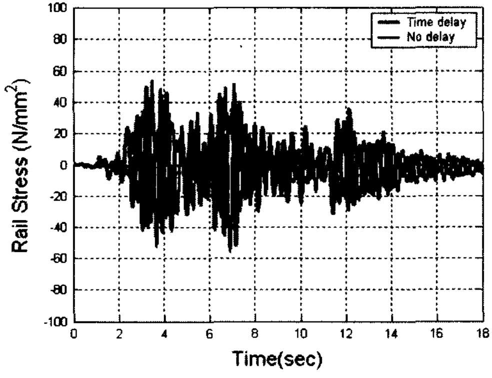
$$\triangle t=\frac{S}{V_s}=0.203\ \mathrm{sec} \tag{2}$$

The time domain nonlinear dynamic analysis method performed in this study applies Newton-Raphson techniques in finite element methods to solve the nonlinear structural problem. Using the nonlinear dynamic analysis mentioned above, results are obtained for the bridge model described in chapter 3.

Fig. 6 compares the relative displacement of the decks and rail stress at the joints of two continuous bridges (A and B in Fig. 2) with a difference of 25.72% in their natural periods subjected to ground motion according to the consideration of time shift. Results show that relative displacements and rail stresses reduce only by 0.9337 times and 0.9156 times, respectively, when considering time shift. Fig. 7 compares the relative displacement of the decks and rail stress at the joints of two continuous bridges (B and C in Fig. 2) with a difference of 8.39% in their natural periods subjected to ground motion according to the consideration of time shift. Results show that relative displacements and rail stresses increase by 3.6893 times and 2.4971 times, respectively, when considering time shift. Results of Figs. 6 and 7 corroborate the importance of the proximity of the natural periods between contiguous bridges on the relative displacements of decks and rail-stresses at the deck joints, proving that multi-supports wave passage effects constitute an essential feature in long rail-stress analysis.

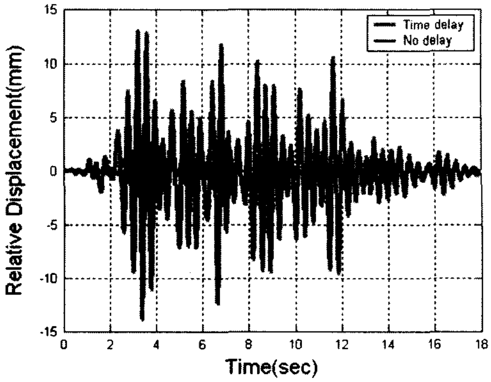


(a) Relative displacement of the decks

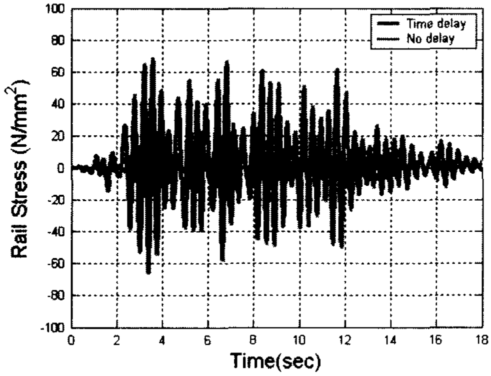


(b) Stress in the rail

Fig. 6. Effects of seismic forces on contiguous bridges with more than 20% difference in their natural periods according to wave passage effect



(a) Relative displacement of the decks



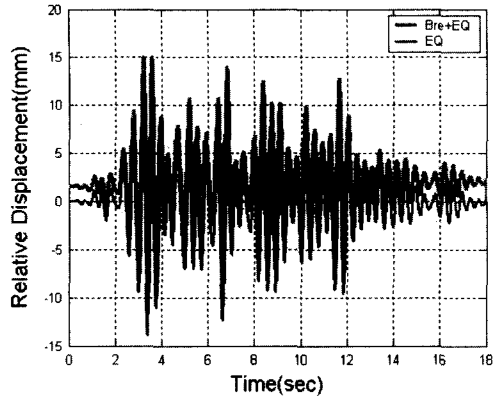
(b) Stress in the rail

Fig. 7. Effects of seismic forces on contiguous bridges with less than 10% difference in their natural periods according to wave passage effect

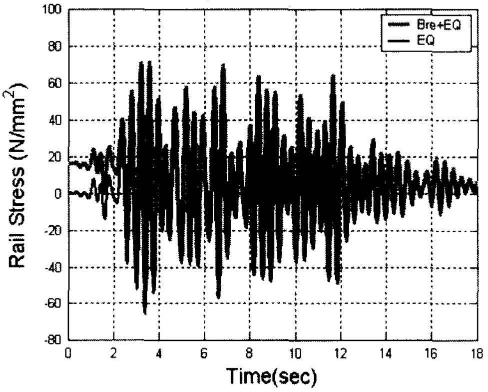
In the case braking force acts in one of the two tracks from 0 to 300m, the effects of the displacement and stress in the loaded track were seen to affect a region extending to 150m at both end of the loaded length. In case seismic loading acts together with braking force, the relative displacement of the decks increases by 1.165mm, representing a reduced augmentation of 27.2% regard to 1.6mm obtained from static analysis, while the stress in the rail increases by 2.53N/mm^2, which is 84.3% smaller regard to 16.1 N/mm^2 also obtained from static analysis(Fig. 8).

6. Conclusions

Former researches and design criteria limited stresses in long rails by restricting the relative displacements between contiguous bridge decks of the high-speed railway using seismic analyses which



(a) Relative displacement of the decks



(b) Stress in the rail

Fig. 8. Effects of seismic and braking forces on contiguous bridges with less than 20% difference in their natural periods according to wave passage effect

modelled the bridges without rails. However, such approach has been proven to be inadequate to limit stresses in rails since stiffness of long rails increases with the length of the train and, rails and decks interact.

Damage of rails under seismic events has been also disregarded in the seismic design of the KTX bridges. However, high-speed trains running at operational speeds need long distances to stop. Therefore, safe stoppage of trains under seismic occurrence appears to be a very important aspect that cannot be ignored. In addition, even if structural response of large structure is known to be sensitive to the properties of ground motion, spatial variation of ground motion has been ignored in determining the relative displacement of the decks and rail stress in continuous high-speed railway bridges.

Considering such additional stresses due to long rails, sensibility of structural response to the properties of the ground motion and braking distance needed by the train to stop safely, this paper proposes and establishes a time domain nonlinear dynamic analysis method that accounts for braking loads, spatial variation of the seismic ground motion and material nonlinearities of rails to analyze long rail stresses in high-speed railway bridges subjected to seismic event. The accuracy of the proposed method has been demonstrated through an application on a typical site of the Korean high-speed railway. Modelling rails, bridges, rail-bridge interaction and accounting for spatial variation of the input seismic waves (arrival times, multi-supports) has been proved to provide more accurate results. Spatial variation of the seismic ground motion has been proven to affect significantly the relative displacement of the decks and rail stress at the deck joints of contiguous bridges with close natural periods.

Consequently, dynamic nonlinear analysis considering spatial variation of seismic wave and modelling the bridge, rails and rail-bridge interactions must be applied to compute rail stresses. The proposed analysis performed in this study is believed to be applicable for the safety examination of the KTX subjected to seismic loading corresponding to operational earthquake performance level.

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