중약진 지역에서의 고속철도 연속교량 장대레일의 응력 해석

Rail-Stress Analysis of High-Speed Railway Bridges using Long Rails in Low and Moderate Seismic Areas

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국문요약

철도나 고속철도 교량에 사용되는 장대레일은 차량에 의한 동적충격의 완화, 주행시 승차감의 향상과 같은 장점을 가져온 반면에, 인접한 교량의 연결부에서 레일과 교량 상부구조간의 거동 불일치로 인해 레일에 부가적인 응력을 발생시킨다. 이러한 부가적인 레일응력과 지반운동의 특성에 따른 구조적 응답의 민감도 및 열차의 안전한 정지를 고려하여, 지진 발생시 고속철도교량의 장대레일 응력을 해석하기 위해 레일의 재료비선형성, 지반운동의 위상차 등을 고려한 비선형 시간이력해석 방법을 제시하였다. 그리고 우리나라의 여러 지반조건을 고려하고 고속철도의 대표적인 연속교량 모델에 적용하여 제시한 방법의 타당성을 검토하였다.

1. Introduction

Long rails have been introduced in railway to mitigate dynamic shocks and offer smoother vehicle ride and optimal riding comfort to the passengers. However, railway bridges induce additional forces, and so forth additional stresses, into long-rails due to nonlinear behaviors between the rail and bridge decks inducing discordant displacements between the upper structures of the bridge in the neighborhood of the deck joints. And, such phenomenon becomes more noticeable in continuous bridges than in single-span bridges.

As excessive stresses and displacements may cause trains to derail, safety should be secured in 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

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avoid collapse of the piers or unseating of the superstructure during earthquakes (KRTC, 1991 KMCT, 2001), damage of the rails under seismic events that can cause derailment of trains has been disregarded up to now. However, high-speed trains running at operational speeds need long distances, up to several kilometers, to stop. Therefore, safe stoppage of trains under seismic occurrence appears to be a very important aspect that cannot be ignored and, not only bridges but also rails should be designed regard to such feature.

Even if numerous researches have been led to develop methods analyzing stresses in rails subjected to thermal loading and accelerating or braking loads, these methods remain based on static nonlinear analysis, which does not consider seismic loading requiring dynamic nonlinear analysis. In addition, design criteria in several countries (Premersberger, 1987; Hasuda, 1992; UIC, 1985) 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 analyzing 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 analyze 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 (Kim, 2002), introducing material nonlinearities in rail-structure interaction to reflect the characteristics of the elements connecting the rail and bridge superstructure (ballast and fastening).

2. Design Ground Motion

The accuracy of the proposed method will be demonstrated through an application on a typical site of the KTX. As the Korean peninsula is a region of low to moderate seismic activities, artificial ground motion must be generated and used as input ground motion to overcome the lack of real earthquakes records. Tables 1, 2 and 3 summarized the criteria and features necessary for the generation of design ground motion in Korea. Considering operational performance level in Table 1 (EESK, 1997), the corresponding seismic risk factor is 0.57.

Table 1 Seismic risk factor of KTX bridges according to performance levels

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

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 according to Table 2 (EESK, 1997). The region where the KTX is constructed pertains to a seismic zone factor of 0.11 corresponding to the seismic zone I of Table 3 (EESK, 1997).

Table 2 Soil type and site coefficient

Soil type	Shear wave velocity (m/s)	Soil profile	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 500 years)

Seismic zone	Seismic zone factor
I	0.11
II	0.07

3. Modeling of the Bridge System

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 analyze adequately stresses in railway bridge rails. Owing that the appearance of additional stresses in rails is more noticeable in continuous bridges than in single-span bridges, the bridges selected for the analysis are two 3-span continuous bridges of 100m (B and C in Fig. 1). 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 behavior according to the presence or not of vertical loading (Fig. 2). The railway is constituted by two tracks. The rails and the bridge superstructure are modelled so as to have 1 node each 5m (Fig. 1). The high-speed train considered here corresponds to a typical convoy averaging a length of about 300m.

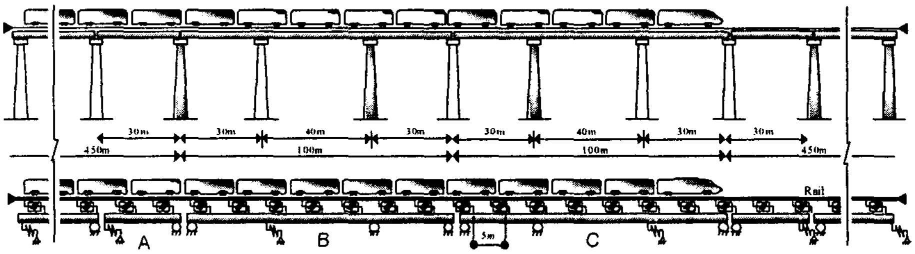

Fig. 1 Bridge system model

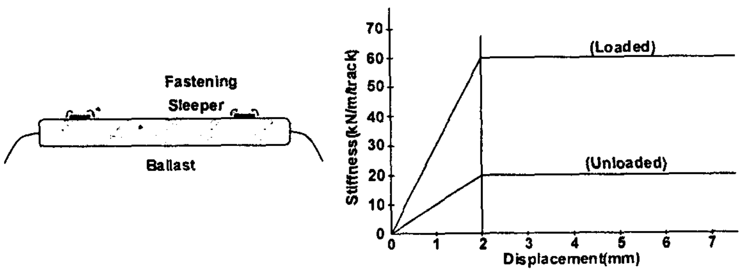

Fig. 2 Model of ballast and fastening

4. Analysis Procedure

As structural response is known to be sensible to the properties of 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 the nonlinear time domain analysis.

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 displacements of contiguous bridge decks and the joint rail stresses. Assuming that contiguous bridges show linear behaviour independently, Fig. 3 compares the effects of such spatial variation on the relative displacement between contiguous decks and stress in rails. It can be seen that as the difference between periods of contiguous decks reduces, bridge responses magnify. 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.

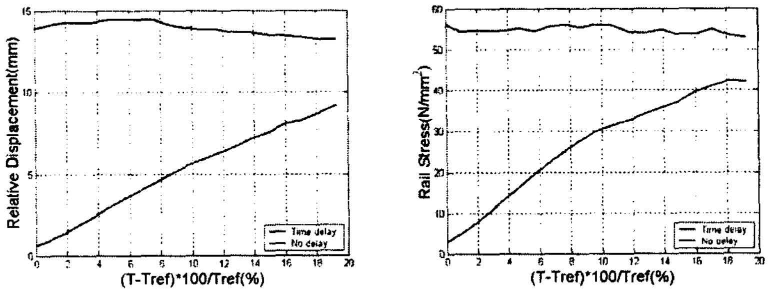

Fig. 3 Effects of spatial variation of earthquake on high-speed railway bridge responses

Fig. 4 depicts the proposed analysis procedure. Introducing models of the bridges, the rails and rail-bridge interactions in the structural model, the structural model is established at first. Thereafter, analysis is performed for seismic and braking loads by means of a direct time domain integration method 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.

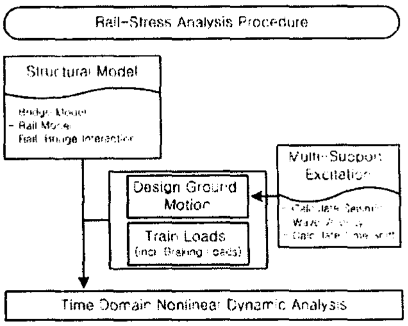

Fig. 4 The proposed rail-stress analysis procedure

5. Analysis Results

Typical sites of the KTX are selected to demonstrate the accuracy of the proposed method and emphasize the effects of the characteristics of the ground motion on the structural responses. The boring data adopted in the analysis correspond to usual satisfactory soil and are summarized in Table 4.

Table 4 Boring data

Layer i	Thickness H_i(m)	Soil type	Shear wave velocity V_S(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

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. 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.

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 as shown in Fig. 5.

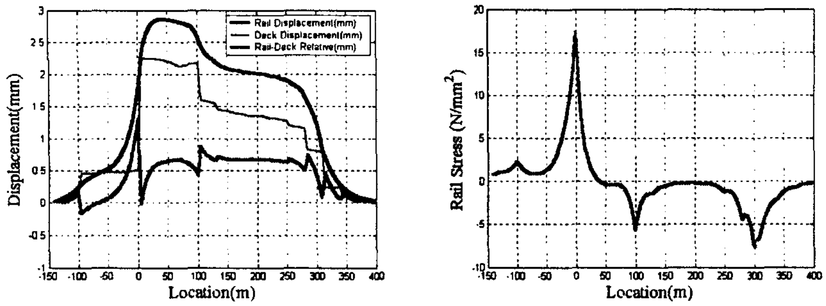

Fig. 5 Deck displacements and stresses in rails according to braking load

Results of Fig. 5 confirm that braking high-speed trains involve very long track lengths comprising not only the distance needed by the train to stop but also long track lengths at both sides of the braking distance. Such feature emphasizes the importance of checking the safe stoppage of the train under seismic event.

Fig. 6 compares the relative displacement of the decks and rail stress at the joints of two continuous bridges (A and B in Fig. 1) with a difference of 25.72% in their natural periods subjected to ground motion considering time shift. Results show that relative displacements and rail stresses reduce only by 0.9337 times and 0.9156 times, respectively, when accounting for 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. 1) 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. 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 2.53 N/mm^2, which is 84.3% smaller regard to $16.1N/mm^2$ also obtained from static analysis (Fig. 8).

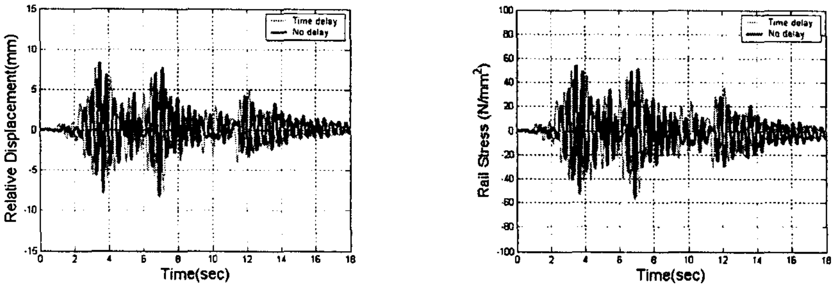

Fig. 6 Effects of seismic forces on contiguous bridges with more than 20% difference in their natural periods according to wave passage effect : (a) Relative displacement of the decks, (b) Stress in the rail

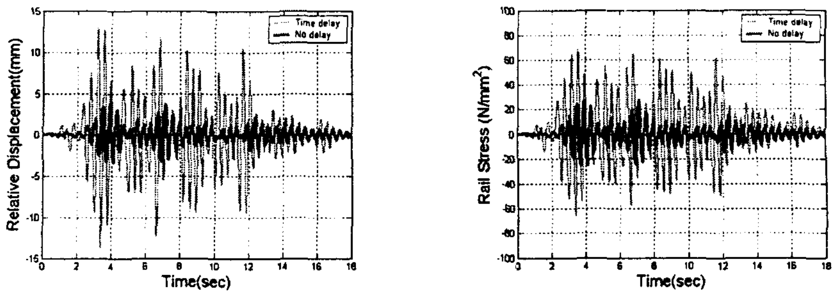

Fig. 7 Effects of seismic forces on contiguous bridges with less than 10% difference in their natural periods according to wave passage effect : (a) Relative displacement of the decks, (b) Stress in the rail

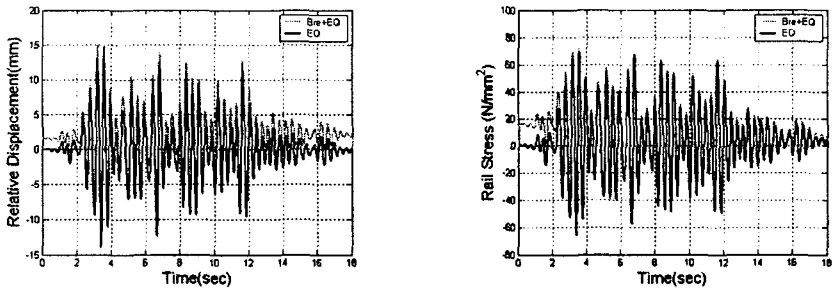

Fig. 8 Effects of seismic and braking forces on contiguous bridges with less than 20% difference in their natural periods according to wave passage effect : (a) Relative displacement of the decks, (b) Stress in the rail

6. Conclusions

Former researches and design criteria prescribed seismic analyses, which modeled the bridges without rails, to limit stresses in long rails by restricting the relative displacements between contiguous bridge decks of the high-speed railway. However, our study showed that such approach is inadequate to limit stresses in rails since stiffness of long rails increases with the length of the train and, rails and decks interact.

On the other hand, the seismic design performed for the KTX bridges disregarded damages that may be suffered by rails under seismic events. However, we have seen that 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 also been ignored in determining the relative displacement of the decks and, by the way, 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 shown 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 modeling not only the bridge, but also rails and rail-bridge interactions must be applied to compute adequately 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. The proposed procedure makes it possible to produce economical design of long rails compared to former conservative approaches.

Acknowledgement

This work was supported by the Brain Korea 21 Project. The authors would like to thank the practical assistance of the Research Institute of Engineering Science, Seoul National University.

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