Risk Assessment of a High-Speed Railway Bridge System Based on an Improved Response Surface Method

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ABSTRACT

A refined three-dimensional finite element interaction model between the high-speed train and railway bride deck has been developed in the present study. Analytical predictions of vertical deflections for a railway bridge are compared with in-situ test results and a good agreement is achieved. Then, input variables employed in the analytical comparisons are selected as random variables for the limit state functions, followed by risk assessment. For this purpose, a linear adaptive weighted response surface method has been developed and applied. A typical railway bridge has been selected and the limit state functions are employed from UIC and Korean specifications in the comparative studies. The results reveal that Korean specifications give significantly risky reliability indices in comparison with UIC specifications. It is thus encouraged from the above that the present linear adaptive weighted response surface method can be an alternative for the fast estimation of nonlinear structural systems.

Keywords: *Railway Bridge, Risk Assessment, System Reliability, Improved Response Surface Method*

1. Introduction

As the operating speed of the train becomes higher and reaches 300 km/h or more, railway bridges carrying the high-speed train loads are of particularly importance because of train-bridge interactions. The interactive dynamic analysis between moving vehicle loads and bridge has numerous uncertainties including bridge resistance, moving train speed, moving train induced loads and etc. Subsequently, the estimation of safety in terms of the probability of exceeding the design criteria during the design life of the structural system is mandatory. However, little effort has been made to identify that which random variable has to be considered in the probabilistic analysis and what criteria should be selected to determine the probabilistic safety. In particular, probabilistic modeling of a moving load and probabilistic analysis of the interaction between train and bridge system have not been intensively and qualitatively investigated. This is mainly due to the high cost of conducting field experiments. In this regard, the stochastic prediction of uncertainties can be an alternative.

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In view of the above, a refined 3-dimensional finite element analytical interaction model between the high-speed train and railway bridge deck is proposed in the present study. In this model, a complete interaction between moving loads and bridge system is constructed in terms of deriving the equations of forces acting on the bridge. The response of the interative system is analyzed to compose an explicit limit state function based on the developed FE model. The limit state functions composed by emplying Response Surface Method (referred to as RSM hereafter)[(1)]. The detailed description of the probabilistic evaluation is found in subsequent sections, interms of the comparative studies, carried out using the developed LAW-RSM in between Korean high-speed railway design specifications and the design specifications for the International Union of Railways [(2)].

2. DESCRIPTION OF PROBABILISTIC ANALYSIS SCHEME

The stochastic analysis of a distributed parameter system under moving loads is usually performed in two ways; firstly,by assuming the characteristic of the structural systems as deterministic and the intensity of the moving force as stochastic [(3)]; secondly, by assuming the force amplitudes and the time arrivals on the system as stochastic [(4)]. Hwang and Nowak [(5)] and Nassif and Nowak [(6)] studied a dynamic load effect due to moving trucks using a Fourier transformation of power density function. However, the uncertainties in load and resistance are ignored and treated by using approximated Monte Carlo Simulation. Consequently, the stochastic reliability analysis has not been applied for the interaction between train and bridge system.

For this purpose, a Linear Adaptive Weighted RSM (LAW-RSM) has been employed [(7)] to compose the ultimate limit state functions in order to assess the uncertainties of moving train using parameters, such as stiffness, moment of inertia and damping ratio. Consequently, comparative studies have been carried out using the developed LAW-RSM in between Korean high-speed railway design specifications and the design specifications for the International Union of Railways.

3. APPLICATION TO THE HIGH-SPEED TRAIN-BRIDGE INTERACTION SYSTEM

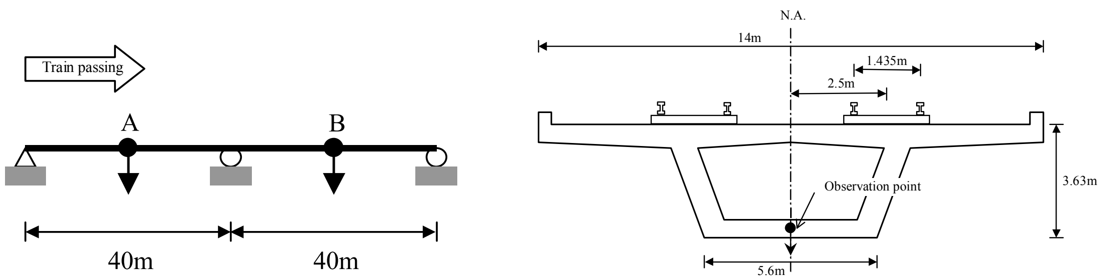
Three-dimensional beam finite elements are employed to model the rails and sleepers of track structures. The beam element has segment-wise constant cross-section and resists two bending moments along the principle axes and torsions in the centroid of the cross-section. No coupling effects among axial forces, bending moments and torsions are taken into account. The beam elements with the off-set of beam node are employed to model the rails. Ballast is selected as a crushed material placed on the top layer of the substructure in which the sleepers are embedded [(8)].

The high-speed train model in the present study is an articulated vehicle model in which bogies are located between car bodies and are connected at car body-bogie joints. Thus, vibration generated in each car body, particularly at the junctions of two car bodies can be considerably reduced. Withregard to the motions in the vehicle model, the rolling and sliding motion of a car body are not taken into account. Al-though the rolling and sliding motion may occur due to the presence of torsional vibrations and track irregularities, such motions are ignorable without violation of formulation and thus are constrained to be zero for the efficiency of formulation. Therefore, the equations of motion of the vehicle, which are com-posed of the degrees of freedom at the joints, bogies and bridge, can be determined by identifying the position of a series of bogies. Car bodies and bogies are modeled as rigid bodies with masses and they are assumed to move along a straight track at constant speed. In addition, it is assumed that wheels and rails always keep in contact.

4. RELIABILITY ANALYSIS OF TWO SPAN CONTINUOUS PSC BOX-GIRDER BRIDGE

4.1 Analytical modeling approach for a railway bridge

Using the developed FE analytical modeling approaches as described in section 3, a two span continuous PSC box girder railway bridge is modeled and verified with the experimental results of the bridge over which 20-car formation high-speed train is running, before performing reliability analysis of the bridge in terms of the linear weighted response surface method.
The high-speed trainis 380.03 m long and comprises 16 passenger cars carried by 2 power cars and 2 power passenger cars. The high-speed train running at the speed of 300km/h is selected for the current verification.



(a) Longitudinal view (b) Cross-section details

Figure 1. Graphical representation of the two span continuous PSC box-girder railway bridge.

Table 3. Material properties of the bridge.

Remark		Design value
Concrete	Young' s modulus (kN/m^2)	29,430,000
	Poisson' s ratio	0.15

Specific weight (kN /m^3)	24.53
Damping ratio (%)	2.40
Permanent weight of track structure (kN /m)	65.67

The selected PSC box girder railway bridge has 14m wide with ballasted double tracks having the eccentricity of 2.5m, and 40m span length. Both graphical representation of the bridge and cross-section details are shown in figure 1, while material properties of the bridge are given in table 3. The bridge is modeled by 4-node, variable-node NFS elements and beam elements. The analytical modeling is employing 1344 four-node elements, 288 variable-node NFS elements and 578 beam elements. To model the beam elements on two-parameter elastic foundation, the foundation stiffness k = 5×10^7 (N/m) and the second parameter k_1 = 1×10^2 (N·m) are used.

4.2 Limit state functions for reliability analysis

Two limit state functions are considered for the evaluation of ultimate state. The ultimate limit state for the driving safety of train has been considered in terms of limiting accelerations induced by a dynamic load of train, passing through the bridge. Time-dependent ultimate limit state functions are selected using UIC and Korean specifications at the both span center A and B (figure 1(a)). Thus,

Driving safety of train (UIC): $g(i,t) = 0.35g - v^{"}(t) = 3.43 - v^{"}(t), m/s^2$ (1)

Driving safety of train (Korean specification): $g(i,t) = 2.04 - v^{"}(t), m/s^2$ (2)

where $g(i,t)$ is the limit state function at time t(sec) of the Girder i, i is the location of observation (A: span A; B: span B), $v^{"}(t)$ is a time dependent acceleration of the girder i. When demand exceeds supply in the limit state functions, the function becomes less than 0.

The selected random variables are area of box girder, damping ratio, and the elastic modulus of concrete for demand terms in the limit state functions. The supplying terms in the limit state functions are the threshold value of acceleration based on each design specifications. Each random variable is assumed to be uncorrelated. Table 4 shows the statistical properties of the selected random variables. Table 5 summarizes the axial points and 3D moving load analysis results in order to compose the response surface functions for 2n+1 cases.

Table 4 Random variables and statistical values.

Random Variables	Index	Mean value	C.O.V.	Distribution
Area of box girder (%)	X_1	100 %	0.17	Normal
Damping ratio	X_2	2%	0.060	Normal
Elasticity of concrete	X_3	3.0e10 N/m^2	0.053	Normal

Threshold value of acceleration in UIC	X_4	3.43	0.10	Log−Normal
Threshold value of acceleration in Koran specification	X_4	2.04	0.10	Log−Normal

*C.O.V.: Coefficient of Variation

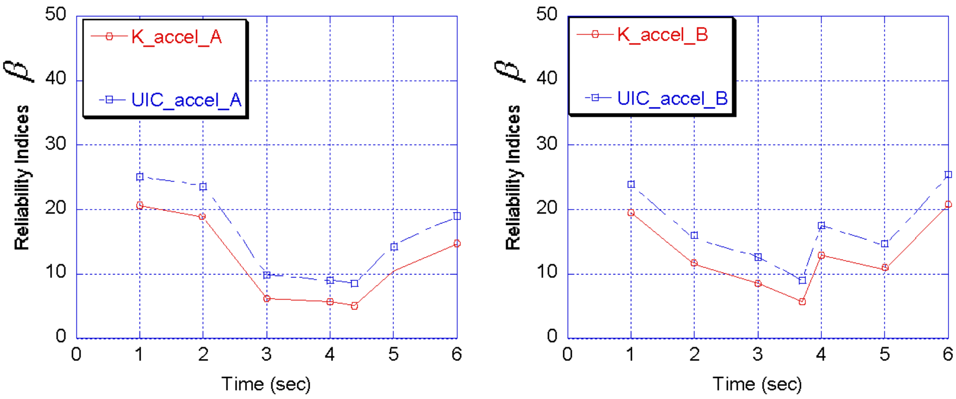


Figure 3. Comparison of reliability indices at span A and B for the violation of acceleration limit.

Using the variation of input and output data in table 5, the limit state functions based on the Korean specification are established in terms of the determined coefficients of response surfaces for the driving safety of train. After the first evaluation, the weighting matrix is calculated, which is multiplied to find the second improved response surface in the LAW−RSM. Once the limit state functions are established, the reliability indices and the probability of failure are evaluated in terms of using the first order second moment method (FOSM) proposed by Rackwitz−Fiessler (1978).

In Figure 3, the fitted limit state functions are used to evaluate the reliability indices. As observed, the safety of the bridge is increased after 5.5 seconds for both specifications when the train has passed span A. Reliability indices exceeding the UIC specification value (3.43 m/s^2) show large safety in comparison with the indices for the case of Korean specification which defines a smaller criterion for the driving safety of train. Reliability indices are fluctuating, due to the oscillatory behavior of the bridge analysis results.In general, Korean specifications predicts more risky reliability index than the UIC specifications. This is due to the conservative threshold value in the Korean specifications. The evaluated minimum reliability index for UIC and Korean specification is 9.072 at span B and 5.040 at span A respectively.

5. CONCLUDING REMARKS

A refined three-dimensional finite element interaction model between the high-speed train and railway bride deck has been developed in the present study. A complete interaction between moving loads and bridge system has been established in terms of deriving the equations of forces acting on a bridge. Analytical predictions of vertical deflections for a railway bridge show good agreement with the in-situ test results. Subsequently, input variables employed for the analytical comparisons are selected as random variables in the limit state functions of the following reliability analyses.

Reliability analyses have been carried out using limit state functions taking into account the safety of train. For the analyses, a linear weighted response surface method has been utilized in order to model the uncertainties of moving trains. Comparative studies have also been performed using the developed linear weighted response surface method for the assessment of driving safety of train. The limit state functions are selected from UIC and Korean specifications in the comparative studies. The results reveal that Korean specifications give significantly risky reliability indices in comparison with UIC specifications.

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