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REDUCTION OF ACCELERATIONS OF THE BRIDGE VIBRATION FOR HIGH-SPEED TRAINS

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Abstract

The Gyeongbu high-speed railway line inaugurated on April 1, 2004 with the operational trial running of the KTX (Korean High Speed Train) is now in operation with the train running at a very high design speed of 350 km/hr. Since one-third of the 410 km of the Gyeongbu line is composed of bridges, the dynamic behavior of the bridges constitutes a feature of extreme importance in securing the stability of the running trains. The data acquired in the trial section of the line since 1997 through measurements performed on 2@40m PSC box girders, being one of the representative bridge types of the Gyeongbu line, revealed that the acceleration responses are exceeding the design limit of 0.35g. Such responses are the results of the impact at the interface between the ballast and sleepers, the effects of the elastic bearing installed in the bridge, the local behavior in the large section of the box girder and the impact caused by the train like wheel flat.

This study investigates the feasibility of solutions reducing local vibrations and solutions increasing the mass of the bridge in order to reduce such excessive accelerations. To that goal, all types of devices like dampers were installed in the bridge section to reduce local vibrations and, their effectiveness was verified through field test and theoretical study. The laying of additional masses inside the box girders for reducing the overall acceleration responses of the bridge is also examined through theoretical study using analytical method and through experiments implemented on an actual bridge.

INTRODUCTION

Approximately one-third of the whole length of the Gyeongbu high-speed railway line, which opened to traffic on April 1, 2004 in Korea, is constituted by bridge structures. Except for particular sections like stations, crossings of highways and expressways, the elevated bridge structures have been typically built as PSC box girder bridges with span compositions of 2@40 m or 3@25 m. Especially, PSC box girder bridges with span composition of 2@40 m can be considered as the most representative bridge type among the bridges that have been designed and built on the Gyeongbu high-speed railway line. This selection has been decided since the design stage after comparative survey of various bridge types presenting reduced construction costs like PSC beam, preflex, T-shape girder, rahmen and PSC box girder bridges. Comparison finally resulted in the choice of PSC bridges due to the remarkable stability of their dynamic responses. Although diversified construction methods have been implemented according to the builders and site conditions, identical features and characteristics, that are a single box with a girder height of 3.5 m and a width of 14 m, have been applied for the bridges. Such large sectional shapes led to long spans of about 7 m for the floor slab between the webs of the box girder and overhanging beams exceeding a length of 3 m in both sides.

Differently from ordinary highway bridges crossed by indeterminate wheels on variable lanes, railway bridges present determinate loading conditions since trains are running on assigned tracks. In addition, at an arbitrary point of the bridge, vehicles running on a highway bridge act irregularly, as punctual dynamic loads, while trains are producing repeated dynamic loads through their regularly spaced wheels moving on a determinate track. Trains are thus acting as loading with definite frequency. However, if this frequency coincides with the natural frequency of the bridge, resonance will occur, producing excessive responses of the bridge and causing disastrous effects on the safety of the train crossing the bridge. As the dynamic response characteristics of the bridge depend on the relationship between its natural vibration modes (especially flexural modes) and the frequency of the applied load, it is necessary to perform investigations on the dynamic behavior of the bridge in order to secure running safety of the trains when deciding the type of high-speed railway bridge. To that goal, selected criteria have been set up in BRDM based on the European UIC. The major specifications related to the safety of the track are the acceleration of the deck (0.35g), the deflection (L/1700) and the end rotation (5×10^{-4} radian).

In spite of the importance of safety for high-speed railway bridges, studies on the dynamic behavior of high-speed railway bridges were practically neglected until the early 1990s. Recently, Chang et al. (1998) proposed a two-dimensional train model considering bouncing and pitching motions to perform vibration analyses of bridges subject to moving articulated bogies train. In this study, the ballast covering the bridge was idealized by means of the classical theory of beam on elastic foundation. Thereafter, Ahn et al. (2000) and Kim (2000) attempted to suppress resonance by relating the span length of the bridge and the arrangement of the train. However, most of these studies remain theoretical and the absence of experimental studies is particularly overwhelming. Kwark et al. (2003) proposed a first attempt to fill this void through experimental research performed to investigate the dynamic responses of concrete box-girder bridges in 2003.

MEASUREMENT OF DYNAMIC RESPONSES IN THE GYEONBU HIGH-SPEED RAILWAY LINE

Running tests were performed in the test lane of the Gyeonbu high-speed railway line in order to check and inspect the trains, structures and facilities before the opening to traffic in 2004. Measurements of the dynamic responses of Yeon-Jae Bridge (see Figure 1) crossed by the KTX, the Korean version of the French TGV, were carried out since 2002. Yeon-Jae Bridge is a PSC box girder bridge with span length of 2@40 m located in the experimental section of the Gyeonbu high-speed railway line.

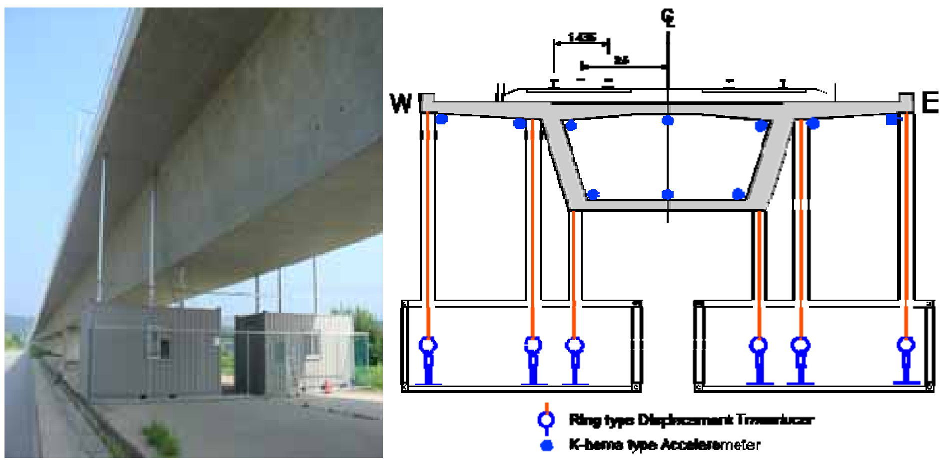


Figure 1. General view and measurement system of Yeon-Jae Bridge

Diversified types of sensors like displacement transducers, accelerometers and end rotation measuring devices were installed in Yeon-Jae Bridge for site measurement. Measurements were performed irregularly during the running tests and at fixed intervals after the beginning of operational service.

Measurement results of the bridge responses obtained through the sensing devices during the crossing of the KTX revealed that, except for the acceleration, all the responses exhibited sufficient level to secure running safety. Measured deflections and end rotation were seen to be largely below L/1700 and 5×10^{-4} rad, respectively. However, excessive acceleration responses were measured, which in extreme cases, exceeded the limit specified by BRDM.

BRIDGE RESPONSES DUE TO HIGH-SPEED TRAIN

Excessive acceleration responses in PSC single box girder bridges were observed through site measurements during the preliminary tests performed in 2002 to examine the dynamic responses of high-speed railway bridges due to the crossing of the KTX. The occurrence of such phenomenon could be explained by the fact that measurements were carried out before operational service for trains without variation of their loads, and decision was taken to pursue long-term measurement. As a result, excessive accelerations were measured in winter as temperature decreased. Figure 2 plots the maximum accelerations and displacements measured in Yeon-Jae Bridge, according to time.

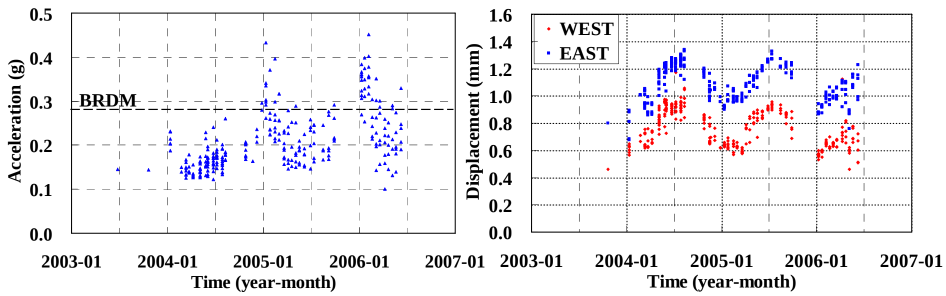


Figure 2. Variation of maximum accelerations and displacements with time

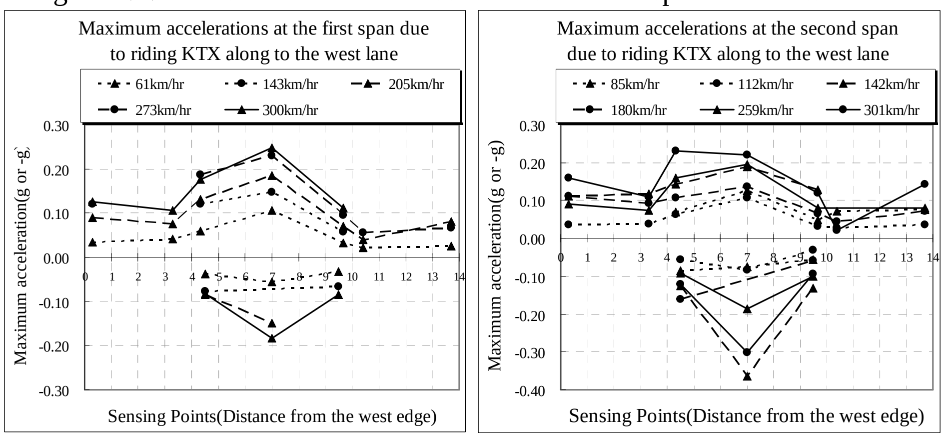


Figure 3. Distribution of the maximum acceleration in the section of Yeon-Jae Bridge according to the crossing of KTX

On the other hand, even if accelerations were seen to surpass the limit value under very low temperatures, acceleration responses were also observed to be very large and to approach the limit of 0.35g under normal temperatures. The reasons can be found in the conditions of the wheels and rails like side wear, the interface conditions between the ballast and the sleepers, the maintenance conditions of the ballast and the type of bridge. Most of these reasons depend on the state of the ballast and train rather than on the type of bridge. Measurements revealed that perfect adhesion of the sleepers with the ballast could not be obtained, which led to impacts on the bridge each time wheels ran over the sleepers. Following, the regularly and continuously spaced sleepers together with the speed of the moving wheels were seen to affect the acceleration responses of the bridge. Moreover, local vibrations were predicted in Yeon-Jae Bridge since its section corresponds to a very large single box girder bridge. This prediction and the influence of the sleepers disposed at regular intervals were verified in view of the measurements plotted in Figure 3.

REDUCTION OF ACCELERATION RESPONSE THROUGH THE APPLICATION OF DAMPING DEVICES

The acceleration responses occurring in Yeon-Jae Bridge under resonance appeared to be extremely large. Such resonance frequency corresponds to the first mode of the bridge under resonance speed. Three alternatives may offer solutions in order to prevent or reduce these excessive accelerations, which are preventing resonance, installing vibration-reducing devices, or adding masses in the inner sections of box-girder. Even if adjusting the stiffness of the bridge or adopting the recently reported resonance cancellation span length may prevent resonance, the former is economically inefficient and the latter cannot be applied on completed bridges. On the other hand, the methods which proceed by introducing isolating devices, or adding masses in the whole system of previously built bridges develop their performances only when the defection exceeds a definite level. However, in the bridge of interest, the stiffness being extremely large, deflection reaches barely several millimeters, which renders to such method unpractical. Recalling that local vibrations and large accelerations occur in the bridge, a solution can thus be provided by reducing such local vibrations which will in turn reduce these excessive acceleration responses.

The reducing effects on the local vibrations have been examined by applying external forces with frequencies corresponding to bending, torsion and flap modes at locations occupied by the moving train. The adopted isolating device is a viscous damper sustained between the top and bottom flanges at the center of the section of the bridge. A damping value of 5×10^8 N·sec/m has been considered in regard to the specs provided for actually commercial viscous dampers.

For a study on the method of vibration reduction of the bridge, a computer program for dynamic analysis of the bridge due to moving loads of high-speed trains was developed considering local vibration of box-girder and simulating damper device. Applicability of damper device to vibration diminution was evaluated numerically using the developed program. Dynamic responses according to trains running at various speeds from 150 km/hr to 400 km/hr were analyzed for the bridge installed with one and three dampers (case1 and case 3, respectively) or without damper (case 0). Figure 4 plots the time histories of bridge accelerations due to high-speed train crossing with speed of 275 km/hr according to the eventual presence of a damper device. Figure 5 shows the reduction ratio of bridge accelerations brought by the set of dampers according to the speed of the train.

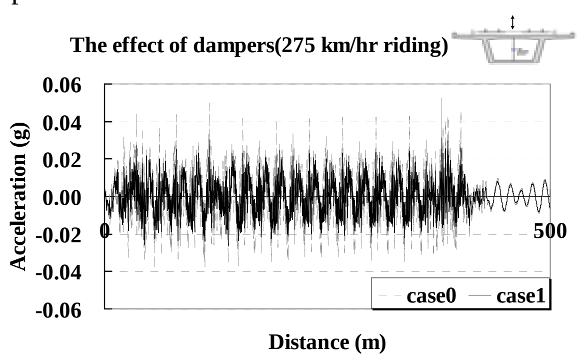


Figure 4. Comparison of accelerations of case 0 (without damper) with case 1 (with one damper)

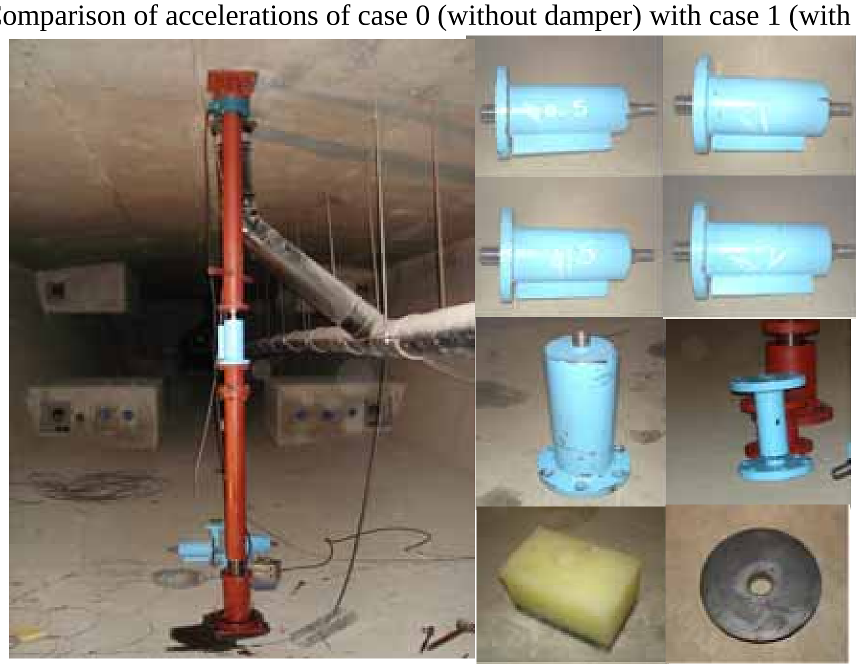


Figure 5. Installed dampers for the reduction of local vibrations and adopted devices

In order to examine the performances of the damping devices in reducing the local vibrations, various dampers were installed in the 2@40m PSC box girder bridge and running tests were conducted.

A total of 8 load cases were considered. Figure 5 shows a view of the installed dampers for the reduction of local vibrations as well as pictures of the adopted devices. Table 1 arranges the reduction ratios of the vibrations caused by actually running high-speed trains obtained through the application of the dampers. In regard to the field tests, results verified that the vibration reduction effect reached a maximum of 26% owing to the use of the local vibration-reducing devices.

Table 1. Vibration reduction ratio according to the damping devices

Case	2nd span	1st span
Orifice damper Φ0.5	4.17 %	7.32 %
Orifice damper Φ1.0	25.85 %	11.12 %
Orifice damper Φ1.5	6.88 %	2.72 %
Orifice damper Φ2.0	13.65 %	10.68 %
Turnbuckle	-0.12 %	11.16 %
Rigid linkage	5.39 %	15.43 %
Urethane	8.91 %	10.15 %
Rubber	8.81 %	23.53 %

REDUCTION OF ACCELERATION RESPONSE BY INSTALLING ADDED MASSES

The damping devices proposed to reduce the local vibrations were seen to produce effects to a certain extent in regards to the field test results. However, these vibration reduction effects are lacking consistency, which makes such a solution of poor efficiency in the long-term, especially in view of the difficulties that are likely to occur in the maintenance. Since the vibration accelerations observed in the actual bridges of the Gyeongbu high-speed railway line are approaching or exceeding slightly the design values, necessity is to provide, economically efficient, as well as effective solutions for maintenance while obtaining only vibration reduction effects. A solution can be supplied by increasing the mass of the bridge without changing its stiffness so as to realize reduction of the acceleration responses. Most of the bridges of the Gyeongbu high-speed railway line being box girder bridges, sufficient space can be secured inside the boxes to implement works. Accordingly, this space has been exploited to increase the mass of the bridges. A trial construction is planned on an actual bridge in the mid of 2007, and the expected effects of this solution have been verified theoretically through analytic study to date.

Figure 6 illustrates schematically the laying of the additional masses. The added masses are laid inside the box girders above the bottom flange at 2 spans. The masses with length of 10 m, thicknesses of 25 cm (T25) and 50 cm (T50) are made of ordinary concrete so as to prevent change in the stiffness.

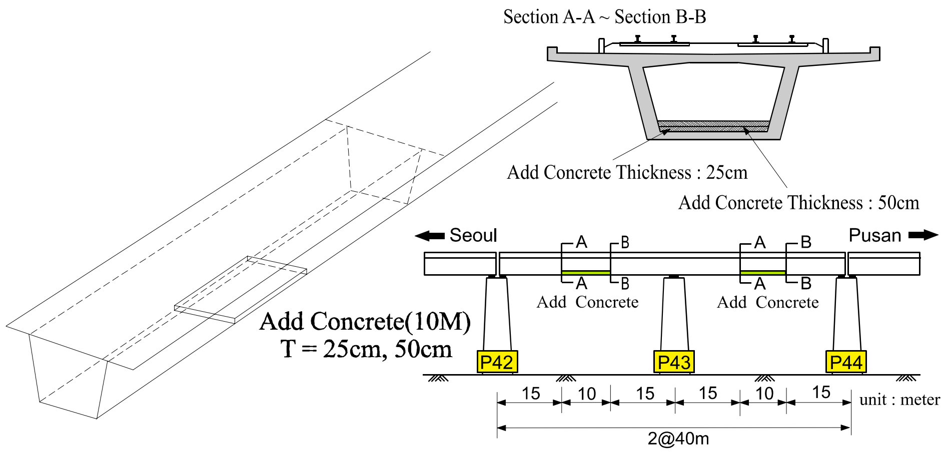


Figure 6. Schematic drawing of the performance improvement of existing bridges using additional masses

Table 2 summarizes the values used to model analytically the bridges for the verification of the vibration-reducing effects of the bridges using the additional masses. The ratio of the additional masses to the whole self-weight reaches approximately 1.3% for the case with thickness of 25 cm, which corresponds to a very slight augmentation of the dead load while the first flexural frequency increases by about 14%.

Table 2. Analytic model applying the additional masses

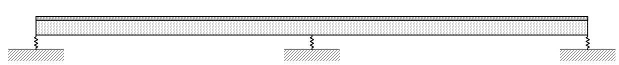
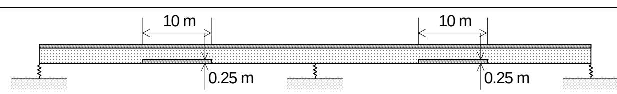
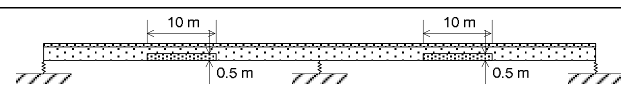
Mod-el	Nat. Freq. (Hz)	Add-ed Mass (%)	Locations of added mass
T0	4.49	0.0	
T25	3.87	1.3	
T50	3.81	2.6	

Figure 7 shows the acceleration response ratio according to the additional masses in the top flange at mid-section of the span under high-speed train running at 300 km/hr. It can be seen that the maximum response ratio of the models T25 and T50 are reducing respectively by 37% and 43%. Table 3 arranges the maximum reduction ratio for each model.

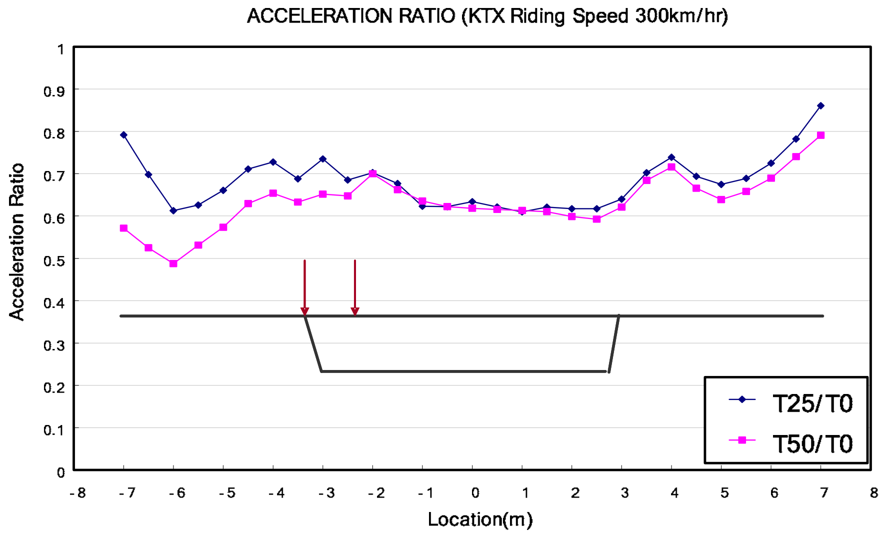


Figure 7. Reduction of the acceleration response brought by the added masses

Table 3. Maximum reduction ratio of the acceleration according to the added masses

Model	Speed (km/hr)	Reduction ratio (%)	
		Cantilever	Center of upper flange
T25	300	20.8	36.6
	Resonance	9.8	7.6
T50	300	42.9	38.2
	Resonance	11.5	9.4

CONCLUDING REMARKS

The most simple and efficient alternative to reduce the excessive acceleration responses occurring in high-speed railway bridges crossed by trains has been provided by means of small-size dampers and added masses. The applicability of these viscous dampers to reduce local vibrations has been examined theoretically and experimentally. The dynamic behavior of the bridge subjected moving loads by crossing trains has been analyzed using a three-dimensional bridge model and tested at a field using various devices. Even if the solution reducing local vibration through the installation of such damping devices is also bringing some drawbacks in terms of maintenance, consistency of reduction effect and effectiveness, the method using additional masses to reduce excessive accelerations by simply increasing the mass is providing numerous advantages and, its significant effectiveness has been verified by means of theoretical study.

Even if the solution reducing the acceleration responses using local vibration-reducing devices has been verified to be effective, this solution appeared to be extremely disadvantageous in terms of maintenance, which makes such method of poor economic viability. Based on the study results, the method adopting orifice dampers has been seen to be the most effective among the methods using local vibration-reducing damping devices. The solution reducing local vibrations using additional masses appeared to be extremely economical and was assessed as a valuable method. Since the reduction effects appeared to not increase significantly with the size of the added masses, the selection of appropriate masses should be done with careful consideration. Finally, field tests are previewed for the method applying added masses to reduce the local vibrations.

Acknowledgements

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References

1. Ahn Y.J., Kim S.J. & Shin Y.S., `Dynamic Behavior of High-Speed Railway Bridges`, Journal of Korean Society for Steel Construction, 20(3)(2000) 375-384.
2. Chang S.P., Kwark J.W. & Kim S.I., `Vibration of steel composite railway bridges subjected to high speed train', Journal of Korean Society for Steel Construction, 10(4)(1998), 577-587.
3. Kim S.I., `Bridge-train interaction analysis of high-speed railway bridges`, Ph.D. Thesis. (Seoul national university, Korea, 2000).
4. Kwark J.W., Chin W.J., Kim Y.J. & Kim B.S., `Dynamic Behavior of Concrete Box Girder Bridge due to Riding Korean High-Speed Train`, Journal of Korean Society for Steel Construction, 23(1)(2003), 27-36.