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고속철도 교량의 진동저감

Diminution of bridge vibration for high-speed trains

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Abstract

고속철도 교량구간에 차량(KTX)이 주행할 경우 교량 바닥판에서는 큰 가속도 응답이 계측된다. 이러한 가속도의 원인으로는 큰 단면의 국부 진동, 일정한 간격의 침목의 충격 그리고 차량 자체의 진동 등 여러 가지 원인이 있다. BRDM(Bridge Design Manual)에서는 이러한 동적 특성치들에 대한 제한치를 규정하고 있는데, 가속도인 경우는 0.35G 이하로 규정하고 있다. 실교량 실험에 의해 계측된 가속도 응답은 규정한 제한치인 0.35G 보다는 작지만, 이러한 가속도 응답치들은 차량이 고속으로 주행할 경우 안전성에 문제를 일으킬 수 있다. 본 논문에서는 큰 단면에서 과도한 국부 진동을 지배하는 가속도 응답을 줄이기 위해서 진동저감 방법을 연구하였다. 비록 휨이나 비틀림 같은 전체 진동모드에는 효과가 작지만, 일반적으로 매우 큰 단면을 가진 고속철도 프리스트레스트 상자형 교량의 국부진동인 날개짓 모드를 감소시키는데 진동저감 장치는 효과적이라고 판단된다. 실교량에서 진동저감 장치의 실험은 추후 연구를 수행할 예정이다.

Keywords : High Speed Train(고속철도), Acceleration(가속도), vibration(진동)

1. 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 single box with girder height of 3.5 m and width of 14 m, have been applied for the bridges. Such large sectional shape led to long span of about 7 m for the floorslab 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 wheels spaced at regular spacing and moving on a determinate track. Trains are thus acting as loading with definite frequency. However, if this frequency coincides with the

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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 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 based on BRDM of the European UIC. The major specifications related to the safety of the track are the acceleration of deck (0.35g), the deflection (L/1700) and the end rotation (5×10^{-4} rad).

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 researches performed to investigate the dynamic responses of concrete box-girder bridges in 2003.

2. Measurement Of Dynamic Responses in the Gyeonbu High-Speed Railway Line

Running tests were performed in the experimental section 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 Yeonjae Bridge (see Figure 1) crossed by the KTX, a version of the French TGV, were carried out since 2002. Yeonjae 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.

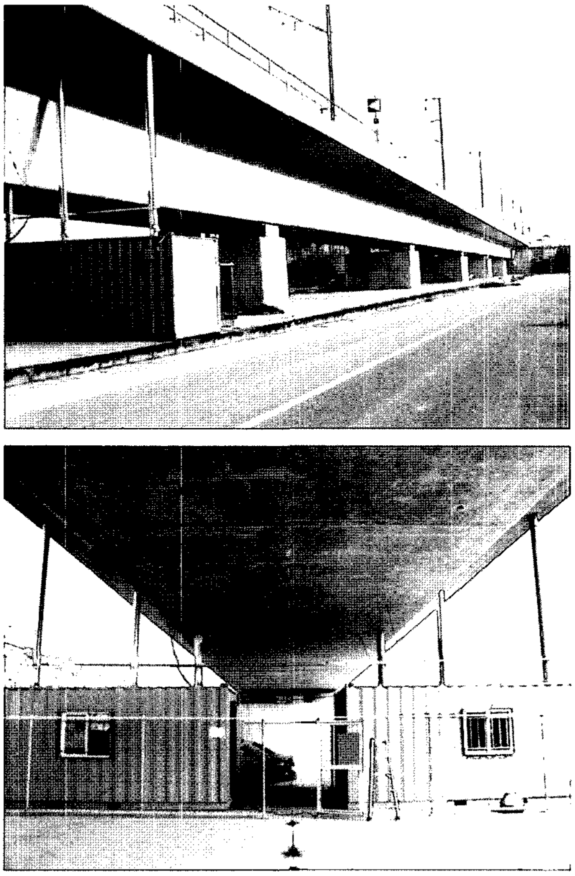


Fig. 1. General view of Yeonjae Bridge and running KTX

Diversified types of sensors like strain gauges, accelerometers and end rotation measuring devices were installed in Yeonjae Bridge for site measurement. Measurements were performed irregularly during the running tests and at fixed intervals after the beginning of operational ser-vice. Figure 2 illustrates the location of the sensing devices in the bridge.

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.

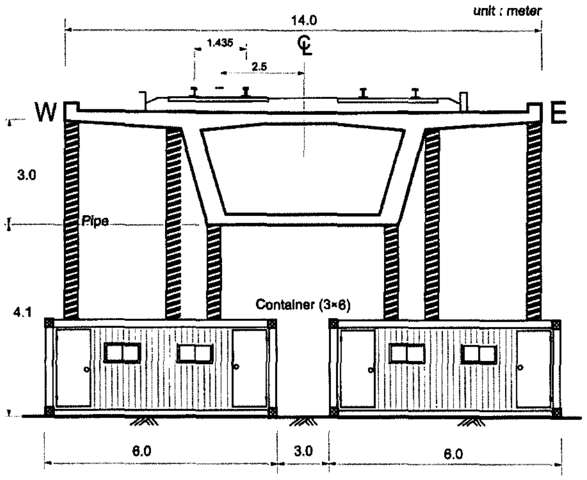


Fig. 2. Measurement system on site

3. Bridge Responses Due to High-Speed Train

Excessive acceleration responses in PSC single box girder bridges were observed through site measurements during 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 3 plots the maximum acceleration responses measured in Yeonjae Bridge according to time.

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 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 Yeonjae 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 4 and Figure 5. Figure 5 compares the low-passed filtered responses referring to the vibrational frequency of the wheels determined with respect to the regularly spaced sleepers and the speed of the train and the non-filtered responses.

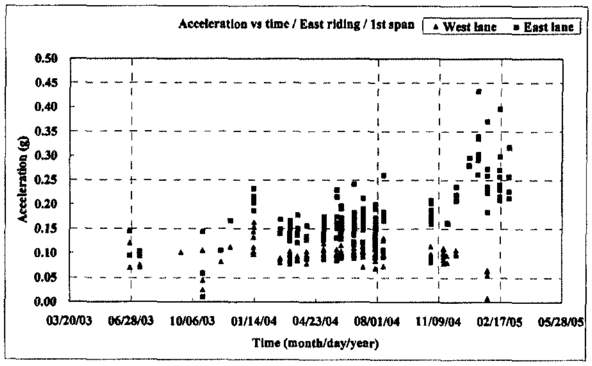


Fig. 3. Variation of maximum acceleration responses with time

4. Reduction of Acceleration Response Through the Application of Damping Devices

The bridge as a single-box girder bridge exhibits the natural modes plotted in Fig. 6. The acceleration responses occurring in Yeonjae Bridge under resonance appeared to be extremely large. Such resonance frequency corresponds to the first mode of the bridge under resonance speed. Two alternatives may offer solutions in order to prevent or reduce these excessive accelerations, which are preventing resonance or installing vibration-reducing devices in the whole system. Even if adjusting the stiffness of the bridge or adopting the recently reported resonance-sweeping span length may prevent resonance, the former is economically inefficient and the latter cannot be applied on completed bridges. On the other hand, the method which proceeds by

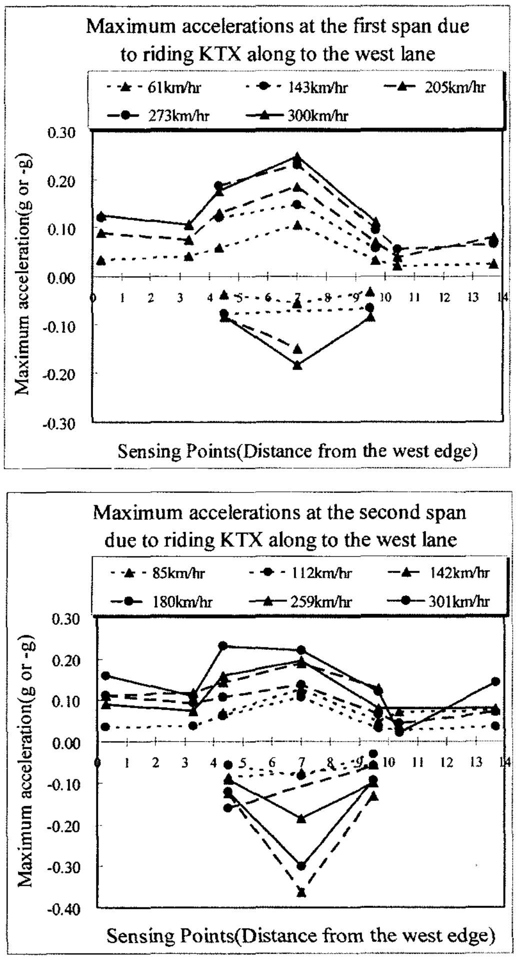


Fig. 4. Distribution of the maximum acceleration in the section of Yeonjae Bridge according to the crossing of the KTX

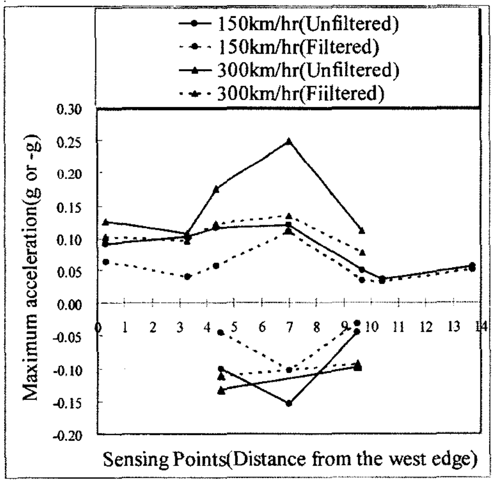


Fig. 5. Effects of the regularly spaced sleepers on the maximum acceleration of the bridge

introducing isolating devices in the whole system of previously built bridges develops its performance 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 such method unpractical (Figure 6). 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.

Figure 7 and Table 1 summarize the bending, torsion and flap mode shapes as well as the cor-responding frequencies of Yeonjae Bridge. 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. Three damping values of actual commercial viscous dampers have been considered that are 5×10^6 N·sec/m, 5×10^7 N·sec/m and 5×10^8 N·sec/m, denoted respectively by SD, MD and LD. UD stands for the case without damper.

Figure 8 compares the time histories of the damped and undamped bridge, and Figure 9 gives comparison of the acceleration responses due to external forces with frequencies corresponding to bending, torsion and flap modes at the central section according to the presence or not and the type of the damper.

As can be seen in the table, the reduction is not remarkable in the case of the first bending mode and first torsional mode while, in the first flap mode, vibration reducing effect appears distinctively at each node following the installation of the damper. For WLD of node 1 located at the extremity of the Western cantilever of the top flange, the reduction ratio for the acceleration reaches a maximum of 43.52%. For WMD of node 29 located at the extremity of the East-ern cantilever of the top flange, the acceleration response is seen to reduce by 19.71%. Also in the case of WLD of node 15, the center of the top flange section, a reduction of 43.54% was observed for the acceleration.

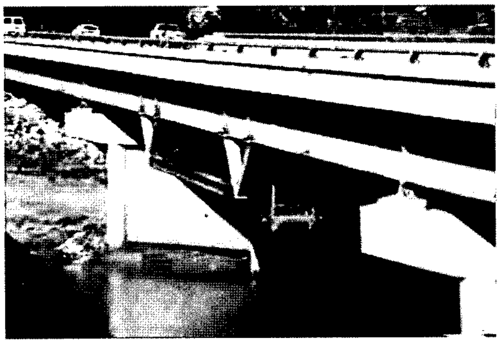
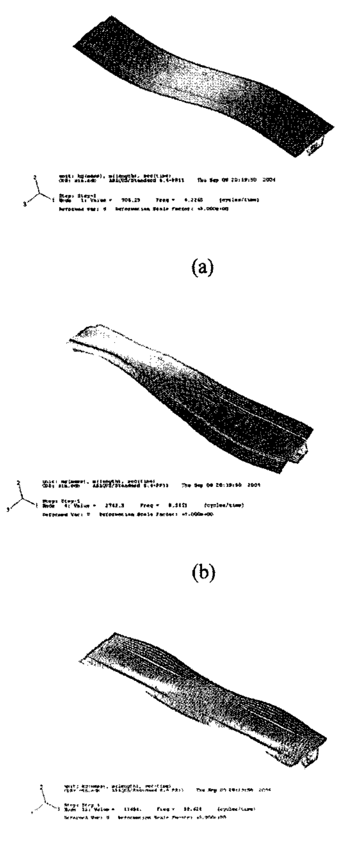


Fig. 6. Example of damping devices installed in the whole bridge system



(a)

(b)

(c)

Fig. 7. Major vibration modes of Yeonjae Bridge (a) flexural mode (b) torsional mode (c) wing mode

Table 1. Natural frequencies of Yeonjae Bridge

Mode number	Mode	Frequency(hz)
1	Bending	4.2265
2	Torsion	8.3651
3	Wing	18.626

S/W : ABAQUS(v6.4)

Slab modeling - 4node shell element

Ballast modeling - solid element

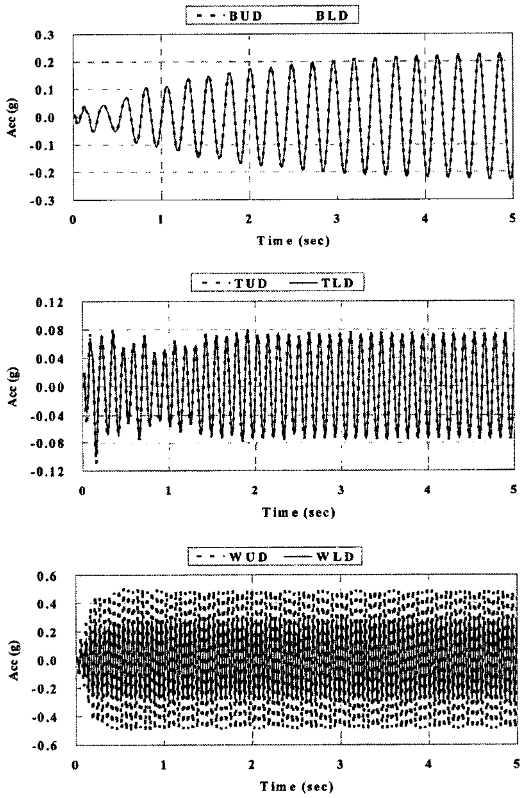


Fig. 8. Typical time histories on the accelerations of the damped and undamped bridge

5. CONCLUDING REMARKS

The most simple and efficient alternative to reduce the excessive acceleration responses occur-ring in high-speed railway bridges crossed by trains has been provided by means of small-size viscous dampers. The applicability of these viscous dampers to reduce local vibrations has been examined. To that goal, the dynamic behavior of the bridge has been analyzed using three-dimensional bridge model.

Analysis results revealed that the installation of the damper made it possible to reduce significantly the acceleration response in the case of the first flap mode. In order to improve the efficiency of the damper in reducing local vibrations, further studies will investigate reduction effects regard to varying damping coefficients, the number of dampers and their location. In addition, the vibration

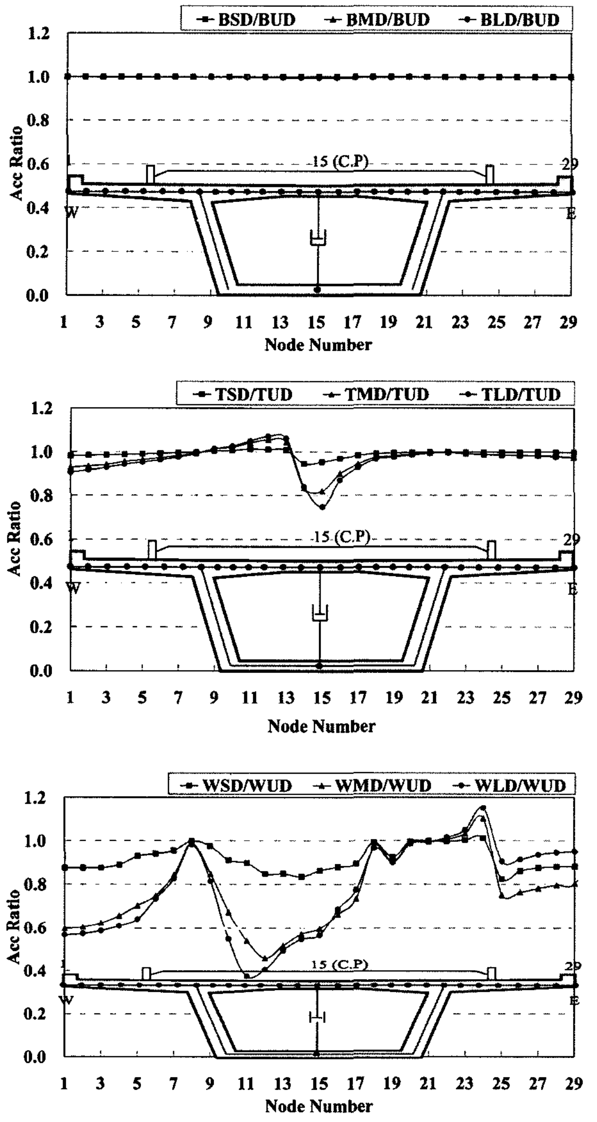


Fig. 9. Reduction of the accelerations using dampers

reducing devices will be optimized through finite element analysis considering diversified parameters and observation of the results, and experimental research will be performed in order to verify the effects the devices.

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