TMD-Based Structural Control of High Performance Steel Bridges

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Abstract. The purpose of this study is to investigate the effectiveness of structural control using tuned mass damper (TMD) for suppressing excessive traffic induced vibration of high performance steel bridge. The study considered 1-span steel plate girder bridge and bridge-vehicle interaction using HS-24 truck model. A numerical model of steel plate girder, traffic load, and TMD is constructed and time history analysis is performed using commercial structural analysis program ABAQUS 6.10. Results from analyses show that high performance steel bridge has dynamic serviceability problem, compared to relatively low performance steel bridge. Therefore, the structural control using TMD is implemented in order to alleviate dynamic serviceability problems. TMD is applied to the bridge with high performance steel and then vertical vibration due to dynamic behavior is assessed again. In consequent, by using TMD, it is confirmed that the residual amplitude is appreciably reduced by 85% in steady-state vibration. Moreover, vibration serviceability assessment using ‘Reiher-Meister Curve’ is also remarkably improved. As a result, this paper provides the guideline for economical design of I-girder using high performance steel and evaluates the effectiveness of structural control using TMD, simultaneously.

1. Introduction
High performance steel for bridges (HSB) has emerged a promising material that offers innovative opportunities to design cost-effective steel bridges with respect to tensile strength, yield strength, and so on. HSB800, the most developed grade in Korea, is recently manufactured and has entered the bridge industry. Due to these outstanding factors, the total amount of steel used in bridge construction will be fairly reduced and weight lightening has become a possibility in the construction industry. Moreover, if fabrication costs associated with HSB800 steel are similar to those associated with conventional grade such as HSB600, these decreases in weight will translate into cost reduction. However, in the case of reduced girder by using HSB800, its structure can be exposed to vibrational problems such as deterioration of vibrational serviceability, dynamic displacement, and so on. To resolve these weaknesses of HSB, structural stability should be guaranteed in advance.

In this research, the adaptability of HSB800 is analyzed in comparison with HSB600 in terms of vibration serviceability. And also, TMD-based structural control is conducted in order to improve the serviceability problem induced by adopting HSB with the road-surface roughness. By using Meister

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Curve associated with human response to steady-state vibrations, the damping effects of TMD are finally examined.

2. Three-dimensional dynamic analysis of the steel plate girder with HSB

2.1. Analysis model for vehicle loading

Based on diverse vehicle specification, vehicle models influencing to dynamic behavior of bridges are also diverse. In Bridge Design Specification Interim (Korea), the standard truck load is expressed in DB-Load, while triaxial truck is denoted by HS-loading in ASSHTO LRFD Bridge Construction Specification, as shown in the figure 1. However, because the condition of DB-Load is similar to HS-loading, this study just focuses on HS-loading as a truck model in order to facilitate comparison of DB and HS-loading.

When it comes to modeling for vehicle loading, Li Hong (2005) developed techniques for modeling of triaxial truck as depicted in figure 2. This model is consist of two rigid bodies such as car body \((m_1)\), and trailer \((m_2)\) and also the degree of freedom (DOF) of each wheel is also composed of vertical displacement \((Z_1', Z_2')\), pitching rotation \((\theta_1, \theta_2)\), and rolling rotation \((\alpha_1, \alpha_2)\). In addition, as shown in figure 2, spring-dashpot systems are also attached to each mass in order to simulate a real truck. Based on the principle of virtual work, equilibrium equation of motion for vehicle having 11 degrees of freedom is constituted by the relationship from the gravity \((M_{1g}, M_{2g}, m_{ig}, i=1\ldots6)\), inertia force and moment \((M_iZ_j, I_{0j}, I_{aj}, \ddot{u}_j, j=1,2; m_i2Z_i, i=1\ldots6)\), suspension force \((F'_i, i=1\ldots6)\), to tire force \((F_1, i=1\ldots6)\).

![Figure 1. Truck Load (AASHTO, 2002)](image1)

![Figure 2. Model for triaxial truck (Li, 2005)](image2)

2.2. Dynamic analysis for the vibrational behavior of a steel plate girder

To investigate the application of high performance steel for bridges, a modeling for 1-span steel plate girder bridge arrangement with 54m span length is constructed using ABAQUS/Explicit 6.10, as shown in the figure 3. Based on allowable bending compressive stresses introduced by Bridge Design Specification Interim (2010) regarding HSB800 and 600, the modeling of two girders is performed and analysed, respectively.

![Figure 3. Specification for design of girder](image3)

Class: 1st class bridge (DB-24/ DL-24)
Width: 15 m
Span: 54 m
Line : 4 lines, Type : Steel Plate Girder

The design of bridge is based on the first class bridge design load. And also, the fixed and live loads are considered in bridge. In the design of girder, the size of top flange (width is 508 mm and thickness
is 29 mm), bottom flange (width is 610 mm and thickness is 29 mm), and web (thickness is 29 mm) of HSB800 is same as the size of HSB600, excepting the height of girder: HSB800 is 1700 mm and HSB600 is 2100 mm, respectively. Throughout adapting the HSB800, the effectiveness in reducing height of girder is about 400mm and the total weight of the structure is reduced about 10%, simultaneously.

2.3. Power Spectral Density theory for the road surface roughness

When it comes to considering the roughness, commonly used method is ‘Power Spectral Density (PSD) theory. Dodds and Roboson(1973) have proposed the form of power law, \( S(r) \) as shown is equation (1) and (2).

\[
S(r) = L(r_0)(r/r_0)^{-w_1}, \quad r \leq r_0
\]

(1)

\[
S(r) = L(r_0)(r/r_0)^{-w_2}, \quad r \geq r_0
\]

(2)

Where, \( L(r_0) \) is called the roughness coefficient (m); \( r \) represents wave number and \( r_0 \) is 1/2 \( \pi \) (cycle/m) — both are determined from field experiments. In this research, road surface roughness is generated by using ‘Power Spectral Density (PSD)’ theory. By using the probability distribution, equation (1) and (2) are changed into combination of amplitude, circular frequency, and phase angel as shown in equation (3).

\[
Y(t) = \sum_{k=1}^{n} \sqrt{4S(r_0) \cdot \left(\frac{\pi k}{Lw_0}\right)^{-2} \cdot \frac{\pi}{L} \cos\left(\frac{\pi kx}{L} + \theta_k\right)}
\]

(3)

Here, \( Y(t) \) is the changed surface height using power spectral density: \( \theta_k \) is independent phase angle from 0 to 2\( \pi \). \( L \) is the length of span, \( w_0 \) is 1/2 \( \pi \) 1, and \( S(r_0) \) is the roughness coefficient proposed by International Organization for Standardization (ISO). ISO has assorted the road surface roughness into four levels: Very Good, Good, Average, and Poor. In this research, using the principle of PSD theory and the changed surface coordinate, dynamic analysis for the behavior of bridge is conducted by considering Poor level of the roughness.

3. Comparison for dynamic responses of HSB800 and 600

In this project, three-dimensional numerical analysis is performed by using structural analysis program ABAQUS 6.10. The numerical analysis of HSB-girder generally involves three major steps:

- Natural frequency
- Time history analysis for acceleration and vertical displacement
- The evaluation for serviceability by using ‘Reiher-Meister curve’

3.1. Time history analysis

Firstly, the modal analysis is conducted in order to analyse the dynamic behavior of the girder. By applying the high performance steel, the height and the total weight of the girder is fairly reduced. Throughout the modal analysis, it is concluded that the natural frequency of HSB 600 indicates 1.635 Hz. On the other hand, the natural frequency is 1.334Hz in case of HSB800. In order to scrutinize the effect of vertical vibration at the center of span, a HS-24 model (80km/h), as mentioned in chapter 2.1, is applied on the middle of the lane in the numerical model and dynamic analysis is performed. During this analysis, the surface of the girder is changed according to the poor level of roughness. As shown in Figure 4, the result of numerical analysis shows that the maximum displacement induced by vehicle model is 14 mm in HSB600. However, the maximum displacement is increased by 25 mm in HSB800 model. Moreover, the residual amplitude in a steady-state is fairly increased in the model of HSB800, compared to HSB600. However, it is hard to distinguish dynamic behavior between HSB600 and HSB800 on the acceleration history as shown in Figure 5. In addition, the maximum acceleration is
abnormally taken place in HSB600. According to these results, it is finally concluded that the displacement history is influenced by the height of girder.

**Figure 4.** Vertical displacement at the center of span  

**Figure 5.** Acceleration history at the center of span

3.2. *The evaluation for serviceability by using ‘Reiher-Meister curve’*

Based on the vertical displacement in subchapter 3.2, the evaluation for dynamic serviceability is performed by using Reiher-Meister curve, as depicted in Figure 6. As a result, the B level (Disturbing) is appeared in case of HSB800 and the C level (Distinctly Perceptible) is occurred in case of HSB 600.

**Figure 6.** Dynamic Serviceability Evaluation using Reiher-Meister curve

4. *The application of TMD for Structural Control of HSB800-Bridges*

In order to control the vertical vibration of bridges, control performance, and constructability should be certainly guaranteed in advance. In the perspective of construction cost and constructability, it cannot be said that stiffening girder is also suitable for suppressing traffic induced vibrations. Consequently, when it comes to construction availability, serviceability, and efficiency, it can be generally said that Tuned Mass Damper (TMD) is the most adaptive equipment.

4.1. *The principle and design of TMD*

TMD is generally consisted of a secondary mass with properly tuned spring and damping elements, providing a frequency-dependent hysteresis that increases damping in the primary structure. To design
of TMD, this project introduces the concept of effective mass and calculates optimal damping ratio using Den Hartog theory. Effective mass is the mass which must be added to the suspended mass to correctly predict the behavior of the entire system. It is also expressed in equivalent lumped mass at a particular point. In case that stiffness at a certain point is calculated, then the equation of natural frequency is simplified as expressed in equation (4). The figure 7 describes a second degree of freedom of TMD-adapted bridge deck.

![TMD Diagram](image)

**Figure 7.** The concept of TMDs for structural applications

\[ f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m_{\text{eff}}}} \]  

(4)

Here, \( f_n \) means natural frequency, \( k \) means stiffness at the center of bridges, and \( m_{\text{eff}} \) means effective mass. Natural frequency \( f_n \) is considered as first natural frequency throughout modal analysis as mentioned in chapter 3. And also, the stiffness is calculated by considering vertical unit load at the center of bridge. Therefore, the determined values of natural frequency and stiffness are 1.334 Hz and 18,191N/mm, respectively. By using these values, the effective mass \( m_{\text{eff}} \) is finally calculated and the value indicates 259,112kg. Dan Hartog has proposed ‘optimum TMD’ theory in 1956. Using this theory, optimal mass ratio and frequency of TMD can be calculated as depicted in equation (5) and (6).

\[ \mu = \frac{m_a}{m_{\text{eff}}} = \frac{2600}{259,112} \approx 0.01 \]  

(5)

\[ f_a = \frac{f}{1+\mu} = \frac{1.334}{1+0.01} = 1.321Hz \]  

(6)

Here, \( \mu \) indicates the mass ratio in the relationship between the calculated mass \( m_a \) and the effective mass \( m_{\text{eff}} \), and \( f_a \) means optimized frequency of TMD. Finally, optimized damping ratio \( \zeta_{\text{opt}} \) of the bridge can be determined by equation (7) as follow:

\[ \zeta_{\text{opt}} = \sqrt{\frac{3\times0.01}{8(1+0.01)}} = 0.0609 \]  

(7)

Throughout this sequence, variables for mass and damping of TMD are obtained.

4.2. Dynamic behavior of TMD-adopted steel plate girder

In this subchapter, TMD-based structural control of bridges applied HSB800 is evaluated through the three-dimensional dynamic analysis, in order to redeem the vibrational displacement to its original state prior to adopting high performance steel. As mentioned in subchapter 2.3, the poor level of roughness on the surface of bridges is also described in order to inspect the effect of roughness. Consequently, the result of dynamic analysis considering TMD is depicted in figure 8. As shown in figure 8, the dynamic behavior of HSB800 is similar to HSB600 in the field of transient vibration because it involves to the static displacements induced by the vehicle model. However, after the vehicle load is disappeared, it is confirmed that the residual amplitude is appreciably reduced by 85%. Figure 9 shows that vibration serviceability assessment using 'Reiher-Meister Curve' is also
remarkably improved. Namely, it is concluded that the control effectiveness of TMD is obviously proved.

![Figure 8](image1.png)  ![Figure 9](image2.png)

**Figure 8.** The control effectiveness of TMD

**Figure 9.** Dynamic Serviceability Evaluation of TMD-adopted bridge

5. **Concluding Remarks**

This study covers the TMD-based structural control of bridges being built using High performance Steel for Bridges (HSB). The applicability of HSB800, the most recently developed HSB grade is verified by three-dimensional dynamic analysis, serviceability evaluation, and structural control. Throughout this study, several developments and key results were determined as follows:

- This study proposed the method for applying HSB800 and 600 in the design of steel plate girder. When it comes to HSB800, it is verified that the effectiveness in reducing height of girder is about 400mm in comparison with HSB600 and the total weight of the structure is reduced about 10%, simultaneously.
- The vibration serviceability assessment using Reiher-Meister curve is conducted to evaluate the stability of HSB800 and HSB600. As a result, the application of HSB800 and HSB600 induces dynamic serviceability problem.
- The structural control using tuned mass damper (TMD) is implemented in order to alleviate dynamic serviceability problems. In consequent, by using TMD, it is confirmed that the residual amplitude is appreciably reduced by 85% in steady-state vibration.

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**References**

[1] AASHTO(American Association of Standard Highway and Transportation Officials) 2002 AASHTO LRFD Bridge Design Specification
[2] Chun P 2010 Skewed bridge behaviors: Experimental, analytical, and numerical analysis (Ph.D. diss.) Wayne state University
[3] Ellis B R and Ji T 1997 Human-structure interaction in vertical vibration, *Proc. Instn Civ. Engrs Structs & Bldgs* 122 Feb 1-9
[4] Li H 2005 Dynamic response of highway bridges subjected to heavy vehicles (Ph.D. diss) The Florida State University
[5] Ministry of Land, 2010 Transport and Maritime Affairs, Bridge Design Specification Interim
[6] Shi X and Cai C S 2008 Suppression of vehicle-induced bridge vibration using tuned mass damper *Journal of vibration control* 14 7 1036-1054