An Optimal Design of TMD for the Improvement of Fatigue Reliability of Steel-composite High-speed Railway Bridges using Target Performance Approach

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Summary

Many efforts have been strived to use Tuned Mass Damper (TMD) for the mitigation of bridge dynamic responses. Kwon et al. [1] and Wang et al. [2] investigated the control effectiveness of TMD on high-speed railway bridges. Yau et al. [3] also applied TMD to reduce vibrations of cable-stayed bridges crossed by high-speed trains. Recently, a quantitative evaluation method was also developed in order to investigate the effects of TMD on the fatigue reliability of bridge by combining dynamic analysis of the bridge subjected to the high-speed trains with the S-N curve-based approach [4,5]. The S-N curve-based approach being a useful method to visualize time to failure in terms of stress ranges versus cycles to failure, its application for fatigue reliability analysis requires the number of cycles at stress-range levels endured throughout the intended service life of the bridge. Therefore, time domain dynamic analysis is performed for the bridge crossed by high-speed trains running at various velocities in order to obtain stress time histories at critical structural components. In the dynamic analysis, the bridge structure is modelled as an assembly of grillage members of which flexural and torsional stiffnesses approximate the behavior of the slab, girders and cross-beams [6]. The high-speed train used in this study is the Korea Train eXpress(KTX) actually operating in Korea. Simple moving forces without consideration of the train-bridge interaction are employed to model the high-speed train for simplicity. This choice has been conducted because of the tremendous amount of repetition of the dynamic analysis required for fatigue reliability analysis requires and the extreme time-consumption brought by the train-bridge interaction consideration. The numerical solution of the dynamic equilibrium equation of the bridge subjected to the high-speed trains is obtained using Newmark’s method [7].

It is well-known that resonance in high-speed railway bridges occurs due to the correspondence of the bridge frequency and the train frequency induced by the periodicity of the high-speed train loading. In order to reduce resonance-induced vibration, TMD is assumed to be installed at mid-span of the bridge where the maximum displacement response is expected.

In this study, it is assumed that the uncertainty of the damping ratio of the bridge has the largest influence on the fatigue life of the bridge subjected to large dynamic loads. Thus, the damping ratio of the bridge is adopted as random variable. Therefore, the damping ratio is assumed to have lognormal distribution of which a number of sampling values are selected to perform dynamic analysis. The corresponding number of stress-cycles and stress ranges are calculated from stress time histories by applying the rain-flow counting method [8] and used to estimate the fatigue failure probability by the S-N curve-based approach [4,5]. The fatigue reliability considering the uncertainty of the damping ratio is evaluated after the fatigue failure probability is integrated over all sampling points of the damping ratio. The effectiveness of TMD on the extension of fatigue life of the example bridge is examined and the results are presented. The optimal design parameters of TMD including the mass ratio, natural frequency and damping ratio are also investigated and

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determined. Investigation is performed considering target reliability index and target service life for trains running at all possible operational velocities

Accordingly, Fig.1 plots the results corresponding to varying mean velocities for a target service life of 75 years, a target reliability index of 4.0, and 4 different mass ratios that are 0.5%, 1.0%, 1.5%, and 2.0%. For mass ratios of 1.5% and 2.0%, the fatigue reliability index takes smallest values at critical velocity (300km/h) as expected. However, an interesting result is that, for mass ratios of 0.5% and 1%, the fatigue reliability index exhibits smaller value in the vicinity of the critical velocity and not at critical velocity as can be expected. This means that the consideration of the sole critical velocity when evaluating fatigue is not sufficient to secure safety. Taking into account the fact that the mass ratio is generally assumed to have value of about 1.0%, fatigue reliability evaluation needs to be conducted not only at critical velocity of the train but also on the whole range of possible velocities.

Despite of the numerous researches conducted to apply TMD for the mitigation of bridge dynamic responses, quantitative examination of its impact on the fatigue reliability of the bridge has not been addressed to date. Accordingly, this study evaluated quantitatively the effects of TMD on the fatigue reliability of steel-composite high-speed railway bridges.

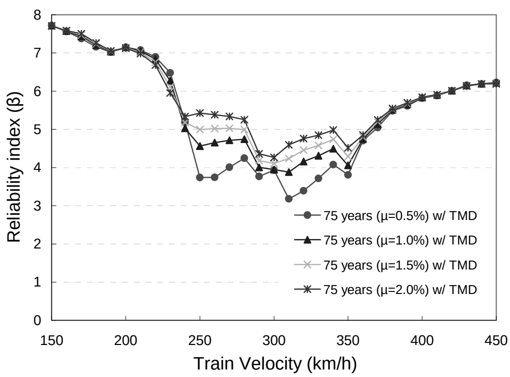

Fig. 1: Fatigue reliability indices with respect to the mass ratio and the mean velocity of train

Fatigue reliability indices have been evaluated based on the S-N curve-based approach using time domain dynamic analysis of the bridge crossed by the high-speed train. Results revealed that the mass ratio and damping ratio have significant influence on the fatigue reliability. Therefore, fatigue reliability should be estimated considering dynamic parameters such as the mass ratio and damping ratio. Moreover, fatigue evaluation considering target reliability index and target service life showed that fatigue reliability evaluation needs to be conducted not only at critical velocity of the train but also on the whole range of possible velocities since the fatigue reliability index was seen to exhibit possibly smaller value around the critical velocity and not at critical velocity as can be expected.

TMD has been seen to increase the fatigue reliability by mitigating efficiently responses and stresses induced by high-speed trains running at critical resonant speed. Therefore, using TMD as control device can constitute a good design alternative against traffic-induced fatigue instead of strengthening solutions.

Keywords: tuned mass damper; steel-composite high-speed railway bridge; dynamic analysis; S-N curve; fatigue reliability