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Design method for steel restrainer bars on railway bridges subjected to spatially varying earthquakes

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ABSTRACT

The unseating and pounding damage at expansion joints during earthquakes emphasizes the need to restrain the relative opening and closing displacements between adjacent bridge spans. Traditional cable restrainers perform well in preventing unseating damage but may increase the pounding damage between adjacent decks sometimes. Considering the limitation of the cable restrainer, a steel restrainer bar installed between a pier and a deck is proposed to restrain both the relative opening and closing displacement to prevent unseating and pounding damage to railway bridges. In this paper, theoretical formulas for the mechanical properties of the restrainer bar, experiments and numerical analyses are conducted. A design procedure for the steel restrainer bar, which considers spatially varying earthquakes and the hysteretic behaviour of the restrainer, is developed. The procedure accounts for the dynamic out-of-phase motion characteristics between adjacent bridge spans, and the pounding is assumed to be completely avoided by the restrainer bar. A series of case studies with different pier heights and different earthquake characteristics are conducted to evaluate the effectiveness of the design method; the time history analysis results are consistent with the case study results. The restraint effect of the rails is also considered in this paper. The results of the numerical analyses reveal that both the pier height and the rails significantly influence the effectiveness of the steel restrainer bar. As the pier height increases, the effectiveness of the restrainer in reducing the relative displacement also increases, whereas the effectiveness in mitigating shear decreases with a pier height greater than 15 m. The rails reduce the effectiveness of the steel restrainer bar when subjected to spatially varying ground motions.

1. Introduction

Due to the convenient construction of simply supported bridges, nearly 70% of railway bridges in China are simply supported bridges. However, during high-intensity earthquakes, adjacent bridge spans of simply supported bridges exhibit out-of-phase vibrations, which will produce a relative displacement at the expansion joint. If the relative displacement exceeds the provided clearance of the expansion joint (ranged from 40 mm to 80 mm) based on the Fundamental code for design on railway bridge and culvert [1], adjacent decks will be subjected to pounding. If the relative displacement between a deck and a pier is larger than the available seating width, unseating damage occurs [2]. To reduce unseating damage, the Chinese Department of Transportation initiated a retrofit programme that links adjacent bridge spans with cable restrainers at expansion joints. Although cable restrainers have performed well in many earthquakes, failure of the cable restrainers was observed in several bridges during the 1989 Loma Prieta earthquake [3] and the 1994 Northbridge earthquake [4]. To improve the effectiveness of cable restrainers, many researchers have studied the influencing factors of the behaviour of the restrainers. The results of these studies have revealed that the relative displacement is sensitive to the characteristics of the ground motion, the period ratio of adjacent piers and the restrainer properties [5,6]. The results have also indicated that the yielding of the cable restrainers during strong earthquakes and inappropriate design methods are the major reasons for the failure of restrainers [7–9].

Due to the importance of restrainers, many specifications have taken the restrainer design into account. The American Association of State Highway and Transportation Official (AASHTO) [10] specification requires a positive horizontal linkage between adjacent bridge spans of the superstructure. The required linkage force is equal to the design acceleration coefficient multiplied by the weight of the lighter span of the two adjacent spans. The Japanese specification [11] is similar to the AASHTO method, in which the required restrainer force is equal to the weight of the superstructure on the pier and the effective weight of the pier multiplied by the design acceleration coefficient.

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Nomenclature

Symbols list

a	coefficient of displacement
c_k	damping ratio of the contact spring
D_{avg}	average independent horizontal displacement of adjacent spans
D_{eq}	relative displacement of adjacent bridge spans
D_r	maximum displacement of the restrainer
D_s	initial slack of the restrainer
D_m	clearance of expansion joint
D_1, D_2	displacement of each bridge span
d_0, d_1	diameter of the section on both sides of the model
d_e	diameter of the equivalent section
d_{ij}	displacement between location i and j
E	elasticity modulus
F_e	elastic limit force
F_y	yield force
F_{max}	maximum design force
f_y	yield force of the material
I_e	inertia moment of the equivalent section
I_x	inertia moment of each section of the model
I_0	inertia moment of the section with d_0 diameter
K_e	initial stiffness of a single restrainer
K_d	post-yield stiffness of the restrainer
K_r	equivalent stiffness of the steel restrainer bar
K_{meff}	effective stiffness of the bridge
$K_{initial}$	initial stiffness of the restrainers on the bridge
K_{eff}	effective stiffness of each bridge spans
K_v	stiffness of the contact spring
K_{abut}	stiffness of the abutment
K_1, K_2	elastic stiffness of the adjacent piers
k	ratio between the diameter of both sides of the model
L	total length of the restrainer bar
L_1	length of the installment segment
L_2	length of the bending segment
l	length of a quarter of the restrainer bar
M	mass of bridge piers
m	ratio between the length of the bending segment and the installment segment
m_1, m_2	mass of adjacent girders
P_{bw}	pressure force of the abutment
P_1	force at Point B and C
P_2	force at Point A and D
p	probability coefficient, usually less than 0.85
$S_a(\omega)$	acceleration response spectrum
$S_g(\omega)$	power spectral density
T	duration of the earthquakes
T_L	longer period of the adjacent bridge spans
T_S	shorter period of the adjacent bridge spans
u_e	elastic limit displacement
u_y	yield displacement
u_{max}	maximum design displacement
y	deflection equation of the model
δ	post-yield stiffness/initial stiffness ratio
Δ	displacement of Point A
α	incident angle of the earthquake
β	coherency loss coefficient
γ	conversion ratio
ξ	damping ratio
ξ_e	effective damping ratio of the restrainer
ξ_i	damping ratio of the pier, assumed as 0.05
ξ_ω	effective damping ratio of bridge span
ω	frequency of adjacent bridge spans
$\gamma_{ij}(i\omega)$	coherency loss function
v_{app}	apparent wave velocity of the earthquake
ρ_{12}	cross-correlation coefficient
μ	displacement ductility ratio

However, both specifications do not consider the characteristics of the ground motion and the vibration periods of the adjacent bridge spans, which influence the relative displacement at the expansion joint greatly.

Several studies have been conducted to investigate the design method of bridges with cable restrainers. Trochalakis et al. [5] proposed a modified procedure based on the equivalent static procedure provided by bridge design specifications [12]. In this procedure, the maximum relative displacement is estimated from the average displacement of adjacent spans as follows:

$$D_{eq} = \frac{D_{avg} \times T_L}{2 \times T_S} \leqslant 2D_{avg} \tag{1}$$

where D_{eq} is the relative horizontal displacement between the two bridge spans and D_{avg} is the average independent horizontal span displacement; T_L and T_S represent longer periods and shorter periods, respectively, of the uncoupled spans. Eq. (1) is based on a regression analysis of numerous cases. This method is based on an analysis of bridges with ductile structures; however, the level of inelastic deformation is not explicitly included. DesRoches et al. [13,14] proposed a design procedure that is based on a linear model and considers the dynamic characteristics of out-of-phase motion of adjacent bridge frames. The inelastic behaviours of bridge frames are considered using the substitute structure method [2]. Ruangrassamee et al. [15] developed relative displacement response spectra by analysing a two linear single-degree-of-freedom system and considering the influence of pounding. The researchers presented the formula for the normalized relative displacement response spectra and determined that the seat width derived from the proposed relative displacement response spectra is similar to the value specified in the Japanese design specifications.

However, these design procedures are determined under uniform ground excitations. Both the Trochalakis and DesRoches methods assume that the cable restrainers remain elastic during earthquakes and do not consider the pounding between adjacent decks, which will enlarge the relative displacement at expansion joints. Note that the relative displacement between adjacent bridge spans is affected not only by the different dynamic characteristics of each involved member but also by the inevitable spatially varying ground motions at multiple bridge supports. Studies [16,17] have been conducted to evaluate the influence of spatially varying earthquake on bridges; the results have indicated that spatially varying earthquakes can amplify the relative displacement of adjacent bridge spans and pounding forces. Sometimes, the pounding forces for a bridge under spatially varying ground motions can be 3–4 times larger than the pounding forces derived from uniform ground motions.

Although the cable restrainer has been used widely, there are still some deficiencies. A comparison of the results from Shrestha et al. [18] reveals that the pounding force and pounding number of the bridge with cable restrainers may be greater than that of the bridge without restrainers for some earthquake cases. Due to the elastic design of the cable restrainers, the seismic energy can only be dissipated by the plastic hinges that form in piers, which are not suitable for simply supported bridges due to the possibility of producing a statically unstable structure. The elastic design method also requires the utilization of a large number of cable restrainers to limit the relative displacement