The Stress-related Damping Ratio of Box Girder with Corrugated Steel Webs

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Abstract: In this paper, the stress-related damping ratio formula of box girder with corrugated steel webs is introduced. Using response spectrum method, an iterative algorithm is proposed to calculate the seismic response and the stress-related damping ratio under different seismic intensities. Based on a simply supported composite box girder bridge with corrugated steel webs, the stress-related damping ratios are calculated under different seismic intensities through iteration. The analysis and comparison show that the stress-related damping ratio increased with the seismic intensity, which is smaller than 0.05 under the lower seismic fortification intensity, and larger than 0.05 under the higher seismic intensity. Different damping ratios should be considered under different seismic intensities for the seismic response analysis of the bridge.

Keywords: Box girder with corrugated steel webs, iteration, seismic peak ground accelerations, stress-related damping ratio.

1. INTRODUCTION

Box girder with corrugated steel webs represents a new innovative system which has emerged in the past decade for short and medium span bridge. The new system usually combines the usage of corrugated steel plates as webs and reinforced/prestressed concrete slabs as flanges for plate or box girders [1]. This bridge type has been widely applied since the French built the first box girder bridge with corrugated steel webs in 1986 [2]. Numerous researches on the mechanical properties have been carried out, especially on the bending, shearing, buckling and connection joints performance [3-6]. But there were fewer researches on its dynamic performance. Currently the dynamic characteristics research of this bridges type is just on analysis and measurement of the natural frequency. Liu Baodong proposed that appropriately adding the diaphragm can improve the torsional behavior of corrugated steel webs through comparing the natural frequency of different diaphragm schemes [7]. Zhang Yongjian derived the natural frequency formula of composite box girder with corrugated steel webs by considering the influence of shear lag and shear deformation [8]. Li Bo deduced dissipation factor formula of box girder with corrugated steel webs using the unit volume dissipation factor of corrugated steel webs and concrete, and calculated the equivalent damping ratios under free vibration and vehicle load [9]. As to the damping performance under varying stress situation for this type of composite bridge, there is no related report now.

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Damping ratio is an important part of dynamic property. It has a great influence on the dynamic response of structures. Large numbers of measured data show that, the structural damping ratio is different under different loading conditions, and the difference has a great gap. Under different seismic intensities, Newmark did a lot of research work to determine the damping ratio of the nuclear reactor in 1971, and got the experimental results that the damping ratio could have magnitude difference in different working stresses [10]. Hart identified the first three modes of damping ratio according to the earthquake records data of 12 high-rise buildings [11]. He found that the damping ratio of the structure increases when the ground motion got stronger. Celebi collected five structural damping data under Loma Prieta Earthquake in San Francisco on October 17, 1989, and the damping data was measured in part of the buildings before and after the earthquake under low amplitude of vibration [12]. The analysis results showed that the structure damping ratio in strong earthquake ground motion was significantly larger than that under the low amplitude of vibration. Lagomarsino collected damping ratio measured data of 182 buildings, and found that the damping ratio value relates to the natural frequency of structure[13]. Based on damping ratio measured data of tall buildings, Jeary found that structural damping ratio relates to the amplitude, and gave a proposal formula between damping ratio and amplitude[14]. Li tested the damping ratio of some tall building under typhoon. The amplitude-dependent characteristics of damping that were obtained using the random decrement technique on the basis of the field measurements are investigated [15-17]. MahirUlker-Kaustell and Raid Karoumi analyzed the equivalent viscous modal damping ratio of the first vertical bending mode of a ballasted, single span, concrete-steel composite railway

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bridge and the damping ratio was found increased with increasing amplitude of vibration [18]. They also illustrated that the influence of the increasing damping ratio leads to a considerable decrease in the resonant amplitude [19]. Eyre and Tilly test 23 steel and composite bridges having spans 17m to 213m long with the free decay. From the measurements taken it was found that damping increases with amplitude of vibration and stabilitises at an upper level which can be up to four times higher than the level at small amplitudes [20, 21]. C.Rebelo made the results of experimental measurements on a number of existing small to medium single span ballasted railway bridges in Austria, it was found that the damping ratios were much bigger when the train passed by than the value obtained from the ambient vibration [22].

According to Chinese Guidelines for Seismic Design of Highway Bridges (MCPRC 2008), when using response spectrum method for seismic response analysis of concrete bridge structures, the value of damping ratio is 0.05 without special provisions [23]. But there is no provision for the composite bridge. Considering the structural characteristic of the box girder with corrugated steel webs, this paper introduces a stress-related damping ratio formula based on the loss energy per unit volume of metal material [24] and reinforced concrete material [25]. Meanwhile, an iterative algorithm is proposed and the damping ratios under different seismic intensities are iteratively calculated based on a real simply supported composite box girder bridge with corrugated steel webs. And the seismic responses with stress-related damping ratio and constant damping ratio are compared using response spectrum method.

2. STRESS-RELATED DAMPING FORMULAS

Lazan B J (1968) [24] proposed the relationship between the unit volume loss energy Δu_1 and the maximum stress amplitude for most metal materials. It can be written as follows:

$$\Delta u_1\left(\sigma_s\right)=0.006895(\sigma_s/\sigma_f)^{2.3}+0.041360(\sigma_s/\sigma_f)^{8} \qquad (1)$$

Where σ_f is the fatigue limit stress of metal, σ_s is the average maximum shear stress amplitude of every metal unit.

Wen Jie established unit volume loss energy Δu_2 of reinforcement concrete considering the working conditions. It can be written as follows:

$$\Delta u_2\left(\sigma_c,f_c,r,ac\right)=\frac{0.0193013\ \sigma_c^{3.88}\cdot(1+r)^{-31.93}}{(1\text{-}41.66\cdot f_c-0.57\cdot f_c^2)\cdot(1-56977.5\cdot ac+44634.7\cdot ac^2)} \qquad (2)$$

Where σ_c is the average maximum bending stress amplitude of each concrete unit, r is the longitudinal reinforcement ratio, f_c is the standard value of concrete compressive strength, ac is the axial compression ratio.

When the box girder with corrugated steel webs under vertical loads, the bending moment mainly undertook by the concrete slabs and the shear force mainly undertook by corrugated steel webs. Using the finite element discrete form, after obtaining the maximum stress of each element under different working conditions using finite element method, the loss factor could be calculated as follows [9]:

$$\eta=\frac{1}{2\pi}\frac{\Delta U}{U}=\frac{1}{\pi}\cdot\sum_{i,j}\frac{A\sigma_i^{3.88}V_i+\left[B\left(\frac{\tau_j}{\sigma_f}\right)^{2.3}+C\left(\frac{\tau_j}{\sigma_f}\right)^{8}\right]V_j}{\left(\frac{\sigma_i^2}{E}V_i+\frac{\tau_j^2}{G}V_j\right)} \qquad (3)$$

Where,

$$A=\frac{0.0193013(1+r)^{-31.93}}{(1\text{-}41.66\cdot f_c-0.57\cdot f_c^2)\cdot(1-56977.5\cdot ac+44634.7\cdot ac^2)},$$

B is 0.006895, C is 0.04136, σ_i is the average maximum bending stress of i-th element at two nodes of concrete unit, τ_j is the average maximum shear stress of j-th steel plate unit, V_i 、 V_j is the volume of each unit, E is the elastic modulus of concrete, G is the shear modulus of steel.

By the theory of structural dynamics, when the harmonic excitation force consistent with the structure frequency, the damping ratio could be showed as Eq. (4) [26]:

$$\xi=\frac{\eta}{2} \qquad (4)$$

Although the excited force is mostly not harmonic excitation force in actual engineering, the relation between the structural modal damping ratio and the material loss factor approximately satisfies Eq. (4) [27]. So the value of equivalent damping ratio could be calculated according to the loss factor.

3. CALCULATION OF DAMPING RATIO UNDER DIFFERENT SEISMIC INTENSITIES

3.1. Iteration Algorithm

In order to get the stress-related damping ratio of box girder with corrugated steel webs under different seismic intensities, the seismic response is calculated using response spectrum method by the chinese Guidelines for Seismic Design of Highway Bridges [23]. The seismic response of bridge structure can be calculated as follows:

$$S_{\max}=2.25C_\mathrm{i}C_\mathrm{s}C_\mathrm{d}A \qquad (5)$$

Where $S_{\max}$ is the horizontal maximum acceleration response for seismic design, C_i is the importance coefficient, C_s is the site coefficient, C_d is the damping adjustment factor, A is horizontal of peak ground acceleration for seismic design.

Chinese Guidelines for Seismic Design of Highway Bridges provides an adjustment method on response spectrum parameter in different damping ratios, when the damping ratio ξ is 0.05, the damping adjustment factor C_d is 1.0. For other value of damping ratios, the damping adjustment factor C_d should be calculated as follows:

$$C_d = 1 + \frac{0.05 - \xi}{0.06 + 1.7\xi} \geq 0.55 \tag{6}$$

This paper focus on the stress levels of the box girder under different vertical seismic excitations. So the vertical seismic response spectrum needs to be inputted. The vertical maximum acceleration response can be calculated by the horizontal maximum acceleration response multiplied to 0.65 [23].

Due to the difference seismic intensities, the stress levels of the structure are different, thus the equivalent damping ratio corresponding to this stress level is different. So by assuming an initial damping ratio, the equivalent damping ratio under different seismic intensities could be calculated by the following iterative algorithm shown in Fig. (**1**).

3.2. Establish and verification of FEM for actual bridge

This paper selected a real simply supported composite box girder bridge with corrugated steel webs as an example, which had single box with double chamber. The calculated span is 49.92m, the height of the girder is 2.5m, the top slab width is 12m, the bottom slab width is 6.5m, the vertical tilt angle of corrugated steel webs is 70°, the thickness of corrugated steel plate is 12mm, the width of horizontal panel is 430mm, the folding angle is 31 °, the wave height is 220mm, the steel pattern is Q345, and the concrete grade of the girder is C50. The cross-section of the girder and the size of the corrugated steel webs are shown in Figs. (**2** and **3**).

The finite element model of the girder was built by MIDAS / CIVIL. 8-node solid element was used in concrete roof and floor. The plate element was used in corrugated steel webs. The finite element model had a total of 4935 solid elements and 1959 plate elements.

Pulsation test was adopted in testing dynamic characteristic of the actual bridge. The measured frequency was 2.734Hz and the calculated frequency was 2.664Hz. Considering the influence of the reinforced steel bars and the bridge deck of the real bridge, we think the finite element model has sufficient precision and can be used to calculate the seismic response of the girder.

3.3. Iterative Results and Analysis

The bridge seismic fortification intensity is 8 degrees and the horizontal of peak ground acceleration (PGA) for seismic design is 0.20g. The site type is Class Ⅱ. The bridge seismic fortification category is class B. On the basis of the Guidelines for Seismic Design of Highway Bridges, the number of vibration mode considered in mode-decom-position response spectrum analysis should make the modal mass participation ratio more than 90% in the calculation direction. Based on the finite element model in front, by combining the first 20 modes, the modal mass participation ratio is more than 90% in the x,y,z directions.

In order to discuss the stress-related damping ratio under different seismic intensities, the PGA is assumed as 0.05g, 0.10g, 0.20g and 0.40g. The initial damping ratio ξ_0 is

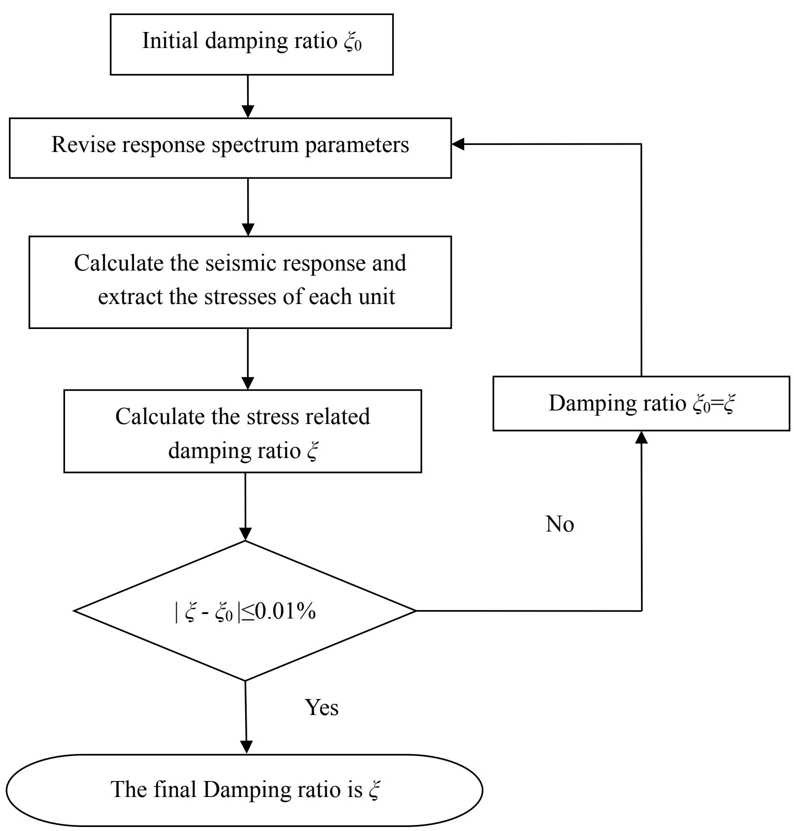

Fig. (1). Flow chart of iterative algorithm.

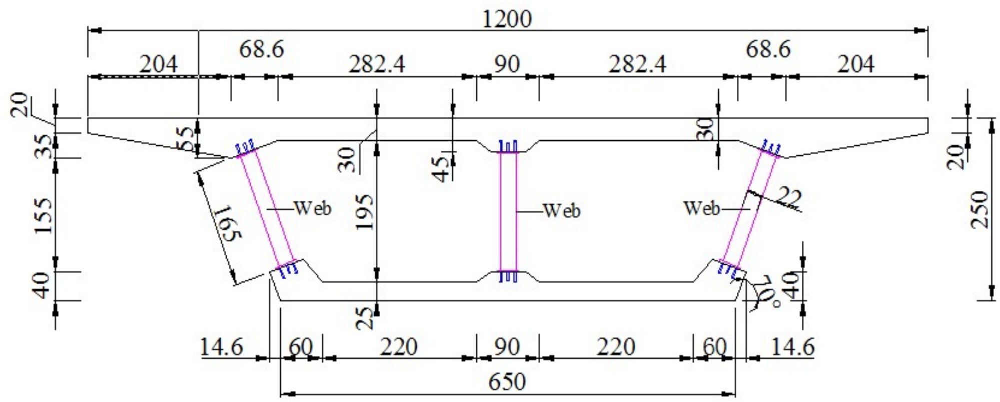

Fig. (2). Cross-section of box girder with corrugated steel webs (cm).

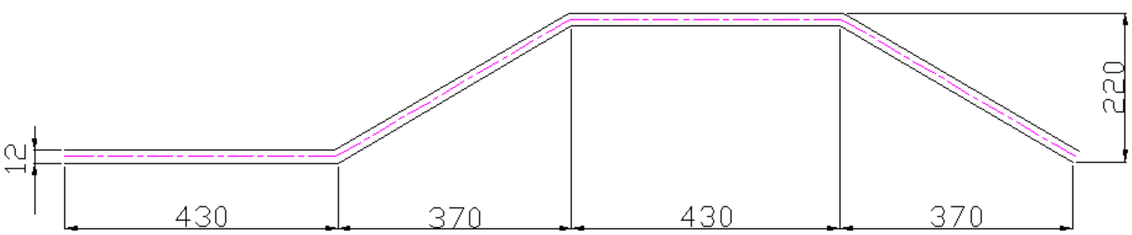

Fig. (3). Size of corrugated steel webs (mm).

assumed as 0.04. The iterative processes under different PGA are shown in Figs. (**4-7**).

The final stress-related damping ratios under different PGA are shown in Table **1**.

As can be seen from the table above, the damping ratios under different PGA are different. With the increasing of the PGA, the damping ratio increased. It could found that when the PGA is 0.40g, the calculated damping ratios are 523.33%, 250.63% and 91.47% larger than that when the PGA are 0.05g, 0.01g and 0.20g.

The higher the PGA, the higher the stress amplitude corresponded. With increasing of the stress, the material energy consumption and damping ratio increased. The volume and stress in each unit of the corrugated steel webs and concrete are extracted, and then the average stress level in different PGA can be calculated by the equation (7):

$$l = \frac{\sum_i \sigma_i V_i + \sum_j \sigma_j V_j}{\sigma_1 V_1 + \sigma_2 V_2} \qquad (7)$$

Where σ_i . is the stress of the i-th concrete unit, V_i is the volume of the i-th concrete unit, σ_j is the stress of the j-th steel web unit, V_j is the volume of the j-th steel web unit, σ_1 is the limit stress of concrete, V_1 is the total volume of concrete, σ_2 is the limit stress of steel web, V_2 is the total volume of steel webs.

The average stress levels of the girder under different PGA are shown in Table **2**.

Newmark [10] pointed that when the stress level was below the quarter of the yield point, the critical damping ratio was between 0.5% and 1%. When the stress level was between half of the yield point and the quarter of the yield point, the critical damping ratio was between 2% and 7%. The damping ratios and stress levels calculated under different PGA in this paper keep up with the conclusion with Newmark [10], who verifies the reasonable results in this paper.

Table 1. Damping ratio calculated under different PGA.

PGA	Damping ratio(%)
0.05g	0.90
0.10g	1.60
0.20g	2.93
0.40g	5.61

Table 2. Average stress levels of the girder under different PGA.

PGA	Average stress level
0.05g	0.131
0.10g	0.239
0.20g	0.412
0.40g	0.669

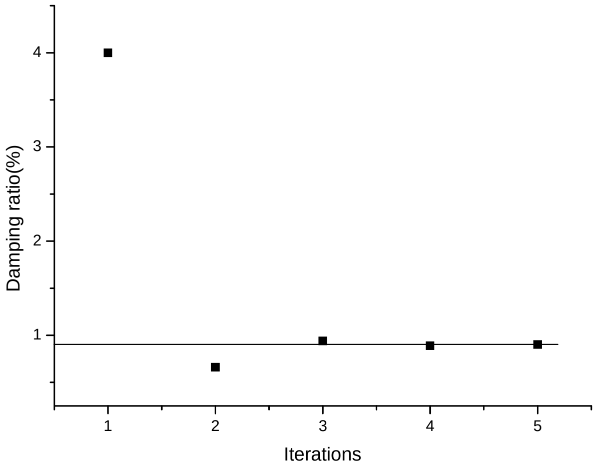

Fig. (4). Iteration of damping ratio when PGA is 0.05g.

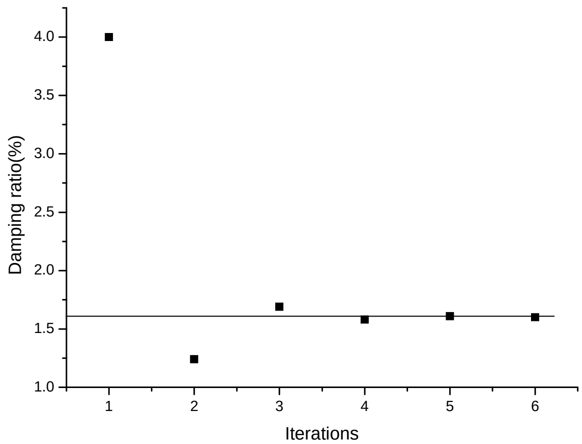

Fig. (5). Iteration of damping ratio when PGA is 0.10g.

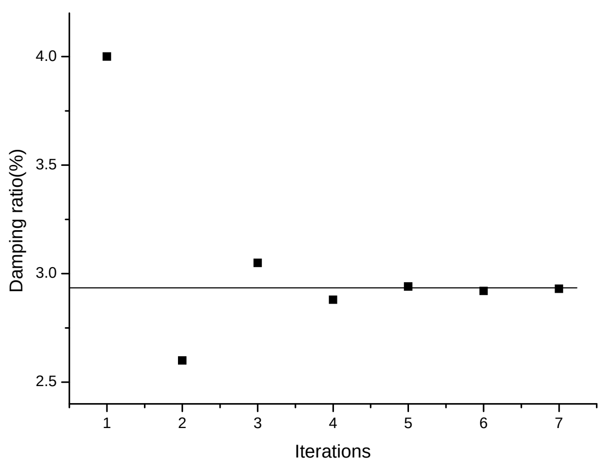

Fig. (6). Iteration of damping ratio when PGA is 0.02g.

CONCLUSION

(1) The stress-related damping ratio formula of box girder with corrugated steel webs is introduced, which

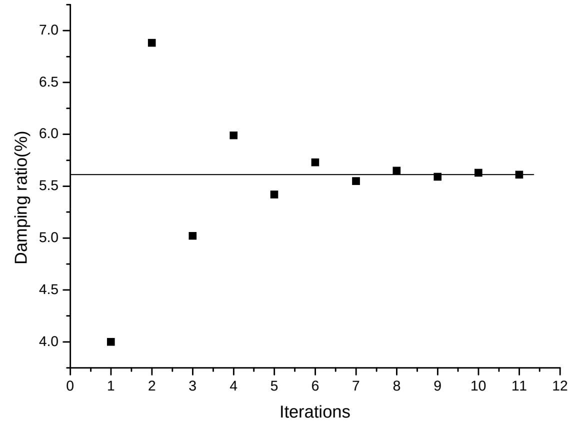

Fig. (7). Iteration of damping ratio when PGA is 0.40g.

considered the energy dissipation of both the concrete slabs and the corrugated steel webs.

(2) The stress-related damping ratios of the box girder with corrugated steel webs change along with the seismic intensities. The higher the seismic fortification intensity, the larger the damping ratio. Therefore, we suggest that different damping ratios should be considered under different seismic intensities for the seismic response analysis of the bridge.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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