AN ENERGY-BASED DAMPING EVALUATION FOR INTERPRETATION OF DAMPING INCREASE DUE TO DAMAGE IN AN EXISTING STEEL TRUSS BRIDGE

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1. INTRODUCTION

Structural health monitoring (SHM) of steel truss bridge based on a theoretical-experimental framework using damping was investigated in this study. Vibration measurements were conducted with five sensors at an existing Warren steel truss bridge with damage in a diagonal member before and after an emergency repair work (Yamaguchi et al. (2015)). A substantial increase in the modal damping ratio of global mode coupled with vibration of the damaged diagonal member was observed, although no significant change in the natural frequency of that mode was observed. In the present study, the contribution to modal damping ratios from different structural elements was evaluated analytically utilizing the experimentally identified modal damping ratios to obtain theoretical insights into the substantial change in damping for coupled global mode.

2. ENERGY-BASED DAMPING EVALUATION FOR TEST BRIDGE

Using energy-based definition, the damping of structures in terms of equivalent viscous damping ratio can be defined as the ratio of the dissipated energy per cycle, D_n to the maximum potential energy in a cycle, U_n. Hence, the *n*th modal damping ratio, ξ_n can be expressed as:

$$\xi_n \equiv \frac{D_n}{4\pi U_n} \tag{1}$$

The *n*th modal dissipating energy, D_n can be expressed as the summation of dissipating energies due to different sources, such as damping capacity of materials, friction at structural connections, and energy dissipation at supports. The studied steel truss bridge was considered to be composed of five sub-structures: diagonal members (D), girders (G), upper chord members (UC), top lateral bracings (TLB), bottom lateral bracings (BLB), and supports (S). After calculating D_n, the *n*th modal damping ratio for the steel truss bridge can be evaluated using Eq. (1) as

$$\xi_n = \frac{2\pi\eta_d V_{d,n}}{4\pi U_n} + \frac{2\pi\eta_g V_{g,n}}{4\pi U_n} + \frac{2\pi\eta_{uc} V_{uc,n}}{4\pi U_n} + \frac{2\pi\eta_{tlb} V_{tlb,n}}{4\pi U_n} + \frac{2\pi\eta_d V_{blb,n}}{4\pi U_n} + \frac{8A_{s,n}\mu_s R}{4\pi U_n} \tag{2}$$

where η_i and $V_{i,n}$ represent the equivalent loss factor and *n*th modal strain energy of the sub-structure *i* respectively. $A_{s,n}$, μ_s and *R* are the *n*th modal amplitude at the movable support, dynamic friction coefficient and support's reaction due to vertical load respectively. The unknown loss factors and friction coefficient can be evaluated by using experimentally identified modal damping ratios and corresponding energy ratios obtained from updated FE-model developed by Dammika et al. (2014).

3. APPLICATION TO SHM

3.1 Problem description

A large crack at the lower end part of D5u diagonal member was observed in the fourth span of the bridge as shown in Fig. 1(a). As an emergency measure, reinforcing plates were installed inside and outside of the flange and web as shown in Fig. 1(b). Field vibration measurements of this span were carried out before and immediately after reinforcement. Five accelerometers only were used as limited time was available for the measurement. Table 1 shows the modal identification results by Eigensystem Realization Algorithm for before and after reinforcement of D5u diagonal member. It was observed that the changes in natural frequencies of the global modes due to damage are much smaller than the change in modal damping ratios. However, the change in modal damping ratio of 3rd bending mode was much higher than the changes in other modes. The details can be found in Yamaguchi et al. (2015).

In this study, an analytical explanation for this substantial change in experimentally identified modal damping ratio for 3rd bending mode was given and possible reasons were discussed. In order to simulate the damage in the FE-model, the sectional properties of all the elements of D5u diagonal member were reduced to half. The frequencies of the FE-model showed a reasonable agreement with the corresponding experimental identification, as observed in Table 1. It can be observed that the frequency of the diagonal mode came very close to the frequency of the 3rd bending mode due to damage. Because of this closeness in frequency, dynamic coupling of D5u diagonal member was observed in the 3rd bending mode as can be seen in Fig. 2(b).

3.2 Identification of loss factors for damaged span

To understand possible causes of the significant change in experimentally identified modal damping ratios for global modes due to damage in D5u diagonal member, the analytical modal damping ratios were evaluated for this span. Due to the limitation of number of identified modes shown in Table 1, only the loss factors of D, G and UC were estimated using the experimentally identified modal damping ratios at the fourth span. The loss factors of TLB and BLB and the dynamic friction coefficient at support were assumed to be the same as those of the first span for which experimental

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data with 17 locations were available. At first, the analytical modal damping ratios corresponding to the after reinforcement (AR) condition were evaluated. For before reinforcement (BR) condition, the equivalent loss factor of damaged D5u member (η_{d5}) was estimated by considering D5u diagonal in-plane mode as shown in Fig. 2(a). In this step, the equivalent loss factor for other diagonal members was taken as 0.0115 which corresponds to that in AR condition. Table 2 shows the identified damping parameters for the fourth span for AR and BR conditions. From Table 1, it can also be seen that the analytically evaluated modal damping ratios agree well with the corresponding experimental ones while there was increase in loss factor of girders along with the increase in loss factor of damaged diagonal member for BR condition.

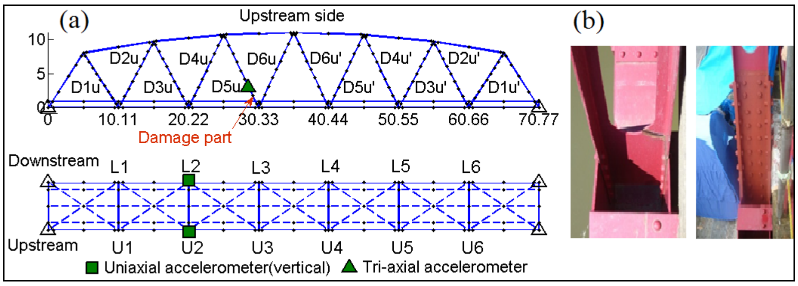

Fig. 1. (a) Layout of sensors; (b) Damaged and reinforced conditions

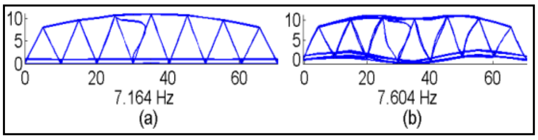

Fig. 2. (a) Diagonal; (b) 3rd bending mode

Table 1. Modal identification results of frequencies and damping for the fourth span

Identified modes	Natural frequency (Hz)					Modal damping ratio					
	Experimental			FE-model		Experimental			Analytical		
	Before	After	Rate	Before	After	Before	After	Rate	Before	After	Rate
1st bending	2.577	2.604	-1%	2.615	2.629	0.0093	0.0069	35%	0.0092	0.0070	31%
2nd bending	5.254	5.313	-1%	5.394	5.463	0.0072	0.0061	18%	0.0078	0.0061	28%
3rd bending	7.143	7.295	-2%	7.604	7.756	0.0106	0.0060	77%	0.0097	0.0059	64%
Diagonal	7.135	9.783	-27%	7.164	9.184	0.0055	0.0039	41%	0.0061	0.0046	33%

Table 2. Damping parameters corresponding to AR and BR conditions

Damping parameters	η_{d5}	η_d	η_g	η_{uc}	η_{tlb}	η_{blb}	μ_s
AR	0.0115	0.0115	0.0130	0.0078	0.0963	0.0229	0.3796
BR	0.0172		0.0258	0.0078			

3.3 Discussion on loss factors and damping

Possible reasons for the increase in the loss factor of girder with no significant damage reported could include the amplitude dependence of the loss factor. Table 3 shows the initial modal amplitudes of vibration at measurement locations obtained from ERA. From this table, it can be seen that the initial modal amplitudes of girders for 1st and 2nd bending modes are much higher in BR condition compared to AR condition which might have caused the increase in the modal damping for these two modes. For the 3rd bending mode, a significantly large amplitude of D5u member was observed in BR condition. If the loss factor of D5u is amplitude-dependent, then the loss factor of D5u member for the 3rd bending mode in BR condition would be 0.1047 compared to 0.0172 for the damaged diagonal mode and this increase in the loss factor might have caused the significant increase in the modal damping ratio for the 3rd bending mode.

Table 3. Initial modal amplitudes at measurement locations for AR and BR conditions

Mode	Amp. at AR condition (m/s^2)			Amp. at BR condition (m/s^2)		
	Amp. at U2	Amp. at L2	Amp. at D5u	Amp. at U2	Amp. at L2	Amp. at D5u
1st bending	0.0058	0.0062	0.0001	0.0255	0.0270	0.0050
2nd bending	0.0126	0.0128	0.0033	0.0261	0.0246	0.0015
3rd bending	0.0053	0.0043	0.0021	0.0053	0.0083	0.1488
Diagonal	0.0008	0.0014	0.0342	0.0024	0.0011	0.0583

4. CONCLUSIONS

From the damping analysis performed in this study it was found that the substantial change in damping for coupled global mode may be mainly attributed to significant increase in equivalent loss factor of damaged diagonal member due to its dependence on the amplitude of vibration.

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