DAMAGE DETECTION BASED ON MODAL DAMPING CHANGE IN BRIDGES

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Abstract

Structural Health Monitoring has drawn more attention from bridge engineers since the tragic collapse of the I-35W Mississippi River Bridge. In health monitoring of bridges, visual inspection has been the principal technique, while the reliability of this subjective technique heavily depends on the skills and experiences of the inspector. Objective techniques for structural monitoring should be useful to assist the visual inspection. A possible objective technique that has been investigated worldwide is vibration-based health monitoring. This paper aims to discuss the feasibility of vibration-based health monitoring in bridges, focusing on the damage detection based on the identification of change in their modal damping, by reporting the results of three different studies. A possibility of the damping change based damage detection was first examined by using the measurement data acquired from load car running test in the truss bridge with the cracks in the diagonal member. The energy-based modal damping analysis was next carried out to authenticate the accuracy of experimentally identified modal damping ratios in the steel arch bridge. Furthermore, by paying attention to the fact that the corrosion of RC structures is invisible, the detection of the corrosion-induced damage in RC beams by modal damping identification was studied experimentally. The main conclusions derived in this study are as follow: 1) The damping ratio of diagonal member-coupled mode was definitely increased by coupling of damaged diagonal member, suggesting the possibility of structural member's damage detection by identifying changes in modal damping ratio of steel truss bridges. 2) Possibility of finding equivalent loss factors of the steel arch bridge components using energy-based damping analysis was successfully presented, and the energy-based damping analysis can be a powerful tool for the damage detection of bridges. 3) The modal damping is very sensitive indictor against corrosion-induced damage in the RC beams, and the local corrosion level might be detectable by measuring the modal damping ratio of RC structures.

Keywords: structural health monitoring, damage detection, modal damping, steel bridge, concrete bridge

1. Introduction

Structural Health Monitoring (SHM) has drawn more attention from bridge engineers since the tragic collapse of the I-35W Mississippi River Bridge in Minnesota in the United States. In Japan, extensive inspections after the collapse of the bridge in Minnesota revealed cracks and fractures in members of steel truss bridges, some of which reached a complete loss of the cross section of a member. In health monitoring of bridges, visual inspection has been the principal technique, although the reliability of this subjective technique heavily depends on the skills and experiences of the inspector. Objective techniques for structural monitoring should be useful to assist the visual inspection. A possible objective technique that has been investigated worldwide is vibration-based health monitoring (Doebling (1996), Balageas et al. (2006), Boller et al. (2009)). Most techniques for vibration-based monitoring are based on the identification of changes in the dynamic characteristics of structure from recordings of structural vibration induced by various natural and artificial sources (e.g., Siringoringo & Fujino (2008)). The present paper aims to discuss the feasibility of vibration-based health monitoring in bridges focusing on the damage detection based on the identification of change in their modal damping.

2. Modal damping change in damaged steel truss bridge

A possibility of the damage detection was examined by using the measurement data acquired from load car running test in the truss bridge with the damage in the diagonal member. Although the change of the natural frequency of the diagonal coupling mode was very small, it was observed that the damping ratio was definitely increased by coupling of the damaged diagonal member. This chapter summarizes a part of our research outcomes that have been reported in Yoshioka et al. (2008, 2009, 2010a, b).

2.1 Outline of steel truss bridge and field measurement

The studied bridge is five simple Warren through type trusses with a span length of 70.77m. The bearing supports are pin and pin-roller bearing. As for the diagonal members, the tension diagonal members are a H-section, and the compression members are made of a box section with elliptical holes to reduce steel weight in the web of tension diagonal members. In July 2007 after 42 years since service, crack damages were discovered among D5 diagonal members at the top and bottom ends. The reinforcing plates were installed as an emergency measure. The crack occurred at a flange of the neighborhood of border with a gusset plate of diagonal members, and there was a part where a crack progressed into the web. The reinforcing plates were installed inside and outside of the flange and web for about 1.5m ranges for one-web opening hole measured from the gusset plate. These plates were joined by high tension bolts.

In the fourth span of the bridge with a large crack in the lower end part of D5 diagonal member, a loading truck running test was performed before and after the reinforcement. Figure 1 shows the crack in the D5 member, its reinforcement and the setting positions of piezoelectric accelerometers. The accelerometers were set at the quarter point of the damaged D5 and the points U2 and L2 of the lower chord members. The loading truck was a dump truck with a gross weight of 196 kN. The truck ran alone with a running speed of 20km/h, 30km/h and 40km/h., and the measurements were taken for 3 times each. The sampling frequency was 200Hz.

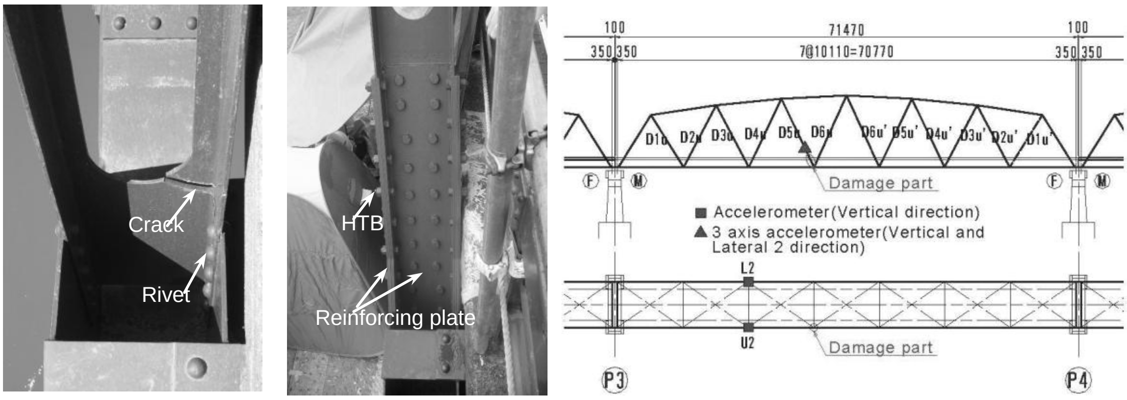


Figure 1: Crack of D5, its reinforcement and positions of accelerometers

2.2 Damping change in coupled mode

Figure 2 shows the changes in the modal frequencies and damping ratios before and after the reinforcement of the diagonal member. In the local vibration mode dominated by the motion of the diagonal member damaged and repaired, as shown in the figure, the modal frequency largely increased from 7.1 Hz to 9.8 Hz, but the modal damping ratio slightly decreased from 0.005 to 0.004 after the reinforcement. In the global vibration modes involving the motion of the whole structure, there appeared to be changes in the modal damping ratio with minor changes in the modal frequency. It was noted that there was more variability in the identification of the modal damping ratio in the lowest order vibration mode at about 2.6 Hz, which could be caused by the friction damping at the bearing supports. In the global mode at about 7.3 Hz, however, there was less variability in the damping identification and the large change in the modal damping shown in Fig. 2 was more reliable than the changes in the lowest order vibration mode.

Figure 3 shows the relation between the changes in modal damping ratio found in the vibration mode at 7.26 Hz and the dynamic coupling between the diagonal and lower chord members, which is represented by the ratio of the modal amplitude of the diagonal member to the modal amplitude of the lower chord member. The decrease in the amplitude ratio from about 16 to 0 in the global mode at 7.26 Hz, as shown in Fig. 3(b), implies that there was no dynamic coupling between the diagonal member D5 and the lower chord member after the reinforcement due to the increase in the modal frequency of the local mode of D5. The decrease in the modal damping ratio of the global mode at 7.26 Hz may be associated with the loss of coupling that was caused by the change in the mechanical property of the diagonal member. This finding suggests that the modal damping ratios of global modes may be used as an indicator of local damages in diagonal members in steel truss bridges.

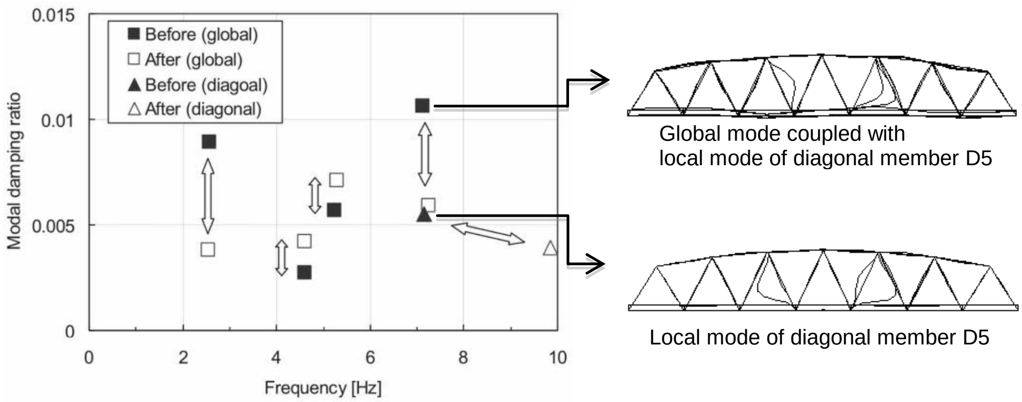


Figure 2: Changes in modal frequencies and damping ratios before and after reinforcement

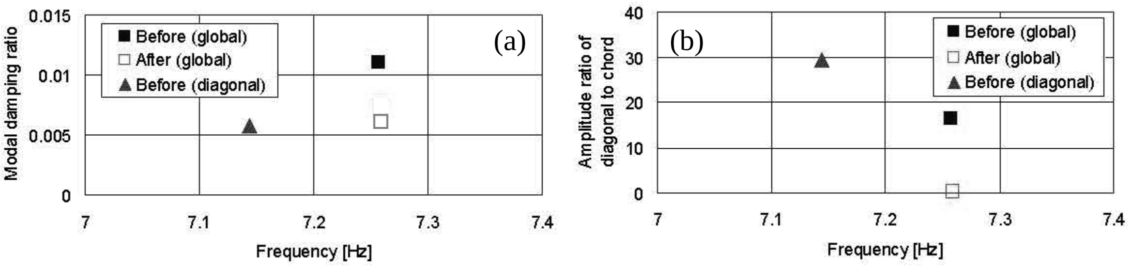


Figure 3: Relation between changes in (a) modal damping ratio and (b) dynamic coupling between diagonal and lower chord member before and after reinforcement

3. Energy-based damping analysis of steel bridge and its applicability to damage detection

Analytical estimation of modal damping ratio is one of the possible approaches to verify the accuracy of the experimentally estimated modal damping ratios that could be used for vibration measurement based SHM. Yamaguchi et al. (1997a, b, 2002) have applied the energy-based approach to analytically estimate the modal damping ratios mainly in cable-stayed bridges with emphasis on their mode dependence. With this background, the study in this chapter was carried out to authenticate the accuracy of experimentally identified modal damping ratios through the energy-based modal damping estimation. Experimental and analytical damping evaluation of steel arch bridge was done and applicability of proposed methodology. This in turn will help to verify the reliability of using changes in modal damping ratio as a damage indicator in SHM.

3.1 Energy-based modal damping analysis

The damping ratio of a single degree of freedom damped system is defined as the ratio between the energy dissipated in one vibration cycle to the total potential energy stored at the maximum displacement during vibration. Expanding this idea to the *n*-th vibration mode of structure, the *n*-th modal damping ratio ξ_n can be defined as $\xi_n = D_n / 4\pi U_n$, where U_n is the potential energy and D_n is the dissipated energy in one oscillation cycle in the *n*-th vibration mode. In the case of steel arch bridges, the energy dissipation is taken place in various damping sources and, therefore, the modal damping energy D_n is expressed as a summation of dissipated energy of all the damping sources; $D_n = \sum D_{i,n}$, where $D_{i,n}$ are the internal energy dissipation of bridge members and frictional damping at bridge's moveable supports. The energy dissipated by structural members due to material hysteresis is proportional to strain energy and can be expressed as $2\pi\eta V_n$, where η is material loss factor related to structural member and V_n is its *n*-th modal strain energy. The frictional energy dissipation at supports during one vibration cycle is expressed as $\sum_j 4 A_j \mu_j W_j$, where W_j, μ_j and A_j are the vertical dead load, dynamic friction coefficient and slip amplitude of the *j*-th support, respectively.

3.2 Field vibration measurement of steel arch bridge

The studied steel arch bridge is a Langer type arch bridge having the span length of 86.3 m and the width of 17.8m, constructed in 1971. The bridge has three spans over the river, which is a part of whole bridge spreads over the length of 810m, supported by pin and roller bearings on either side of the span. The arch rib has box-shaped cross-section while the vertical members have H sections. The bridge deck is a composite deck of steel plate girders and reinforced concrete slab. It is noted that no remarkable damage or deterioration is observed in the bridge.

The vibration measurement of the bridge was performed during the service. Ten piezoelectric accelerometers and three servo velocimeters were placed on the bridge, and two displacement gauges were set to measure the displacement at the moveable supports, as shown in Fig. 4. Ten minutes duration of ambient vibration measurement were recorded with sampling rate of 100Hz at the service condition of having relatively high-traffic. Five measurements were recorded and ten free vibration (FV) records were extracted from them according to the traffic flow. Those 10 FV records were utilized in estimating the natural frequencies, mode shapes, and modal damping ratios by applying the Eigensystem Realization Algorithm (ERA) technique. Even though several numbers of modes were identified from each FV record, only the modes identified with Extended Modal Amplitude Coherence (EMAC) value (Pappa and Eliott (1993)) greater than 0.6 were considered by quantitatively distinguishing the system and noise modes. Furthermore MAC (Modal Assurance Criteria) value calculated by mode vector greater than 0.8 was accepted in order to improve the reliability of the experimental outcomes. Thus identified modal frequencies and associated modal damping ratios are all plotted in Fig. 5.

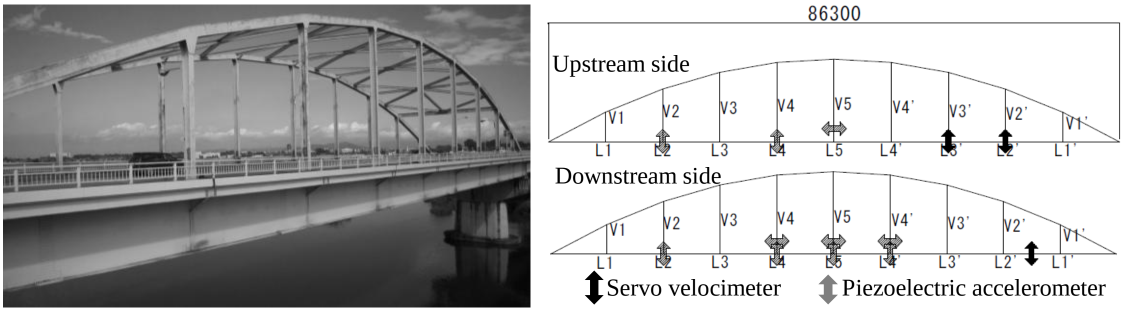


Figure 4: View of the arch bridge and position of sensors for field vibration measurements

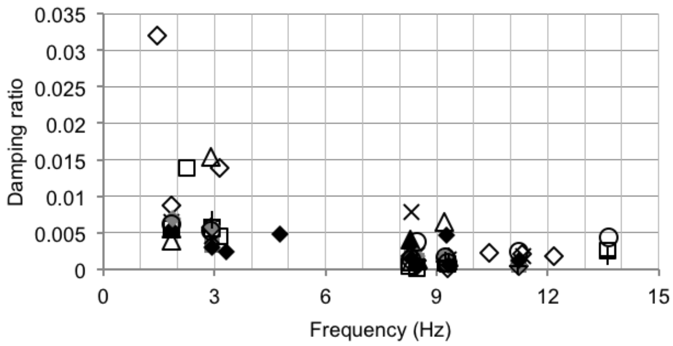
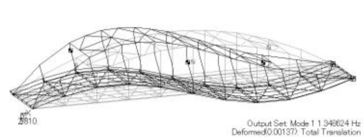


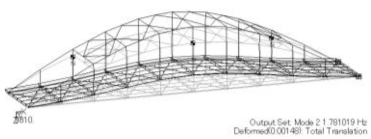
Figure 5: Experimentally identified modal damping ratio vs. natural frequency

3.3 Natural frequency and mode shape analysis of the arch bridge

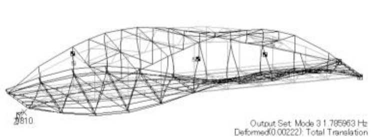
The Finite Element (FE) model was created for eigenvalue analysis of the studied bridge. All structural members were modeled by general beam element with assigned mass and geometric properties. Equivalent section concept was utilized in modeling the concrete deck slab with added mass and stiffness properties to the stringer beams and added stiffness to the cross beams. The pin and roller support conditions were used on either side of the span. It should be noted that spring elements were introduced to model the dynamic friction at moveable supports by assuming the dynamic friction coefficient of 0.005, which is an average value for same type of new bearings, for defining their equivalent spring constants. The analytically evaluated natural frequencies and associated mode shapes for the FE model are summarized in Fig. 6. The error in the natural frequency compared to the experimentally identified one is at most -6.2%.



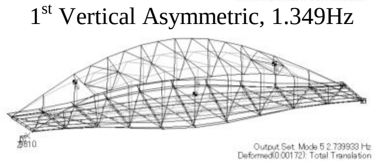
1st Vertical Asymmetric, 1.349Hz



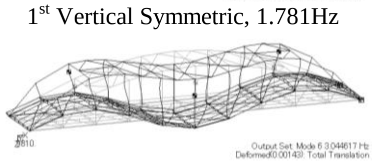
1st Vertical Symmetric, 1.781Hz



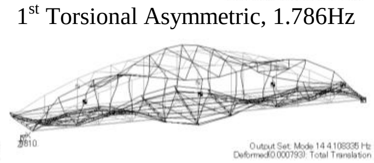
1st Torsional Asymmetric, 1.786Hz



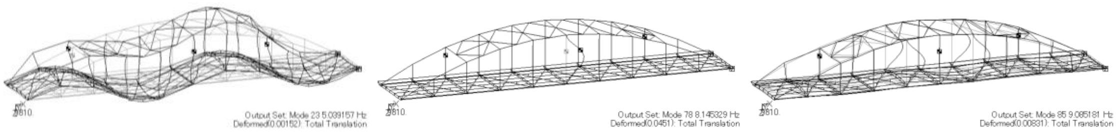
1st Torsional Symmetric, 2.79Hz



2nd Vertical Symmetric, 3.045Hz



2nd Torsional Symmetric, 4.108Hz



2nd Vertical Asymmetric， 5.039Hz V5u local， 8.145Hz V4 Coupled， 9.085Hz

Figure 6: Analytically evaluated vibration modes and natural frequencies of the arch bridge

3.4 Damping analysis of the steel arch bridge and its results

The sources of damping in the arch bridge were considered as the material viscous damping of bridge's arch rib, vertical member and girder, and the frictional damping at the moveable support. The energy dissipation at the members' connection was assumed to be included in the energy dissipation of each member and the energy dissipation in the girder implicitly accounts for that of the deck slab. That is, the equivalent loss factors, h_a, h_g and h_v, were introduced for respective components of arch rib, girder and vertical members. Therefore, the modal damping ratios of arch bridge are represented by Eq. (1), which is solved with respect to the unknown loss factors and dynamic friction coefficient by applying least square method using experimentally identified modal damping ratios and analytically calculated modal energy quantities. Once the damping parameters are estimated, the modal damping ratios can be estimated analytically by back substituting the estimated damping parameters to Eq. (1).

$$\begin{Bmatrix} \xi_1 \\ \vdots \\ \xi_n \end{Bmatrix} = \begin{bmatrix} \frac{2\pi V_{a,1}}{4\pi U_1} & \frac{2\pi V_{g,1}}{4\pi U_1} & \frac{2\pi V_{v,1}}{4\pi U_1} & \frac{8A_{s,1}R}{4\pi U_1} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{2\pi V_{a,n}}{4\pi U_n} & \frac{2\pi V_{g,n}}{4\pi U_n} & \frac{2\pi V_{v,n}}{4\pi U_n} & \frac{8A_{s,n}R}{4\pi U_n} \end{bmatrix} \begin{Bmatrix} \eta_a \\ \eta_g \\ \eta_v \\ \mu_s \end{Bmatrix} \tag{1}$$

In this study, the damping parameters were estimated from the FV data under two conditions. One is the condition of support movement with the assumption of dynamic friction coefficient $\mu_s = 0.005$ and another is the condition of no movement at support. The estimated loss factors are summarized in Table 1. The averaged values of loss factors in the table were then used to analytically estimate the modal damping ratios, and the results of estimated damping ratios are compared with experimentally identified values in Figs. 7 and 8. The accuracy of estimated loss factors are guaranteed by the closeness of those estimated modal damping ratios from both approaches. While the present study is still ongoing to discuss many details, it is concluded that the energy-based damping analysis can be a powerful tool for the damage detection of bridges in the vibration measurement based SHM.

Table 1: Estimated loss factors for FV data with and without support movement

Loss factor	*With support movement*			*Without support movement*			
	FV 3	*FV 8*	*Average*	*FV 1*	*FV 6*	*FV 7*	*Average*
Arch rib, h_a	*0.01341*	*0.00304*	*0.00823*	*0.00791*	*0.01427*	*0.01468*	*0.01229*
Girder, η_g	*0.00688*	*0.00867*	*0.00778*	*0.00791*	*0.00628*	*0.00971*	*0.00797*
Verticals, η_v	*0.00320*	*0.00648*	*0.00484*	*0.00268*	*0.00452*	*0.00378*	*0.00366*

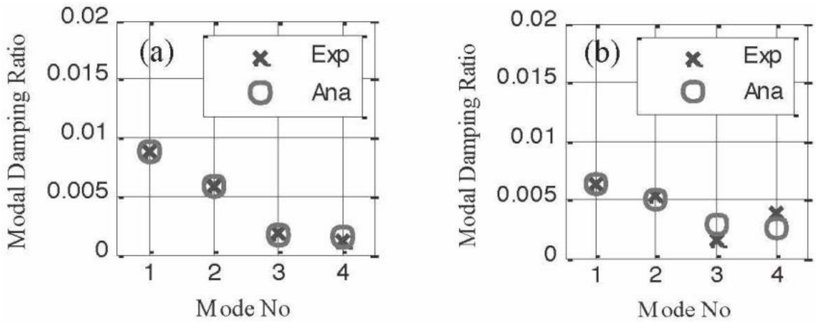


Figure 7: Comparison of experimentally and analytically estimated modal damping ratios from analysis with support movement: (a) FV3, (b) FV8.

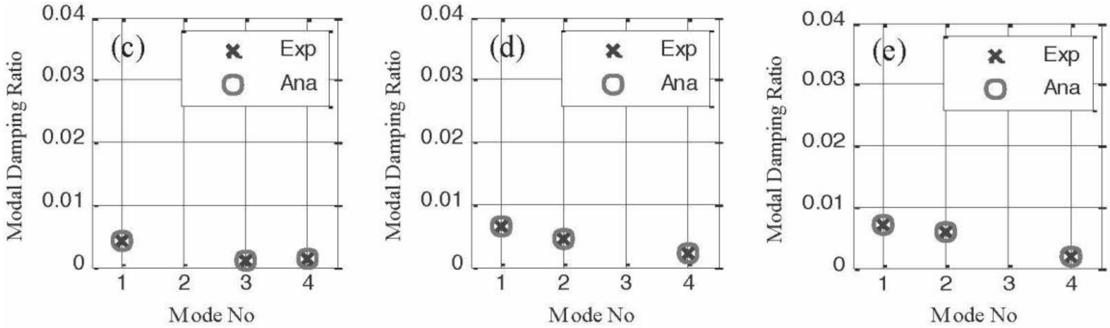


Figure 8: Comparison of experimentally and analytically estimated modal damping ratios from analysis without support movement: (a) FV1, (b) FV6, (c) FV7.

4. Detection of corrosion-induced damage in reinforced concrete beams based on damping identification

The deterioration of Reinforced Concrete (RC) bridges has been reported in literatures and the main cause of deterioration is corrosion of reinforcement. Due to the corrosion, there are loss of bond between steel reinforcement and concrete as well as micro cracking inside the concrete. These factors have relevant influence on strength of RC member. Because the corrosion occurs inside the RC structures and is invisible, it is an urgent need of study to detect these damages at their earliest stages. In this chapter, an experimental investigation is briefly explained to detect the corrosion-induced damage in RC beams by modal damping identification.

4.1 Accelerated corrosion test of RC beam

Four RC beams were casted. The size of beam was 600 mm long, 70 mm height and 70 mm wide. Two different corrosion patterns, “uniform corrosion” and “local corrosion”, were induced. In the uniform corrosion, the beam reinforcement was corroded throughout the length, while the central 100 mm portion of reinforcement was corroded in the local corrosion. The beams were corroded by the artificial impressed current technique (Rinaldi et al. (2010)), in which the test beam was immersed in 5% NaCl solution and electric current was impressed on the steel. The experimental setup used for these corrosion patterns are illustrated in Fig. 9. The corrosion amount and beam conditions are listed in Table 2, and the severities of damaged beams in the uniform corrosion and in the local corrosion are shown in Fig. 10.

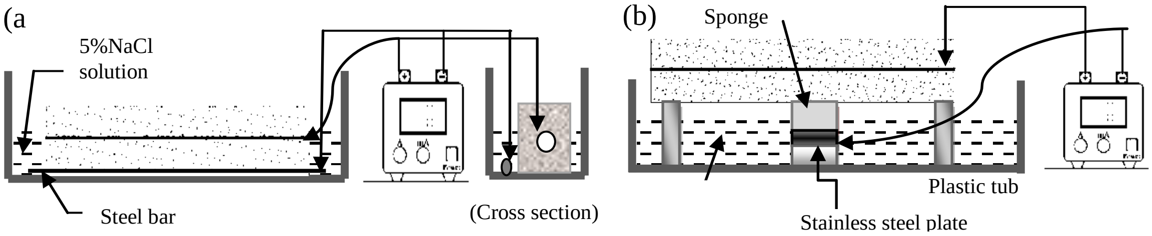


Figure 9: Experimental setup for (a) uniform corrosion and (b) local corrosion

Table 2: Corrosion amount and condition of beams

Uniform corrosion			*Localize corrosion*		
Beam	*Corrosion (% loss of mass)*	*Condition of specimen*	*Beam*	*Corrosion (% loss of mass)*	*Condition of specimen*
U_o	*0*	*Undamaged*	L_o	*0*	*Undamaged*
U_1	*1.03*	*No crack appeared*	L_1	*5.14*	*Minor cracks occurred along height and width directions*
U_2	*6.18*	*Cracks appeared along length direction*	L_2	*14.52*	*Major cracks occurred along height and width directions*

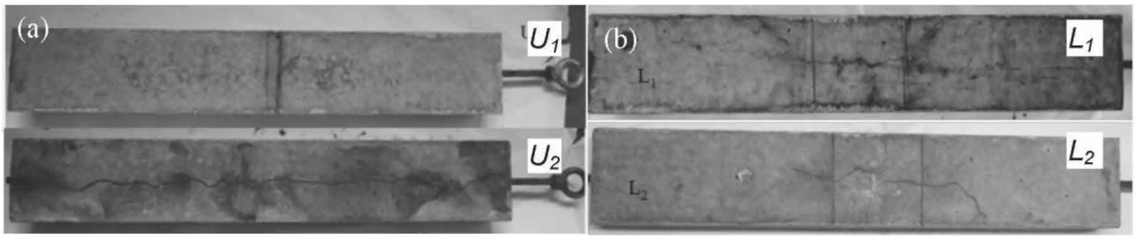


Figure 10: Cracking pattern in (a) uniform corrosion and (b) local corrosion

4.2 Dynamic testing and data analysis

The beam was set in free end condition in the dynamic testing by vertically hanging the beam with very thin wire at one end. The accelerometer was attached at the midpoint of beam, and the beam was excited in the first bending mode by giving the impact with an impact hammer at the midpoint on the opposite face of accelerometer attached. For each test beam the dynamic testing was repeated five times. The recorded duration of free vibration was 10 sec, and the sampling frequency of 15000 Hz was used for avoiding aliasing effect in data analysis. After getting vibration data, the modal damping ratio was identified firstly by applying the conventional log-decrement method and secondly by applying the curve fitting method with the damping model, proposed by Franchetti et al. (2009), to the free decay vibration envelope. This model contains two damping parameters, that is, the viscous damping ratio and the quadratic damping factor that represents the nonlinear damping, as represented in Eq. (2).

$$a(t) = \frac{(a_0 c_1).e^{-c_1 t}}{c_1 + a_0 c_2 (1 - e^{-c_1 t})}, \qquad c_1 = \omega\xi, \qquad c_2 = \frac{4}{3\pi}\delta\omega \tag{2}$$

where w, x, d, a_0 and t are circular frequency, viscous damping ratio, quadratic damping factor, initial amplitude and time of one vibration cycle, respectively.

4.3 Results and discussions

In the case of uniform corrosion, the changes in the natural frequency of corroded beams as compared to undamaged beam (786 Hz) were not so large, that is, 0.67% and 2.6% for the corroded beams U_1 and U_2, respectively. On the other hand, the changes in the modal damping ratio are relatively large, that is, 28% and 47% for the beams U_1 and U_2, respectively, as shown in Fig. 11, where the modal damping ratio of corroded and uncorroded beams calculated by the log-decrement method and by the curve fitting method with the damping model are given. It is noted that the damping model was dominated by the viscous damping without any contribution of nonlinear damping in the case of uniform corrosion. We conclude from Fig. 11 that the modal damping ratio of RC beam can be reasonably increased with the increase of corrosion level.

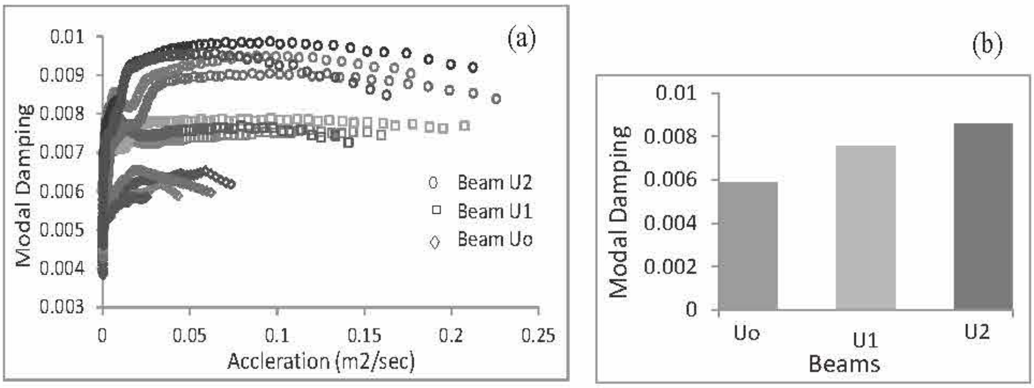


Figure 11: Modal damping ratios of uniformly corroded and uncorroded beams identified by (a) log-decrement method and (b) curve fitting method

In the cases of local corrosion, unstable phenomenon was observed in the impact testing. That is, the response frequency was dropped and converged to a constant value by repeating the impact testing five times, as shown in Fig. 12(a). This might be due to the unstable surface crack condition, which was changed with every impact testing. The unstable surface crack condition also has an affect on the modal damping characteristics as shown in Fig. 12(b), which indicates significant contribution of nonlinear damping. The nonlinear damping increases with up to the fourth testing then it decreases. This means that cracks were fully open at that stage and offered less friction between crack surfaces. Figure 13 shows the modal damping ratio identified by the log-decrement method after the stabilization of vibration for the locally corroded beams. While the strong amplitude dependence of modal damping ratio is observed, the modal damping ratios for two corrosion level L_1 and L_2 are well separated with each other, indicating that the local corrosion level might be detectable by measuring the modal damping ratio of RC structures.

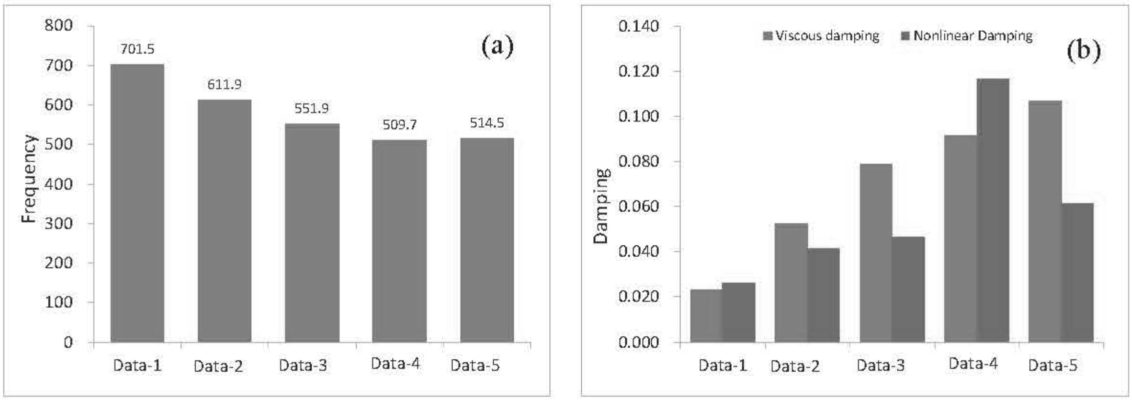


Figure 12: Results of locally corroded beam L_1: (a) frequency drop and (b) increase of viscous and nonlinear damping induced by 5 times repeated impact testing

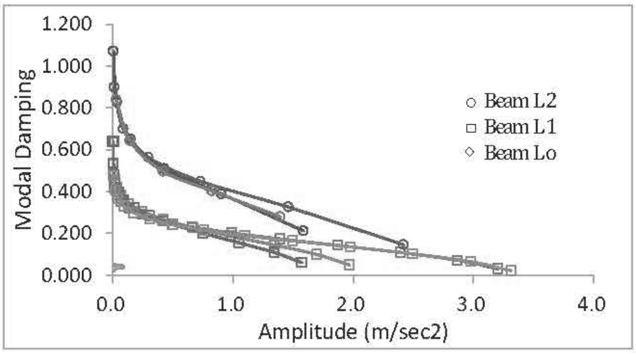


Figure 13: Modal damping ratios of locally corroded and uncorroded beams identified by log-decrement method

5. Concluding remarks

The feasibility of vibration-based structural health monitoring in steel and concrete bridges, focusing on the damage detection based on the identification of change in their modal damping, was discussed in this paper and the conclusions are summarized as follows.

- The change of local structure characteristic by a reinforcing plate of the diagonal member in the steel truss bridge was identified clearly as a change of modal damping of the diagonal member-coupled mode. That is, the damping ratio of diagonal member-coupled mode was definitely increased by coupling of damaged diagonal member. This result suggests the possibility of structural member's damage detection by identifying changes in modal damping ratio of truss bridges.

- Possibility of finding equivalent loss factors of the steel arch bridge components using energy-based damping analysis was successfully presented by verifying the accuracy of experimentally identified modal damping ratios. This means that the energy-based damping analysis can be a powerful tool for the damage detection of bridges in the vibration-based SHM, while further studies are required by paying attention to how to handle the erroneous field data of modal damping ratio, more diversified damping modeling and so on.

- The modal damping is very sensitive indictor against corrosion-induced damage in the RC beams. Even at very small damage level without any visible crack, it was possible to detect this damage with damping identification, indicating that the local corrosion level might be detectable by measuring the modal damping ratio of RC structures.

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