Relation between changes in the modal properties and structural changes in an existing steel truss bridge

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Abstract: *This paper describes an investigation of the applicability of changes in modal properties of a bridge to structural health monitoring. Vibration measurements were conducted at an existing Warren truss bridge for road traffic in-service for more than 40 years. Experimental modal analysis applied to the measured data identified global vibration mode of a bridge span and local vibration modes dominated by vibrations of diagonal members. There were a partial fracture, cracks and pitting corrosions in diagonal members of the truss bridge detected during recent visual inspections and some of those damages were repaired during the investigation described in this paper. The effects of those structural changes on the modal properties identified were discussed with the results of finite element analysis so as to investigate the applicability of modal properties changes in global and local vibration modes to the identification of structural changes in truss bridges.*

Keywords: *vibration-based structural health monitoring, natural frequency, modal damping, truss bridge, vibration measurement*

1. INTRODUCTION

Recently, structural health monitoring has drawn more attention from bridge engineers, particularly in developed countries where the design life of substantial number of bridges is approaching to its end. The tragic collapse of the I-35W Mississippi River Bridge in Minnesota in the United States in 2007 may have emphasized needs for appropriate structural health monitoring. 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 (e.g., Doebiling *et al*, 1996; Balageas *et al*, 2006; Boller *et al*, 2009). Most techniques proposed 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). It is assumed that structural damages are associated with changes in the mass, stiffness and damping of the structure that yield changes in the dynamic characteristics, such as natural frequencies, mode shapes, and modal damping.

The objective of the present study was to investigate the relation between changes in the natural frequencies and modal damping and structural changes in an existing steel truss bridge. There were local damages found recently in the bridge used in this study. Sets of vibration measurements were conducted to obtain vibration data for different structural states. The contents of this paper include a part of outcomes from studies reported in Yoshioka *et al* (2008, 2009, 2010a, b) that was summarised in Matsumoto *et al* (2010).

2. FIELD MEASUREMENTS

2.1. Bridge used in this study

A bridge over a river for road traffic in-service from 1965 was used in this study. The bridge consisted of five separated spans, each of which was a Warren truss with a span length of 70.77 m and a width of 6.0 m (Figure 1). The tension diagonal members had a H-section, whereas the compression diagonal members had a box section, as shown in Figures 1 (c, d). There were eight or nine oval holes in the web of each tension diagonal members, except those at the ends of each span, for the reduction of the weight of steel.

During a visual inspection in July 2007, a partial fracture was found near the bottom end of a longest tension diagonal member (D5 in Figure 1), which resulted in loss of the half of its cross section. There were cracks in four other longest tension diagonal members also. In August 2007, those damages were repaired by fixing additional steel plates with the same thickness as that of the member (i.e., 8 mm) by high strength bolts to cover both sides of the flanges and web for a length of about 1.5 m from the end of the member. Additionally, there were pitting corrosions in several shortest diagonal members (D1 in Figure 1) detected in the following inspections in 2009.

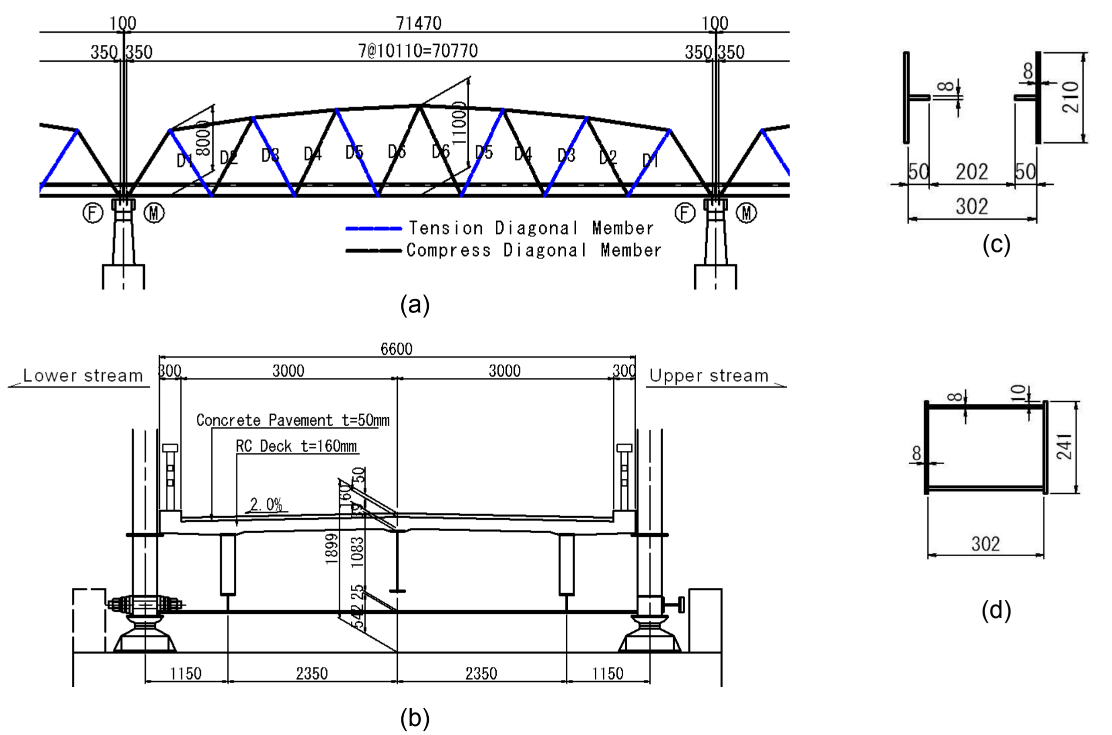


Figure 1 Steel truss bridge investigated: (a) side view of single span, (b) cross section of the bridge, (c) cross section of tension diagonal member, (d) cross section of compression diagonal member. Unit [mm].

2.2. Vibration measurements

Several sets of vibration measurements were made for different objectives. The objectives of those sets of measurements were to identify the effect of the partial fracture, cracks and pitting corrosions on the dynamic characteristics of the local dynamic characteristics of the diagonal members (Measurement 1) and the whole bridge (Measurement 2), and obtain better understanding of the dynamic characteristics of the bridge (Measurement 3), respectively.

Impact testing of the diagonal members was conducted in those with damage and without so as to identify the effect of damage on local vibration characteristics of the tension diagonal members (Measurement 1). Either a three-axis accelerometer unit consisting of three single-axis piezoelectric accelerometers or a set of four single-axis piezoelectric accelerometers was attached to the flange of tension diagonal members at the quarter point from the bottom. Impacts were applied by an impact hammer to the web of the diagonal member at the quarter point from the bottom. Additionally, ambient vibrations of a diagonal member were measured so as to understand the difference between the vibration modes of the diagonal member induced by impact testing and those induced by ambient vibration.

In order to identify the effect of damages on the dynamic characteristics of the bridge (Measurement 2), vibration of the bridge was measured at three locations: the lower chord members on both sides of the bridge and a longest tension diagonal member, D5 (Figure 2). The number of measurement locations was limited because the measurement needed to be completed during a short time period between the detection of the damages and the urgent reinforcement of the diagonal members. The measurement was conducted in the span with the local fracture found and, for comparison, in a span without damages. The acceleration of the lower chord member was measured in the vertical direction at the quarter point of the span. The accelerations in three orthogonal axes were measured in D5 at the quarter point from the bottom. Piezoresistive accelerometers were used in the measurement. Vibration of the bridge was induced by a dump truck with a total mass of about 200 kN running at different speeds between 20 and 40 km/h while the bridge was closed to other traffic.

Figure 3 shows the positions of transducers in Measurement 3 to obtain better understanding of the dynamic characteristics of the bridge. Four servo velocimeters were placed at different positions of a lower chord member and three piezoelectric accelerometers were attached at another lower chord member, as shown in Figure 3. The motion in the vertical direction was measured at all those locations. Additionally, the motions of five tension diagonal members were measured with piezoelectric accelerometers. At the quarter point from the bottom, two accelerometers were attached to the web to measure in-plane motion of the diagonal member and another accelerometer was attached to the flange to measure out-of-plane motion. A particular interest in this measurement was to understand more about the dynamic coupling between the diagonal members and the whole structure.

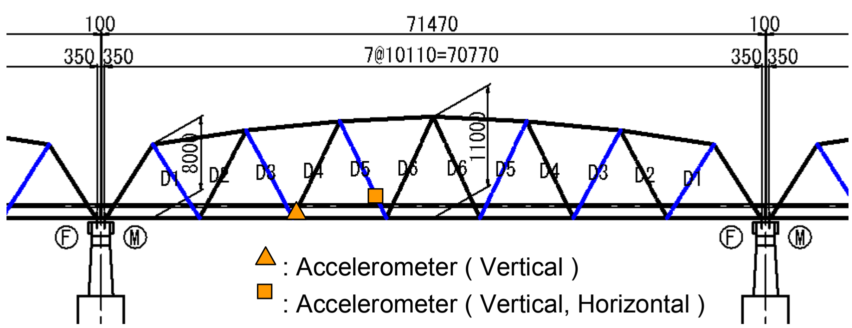


Figure 2 Positions of accelerometers in Measurement 2

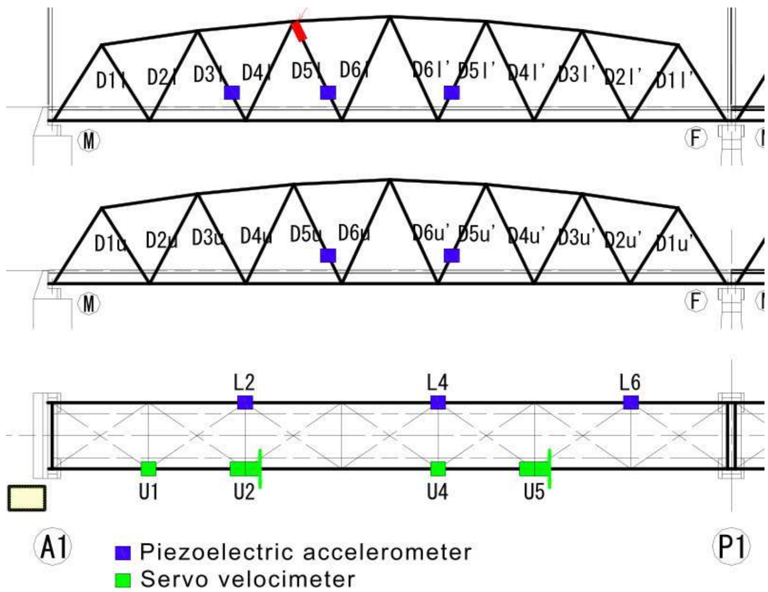


Figure 3 Positions of accelerometers in Measurement 3

3. NATURAL FREQUENCY CHANGE IN LOCAL MODES

Figure 4 shows an example of the results of impact testing that compares the Fourier spectra of the response to impact of a diagonal member D1 with pitting corrosions (referred to as corroded in the figure) and that of a D1 without corrosion (referred to as healthy). In the figure, the stabilization diagram obtained from the Eigensystem Realization Algorithm, ERA (Juang & Pappa, 1985) for the diagonal member without corrosion is compared with the corresponding Fourier spectrum. The Modal Amplitude Coherence, MAC, was used to identify reliable natural frequencies in the ERA. The comparison between the Fourier spectrum and the stabilization diagram from the ERA implies that the natural frequency identified from the measurement records in the impact testing were reliable.

It was observed that the natural frequencies observed at frequencies above 100 Hz were different between healthy and corroded diagonal members, while there were minor differences in the frequency range below 100 Hz (Figure 4). The natural frequencies of the diagonal member with pitting corrosions appeared to be lower than those of the diagonal member without corrosions. Similar trend were found with the comparison between this diagonal member with pitting corrosions and other healthy diagonal members with nominally the same dimensions. The decreases in the natural frequencies in the frequency range above 100 Hz for the corroded diagonal member may be associated with decreases in the modal stiffness of higher order local vibration modes that are attributed to the pitting corrosions.

Figure 5 compares the natural frequencies of the healthy diagonal member identified by impact testing and those identified from twenty different records of ambient vibration in the frequency range between 100 and 200 Hz where the effect of the pitting corrosions was observed. In the analysis of the ambient vibration records, the ERA was applied to free vibrations observed after vehicle pass-bys. The natural frequencies identified from ambient vibration records were a subset of the natural frequencies identified by impact testing. However, what natural frequencies were observed varied depending on the ambient records used in the analysis as observed in Figure 5. In practical applications, a continuous ambient vibration measurement combined with some statistical analysis can be used to identify all natural frequencies within a frequency range of interest.

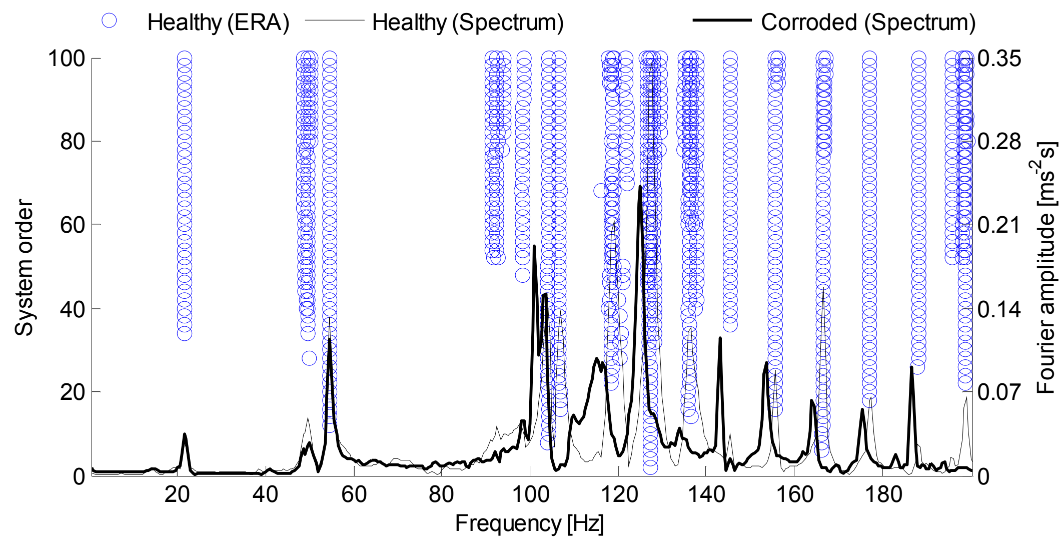


Figure 4 Fourier spectra of response of healthy and corroded diagonal members to impact. Stabilization diagram from ERA obtained for health diagonal member are also shown.

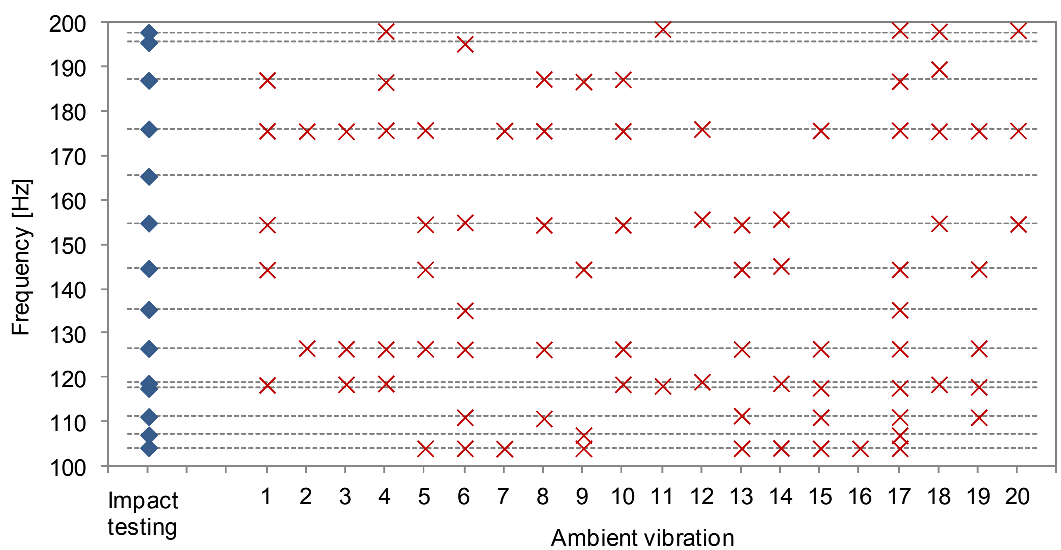
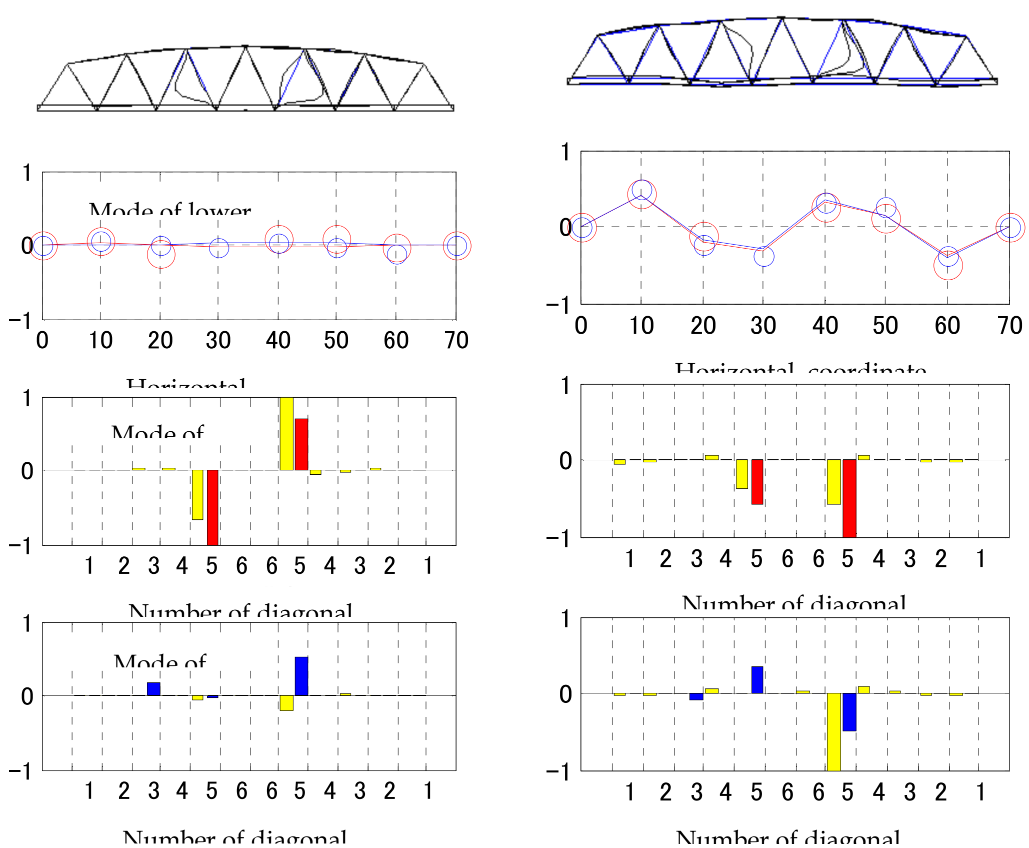


Figure 5 Natural frequencies identified by impact testing and 20 ambient vibration records

4. DAMPING CHANGE IN COUPLED MODE

It was understood that there were closely spaced vibration modes at frequencies around the natural frequencies of the diagonal members. This was partly because there were four diagonal members in a span that had nominally the same dimensions. Additionally, there were coupled vibration modes between the diagonal members and the whole structure. Figure 6 shows the mode shapes involving significant motion of the longest tension diagonals (D5). In the figure, the mode shapes identified from the field records measured in Measurement 3 by the ERA are compared with those obtained from theoretical modal analysis by finite element analysis. The figure shows a vibration mode dominated by the motion of the diagonal members (referred to as a local mode in this paper) and a mode involving the motions of the diagonal members and lower chord members (referred to as a coupled mode).
Figure 7 shows the changes in the modal frequencies and damping ratios before and after the

reinforcement of the diagonal members identified in Measurement 2. The modal properties shown in the figure were obtained by the ERA. The figure shows that, in the local vibration mode dominated by the motion of the diagonal member damaged and repaired, the modal frequency increased from 7.1 Hz to 9.8 Hz, approximately, and the modal damping ratio decreased from 0.0055 to 0.0039 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 from the measurement records in the lowest order vibration modes, such as the mode at about 2.6 Hz in the figure, although the data are not presented in this paper. This variation in the damping was considered to be caused by the friction damping at the bearing supports that was dependent heavily on the displacement amplitude of vibration. In the global mode at about 7.3 Hz, however, there was less variability in the identification of modal damping ratio and the change in the modal damping shown in Figure 7 was more reliable than the changes in the lowest order vibration modes.
Figure 8 shows the relation between the changes in modal damping ratio found in the vibration mode at 7.26 Hz, as shown in Figure 7, and the dynamic coupling between the diagonal and lower chord members. The dynamic coupling between the diagonal and lower chord members are represented by the ratio of the modal amplitude of the diagonal member to the modal amplitude of the lower chord member in the figure. The modal amplitude of the diagonal member was obtained by subtracting the modal amplitude at the end of the diagonal member from that identified for the measurement location in the diagonal member.



(a) (b)

Figure 6 Modal amplitudes corresponding to (a) local mode at 9.264 Hz and (b) coupled mode at 9.325 Hz. The vi-bration modes identified experimentally are compared with those obtained theoretically.

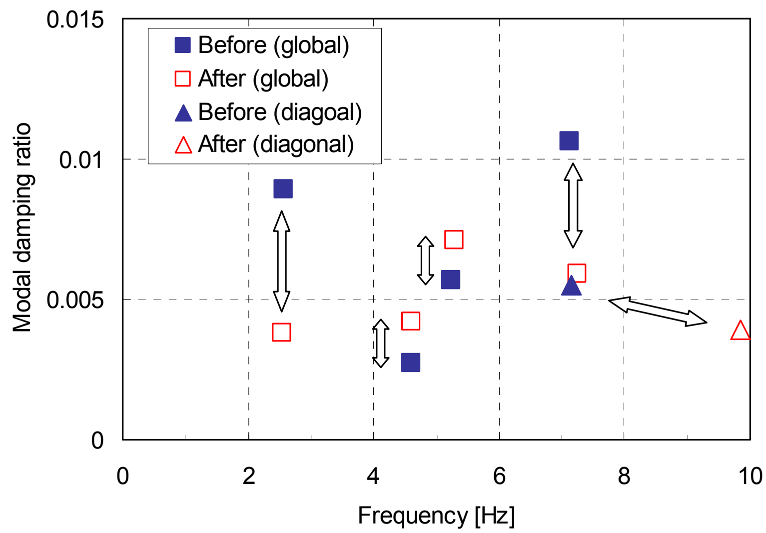
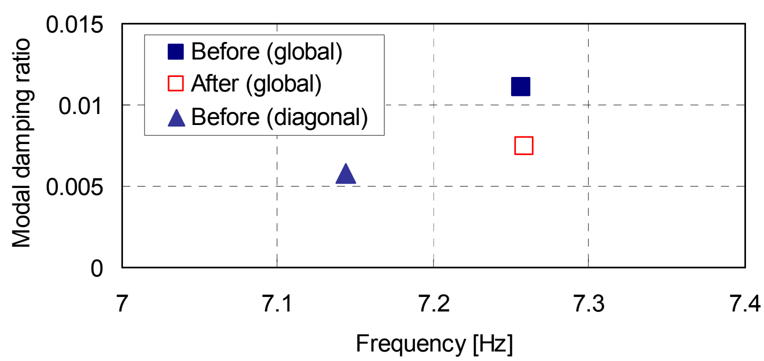
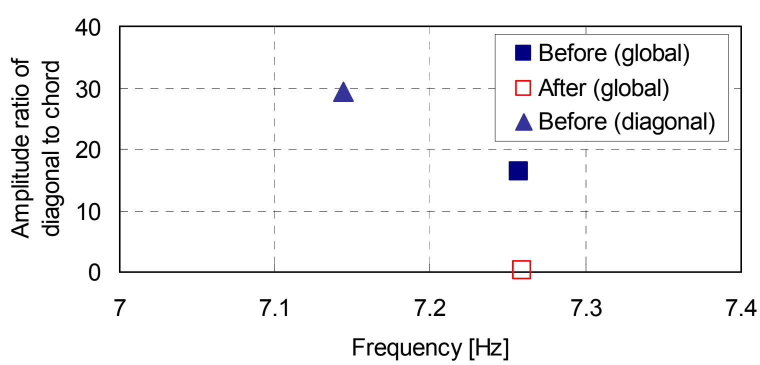


Figure 7 Examples of changes in modal frequencies and damping ratios before and after reinforcement of diagonal members.



(a)



(b)

Figure 8 Relation between changes in modal damping ratio and dynamic coupling between diagonal and lower chord members. (a) modal damping ratios and (b) amplitude ratios of diagonal member to lower chord member in local and global vibration modes before and after reinforcement.

The vibration mode at 7.14 Hz shown in Figure 8 was the local mode dominated by the motion of the damaged tension diagonal member D5 as indicated by a high amplitude ratio of the diagonal member to the lower chord member (i.e., about 30). As shown in Figure 7, the modal frequency of the local mode increased from 7.14 Hz to 9.80 Hz after the reinforcement of the diagonal member: the modal properties of the mode after the reinforcement are not shown in Figure 8.

The decrease in the amplitude ratio of the diagonal member D5 to the lower chord member from about 16 to 0 in the global mode at 7.26 Hz, as shown in Figure 8, 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 between the diagonal and lower chord members 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.

5. CONCLUSIONS

The results presented in this paper shows a possibility of the identification of local damages in steel truss bridges, such as damages in diagonal members, from changes in the modal properties of the structure obtained from vibration measurements. The natural frequencies of higher order local vibration modes of diagonal members can be a direct indicator of damages, although a practical implementation of the identification of natural frequencies of a number of diagonal members may need further development. A possible solution may be applying impact testing only on diagonal members that are identified as critical members in redundancy analysis. Ambient vibration may be able to be used instead of impact testing to identify natural frequencies of diagonal members. The identification of changes in the damping of global mode may be more practical in terms of the feasibility of measurement, although there is a need to improve the reliability of the identification of modal damping. The development of quantitative relation between changes in modal properties and damages requires further investigations.

6. REFERENCES

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