BASIC STUDY ON DAMAGE LOCALIZATION OF STEEL BRIDGES BASED ON THE CHANGES OF MODAL AMPLITUDE

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ABSTRACT

"Structural Health Monitoring (SHM)" attracts interest in infra management. SHM aims real time monitoring of structural integrity. It is effective if the structural damage could be found by the monitoring in early stage of deterioration. However, early damage grows in difficult to see members such as joint. The vibration-based SHM has been researched that the way to assess the damage by comparing the vibration characteristics between the past and present state. It is expected that position of damage could be found early and accurately by using these objective parameters.

This paper presents structural damage detection method based on changes in amplitude of vibration modes. Structural slight damage is considered as minimal reduction of plate thickness on a local part. Modal amplitude differences between undamaged state and damaged state at each node are summed up in multiple vibration modes. And the calculated value is defined as a damage index. The index shows the biggest value at the region of damage because the flexibility of damaged member increases and modal amplitudes are affected in plural modes which have a bulge near damaged point. As a basic study, two damage scenarios are considered at the connection between main girder and crossbeam. From eigenvalue analysis, the proposed method is able to locate damages. And a smaller damage can be detected more accurately.

Keywords: Damage detection, Structural Health Monitoring, Modal amplitude difference.

1. INTRODUCTION

In modern countries, there are old bridges more than 50 years in service. Bridges are inspected by visual inspection which is adopted as a general method for evaluating structural integrity. However, visual inspection by human is concern about efficiency and objectivity. "Structural Health Monitoring (SHM)" evaluates structural integrity by using sensors and damage detection algorithms.

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It is expected that SHM gets over the demerits of visual inspection by human. The vibration-based SHM has been researched that the way to assess the damage by comparing the vibration characteristics between the past and present state (Boller et al. 2009; Doebling et al. 1996; Oshima 2000). It is expected that location of damage could be found early and accurately by using some damage detection method. In particular, structural damage in early stage grows in difficult to see members such as joint between a main girder and a crossbeam. Therefore, early damage localization method by using vibration-based SHM will enhance applicability of such technique for infrastructure management.

References (Beskhyroun et al. 2006; Oshima et al. 2011) assessed the damage by comparing the power spectrum density between the past and present state. In these studies, small actuators were applied as a bridge exciter and location of damage was assessed. However, early detection of damage remains as a problem.

This paper presents a basic consideration of structural damage detection method based on changes in amplitude of vibration mode shapes. The basic concept of the method comes from that a thickness reduction leads to changes of modal amplitudes. For a multi degree of freedom system, the effect of thickness reduction appears near damaged member in some vibration modes. And the effect may not appear in other vibration modes. Therefore, plural vibration modes are considered in this study. A FEM model of a small steel railway bridge is composed to discuss the effectiveness of the concept. Some damage scenarios are applied in the FEM model and modal shapes are obtained by eigenvalue analysis in each damage case. Modal amplitude differences between undamaged state and damaged state are represented as an index. The proposed method is able to locate damages. And smaller damage can be detected more accurately.

2. TARGET BRIDGE AND ANALYTICAL PROCEDURES

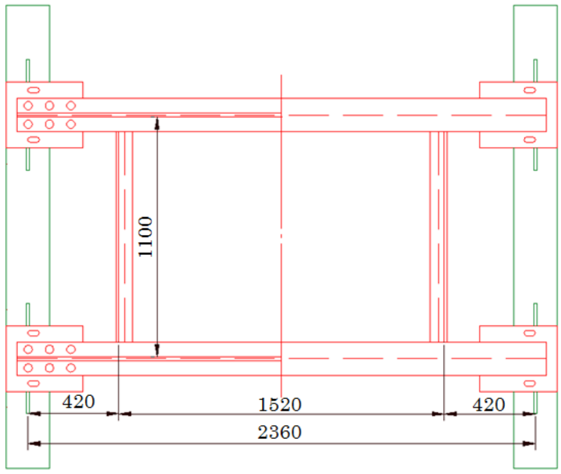
2.1. Target bridge and vibration characteristics

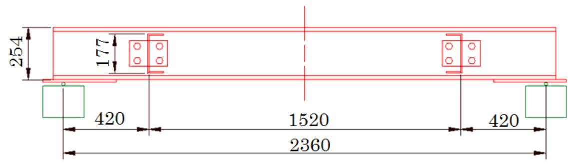
The bridge used in this paper is Iwaogawa Bridge moved from old Chihoku Kougen Railway as shown in Figure 1. This 2.4m bridge is composed of 2 I shaped beam girders and 2 channel steel crossbeams. Main girders are supported by 4 round steel bar on timbers as shown in Figure 2. Material properties of bridge are summarized in Table 1. Figure 3 shows the section of each

Figure 1: Target steel bridge

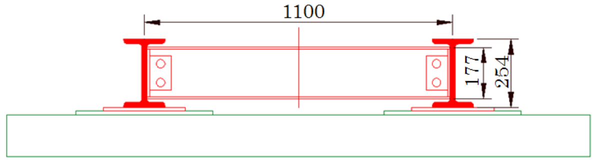
Table 1: Material properties of specimen

Young's modulus (kN/m^2)	2.0×10^8
Modulus of transverse elasticity (kN/m^2)	7.7×10^7
Poisson's ratio	0.3
Weight density (kN/m^3)	7.7×10



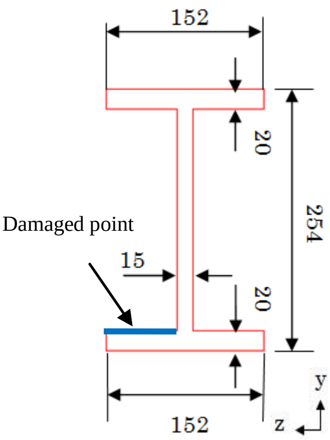


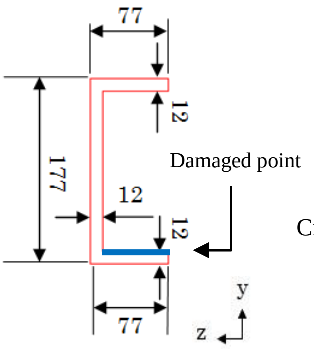
(b) Side view (mm)



(a) Plan view (mm) **(c) Cross section (mm)**

Figure 2: General drawing





(a) Main girder **(b) Crossbeam**

Figure 3: Dimension of member (mm)

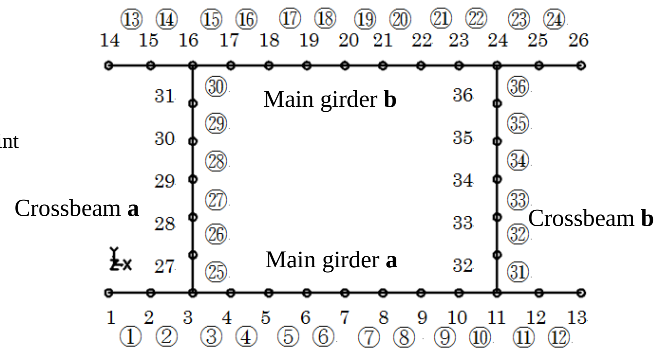


Figure 4: Node numbers and element numbers (Circled)

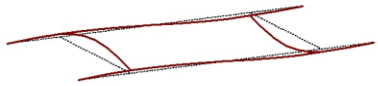
member of the bridge. FEM model of this bridge composed of these properties. For simplification, these members are modeled as beam elements. The bridge model is divided by 36 elements and the model has 36 nodes as shown in Figure 4. Node 1, 13, 14 and 26 are supported points. All displacements are restrained and rotation of Y-axis is only free on these nodes. For FEM analysis, TDAP3 which is a general structural analysis program is used in this study. Natural frequencies and mode shapes less than 1000Hz are shown in Figure 5 from eigenvalue analysis.

2.2. Damage scenarios

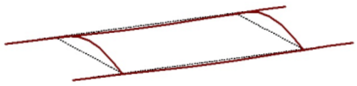
Structural damage is expressed as a thickness reduction of member section due to crack or corrosion. 3 damage scenarios are considered as follows. Scenario A: the plate thickness of lower flange at the center of the main girder **a** (element #(6)) is reduced as the simplest case. Scenario B: the thickness of lower flange at the center of the crossbeam **a** (element #(27)) is reduced as another simple case.

(a) 1st mode: 47.9Hz

(b) 2nd mode: 50.7Hz



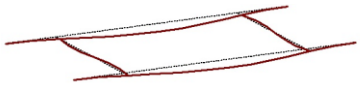
(c) 3rd mode: 140.0Hz



(d) 4th mode: 157.5Hz

(e) 5th mode: 192.1Hz

(f) 6th mode: 223.5Hz



(g) 7th mode: 345.2Hz

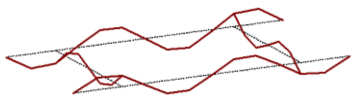
(h) 8th mode: 416.2Hz

(i) 9th mode: 445.1Hz

(j) 10th mode: 582.2Hz

(k) 11th mode: 608.8Hz

(l) 12th mode: 791.7Hz



(m) 13th mode: 812.3Hz

Figure 5: Natural frequencies and mode shapes

Table 2: Section properties and damage scenarios

Thickness reduction	Main girder					Crossbeam				
	A $\times 10^3$(mm^2)	*I* $\times 10^6$(mm^4)		Damaged member & scenario		*A* $\times 10^3$(mm^2)	*I* $\times 10^6$(mm^4)		Damaged member & scenario	
		y	z	#(6)	#(3)		y	z	#(27)	#(25)
none	9.3	95.7	11.8	A0	C0	3.7	16.2	1.9	B0	C0
1mm	9.2	94.9	11.6	A1	C1	3.6	15.8	1.9	B1	C1
6mm	8.9	90.5	10.9		C6	3.3	13.4	1.6	B6	C6
10mm	8.6	86.4	10.2	A10						
12mm	8.5	84.2	9.9		C12	2.9	9.4	1.1	B12	C12
20mm	7.9	73.6	8.4	A20						

Scenario C: the thickness of lower flange of both I-beam and channel member are reduced at the connection (element #(3) and #(25)) for considering probable damage scenario in real structure. The damaged points in each section are pointed in Figure 3. Table 2 shows section area and moment inertia of each cross section with damage scenario. In each damage scenario, 4 damage levels are considered. A0, B0 and C0 are intact cases. A1 B1 and C1 are cases which have minimal damage. More severe damages are assumed in A10, B6, C6 and A20, B12, C12 respectively.

2.3. Damage index

To find elements of thickness reduction, damage index d_n is introduced as the following equation for n mm thickness reduction.

$$d_n = \sum_{k=1}^{13} |\phi_k - \phi_{dk}| \tag{1}$$

where ϕ is modal amplitude of each node in undamaged state, ϕ_d is modal amplitude of each node in damaged states and k is mode order. The maximum mode order is 13 because modes less than 1000Hz of natural frequencies are considered in this study as shown in Figure 5. The index is the accumulation of modal amplitude differences in each nodal point. d_n is calculated for each damage scenario and damage level based on eigenvalue analysis of FEM model.

3. RESULTS AND DISCUSSIONS FOR DAMAGE ANALYSIS

3.1. Damage scenario A: element #(6)

The damage index obtained by eigenvalue analysis for the damaged element #(6) is shown in Figure 6. Horizontal axis shows node and element number and vertical axis shows normalized d_n by the maximum value. The index is dimensionless number and it takes between 0 and 1. d_ns at the node #6 and #7 which are both ends of the damaged element #(6) show the largest values in all nodes for damage scenario A1 and A10. It is considered that element #(6) is easily affected by reduction of the moment of inertia and its deflection increases. However in the severe damage scenario A20, the second maximum value of d_n is not obtained in the node #7 but it is obtained in the node #8.

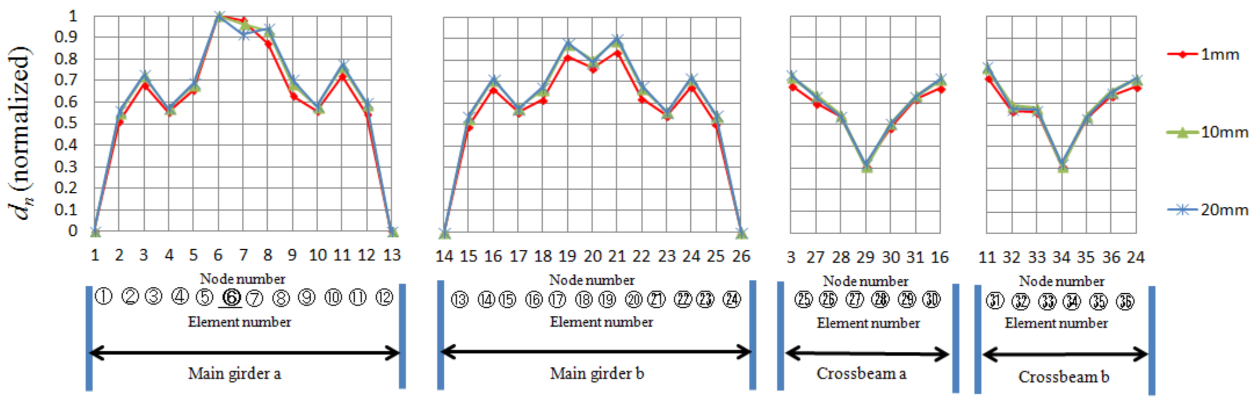


Figure 6: Damage index d_n in damage scenario A

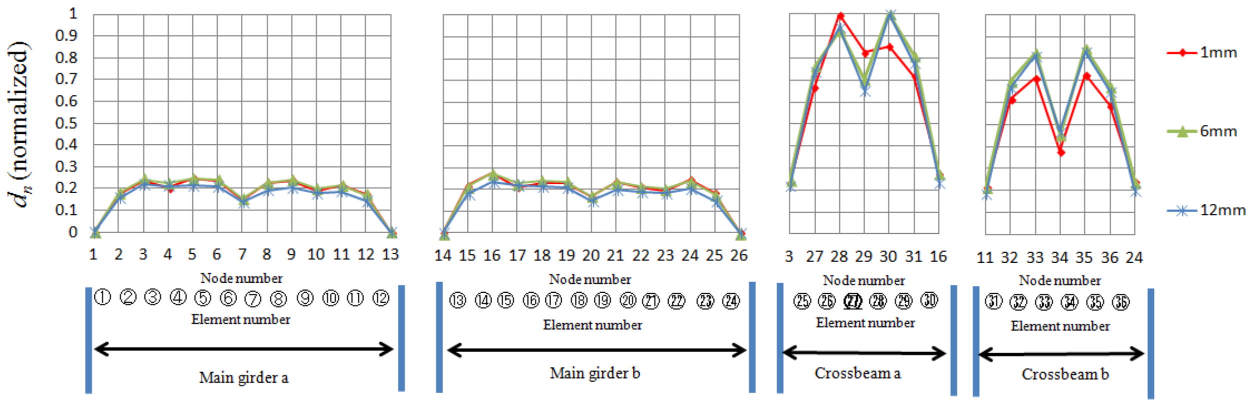


Figure 7: Damage index d_n in damage scenario B

Moreover, d_n increased in nodes on the undamaged main girder **b**. This result indicates that larger structural damage affect mode shape in whole of structure not only around damaged point.

3.2. Damage scenario B: element #(27)

The damage index obtained by eigenvalue analysis for the damaged element #(27) is shown in Figure 7. The indices of nodes on crossbeams are comparatively larger than indices on main girders. The largest value of d_n in the damage scenario of B6 and B12 appears at the node #30 although B1 has the maximum value at the node #28. This result is same in the damage scenario A as shown in Figure 6. Therefore, small thickness reduction gives more accurate result than large thickness reduction if the damage index considers modal amplitude changes in each node.

3.3. Damage scenario C: element #(3) and #(25)

The damage index obtained by eigenvalue analysis for the damaged element #(3) and #(25) is shown in Figure 8. Nodes #3, #4 and #27 adjoin both ends of the elements #(3) and #(25). d_n in the node #27 on the crossbeam **a** shows the maximum value in all damage levels C1, C6 and C12. Nodes #3 and #4 have the largest d_n in main girders. As for C1, d_n is large at the nodes #27, #3 and #4 in that order. Therefore, d_ns at both ends of damaged elements show large amplitude in case of small damage. On the other hand, d_ns in undamaged nodes become larger than d_ns at nodes #3 and #4 for C6 and C12. In these cases, d_n cannot locate damage accurately. This reason is considered that mode shapes of multi degree of freedom system appear complicatedly. A part of cross-sectional reduction causes change in mode shapes. However, modal amplitudes also change at undamaged members. For example, d_ns at the node #33 and #35 increase although the crossbeam **b** is undamaged member. Therefore, the influence of each mode in d_n should be discussed.

Contribution of each mode for d_n in C1 is shown in Figure 9. On the whole, influence of plural modes is shown in each node. Large d_n of the node #27 is influenced from the 10th mode. In other damage scenarios, other vibration modes give influence to the damage index. For example, the d_n of the node #6 becomes the largest in the damage scenario A1 as shown in Figure 10. In this case, contributions of the 1st and 8th modes are large. Moreover, d_n of the node #28 becomes the largest in the damage scenario B1 as shown in Figure 11 by contribution of the 3rd and 10th modes. These mode shapes have bulge which node adjoins element with thickness reduction. In small thickness reduction, only modal amplitude having bulge in damaged location changes large. Therefore, d_n which accumulates modal amplitude differences of nodes in the model can detect damage location.

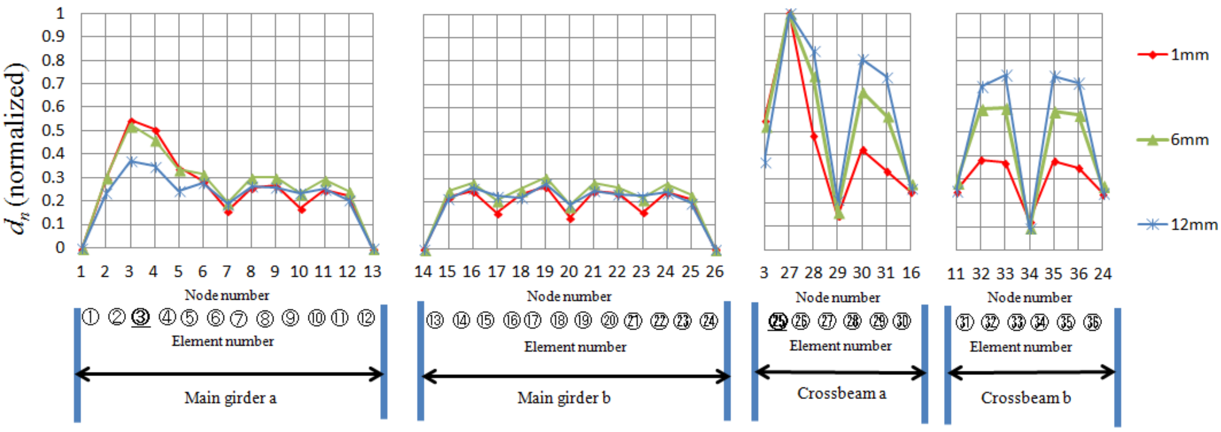


Figure 8: Damage index d_n in damage scenario C

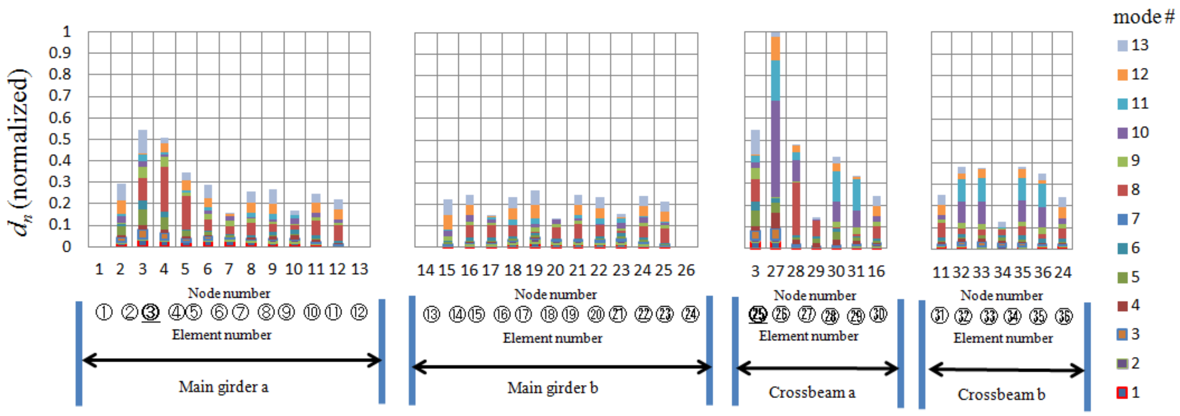


Figure 9: Damage index d_n and contribution ratio of each mode in C1

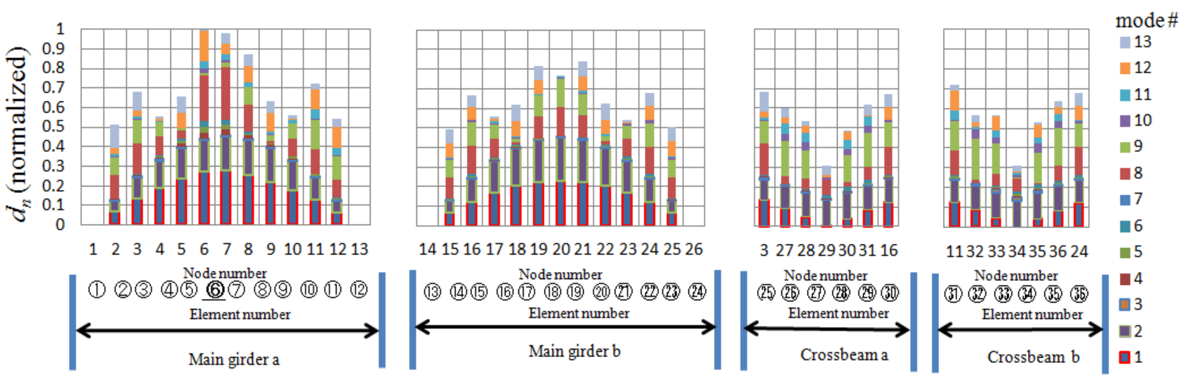


Figure 10: Damage index d_n and contribution ratio of each mode in A1

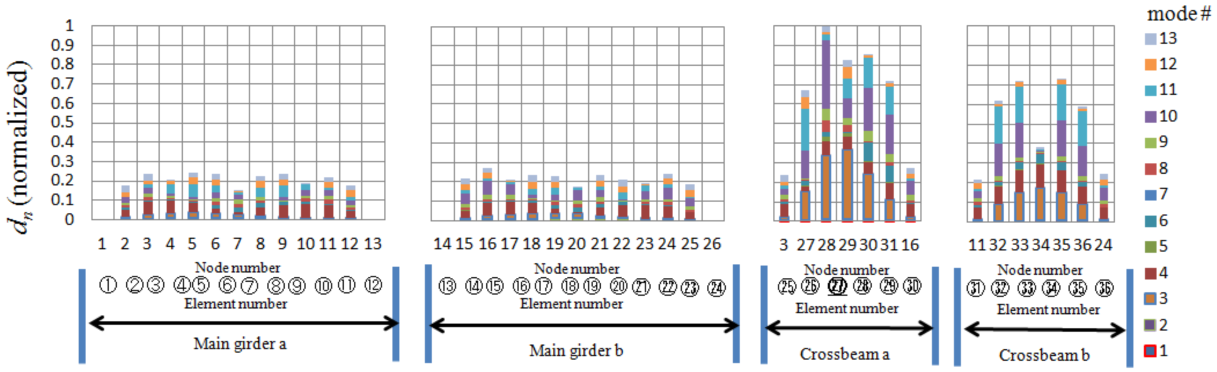


Figure 11: Damage index d_n and contribution ratio of each mode in B1

4. CONCLUSIONS AND FUTURE WORKS

This study discussed structural damage detection method by eigenvalue analysis using FEM. Damaged states show thickness reduction of main girder, crossbeam and joint. Damage index defined the accumulation of modal amplitude differences between undamaged state and damaged state at each node. As the result, the proposed method is able to locate damages. And smaller damage can be detected more accurately. Furthermore, influence of each mode in the damage index is discussed. Modal amplitudes differences are affected in plural modes which have a bulge near damaged point. Therefore, the damage index which accumulates modal amplitude of nodes in the model can detect damage location. As a future study, the effect will be detected actual structure.

5. ACKNOWLEDGMENTS

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