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Author(s)	CHUN, P.; AONO, A.; MORI, S. et al.
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A NUMERICAL STUDY OF EFFECTS OF BRIDGE DETERIORATION, AND CHANGES IN SUPPORTING CONDITIONS ON NATURAL FREQUENCIES

P. CHUN[1*], A. AONO[1], S. MORI[1], and M. OHGA[1]

[1] *Department of Civil and Environmental Engineering, Graduate School of Science and Engineering, Ehime University, Japan*

ABSTRACT

This manuscript proposes a method to detect damage in bridges from the changes in natural frequencies. This research topic has been the subject of considerable investigation over the past few decades, owing to the increasing number of ageing bridges. Many works in the literature on this topic show excellent damage detection results. However, these attempts have suffered from the difficulty that the effect of changes in supporting conditions, owing to ageing on the natural frequencies, is much larger than that of damage in bridge members, including beams. Thus, it is not easy to identify the damage by this procedure if the supporting conditions are changed. In order to eliminate the bottleneck, this research attempts to clarify how much the change in supporting conditions affects the natural frequencies of several modes, including pure bending mode and torsional mode. After eliminating the effect of supporting conditions, it is expected that damage in bridge members will be detected more clearly.

We applied this procedure to an actual concrete bridge Y, by assuming several damage scenarios, using the commercial finite element analysis package SAP2000. We measured the first natural frequency of bridge Y at several construction stages, and the results are employed to verify our finite element model. After confirming the validity, the degradation of concrete beams and changes in supporting conditions are given in the finite element model, to analyze the effect of them on the natural frequencies. After the finite element analysis and measurement, we can easily detect and identify abnormal changes occurring in bridges by inverse analysis. The developed method is expected to help bridge owners to understand the degree and location of damage in bridges, which in turn, will help them to develop appropriate maintenance strategies.

Keywords: Health monitoring, bridge engineering, natural frequency, damage detection.

* Corresponding author and presenter: Email: chun.pang-jo.mj@ehime-u.ac.jp

1. INTRODUCTION

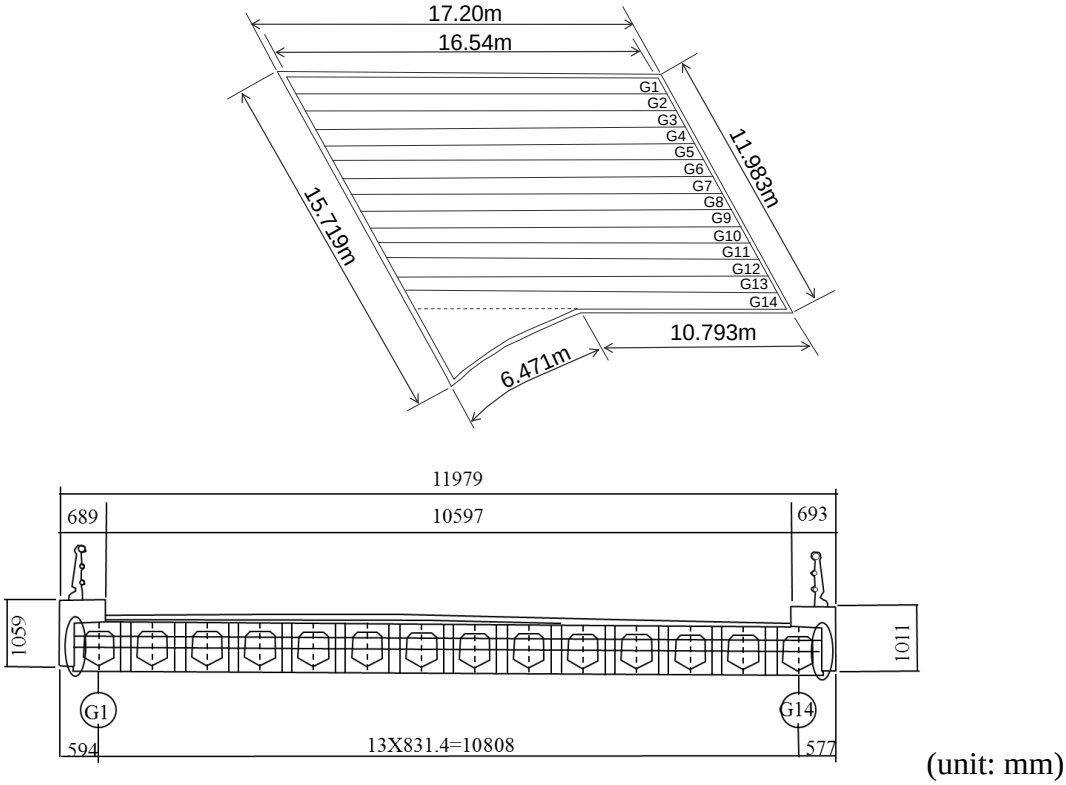
The deterioration of bridges as a result of ageing, and which can cause bridge disasters, is a serious problem. For example, roughly half the bridges in Japan will be 50 years old or more within 15 years (Fujino & Abe 2002). In addition, traffic growth of recent years has led to an increase in the applying load. Therefore, a suitable quantitative and objective damage identification method is required for appropriate bridge maintenance. Recently, for that purpose, there has been considerable interest in the method focusing on and monitoring the changes in natural frequencies, which are caused by bridge deterioration (Salawu 1997, Chang et al. 2003). Many works in the literature on this topic showed excellent damage detection results. However, these attempts have suffered from the difficulty that the effect of changes, in supporting conditions owing to ageing on the natural frequency, is much larger than that of damage in bridge members including beams. For instance, the changes in the supporting conditions can result in considerable changes in the first natural frequency, such as a 150% increase or more, though an appreciable extent of damage results in only small percentage increase. Thus, it is not easy to identify the damage in beams by this procedure if the supporting condition is changed. In order to eliminate the bottleneck, this research attempts to clarify how much the change in supporting conditions affects the natural frequencies of several modes, including pure bending mode and torsional mode. After eliminating the effect of supporting conditions, it is expected that damage in bridge members will be detected more clearly.

As an example of the application of the developed method, we applied this procedure to an actual prestressed concrete bridge in Japan (hereinafter referred to as “bridge Y”), assuming several damage scenarios using the commercial finite element analysis package SAP2000. It is shown numerically at the end of this manuscript that the developed method can successfully identify the degree and location of damage and changes in supporting conditions.

2. FINITE ELEMENT MODEL OF BRIDGE Y

2.1. Bridge Y

Since causing damage to a real bridge can be prohibitively expensive, analysis by finite element method (FEM) is conducted, to understand the behavior of damaged bridges after validation by using the measurement results of bridge Y. The dimensions of bridge Y are shown in Figure 1. In the measurement process, the first natural frequency has been measured under as-built condition, as well as under construction process.



(unit: mm)

Figure 1. Top view and cross-section of bridge Y

2.2. Finite element model

A three-dimensional finite element analysis of the bridge Y is performed here, using the commercial program SAP2000. The number of nodes and elements are 103,657 and 83,649, respectively. Figure 2 shows the isometric view of the FEM model of bridge Y, and Table 1 shows the material properties of concrete, steel, rubber, and asphalt used in the model. The material properties of concrete have been measured using compression tests of cylindrical specimens made simultaneously with bridge Y. On the other hand, for the material properties of other materials, we used the data shown in the literature, owing to the difficulty of testing them.

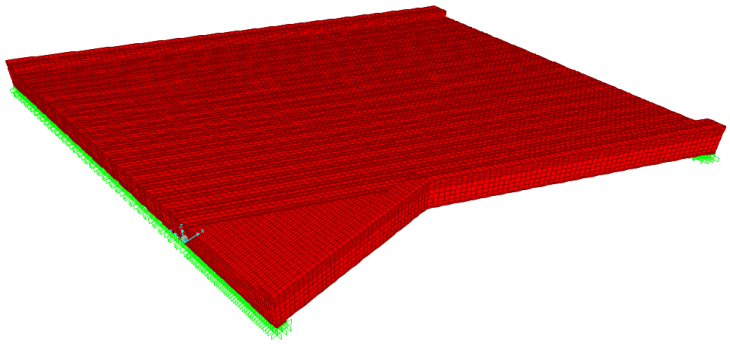


Figure 2. Finite element model of bridge Y

Table 1. Material properties used in the finite element model

Case	Young's modulus	Poisson's Ratio	Unit weight
Concrete	33GPa	0.167	23.56kN/m^3
Rubber	0.1GPa	0.4	76.97kN/m^3
Asphalt	8GPa	0.3	22.5kN/m^3

To demonstrate the validity of the FEM model, the first natural frequencies under the as-built condition, as well as under the construction process, are compared with measurement data. Note that in some construction processes, the material age of the concrete is less than 28 days. In these cases, the Young's modulus of concrete is corrected, as shown in Table 2, by using the following equation (Onodera and Seki 1972).

$$E_t = E_{28} \times \frac{8}{7 + 28/t} \tag{1}$$

where E_t is the Young's modulus of concrete of which material age is t days.

Table 2. Material age and Young's modulus of concrete of five construction stages

Construction stage	Bridge member	Material age (days)	Young's modulus
I	Beams	More than 28	33GPa
II	Beams	More than 28	33GPa
	Shear key	5	21GPa
III	Beams	More than 28	33GPa
	Shear key	14	29.3GPa
	Extended deck	6	22.6GPa
IV	Entire bridge	More than 28	33GPa
V	Entire bridge	More than 28	33GPa

Figure 3 shows the comparison results between FEM and the measurement results. The meaning of the Roman numerals for the construction stages in the figure is as follows: (I) only one individual beam; (II) after introducing shear key to connect beams; (III) after placing extended deck; (IV) after placing wheel guard; and (V) after the asphalt pavement. For stages (I) to (IV), the difference between FEM and measurement results is less than 2%. For stage (V), the measurement results range from 7.1Hz to 7.9Hz, since Young's modulus of asphalt pavement is sensitive to air temperature change, and the change in Young's modulus results in the change in the first natural frequency. Therefore, it is impossible to evaluate how much the FEM and measurement results are close to each other. However, it can be said from Figure 3, that our FEM results fall inside this range. From the comparison results, it is safe to say that our FEM model is well-verified, and the model is used for the further analysis in the next section.

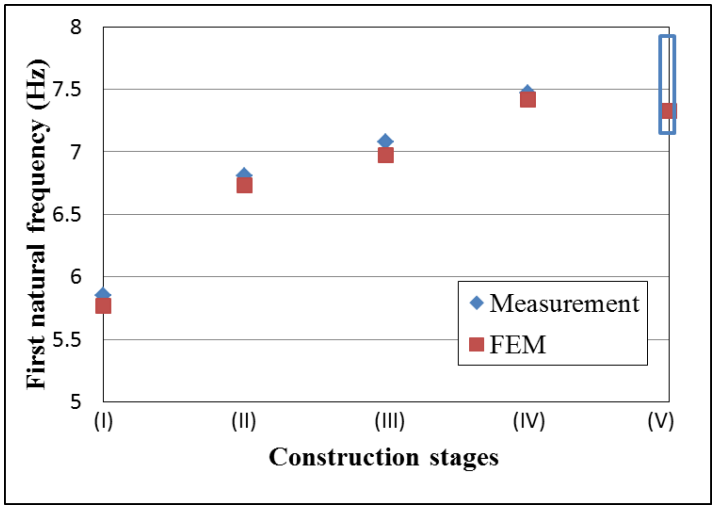


Figure 3. Comparison between measurement and FEM results of five construction stages

3. EFFECT OF LOCATION OF DAMAGE ON NATURAL FREQUENCIES

In this section, damage is introduced to the FEM model developed in the last section, to investigate the effect of location and degree of damage on natural frequencies. Damage is expressed in the FEM model as the Young's modulus degradation, with reference to the literature (Nechnech et al. 2002). For example, it has been reported that Young's modulus of concrete can be reduced by more than 50% by the alkali-aggregate reaction (Takashiba et al. 1998).

The location of damage affects the changing trend of natural frequencies. To illustrate this concept, the current section uses a simple example. Bridge Y is divided into 6 parts (see Figure 4), and natural frequencies of the following three cases are compared as follows: (1) nothing is damaged; (2) only parts 3 and 4 are damaged; and (3) only parts 2 and 5 are damaged. The damage is expressed by a 40% reduction in Young's modulus. Figure 5 shows the contour of mode shape of the first and second bending modes, and Table 3 shows the natural frequencies of these modes of the above three cases. As seen in the Table 3, the natural frequency of first bending mode is reduced more when parts 3 and 4 are damaged, while that of the second bending mode is reduced more when parts 2 and 5 are damaged. It is found from these results that if the damage and antinode of mode shape are located close to each other, the natural frequency of the corresponding mode is reduced remarkably. It means that the location of damage can be identified by using the changing trend of natural frequencies, as detailed in the next section

Table 3. Effect of damage location on the change trends of natural frequencies

	No damage	Part 3 and 4 are damaged	Part 2 and 5 are damaged
1st bending mode	7.33Hz	6.80Hz	7.11Hz
2nd bending mode	26.88Hz	26.01Hz	25.55Hz

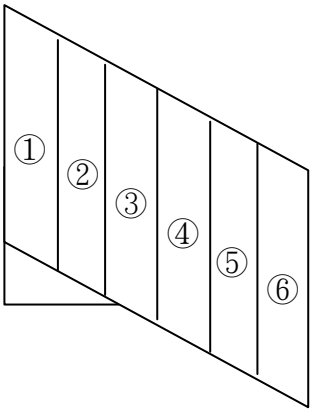


Figure 4. Division of bridge Y to six parts

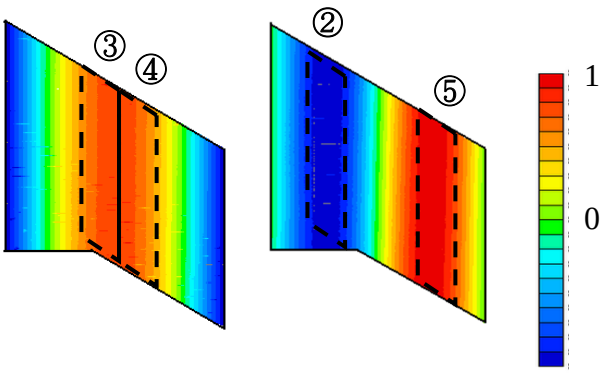


Figure 5. Contour plot of mode shape

4. DAMAGE IDENTIFICATION USING NATURAL FREQUENCIES

4.1. Damage identification when supported conditions are not changed

The following equation is suggested to identify the degree and location of damage from the changing trend of natural frequencies.

$$\sum_{j=1}^{m}\left\{\left(1-\prod_{i=1}^{n}a_i v_{ij}\right)-x_j\right\}^2 \longrightarrow \min \tag{2}$$

where j indicates the order of modes ($j = 1 \ldots m$), i indicates the location of damage ($i = 1 \ldots n$), v_{ij} is the decrease ratio of natural frequency of mode j , derived beforehand when location i is damaged by Young's modulus of 100% to that of 60%, x_j is the decrease ratio of natural frequency of mode j from as-built condition to current condition, a_i is the degree of damage at location i ($a_i = 1$ when Young's modulus is 60%), m is the number of natural frequencies which can be measured, and n is the number of parts divided beforehand to identify the damage location. In equation (2), unknown quantities are only a_i, and other quantities can be measured or calculated. This study solves the above minimization problem to derive a_i using the Nelder-Mead method (Nelder and Mead 1965).

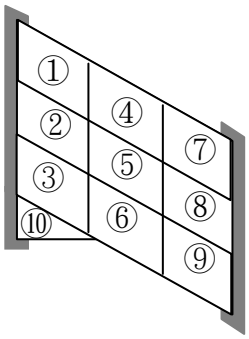


Figure 6. Division of bridge Y into 10 parts

To show the validity of the method, this section shows the example of the application using the FEM model of bridge Y. First of all, the FEM model is divided into 10 parts, as in Figure 6, and Young's modulus of parts 5 and 7 are reduced by 40% and 20%, respectively, to express the damage. Then, 24 natural frequencies of the damaged bridge model are derived, and compared to those of as-built bridge model. At last, these natural frequencies are substituted into equation (2), to derive a_i. Calculation results are shown in Table 4, which shows that the developed model can clearly identify the location and degree of bridge damage.

Table 4. Identification of damage location using equation (2)

Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10
96%	98%	97%	99%	61%	97%	81%	98%	96%	96%

4.2. Theory when supported conditions are changed

In the above section, the theory for identifying the damage degree and location is developed, and the validity of the theory is shown. However, the developed theory is based on the assumption that supporting conditions are not changed at all, although the deterioration of them can often be seen. Since the change in supporting conditions greatly affects the natural frequency, this section provides equation (3), in which the rotation capacity is also the unknown.

$$\sum_{j=1}^{m}\left\{\left(1-\prod_{i=1}^{n}a_i(1-v_{ij}(\log T))\right)-x_j\right\}^2 \longrightarrow \min \tag{3}$$

where T indicates the degradation of rotation capacity by increasing the Young's modulus by T times. This minimization problem is also solved by the Nelder-Mead method, and a_i and T are derived.

To show the validity of the method, we solved a similar example problem in section 4.1. The location and degree of damage are the same, but in addition to this damage, the Young's modulus of rubber bearing is increased 100 times. Then, 24 natural frequencies of the damaged bridge model are derived and compared to those of the as-built bridge model. By substituting known values into equation (3), a_i and T are derived (see Table 5). As shown in the results, the developed equation clearly evaluates the location and degree of damage, and changes in the supporting conditions.

Table 5. Identification of damage location and changes in the supporting conditions using equation (3)

Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7	Part 8	Part 9	Part 10	T
98%	99%	96%	100%	61%	97%	81%	95%	98%	97%	97

5. CONCLUSIONS

We developed the method to predict the location and degree of damage, and changes in supporting conditions, and the validity is confirmed using the FEM model of an actual prestressed concrete

bridge. The developed method is expected to help bridge owners to understand the degree and location of damage in bridges, which in turn, will help them to develop appropriate maintenance strategies.

For further work, it is necessary to apply the method to a real structure. The details of this will be reported in our next paper.

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