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ESTIMATION METHOD OF DEGRADATION STATE FOR TIMBER BRIDGES USING VIBRATION ANALYSIS

Daisuke Oikawa[1], Shuya Nemoto[2], Humihiko Gotou[3], Yukari Aoki[4]

ABSTRACT: In this study, a new degradation diagnosis method is developed by vibration analysis. The natural frequency of aging timber bridge is normally decreased due to decay and degradation partially and entirely. In Japan, one of the timber bridges has been in service more than 35 years and its natural frequency is about 8.7Hz. In this study, a numerical bridge model is designed by FEM software considering the decay parts which are end supports and connections between spandrel column and arch rib. When the bridge members are healthy, the Young's modulus is 9.6GPa and the natural frequency is about 12.7Hz. In order to adjust calculated value to the measured value 8.7Hz, the Young's modulus of the bridge model has to be decreased to 4.49 GPa, which is significantly low. Furthermore, we calculated frequencies for each mode parametrically varying the decay parts to find the most affected parts to decrease the natural frequency of the bridge. According to this analysis, the connection between spandrel column and arch rib is the most affected.

KEYWORDS: Glulam timber bridges, Natural frequency, Elastic modulus, Decay, Degradation diagnosis method

1 INTRODUCTION

While degradation diagnosis for timber bridges is important, it is not possible to measure the strength and stiffness by extracting partial members from an existing bridge. In that sense vibration analysis, which makes it possible to measure the natural frequency of an entire bridge by non-destructive test method, is useful. In the real bridges, especially aging ones, decay and degradation would be found at every part especially end support and connection. Thus, when the vibration analysis is adopted as degradation diagnosis, the local decay and degradation should be considered. Unfortunately, a current used vibration method in the literatures[1], [1], [1] can not take into account the local decay.

In this study, we at first evaluate typical modal analysis model using beam/shell element and more exact model using tetrahedral element. Then we adopt the better model to find the effect of the local decay and degradation for the bridges.

3D numerical bridge model (Kajika Bridge in Japan) is created for includes the localized decay and degradation by decreasing Young's modulus. To validate this numerical model, we used for which the natural frequencies obtained by the numerical analysis and by the vibration test are compared.

By this method, we can determine whether natural frequency of the bridge model would decrease or not, that is, how the local decay would affect to the stiffness and strength of the entire bridge. By this method, we can determine whether natural frequency of the bridge model would decrease or not, that is, how the local decay would affect to the stiffness and strength of the entire bridge.

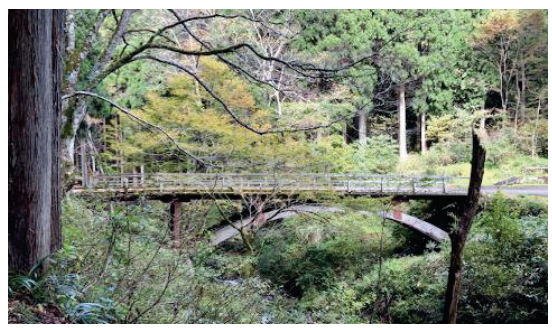

***Figure 1:** Kajika Bridge in Ishikawa prefecture1*

***Figure 2:** Kajika Bridge in Ishikawa prefecture2*

[1] Daisuke Oikawa, Akita University, Graduate School of Engineering Science, Japan, d.oikawa1987@gmail.com
[2] Shuya Nemoto, Akita University, Faculty of Engineering Science, Japan,
[3] Humihiko Gotou, Akita University, Graduate School of Engineering Science, Japan, gotou@gipc.akita-u.ac.jp
[4] Yukari Aoki, Akita University, Graduate School of Engineering Science, Japan, yaoki@gipc.akita-u.ac.jp

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2 MODEL SETTING

In this study, measured data for the existing bridge 'Kajika Bridge' in Ishikawa prefecture in Japan, is used. This bridge shown in Figure.1, 2 is a two-hinged deck arch bridge built in 1987. This bridge has been used as roadway bridge for 35 years till now. In 2019, measurements such as investigations of natural frequencies and of degradation area for the bridge were carried out [1]. Here we numerically simulate the measured condition of the bridge by vibration analysis using FEM tool Salome-Meca[1].

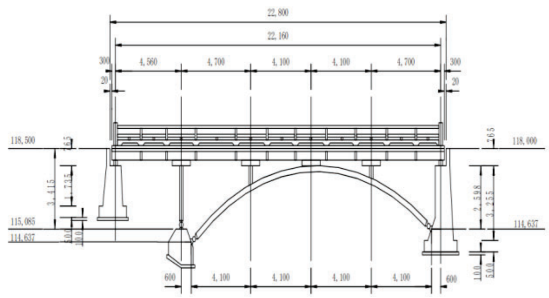

Figure 3: General drawing of Kajika Bridg

Table 1: *Properties of Kajika Bridge*

Location	Ishikawa pref, Japan
Type	Deck arch bridge
Total length	22.8m
Span	16.4m
Traveled way width	3.0m
Design load	Roadway 6tf
Completion	1987-12
Material	Glulam of Hiba (Thujopsis)

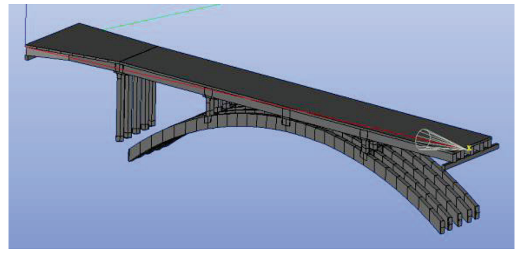

Figure 4: *Numerical Model for Kajika Bridg*e

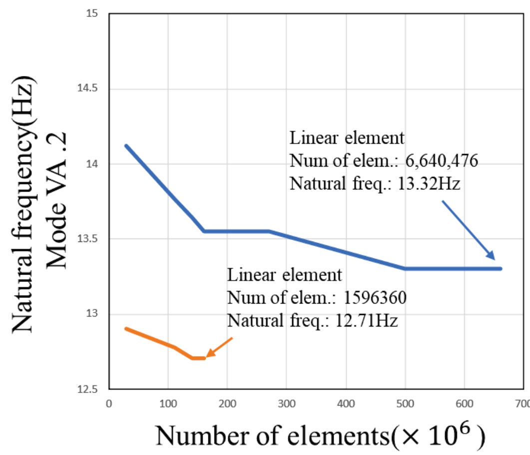

Figure 5: Convergency of tetrahedral element

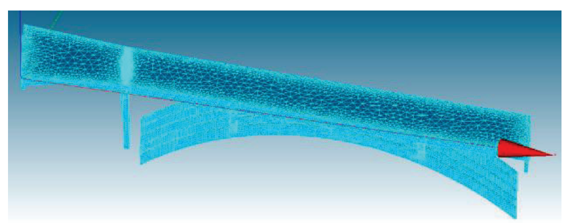

Figure 6: *Mesh of tetrahedral element*

3 COMPARISON OF TWO MODELS

In modal analysis for bridges such as truss, arch and so on, which consist of slender members, beam element is generally used, while solid element such as tetrahedral element is not often used because of large calculation load. In this section we compare typical modal analysis model using beam/shell element and more exact model using tetrahedral element for Kajika Bridge.

3.1 CONVERGENCY OF TETRAHEDRAL ELEMENT

Here we investigate convergency of tetrahedral element. In the case of linear element, it needs 6,640,476 elements for natural frequency to be converged to two significant digit, while in the case of quadratic element, it needs 1,596,360 to be converged to two significant digit. Figure. 5 shows convergency for the vibration mode of vertically antisymmetric two sin half-waves, which is the most dominant mode for Kajika Bridge.

According to this result, quadratic element, which can obtain high accuracy with less number of elements, is adopted for the analysis hereafter.

3.2 COMPARISON TO MEASURED VALUE UNDER FITED YOUNG'S MODULUS

Natural frequencies measured in 2004, which is the first year of measurement since the beginning of service in 1987 for Kajika Bridge are shown in Table 2 for the following four dominant modes: H.S.1 is horizontally symmetric one sin half-wave shown in Figure. 6; V.A.2 is vertically antisymmetric two sin half-waves shown in Figure7; V.S.1 is vertically symmetric one sin half-wave shown in Figure.8 and V.S.4 is vertically symmetric four sin half-waves shown in Figure.9

We try to compare accuracy of the tetrahedral element model with beam/shell element model. Beam/shell element mode means the model in which the deck part is modeled by shell element, while the other parts such as arch, longitudinal beam and spandrel column are modeled by beam element shown in Figure 10. Each Young's

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modulus of the tetrahedral element model and of the beam/shell element model is fitted to each appropriate value so that the natural frequency for the dominant vibration mode V.A.2 can coincide with the measured value 11.62Hz. Natural frequencies for the other three modes are calculated for the two models as shown in Table. 2. The relative errors for H.S.1 and V.S.1 of the tetrahedral element mode are smaller than those of the beam/shell element model. Although relative error for V.S.4 of the tetrahedral element mode are larger than that of the beam/shell element model. we think that this

Table 2: *Comparison of analysis accuracy*

Vibration mode	Natural frequency Measurement value (2004)	tetrahedral element	beam/shell element
H.S.1	11.62 Hz	4.95 Hz (-4.3%)	4.57 Hz (-13.2%)
V.A.2	5.17 Hz	11.62 Hz (0%)	11.62 Hz (0%)
V.S.1	15.82Hz	15.20 Hz (-3.9%)	14.00 Hz (-11.5%)
V.S.4	19.14Hz	20.77 Hz (8.5%)	18.00 Hz (-5.5%)

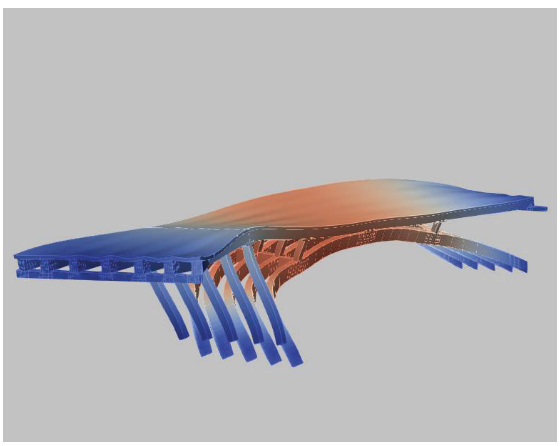

Figure 6: *Horizontally symmetric 1 sin half-wave (H.S.)*

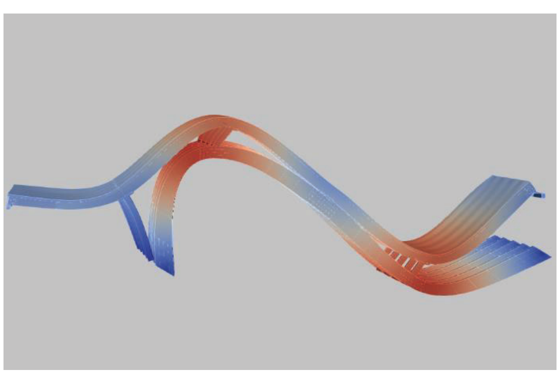

Figure 7: Vertically antisymmetric 2 sin half-waves (V.A.)

because of loss of measurement accuracy in higher mode vibration. According to the above, the tetrahedral element model is more suitable for modal analysis and this model will be used for all analyses hereafter. Incidentally materials for deck parts are orthotropic, while material for arch parts and so other parts is isotropic, since it is difficult to set appropriate othotropic condition corresponding to each local coordinate along the arch rib. Handrails with less influence to structure is not modeled.

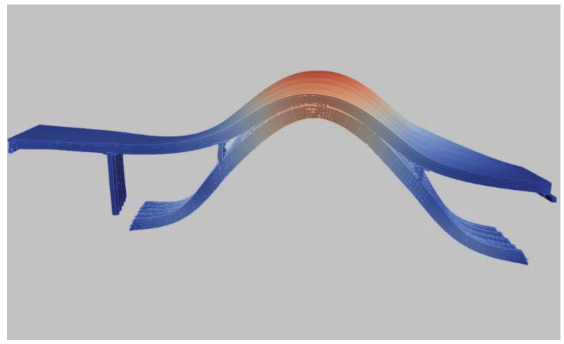

Figure 8: *Vertically symmetric 1 sin half-wave (V.S.)*

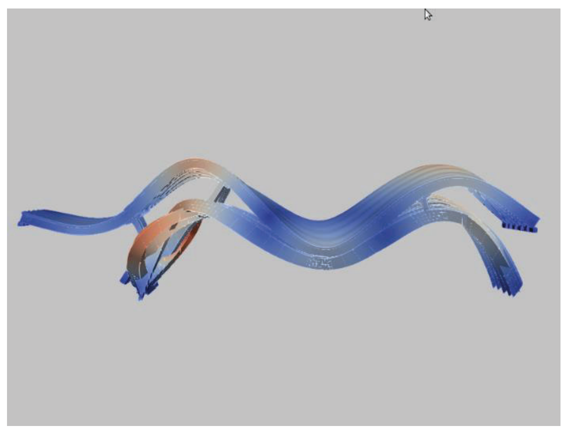

Figure 9: *Vertically symmetric four sin half-waves (V.S.4)*

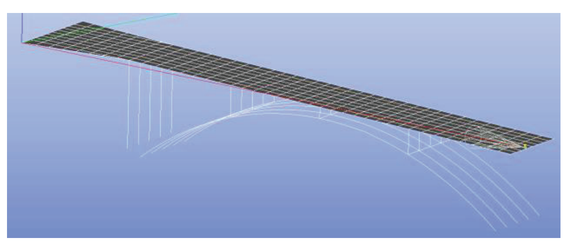

Figure 10: *Beam/shell element model*

Table 3 Natural frequencies for measured value and calculated value, also estimated Young's modulus

	1987 years	2004 year		2012 year		2015 year		2017 year		2019 year	
	Analysis value	Measured value	Analysis value	Measured value	Analysis value	Measured value	Analysis value	Measured value	Analysis value	Measured value	Analysis value
V.A.2	12.71	11.62	11.62	9.47	9.47	9.46	9.46	8.79	8.79	8.69	8.69
H.S.1	9.34	5.17	8.56	3.12	6.98	2.92	6.98	2.81	6.46	2.73	6.39
V.S.1	20.02	15.82	19.25	15.82	15.68	15.51	15.67	15.43	13.85	15.38	13.69
V.S.4	29.79	19.14	27.67	18.95	22.54	18.04	22.52	17.68	20.63	17.18	20.39
Estimated Young's modulus											
Deck parts (GPa)		8.60		5.71		5.70		4.92		4.81	
Other parts (GPa)		8.03		5.33		5.32		4.59		4.49	
Decreasing rate (%)		16.44		44.52		44.63		52.17		53.23	

4 YOUNG'S MODULUS FITTING TO MEASURED VALUE

The natural frequencies of the four modes for Kajika Bridge measured five times during fifteen years are shown in Table.4. The natural frequency for V.A.2, which is 11.62Hz in 2004, decreases to 8.69Hz in 2019. When we adjust Young's modulus in the tetrahedral element model so that the natural frequency for V.A.2 can be fitted to the value 8.69Hz, the Young's modulus for members of deck part becomes 4.81GPa and that for members of the other parts becomes 4.49GPa. If we assume that Young's modulus for all members decreases uniformly, it follows that Young's modulus for members of Kajika Bridge decreases by 53.23%, drastically. Young's moduluses adjusted in the same fitting manner for the measured values are also shown in Table 3. Figure 11 shows decreasing of the adjusted Young's moduluses for the measurement years. Young's moduluses decrease sharply from 2004 to 2012 and from 2015 to 2017, while Young's modulus decrease gradually in the other periods.

However from the realistic view point, the situation that the Young's moduluses for all members decrease uniformly by 53.23% is unlikely to happen, whether they sharply decrease or gradually decrease depending on periods during fifteen years. We guess that the decrease of the natural frequency is significantly influenced by partial decay of members. In fact the typical examples of partial decay are recognized at easily decayable parts such as ends of arch rib, connection between members and so on, which are shown in Figures 11, 12, 13 and 14. On the other hand, it seems that most of parts except for the decayable parts are not decayed so much by visual inspection.

Therefor we try a new approach fitting natural frequency by adjusting Young's modulus of partially set decay parts instead of adjusting Young's modulus of all members in the following section.

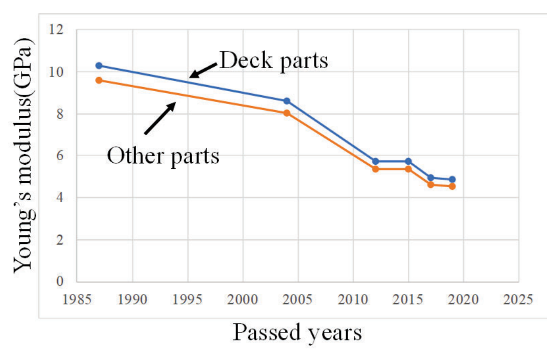

Figure 11: *Reduction in Young's modulus by passing age*

Figure 12: *Decay at the end of arch rib*

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Figure 13: Decay of connection between longitudinal beam and sleeper berm

Figure 14: Decay of connection between spandrel column and arch rib

5 EVALUATION OF DECAY EFFECT

Here we numerically simulate the measured condition of the bridge by vibration analysis using FEM tool Salome-Meca considering decayed areas such as connection between longitudinal beam and sleeper beam, connection between spandrel column and arch rib, and end supports corresponding to the measurement. The numerical model with decayed areas is shown in Fig.15, 16.

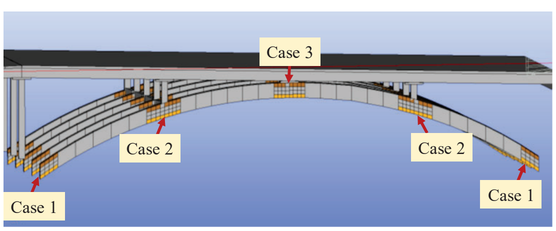

Figure 15: Bridge model with decayed areas

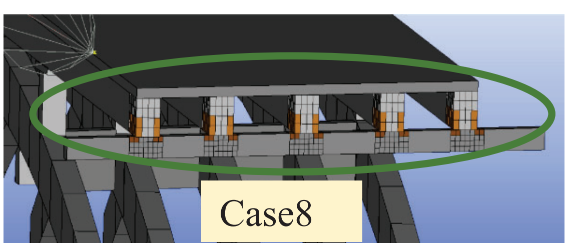

Figure 16: Bridge model with decayed areas(sleeper beam)

6 NUMERICAL ANALYSIS METHOD

In this study, the FEM model for the bridge is meshed by tetrahedral solid elements and the ends of each arch rib are hinged at the middle line of the section. The following two types of analyses are carried out.

6.1 COMPARISON BETWEEN MEASURED DATA AND NUMERICALLY DERIVED DATA

According to the measurement in 2019, the dominant natural frequency of Kajika bridge is 8.69Hz. In the numerical estimation, we firstly assume the model with only healthy areas whose Young's modulus is 9.6GPa (without decay), secondly we set the decayed areas whose Yong's modulus is 96MPa (Reduction 0%) and thirdly we gradually reduce the Young's modulus for the healthy areas (from 10% to 50%) with the same Young's modulus 96MPa for the decayed areas, until the natural frequency of the model would be enough close to the measured value.

6.2 EFFECT ESTIMATION FOR LOCAL DECAY PARTS

The case study has been conducted to identify the most significant part affecting the natural frequencies. The following cases shown in Table 4 are considered. It should be noted that the decay part for analysis 6.1 includes all cases, that is, the combination of Case 7 and Case 8.

Table 4: Cases considering decay parts

	Decay parts
Case 1	End supports
Case 2	Connection between spandrel column and arch rib
Case 3	Connection between deck and arch rib at center
Case 4	Combination of Case 1 and Case 2
Case 5	Combination of Case 1 and Case 3
Case 6	Combination of Case 2 and Case 3
Case 7	Combination of Case 1, Case 2 and Case 3
Case 8	Connection between longitudinal and sleeper beams

7 RESULTS AND DISCUSSION

The results of the analysis 6.1 are shown in Table 5. The dominant vibration mode of the arch bridge has vertically in-plane two sine half-waves as shown in Figure 3. While the measured natural frequency for Kajika bridge is 8.69Hz, that of numerical model with the decay parts and the healthy parts whose Young's modulus remains 9.6GPa (Reduction 0%) is 11.79Hz, which is about twice as large as the measured value. When Young's modulus of healthy parts is reduced by 40%, the calculated natural frequency is close to the measured value. And when the Young's modulus is reduced by 45.59%, the calculated natural frequency almost coincides with the measured value. At this time, the Young's modulus of this bridge is 5.22GPa which is less than half of the model without decay. This estimation is smaller than expected and not realistic.

The results of the analysis 6.2 are shown in Table 6. According to the results, Case 2, 4, 6, and 7 shows the lower frequencies. The decay parts in these cases includes connection between spandrel column and arch rib. Therefore, the connection has significant influence on natural frequencies.

Table 5: *Young's modulus estimation*

	Mode V.A. (Hz)	Young's modulus estimation (GPa)
Measured value	8.69	
Without decay	12.71	9.60
Reduction 0%	11.79	9.60
Reduction10%	11.19	8.64
Reduction20%	10.55	7.68
Reduction30%	9.87	6.72
Reduction40%	9.13	5.76
Reduction50%	8.34	4.80
Reduction45.59%	8.69	5.22

Table 6: *Effect of decay parts*

	Frequency (Hz)	Relative error
Without decay	12.71	0.00%
Case1	12.68	0.20%
Case2	11.97	5.79%
Case3	12.53	1.41%
Case4	11.95	5.95%
Case5	12.50	1.64%
Case6	11.87	6.57%
Case7	11.85	6.73%
Case8	12.67	0.31%

8 CONCLUDING REMARKS

In this study, we carried out vibration analysis to estimate the proper Young's modulus and the most significant decay part affected to decreasing of the natural frequency for the bridge model with the considered local decay, comparing calculated values to the measured value. Basing on the results of the study, the following conclusions are made:

1) According to numerical comparison between tetrahedral element model and beam/shell element model, it is found that tetrahedral element mode gives more fitted natural frequencies for each dominant vibration mode than beam/shell element model.
2) As a result of simplified analysis, in which Young's moduluses for all members decrease uniformly, the adjusted value of Young's modulus becomes 53.23% to the original, while it is unlikely to happen.
3) In order to adjust the calculated natural frequency to the measured value, the Young's modulus of the healthy parts of the bridge has to be 5.22GPa, which is significantly low and still not realistic.
4) The decay at connection between spandrel column and arch rib has significant influence on natural frequencies of the bridge.

It is difficult to estimate which is more significant, reduction of Young's modulus for healthy parts or influence of decay parts. In the further study, the decay parts should be more parametrically studied considering conditions such as size, position, level of decay and so on.

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