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Sensitivity analysis of mechanical behaviors for bridge damage assessment

Ayaho Miyamoto* and Satoshi Isoda[a]

Graduate School of Science & Engineering, Yamaguchi University, Ube, Japan

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Abstract. The diagnosis of bridge serviceability is carried out by a combination of in-situ visual inspection, static and dynamic loading tests and analyses. Structural health monitoring (SHM) using information technology and sensors is increasingly being used for providing a better estimate of structural performance characteristics rather than above traditional methods. Because the mechanical behavior of bridges with various kinds of damage can not be made clear, it is very difficult to estimate both the damage mode and degree of damage of existing bridges. In this paper, the sensitivity of both static and dynamic behaviors of bridges are studied as a measure of damage assessment through experiments on model bridges induced with some specified artificial damages. And, a method of damage assessment of bridges based on those behaviors is discussed in detail. Finally, based on the results, a possible application for structural health monitoring systems for existing bridges is also discussed.

Keywords: bridge; damage assessment; diagnosis; sensitivity analysis; static behavior; dynamic behavior

1. Introduction

The aim of this study is to establish a method for quantitative assessment of damage to the superstructure of an existing bridge. The influence of different degrees of damage on mechanical behavior is investigated through model calculation and bridge model experiments. On the basis of these results, the usability of mechanical behaviors in damage assessment (e.g., degree of damage, degree of accuracy) is evaluated. Since, however, the structural condition of in-service bridges and their damage vary widely, it is impossible to examine all combinations of such parameters. The bridge model used in this study, therefore, is a simply supported girder bridge model with three main girders, which is the minimum number of girders needed to obtain necessary information such as load distribution characteristics in the direction perpendicular to the bridge axis. The decrease in flexural stiffness was mainly considered because it is an effect capable of modeling many types of damage in an idealized way. The settlement and rotational restraint of bearings were also considered as damage effects that occur frequently (Urban Expressway Research Group 2004, Yanev 2007) in real bridges (e.g., cross section deficiency due to the corrosion in a steel bridge, looseness of joints, stiffness reduction due to cracks in concrete bridges, the deterioration of the concrete, etc) and

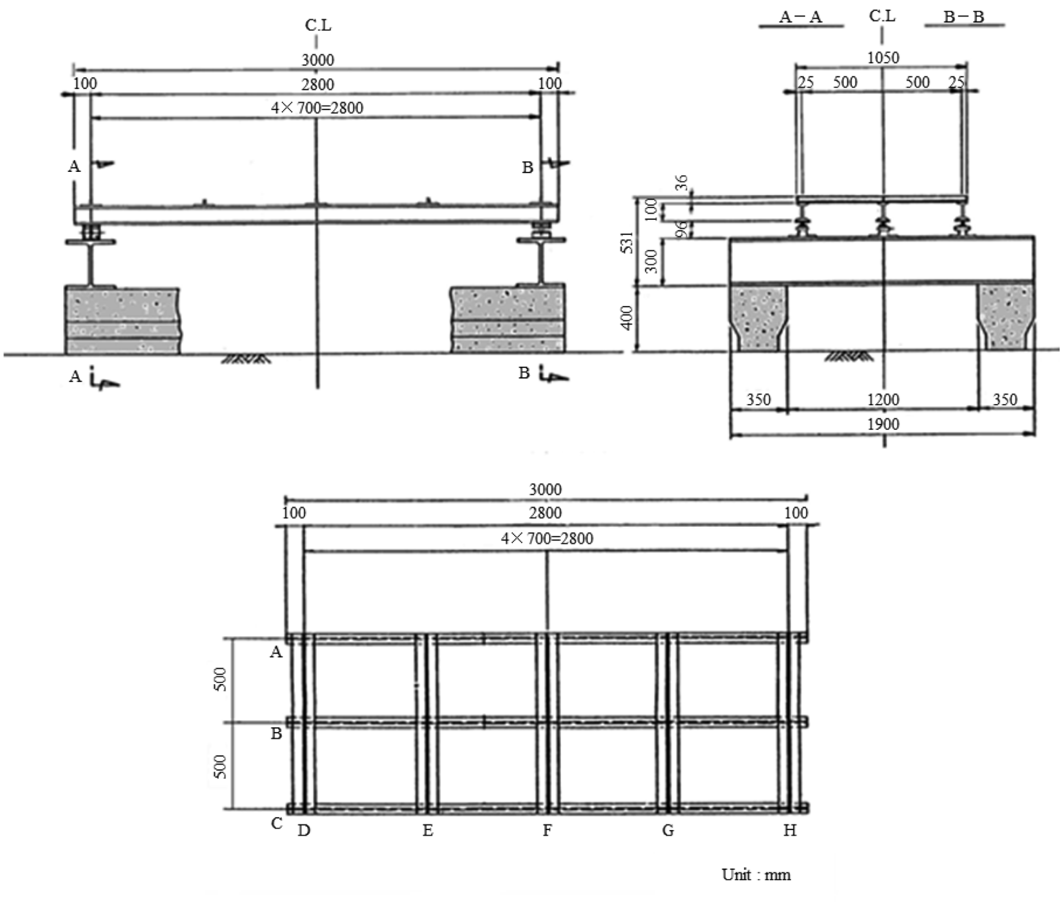
*Corresponding author, Professor, E-mail: miya818@yamaguchi-u.ac.jp
[a]Master Student

greatly influence the mechanical behavior of bridges.

2. Bridge model test and analysis

2.1 Bridge model

Fig. 1 shows side-, top- and cross-section views of the bridge model prepared for the purposes of this study. The bridge model has no floor slab so that the number of factors affecting mechanical behavior can be minimized by simplifying the structural model and only the influence of decreases in the girders and crossbeams is reflected in mechanical behavior. In order to make the natural frequency of the bridge model reflect the typical natural frequency (below about 10 Hz) of a real bridge, the smallest commercially available H-beams (H-100 × 50 × 5 × 7.5 mm (SS400)) were used as girders. A total of six girders damaged to decrease girder stiffness, were prepared. As shown in Table 1(a), the state of girder damage was varied by reducing stiffness (moment of inertia) by about

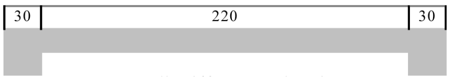
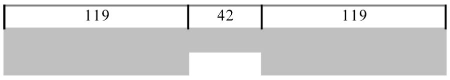


(Girders and crossbeams are connected by M87T(standard bolts))

Fig. 1 Details of the bridge model

Table 1 Specification of main girders and crossbeams

(a) MAIN GIRDER

No.	Damage location (cm)	Correspondence damage in real bridge	Ratio to stiffness of No.1
1	No damage	-	1.00
2		Main Girder Corrosion composite girder shear connector damage, RC girder cracking	0.79
3	Overall stiffness reduction		0.60
4		Girder damage such as local corrosion, joint damage, etc	0.79
5	Local (*L*/2) stiffness reduction		0.60
6		Girder damage such as local corrosion joint damage, etc	0.79
7	Local (*L*/4) stiffness reduction		0.60

(b) CROSSBEAM

No.	Description	Ratio to stiffness of main girder
1	Corresponding to a load distribution crossbeam of a real bridge	0.14
2	Corresponding to sway bracing of a real bridge	0.066
3	Near-zero stiffness	2.8×10^{-4}

20% and 40% over the entire girder length and around the *L*/2 (midspan) and *L*/4 (quarter-span) points. These girders were replaced with undamaged (sound) girders and girders with varying conditions of damage. The main reasons why these percentages of stiffness reduction were used are as follows: (1) the model calculation results described later in this paper and the results of simple beam experiments (Nishimura *et al.* 1987, Sohn 2008) show that mechanical behavior begins to change at a percentage of reduction of about 20%; (2) stiffness reductions of 20% to 30% have been actually observed in some existing bridges (Maekawa *et al.* 1997, Nishimura *et al.* 1985, Japanese Society of Steel Construction 1972), (3) stiffness may decrease by 50% or more if the function of shear connectors is completely lost; and (4) by giving two levels of damage, the degree of change in mechanical behavior can be identified.

Stiffness reduction was induced by reducing lower flange width. Since, however, it is thought likely that in many cases the mass of a real bridge remains unchanged even if its stiffness has decreased because of damage, the mass of the girder as a whole was kept constant by bonding pieces of steel to the reduced lower flange so that stiffness would not be affected by the decrease in

Table 2 Combinations in the experiments

Series No.	Exp. No.	Main girder			Crossbeam				
		A	B	C	D	E	F	G	H
1	1	1	1	1	2		1		2
	2	1	2	1	2		1		2
	3	1	3	1	2		1		2
	4	1	5	1	2		1		2
	5	1	7	1	2		1		2
	6	1	1	2	2		1		2
	7	1	1	3	2		1		2
	8	1	1	4	2		1		2
	9	1	1	5	2		1		2
	10	1	1	6	2		1		2
	11	1	1	7	2		1		2
	12	2	1	2	2		1		2
	13	2	2	2	2		1		2
	14	2	1	3	2		1		2
	15	2	3	2	2		1		2
2	1	1	1	1	2		2		2
	3	1	3	1	2		2		2
	4	1	5	1	2		2		2
	5	1	7	1	2		2		2
	7	1	1	3	2		2		2
	9	1	1	5	2		2		2
	11	1	1	7	2		2		2
	14	3	1	3	2		2		2
	16	3	3	3	2		2		2
3	17	1	1	1	2	2	2	2	2
	18	1	1	1	2	3	2	3	2
	19	1	1	1	3	3	2	3	3
	20	1	1	1	3	3	3	3	3
	21	1	1	1	1		1		1
	22	1	1	1	2		1		2
	23	1	1	1	2		2		2
4	A	1	1	1	2		1		2
	B	1	1	1	2		1		2

Note : · For the girder symbols shown in the table, see Fig. 1.
· The numbers shown in the table indicate the girder numbers (see Table 1).
· A blank space means the absence of a crossbeam.

mass. The stiffness of crossbeams was determined so that the ratio of crossbeam stiffness to girder stiffness became close to that of a real bridge. For this purpose, T-beams were used to model load distribution crossbeams and sway bracing as shown in Table 1(b). In addition to these two types of beams, beams mimicking load distribution crossbeams with reduced stiffness were also prepared. Thus, three types of crossbeams were prepared.

As the first step, the seven types of girders including undamaged (sound) girders were subjected to static and dynamic tests to make sure, by examining the displacements, strains and natural frequencies thus obtained, that each girder had the required stiffness. Then, the seven types of girders and the three types of beans were tested in 34 cases as shown in Table 2 (including the case where all girders are undamaged (sound) (No. 1)). These 34 cases are divided into four series:

(1) Series 1 (15 cases): The crossbeams were not changed, and the effect of girder stiffness reduction on overall mechanical behavior was investigated. The reason why crossbeams were not installed at *E* and *G* (see Fig. 1) was to minimize the number of factors affecting mechanical behavior. In the series described below crossbeams were also omitted except in cases where they were necessary.

(2) Series 2 (9 cases): Representative cases of girder combinations were chosen from Series 1, and the midspan crossbeam (*F* in Fig. 1) in those cases was replaced with a crossbeam (sway bracing model) with half the stiffness of an undamaged (sound) crossbeam. This means that the effect of changes in crossbeam stiffness on mechanical behavior due to girder stiffness reduction was investigated by comparison with the Series 1 results.

(3) Series 3 (7 cases): Unlike in the Series 1 and Series 2 cases, the girders were kept in an undamaged (sound) condition and only crossbeam combinations were varied to investigate the effect of stiffness reduction in the transverse direction (direction perpendicular to the bridge axis) on mechanical behavior.

(4) Series 4 (2 cases): The girders and crossbeams (No. 1 in Table 1(b)) were kept in an undamaged (sound) condition as in the Series 1 cases, and a support roller for an external girder or an internal girder was removed to create a free-end condition and investigate the effect of support subsidence.

2.2 Experiment method

Figs. 2(a) and (b) illustrate the dynamic and static tests respectively. In the static tests, loads were applied at the two indicated points, and strain and deflection were measured. Strain was measured at the underside of the lower flange at the locations shown in Fig. 2(b). The amount of load applied was 1.96 kN, which was chosen so that the deflection-to-span ratio became close to that of a three-girder bridge when a load of 196 kN is applied. In the dynamic tests, in order to use modal analysis (Hewlett 1978, Ewins 1984), accelerometers were installed at the 11 locations shown in Fig. 2(a) and single impacts were applied to flour points. To enhance the accuracy of the transfer function, impacts were applied 20 times at each point. The transfer function used in the modal analysis was derived as the weighted average of the responses to the 20 impacts mentioned above.

2.3 Model calculation

Concurrently with the model experiments, calculated changes in mechanical behavior were examined to evaluate the degree of agreement with the experiment results and consider the accuracy

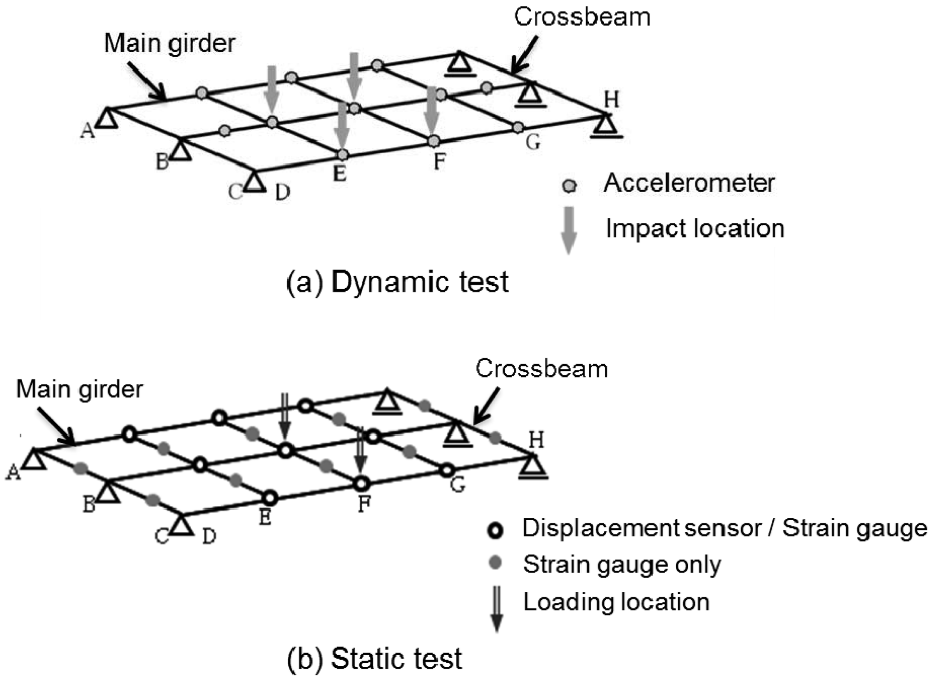


Fig. 2 Details of dynamic and static tests

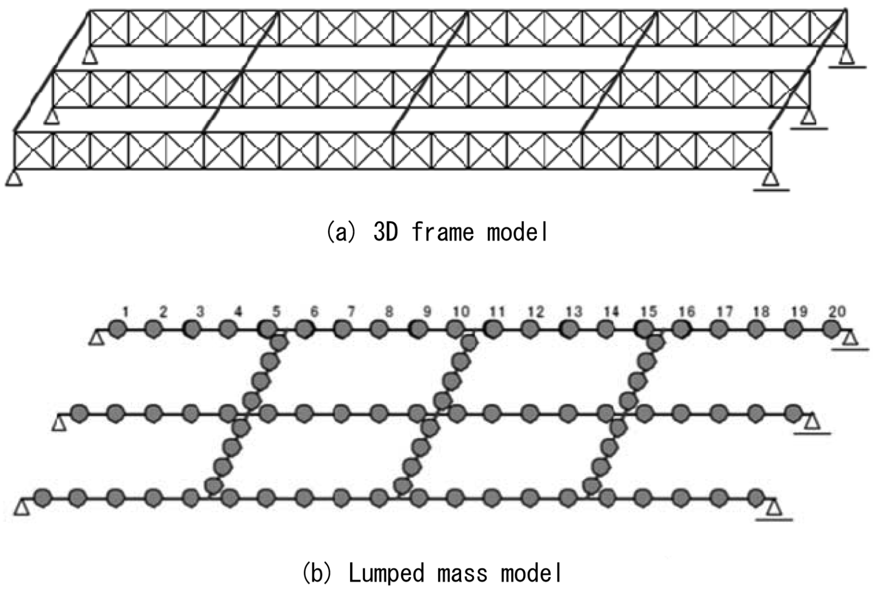


Fig. 3 Analytical models

of analysis models to be applied to real bridges. Also, the effect of stiffness reduction in the ranges not covered by the experiments and the effect of rotational restraint at the supports were calculated. The models used are briefly explained below.

The static analysis model used is the 3D frame model shown in Fig. 3(a). This model was used because it has been reported (Heins *et al.* 1982, Ostachowicz *et al.* 2009) that when investigating the load distribution functions of girders and crossbeams whose stiffness has been locally reduced, higher accuracy can be achieved by using such a 3D model. The dynamic model used is a lumped mass model defined as a grillage girder with torsional stiffness consisting of twenty girder point masses and eight crossbeam point masses as shown in Fig. 3(b), and natural frequency and vibration modes were determined by the transfer matrix method.

3. Model calculation and experiment results

3.1 Static displacement and strain

Figs. 4(a) and (b) show the analytical results and experimental results for displacement and strain distributions in the Series 1 cases where the stiffness of an external girder has decreased (by 40% reduced). Comparison reveals that the analytical results and the experimental results agree closely in terms of strain, clearly showing the influence of local stiffness reduction. In terms of displacement,

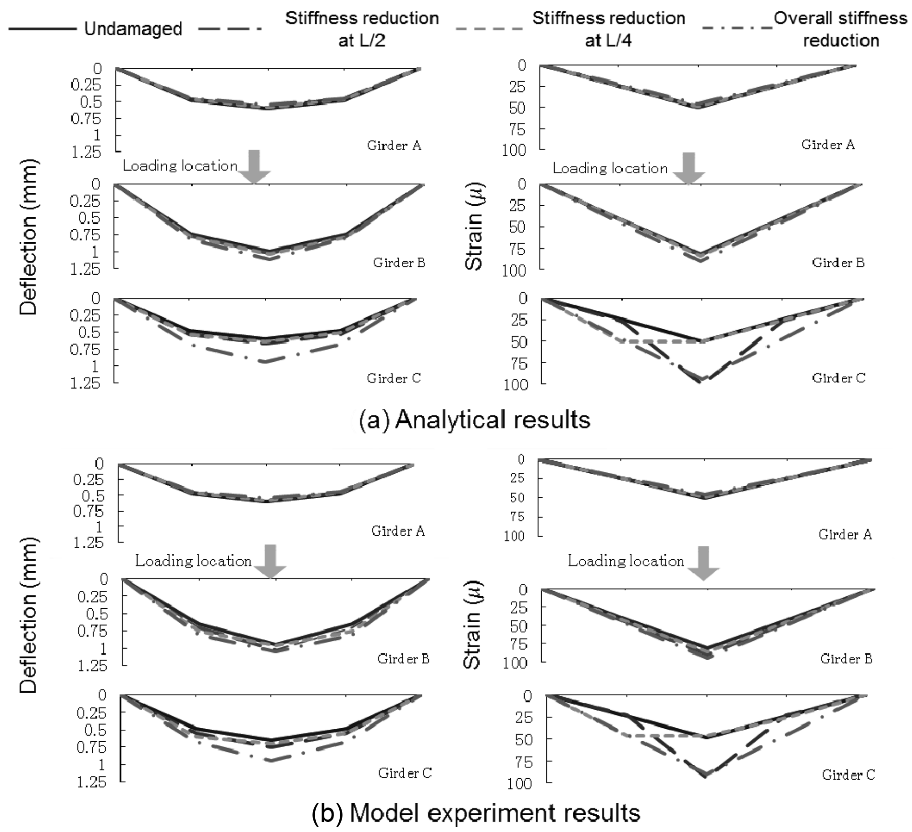


Fig. 4 Displacement and strain distributions under reduced stiffness of external girder (loading at central girder)

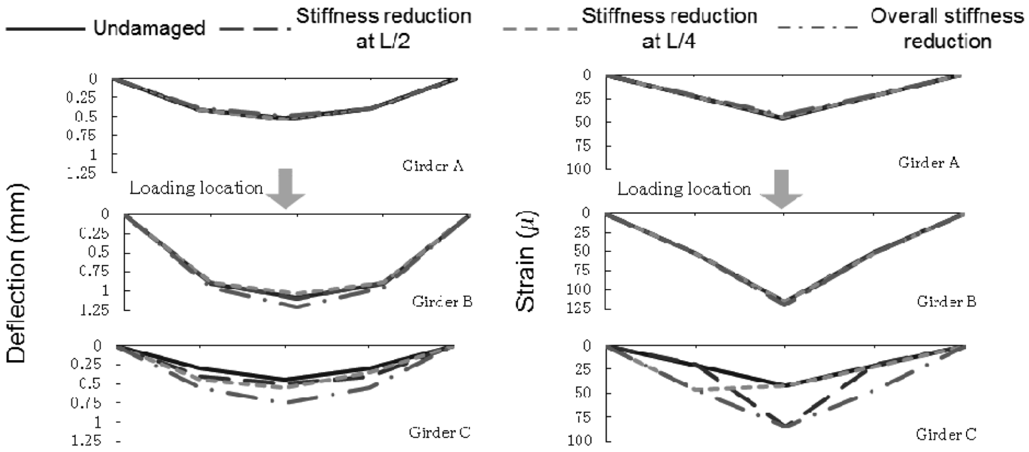


Fig. 5 Displacement and strain distributions under reduced stiffness of external girder (loading at central girder) in Series No.2

the analytical and experimental results showed good agreement in the cases where the stiffness of an entire girder decreased, but the experimental results did not show small changes reflecting local stiffness reduction although such changes were indicated by the calculation results. This may be related to measuring accuracy, but the reason is thought to be that essentially, displacement does not easily reflect the influence of local stiffness reduction. In the cases where similar stiffness reduction occurred in the central girder, the influence on the entire bridge structure was smaller than when such stiffness reduction occurred in an external girder.

Fig. 5 shows the experimental results obtained in the Series 2 cases, in which girder stiffness was reduced as in the cases shown in Fig. 4 and crossbeam stiffness was also reduced. Comparison with Fig. 4 reveals that because of lower efficiency in overall load distribution, the influence on the girders other than the girder whose stiffness has been reduced (Girder *C* in Fig. 1) tended to be small, and the influence was observed only in the reduced-stiffness girder.

Finally, support damage, settlement and rotational restraint were investigated in the analyses, and settlement was investigated in the experiments. The analyses and experiments showed that in the cases where such damage occurred at a support, displacement and strain distribution in the longitudinal direction changed considerably. Although strain distribution in the support settlement cases showed little difference from that in the undamaged case, only the crossbeam strain over the support showed a tendency to increase.

3.2 Natural frequency

This study focuses on five orders of vibration, namely, 1–1st, 1–2nd, 1–3rd, 2–1st and 3–1st. Fig. 6 illustrates these modes with mode visualization. The frequencies of these five modes of vibration showed characteristic changes depending on the location in a girder or crossbeam whose stiffness had been reduced. Figs. 7(a) and (b) show the calculated changes in bending vibration frequency in the cases where the stiffness of an entire external girder or the entire central girder was decreased and the cases where the stiffness of an external girder was decreased locally. Figs. 8(a) to

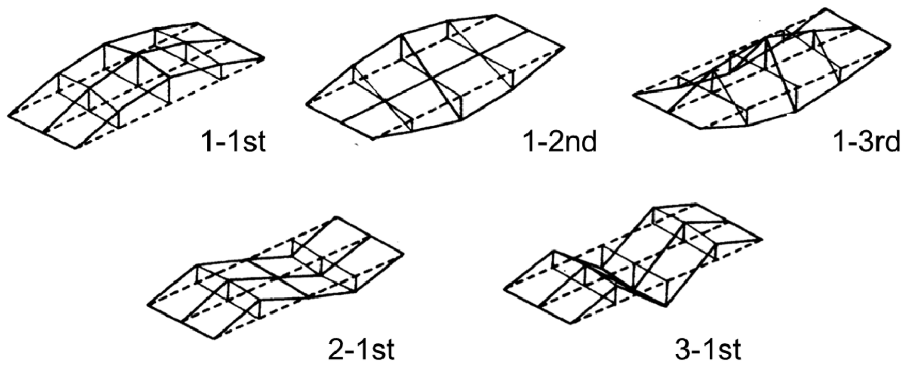


Fig. 6 Target orders and modes of vibration

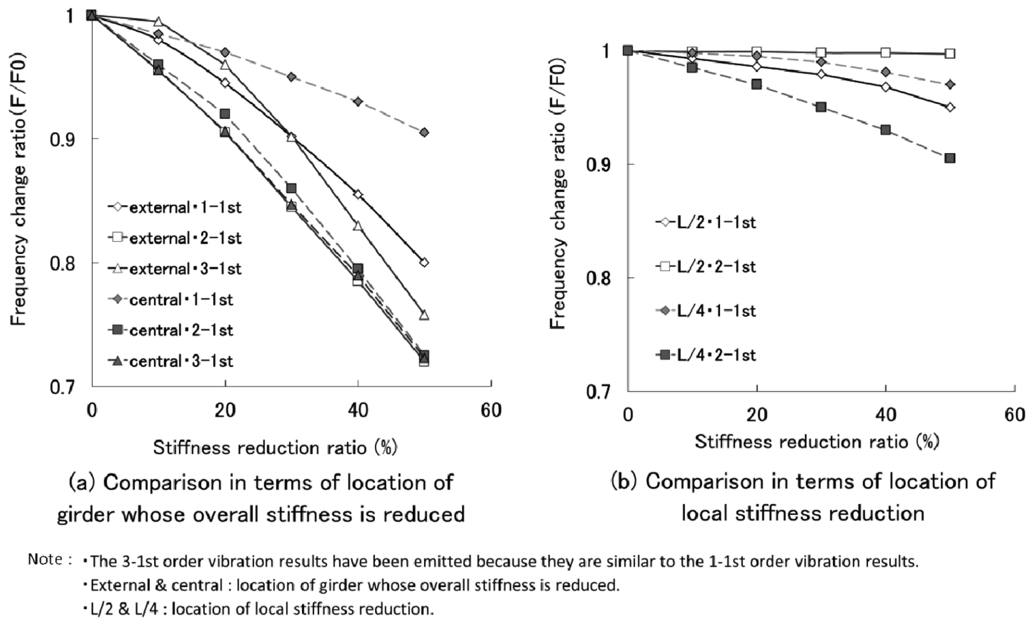


Fig. 7 Relationship between the stiffness change ratio and the frequency change ratio (analytical results)

(d) summarize the experimental results roughly corresponding to the analytical results. These results clearly indicate the following:

(1) In the cases where the stiffness of an entire external girder was decreased, the degrees of change in the 1–1st to 1–3rd order vibration frequencies are similar. In contrast, in the cases where the stiffness of the entire central girder was decreased, the amount of change in the 1–1st order vibration frequency is smaller than the amounts of change in the frequency of vibration modes of other orders. These tendencies show fair agreement with the analytical results (see Fig. 7(a) and Fig. 8(a)).

(2) In the cases where the stiffness of an entire girder was decreased, the amount of change in the frequency of vibration of each order is greater than the amount of change resulting from local stiffness reduction (see Figs. 7(a) & (b) and Figs. 8(a) to (d)).

Table 3 Frequency change ratio in cases of local stiffness reduction

Damage location	Series No.	Order of vibration		
		1-1st	2-1st	3-1st
L/2	1	3.2	2.3	2.3
	2	3.8	0.7	3.4
L/4	1	1.6	9.2	3.1
	2	1.1	5.7	3.0

Unit: %

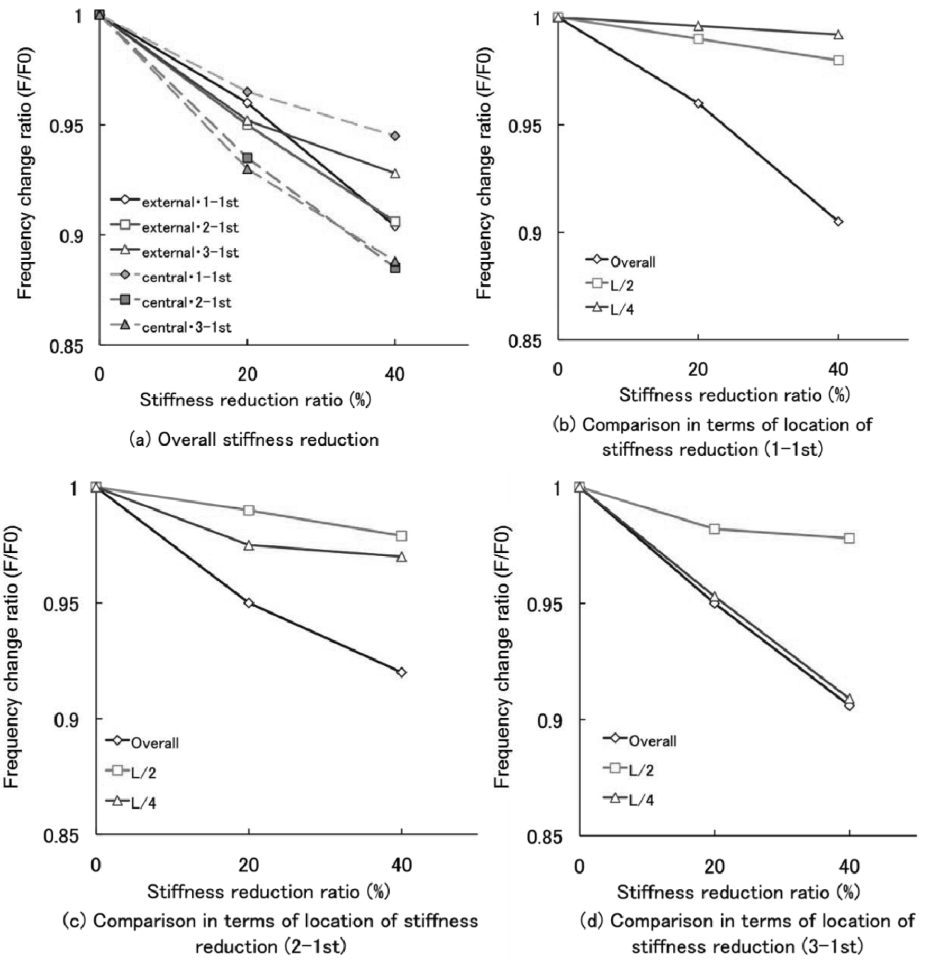


Fig. 8 Relationship between damage degree and frequency changes (experimental results)

(3) Examination of the experimental results related to frequency changes depending on the location of the stiffness reduction region reveals the following. The frequency of the vibration mode of the 1–1st order is greatly affected by local stiffness reduction at *L*/2, and that of the

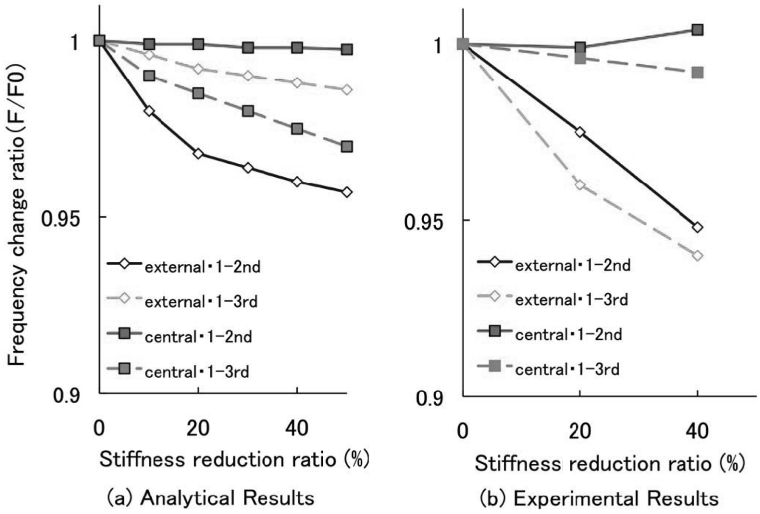


Fig. 9 Influence of overall stiffness reduction on torsional vibration

2–1st and 3–1st orders is greatly affected by local stiffness reduction at *L*/4. These are thought to be related to the locations of antinodes and nodes in each vibration mode. This means that if stiffness decreases locally at the location of an antinode in a vibration mode, the frequency of vibration changes considerably. Comparison of these with the analytical results reveals fair agreement with the tendencies for the 1–1st and 2–1st order vibration. For the 3–1st order vibration, however, an opposite tendency is shown; it is thought likely that in the experiments the effect of crossbeams was great, and the influence of stiffness reduction at *L*/2 became small (see Fig. 7(b) and Fig. 8(d)).

Fig. 8 also shows the experimental results for Series 1 (see Table 2), which involves the cases in which crossbeam stiffness is relatively high. To clarify the influence of crossbeam stiffness reduction, Table 3 compares the Series 1 results with the Series 2 results in the cases in which crossbeam stiffness was reduced. As shown in the table, unlike in the Series 1 cases, in the Series 2 cases (crossbeam stiffness reduction) the influence on the frequency of 3–1st order vibration is not affected significantly by the location of damage (*L*/2, *L*/4). Thus, experimental results for higher-order vibration frequency can vary greatly.

Figs. 9(a) and (b) show the calculated and measured changes in torsional vibration in the cases in which the stiffness of the entire central girder or an entire external girder was reduced. Figs. 10(a) and (b) show the calculated and measured results for torsional vibration in the Series 3 cases in which crossbeam stiffness was changed. As shown, the frequency of torsional vibration tends to change greatly in higher order modes when the bridge is damaged so that stiffness balance in the transverse direction is destroyed or when crossbeam stiffness is reduced. Thus, the measured changes in natural frequency obtained from the model experiments show relatively good agreement with the calculated results. It has also been found that the results other than the frequencies of higher order vibration such as the 3–1st order vibration show low variability and high repeatability, and the influence of small changes in stiffness can be observed clearly.

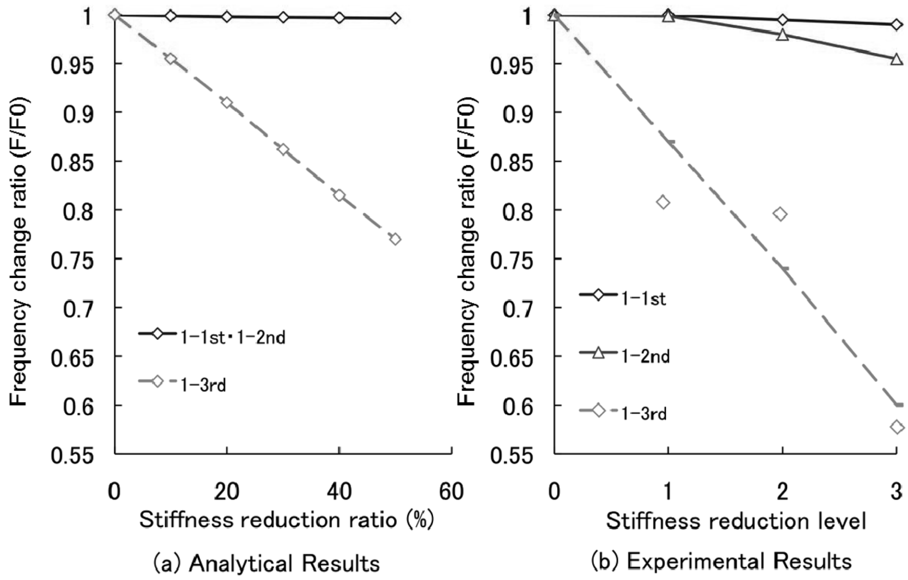


Fig. 10 Influence of crossbeam stiffness reduction on torsional vibration

3.3 Vibration mode and amplitude

Figs. 11(a) to (f) show examples of vibration mode changes observed in the experiments. Changes in vibration modes are shown in the form of a reference vibration mode using the Girder *B*-*L*/2 values with both the undamaged case and stiffness reduction(1.0) as a reference value. These results indicate the following:

(1) The mode of vibration in the case in which the central girder (Girder *B* in Fig. 1) is damaged (stiffness reduction), the vibration mode shows little difference from the undamaged case (see Fig. 11(b)).

(2) In the case in which an external girder (Girder *A* or *C* in Fig. 1) is damaged (stiffness reduction), the vibration mode shows considerable changes compared with the undamaged case even if the damage is localized. There are also differences between changes observed in the case of local stiffness reduction at *L*/2 and changes observed in the case of local stiffness reduction at *L*/4 (see Figs. 11(b) and (c)).

(3) In the case of damage that causes support settlement, the mode distribution of the support damage girder in the bridge axis direction changes considerably (see Fig. 11(d)).

(4) In the case of damage that does not affect girder stiffness but reduces crossbeam stiffness, the amplitude of external girder vibration tends to become smaller because of the decrease in the load distribution effect (see Fig. 11(e)).

Figs. 12(a) and (b) show the amplitude change rates in the cases in which the stiffness of an entire external girder was reduced and the cases in which the stiffness of the entire central girder was reduced. As shown, a reduction in central girder stiffness has little influence on the amplitude change ratio, while a reduction in external girder stiffness greatly affects the amplitude change ratio.

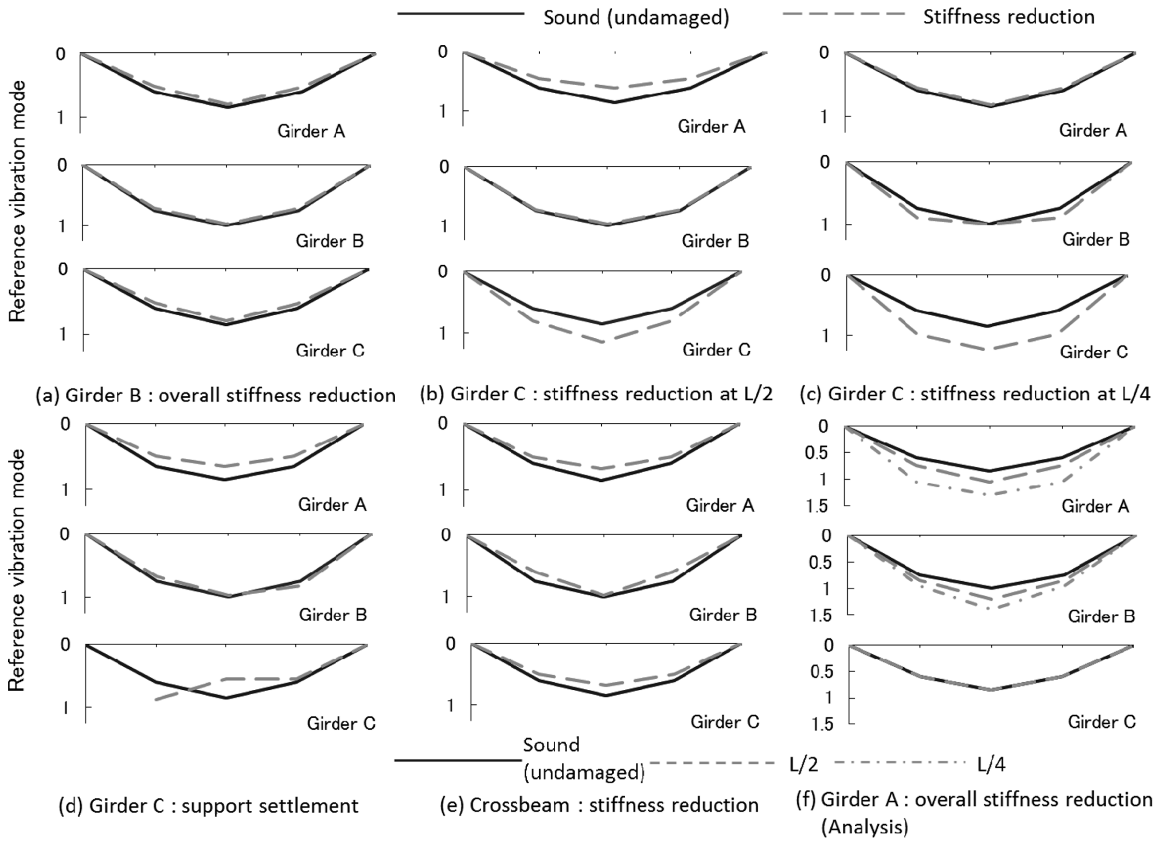


Fig. 11 Changes in vibration mode (1-1st) (experimental results)

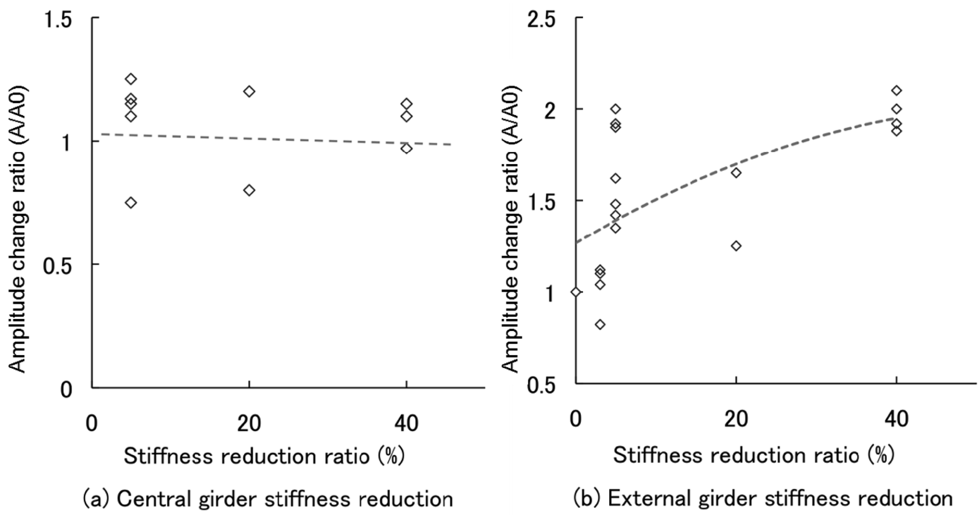


Fig. 12 Influence of overall stiffness reduction on amplitude change ratio

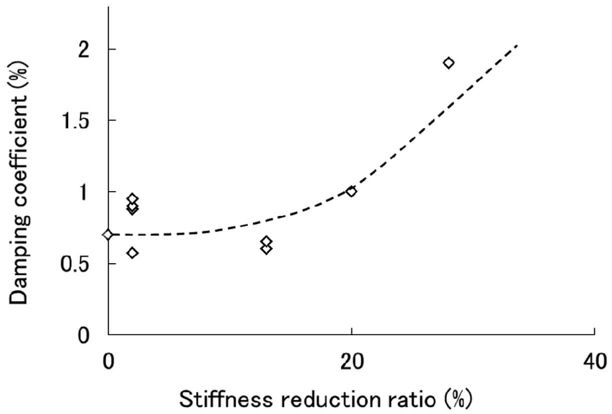


Fig. 13 Relationship between stiffness reduction and damping coefficient

3.4 Damping coefficient

There are many factors that affect the damping of vibration (Ito *et al.* 1965, Douglas *et al.* 1982, Hart 1977, He *et al.* 2008), and this is reflected in the variability of the results from the model experiment. Fig. 13 shows the relationship of girder length and the value derived by converting local stiffness reduction to overall girder reduction with changes in the damping factor. As shown in Fig. 13, unless the degree of stiffness reduction exceeds a certain level, discernible changes in the damping factor do not occur. This means that if discernible changes occur in vibration damping, considerable damage may have occurred.

3.5 Summary

Tables 4(a) and (b) summarize the observed changes in mechanical behaviours both of static and dynamic tests. Overall, it can be said that in the event of damage (stiffness reduction) to an external girder, instead of the central girder, mechanical behavior tends to be very sensitive to the kind of damage that causes imbalance in the direction perpendicular to the bridge axis.

Table 4(a) Changes in mechanical behavior due to stiffness reduction (Static behaviours)

Damage		Static behavior	
Location	Description	Displacement	Strain
Central girder	Local stiffness reduction	Highly variable	Low variability and increase proportional to stiffness
	Overall stiffness reduction	Gradual increase	
External girder	Local stiffness reduction	Greater change than in central girder	Low variability and increase proportional to stiffness
	Overall stiffness reduction	Great influence on behavior of other girders	
Crossbeam	Stiffness reduction	Reduced load distribution effect and smaller influence of damage to other girders / beams	
Support	Settlement	Changes in distribution in bridge axis direction	Little change

Table 4(b) Changes in mechanical behavior due to stiffness reduction (Dynamic behaviours)

Damage		Dynamic behavior			
Location	Description	Frequency 1-1st, 2-1st, 3-1st	Torsional vibration frequency, 1-2nd, 1-3rd	Mode shape	Damping coefficient
Central girder	Local stiffness reduction	The 1-1st order reduction ratio is high in case of $L/2$ damage; the 1-2nd order reduction ratio is high in case of $L/4$ damage.	The 1-3rd frequency decreased, and the 1-2nd frequency did not change.	Almost no change	Highly variable
	Overall stiffness reduction	The 1-1st order reduction ratio lower than 2-1st and 3-1st order reduction ratios.			Frequency to increase at a reduction ratio of 40%
External girder	Local stiffness reduction	The 1-1st order reduction ratio is high in case of $L/2$ damage ; the 1-2nd order reduction ratio is high in case of $L/4$ damage.	Both decreased : the 1-3rd order reduction ratio is higher.	Change at 20% : great influence in case of $L/4$ damage.	Highly variable
	Overall stiffness reduction	The reduction ratios of three frequencies are the same.		Considerable change	Tendency to increase at a reduction ratio of 40%
Cross-beam	Stiffness reduction	Almost no change	Considerable decrease in 1-3rd	Central girder amplitude greater than external girder amplitude.	Highly variable
Support	Settlement	Slight decrease	Slight decrease	Changes in distribution in bridge axis direction.	Highly variable

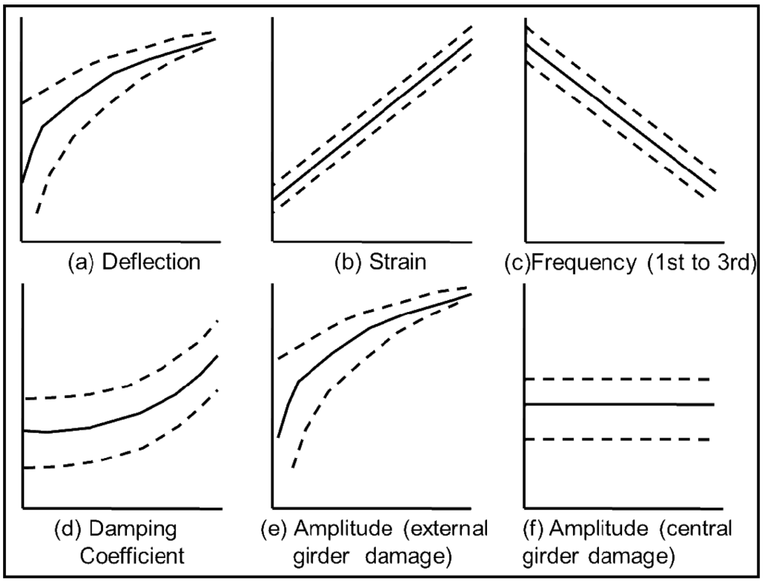
4. Evaluation of usability of mechanical behavior in damage assessment

In view of the study results and characteristics of the data obtained from the model experiments described in the preceding sections, this section evaluates the validity of damage assessment based on mechanical behavior and proposes a damage assessment method. The changes in mechanical behavior resulting from girder and crossbeam damage (stiffness reduction) that have been identified through the model experiments and analyses are shown in a simplified form in Figs. 14(a) to (f). The characteristics of these changes in mechanical behavior are categorized, compared and illustrated in Figs. 15(a) to (d). These mechanical behavior characteristics can be summarized as follows:

(1) Displacement (deflection) is very sensitive even to slight damage. Since, however, it emerges as an averaged behavioral change, it is small in absolute terms and is apt to vary widely under the influence of such factors as measuring accuracy. Deflection is also less sensitive to local damage and crossbeam damage.

(2) Strain is thought to satisfy the requirements for a damage indicator in terms of sensitivity to damage and data variability. Since, however, strain tends to change only in damaged regions, damage in regions without measuring points cannot be detected.

(3) Frequency is mediocre in terms of sensitivity to damage among the mechanical behaviors under consideration, but frequency enables accurate assessment for lower-order vibration.



Note : The vertical axis shows changes in behavior ; the horizontal axis : the stiffness reduction ratio ; and the distance between the dotted lines : the degree of variability.

Fig. 14 Changes in mechanical behavior due to stiffness reduction

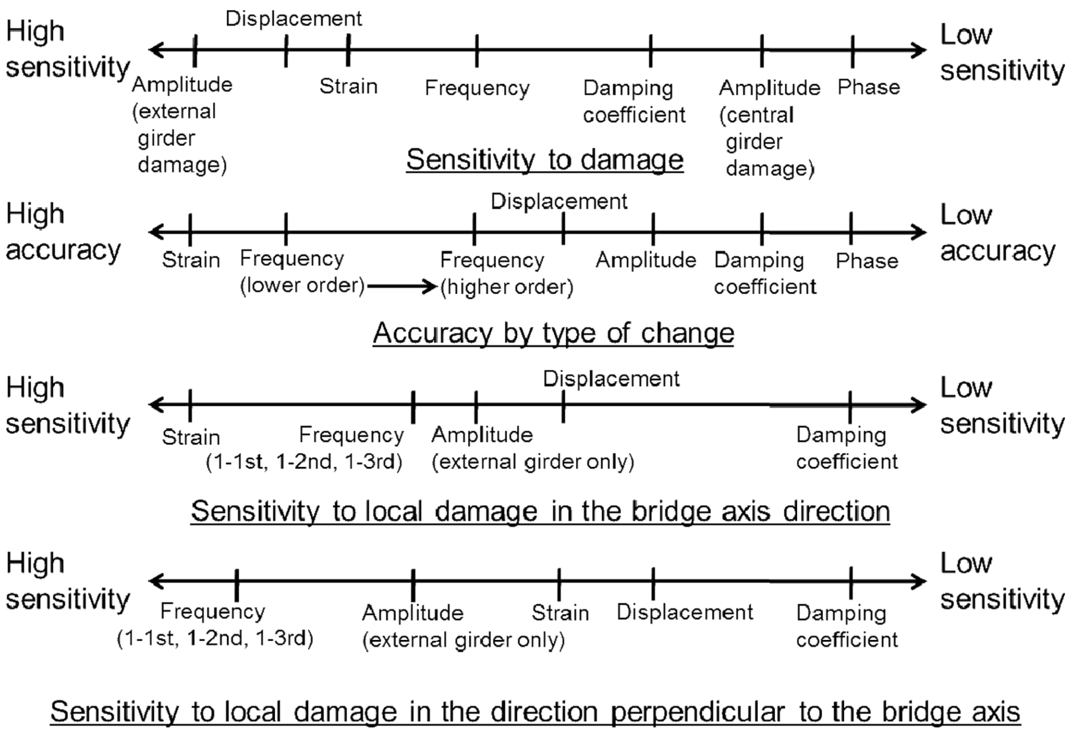
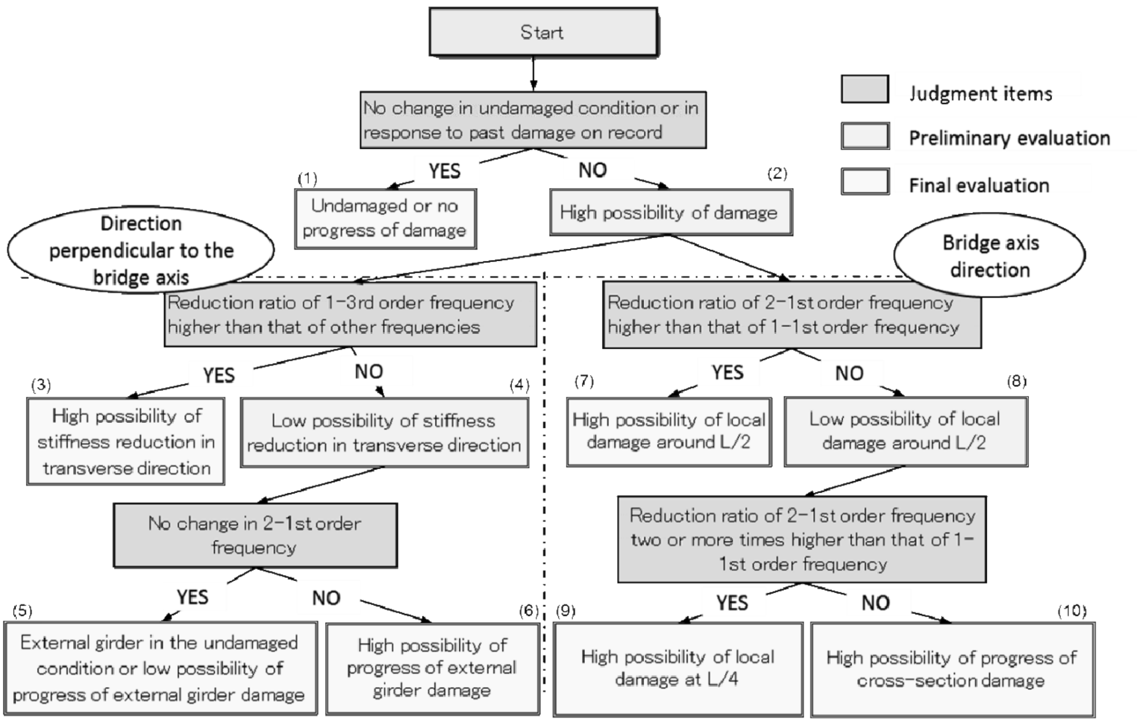


Fig. 15 Comparison among mechanical behaviours



[Other check items]

Evaluation No.	Check item	Description
(1)	All behaviors	No change
(2)	All behaviors	Identification of change items
(3)	Strain & Displacement	Reduced load distribution effect
	Vibration mode	Small amplitude of external girder vibration
(4)	Strain & Displacement	No change in load distribution
	Vibration mode	No change in amplitude of external girder vibration
(5)	Strain & Displacement	Increase of central girder values
	Vibration mode	No overall change
(6)	Strain & Displacement	Increase of external girder values
	Vibration mode	Large amplitude of external girder vibration
(7)	Strain	Increase of values around L/2
(8)	Strain	Values around L/2 not significantly greater than the values in other regions
(9)	Strain	Increase of values around L/4
(10)	Strain & Displacement	Increase mainly in damaged girder / beam
	Damping coefficient	Attention to be paid to the change ratio

Fig. 16 Flow of damage assessment based on natural frequency

Because it may be possible to assess local damage by measuring torsional vibration and higher-order bending vibration, frequency is thought to satisfy the greatest number of requirements for a damage indicator among the mechanical behaviors evaluated in this study.

(4) The damping coefficient varies widely in measurements and is very insensitive to minor damage. This means, however, that serious damage can be detected if the damping factor shows a considerable change.

(5) Amplitude and the mode of vibration show considerably different degrees of sensitivity to damage depending on where it is located (i.e., external girder or central girder). The mode of vibration is almost insensitive to central girder damage that does not cause stiffness imbalance in the direction perpendicular to the bridge axis. It is more sensitive, however, than other mechanical behaviors to external girder damage that destroys such balance.

From the study results described above, it is thought that a good approach to damage assessment is to evaluate changes in the natural frequency of each order first and then check, if necessary, on mechanical behaviors that are highly sensitive to damage. In view of the results of the analyses and model experiments, therefore, a natural-frequency-based damage assessment method (assessment flow) for the bridge model used in this study is developed, and the level of damage assessment that can done by the newly developed method is determined.

By examining the tendencies of changes in the natural frequency of each order identified from the analytical and experimental results, characteristics of those tendencies can be classified into a number of categories. By using this approach, a procedure for estimating the location of damage has been developed (see Fig. 16). The flow shown in Fig. 16 is based on the IF–THEN–ELSE rule. Below the evaluation step (2) in the flowchart of Fig. 16, the assessment branches into assessment as to damage in the direction perpendicular to the bridge axis due to torsional vibration and assessment as to damage in the bridge axis direction due to bending vibration. The aim is to estimate the two-dimensional location of damage through comprehensive evaluation of the results of these assessments. Fig. 16 also shows a list of check items related to characteristics of changes in mechanical behaviors other than natural frequency. By checking on these check items after evaluation results are obtained, the accuracy of assessment can be enhanced.

The next step is to decide on a method for estimating the degree of damage after the location of damage is estimated by following the flowchart of Fig. 16. In this study, by using the fact that stiffness reduction and changes in lower-order natural frequencies are roughly related linearly, the relationship between the 1–1st order frequency and stiffness reduction at the locations estimated by following the procedure shown in Fig. 16 is determined through a model experiment or analysis, and, by using the regression equation derived from the results thus obtained, the degree of damage is estimated. The flow of this method is shown in Fig. 17. Table 5 shows examples of degrees of damage estimated from the model experiment results by following the procedure shown in Fig. 17.

When a damage assessment of an existing bridge is made, damage is estimated from analytical results because it is difficult to make a model of each bridge. Judging from the results shown in Table 5, however, fairly accurate assessment results can be obtained even when damage is estimated from analytical results. This is thought to be because the natural frequencies used for this estimation are lower-order frequencies, which are highly accurate and tend to agree well with calculated values. In this study, it was possible to experimentally verify the frequencies in the undamaged condition. When making a damage assessment of an existing bridge, however, data on the bridge in the undamaged condition are rarely available. This means that the undamaged condition needs to be theoretically estimated. Since, however, the proposed estimation method uses the fact that frequency

Step 1. Estimate the location of damage according to the flowchart of Fig.16.

↓

Step 2. For the damage location identified in *Step 1* above, calculation the relationship between the degree of damage and the change ratio of the 1-1st order vibration frequency and linearly regress the results.

↓

Step 3. Substitute the change ratio of the 1-1st order natural frequency obtained by experiment into the linear regression equation derived in *Step 2* above, and estimate the damage degree.

Fig. 17 Flow of damage assessment

Table 5 Estimated stiffness reduction ratio (%)

Exp. No.	Estimated value		Actual reduction ratio
	Experiment	Analysis* (model calculation)	
1-2	22.3	20.6	20
1-3	30.5	25.5	40
1-4	5.1	6.9	6.0
1-5	4.5	2.7	6.0
1-6	23.7	21.5	20
1-7	43.4	33.2	40
1-8	2.4	3.3	3.0
1-9	5.7	7.2	6.0
1-10	4.5	2.7	3.0
1-11	6.0	5.4	6.0

* : Local stiffness reduction converted to a overall cross-section value.

changes linearly, it may be thought that the degree of damage can be estimated even from data on a bridge that has been damage to some degree.

5. Conclusions

This study has verified the validity of using mechanical behaviors in bridge damage assessment from the viewpoint of sensitivity, accuracy, etc., through model analyses and bridge model experiments and developed a damage assessment method using mechanical behaviors as damage indicators. The results obtained from this study can be summarized as follows:

(1) Changes in mechanical behavior commonly used in damage assessment show different characteristic tendencies depending on the location and degree of damage. By using them in

combination, the location and degree of damage can be estimated.
(2) By evaluating the natural frequencies of not only lower order vibration, which are widely used for assessment purposes, but also torsional vibration and higher order vibration, the location of damage can be estimated and the accuracy of estimation can be enhanced. Because of a number of advantages including a roughly linear relationship with the degree of damage (stiffness reduction), natural frequency can become the most useful parameter for damage assessment.
(3) Various damage assessment methods based on the natural frequencies of different orders of vibration have been studied. As a result, it has been found that a knowledge-based method basically using the IF-THEN-ELSE rule enables the estimation of damage locations and its assessment results are fairly accurate.
(4) The tendencies of changes in mechanical behavior determined through the model calculation and bridge model experiments show relatively good agreement. Data on the initial condition of the bridge of interest can be reproduced by enhancing the accuracy of the analysis model.

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