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Dynamic Behaviour in Existing Concrete Bridges and Damage Detection

Comportement dynamique des ponts en béton et détection des dommages

Dynamisches Verhalten bestehender Betonbrücken zur Schadenerkennung

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SUMMARY
In this paper, the sensivities of the dynamic behaviour of concrete bridges constituted by natural frequency, mode shape, damping and phase angle in damage detection is studied utilizing an analysis of the complex eigenproblem considering non-proportional damping and using dynamic loading tests on an existing bridge in which some specified artificial damage had been included. Also, a method of damage assessment for concrete bridges integrated from both the concise detection of damage location based on the difference in the sensitivities of modal parameters and the exact evaluation by localization and quantification of multiple damage based on the system identification method, is discussed.

RÉSUMÉ
Les sensibilités du comportement dynamique des ponts en béton constituées par la fréquence naturelle, la forme modale, l'amortissement et le déphasage sont examinées en vue de la détection des dommages, avec le recours à l'analyse de problèmes propres complexes, et en tenant compte de l'amortissement non proportionnel et des essais en charge dynamiques sur des ponts existants où quelques dommages artificiels spécifiques ont été induits. On y discute également une méthode d'estimation des dommages des ponts en béton intégrée à la fois par une détection concise de la localisation du dommage selon la différence des sensibilités des paramètres modaux et par une évaluation exacte par localisation et quantification des dommages multiples selon la méthode d'identification des systèmes.

ZUSAMMENFASSUNG
In dieser Arbeit wird die Empfindlichkeit im dynamischen Verhalten, ausgedrückt durch natürliche Frequenz, Modalform, Dämpfung und Phasenwinkel, von Betonbrücken in der Schadenserkennung untersucht. Dabei wird die Analyse von komplexen Eigenproblemen unter Berücksichtigung der nicht-proportionalen Dämpfung und dynamischer Belastungstests auf vorhandenen Brücken, bei denen spezifizierte künstliche Lasten aufgebracht wurden, eingesetzt. Ausserdem wird eine Methode der Schadensbewertung von Betonbrücken diskutiert, bei der die schnelle Erkennung der Schadenslage und die genaue Bewertung der Lage und Quantifizierung von mehrfachen integriert sind. Erstere basiert auf dem Unterschied der Empfindlichkeit modaler Parameter, während für letztere die Systemindenfikation eingesetzt wird.

1. INTRODUCTION

The need for damage assessment of existing concrete bridges by a combination of visual inspections, loading tests and analytical studies, has been pointed out with reference to the diagnosis of bridge serviceability [1]. Since there are a number of factors included in the relationship between the damage to existing bridges and dynamic behavior, it is necessary to develop an efficient method for damage detection based on dynamic loading tests [2]. The most important aspect of this problem is to focus on the dynamic sensitive parameters to the damage, because this has a significant influence on the accuracy of assessment.

In this paper, the sensitivities of dynamic behavior constituted by the natural frequency, the mode shape, the damping constant and the phase angle, for damage detection was studied using an analysis of the complex eigenproblem considering non-proportional damping and also dynamic loading tests. For the analytical study, the component mode synthesis (CMS) method, which is one type of coupling technique for substructures in the dynamic analysis was applied to the complex eigenproblem for simplification and an iterative analyses for damage detection was utilized. The system identification (SI) method was developed based on sequential linear programming (SLP), combined with the dynamic sensitivity analysis, to quantify the degree of damage for each member in the whole system.

For the application of this method to existing concrete bridges, parametric analyses for simply supported RC-T beam bridges in service were executed to evaluate the sensitivities of damage to dynamic behavior and to construct a concise flow for damage detection. Furthermore, the SI method was applied to the results from the dynamic loading tests, performed on an existing bridge in whichsome specified artificial damages were induced. Finally, the concise flow and the SI method were integrated, to enable an efficient damage assessment by multi-level and multi-aspect approaches.

2. ANALYTICAL METHOD FOR DAMAGE DETECTION OF EXISTING BRIDGES

2.1 Modeling of bridges

For existing concrete bridges, stiffness reduction of the main girder has been caused due to the interactive effect of flexural cracks and retrogression in the modulus of elasticity of the concrete, The safety of bridges is strongly influenced by this process as due to a change of load distribution and hence a reduction in load carrying capacity. In this research, the stiffness reduction and change of damping constant were considered to be the damage factors. The modeling of the target bridge was carried out by using a lumped mass gridform model of finite beam elements and spring elements for the elastic restraint of rotation at the supports. Fig.1 shows an example of the model for an existing RC-T beam bridge, "Nakaibashi" located in Hyogo prefecture in Japan.

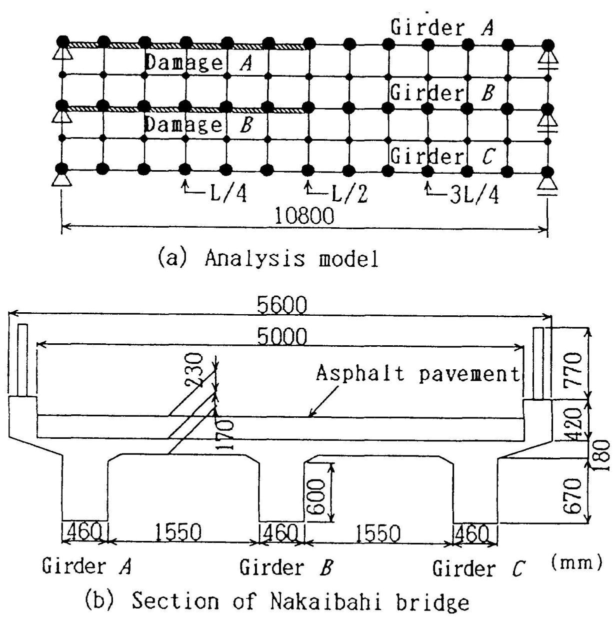

Fig.1 Modeling of existing RC-T beam bridge

2.2 Component mode synthesis method in the complex eigenproblem

The CMS method deals with the equation for the whole structure in modal coordinates obtained by synthesis of the boundary modes of substructures previously evaluated by modal analysis in the physical coordinates. When the whole structure is divided into n pieces of substructures, the equation of motion for the substructure i can be expressed by:

$$\begin{bmatrix} M^i_{aa} & M^i_{ab} \\ M^i_{ba} & M^i_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{\delta}_{ia} \\ \ddot{\delta}_{ib} \end{Bmatrix} + \begin{bmatrix} C^i_{aa} & C^i_{ab} \\ C^i_{ba} & C^i_{bb} \end{bmatrix} \begin{Bmatrix} \dot{\delta}_{ia} \\ \dot{\delta}_{ib} \end{Bmatrix} + \begin{bmatrix} K^i_{aa} & K^i_{ab} \\ K^i_{ba} & K^i_{bb} \end{bmatrix} \begin{Bmatrix} \delta_{ia} \\ \delta_{ib} \end{Bmatrix} = \begin{Bmatrix} 0 \\ f \end{Bmatrix} \tag{1}$$

where subscript a, b denote the internal area and the boundary area, respectively.

By using Guyan reduction of the stiffness matrix, a correlation between the displacement in the internal area and the boundary area can be expressed by:

$$\delta_{ia} = -\left[K_{aa}^{i}\right]^{-1}\left[K_{ab}^{i}\right]\delta_{ib} = T_i\,\delta_{ib} \qquad (2)$$

After this, an analysis of the complex eigenproblem for the synthesized whole structure, of which the matrix size is reduced to the degree of freedom for the boundary area of each substructure, is carried out. Displacement at the boundary area b can be evaluated in the form of complex conjugates by linear combination of each mode as:

$$y_b = \phi_b\,\xi_b \quad (3), \qquad \text{where } \phi_b = \left[\phi_{b1}, \bar{\phi}_{b1}, \phi_{b2}, \bar{\phi}_{b2}, \cdots, \phi_{bk}, \bar{\phi}_{bk}\right] : \text{the complex mode matrix,}$$

k denotes the adopted number of modes, $y_b = \left\{\dot{\delta}_b, \delta_b\right\}^{\mathrm{T}}$, $\xi_a = \left\{\xi_{1b}, \xi_{2b}, \cdots, \xi_{nb}\right\}^{\mathrm{T}}$: the modal coordinates.

On the other hand, carrying out the analysis of the constrained mode for each substructure, displacement at the internal area a for each substructure can be expressed by:

$$y_{ia} = \left[T_i'\phi_{ib}, \phi_{ia}\right]\xi_i \quad (4), \qquad \text{where } \phi_{ia} = \left[\phi_{ia1}, \bar{\phi}_{ia1}, \phi_{ia2}, \bar{\phi}_{ia2}, \cdots, \phi_{iam}, \bar{\phi}_{iam}\right] : \text{the complex mode matrix,}$$

m denotes the adopted number of modes, $\xi_i = \left\{\xi_{ib}, \xi_{ia}\right\}^{\mathrm{T}}$, $T_i' = \begin{bmatrix} T_i & 0 \\ 0 & T_i \end{bmatrix}$

Displacement of the whole structure can be expressed by using the modes at the boundary area and the internal area, as:

$$\left\{y_b, y_a\right\}^{\mathrm{T}} = X\left\{\xi_b, \xi_a\right\}^{\mathrm{T}} = X\,\xi \quad (5), \qquad \text{where } y_a = \left\{y_{1a}, y_{2a}, \cdots, y_{na}\right\}^{\mathrm{T}},\ \xi_a = \left\{\xi_{1a}, \xi_{2a}, \cdots, \xi_{na}\right\}^{\mathrm{T}},$$

$$X = \begin{bmatrix} \phi_b & 0 \\ T\phi_b & \phi_a \end{bmatrix}, \quad T = \begin{bmatrix} T_1' & & & \mathrm{O} \\ & T_2' & & \\ & & \ddots & \\ \mathrm{O} & & & T_n' \end{bmatrix}, \quad \phi_a = \begin{bmatrix} \phi_{1a}' & & & \mathrm{O} \\ & \phi_{2a}' & & \\ & & \ddots & \\ \mathrm{O} & & & \phi_{na}' \end{bmatrix}$$

Finally, the equation of motion for the whole structure can be written as:

$$X^{\mathrm{T}}PX\,\dot{\xi} + X^{\mathrm{T}}QX\,\xi = 0 \quad (6), \qquad \text{where } P = \begin{bmatrix} 0 & M_{bb} & 0 & M_{ba} \\ 0 & M_{ab} & 0 & M_{aa} \\ M_{bb} & C_{bb} & M_{ba} & C_{ba} \\ M_{ab} & C_{ab} & M_{aa} & C_{aa} \end{bmatrix}, \quad Q = \begin{bmatrix} -M_{bb} & 0 & -M_{ba} & 0 \\ -M_{ab} & 0 & -M_{aa} & 0 \\ 0 & K_{bb} & 0 & K_{ba} \\ 0 & K_{ab} & 0 & K_{aa} \end{bmatrix}$$

By analyzing the eigenproblem for Eq.(6), the modal parameters for the whole structure can be obtained. Furthermore, substituting the modes evaluated by Eq.(6) into Eq.(5), the modes of the whole structure in the physical coordinates can be obtained. The degree of freedom for this analysis is the sum of the adopted number of modes for the whole structure synthesized by the modes for the boundary area of all substructures; $2k$, and the adopted number of modes for the internal area of all substructures; $2\Sigma m_i$, (i=1, n, n: number of substructures), and it can be seen to be much less than the total degree of freedom for the whole structure. Through study of the accuracy of this method using the existing bridge model shown as Fig.1, it was founded that the results of this analysis were sufficiently accurate for the target modes of bridge vibration as shown in Fig.2, even if the adopted degree of freedom for the whole structure was half the total degree of freedom.

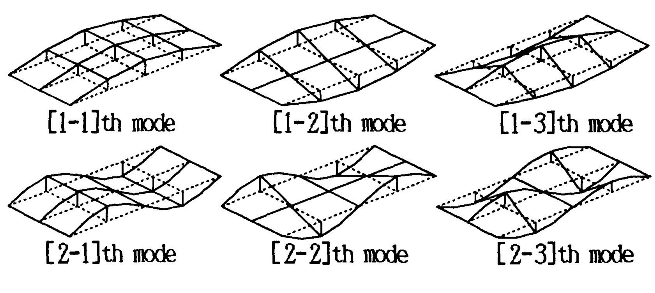

Fig.2 Shape of target modes

2.3 SI method using sensitivity analysis

The SI method [3] is one type of back analysis method, which can be used to identify system parameters such as the flexural rigidity corresponding to the degree of damage in the problem, by minimizing the error between the mechanical behavior as obtained from test and analysis. Here, the existing concrete bridge was modeled as shown in Fig.1, considering spring elements for the friction restraint of rotation at the supports. In this research, the sensitivity analysis of damage to mechanical behaviors and the SLP method were integrated. The objective function was defined as minimizing the total squared error between the mechanical behavior obtained from the field test and the analysis, by:

$$F = W_1\left(\frac{\mu_p}{\mu_p^m} - 1\right)^2 + W_2\sum_{k=1}^{n}\left(\frac{Z_{pk}}{Z_{pk}^m} - 1\right)^2 \rightarrow min \tag{7}$$

where p is the order of normal vibration, n is the number of measuring points, μ, μ^m are the eigenvalues obtained from the analysis and the field test, respectively, Z, Z^m are the normalized modes of vibration, and W_1, W_2 are the weights for the eigenvalue and the vibration modes. Here, it is assumed that W_1=1.0, W_2=1/n.

The sensitivity (derivative) of the design variable(for identification, here assign it the rigidity K_i, i=1~l, l: the number of members) to the objective function, can be expressed by:

$$\frac{\partial F}{\partial K_i} = \frac{2W_1}{\mu_p^m}\left(\frac{\mu_p}{\mu_p^m} - 1\right)\frac{\partial \mu_j}{\partial k_i} + \sum_{k=1}^{n}\frac{2W_2}{Z_{pk}^m}\left(\frac{Z_{pk}}{Z_{pk}^m} - 1\right)\frac{\partial Z_j}{\partial k_i} \tag{8}$$

where

$$\frac{\partial \mu_p}{\partial k_i} = Z_p^T\frac{\partial K}{\partial k_i}Z_p\,, \quad \frac{\partial Z_p}{\partial k_i} = \sum_{j=1}^{n}\left(-\frac{1}{\mu_j^m - \mu_p^m}Z_j^T\frac{\partial K}{\partial k_i}Z_p\right)Z_j$$

and K is the stiffness matrix of the whole structure.

Following this, identification of the design variables can be performed by applying the SLP method using the objective function and its derivative for the design variables. Fig.3 shows the flow of the SLP method for the dynamic problem. Firstly, the initial values of the design variables are evaluated by analysis. Linearization of the objective function is then carried out within the region of movement limits for the design variables, and a search for the minimum point of the objective value is tried using the simplex method. In the event that the change of design variables exceeds the movement limits, reanalysis of the modal parameters and restart of the search for the minimum values from updated initial values are executed by the same procedure iteratively up to the stage at which the objective function is within the allowable limits.

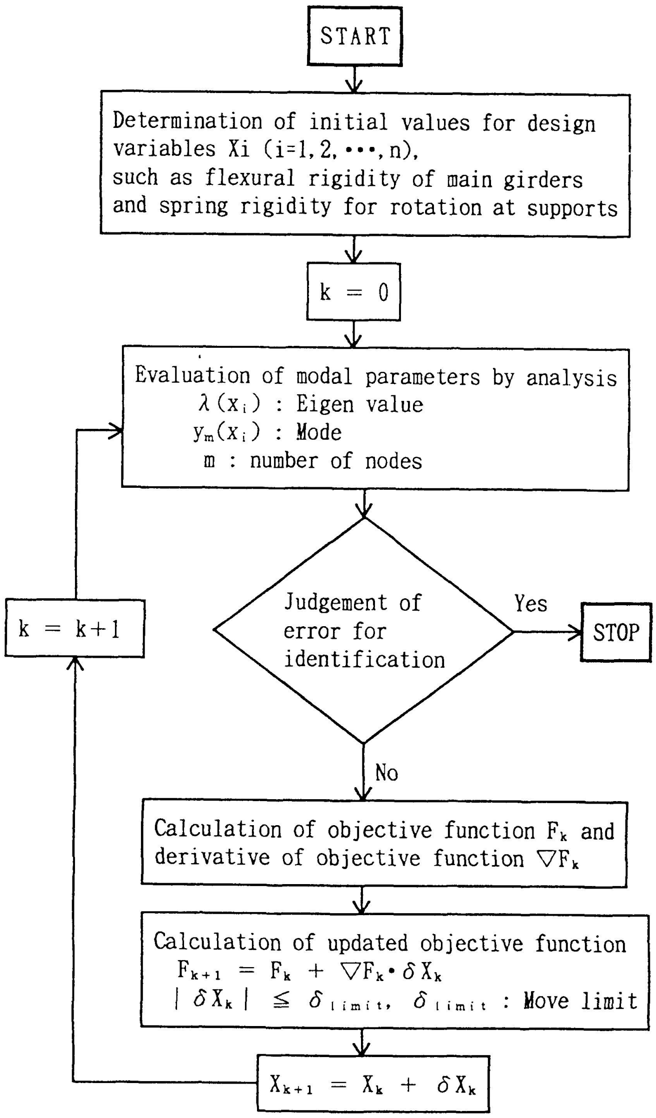

Fig.3 Flow of SLP (for dynamic problem)

3. APPLICATION TO AN EXISTING RC BRIDGE WITH ARTIFICIAL DAMAGE

3.1 Outline of target bridge

The target existing bridge "Oyasubashi" is 27 years old and a simply supported 4 girder RC-T beam bridge with a skew angle of 46 degrees and a span length of 14.7m. This bridge seemed to be almost intact according to the results of visual inspections. Fig.4 shows an outline section for this bridge.

3.2 Inducement of artificial damage

The artificial damage corresponding to

flexural cracks in concrete in the tensile region were induced partially in the girders *A* and *B* as shown in Fig.5. Introduction of cracks was carried out by core boring along a vertical line from the bottom surface of concrete in the tensile region to the neutral axis, as shown in Fig.6. The core concrete blocks were then replaced in the holes from which they had been extracted, in order to avoid altering the weight of the girders.

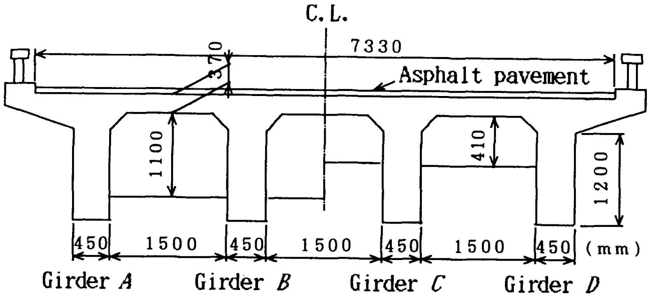

Fig.4 Section of *Oyasubashi* bridge

3.3 Procedure for field test [4]
Prior to the field test, the target bridge was modeled as the lumped mass system shown in Fig.7, and the modal parameters were evaluated by analysis. From this a measurement method was determined focusing the antinodes of target vibration modes, as shown in Fig.5. Positions of forced vibrations by falling mass were arranged to obtain the various modes of vibration and the mass dropping was carried out from about 70cm height for ten times at the same loading point to cancel white noise and to obtain a stable average value. The modal analysis [5] was then applied to the acceleration data to identify the modal parameters.

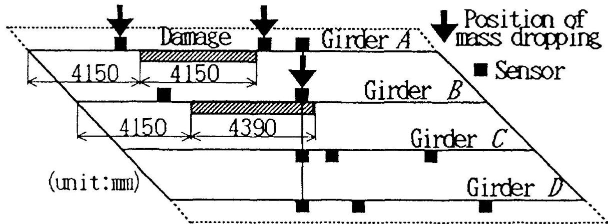

FIg.5 Outline of dynamic loading test

3.4 Identification of damage parameters
The stiffness reduction of main girders was identified by the SI method based on the [1-1]th eigenvalue and eigenvector obtained from the field tests, using the following procedure:
(1)For the target bridge before inducement of the artificial damage, the system parameters constituted by the stiffness of main girders and cross beam, and the spring coefficient of rotation at the supports, were identified.
(2)After inducement of the artificial damage, the stiffness of the main girder in the damaged region and the spring coefficient of rotation at supports were identified under the condition that the girder stiffness except for damaged region was fixed at the value identified in (1).

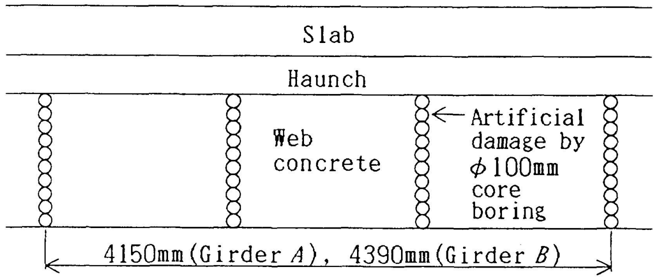

Fig.6 Inducement of artificial damage

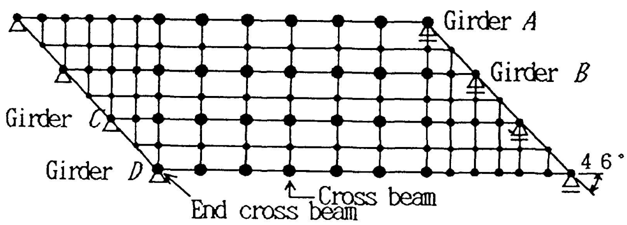

Fig.7 Analysis model for *Oyasubashi* bridge

Table.3 shows the results of the above procedure. According to the results, the change of natural frequency due to inducement of artificial damage is about 8% i.e. relatively great. The results of the SI method can be seen to show that the spring rigidity of rotation at the supports changed sharply due to inducement of the damage, although this bridge has simple support conditions in its design. In such cases, the SI method considering the spring rigidity of rotation at the supports as the design variables is effective. Identified girder stiffness before inducement of the damages was equivalent to the theoretical value considering the stiffness of concrete in the tensile region, and it agreed with the results of visual inspections and material tests of concrete cores extracted from the target bridge. Also the evaluated degree of damage was then relatively great and qualitatively matched the theory.

Table 1 Results of damage detection for *Oyasubashi* bridge

	Girder stiffness($\times 10^{12}$Kg·cm^2)				Spring rigidity of rotation at supports ($\times 10^{9}$kg·cm/rad)				1st natural frequency
	Girder				Girder				
	A	B	C	D	A	B	C	D	(HZ)
Theoretical value	7.198	6.755	6.755	7.255	—	—	—	—	—
Identified value without damage	8.242	7.701	7.160	6.346	1.310 1.310	1.100 1.100	0.900 0.900	0.690 0.690	12.69
Identified value with damage	5.496*	5.671*			0.0203 0.0122	0.0100 0.0089	0.0075 0.0073	0.0046 0.0044	11.71

* : Value at damaged region

4. EFFECTIVENESS OF MODAL PARAMETERS IN DAMAGE DETECTION

4.1 Modeling of bridge with damage

The target bridge is shown in Fig.1, and this was modeled considering partial damage. For the damage condition, the change of damping constant in the region of 0~30% in the region of *A*, *B* were assumed.

4.2 Damping characteristics

Fig.8 shows the relationship between the change of damping constant in the damaged area and that for the whole bridge system. For the [1-1]th mode of vibration, the sensitivities of damage *A* and *B* are the same and have linearity, independently of the change of damping constant in the non-damaged area. On the other hand, according to the results for the [1-2]th mode, damage *B* in girder *B* which is the node of vibration has no influence on the whole bridge system. Accordingly, localization of the damage can be carried out using the damping characteristics for both the [1-1]th and [1-2]th modes.

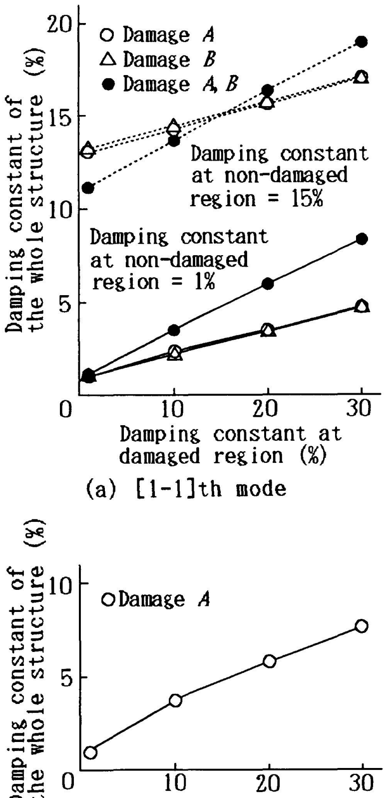

Fig.8 Damping characteristics

4.3 Phase angle

Fig.9 a)~c) shows the relationship between the change of damping constant in the damaged area and the difference in phase angle for each girder for the [1-1]th mode of vibration. Here, the difference in phase angle was evaluated on the basis of the phase angle at the midpoint of girder *B*. The difference in phase angle in the damaged girder is greatest, in particular, the influence of damage *A* is significant. The sensitivities of these parameters have linearity independently of the change of damping constant in the non-damaged area. On the other hand, Fig.9 d) shows the result for the [2-1]th mode and it can be seen that the sensitivity of damage *A* is great and the difference in phase angle between girder *A* and *C* is about 0.5rad i.e. largest. Accordingly, localization of the damage can be carried out by using these characteristics, similar to the above-mentioned damping characteristics.

4.4 Flow of damage detection based on modal parameters

Fig.10 shows the flow of damage detection by localization and quantification based on the sensitivities of modal parameters to damages. Firstly, a brief evaluation for the location of damage can be carried out using all or a portion of modal parameters constituted by natural frequencies $f_{1\text{-}1}$, $f_{1\text{-}2}$, $f_{2\text{-}2}$, damping constants $\zeta_{1\text{-}1}$, $\zeta_{1\text{-}2}$, and phase differences $\psi_{1\text{-}1}$, $\psi_{2\text{-}1}$. At the first

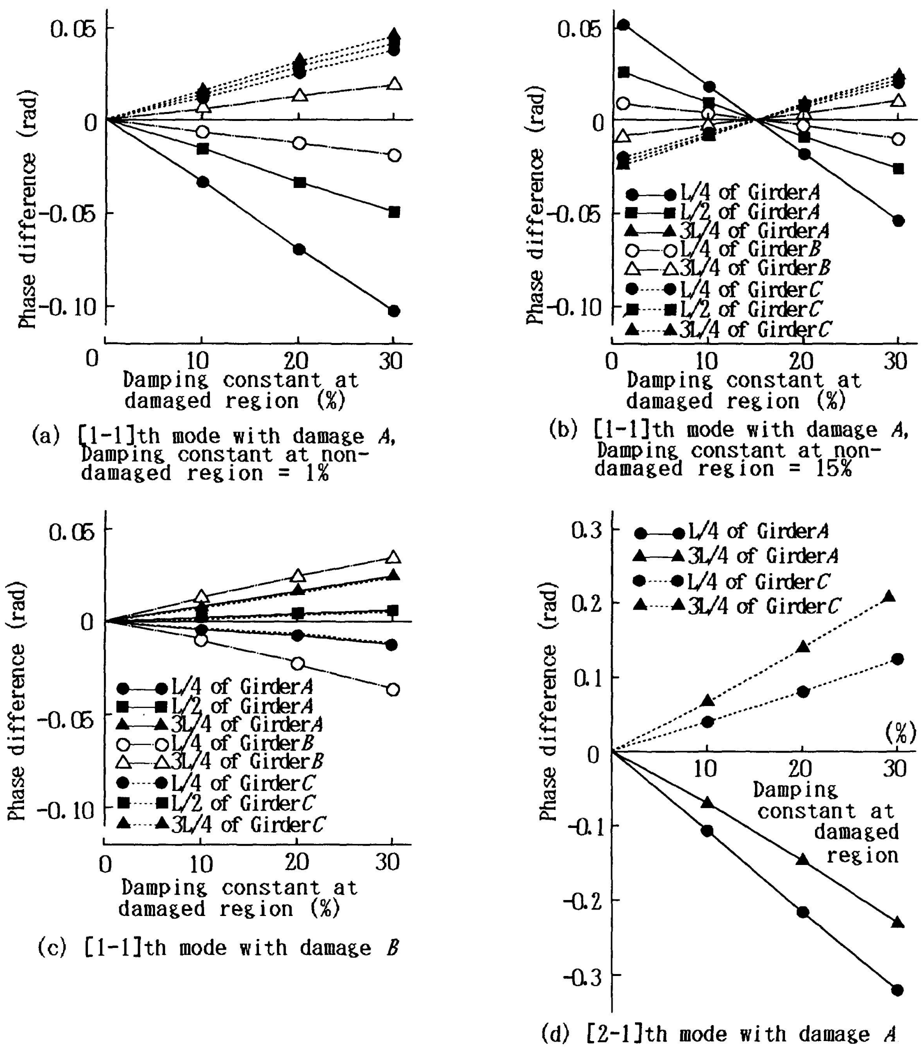

Fig.9 Characteristics of phase angle

step, the existence of damage can be detected by searching whether the parameters ($f_{1\text{-}1}$ and $f_{2\text{-}1}$), $\zeta_{1\text{-}1}$, $\psi_{1\text{-}1}$ indicate large values. After this, at the second step, localization of the damages i.e. the distinction between damage the inside girder or the outside girder, can be carried out by searching whether parameters $f_{2\text{-}2}$, $\zeta_{1\text{-}2}$, $\psi_{2\text{-}1}$ indicate large values. Though the above evaluation can be carried out independently for each modal parameter, the final decision for damage detection should be carried out comprehensively by comparison among the results from all parameters. Furthermore, the exact evaluation by localization and quantification of multiple damages can be carried out by the SI method. As the above mentioned procedure, the concise flow and the SI method can be integrated, to enable an efficient damage assessment by the multi-level and multi-aspect approaches.

5. CONCLUSIONS

The main conclusions obtained from this study can be summarized as follows:

(1)For the simplification of analysis of the complex eigenproblem considering non-proportional damping, the CMS method was applied and its suitability was demonstrated.

(2)The SI method based on dynamic sensitivity analysis and the SLP method has been studied and applied to the results of dynamic loading tests performed on an existing concrete bridge in which some specified artificial damage was induced.

(3)The sensitivities of dynamic behaviors to damage were evaluated by analysis and the results could be seen to show that the [2-1]th and [2-2]th natural frequencies, the [1-1]th, [1-2]th and [2-1]th damping constants, and the [1-1]th and [2-1]th phase differences had high sensitivity.

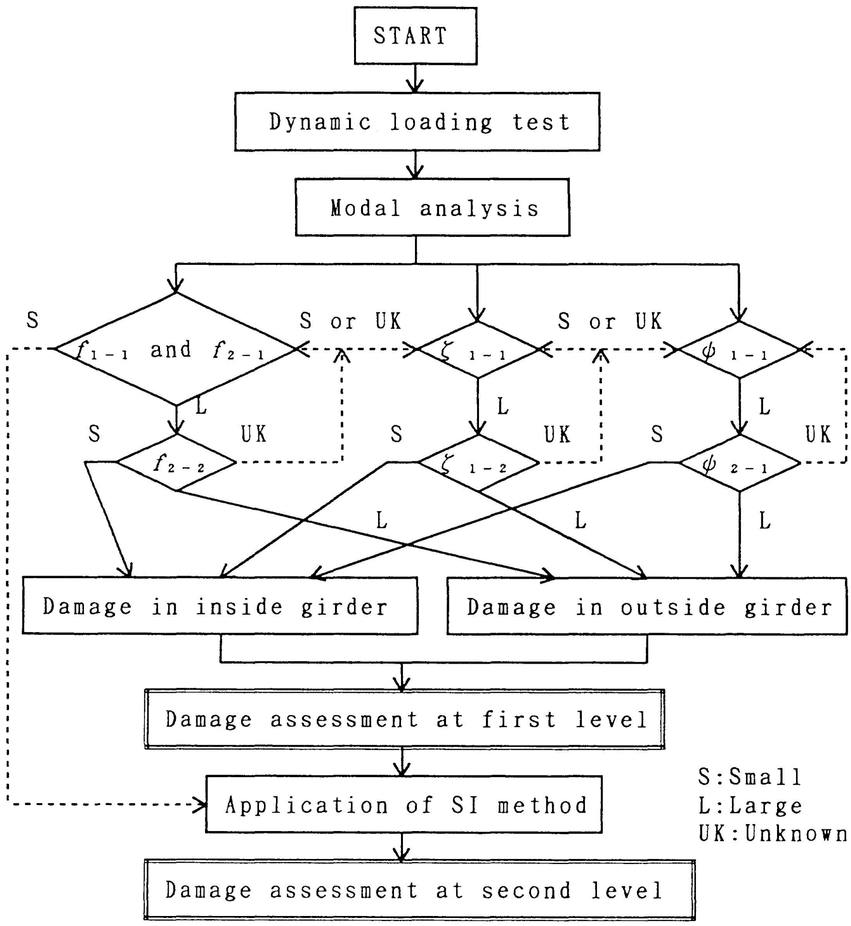

Fig.10 Flow of damage detection

(4)By using these modal parameters, a concise flow of the damage detection without any complex analysis was constructed. Furthermore, this concise flow and the SI method were integrated, to allow efficient damage assessment by multi-level and multi-aspect approaches.

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