모드민감도 패턴인식에 의한 복잡한 구조물의 손상발견

Damage Detection in Complex Structures using Pattern Recognition of Modal Sensitivity

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ABSTRACT

A methodology to identify a baseline modal model of a complicated 3-D structure using limited structural and modal information is experimentally examined. In the first part, a system's identification theory for the methodology to identify baseline modal responses of the structure is outlined. Next, an algorithm is designed to build a generic finite element model of the baseline structure and to calibrate the model by using only a set of post-damage modal parameters. In the second part, the feasibility of the methodology is examined experimentally using a field-tested truss bridge for which only post-damaged modal responses were measured for a few vibration modes. For the complex 3-D bridge with many members, we analyzed to identify unknown stiffness parameters of the structure by using modal parameters of the initial two modes of vibration.

1. INTRODUCTION

For large structures such as bridges, buildings, and offshore jackets, an accurate and reliable capability of damage detection in critical members is the key to ensure the structural safety since damage in those members causes local or global failures of the structural systems and also results in catastrophic disasters, such as loss of lives, human suffering, and expenses of properties. During the past decade, a significant amount of research has been conducted in the area of damage detection via changes in modal responses of a structure. For example, research studies have related changes in eigenfrequencies to changes in beam properties,[1] located defects in beam elements from changes in eigenfrequencies,[2,3] attempted to monitor the integrity of offshore platforms,[4] attempted to monitor structural integrity of bridges,[5] and investigated the feasibility of damage detection in space structures using changes in modal parameters.[6] Recently, research efforts have been focused on solving the problem: to detect damage in civil engineering structures: (1) with many members (e.g., complex structures such as 3-D truss structure); (2) for which only a few modal parameters are available; and (3) for which baseline (i.e., as-built, undamaged state) modal responses were not recorded (e.g., the majority of existing structures).[7-10]

By definition, a baseline structure is a structure with the same topology as the one given minus the damage accumulated over the period of interest. It is impossible to know with complete certainty the initial stiffness and mass distribution of the pristine structure. However, given a knowledge of the structure and engineering judgment, we can propose possible pristine structure. In case of simple structures such as beams, we can make such judgments with great certainty. [1] In case of more complicated structures, our confidence to propose a related pristine structure will depend on the availability of as-built documentation of the structure. Once a pristine structure has been proposed, techniques from system identification along with the dynamic response of the post-damaged structure can be used to evaluate the defining parameters of the pristine structure.

The objective of this paper is to present a robust methodology that identifies baseline modal models from the use of limited structural and modal information of existing structures. The presentation is outlined in two parts. In the first part, we describe the general methodology of baseline modeling. We first outline a system's identification theory to identify baseline modal responses of the structure.

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Next, we schematize an algorithm to design a generic finite element model of the baseline structure and to calibrate the model by using experimental data. In the second part, we examine the feasibility of the methodology using a field-tested truss bridge for
which only post-damaged modal responses were measured for a few vibration modes. For the complex bridge with many members, we are partially lack of knowledge on structural geometry, material properties, and boundary conditions.

2. SMART BASELINE MODELING METHODOLOGY

The general scheme shown in Fig. 1 represents an algorithm of damage detection in structures for which only post-damaged modal parameters are available.[10] It is clear from Fig. 1 that the reliability of damage detection model of structure lies upon the accuracy of baseline modal parameters.

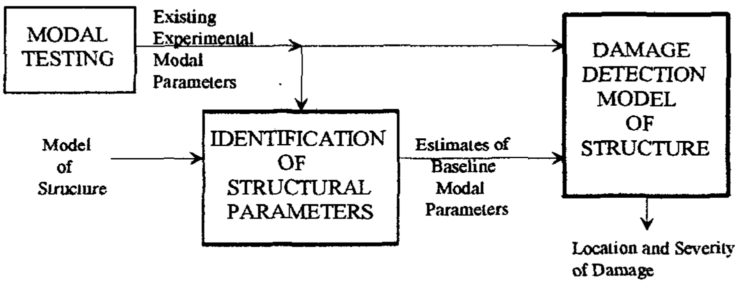

Fig. 1. Schematic of Approach Used to Detect Damage in Structures Without Baseline Modal Data

Then the problem to be solved is to develop a system identification method to generate baseline modal parameters of a structure for which only a set of post-damage modal parameters are available. We provide the solution to the problem in two steps. Firstly, we outline a system's identification theory of baseline modal responses of the structure. Secondly, we design a baseline modeling methodology by first proposing a generic finite element model of the baseline structure and next calibrating the model experimentally by using the post-damage modal parameters.

2.1 System's Identification Theory

Consider a linear skeletal structure with *NE* members and *N* nodes. Then suppose $\mathbf{k}_j^*$ is the unknown stiffness of the j^{th} member of the structure for which *M* eigenvalues, λ^{ST}, are known. Also, suppose $\mathbf{k}_j$ is a known stiffness of the j^{th} member of a finite element (FE) model for which the corresponding set of *M* eigenvalues, λ^{FE}, are known. Then, relative to the FE model, the *fractional stiffness change* of the j^{th} member of the structure, α_j, and the stiffnesses are related as follows:

$$\mathbf{k}_j^* = \mathbf{k}_j(1+\alpha_j) \quad (1)$$

The fractional stiffness change of *NE* members may be obtained using the following equation (see Stubbs and Osegueda (1990) for details)

$$\alpha = \mathbf{F}^{-1}\mathbf{Z} \quad (2)$$

The term α which is a $NE \times 1$ matrix containing the fractional changes in stiffnesses between the FE model and the structure can be determined from Eq. (1). Also, the term **Z** which is a $M \times 1$ matrix containing the fractional changes in eigenvalues between the two systems can be determined as follows:

$$Z_i = \frac{\lambda_i^{ST} - \lambda_i^{FE}}{\lambda_i^{FE}} \quad (3)$$

The term **F** which is a $M \times NE$ modal sensitivity matrix relating the fractional changes in j^{th} member's stiffnesses to the fractional changes in i^{th} modal eigenvalues can be determined as follows:

$$F_{ij} = K_{ij}/K_i \tag{4}$$

In Eq. (4), K_i and K_{ij} are, respectively, the i^{th} modal stiffness and the contribution of the j^{th} member to the i^{th} modal stiffness.

$$K_i = \Phi_i^T \mathbf{C} \Phi_i \ , \quad K_{ij} = \Phi_i^T \mathbf{C}_j \Phi_i \tag{5}$$

where Φ_i is the i^{th} modal vector, $\mathbf{C}$ is the system stiffness matrix, and $\mathbf{C}_j$ is the contribution of j^{th} member to the system stiffness matrix of the FE model.

An approach to estimate stiffness parameter $\mathbf{k}$ of the FE model is the minimization of an object function in the form of an error function. We consider the simplest case in which the mass of the system is known. Then the following object function is considered

$$\mathbf{J}(\mathbf{k},\mathbf{k}^*) = \frac{1}{\mathrm{M}}\sum_{i=1}^{\mathrm{M}}\left\|(\lambda_i^{ST} - \lambda_i^{FE})/\lambda_i^{FE}\right\| \ , \quad \lambda_i^{ST} = \lambda_i(\mathbf{k}^*) \text{ and } \quad \lambda_i^{FE} = \lambda_i(\mathbf{k}) \tag{6}$$

which represents a norm of the fractional changes in eigenvalues between the FE model and the structure. The optimal set of stiffness parameters can be found from solving the following problem

$$\text{Find} \quad \mathbf{k} \in \mathbf{R}^{NE} \quad \text{to minimize} \quad \mathbf{J}(\mathbf{k},\mathbf{k}^*) \tag{7}$$

Formally, the problem is solved by first explicitly solving Eq. (2) to estimate stiffness changes (i.e., to compute the $NE \times 1$, α matrix) and next solving Eq. (1) to update the stiffness parameter $\mathbf{k}_j$ of the FE model until $\mathbf{Z} \cong 0$ or $\alpha \cong 0$ (i.e., as they approach zero).

2.2 Design of Methodology

The minimum design requirements for the methodology to be described include the following: first, the methodology should accurately identify the baseline modal model; second, the methodology should use minimum modal parameters; and third, the methodology should be so general to be applied to any structures for which measured modal parameters are available. A series of components which include all methods and techniques needed to satisfy the design requirement are schematized in Fig. 2. Each component is described below.

Existing Structure: An existing structure with unknown stiffness $\mathbf{k}^*$ is defined as input. The input data include modal parameters (i.e., modes measured, resonance frequencies, and mode shapes) and structural information on geometry, boundary conditions, and material types used in the structure.

Initial FE Model: A linear FE model with stiffness $\mathbf{k}$ of NE specific types of elements is selected and structural mass is assumed to be known. Its modal parameters of the M modes are computed numerically. Then modal sensitivities of M modes and NE elements are computed using Eq. (4).

Smart Modeling: In the first step, we define element groups of the FE model. In order to avoid ill-conditioning Eq. (2), the total number of element groups should not be quite larger than the number of measured modes M (see Ref. 6 for details). Each element group is selected by quantifying its sensitivities to vibration modes. In the second step, we define a membership function $m_A(x)$ (see Ref. 11 for details)

$$m_A(x) = Degree(x \in A) \tag{8}$$

where A is an element group and x is an element of the initial FE model. The membership function measures the elementhood or degree to which the element x belongs to the element group A.

Element-Group To Fine-Tune: In the first step, element groups which have a lack of knowledge on structural parameters such as geometric or material properties are selected to be fine-tuned. The number of element groups (NG) to be fine-tuned is equal to the total element groups minus element groups not to be fine-tuned. The element groups not to be fine-tuned are selected on the basis of the availability of structural properties. In the second step, the $M \times NG$, F-matrix for M modes and NG groups is determined From Eq. (4).

Parameter Identification: Firstly, a $M \times 1$, **Z**-matrix (i.e., the fractional changes in eigenvalues between the FE model and the structure) is computed using Eq. (3). Secondly, a $NG \times 1$, α-matrix (i.e., the fractional changes in stiffnesses between the FE model and the structure) is solved using Eq. (2). Thirdly, the stiffness parameters $\mathbf{k}$ of NG element groups is computed using Eq. (1). Finally, the optimal set of stiffness parameters of NG element groups are determined by solving Eq. (7).

Baseline Modal Model: We select the identified FE model with the optimal set of stiffness parameters as the baseline model. It has a set of NG element group's stiffnesses which are constant to all elements in each element group. Also, it has the frequencies of the damaged (i.e., target) structure but none of its members are damaged. Furthermore, the mode shapes of the baseline model differs from those of the damaged structure. Once the baseline model is identified, its modal parameters for M modes are numerically generated.

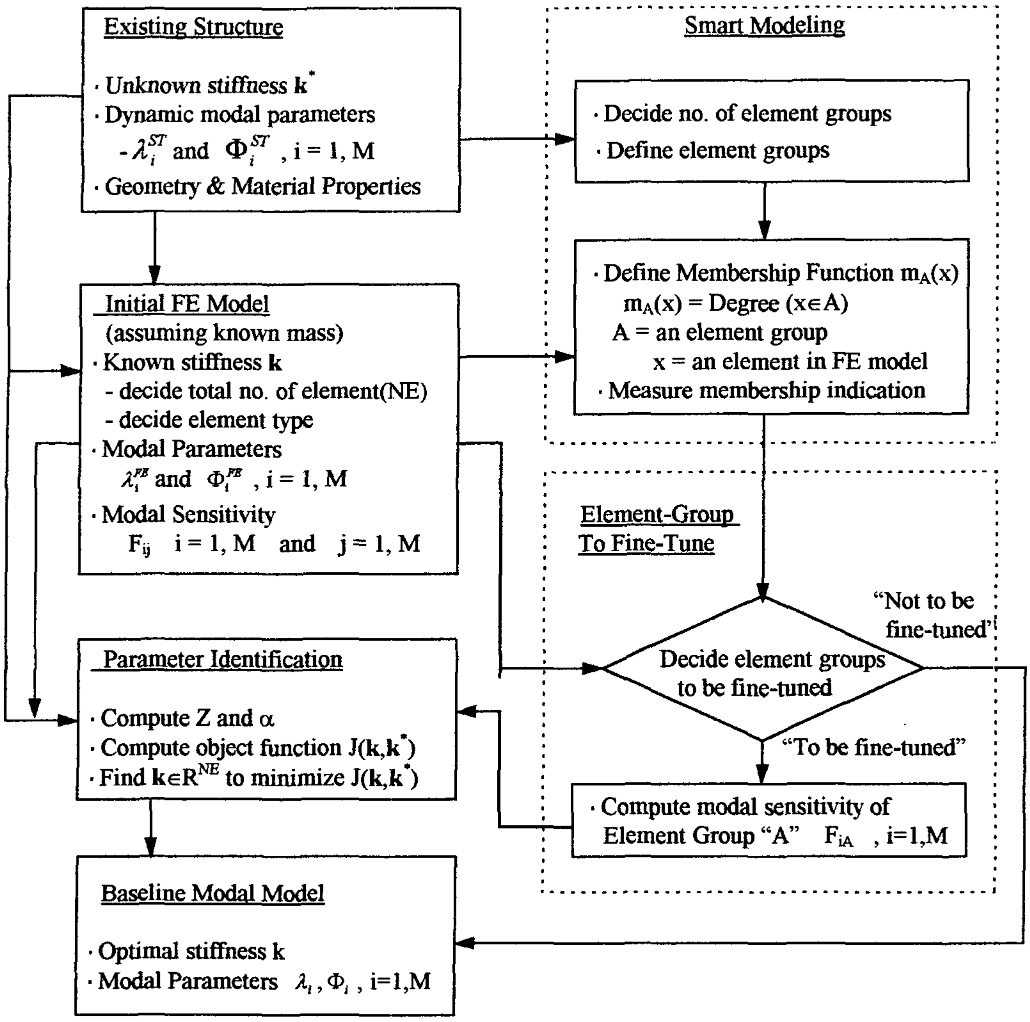

Fig. 2. Schematic of Smart Baseline Modeling

3. EXAMINATION OF METHODOLOGY

3.1 Test Structure

The selected 3-D truss structure is shown in Fig. 3. The truss was constructed in about 1908. After undergone several repairs and modifications, the structure has shaped as a steel truss bridge with a steel framing and 4 inch precast-concrete-slab decks with three 12 inch water lines added to the decks. The 40 foot high steel truss structure supports a 19'-4" roadway. It consists of eleven (11) main structural subsystems which are bottom chords, top chords, middle chords, lower lateral members, upper lateral members, vertical members, diagonal members, portals, precast concrete slab, steel stringers, and three water lines (see Ref. 12 for details).

Vibrational test data of the truss were provided by two accelerometers: a fixed accelerometer placed in the z-direction of node 45 (see Fig. 4) and a roving accelerometer that was moved from joint to joint of the bridge. As shown in Fig. 4, accelerations were measured at the total 66 joints in the bridge. At each joint the roving accelerometer recorded accelerations in the x, y, and z directions. The bridge was excited with an impact from a mass weighing eighty pounds which was dropped about 1.5 feet. The location of excitation was held constant throughout the course of testing. Records of acceleration versus time were recorded for each accelerometer. In all, approximately 170 time histories were recorded for the bridge. Frequency response functions between the roving accelerometer and the fixed accelerometer were generated. Mode shapes and resonant frequencies were extracted from the frequency response function. The extracted (post-damage) modal responses of the bridge include resonant frequencies and mode shapes of the first bending mode and the first torsional mode. The resonant frequencies were (1) 2.1875 Hz for the first bending mode and (2) 3.50 Hz for the first torsional mode. The measured mode shapes of those two modes are shown in Fig. 5.

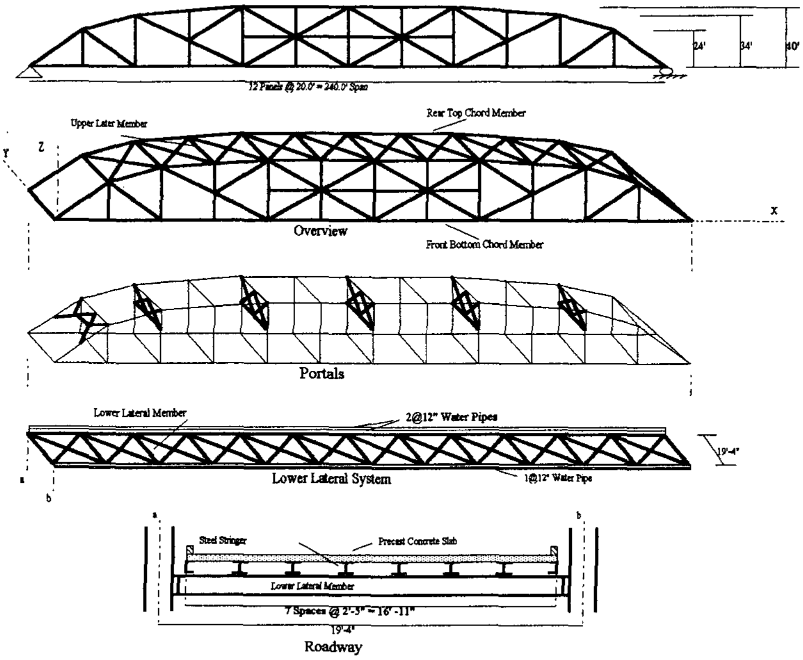

Fig. 3. Schematic of the 3-D Truss Bridge

3.2 Smart Baseline Modeling

The proposed methodology schematized in Fig. 2 was used to identify a baseline modal model of the test structure. In Step One, we selected modal parameters of the two measured modes and structural data of the test structure with unknown stiffness parameters. In Step Two, we selected an initial FE model of 66 nodes and 211 elements as shown in Fig. 4. The FE model consists of eleven subsystems: bottom chords (Subsystem 1), top chords (Subsystem 2), middle chords (Subsystem 3), lower lateral members (Subsystem 4), upper lateral members (Subsystem 5), vertical members (Subsystem 6), diagonal members (Subsystem 7), portals (Subsystem 8), precast concrete slab (Subsystem 9), steel stringers (Subsystem 10), and three water lines (Subsystem 11).

Initial values of material and geometric properties of the FE model were estimated as follows. For elements of Subsystems 1 to 8, Poisson's ratio $\upsilon = 0.3$; the elastic modulus $E = 29 \times 10^6 psi$; the linear mass density $\rho = 7.33 \times 10^{-4} lb \cdot s^2/in^4$. For elements of Subsystem 11, $E = 0$; $\rho = 1.0 \times 10^{-4} lb \cdot s^2/in^4$; and the radius of the pipe section $r = 6\ in$. For plate elements of Subsystem 9, $E = 3.6 \times 10^6 psi$; $\upsilon = 0.15$; $\rho = 2.26 \times 10^{-4} lb \cdot s^2/in^4$; and the plate thickness $t = 4.0\ in$. For plate elements of Subsystem 10, $E = 29 \times 10^6 psi$; $\upsilon = 0.3$; $\rho = 7.33 \times 10^{-4} lb \cdot s^2/in^4$; and the thickness of steel plate $t = 0.2\ in$. See Ref. 12 for detailed data on cross-sectional area and second moment of area of all elements. Modal parameters of the FE model were computed numerically as (1) 2.373 Hz for the first mode and (2) 2.7854 Hz for the second mode. Mode shapes of the two modes are shown in Fig. 6. Next, modal sensitivities for 2 modes and 211 elements of the initial FE model were computed using Eq. (4) (see Fig. 7). In Step Three, we selected three element groups (Group One, Group Two, and Group Three). As shown in Fig. 4, the 11 subsystems of the initial FE model were assigned to one of three element groups based on the availability of structural parameters (e.g., stiffness or flexibility) as well as the sensitivity of those subsystems to vibrational modes. Group One represents elements for which sufficient information on structural parameters is available from field-measurements and as-built designs. As Group One elements, we selected elements in the top, bottom, and middle chords, the diagonal truss members, and the water lines.

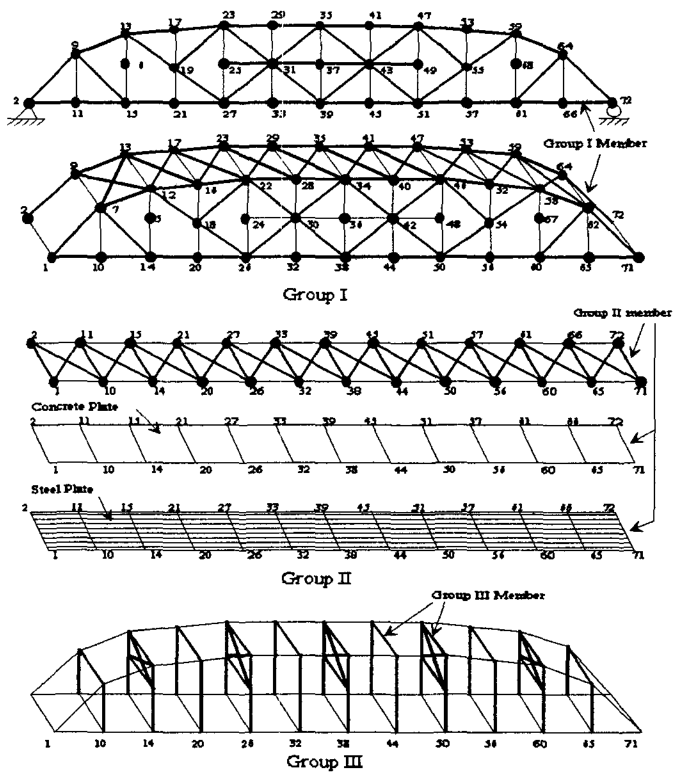

Fig. 4. Schematic of Finite Element Model of the 3-D Truss

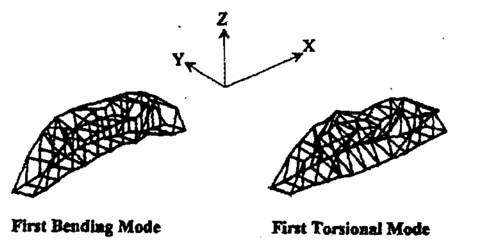

Fig. 5. Measured Mode Shapes of Test Structure

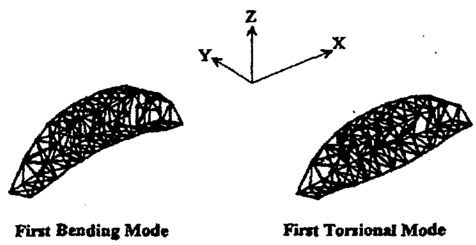

Fig. 6. Mode Shapes of the Finite Element Model

However, Groups Two and Three represent elements with insufficient information on structural parameters. Elements for Groups Two and Three were determined using membership functions. In Table 1, each element group is defined as a function of its sensitivity to the two vibration modes, the first bending mode and the first torsional mode. Group Two has a very small (VS) sensitivity to the motion of the first bending mode and it has also a very large (VL) sensitivity to the motion of the first torsional mode. The membership function of Group Two is "IF X^1 is VS AND X^2 is VL, THEN X is Group Two", in which X denotes an FE element and the superscripts "1" and "2" denote the first mode and the second mode, respectively. For example, X^1 represents the element X's sensitivity to the first mode and X^2 represents the element X's sensitivity to the second mode. Meanwhile, Group Three has a relatively small (RS) sensitivity to the motion of the first bending mode and it has also a relatively large (RL) sensitivity to the motion of the first torsional mode. The membership function of Group Three is "IF X^1 is RS AND X^2 is RL, THEN X is Group Three". Using these membership functions, the lower lateral members, the pre-cast concrete slab, and the steel stringers were selected as Group Two elements. Also, the upper lateral members, the vertical truss members, and the portal members were selected as Group Three elements. In Step Four, two element groups, Groups Two and Three, were selected to be fine-tuned. The two element groups were selected since elements in those groups have insufficient information on the geometric and material properties (note that Group One was not selected as stated previously). The 2x2 F-matrix for the two measured modes and the two element groups (i.e., Groups Two and Three) was computed as shown in Table 2. For a given mode, each sensitivity represents the fraction of modal energy stored in the particular element group.

Table 1. Element-Group's Membership to Vibration Modes

MODE / GROUP	First Bending Mode	First Torsional Mode
Group Two	VS	VL
Group Three	RS	RL

In Step Five, stiffness parameters of Groups Two and Three were optimized to identify a realistic analytical model of the 3-D truss. For the fine-tuning exercise, flexural rigidity and torsional rigidity were selected as stiffness parameters of Group Two and Group Three, respectively. The results, using two frequencies and five iterations, are listed in Table 3. After the iterations, the frequencies were identified within one percent error-range of the target values. The values of the material properties (the elastic moduli) under the five iterations are summarized in Table 4. Note that the values of the effective elastic moduli represent stiffness parameters of Group Two and Group Three assuming that the geometric properties remain constant. In Step Six, from the results of parameter identification, the FE model after the fifth iteration was selected as the baseline modal model. Natural frequencies of the two modes are 2.1946 Hz for the first flexural mode and 3.4761 Hz for the first torsional mode. Typical numerically generated mode shapes of the first two modes are shown in Fig. 6.

Table 2. Modal Sensitivity Used to Fine-Tune the FE Model

	Sensitivity	
Mode	Group Two	Group Three
1 (First Bending)	0.5609	0.4391
2 (First Torsion)	0.0913	0.9087

Table 3. Values of Natural Frequencies for Parameter Identification

		Iteration Number					
Mode	Initial-Guess	1	2	3	4	5	Target
1	2.3730	2.2268	2.2042	2.1982	2.1958	2.1946	2.1850
2	2.7854	2.9955	3.2445	3.3797	3.4462	3.4761	3.5000

Table 4. Values of Elastic Moduli (psi) of Element-Groups for Parameter Identification

Element Group	Initial-Guess	Iteration Number 1	2	3	4	5
Group Two	29.0E6	4.87E6	2.87E6	2.35E6	2.15E6	2.05E6
Group Three	29.0E6	49.9E6	72.01E6	86.30E6	93.93E6	97.60E6

3.3 Quantification of Baseline Modal Model

In order to justify the selection of the baseline structure, we quantify the differences between the modal sensitivities of the identified baseline model and the modal sensitivities of the existing structure (i.e., the 3-D truss bridge). Let a set of sensitivities of the baseline model be given by $\mathbf{u} \in R^N$ and another set of sensitivities of the existing structure be given by $\mathbf{v} \in R^N$, in which R^N is the space of order NE (i.e., the number of elements). Given the two sets of the sensitivities of the first two modes, we computed the sensitivity assurance criterion (SAC) which is defined as (see Ref. 9 for details)

$$\mathrm{SAC}(\mathbf{u},\mathbf{v}) = 1 - \frac{(\mathbf{u},\mathbf{v})^2}{(\mathbf{u},\mathbf{u})(\mathbf{v},\mathbf{v})} \tag{9}$$

Eq. (9) quantifies the difference in orientation between **u** and **v**, without regard to scaling difficulties arising from choice of numerical distance units. If $\mathrm{SAC}(\mathbf{u},\mathbf{v}) = 0$, then the vectors **u** and **v** are perfectly correlated.

The sensitivities of the baseline model were computed for 2 modes and 211 elements by solving Eq. (4) from the modal parameters and stiffness parameters of the identified FE model. Fig. 7 shows modal sensitivities of the baseline model. The corresponding modal sensitivities of the existing structure were computed by solving Eq. (4) from the measured modal parameters of the existing structure and the stiffness parameters of the identified FE model. Fig. 8 shows modal sensitivities of the existing structure. From substituting the results of Fig. 7 and Fig. 8 into Eq. (9), the SAC value between the existing structure and the identified baseline model was found to be 0.015. From this result, we observe that the baseline model shows good identification to the existing structure except at several elements which may be severely damaged. Noting that assessing the effect of modeling errors and measurement noises is the topic of another on-going research, we conclude the baseline modal parameters are identical to undamaged modal parameters of the existing structure.

4. SUMMARY AND CONCLUSION

A structural identification methodology was experimentally tested to examine its feasibility to identify baseline modal model of complicated 3-D structure from the use of limited structural and modal information. The investigation was presented in two parts. In the first part, we described the general methodology of baseline modeling. We first outlined a system's identification theory to identify baseline modal responses of the structure. Next, we schematized an algorithm to design a generic finite element model of the baseline structure and to calibrate the model by using experimental data. In the second part, we examined the feasibility of the methodology using a field-tested truss bridge for which only post-damaged modal responses were measured for a few vibration modes. For the complex 3-D bridge with many members, we were partially lack of knowledge on structural geometry, material properties, and boundary conditions.

Results of the baseline modeling in the 3-D truss bridge demonstrated the feasibility of the methodology. Using the methodology, we analyzed to identify unknown stiffness parameters of the structure by using modal parameters of the initial two modes of vibration. On-going research by the authors includes the assessment of the methodology's practicality on the damage detection practice of large structures with many complex members for which limited structural and modal information are available.

ACKNOWLEDGMENTS

The study presented in this paper was supported by KOSEF (Korea Science & Engineering Foundation) under research project 961-1203-015-1.

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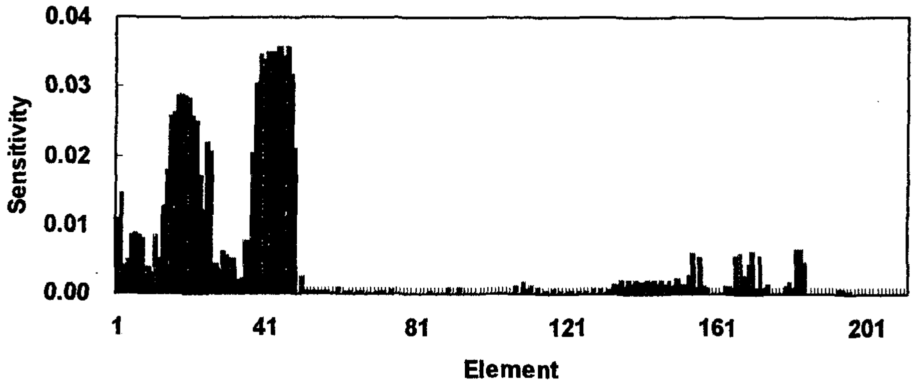

Fig. 7. Modal Sensitivity of the Baseline (Identified FE) Model for Mode 1

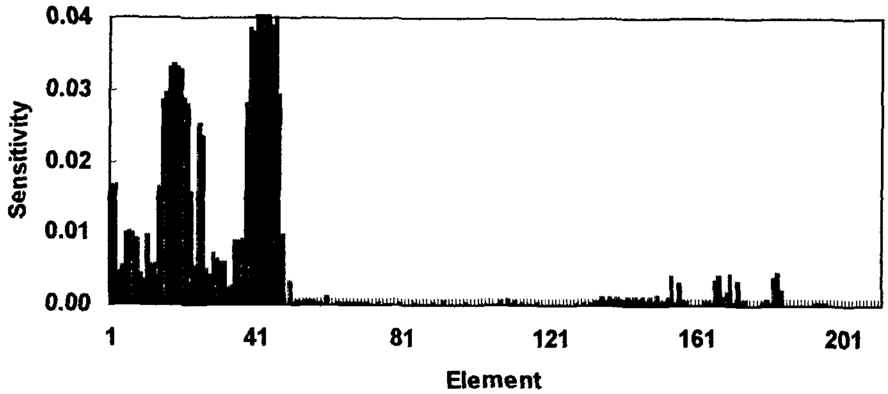

Fig. 8. Modal Sensitivity of the Existing Structure for Mode 1