⊙ 論 文

Damage Detection in Jacket-Type Offshore Structures From Few Mode Shapes

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(1994년 4월 30일 접수)

소수의 모드형상을 이용한 자켓형 해양구조물의 손상추정에 대한 연구

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Key Words : Dynamic Responses, Modal Analysis, Damage Detection, Nondestructive, Sensitivity Analysis, Offshore Jacket Structures

초 록

본 연구에서는, 소수의 모드형상의 진동반응만이 측정된 자켓형 해양구조물에 존재하는 손상의 위치와 그 크기를 결정할 수 있는 알고리듬이 제시된다. 먼저, 모드형상의 변화로부터 직접 손상위치와 크기를 결정하는 이론이 제시된다. 다음으로, 세개의 진동모드형상이 측정된 자켓형 해양구조물의 수치예를 이용하여 알고리듬의 적합성이 예증된다. 본 연구의 결과는 다음과 같다. 첫째로, 자켓형 해양구조물에 존재하는 손상의 위치가 정확하게 예측되었다. 둘째로, 예측된 손상의 크기가 비교적 정확하게 예측되었다.

Abstract

An algorithm to locate and estimate severity of damage in jacket-type offshore structures for which modal responses are available for very few vibrational modes is presented. First, a theory of damage locaization and severity estimation(which yields information on the location and severity of damage directly from changes in mode shapes) is formulated. Next, the feasibility the damage detection algorithm is demonstrated by using a numerical example of an offshore jacket platform for which only three vibration modes are measured. Form the material presented here, two major results are observed. First, all damage locations in the offshore jacket platform are correctly predicted. Next, predicted damage is relatively correctly estimated.

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1. INTRODUCTION

This paper deals with the general problem of utilizing changes in modal parameters(i.e., frequencies, damping, and mode shapes) to nondestructively detect, locate, and size damage in offshore platforms. Structural damage may be defined as any deviation of a geometric or material property defining a structure that may result in unwanted responses of the structure. A solution to this problem is important for at least two reasons. Firstly, damage localization and severity estimation are the first two steps in the broader category of damage assessment. Secondly, a timely damage assessment could produce, among other things, desirable consequences such as saving of lives, reduction of human suffering, enhanced protection of property, increased structural reliability, increased productivity of operations, and reduction in maintenance costs.

The majority of offshore oil-production platforms are jacket-type, welded, steel tubular, space frames[1]. Periodic inspections for damage in these structures are mandatory, because critical damage can result from hostile environmental loads such as fatigue or ship collision. Such inspections are currently performed by divers using visual inspection techniques[2]. However, many adverse conditions (e.g., poor visibility, concealment of damage by marine growth, prohibitive cost, unacceptable hazard in deep water, non availability of properly trained divers, and dependence of inspection on weather condition) limit, both technically and economically, the effectiveness of the inspection[3, 4].

During the past decade, a significant amount of research has been conducted in the area of nondestructive damage detection (NDD) using changes in modal parameters. Research studies have related changes in eigenfrequencies to changes in beam properties such as cracks, notches or other geometrical changes[5, 6, 7], and also focused on the possibility of using the vibration characteristics of structures as an indication of structural damage[8, 9, 10]. More recently, studies have been made to monitor structural integrity of bridges[11, 12], and to investigate feasibility of damage detection in large space structures using changes in modal parameters[13, 14]. In offshore applications, research efforts have been made to detect changes in structural integrity by monitoring changes in frequencies[15, 16, 17, 18] and by monitoring changes in mode shapes of offshore platforms[3, 4, 19].

Despite these research efforts, many NDD-related problems of jacket-type structures remain to be solved. Outstanding needs still remain to locate and estimate the severity of damage in offshore platforms : (1) with many members, (2) for which only few mode shapes are available (e.g., massive offshore structures for which only the lower modes can be excited and measured), (3) for which undamaged modal responses are not available (e.g., the majority of existing jacket platforms), and (4) in an environment of modeling, measurement, and processing uncertainties.

The objective of this paper is to present a damage detection algorithm to locate and estimate the severity of damage in jacket-type offshore structures for which predamage and post-damage modal parameters are available for very few vibration modes. In order to achieve this objective, the investigation is performed in two parts. First, we propose a damage detection algorithm. We formulate a theory of damage localization and severity estimation which yields information on locations and magnitudes of damage directly from changes in mode shapes of structures. Next, we demonstrate the feasibility of the damage detection algorithm by using a numerical example of an offshore jacket platform for which only three vibration modes are measured. Here, the damage detection algorithm will be considered feasible if damaged members in structures can be located and sized using straightforward computational procedures and criteria.

2. DAMAGE DETECTION ALGORITHM

2. 1 Damage Localization Theory

Consider a linear, undamaged, skeletal structure with NE elements and N nodes. The i^{th} modal stiffness, K_i, of the arbitrary structure is given by[20]

$$K_i = \Phi_i^T C \Phi_i \quad \cdots\cdots (1)$$

where Φ_i is the i^{th} modal vector and C is the system stiffness matrix. The contribution of the j^{th} member to the i^{th} modal stiffness, K_{ij}, is given by

$$K_{ij} / \Phi_i^T C_j \Phi_i \quad \cdots\cdots (2)$$

where C_j is the contribution of the j^{th} member to the system stiffness matrix.

The fraction of modal energy for the i^{th} mode that is concentrated in the j^{th} member(i.e., the sensitivity of the j^{th} member to the i^{th} mode) is given by

$$F_{ij} = K_{ij} / K_i \quad \cdots\cdots (3)$$

Let the corresponding modal parameters in Eqs. 1 to 3 associated with a subsequently damaged structure be characterized by asterisks. Then for the damaged structure

$$F^*_{ij} = K^*_{ij} / K^*_i = F_{ij}\left(1 + \sum_{k=1}^{NE} A_{ik}\alpha_k + H.O.T.\right) \cdots (4)$$

where K^*_{ij} and K^*_i are given by, respectively,

$$K^*_{ij} = \Phi_i^{*T} C^*_j \Phi^*_i, \text{ and } \cdots\cdots (5)$$

$$K^*_i = \Phi_i^{*T} C^* \Phi_i^* \quad \cdots\cdots (6)$$

where A_{ik} represents a set of coefficients associated with the mode i and location k ; α_k is the fraction of damage at location k in the structure ; and H.O.T. stands for higher order terms. On dividing Eq. 4 by Eq. 3, we obtain

$$\frac{F^*_{ij}}{F_{ij}} = \frac{K^*_{ij}}{K_{ij}} \frac{K_i}{K^*_i} \quad \cdots\cdots (7)$$

The quantities C_j and C^*_j in Eq. 2 and Eq. 5 may be written as follows ;

$$C_j = E_j C_{jo}, \text{ and } \cdots\cdots (8)$$

$$C^*_j = E^*_j C_{jo} \quad \cdots\cdots (9)$$

where the scalars E_j and E^*_j, respectively, are parameters representing the material stiffness properties of undamaged and damaged j^{th} member of the structure and the matrix C_{jo} involves only geometric quantities(and possibly terms containing Poisson's ratio).

On comparing Eqs. 3 and 4, we make the following observations : (1) for each location we can write an equation for each mode ; (2) if the damage is to be specified in a small region, then we will have a large number of equations to define the system ; and (3) we must find a way to determine the linear coefficients A_{ik} and the higher order terms. Before we proceed as suggested above, we pose the following question : Is there a way to utilize Eq. 7 without having to determine A_{ik} and solve a large system of linear or nonlinear equations ?

To provide an answer to the question, we resort to the following simplification. We have observed from experiment results (see Ref. [21]) that the geometry of mode shapes in the vicinity of an undamaged element of a structure changes very little when the structure is damaged elsewhere. It has also been experimentally observed that relative modal deformations(i.e., Φ_i) at a given location are larger after damage occurred(i.e., stiffness reduction occurs). Both of these observations are consisten (to a first approximation) with the approximation that the modal strain energy (F_{ij}) in an element remains the same before and after the damaging episode.

Consequently, we impose the approximation :

$$F_{ij}=F^*_{ij} \quad \cdots\cdots (10)$$

On substituting Eqs. 1, 2, 5, 6, 8, 9, and 10 into Eq. 7 ; and rearranging, we obtain

$$\beta_j=\frac{E_j}{E^*_j}=\frac{[\Phi_i^{*T}C_{jo}\Phi^*_i]K_i}{[\Phi_i^T C_{jo}\Phi_i]K^*_i} \quad \cdots\cdots (11)$$

in which the term β_j is the damage localization indicator for the j^{th} member. All quantities on R. H.S. of Eq 11 can be obtained from the experimental measurements and the geometry of the structure.

From Eq. 11, damage is indicated at the j^{th} member if $\beta_j > 1$. However, note that if the j^{th} member is at or near a node of the i^{th} mode, the denominator of Eq. 11 goes to zero and a false prediction of damage results occurs. We overcome this limitation(i.e., that of false positive prediction) in the following manner. Adding unity to both sides of Eq. 10 yields

$$1=\frac{F^*_{ij}+1}{F_{ij}+1} \quad (12)$$

Substituting for F^*_{ij} and F_{ij} using Eqs. 3 and 4 yields

$$1=\frac{(K^*_{ij}+K^*_i)K_i}{(K_{ij}+K_i)K^*_i} \quad \cdots\cdots (13)$$

Utilizing expressions for K^*_{ij} and K_{ij} in Eqs. 2 and 5 along with the relationships given in Eqs. 8 and 9, Eq. 13 is transformed to

$$1=\frac{E^*_j}{E_j}\frac{\left[\Phi_i^{*T}C_{jo}\Phi^*_i+\frac{1}{E^*_j}\sum_{k=1}^{NE}\Phi_i^{*T}C^*_k\Phi^*_i\right]}{\left[\Phi_i^T C_{jo}\Phi_i+\frac{1}{E_j}\sum_{k=1}^{NE}\Phi_i^T C_k\Phi_i\right]}\frac{K_i}{K^*_i} \quad \cdots\cdots (14)$$

Form which a new β_j may be defined as

$$B_j=\frac{\left[\Phi_i^{*T}C_{jo}\Phi^*_i+\frac{1}{E^*_j}\sum_{k=1}^{NE}\Phi_i^{*T}C^*_k\Phi^*_i\right]}{\left[\Phi_i^T C_{jo}\Phi_i+\frac{1}{E_j}\sum_{k=1}^{NE}\Phi_i^T C_k\Phi_i\right]}\frac{K_i}{K^*_i} \quad \cdots\cdots (15)$$

On substituting Eqs. 8 and 9 into Eq. 15, we simplify the latter damage localization indicator

$$B_j=\frac{\left[\Phi_i^{*T}C_{jo}\Phi^*_i+\frac{1}{E^*_j}\sum_{k=1}^{NE}\Phi_i^{*T}E^*_k C_{ko}\Phi^*_i\right]}{\left[\Phi_i^T C_{jo}\Phi_i+\frac{1}{E_j}\sum_{k=1}^{NE}\Phi_i^T E_k C_{ko}\Phi_i\right]}\frac{K_i}{K^*_i}$$

$$\approx\frac{\left[\Phi_i^{*T}C_{jo}\Phi^*_i+\sum_{k=1}^{NE}\Phi_i^{*T}C_{ko}\Phi^*_i\right]}{\left[\Phi_i^T C_{jo}\Phi_i+\sum_{k=1}^{NE}\Phi_i^T C_{ko}\Phi_i\right]}\frac{K_i}{K^*_i} \quad \cdots (16)$$

Next we established statistical criteria for damage localization. For a given set of modes, the locations of damage are selected on the basis of a rejection of hypotheses in the statistical sense. Firstly, the values $\beta_j (j=1, 2, 3, \cdots, NE)$ associated with each member are treated as a realization of a random variable β. The normalized indicator is given by :

$$Z_j=\frac{\beta_j-\bar{\beta}_j}{\sigma_j} \quad \cdots\cdots (17)$$

in which the terms $\bar{\beta}_j$ and σ_j represent, respectively, the mean and the standard deviation of the indicators of β. The localization scheme used here constitutes essentially a detector which accepts a specific value of the damage index as input and provides as output a decision regarding the likelihood that the structure is damaged at that location. The null hypothesis is that the structure is not damaged at the j^{th} member(i.e., H_o). If H_o is true, we assume the distribution of the damage indices to be given by $f_\beta(\beta/H_o)$. The alternate hypothesis is that the structure is damaged at the

j^{th} member (i.e., H_1). For a given damage index β_j, the probability that the structure is not damaged at the j^{th} member when H_1 is true is given by

$$P_j = 1 - \int_0^{\beta_j} f_\beta(\beta/H_o)d\beta \cdots\cdots (18)$$

or the confidence that the j^{th} member is a damaged location is $1-P_j$.

2.2 Damage Severity Estimation Theory

Damage severity can be estimated directly from Eq. 11. Let the fractional change in the stiffness of the j^{th} member be given by α_j, such that $\alpha_j \geq -1$, then by definition

$$E^*_j = E_j(1+\alpha_j) \cdots\cdots (19)$$

Combining Eq. 11 and Eq. 19 yields

$$\alpha_j = \frac{[\Phi_i^T C_{jo} \Phi_i]}{[\Phi_i^{*T} C_{jo} \Phi^*_i]} \frac{K^*_i}{K_i} - 1 \cdots\cdots (20)$$

Note that the use of the approximation of Eq. 10 will result in an overestimate of the damage severity because here we estimate Eq. 6 by the equation $K^*_i \cong \Phi_i^{*T} C \Phi^*_i$ but in reality $|C| > |C^*|$. Note also that we estimate K^*_i in this manner since the damage location and severity are assumed to be unknown.

3. NUMERICAL EXAMPLE : AN OFFSHORE JACKET PLATFORM

The objective here is to demonstrate the feasibility of the proposed damage detection algorithm to locate and size damage in an offshore jacket platform for which pre-damage and post-damage modal parameters are available for very few vibration modes. We meet this objective in four steps. Firstly, the test structure is identified. Secondly, pre-damage and post-damage modal responses of the test structure are generated using the software package ABAQUS[22]. Thirdly, the validity of the assumption that $F_{ij} = F^*_{ij}$ (i.e., Eq. 10) is tested. Finally, the proposed damage detection algorithm is used to locate and size damage simulated in the test structure.

3.1 Description of the Test Structure

The test structure selected here is an analytical model of an offshore jacket platform (see Reference[1]). As shown in Fig. 1, the main structural subsystems of the model consist of 42 elements that include 12 jacket leg members, 12 horizontal brace members, 6 diagonal brace members in horizontal planes, and 12 diagonal brace members in vertical planes. All members have uniform steel pipe-section of 7.0 inch outer diameter and 0.35 inch pipe thickness. Values for the material and geometric properties are assigned as follows : (1) the elastic modulus $E = 30 \times 10^6 psi$ (210

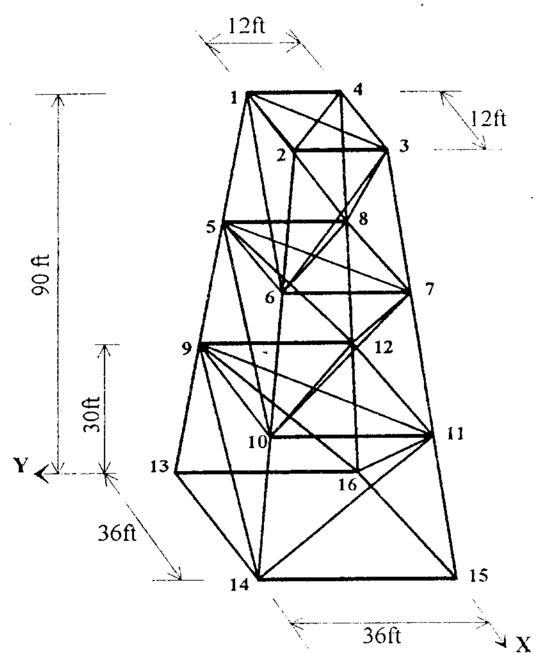

Fig. 1 Test Structure : Offshore Jacket Platform

Gpa) ; (2) Poisson's ratio $\upsilon=0.3$; (3) the cross-sectional area $A=7.7in^2(5.0\times10^{-3}m^2)$; (4) the second moment of area $I=47.12in^4(1.96\times10^{-5}m^4)$; and (5) the linear mass density $\rho=7.33\times10^{-4}$ $lb\cdot s^2/in^4(7850kg/m^3)$. A typical arrangement of 16 sensors(one located at each of the 16 nodal points) on the test structure is also shown in Fig. 1. We assume that each sensor measures motions in all six degrees of freedom. Note that, however, in reality not all degrees of freedom can be measured by sensors.

3.2 Modal Responses of the Test Strcture

We measure, via numerical simulation, modal responses of the test structure. In this example pre-damage and post-damage modal parameters are generated for the first three modes. Here six damage cases are investigated, as summarized in Table 1. The eight damage locations simulated in the six damage cases are shown in Fig. 2. The first four damage cases are limited to the test structure damaged only at a single location. Note that Cases 3 and 4 focused Member 18 in which various magnitudes of damage are simulated. Cases 5 and 6 considered the test structure damaged in two locations. In all cases, damage is simulated in the structure by reducing the second moment of area of the appropriate members. Numerically generated mode shapes for the first three modes are shown in Fig. 3. The pre-damage

Table 1. Damage Scenarios for the Test Structure

Case	Member (s)	Damage	Case	Member (s)	Damage
1	14	−25%	4	18	−25%
2	19	−25%	5	5, 14	−25%, −25%
3	18	−1%	6	18, 32	−25%, −25%

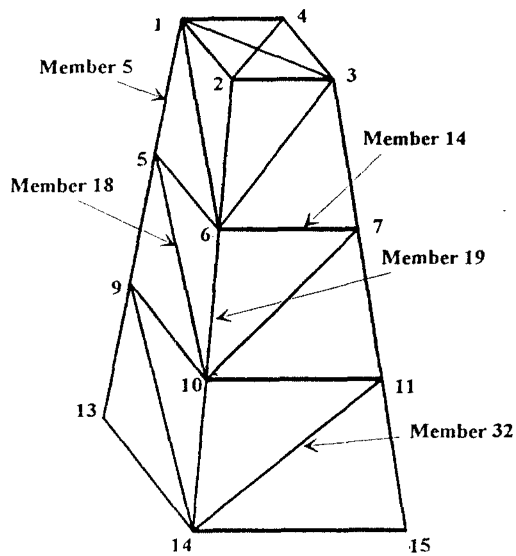

Fig. 2 Damaged Members in Test Structure

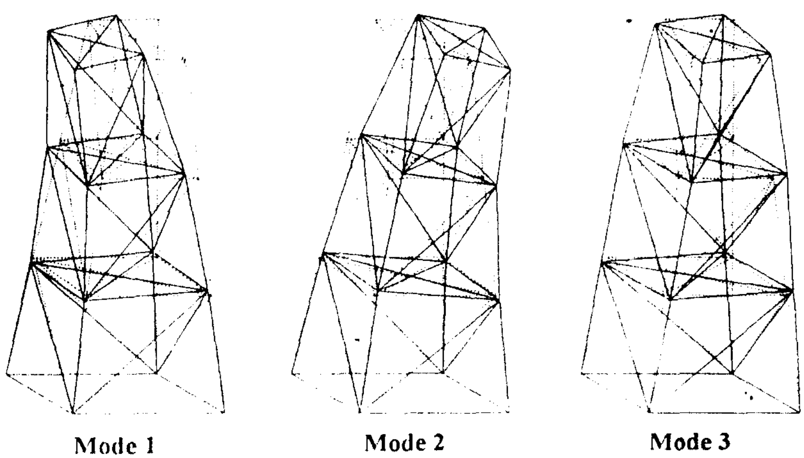

Fig. 3 Mode Shapes of Test Structure

and post-damage (i.e., the six damage cases) frequencies of the first three modes are listed in Table 2. Note that damping coefficients will not be measured in this study since the damage detection technique used here neglect damping.

Table 2. Pre-Damage and Post-Damage Frequencies(Hz) of the Test Structure

Mode Number	Damage Case 1	2	3	4	5	6
1	6.39	6.39	6.39	6.37	6.37	6.35
2	8.92	8.84	8.93	8.88	8.92	8.84
3	13.20	13.22	13.22	13.05	13.20	12.80

3.3 Validation of the Approximation of Eq. 10

We examine the validity of the assumption that $F_{ij}=F^*_{ij}$. Modal sensitivities are generated for the undamaged and damaged structures. First, we select a space frame model (i.e., a model consisting of 42 beam elements). Next, element sensitivities of the model are computed by using Eq. 3 for the undamaged structure and the six damage cases. Note that in this case modal vectors of six degrees of freedom are available for each mode shape. Approximately 252 values of F_{ij} and F^*_{ij} (for j=1,2,3,...42) are computed for the damage cases listed in Table 1. For each corresponding damaged and undamaged case, (F_{ij}, F^*_{ij}) pairs are plotted. The resulting plot is shown in Fig. 4 along with the unity slope line. Except for five points, all other points fall on or very near to the unity line. From these results, we conclude that the assumption is valid for this example.

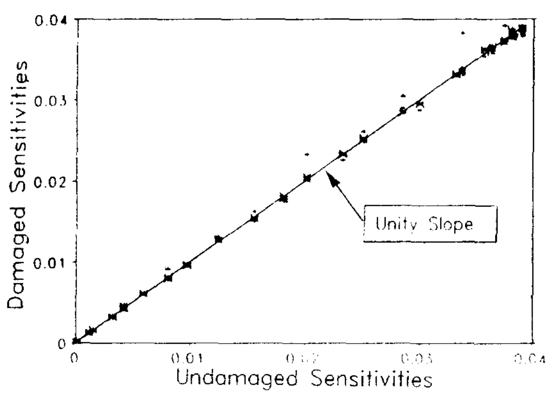

Fig. 4 Comparison of F_{ij} and F_{ij}^* for Test Structure

3.4 Damage Prediction in the Test Structure

The proposed damage detection algorithm is now implemented to locate and estimate severity of damage inflicted in the test structure by using incomplete modal information. This objective is met in three steps. In Step One, we select modal parameters of the test structure. We first obtain a set of incomplete modal data including pre-damage and post-damage mode shapes of the first three modes in which readings at each node consist of only three translational motions in the x, y, and z directions.

In Step Two, we generate modal sensitivities for the undamaged and damaged structures. First, a space truss model (i.e., a model consisting of 42 rod elements) is selected as a damage detection model of the test structure since only three translational motions in x, y, and z directions are available at each joint of the test structure. Here, by damage detection model we mean a mathematical model of a structure with degrees of freedom corresponding to actual sensor readings. Next, the damage localization indicator (i.e., Eq. 16) of the damage detection model is computed for each damage case.

In Step Three, damage localization in the test structure is performed in four steps. Firstly, we compute the damage localization indicator (given by Eq. 16) of the damage detection model (i.e., the space truss model) for each damage scenario. Secondly, the damage localization criterion (given by Eq. 17) is established as follows : (1) select H_0 (i.e., no damage at location i) if $Z_i < 2$ or (2) select the alternate H_1 if $Z_i \geq 2$. This criterion corresponds to a one-tailed test at a significance level of 0.023 (i.e., 97.7 percent confidence level). Thirdly, the criterion is used to select potential damage locations. The predicted and inflicted damage locations for the six damage cases are shown in Fig. 5. Finally, by using the severity estimator (given by Eq. 20), damage severity is es-

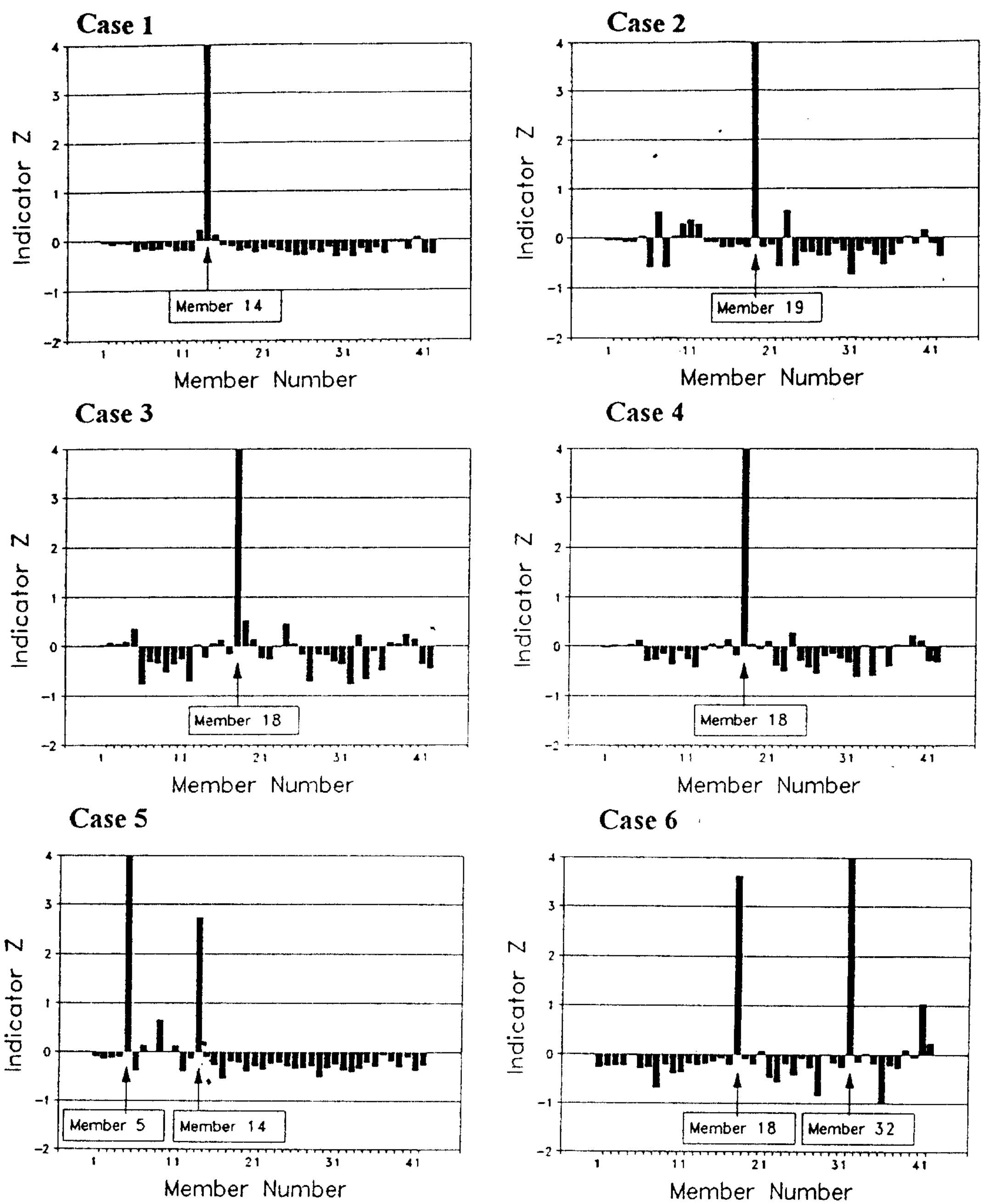

Fig. 5 Damage Localization Results in Test Structure

timated for each predicted demage location shown in Fig. 5. The estinated damage severities are listed in Table 3.

Tabel 3. Severity Estimation Results in the Test Structure.

Damage Case	Damage Location (s)	Simulated Magnitude (s)	Predicted Magnitude (s)	Simulated Predicted Ratio
1	14	−0.25	−0.394	1.58
2	19	−0.25	−0.377	1.51
3	18	−0.01	−0.018	1.80
4	18	−0.25	−0.414	1.66
5	5, 14	−0.25 −0.25	−0.366 −0.380	1.47
6	18, 32	−0.25 −0.25	−0.370 −0.430	1.48

From the damage localization results (shown in Fig. 5) and the severity estimation results (listed in Table 3), the following three observations can be made. Firstly, all eight (8) damage locations simulated in the six damage cases are correctly predicted. Secondly, no false locations are predicted(i.e., additional locations in which no damage is simulated are not predicted). Thirdly, note from Table 6 that the predicted results consistently overestimate the inflicted damage by a factor of 1.6. This trend indicates that there is a systematic error associated with the use of Eq. 20. Also note that we have used modal parameters of only three modes to locate and size damage in a structure with 42 members. These results establish the feasibility that the proposed damage detection algorithm here can locate and estimate the severity of damage in jacket-type structures for which predamage and post-damage modal parameters are available for few modes(in this case three modes).

4. SUMMARY AND CONCLUSIONS

The objective of this paper was to present a damage detection algorithm to locate and estimate the severity of damage in jacket-type structures for which pre-damage and post-damage modal parameters are available for few modes of vibration. In order to achieve the objective, the investigation was performed in three steps. First, a damage detection algorithm was outlined. Next, the feasibility of the damage detection algorithm was demonstrated by using a numerical example of an offshore jacket platform with predamage and post-damage modal parameters of three modes and with mode shapes of x, y, and z translational motions.

From the material presented here we concluded that it is feasible to localize and extimate severity of damage in a jacket-type offshore platform with only few pre-damage and post-damage mode shapes. Research to improve the damage detection algorithm proposed here is continuing along three lines. Firstly, we are developing algorithms to more accurately estimate the size of the damage. Secondly, we are applying the algorithm to different classes of structures. Thirdly, we are now in advanced stages of demonstrating the practicality of the approach in damage localization and severity estimation in laboratory controlled experiments or full-scale field structures.

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