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# Damage detection in jacket type offshore platforms using modal strain energy

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**Abstract.** Structural damage detection, damage localization and severity estimation of jacket platforms, based on calculating modal strain energy is presented in this paper. In the structure, damage often causes a loss of stiffness in some elements, so modal parameters; mode shapes and natural frequencies, in the damaged structure are different from the undamaged state. Geometrical location of damage is detected by computing modal strain energy change ratio (MSECR) for each structural element, which elements with higher MSECR are suspected to be damaged. For each suspected damaged element, by computing cross-modal strain energy (CMSE), damage severity as the stiffness reduction factor -that represented the ratios between the element stiffness changes to the undamaged element stiffness- is estimated. Numerical studies are demonstrated for a three dimensional, single bay, four stories frame of the existing jacket platform, based on the synthetic data that generated from finite element model. It is observed that this method can be used for damage detection of this kind of structures.

**Keywords:** damage detection; modal analysis; strain energy; jacket platforms.

## 1. Introduction

All load-carrying structures such as buildings, bridges, aircrafts, spacecrafts and offshore platforms continuously accumulate damage during their service life due to many source of damage (Lam 1994, Mortazavi and Bea 1996). For instance, damage Source in offshore platforms can be classified as: fatigue and corrosion damage, collisions with supply ships and objects dropped from the platform decks, Member overload during intense storms, and Installation and maintenance activities (Brown 2002, Gandhi *et al.* 2000, Grewal and Lee 2004, Moan *et al.* 1993, Sterndorff *et al*. 1992). In the past, numerous damage inspection methods and monitoring systems such as *x*-ray; electron scanning; ultrasound; magnetic resonance imagery; coin tapping; dye penetration; and visual inspection have been developed. These methods tend to be time consuming and costly, often

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requiring the exposure of structural elements for local damage detection (Kosmatka and Ricles 1999, Lam 1994). The methods for damage identification are commonly classified into four levels: Level 1: determination that damage is present in the structure, Level 2: determination of the geometric location of the damage, Level 3: quantification of the severity of the damage, and Level 4: prediction of the remaining service life of the structure (Doebling *et al.* 1998). Damage would alter the physical properties of structure such as mode shapes and natural frequencies. These Modal parameters characterize the state of a structure, therefore based on changes in natural frequencies, mode shapes, or their combinations, several structural damage detection techniques have been proposed in recent years.

Stubbs *et al.* proposed an algorithm to locate and size damage in jacket-type offshore structures and a Nondestructive Damage Detection (NDD) in large/complex structures via vibration monitoring (Kim and Stubbs 1995, Park *et al.* 2002). Koh, See and Balendra suggested a method for identification of local damage of multi story frame building in terms of changes in story stiffness (Koh *et al.* 1995). Shi *et al.* suggested a method to detect the location of damage using the elemental energy quotient difference and modal strain energy change and to quantification of damage based on sensitivity analysis (Law *et al.* 1998, Shi *et al.* 2000), also proposed an algorithm to improve structural damage quantification based on modal strain energy change (Shi *et al.* 2002). Mangal, Idichandy and Ganapathy used an experimental investigation on a laboratory model of a jacket platform, for exploring the feasibility of adapting vibration responses due to impulse and relaxation, for structural monitoring (Mangal *et al.* 1999). Barroso and Rodriguez proposed a methodology to identify the undamaged state of the structure and using the damage index method to detect the location and severity of damage (Barroso and Rodriguez 2004). Stubbs et al. introduce a new form of damage index based on the changes in the distribution of the compliance of the structure (Choi *et al.* 2005). Udwadia proposed a method from information about some of measured modal parameter for the identification of stiffness matrices of structural and mechanical systems (Udwadia 2005). Xiang *et al.* proposed a method to detect location and severity of damage in jacket offshore platforms via partial measurement of modal parameters of an experimental platform model under white-noise ground excitation (Xiang *et al.* 2008). Hu, Wang, and Li developed a new method to estimate the damage severity termed as cross-modal strain energy method (Hu *et al.* 2006). Some of researchers suggested a method to Damage detection in beam systems or truss type structures (Liu 1995, Vestroni and Capecchi 2000), residual force and weighted sensitivity analysis (Kosmatka and Ricles 1999), parameter estimation method (Pothisiri and Hjelmstad 2003), the geometrical transformation matrix (Escobar *et al.* 2005), and frequency response functions to damage detection (Huynh *et al.* 2005).

## 2. Damage detection method

Structural damage often causes a loss of stiffness in one or more elements of a structure, but not a loss in the mass. Denoting $M$ and $K$ as the mass and stiffness matrices for the undamaged structure model, in the eigenanalysis for the undamaged structure

$$K\Phi_i = \lambda_i M\Phi_i \tag{1}$$

Likewise, corresponding expression for the damaged structure as

$$K^d \Phi_j^d = \lambda_j^d M^d \Phi_j^d \tag{2}$$

Where $K^d$ and $M^d$ are stiffness and mass matrices, $\lambda_j^d$ and $\Phi_j^d$ denote the associated *j*th eigenvalue and eigenvector in damaged structure, respectively.

Occurring damage in the structure can be represented as a small perturbation in the original system. Thus, the stiffness matrix $K^d$, the ith modal eigenvalue $\lambda_i^d$ and the ith mode shape $\Phi_i^d$ of the damaged structure can be expressed as

$$K^d = K + \sum_{n=1}^{N_d} \Delta K_n = K + \sum_{n=1}^{N_d} \alpha_n K_{l_n} \quad (-1 < \alpha_n \le 0) \tag{3}$$

$$\lambda_i^d = \lambda_i + \Delta\lambda_i; \quad \Phi_i^d = \Phi_i + \Delta\Phi_i \tag{4}$$

In Eq. (3) $N_d$ is total number of the damaged elements, $\alpha_n$ is damage extent that is expressed as a fractional change of the elemental stiffness matrix and $l_n$ is the element number of the nth damaged element, respectively. The objective herein is to detect damage location and to evaluate the damage level $\alpha_n$ (with a value between −1 and 0) corresponding to each location (Law *et al.* 1998).

## 3. Modal Strain Energy Change (MSEC)

The elemental modal strain energy (MSE) is defined as the product of the elemental stiffness matrix and the second power of the mode shape component. For the *j*th element and the *i*th mode, the MSE before and after the damage defined as

$$MSE_{ij} = \Phi_i^T K_j \Phi_i; \quad MSE_{ij}^d = \Phi_i^{d^T} K_j \Phi_i^d \tag{5}$$

where $MSE_{ij}$ and $MSE_{ij}^d$ are related to undamaged and damaged MSE of the *j*th element for the *i*th mode shape, respectively. Because the damaged elements are not known, the undamaged elemental stiffness matrix $K_j$ is used instead of the damaged that is one an approximation in expression of $MSE_{ij}^d$.

The modal strain energy change (MSEC) of the *j*th element for the *i*th mode could be obtained from

$$MSEC_{ij} = \Phi_i^{d^T} K_j \Phi_i^d - \Phi_i^T K_j \Phi_i \tag{6}$$

the modal strain energy change ratio (MSECR) defined as follows

$$MSECR_j = \frac{|MSE_{ij}^d - MSE_{ij}|}{MSE_{ij}} \tag{7}$$

The MSECR has been verified to be a good indicator for damage localization.

In the structure, $MSECR_{ij}$ is calculated for all elements. If more than one measured mode is available, $MSECR_{ij}$ is calculated for all the modes, and $MSECR_{ij}$ of the *j*th element is defined as the average of summation of all $MSECR_{ij}$ normalized with respect to the largest value of $MSECR_{ij}$ for each mode

$$MSECR_j = \frac{1}{m}\sum_{i=1}^{m}\frac{MSECR_{ij}}{MSECR_{\max}} \tag{8}$$

where $m$ is total number of measured mode. The location of damage can be identified by examining those values of $MSECR_j$ that are larger than the others (Shi *et al.* 2000).

## 4. Cross-modal Strain Energy (CMSE)

The development of the cross-modal strain energy method is under the assumption that the mass distributions of the undamaged and damaged structures are without changes, i.e., $M^d = M$. Define the structural cross-modal strain energy (CMSE) between the $i$th mode of the undamaged structure and the $j$th mode of the damaged structure as

$$C_{ij} = (\Phi_i)^T K \Phi_j^d \tag{9}$$

and the corresponding elemental cross-modal strain energy for the stiffness matrix $K_{l_n}$ as

$$C_{n,ij} = (\Phi_i)^T K_{l_n} \Phi_j^d \tag{10}$$

In Eqs. (1) and (2), as $\Phi_i$, $\lambda_i$ $K$, $\Phi_j^d$, $\lambda_j^d$ are presumably known, the unknown terms are $K^d$ and M, therefore the first step is to eliminate the mass matrix M From these equations, so premultiplying Eq. (1) by $(\Phi_j^d)^T$ and Eq. (2) by $(\Phi_i)^T$ yields

$$(\Phi_j^d)^T K \Phi_i = \lambda_i (\Phi_j^d)^T M \Phi_i \tag{11}$$

$$(\Phi_i)^T K^d \Phi_j^d = \lambda_j^d (\Phi_i)^T M \Phi_j^d \tag{12}$$

As $M$ and $K$ are symmetric matrices, one shows that $[(\Phi_j^d)^T M \Phi_i]^T = (\Phi_i)^T M \Phi_j^d$ and

$$(\Phi_j^d)^T K \Phi_i = (\Phi_i)^T K \Phi_j^d \tag{13}$$

Also noting the transpose of a scalar equals to itself, i.e., $[(\Phi_j^d)^T M \Phi_i]^T = (\Phi_j^d)^T M \Phi_i$, therefore

$$(\Phi_j^d)^T M \Phi_i = (\Phi_i)^T M \Phi_j^d \tag{14}$$

Theoretically, $\Phi_i$ and $\Phi_j^d$ are not orthogonal with respect to the mass matrix even when $i \neq j$, unless no damage occurred in the structure, therefore $\Phi_j^d = \Phi_j$.

Dividing Eq. (12) by Eq. (11), and using the scalar identities of Eqs. (13) and (14), one obtains:

$$\frac{(\Phi_i)^T K^d \Phi_j^d}{(\Phi_i)^T K \Phi_j^d} = \frac{\lambda_j^d}{\lambda_i} \tag{15}$$

The above equation is only defined when $(\Phi_i)^T K \Phi_j^d$ is not zero. Otherwise, Eq. (15) should be written as $\lambda_i (\Phi_i)^T K^d \Phi_j^d = \lambda_j^d (\Phi_i)^T K \Phi_j^d$. From Eqs. (3) and (15), one shows:

$$1 + \frac{\sum_{n=1}^{N_d} \alpha_n (\Phi_i)^T K_{l_n} \Phi_j^d}{(\Phi_i)^T K \Phi_j^d} = \frac{\lambda_j^d}{\lambda_i} \tag{16}$$

or

$$\sum_{n=1}^{N_d} \alpha_n (\Phi_i)^T K_{l_n} \Phi_j^d = \left(\frac{\lambda_j^d}{\lambda_i} - 1\right) \Phi_i^T K \Phi_j^d \tag{17}$$

Now, Eq. (17) is written as

$$\sum_{n=1}^{N_d} \alpha_n C_{n,ij} = \left(\frac{\lambda_j^d}{\lambda_i} - 1\right) C_{ij} \tag{18}$$

This equation written as

$$\sum_{n=1}^{N_d} \alpha_n C_{n,ij} = b_{ij} \tag{19}$$

where

$$b_{ij} = \left(\frac{\lambda_j^d}{\lambda_i} - 1\right) C_{ij} \tag{20}$$

When $N_i$ and $N_j$ modes are available for the undamaged and damaged structure, respectively, totally $N_q = N_i * N_j$ equations can be formed from Eq. (19). This equation written in a matrix form as

$$C\alpha = b \tag{21}$$

in which $C = N_q$-by-$N_d$ matrix, $\alpha$ and $b$ = column vectors of size $N_d$ and $N_q$, respectively. When $N_q$ is greater than $N_d$, a least squares approach can be taken to solve for $\alpha$. The estimate of $\alpha$ in this approach is

$$\alpha = (C^T C)^{-1} C^T b \tag{22}$$

It should be noted that $N_i$ and $N_j$ are numbers of modes for the undamaged and damaged structures, should started from the first mode but it is not required to be equal. Furthermore, while applying cross-modal strain energy method (CMSE), it is recommended to considering more suspected damage locations (Hu *et al.* 2006).

## 5. Damage detection case study

Numerical study consists of three dimensional, single bay, four stories frame of existing offshore platform in Persian Gulf. The finite element model of this platform consists of 260 elements with 151 nodes and 894-Dofs. Three dimensional view of the platform is shown in Fig. 1, In this figure the assumed damaged element Number is shown. As shown in Fig. 1, the assumed damaged elements are vertical bracings of the second and third stories of the platform; furthermore, as discussed in the next sections, many of suspected damaged elements are vertical bracings and leg

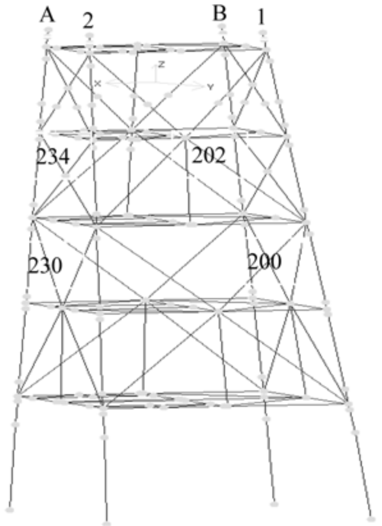


Fig. 1 Three dimensional view of the platform with damaged element numbers

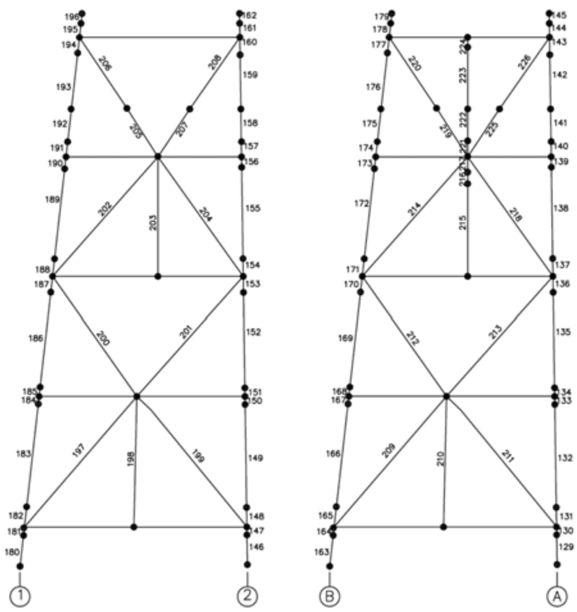

Fig. 2 Element number in *x* direction

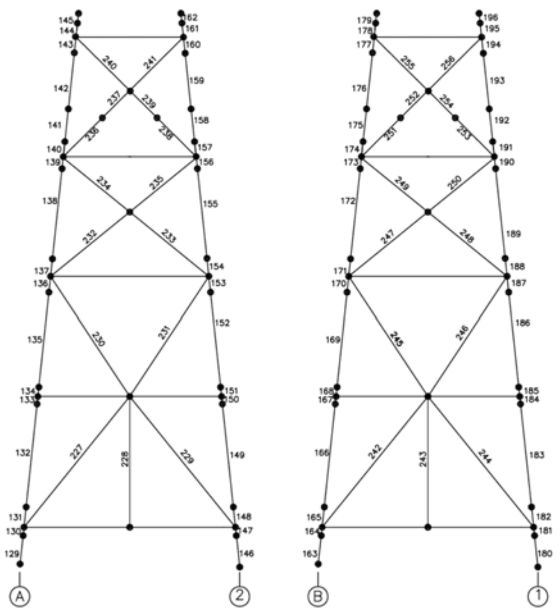

Fig. 3 Element number in *y* direction

elements of the platform. Therefore, details of element numbers of each face of the platform are shown in Figs. 2 and 3, for better perception. As shown in these figures, the platform has four legs and horizontal framings are located at five elevations, which are EL. –55.40m, EL. –39.00m, EL. –24.00m, EL. –9.00m and EL. +6.00m with element numbers between 1-37, 38-56, 57-76, 77-102, and 103-128, respectively.

## 6. Modal analysis

The platform was modeled using 3-D finite element software, OPENSEES (Mazzoni *et al.* 2006); modal analysis was performed and first three mode shapes of vibration are shown in Fig. 4, also the first three natural periods of the platform are listed in Table 1.

According to Fig. 4, the first and second modes of the platform are the swaying of the jacket in $x$ and $y$ direction, respectively, and the third mode is a torsional mode.

As shown in Fig. 1, four damage cases are considered as the following:

Case 1, element 200, one of the vertical bracings in $x$ direction and the second story has been removed.

Case 2, element 230, one of the vertical bracings in $y$ direction and the second story has been removed.

Case 3, element 202, one of the vertical bracings in $x$ direction and the third story has been removed.

Case 4, element 234, one of the vertical bracings in $y$ direction and the third story has been removed.

Results of modal analysis for each damage case were summarized in Table 2. It is noticed that the first period of the damaged platform in damage cases 2 and 4, does not change noticeably compare to the undamaged platform ones. Similarly, the second period of the damaged platform in damage cases 1 and 3, does not change noticeably from their values of the undamaged platform. This also suggested that a damaged vertical bracing in $y$ and $x$ direction does not have discernible effect on the first and the second mode shape, which predominantly vibrates in the $x$ and $y$ direction, respectively. With similar reasoning, the third mode of the vibration is a torsional mode, so a damaged vertical bracing in $x$ or $y$ direction does not have significant effect on natural period of this mode.

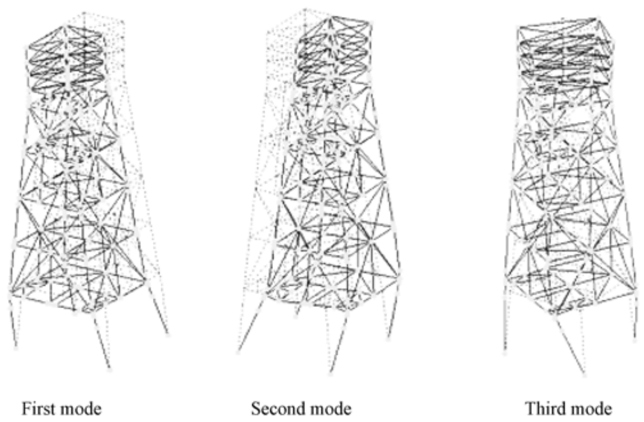


Fig. 4 Mode shapes of the Vibration of the platform

Table 1 Periods of the vibration of the undamaged platform

| Period, s | | |
|---|---|---|
| $T_1$ | $T_2$ | $T_3$ |
| 2.208 | 1.995 | 1.788 |

Table 2 Periods of the vibration for each damage case

| Damage cases | Period, s | | |
|---|---|---|---|
| | $T_1$ | $T_2$ | $T_3$ |
| 1 | 2.239 | 1.995 | 1.788 |
| 2 | 2.208 | 2.041 | 1.787 |
| 3 | 2.228 | 1.995 | 1.782 |
| 4 | 2.208 | 2.016 | 1.783 |

## 7. Damage detection

Damage location detection and severity estimation was performed as the following steps:

1) Modeling the platform using 3-D finite element software, OPENSEES.
2) Performing modal analysis and determining mode shapes and natural frequencies for the first three modes of the vibration.
3) Extracting mode shape of each element. It is noticed that mode shape of element is modal displacement of its ends.
4) Computing element stiffness matrix, then $MSE_{ij} = \varphi_i^T K_j \varphi_i$ and $MSE_{ij}^d = \varphi_i^{d^T} K_j \varphi_i^d$ for each element with respect to the first three modes of the vibration ($i$ = 1, 2, 3).
5) Computing $MSECR_{ij}$ for each mode and normalizing it with respect to largest value of $MSECR_{ij}$ to determine $MSECR_j$ for each element. In this step suspected damaged elements are determined.
6) Considering first two modes of the vibration of the undamaged and damaged platform ($i = j = 2$), computing "C" and "b" matrices based on Eqs. (20) and (21).
7) Estimating damage severity, $\alpha$, for each suspected damaged element by solving Eq. (22).

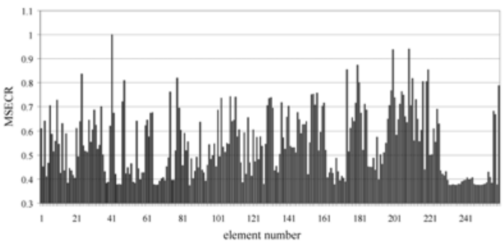


Fig. 5 Damage location detection for damage case 1

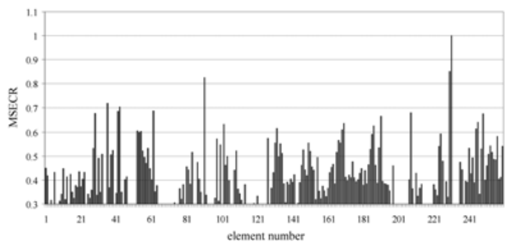


Fig. 6 Damage location detection for damage case 2

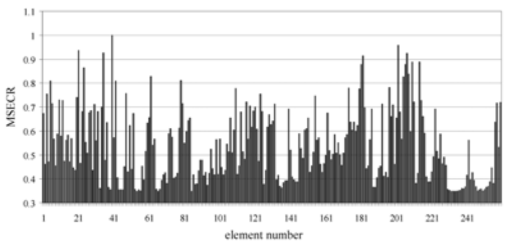


Fig. 7 Damage location detection for damage case 3

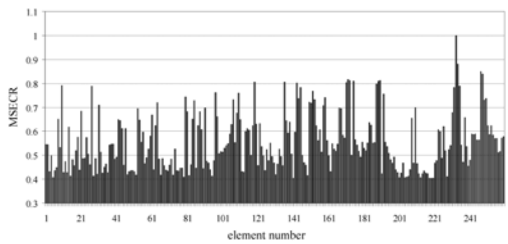


Fig. 8 Damage location detection for damage case 4

Table 3 Suspected damaged elements for each damage case

| Damage case | Suspected damaged elements |
|---|---|
| 1 | 1, 3, 6, 10, 13, 21, 23, 24, 28, 30, 31, 32, 35, 40, 41, 42, 47, 48, 55, 60, 61, 63, 64, 74, 78, 79, 80, 91, 101, 103, 108, 109, 110, 111, 113, 118, 121, 129, 130, 131, 132, 137, 140, 141, 146, 147, 149, 150, 151, 154, 155, 156, 157, 160, 161, 174, 176, 177, 178, 179, 180, 181, 182, 184, 185, 197-217, 219, 220, 223, 225 and 226 |
| 2 | 28, 29, 33, 36, 38, 39, 42, 43, 53, 54, 55, 56, 59, 62, 84, 91, 98, 100, 102, 104, 109, 127, 130, 131, 132, 133, 134, 135, 146, 147, 148, 150, 151, 152, 153, 155, 162, 163, 164, 166, 167, 168, 169, 170, 175, 179, 182, 184, 185, 186, 187, 188, 190, 191, 207, 208, 209, 211, 224, 225 and 227-255 |
| 3 | 1, 3, 5, 6, 10, 12, 20, 21, 23, 24, 27, 28, 30, 31, 32, 34, 35, 37, 40, 41, 42, 48, 50, 52, 60, 61, 62, 73, 77, 78, 79, 83, 84, 109, 110, 113, 116, 118, 119, 120, 121, 122, 124, 125, 128, 129, 130, 131, 132, 140, 149, 150, 151, 155, 162, 174, 175, 176, 177, 179, 180, 181, 182, 183, 187, 193, 197-211, 214, 215, 216, 217 and 223 |
| 4 | 8, 10, 14, 21, 27, 31, 42, 43, 44, 46, 53, 54, 61, 63, 64, 80, 81, 84, 85, 87, 88, 89, 91, 97, 98, 106, 107, 109, 110, 111, 115, 116, 118, 119, 120, 122, 136, 137, 139, 143, 144, 145, 150, 151, 152, 153, 154, 156, 158, 159, 167, 168, 171, 172, 173, 175, 184, 185, 188, 189, 190, 192, 208, 210, 223, 226, 231, 232, 233, 234, 235, 238, 247, 248, 249, 250, 251 and 253 |

## 8. Location of damage

Results of damage location detection are shown in Figs. 5-8. According to Figs. 5, 6, 7, 8 elements with MSECR more than 0.6, 0.5, 0.6, and 0.6 are considered to be damaged, respectively. The suspected damaged elements are summarized in Table 3.

## 9. Interpretation of location detection results

As a result of occurring damage in one of the vertical bracings of the jacket platform in a specific story and direction, stiffness of damaged element and structural stiffness at damaged story and direction will be decreased; Furthermore, according to the inverse relation between structural stiffness and nodal displacement, the displacements in that story will be increased. In the modal analysis, the modal displacement of two ends of elements will be increased, so according to Eq. (5) modal strain energy after damage in the vertical bracings of the damaged story will be increased and modal strain energy change ratio (MSECR) in these elements are larger than the other elements, it means that the vertical bracings of that story are expected to be damaged. Also, because of the behavior of structural elements are not independent from each other, with increasing the displacement in damaged story, displacement at one end of the vertical bracings of the upper and lower stories of the damaged story at damage direction will be increased, so MSECR in those elements have a remarkable value, therefore vertical bracings in the upper and lower stories of the damaged story are expected as damage elements. With similar reasoning, the horizontal bracings of the damaged story and leg elements of the damaged story and the upper and lower stories of this story are expected to be damaged. Based on the above explanation:

For damage case 1, vertical bracings in $x$ direction of the first, second, and third stories, including elements 197-204 and 209-218, leg elements of these stories including elements 131-139, 148-156, 165-173, 182-190 and horizontal bracings of the second story including elements 38-56, 57-76 are expected to be damaged.

For damage case 2, vertical bracings in $y$ direction of the first, second, and third stories, including elements 227-235 and 242-250 and elements of the leg of these stories including elements 131-139, 148-156, 165-173, 182-190 and horizontal bracings of the second story including elements 38-56, 57-76 are expected as damage elements.

For damage case 3, vertical bracings in $x$ direction and the second, third, fourth stories including elements 200-208 and 212-226, leg elements of these stories including elements 134-143, 151-160, 168-177, 185-194 and horizontal bracings of the third story including elements 57-76, 77-102 are expected to be damaged.

For damage case 4, vertical bracings in $y$ direction and the second, third, fourth stories including elements 230-241 and 245-256 and elements of the leg in these stories including elements 134-143, 151-160, 168-177, 185-194 and horizontal bracings of the third story including elements 57-76, 77-102 are expected as damage elements.

With respect to Figs. 5-8, table. 3 and the above statements, the expected and suspected damaged elements have good compatibility.

## 10. Severity of damage

By considering the first two modes of the vibration, calculating cross-modal strain energy and then "C" and "b" matrices, Eq. (22) is solved to estimate damage extent, $\alpha$, for each suspected damaged element that determined earlier. It should be noted that negative value for $\alpha$ (between 1 and 0) denotes the percentage of stiffness reduction in damaged element and other values denote that no damage is occur in element. Results of damage severity estimation are shown in Figs. 9-12 and summarized in Table 4.

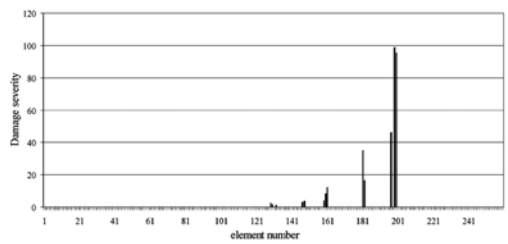


Fig. 9 Damage severity estimation for damage case 1

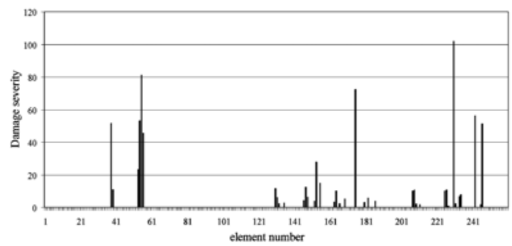


Fig. 10 Damage severity estimation for damage case 2

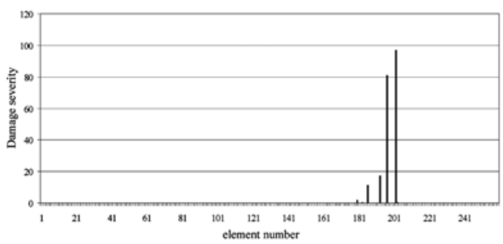


Fig. 11 Damage severity estimation for damage case 3

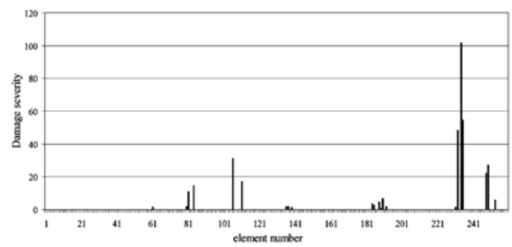


Fig. 12 Damage severity estimation for damage case 4

**Table 4.** Expected severity for each damage case

| Damage case | Element Number | Damage severity | Element Number | Damage severity | Element Number | Damage severity | Element Number | Damage severity | Element Number | Damage severity |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 129, 130, 132 | 3 | 147, 148 | 5 | 156 | 4 | 160 | 8 | 161 | 12 |
| | 181 | 35 | 182 | 16 | 197 | 46 | 199 | 98 | **200** | **95.3** |
| 2 | 38 | 52 | 39 | 11 | 53 | 23 | 54 | 53 | 55 | 81 |
| | 56 | 46 | 130 | 12 | 131 | 6 | 147 | 12 | 148 | 6 |
| | 153 | 28 | 155 | 15 | 164 | 10 | 169 | 5 | 175 | 72 |
| | 182 | 6 | 186 | 4 | 207 | 10 | 208 | 11 | 225 | 10 |
| | 226 | 11 | **230** | **102.1** | 233 | 7 | 234 | 8 | 242 | 56 |
| | 246 | 51 | | | | | | | | |
| 3 | 180 | 3 | 186 | 11 | 193 | 17 | 197 | 80 | **202** | **96.7** |
| 4 | 80 | 3 | 81 | 11 | 84 | 15 | 106 | 31 | 111 | 17 |
| | 136, 137, 139 | 3 | 184 | 4 | 185 | 3 | 188 | 5 | 190 | 7 |
| | 232 | 50 | **234** | **101.9** | 235 | 55 | 248 | 23 | 249 | 27 |
| | 253 | 6 | | | | | | | | |

## 11. Interpretation of damage severity estimation

The CMSE method is a direct, noniterative and exact solution method. For considered offshore platform, taking only the first two modes of the vibration for both the undamaged and damaged structures, i.e., ($i = 2$, $j = 2$), applying the CMSE method, one obtains the exact damage severity estimates for all damage cases. Accordingly, for damage case 1, 2, 3, 4, the estimated severity is 95.3, 102.1, 96.7 and 101.9 percent, therefore the extent of error is −4.7, +2.1, −3.3 and +1.9 percent, respectively. It was found that the severity of damage is underestimate the true damage level in $x$ direction, while it is overestimate in $y$ direction.

Since the first and the second modes of the platform are translational mode in $x$ and $y$ direction, respectively and the third mode is a torsional mode (see Fig. 4), considering the first mode of the vibration of the undamaged and damaged platform (1, 1), the predicted severity and the relative error is 96.3 and −3.7 percent for damage case 1 and 93.9 and −6.1 percent for damage case 3, respectively, but a correct severity estimate is not obtained for damage case 2, 4 in this manner. Also, by using combination (3, 3), the exact damage severity can be estimated for all damage cases.

## 12. Conclusions

Damage affects the stiffness matrix and the nodal displacement of a structure. In the modal analysis, the modal displacement of two ends of the elements is changed, thus the modal strain energy change ratio (MSECR) in the elements of a structure would alter due to damage. The MSECR in the damaged elements is larger than other elements; therefore MSECR is a good indicator for damage location detection. Due to occurring damage in one of the vertical bracings of the offshore platform at the specific story and direction, leg elements and vertical bracings of the damaged story and the upper and lower stories of that story, also the horizontal bracings of the damaged story are suspected damaged elements.

By using cross-modal strain energy (CMSE) method, the exact severity of damage is obtained. Considering the first two modes of the vibration of the undamaged and damaged structures, ($i = 2$, $j = 2$), the correct severity of damage in the vertical bracings of the jacket platform in both $x$ and $y$ direction can be estimated. By combination (1, 1), the exact damage severity at the vertical bracings in direction of the first swaying mode of the platform is obtained, but the severity of damage at vertical bracings in other direction can not be determined. Another numerical observation is that using the same mode for both undamaged and damaged structures, i.e., choosing $i = j$, always yields good estimates. Occurrence of damage in one of the vertical bracings of the platform at the specific story and direction, caused a significant damage in vertical bracings in damage direction, whereas in the horizontal bracings of the damaged story and vertical bracings in other direction, the severity of damage is negligible. It is noticed that for a practical use, the proposed method needs to be further calibrated by using actual data from damaged real three dimensional structures or by using experimental models with controlled damage.

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