Detecting damage location and severity in the leg of SA20 jack up rig (Hull 110) using an iterative modal strain energy method

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Abstract

Harsh marine environment and repeated movements of jack up rigs, make this mobile type offshore structure more vulnerable to failure. Environmental conditions of the Persian Gulf, high temperature, high water salinity, and various hydrocarbon pollutants in water necessitates the condition monitoring of these structures. Besides the above factors, the possibility of extending working life of offshore structures in the Persian Gulf should be also examined. Considering their economic value for Iran's macro economy and potential human injuries in cases of severe damages, monitoring the current state of Iran’s offshore structures and identifying potential damage to them is crucial. A damage detection approach used for structures is the Modal Strain Energy (MSE), in which damage location and severity are determined based on changes in dynamic properties of structure. In order to increase the accuracy of the results, the damage identification process in performed in an iterative manner. In this paper, along with performing an experimental modal analysis, an iterative modal strain energy method is used to damage localization and quantification in the base of the offshore SA20 jack up rig (Hull 110). Results showed that the single and multiple damages of low and high severity were estimated by this method with a good accuracy.

Keywords: jack up rig, Numerical and experimental investigation, damage detection, modal strain energy (MSE), model updating.

1. Introduction

Offshore platforms have been used for various activities such as oil and gas extraction and production, drilling, etc. for more than half a century. These structures can be divided into two general categories: fixed and movable. Mobile platforms are mainly used for drilling purposes and include self-lifting platforms (or so-called jack ups), semi-submersibles and barges or drilling vessels. Jack up platform consists of a buoyant hull fitted with a number of movable legs, makes home of facilities to drill wells, to extract and process oil and natural gas and to temporarily store product until it can be brought to shore (Jiang, et al., 2013). Today, thanks to the advancement of the drilling industry, some self-propelled platforms can drill in harsh sea environments, despite waves 25 meters high and winds of 185 kilometers per hour and up to 150 meters deep in the water.

By increasing the service life of the structure, the unpredictable nature of loads and the possibility of poor design of elements reduce the efficiency of structures. Marine structures, including jack up platforms, are constantly exposed to environmental forces during their useful life. Loads that are exerted on offshore platforms during construction and operation phases resulted in minor and major damages to the platform. The cause of many structural failures is the rupture of its components. The onset of these ruptures is accompanied by local and hidden cracks in the structure that are continuously increasing and can be considered a serious threat to the structure. The effect of cracks on the structure is in the form of local changes in stiffness, which can be seen by changing the natural frequency and mode shape of the structure; analyzing these changes makes it possible to detect the cracks.

The first step in preventing the growth of damages and optimizing maintenance activities, is to find the damage location and severity through a structural health monitoring method. One of the basic health monitoring methods is the use of visual inspection, which leads to important information about the health of the structure. However, visual inspection is a time-consuming and costly process. In addition, due to the unavailability of some members, inspecting the entire structure is impossible which results in impossibility of detecting damage in these members and also the difficulty of diagnosing internal failures and their origin. Non-destructive damage detection methods have been developed to increase safety and ensure the current condition of the structure. One of the structural health monitoring methods is visual inspection, which provides important information about the condition of the structure. One drawback of this method is that visual inspection is very difficult in harsh sea environment. It is also not possible to detect internal faults and their origin using this method. Therefore, the use of non-destructive methods for damage detection is recommended. One of these methods is the vibration-based damage detection method which is used as a complementary solution along with visual inspections to assess the damage in the structure (Doebling, et al., 1996; Balageas, 2006). In all vibration-based damage detection methods, modal properties (frequency, mode shape, and modal damping) of the structure are a function of its physical properties. Therefore, by considering the changes in the static or dynamic responses of structures, it is possible to identify the changes in their physical properties and thus detect structural damage in the early stages of damage. Early detection of these damages reduces maintenance costs and prevents structural failure.

Generally, damage detection in structures is classified into four levels as follows:

Level 1: Determining the presence or absence of damage in structures

Level 2: Level 1 + determining the geometric position of the damage

Level 3: Level 2 + quantifying damage intensity

Level 4: Level 3 + estimation the remaining life of the structure (Doebling, et al., 1995).

Due to their importance in structural failure, damage detection methods have been the subject of extensive research. As one of the first attempts to detect damages in structures, Cawley and Adams (1979) used the natural frequencies of the structure as an indicator in detecting the location of the damage (Cawley & Adams, 1979). Shahrivar and Bouwkamp (1986) used vibrational information to detect damages in an eight-leg steel platform. They examined the effects of diagonal bracing on the frequency and measurable mode shapes of the platform deck (Shahrivar & Bouwkamp, 1986). Hansen and Vanderplaats (1990) used the frequency and mode shapes to detect damages in the structure and determined the location and severity of damage with a high accuracy (Hansen & Vanderplaats, 1990). Doebling et al. (1993) proposed a method based on modal strain energy for selecting a set of vibrational modes of structures and detecting structural damage in them (Doebling, et al., 1993).Presenting an algorithm for damage localization and quantification in jacket platforms, Kim and Stubbs (1995) determined the location of the damage and estimated its severity considering the changes in the mode shapes and then formulated a method to determine the modal parameters of the structure (Kim & Stubbs, 1995). Kim and Stubbs (1995 & 1996) proposed a damage index based on modal strain energy method for beam-like structures, examined the efficiency of this method on a steel bridge, and correctly detected the location of the damage (Stubbs, et al., 1995; Stubbs & Kim, 1996). Salawu (1997) conducted a study on the use of natural frequencies for damage detection and concluded that the use of natural frequencies alone was not sufficient for detection of local damage, although it could be effective in general damage detection (Salawu, 1997). Farrar and Jauregui (1998) examined five damage detection methods, including modal strain energy damage index (MSE-DI) method, mode shape curvature method, change in uniform load surface curvature method, and change in stiffness method on a steel bridge and concluded that modal strain energy damage index method had higher accuracy compared to other methods (Farrar & Jauregui, 1998). Kim and Stubbs (2002) developed an improved damage index to increase the accuracy of damage detection in large-scale structures, and tested its performance on a two-span beam (Kim & Stubbs, 2002). Li et al. (2002) proposed a method for detecting the location of damage in a planar element using the mode shapes obtained by the Rayleigh–Ritz method, and by numerical modeling, demonstrated that this method has a high ability to detect single and multiple damages (Li, et al., 2002).Using modal strain energy changes via two indicators of compression modal strain energy change ratio (CMSECR) and flexural modal strain energy change ratio (FMSECR), Yang et al. (2003) assessed damage in marine structures (Yang, et al., 2003). Ge and Lui (2005) proposed a finite element model that used the dynamic properties of the structure including modal frequencies and mode shapes for damage localization and quantification (Ge & Lui, 2005). Shih et al. (2009) examined the modal strain energy method for detecting damage in beams and plates and concluded that this method can be used to detect damage in girder and bridge decks (Shih, et al., 2009). Hu and Wu (2009) developed a damage index to detect damage in plates based on the modal strain energy method (Hu & Wu, 2009). Seyedpoor (2012) proposed a two-step method for accurately detecting the location and severity of multiple damages in structural systems; in the first step, a modal strain energy index was used to accurately locate damage in a structure and in the second, the severity of the damage was determined via particle swarm optimization (PSO) algorithm and using the results of the first step (Seyedpoor, 2012). Using modal energy strain difference of the structure in intact and damaged modes to detect the location of wind turbine damage, Liu et al. (2014) provided a model based on modal strain energy method that was more sensitive than other traditional strain energy methods (Liu, et al., 2014). Seyedpoor and Yazdanpanah (2014) presented a method for identifying the location of damage based on the strain energy caused by static loads on the structure, in two intact and damaged modes. They studied the applicability of this method on a 31element planar truss, a three-span frame, and a space truss, and concluded that by applying a load on one node of the studied trusses and calculating the displacement of the nodes, identifying the location of the damage was easy (Seyedpoor & Yazdanpanah, 2014). Wang et al. (2014) used the modal strain energy method to locate damage in an offshore platform and concluded that among all the damage detection methods so far, modal strain energy-based methods are more effective than other methods in determining the location of the damage (Wang, et al., 2014). Martinez-Luengo et al. (2016) reviewing issues related to structural health monitoring of offshore wind turbines, concluded that natural frequency analysis is the most common method of damage detection in wind turbine foundations, as other methods are very costly, of low maturity, or with insufficient accuracy (Martinez-Luengo, et al., 2016). Nguyen et al. (2018) used vibration-based artificial neural networks for damage detection in wind turbine towers (Nguyen, et al., 2018).

Many finite element model updating methods have been applied to minimize the differences in structural properties, such as stiffness, mass and/or damping parameters between the real structure and the finite element model. Finite element model updating with experimental data is a useful tool for evaluating the integrity of the structure. Although many methods have been developed up-to-date, one of its drawbacks in general is lack of information. In other words, information available for natural frequencies, mode shapes or number of degree of freedom is limited. For highly indeterminate structures, the number of unknown parameters, such as stiffness properties of a structural system is much greater than the number of measured parameters. Because of insufficient data, inverse problem of finite element model updating might be a structurally underdetermined system which causes ill-conditioning of updating equations. Thus, undesirable errors are generated between finite element models and real structures. The local maximum error can be produced when solving ill-conditioned equations, even though the several target parameters such as natural frequencies of the finite element model, exactly match with measured ones. Jaishi and Ren (2007) presented the modal strain energy residuals and eigenfrequency residuals as two objective functions for carrying out the finite element model updating of bridges and concluded that the modal strain energy residual is effective and efficient to update the finite element models of structure (Jaishi & Ren, 2007). Pedram, et al., (2014) used a model updating method using power spectral density of the structural response for deriving a sensitivity equation and examined that method in stiffness parameter identification (Pedram, et al., 2014). Shadan, et al., (2014) used FRF of strain data for identifying unknown structural parameters using a sensitivity-based model updating (Shadan, et al., 2014). Moradipour, et al., (2015) introduced a new modal strain energy damage identification method that had a superior accuracy in comparison with older studies (Moradipour, et al., 2015).Performing a survey on damage detection using finite element model updating with evolutionary algorithms, Alkayem, et al. (2018) summarized various applications of evolutionary algorithms for structural damage detection with finite element model updating. (Alkayem, et al., 2018). Rahai, et al. (2020) introduced a sensitivity based finite element modal updating using singular value decomposition of frequency response function (Rahai, et al., 2020). Yang, et al., (2020) presented a MSE-based model updating method for damage identification in beam-like structures that could accurately locate the damage and enable an acceptable assessment of damage severity (Yang, et al., 2020).

In this study, a numerical and laboratory study was performed to identify the damages in the base of the SA20 Hull No. jack up platform. 110 deals with the iterative modal strain energy method that is based on the study of (Moradipour, et al., 2015), which is one of the most accurate and practical methods in the discussion of damage detection.

2. Structural damage identification based on model updating

Finite element model updating process is a mathematical procedure by which an initial finite element model of an intact structure is amended to achieve a good agreement between the damaged structure and its finite element model. Various techniques have been developed for finite element model updating purpose. Those methods can be categorized into two main classes as direct methods and iterative and indirect methods as it is shown in Fig.1.

Direct methods use modal characteristics to update the finite element model. They are considered as accurate methods and efficient from computational point of view. Moreover, they do not require updating parameters to be handled. Several direct model updating techniques were developed by various researchers such as the matrix-update, optimal matrix, error matrix, Eigen structure assignment methods (Alkayem, et al., 2018). The advantages of model updating using direct methods are:

- Direct methods do not apply iterative paradigms, so they insure the accurate and convergence to the exact solution with computational efficiency.
- They do not consider updating physical parameters of structures.
- The updated FE model can reflect the exact measured quantities.

Although direct methods are efficient, they have many drawbacks making them non-reliable as:

- They require accurate measurements, and they are highly sensitive for noise.
- Measure and calculated responses need to be equal in size.
- Direct method may produce unrealistic representation of elements along the finite element mesh. In other words, loss of symmetry may appear in model's matrices.
- Possibility of losing the connectivity of the structure and the updated model's matrices are fully populated.

Because of the above-mentioned difficulties, direct methods are not applicable for damage detection purposes. Hence, iterative and indirect approaches come into picture. Those methods can be summarized as:

Sensitivity-based methods: they consider the measured responses as alterations of some design data derived from the initial finite element model of the intact structure and the intact structure and the optimization problem is formulated using a penalty function approach. Using this concept, the measured responses must be near the calculated data deduced from the initial finite element model making the sensitivity methods applicable only when changes in the real structure are within a small scale. Hence, they can be implemented just in the case of structures with minor damage. The main philosophy of sensitivity-based methods is to calculate derivatives of modal characteristics or frequency response data that makes the overall procedure computationally expensive (Alkayem, et al., 2018). Different structural model updating methods are shown in Fig.1.

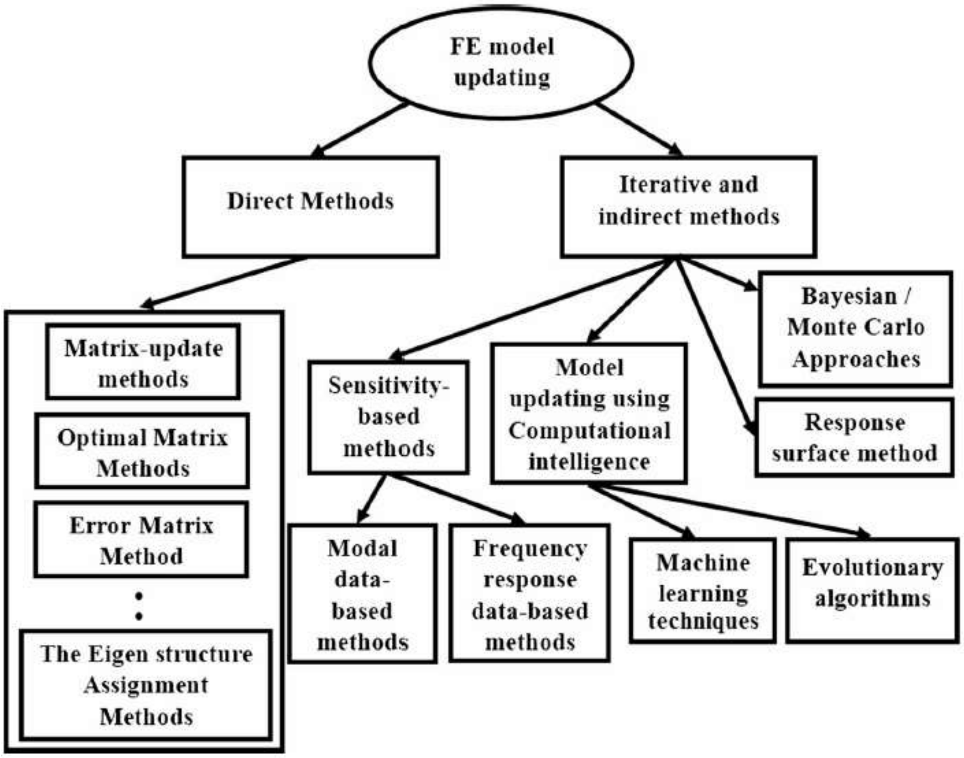

Fig. 1. Finite Element model updating approaches (Alkayem, et al., 2018).

3. Modal strain energy

When a force is applied to an elastic body and generates stress inside of it, the body experiences deformation and the conditions at various points on it change compared to the initial state. Changes in the point of action of forces applied to the body generate work. This work, accompanied by a deformation of body under stress, accumulates some elastic energy in the body, known as strain energy. Modal strain energy is a condition where no force is exerted to the structure and the structure is in free vibration mode. The modal strain energy for each member of the structure is obtained by dynamic analysis and solving the proposed equations. Damage in a structure usually reduces its rigidity without affecting the mass matrix of the structure.

The presence of damage in a structure changes some of its structural parameters such as mode shapes, natural frequencies and stiffness. Mode shape changes can be obtained by the following equation

$$\{\phi_i^d\} = \{\phi_i\} + \{\Delta\phi_i\} = \{\phi_i\} + \sum_{r=1}^{md} c_{ir}\{\phi_r\} \tag{1}$$

where $c_{ir} = \frac{\{\phi_r\}^T[\Delta K]\{\phi_i\}}{\lambda_i - \lambda_r}$ $(i \neq r)$, md is the number of analytical mode shapes and $\{\phi_i^d\}$ and $\{\phi_i\}$ are the damaged and intact mode shapes at mode i, respectively.

Changes of natural frequencies can be written as follows

$$\lambda_i^d = \lambda_i + \Delta\lambda_i \quad (2)$$

Where λ_i^d and λ_i are the damaged and intact eigenvalues at mode i. Also, it can be derived:

$$[K_m^d] = [K_m] + [\Delta K_m] = [K_m] + \alpha_m[K_m] \quad (-1 < \alpha_m \leq 0) \quad (3)$$

where $[K_m^d]$ and $[K_m]$ are damaged and intact stiffness matrix of element m and α_m is the fractional reduction coefficient of m^{th} elemental stiffness matrix. Extending the above equation for all elements and accumulating

$$\sum_{m=1}^{L}[K_m^d] = \sum_{m=1}^{L}[K_m] + \sum_{m=1}^{L}[\Delta K_m] = \sum_{m=1}^{L}[K_m] + \sum_{m=1}^{L}\alpha_m[K_m] \quad (4)$$

Simplifying

$$[K^d] = [K] + [\Delta K] = [K] + \sum_{m=1}^{L}[\Delta K_m] = [K] + \sum_{m=1}^{L}\alpha_m[K_m] \quad (5)$$

where K^d and K are global damaged and undamaged stiffness of the structure, respectively.

Improved Modal Strain Energy method formulation

In this paper, the previous study performed by Shi et al. (2000) has been improved in order to increase the accuracy of damage detection. Initially, the structural damaged stiffness matrix was used for establishing a more accurate modal strain energy equation. It is expected that using the new MSE formulated can get more accurate strain energy which is stored in structural elements and finally provides a proper damage detection model as well as having less computation and iteration efforts (Moradipour, et al., 2015).

Strain energy stored in the j^{th} elements at mode i before and after damage are as follow respectively

$$MSE_{i,j} = \frac{1}{2}\{\phi_i\}^T[K_j]\{\phi_i\} \quad (6)$$

$$MSE_{i,j}^d = \frac{1}{2}\{\phi_i^d\}^T[K_j^d]\{\phi_i^d\} \quad (7)$$

The changes in MSE is

$$\Delta MSE_{i,j} = MSE_{i,j}^{d} - MSE_{i,j} = \frac{1}{2}\{\phi_i^d\}^T[K_j^d]\{\phi_i^d\} - \frac{1}{2}\{\phi_i\}^T[K_j]\{\phi_i\} \tag{8}$$

Substituting for $\{\phi_i^d\}$ and $[K_j^d]$ in the above equation from Eqs. (1) and (3), respectively:

$$\Delta MSE_{i,j} = \frac{1}{2}\{\phi_i + \Delta\phi_i\}^T([K_j] + \alpha_j[K_j])\{\phi_i + \Delta\phi_i\} - \frac{1}{2}\{\phi_i\}^T[K_j]\{\phi_i\} \tag{9}$$

Simplifying and neglecting the higher order term leads to

$$\Delta MSE_{i,j} = \frac{1}{2}\alpha_j\{\phi_i\}^T[K_j]\{\phi_i\} + \frac{1}{2}(1+\alpha_j)[\{\phi_i\}^T[K_j]\{\Delta\phi_i\} + \{\Delta\phi_i\}^T[K_j]\{\phi_i\}] \tag{10}$$

Substituting for $\{\Delta\phi_i\}$ from Eq.1 in Eq.10 yields

$$\begin{aligned}\Delta MSE_{i,j} &= \frac{1}{2}\alpha_j\{\phi_i\}^T[K_j]\{\phi_i\} \\ &\quad + \frac{1}{2}(1+\alpha_j)\left[\{\phi_i\}^T[K_j]\sum_{r=1}^{md}\frac{\{\phi_r\}^T[\Delta K]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}\right. \\ &\quad \left. + \sum_{r=1}^{md}\frac{\{\phi_r\}^T[\Delta K]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_j]\{\phi_i\}\right] \quad (i \neq r)\end{aligned} \tag{11}$$

where i is normally in the range 1 to 5 and r is the number of analytical modes under consideration ($r \leq no. of\ DOFs$)

substituting Eq.4 in Eq. 11 ($[\Delta K] = \sum_{i=1}^{L}\alpha_i[K_i]$) and simplifying

$$\begin{aligned}\Delta MSE_{i,j} &= \frac{1}{2}\alpha_j\{\phi_i\}^T[K_j]\{\phi_i\} + \frac{1}{2}\{\phi_i\}^T[K_j]\sum_{i=1}^{L}\alpha_i\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_i]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\} \\ &\quad + \frac{1}{2}\sum_{i=1}^{L}\alpha_i\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_i]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_j]\{\phi_r\} \\ &\quad + \frac{1}{2}\alpha_j\left[\{\phi_i\}^T[K_j]\sum_{r=1}^{md}\frac{\{\phi_r\}^T[\Delta K]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}\right. \\ &\quad \left. + \sum_{r=1}^{md}\frac{\{\phi_r\}^T[\Delta K]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_j]\{\phi_i\}\right] \quad (i \neq r)\end{aligned} \tag{12}$$

Ignoring the higher order terms leads to final equation of changing in modal strain energy of the element j of the structure at mode i as follow

$$\Delta MSE_{i,j} = \frac{1}{2}\alpha_j\{\phi_i\}^T[K_j]\{\phi_i\} + \frac{1}{2}[\{\phi_i\}^T[K_j]\sum_{i=1}^{L}\alpha_i\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_i]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\} + \sum_{i=1}^{L}\alpha_i\sum_{r=1}^{md}\frac{\{\phi_r\}^T[K_i]\{\phi_i\}}{\lambda_i-\lambda_r}\{\phi_r\}^T[K_j]\{\phi_r\}] \quad (i \neq r) \tag{13}$$

3.1. Damage localization

The method of Shi et al. (2000) is used for damage localization. The change in modal strain energy is upgraded with the improved ΔMSE from Eq.13 for improving the accuracy. In this technique a damage location indicator named MSECR obtained from Eq.14 is used. MSECR can be either derived for a single mode such as mode i and element j as given in Eq.14(a) or normalized for the first five mode shapes of element j as given in Eq.14(b). It is expected that the recent damage indicator to be more accurate in locating the damage. When MSECR is plotted against element numbers, the elements with higher amounts of MSECR are the probable damaged elements.

$$MSECR_{ij} = \frac{\left|MSE_{i,j}^{d} - MSE_{i,j}\right|}{MSE_{i.j}} \tag{14.a}$$

$$MSECR_j = \frac{1}{m}\sum_{i=1}^{5}\frac{MSECR_{ij}}{MSECR_{i,max}} \tag{14.b}$$

Where $MSECR_j$ is the average of $MSECR_{ij}$ summation for the first five mode shapes normalized with respect to the largest value $MSECR_{i,max}$ of each mode.

Therefore, for damage localization, both Eq.14(a) and Eq.14(b) can be used to calculate MSECR indicator. In case of using Eq.14(a) any of the first five modes can be used i.e. i=any of 1-5. Though, the number of modes of damaged structure selected should be necessarily associated with that of undamaged one. However, using Eq.14(b) which mostly gives better results, requires the first five modes of both damaged and intact structures, i.e. $i = 5$.

3.2. Damage quantification

The second attempt in the present study is derivation of a sensitivity matrix using the improved modal strain energy equation. When the damage element is located among the most probable suspected elements from the previous section, damage quantifying process is conducted within those elements seeking for their α values. It is trying to find the amount of α's as the fractional reduction coefficient of elemental stiffness. The amount of α for true damaged elements will converge to their real damage percentage while for other suspected elements converge to zero. However, the exact value of each set of α's may be obtained through a number of iterations. The improve procedure is as follows

From Eq.13 ignoring the coefficient ½, it can be derived

$$[\beta]\{\alpha\} = \{MSEC'\} \tag{15}$$

where $MSEC'$ is obtained from difference of damaged and intact cases as Eq.(18) and β is:

$$\beta_{s,t} = \frac{\partial MSE}{\partial \alpha} = \{\phi_i\}^T[K_j]\{\phi_i\} + \sum_{r=1}^{n}\{\phi_i\}^T[K_s]\frac{\{\phi_r\}^T[K_s]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\} + \sum_{r=1}^{n}\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_s]\{\phi_i\} \tag{16}$$

Where s is a selected element for computation of the MSEC and t is a suspected damaged element.

In previous studies MSEC has been considered as following terms to be used in the right side of Eq. (15);

$$MSEC_{ij} = \{\phi_i^d\}^T[K_j]\{\phi_i^d\} - [\phi_i]^T[K_j]\{\phi_i\} \tag{17}$$

Since the value of $MSE_{i,j}^d$theoretically is a function of $[K_j^d]$, definitely it is expected by using K_j^dinstead of $K_j$get more exact value for $MSEC_{ij}$, therefore

$$MSEC'_{ij} = \{\phi_i^d\}^T[K_j^d]\{\phi_i^d\} - \{\phi_i\}^T[K_j]\{\phi_i\} \tag{18}$$

Substituting Eq. (3) and Eq. (18) into the above equation, simplifying and then arranging

$$MSEC'_{ij} = \alpha_j\{\phi_i^d\}^T[K_j]\{\phi_i^d\} + \{\phi_i^d\}^T[K_j]\{\phi_i^d\} - \{\phi_i\}^T[K_j]\{\phi_i\} \tag{19}$$

Substituting Eq. (17) into Eq. (19) gives

$$MSEC'_{ij} = \alpha_j\{{\phi_i}^d\}^T[K_j]\{\phi_i^d\} + MSEC_{ij} \tag{20}$$

Substituting Eq. (16) and (20) into Eq. (15)

$$\left[\{\phi_i\}^T[K_j]\{\phi_i\} + \sum_{r=1}^{n}\{\phi_i\}^T[K_s]\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\} + \sum_{r=1}^{n}\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_s]\{\phi_i\}\right]\{\alpha\} = \alpha_j\{\phi_i^d\}^T[K_j]\{\phi_i^d\} + \{MSEC\} \tag{21}$$

Simplifying

$$\left[[-\{\phi_i^d\}^T[K_j]\{\phi_i^d\} - \{\phi_i\}^T[K_j]\{\phi_i\}] + \sum_{r=1}^{n}\{\phi_i\}^T[K_s]\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\} + \sum_{r=1}^{n}\frac{\{\phi_r\}^T[K_t]\{\phi_i\}}{\lambda_i - \lambda_r}\{\phi_r\}^T[K_s]\{\phi_i\}\right]\{\alpha\} = \{MSEC\} \tag{22}$$

Substituting Eq. (17) into Eq. (22)

$$\left[[-MSEC] + \sum_{r=1}^{n} \{\phi_i\}^T [K_s] \frac{\{\phi_r\}^T [K_t] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\} + \sum_{r=1}^{n} \frac{\{\phi_r\}^T [K_t] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\}^T [K_s] \{\phi_i\}\right] \{\alpha\} = \{MSEC\} \quad (23)$$

Denoting $\beta^*_{s,t} = -MSEC_{ij}$ and

$$\beta'_{s,t} = \sum_{r=1}^{n} \{\phi_i\}^T [K_s] \frac{\{\phi_r\}^T [K_t] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\} + \sum_{r=1}^{n} \frac{\{\phi_r\}^T [K_t] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\}^T [K_s] \{\phi_i\} \quad (24)$$

Then, $\beta_{s,t}$ can be written in the following form

$$\beta_{s,t} = \beta'_{s,t} + \beta^*_{s,t} \quad (25)$$

4. Technical Specifications of the studied structure

The base of the jack up platform selected for this research is the SA20 Hull No. 110 with horizontal and flexural restraints. This platform, which is one of the most common Jack up platforms, has a height of 124 meters and an isosceles triangle section, the length of each side of which is 9.9 meters. Platform information is given in Table 1. Fig.2. shows a side view of the constructed jack up in the lab.

Table. 1. Basic specifications of the studied platform

Height	124 m
The height of each floor	3.65 m
Modulus of elasticity (E)	210 GP
Shear modulus (G)	79 GP
Special Weight	7850 kg/m^3
Diameter of pipes	0.168 and 0.219 m
Thickness	0.0010 and 0.0018 m
The second moment of the plane with respect to the x-axis	2.9e-4

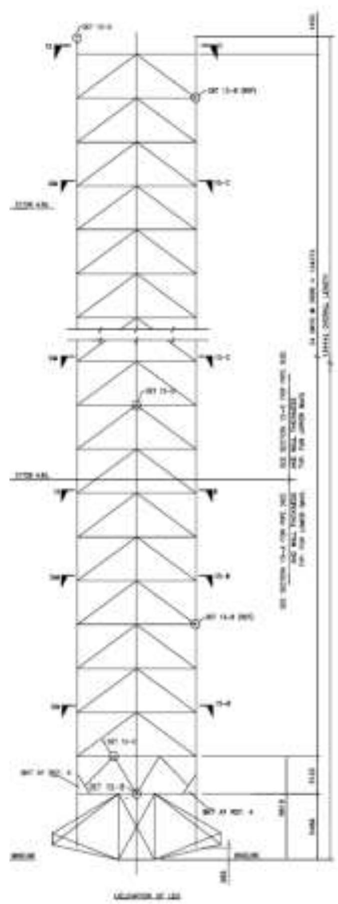

Fig. 2. Side view of the base of the examined jack up

5. Specifications of laboratory model and how to perform experimental modal analysis

In this study, a physical model based on a scale of 1/22 real dimensions of the base structure of the offshore jack up platform SA20 Hull No. 110 was made with the same specifications as Table 1 and Fig.3.

b

a

Fig. 3. Model studied and equipment used for experimental modal analysis.

Modal analysis is the process of determining the intrinsic dynamic properties of a system in the form of natural frequencies, damping coefficients, and mode shapes and applying them to create a mathematical model of the system's dynamic behavior. Structural instrumentation consisted of two lightly assembled ADXL345 three-axis accelerometers for recording structural responses, as well as a data analysis system including a computer for converting raw data.

All three end legs of the structure were welded to a completely rigid and heavy metal plate. The results of the experimental natural frequencies are shown in Table 2.

6. Results of structural modal analysis

As mentioned earlier, to identify damage by modal strain energy method, structural modal information before and after the damage are required. For this purpose, after modeling the base of the jack up platform and defining the elemental stiffness and mass matrices and assembling them to achieve the stiffness and mass matrix of the whole structure, eigenvectors and eigenvalues that are the mode shapes and frequencies, respectively of the structure are obtained. The natural frequencies are then arranged in the ascending order, with the smallest frequency being the first natural frequency of the structure and the corresponding mode shape being the first shape of the structural mode. Lists the first five natural frequencies of the structure are shown in Table 2.

Table. 2. Natural frequencies of the structure related to the first five numerical and experimental modes.

Mode number	1	2	3	4	5
Numerical natural frequency	1.85	5.358	7.65	7.92	10.80
Experimental natural frequency	1.62	4.59	6.88	7.01	9.95

7. Determining damage location and severity in different scenarios

Due to the reduction of structural material characteristics in case of damage, the hypothetical damage is applied by reducing the modulus of elasticity of the element. Then, by defining different scenarios of single and multiple damages, the modal strain energy method is applied for determining damage location and severity. The table below (Table 3) summarizes the various damage scenarios where the selected elements include vertical, horizontal and brace members. Damaged members are shown in Fig 4.

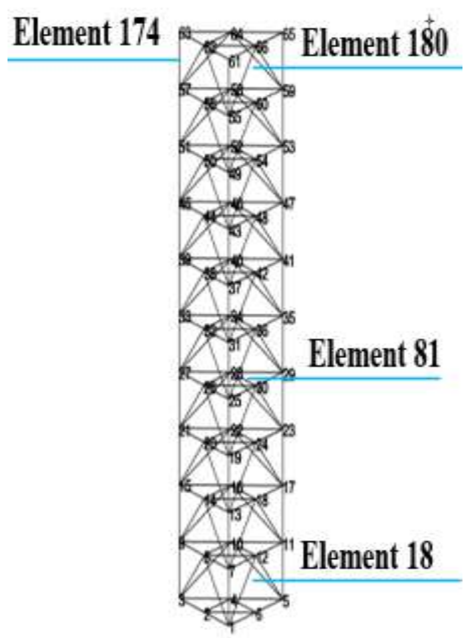

Fig. 4. Damaged elements.

Table. 3. Different damage scenarios.

Scenario number	Element number	Damage rate
1	18	10%
2	81	10%
3	174	5%
4	180	5%
5	81 and 180	10 % and 7%

7.1. First Scenario: 10 percent damage in element No.18

In this scenario, it is assumed that element number 18, that is a brace element in the leg of the platform is approximately 10% damaged. Damage location and severity are plotted in figs. 5 and 6, respectively. As these figures show, the sensitivity-based modal strain energy method is able to localize and quantify the damage in the element. Especially, the method could accurately locate the damage, such that it has caused the damage index to show a higher value for damaged member and a lower value for other unaffected elements.

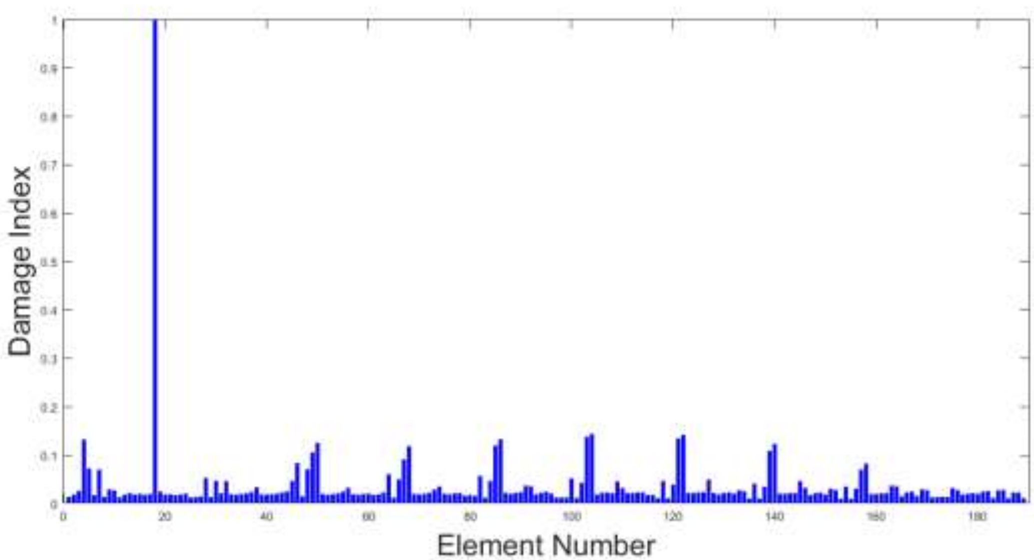

Fig. 5. Detection of damage location using modal strain energy method in the first scenario.

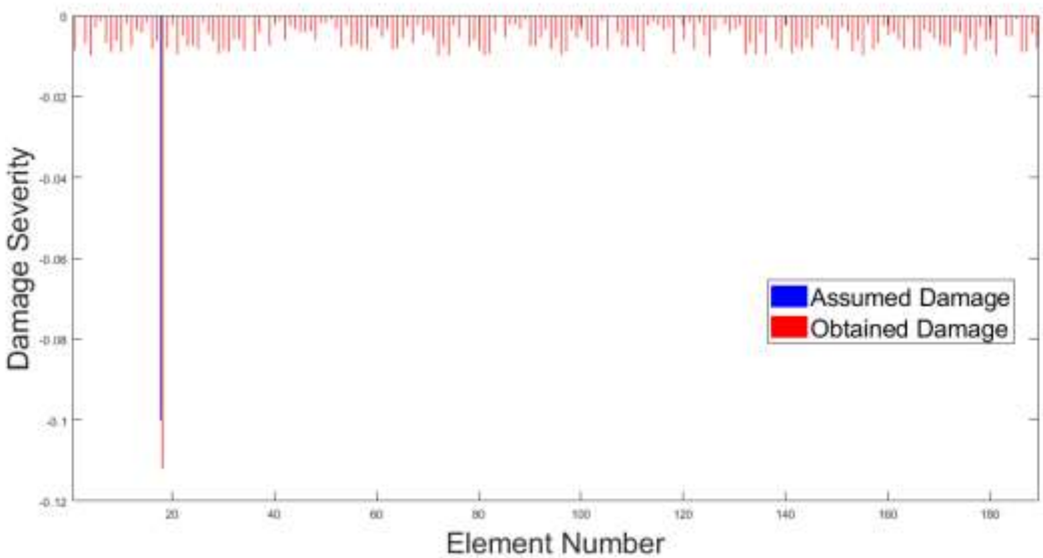

Fig. 6. Determining damage severity using modal strain energy method in the first scenario.

7.2. Second Scenario: 10 damage in element No.81

In this scenario, it is assumed that the element No.81, as one of the horizontal members of the structure is approximately 10 percent damaged. Damage location and severity were plotted in Figs. 7 and 8, respectively. As shown in Fig. 7, the method could accurately locate the damage, such that it has caused the damage index to show the maximum value (1) for damaged member and zero value for other unaffected elements. Fig. 8 shows that the method estimated the amplitude damage with a high accuracy.

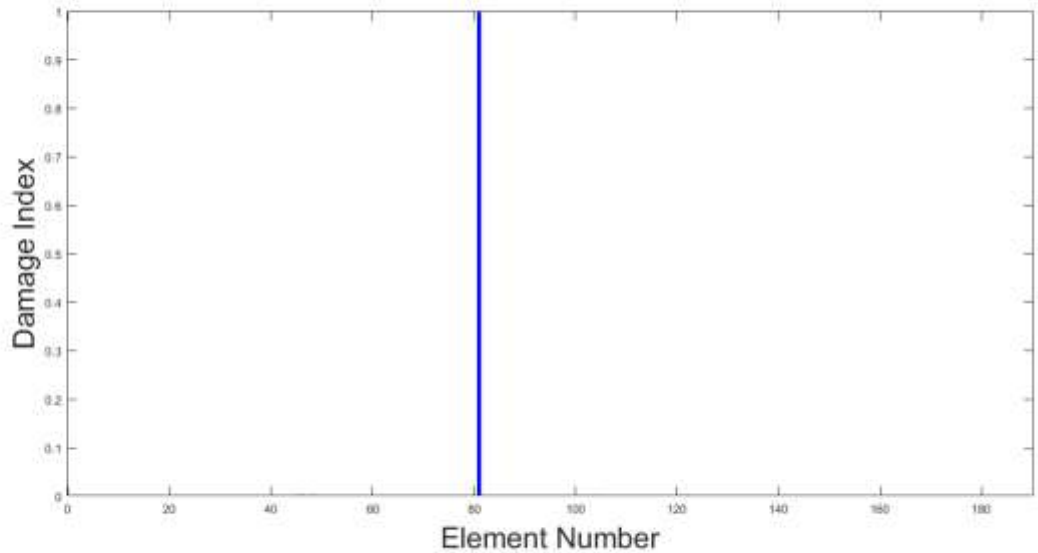

Fig. 7. Detection of damage location using modal strain energy method in the second scenario.

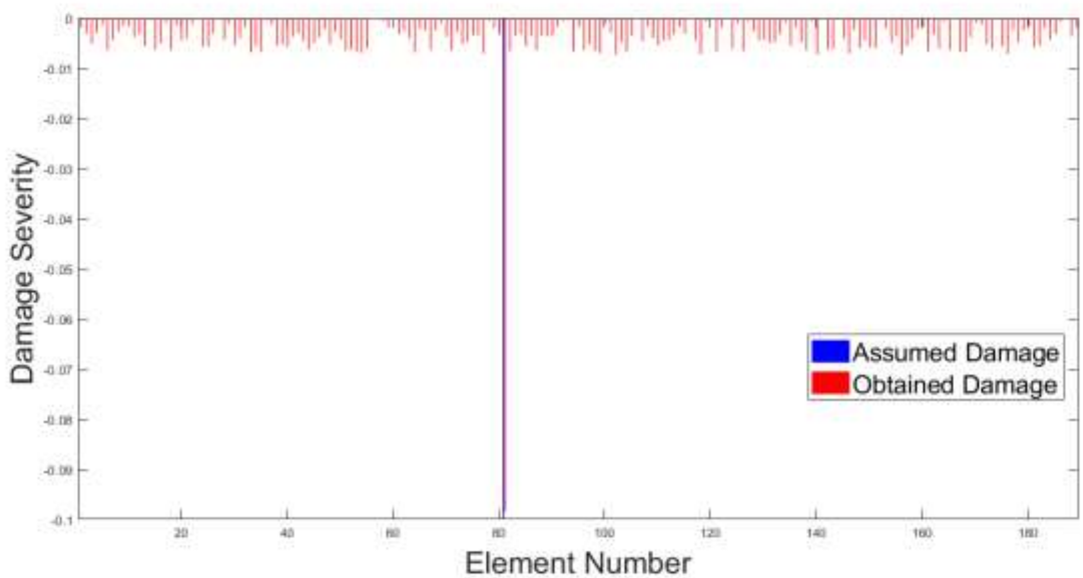

Fig. 8. Determining damage severity using modal strain energy method in the second scenario.

7.3. Third Scenario: 5 percent Damage in element No.174

In this case, it is assumed that a 5 percent damage has occurred in member No.174 one jack up's main legs. As Fig. 9 shows, the damage location index is 1 for the damaged elements and zero for other elements, showing that the method could accurately locate the damage. Fig. 10 shows that the severity of damage is predicted with an acceptable accuracy.

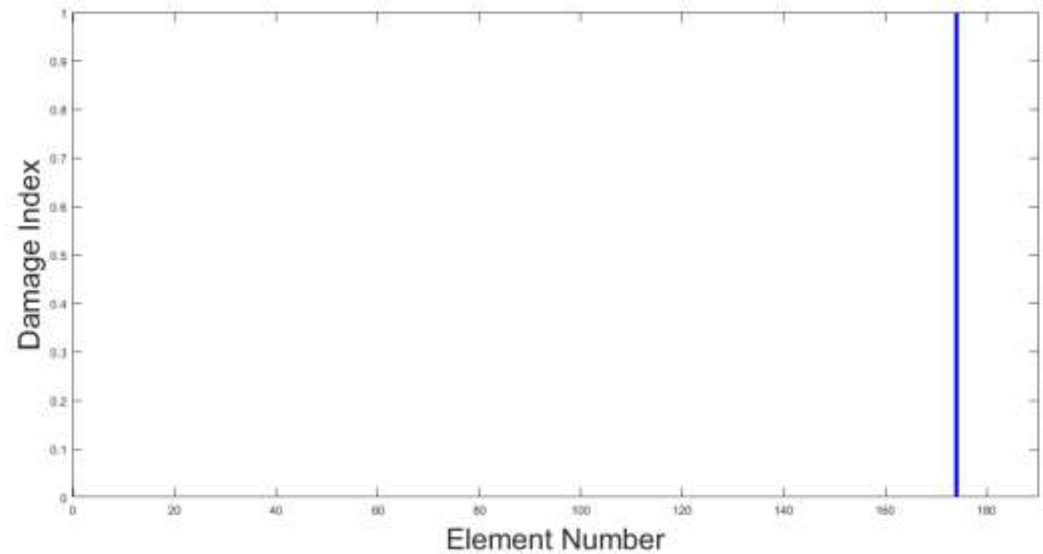

Fig. 9. Detection of damage location using modal strain energy method in the third scenario.

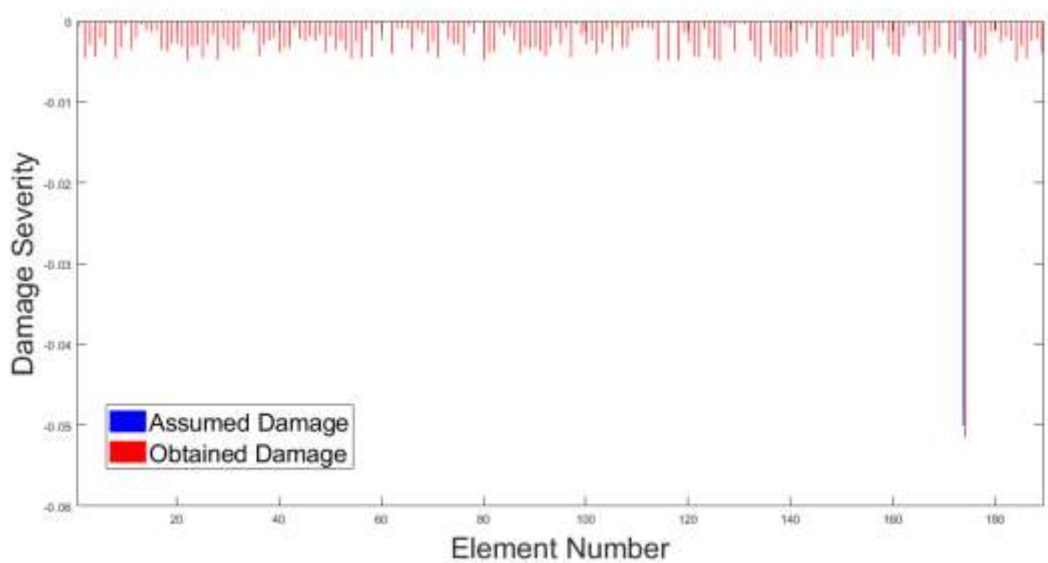

Fig. 10. Determining damage severity using modal strain energy method in the third scenario.

7.4. Fourth Scenario: 5 percent Damage in element No.180

In this scenario, element No.180 has incurred a 5 percent damage. The damage location and its severity in this scenario are plotted in Fig.11 and Fig. 12, respectively. As Fig. 11 shows the sensitivity based modal strain energy method could predict the damage location with a high accuracy. Fig. 12 shows that modal strain energy method has accurately determined the damage severity in jack up structure.

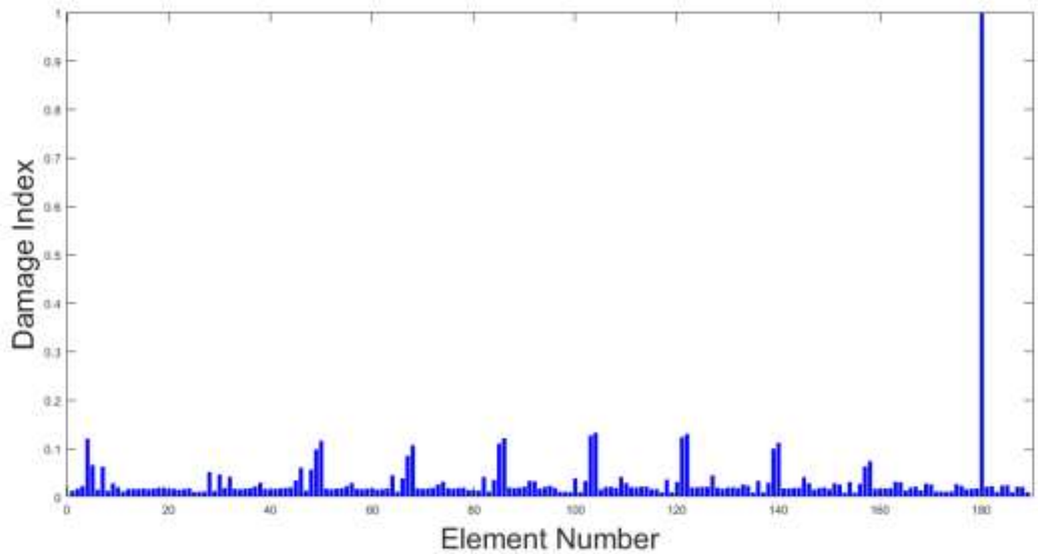

Fig. 11. Detection of damage location using modal strain energy method in the fourth scenario.

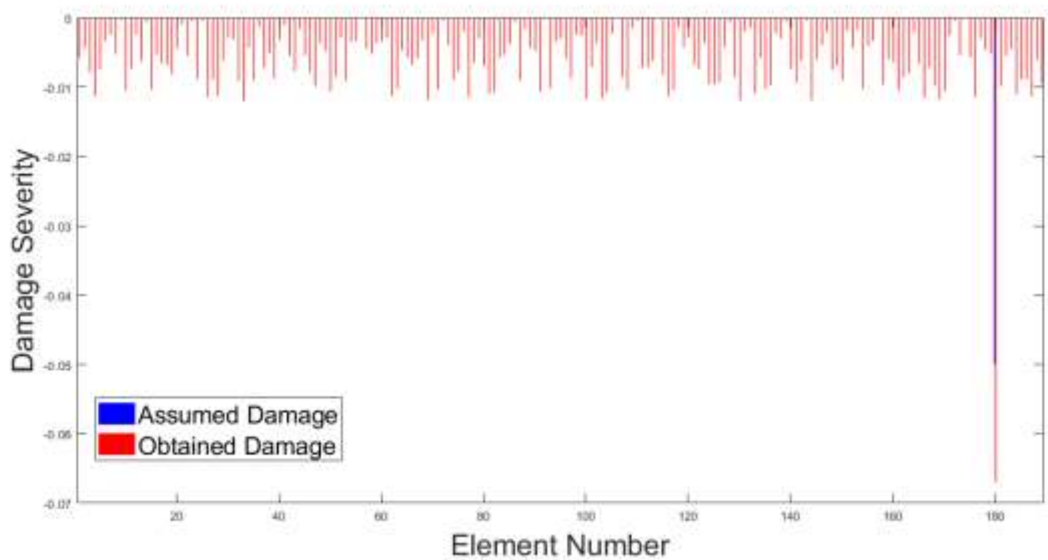

Fig. 12. Determining damage severity using modal strain energy method in the fourth scenario.

7.5. Fifth Scenario: %10 Damage in element No.81, %5 Damage in element No.180

In order to represent the ability of the model to predict multiple damages in jack up, in this scenario, elements No. 81 and 180 have incurred 10 and 5 percent damage, respectively. As Fig. 13 indicates, the damage localization is performed with an acceptable accuracy. Fig. 14 also shows that the modal strain energy method has predicted the damage severity in multiple members with an appropriate accuracy.

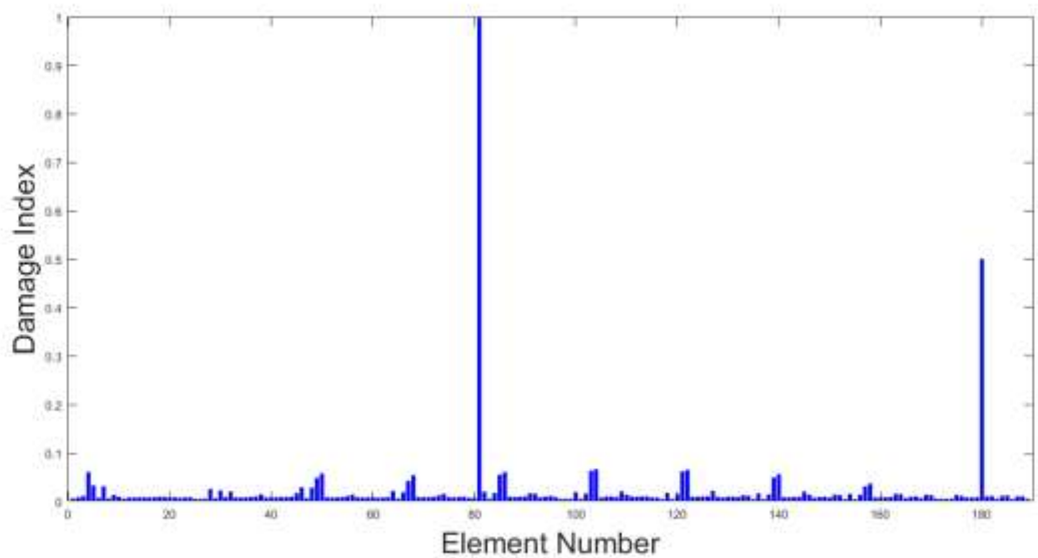

Fig. 13. Detection of damage location using modal strain energy method in the fifth scenario.

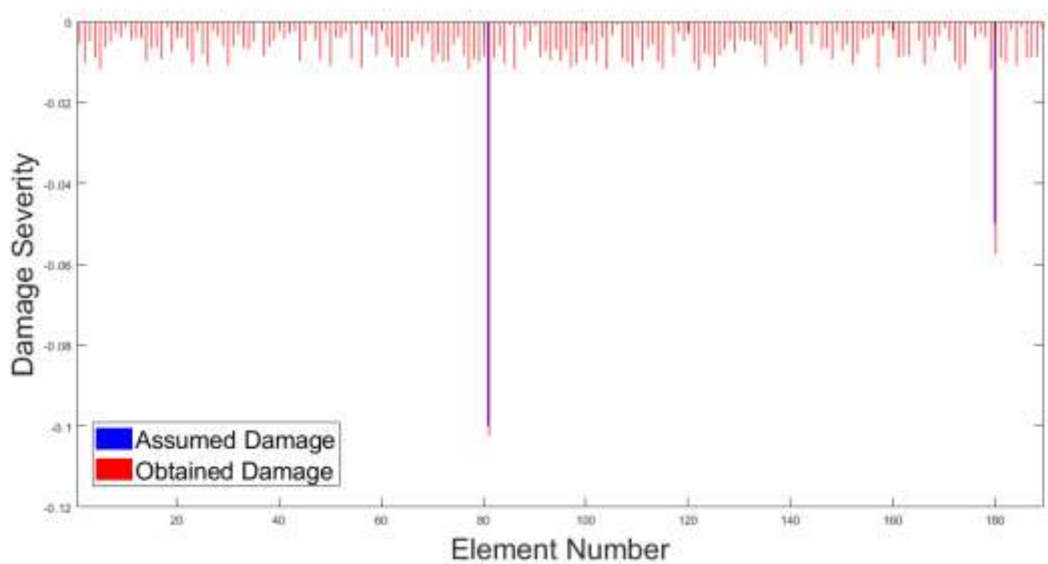

Fig. 14. Determining damage severity using modal strain energy method in the fifth scenario.

8. Conclusion

Jack up are highly important offshore structure. As the service life of these structures increases, the likelihood of damage to them increases; highlighting the necessity of conducting health monitoring to detect location and severity damage to them. In this study, using a modified modal strain energy method (Moradipour, et al., 2015) and performing experimental modal analysis, damage location and severity was predicted in a jack up structure. In order to show the capabilities of this new damage index, detection of single and multiple damages was examined using the 3D simulation of the leg of SA20 jack up rig (Hull 110). Following results were obtained from this research:

1. The modal strain energy method gives acceptable results for damage localization and quantification in the structure.
2. Structural model updating is a suitable tool for damage quantification in structures.
3. The method was more successful in identifying damage in horizontal members of jack up.
4. Single and multiple damages, with low and high severities were predicted with an appropriate accuracy using the iterative modal strain energy method.

CRediT author statement

Seyed Reza Samaei: Conceptualization, Formal analysis, Methodology, Software, Data curation, preparation, Validation, Writing - Original draft. Madjid Ghodsi Hassanabad, Mohammad Asadian Ghahfarrokhi and Mohammad Javad Ketabdari: Conceptualization, Supervision, Resources.

References

Alkayem, N. F. et al., 2018. Structural damage detection using finite element model updating with evolutionary algorithms: a survey. Neural Computing and Applications, Volume 30, pp. 389-411.

Arapogianni, A. et al., 2013. Deep water: The next step for offshore wind energy, s.l.: The European Wind Energy Association.

Balageas, D., 2006. Introduction to Structural Health Monitoring. In: Structural Health Monitoring. s.l.:Wiley, pp. 13-43.

Cawley, P. & Adams, R. D., 1979. The location of defects in structures from measurement of natural frequencies. The Journal of Strain Analysis for Engineering Design, Volume 14, pp. 49-57.

Chen, I. W. et al., 2016. Design and analysis of jacket substractures for offshore wind turbines. Energies, Volume 9, pp. 1-24.

Doebling, S., Farrar, C. R., Prime, M. B. & Shevitz, D. W., 1996. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review, s.l.: Los Alamos National Laboratory.

Doebling, S. et al., 1993. Selection of experimental modal data sets for damage detection via model update. s.l., s.n.

Doebling, S. W., Farrar, C. R., Prime, M. B. & Shevitz, D. W., 1995. A summary review of damage identification methods that examine changes in dynamic properties. Journal of Shock Vibration, Volume 30, pp. 91-105.

Farrar, C. R. & Jauregui, D. A., 1998. Comparative study of damage identification algorithms applied to a brdige: II. Numerical study. Smart Materials and Structures, Volume 7, pp. 720-731.

Ge, M. & Lui, E. M., 2005. Structural damage identification using system dynamic properties. Computers & Structures, Volume 83, pp. 2185-2196.

Hansen, S. R. & Vanderplaats, G. N., 1990. Approximation method for configuration optimization of trusses. AIAAJ, Volume 28, pp. 161-168.

He-Zhen, Y., Hua-jun, L. & Shu-qing, W., 2003. Damage localization of offshore platforms under ambient excitation. China Ocean Engineering, Volume 17, pp. 495-504.

Hu, H. & Wu, C., 2009. Development of scanning damage index for the damage detection of plate structures using modal strain energy method. Mechanical Systems and Signal Processing, Volume 23, pp. 274-287.

Jaishi, B. & Ren, W. X., 2007. Finite elemet model updating based on eigenvalue and strain energy residuals using multiobjective optimisation technique. Mechanical Systems and Signal Processing, Volume 21, pp. 2295-2317.

Jiang, J., Wu, H., Linag, J. & Tang, D., 2013. Micostructural characterization and impact thoughness of a jackup rig rack steel treated by intercritical heat treatment. Materials Scinence & Engineering A, Volume 587, pp. 359-364.

Kim, J. T. & Stubbs, N., 1995. Damage detection in offshore jacket structures from limited modal information. International Journal of Offshore and Polar Engineering, Volume 5, pp. 58-66.

Kim, J. T. & Stubbs, N., 2002. Improved damage identification method based on modal information. Journal of Sound and Vibration, Volume 252, pp. 223-238.

Liu, F., Li, H., Li, W. & Wang, B., 2014. Experimental study of improved modal strain energy method for damage localisation in jecket-type offshore wind turbines. Renewable Energy, Volume 72, pp. 174-181.

Li, Y., Wang, S., Zhang, M. & Zheng, C., 2016. An improved modal strain energy method for damage detection in offshore platform structures. Journal of Marine Science and Application, Volume 15, pp. 182-192.

Li, Y. Y., Cheng, L., Yam, L. H. & Wong, W. O., 2002. Identification of damage locations for plate-like structures using damage sensitive indices: strain modal approach. Computers & Structures, Volume 80, pp. 1881-1894.

Martinez-Luengo, M., Kolios, A. & Wang, L., 2016. Structural health monitoring of offshore wind turbines: A review through the statistical pattern recognition paradigm. Renewable and Sustainable Energy Reviews, Volume 64, pp. 91-105.

Moradipour, P., Chan, T. H. T. & Gallage, C., 2015. An improved modal strain energy method for structural damage detection, 2D simulation. Structural Engineering and Mechanics, Volume 54, pp. 105-119.

Nguyen, C. U., Huynh, T. C. & Kim, J. T., 2018. Vibration-based damage detection in wind turbine towers using artificial neural networks. Structural Monitoring and Maintenance, Volume 5, pp. 507-519.

Pedram, M., Esfandiari, A. & Shadan, F., 2014. Finite element model updating using power spectral density of structural response. Nantes, France, s.n.

Rahai, M., Esfandiari, A. & Bakhshi, A., 2020. Detection of structural damages by model updating based on sigular value decomposition of transfer function subsets. Structural Control Health Monitoring, Volume 27, pp. 1-23.

Salawu, O. S., 1997. Detection of structural damage through changes in frequency: a review. Engineering Structures, Volume 19, pp. 718-723.

Seyedpoor, S. M., 2012. A two stage method for structural damage detection using a modal strain energy based index and particle swarm optimization. International Journal of Non-Linear Mechanics, Volume 47, pp. 1-8.

Seyedpoor, S. M. & Yazdanpanah, O., 2014. An efficient indicator for structural damage localization using the change of strain energy based on static noisy data. Applied Mathematical Modeling, Volume 38, pp. 2661-2672.

Shadan, F., Esfandiari, A., Khoshnoudian, F. & Pedram, M., 2014. Structural parameters identification using FRF of incomplete strain data. Nantes, France, s.n.

Shahrivar, F. & Bouwkamp, G., 1986. Damage detection in offshore platforms using vibration information. Journal of Energy Resources Technology, Volume 108, pp. 97-106.

Shih, H. W., Thambiratnam, D. P. & Chan, T. H., 2009. Vibration based structural damage detection in flexural members using multi-criteria approach. Journal of Sound and Vibration, Volume 323, pp. 645-661.

Stubbs, N. & Kim, J. T., 1996. Damage localization in structures without baseline modal parameters. AIAA Journal, Volume 34, pp. 1644-1649.

Stubbs, N., Kim, J. T. & Farrar, C. R., 1995. Field verification of a non-destructive damage localization and severity estimation algorithm. s.l., s.n.

Wang, S., Liu, F. & Zhang, M., 2014. Modal strain energy based structural damage localization for offshore platform using simulated and measured data. Journal of Ocean University of China, Volume 13, pp. 397-406.

Yang, H. Z., Li, H. J. & Wang, S. Q., 2003. Damage localization of offshore platforms under ambient excitation. China Ocean Engineering, Volume 17, pp. 495-504.

Yang, X., Ouyang, H. & Cao, S., 2020. Modal strain energy-based model updating method for damage identification on beam-like structures. Journal of Structural Engineering, Volume 146, p. 04020246.