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Damage localization and quantification in the Catwalk of Foroozan offshore complex using improved modal strain energy method

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ABSTRACT

As one of the most important components of an offshore oil and gas complex, Catwalk (access bridge) provides support for equipment and act as a passage for staff. Therefore, any damage in this structure may result in casualties as well as financial and environmental losses. Hence, identifying the location and severity of damage in these structures is of a great importance. As a common SHM method, modal strain energy uses the changes in the dynamic properties of the structure for identifying the damage location and severity. Considering natural frequencies in the process of the damage localization is one of modifications that has been successfully applied to this method. In order to show the robustness of this method for identifying damages in real class offshore structures with a large number of elements, the improved modal strain energy (IMSE) method is applied for damage localization and quantification in the access bridge of Foroozan platform in the Persian Gulf. The results showed that the IMSE damage index is more accurate than the original Stubbs index. Both the single and multiple damages were predicted with a good accuracy with this method. However, the method was more accurate in locating the damages in horizontal elements as well as the elements far from the supports of the structure.

1. Introduction

In shallow waters such as the Persian Gulf, steel jacket platforms are commonly used for oil and gas extraction. During their service life, offshore structures are exposed to different loads such as the loads during construction, transportation and installation as well as the loads during operation such as drilling and extraction, environmental loads such as wind, wave, ice and current loads, and accidental loads such as earthquake, fire, storms and ship collisions. Consequently, some damages such as fatigue and crack in joints, corrosion of the elements, perforation and flooding of members, and even total failure and sudden destruction of the platform may occur. Various types of offshore steel structures are found in offshore oil and gas production complexes, including drilling/well-protector platforms, tender platforms, self-contained platforms (template and tower), production platforms, quarter platforms, flare jacket and flare tower platforms, auxiliary platforms, bridges and heliports [1]. Each of these types of platforms has its own characteristics from an operational point of view. One of the most important components of offshore oil and gas complexes is the access bridge between different platforms. Due to the corrosive environment of the installation site as well as the possibility of various damages to the structural members that cause huge financial and human losses, structural health monitoring of these structures is very important.

Various methods have been used for structural health monitoring of structures including access bridges in offshore installations. One of these methods is the visual inspection that gives important information about the condition of the structure. Despite some advantages, this method requires a lot of time and money. Also, due to the unavailability of some members, visual inspection can not detect the damage in some unavailable members. In addition, detecting internal damages and their origin is not possible by this method. In order to increase the safety and ensure the safety of the structure, in recent years, much attention has been paid to non-destructive damage detection methods. One of these methods is using vibrational properties of the structure to assess the damage at the structure level, which is used as a complementary solution along with visual inspections [2,3]. In vibration-based damage detection methods, the modal properties of the structure (natural frequencies, mode shapes and modal damping) are a function of its physical properties. Therefore, by using changes in the static or dynamic response of structures, changes in their physical properties and consequently structural damage can be identified in the early stages. This resulted in a reduction in maintenance costs and prevention of structural failure.

As its purpose is monitoring the structural and operational conditions to prevent catastrophic failures and providing the necessary quantitative design data for engineers and owners of the structure, structural health monitoring has so far attracted a great deal of attention from researchers around the world. 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 to detect the location of the damage [4]. Examining the effects of diagonal bracing on the frequency and mode shapes of the platform deck, Shahrivar and Bouwkamp (1986) used vibrational information to detect damages in an offshore steel platform [5]. Frequency and mode shapes of the structure were successfully used for damage localization and quantification by Hansen and Vanderplaats (1990) for damage detection in the structure [6]. 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 [7]. 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 [8]. 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 [9,10]. 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 [11]. Examining 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, Farrar and Jauregui (1998) concluded that modal strain energy damage index method had higher accuracy compared to other methods [12]. Developing an improved, more accurate damage index, Kim and Stubbs (2002), tested the performance of their index on a two-span beam [13]. Li, et al., (2002) proposed a method for damage localization 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 [14]. 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 [15]. 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 [16]. Applying the modal strain energy method for detecting damage in beams and plates, Shih et al. (2009) concluded that this method can be used to detect damage in girder and bridge decks [17]. Hu and Wu (2009) developed a modal strain energy-based damage index to detect damage in plates [18]. Seyedpoor (2012) proposed a twostep method for accurately detecting the location and severity of multiple damages in structural systems [19]. 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 [20]. Considering a 31 element planar truss, a three span frame and a space truss, 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 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 [21]. Wang et al. (2014) used the modal strain energy method for damage localization 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 [22].

In the field of damage detection studies on bridges, Giles, et al., (2011) used the damage locating vector method (DLV) for damage localization at the second span of the Government Bridge in Rock Island, USA [23]. Modares and Waksmanski (2013) reviewing some areas of structural health monitoring, studied the new and traditional sensors used for monitoring of structural parameters such as corrosion, cracking, displacement, fatigue, force, settlement, strain, temperature, tilt, vibration, water level and wind in steel bridges [24]. Budipriyanto and Susanto (2015) used the responses obtained from a railway steel truss bridge in intact and damaged conditions when it was under the train traffic for damage localization and quantification [25]. Li and Hao, (2016) reviewed recent developments in the field of structural health monitoring, including signal processing methods for operational modal analysis, a user friendly graphical modal analysis toolkit, non-modal methods for evaluating shear joints in composite bridges and determining the free span and support conditions of pipelines, vibration based damage detection methods and model updating including the effects of uncertainty and noise as well as identifying structures under moving loads[26]. Ding, et al., (2019) practically monitored the condition of the scaffold separation process from a large steel span bridge during the bridge construction process and examined changes in strain distribution. They also modeled the bridge to simulate scaffold removal conditions using the finite element method and compared the strain distribution in the girder with the measured values [27].

This comprehensive literature study shows the high accuracy and ability of the modal strain energy method for damage detection in marine structures. The importance and high investment made in Iran's offshore oil and gas facilities, shows the need to check the health of these structures more than before. The Forouzan oil field, located between Iran and Saudi Arabia, is of great importance to the Iranian economy, and it is essential to identify any damage to the platform structure in the early stages. Due to the long service life of the country's offshore platforms and the existence of possible damage in these platforms, in this paper a comparison between the accuracy of different damage detection methods, including the Stubbs index method and improved strain energy method in order to use this method to identify real damage in Offshore platforms took place. For this purpose, the access bridge between the FY and FY-B platforms (Figure1) of Forouzan oil complex located in the Persian Gulf was studied. One of the differences between the present study and other studies is the selection of structures with a large number of members. Also, the accuracy of the method in identifying the location and severity of small and multiple injuries is one of the features of this article.

1.1. Offshore platform access bridge

A bridge with the length of 30-49 m (100-160 ft) that connects two adjacent offshore structures is called a catwalk. This bridge supports pipelines, pedestrian movement, or a bridge of materials handling [1]. The different geometries of bridges are shown in Figure 2.

Figure 1: Foroozan oil complex [28]

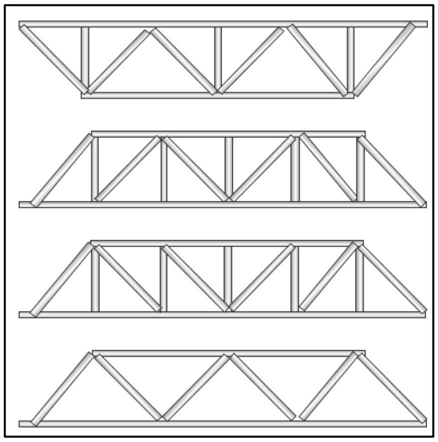

Figure 2: Different Geometries of catwalk [1]

2. Materials and Methods

2.1. Modal Strain Energy

Applying a force to an elastic body leads to a tension as well as a deformation in the body. As a consequence of this deformation, the position of the various points of the elastic object changes. Changing the point of effect of the applied load causes some work to be performed. This work, which is accompanied by the deformation of the object in the tension state, stores some energy in the form of elastic energy in the object called strain energy. Modal strain energy is a condition in which no force is applied to the structure and the structure is in free vibration state. In this condition, the modal strain energy of each element can be obtained by dynamic analysis and solving the related equations. Structural damage usually reduces the stiffness of the structure, but does not affect its mass matrix.

In a linear structure, with NE elements and N nodes, the i-th modal stiffness of structure is obtained from the following equations [13]:

$$K_i = \Phi_i^T C \Phi_i \qquad (1)$$

$$K_i^* = \Phi_i^{*T} C^* \Phi_i^* \qquad (2)$$

where K_i and K_i^* are the stiffness at the i-th mode, C and C^* are the stiffness matrices of the structure and Φ_i and Φ_i^* are i-th mode shaper vectors of the structure in intact and damage states, respectively. In other word, in these equations * shows the damaged state. The Stubbs damage index is obtained from the following equation [13]:

$$\beta_{ij} = \frac{E_j}{E_j^*} = \frac{[\phi_i^{*T} C_{jo} \phi_i^*] K_i}{[\phi_i^T C_{jo} \phi_i] K_i^*} \qquad (3)$$

where, β_{ij} is the damage detection index for j-th element and i-th mode, E_j and E_j^* are the modulus of elasticity of the j-th element in intact and damaged conditions, respectively and C_{jo} is related to the geometric properties of the stiffness matrix. If $K_i^* \approx \phi_i^{*T} C \phi_i^*$ is set, all quantities on the right-hand side (including ϕ_i and ϕ_i^*) can be determined, or estimated from the modal parameters obtained from experimental measurements and geometry of the structure (C_{jo}). According to the above equation, the damage in j-th element and i-th mode shape is determined if $\beta_{jj} > 1$. However, if j-th element is in or near the i-th mode shape, the denominator of the above equation will tend to zero and a false prediction of the damage will be resulted. Based on the study of Kim and Stubbs [13], by considering some approximations, this limitation is overcome and the following relation is obtained:

$$\beta_j = \frac{\sum_{i=1}^{NM} (\Phi_i^{*T} C_{jo} \Phi_i^* + \sum_{i=1}^{NE} \Phi_i^{*T} C_{ko} \Phi_i^*) K_i}{\sum_{i=1}^{NM} (\Phi_i^T C_{jo} \Phi_i + \sum_{i=1}^{NE} \Phi_i^T C_{ko} \Phi_i) K_i^*} \qquad (4)$$

It should be noted that since the structure stiffness matrix is not determined in the damaged mode, the stiffness matrix of the intact structure is used for both intact and damaged cases. After obtaining β_j for each element, the damage index is normalized using the following equation [13]:

$$Z_j = \frac{\beta_j - \bar{\beta}}{\sigma_\beta} \qquad (5)$$

2.2. Improved modal strain energy method

In order to determine the Stubbs's index, only the mode shapes are used and natural frequencies are not considered in determining the location of the damage. However, previous researches have shown that modal frequencies can be determined much more accurately than mode shapes. Measuring the shape of the mode is more difficult than measuring normal frequencies. Mode shape is a unique feature of any structure and in practice it is not possible to measure modes for all degrees of freedom. Another problem of using modes is how to make experimental and analytical mode forms dependent.

In order to improve the Stubbs's method, Li et al. (2016) used frequency information in determining the damage index [29]. They showed that the reduction in stiffness due to damage to the structure affects the natural frequency and this can be the basis of the frequency-based damage detection method. An important advantage of this method is the ease and simplicity of determining natural frequencies. In fact, by placing a sensor in the structure, its various frequencies can be measured. It should be noted that natural frequencies are sensitive to all types of local and general damage. Eigen analysis for intact and damaged structures can be written as follows:

$$K\phi_i = \omega_i^2 M\phi_i \tag{6}$$

$$K^*\phi_i^* = \omega_i^2 M^*\phi_i^* \tag{7}$$

where M and M^* are mass matrices of the system and ω_i and ω_i^* are the i-th modal frequencies in intact and damaged modes, respectively. The improved damage index is obtained from the following equation:

$$\beta_j = \frac{\sum_{i=1}^{m}\left(\phi_i^{*T}K_j\phi_i^* + \omega_i^{*2}\phi_i^{*T}M\phi_i^*\right)\omega_i^2\phi_i^T M\phi_i}{\sum_{i=1}^{m}\left(\phi_i^T K_j\phi_i + \omega_i^2\phi_i^T M\phi_i\right)\omega_i^{*2}\phi_i^{*T}M\phi_i^*} \tag{8}$$

Using equation 5, the above index can be normalized.

2.3. Estimating the severity of the damage

If we show the ratio of the changes in the stiffness of the j-th element with α_j, so that $\alpha_j \geq -1$, we have:

$$E_j^* = E_j\left(1 + \alpha_j\right) \tag{9}$$

Then, the severity of damage can be obtained from the following equation:

$$\alpha_j = \frac{\left[\phi_i^T C_{jo}\phi_i\right]}{\left[\phi_i^{*T}C_{jo}\phi_i^*\right]}\frac{K_i^*}{K_i} \tag{10}$$

2.4. Study Area

Foroozan oil field is located in the Persian Gulf, about 100 km southwest of Kharg Island export terminal. This field is located on the water border of Iran-Saudi Arabia and the Saudi Arabian part is called Marjan field. The field, owned by the National Iranian Oil Company (NIOC), was discovered in 1966 and has 2.3 billion barrels of recoverable reserves. This offshore oil field started to operate with an initial production of 100,000 barrels per day in 1987, but its production fell to 40,000 barrels per day in 2000. In order to double the crude output of the field to 80,000 barrels per day and also increase the gas production capacity, the Iranian Offshore Oil Company (IOOC) has undertaken some reconstruction and redevelopment activities, including the installation of a number of new offshore platforms. Oil and gas produced in Foroozan field are processed in two offshore production complexes FX and FZ.

2.5. Details of Foroozan oil field development

Foroozan oil field was initially developed with 66 wells, two production platforms, one production unit, 12 wellhead platforms, three separators, a desalination unit and two residential platforms named FX and FY. The two-story FX residential platform accommodates 21 people and also supports a control room, a restaurant and a theater, while FY residential platform is a three-story platform for 42 people. The hydrocarbons produced in this field are separated into crude oil, associated gases and water. Crude oil is transported through a 100-kilometer pipeline with a diameter of 20 inches to Kharg export terminal. In 2015, Foroozan oil field was renovated with 24 new production wells with two offshore platforms, including FZ-A processing unit and FY-A residential platform [30].

3. Results and discussions

3.1. Identification of damage location and severity in Catwalk of Foroozan offshore complex

In this section, damage is identified in the access bridge of Foroozan offshore complex. This access bridge is designed to connect FY-B and FY platforms. With an approximate length of 45.65 m, this bridge has a triangular shape. The section of the lower chord is of 355.60D x 15.9 WT in EL +16.75 (TBC) and the upper chord cross section is 457oD X 15.9 WT in EL.+21.250 (TBC). Steel type is API 5L x 52. A summary of the overall layout of the bridge is given in Table 1.

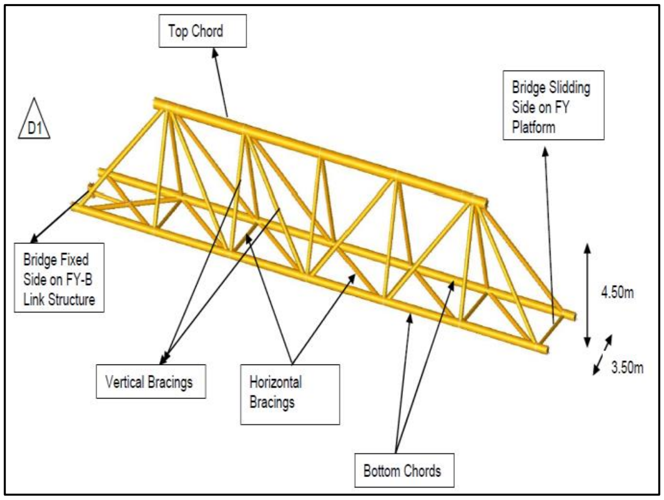

Figure 3: General view of Catwalk structure

Table 1: Specifications of the access bridge

Properties	Design data
Cross section	Triangular
Width of the bridge	3.5 m
Height of the bridge	4.5 m
Number of chords	3
Diameter and thickness of chords	457 mm and 15.9 mm
Diameter and thickness of horizontal bracings	168.3 mm and 9.5 mm
Diameter and thickness of inclined horizontal bracings	219.1 mm and 9.5 mm
Diameter and thickness of inclined vertical bracings	219.1 mm and 9.5 mm
Diameter and thickness of inclined vertical bracings	219.1 mm and 15.9 mm

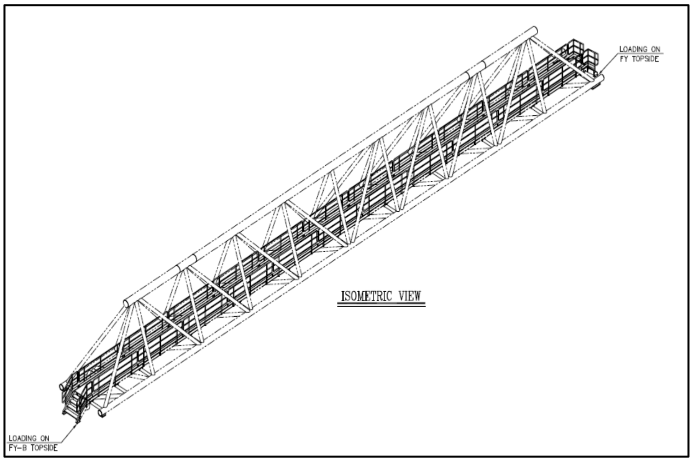

Figure 4: Isometric view of the access bridge

3.2. Applying assumed damage to the structure and defining different damage scenarios

In this research, hypothetical damage is applied by reducing the modulus of elasticity of the element in the Finite Element code. In order to show the accuracy of the modal strain energy method in identifying the location and severity of damage, different single and multiple damage scenarios have been defined. To identify damage by modal strain energy method, structural modal information in the pre- and post-damage condition is required. For this purpose, after modeling the bridge and defining the elemental stiffness and mass matrices and assembling them to achieve the global stiffness and mass matrices of the structure, eigenvectors and eigenvalues that are the mode shapes and natural frequencies of the structure, respectively, are extracted. The natural frequencies are then arranged in ascending order, with the smallest frequency being the first natural frequency of the structure and the corresponding mode shape being the first mode shape of the structure. Table 2 shows the different damage scenarios along with the first three natural frequencies of the damaged structure in each mode. The geometric location of the damaged elements is shown in Figure 5. It should be noted that a first few mode shapes of the structure are considered in the calculations related to damage identification.

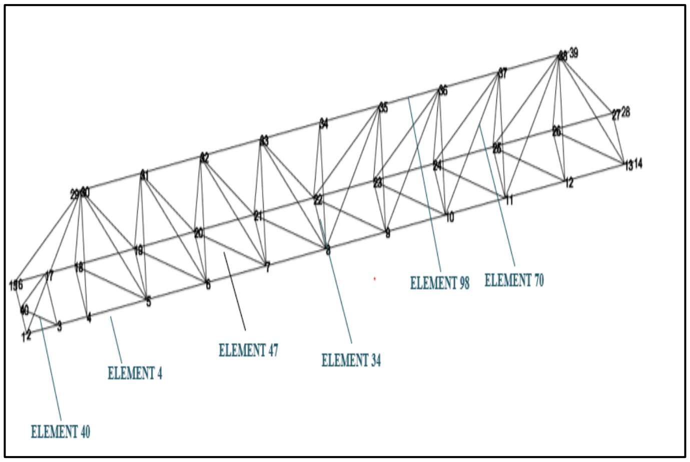

Figure 5: Created Finite Element model of the Catwalk and the hypothetical damaged elements

Table 2: Different damage scenarios to Catwalk structure and the first three natural frequencies of the structure in each scenario

Damage Scenarios	Damage Element	Damage Severity (%)	Natural Frequency (Hz)		
			First mode	Second mode	Third mode
1	4	15	5.1368	5.4146	8.6879

2	34	20	5.1377	5.4284	8.6898
3	40	10	51378	5.4276	8.6864
4	47	20	5.1377	5.4259	8.6869
5	70	10	5.1362	5.4273	8.6776
6	4 and 47	15 and 20	5.1367	5.4118	8.6849

3.3. Identifying the location and severity of damage in different scenarios

3.3.1. First scenario

In this case, a hypothetical 15% damage is applied to element No.4 which is located in the bridge chord. Mode shapes of the structure are extracted in both intact and damaged modes and using modal strain energy, the damage location and severity are plotted in Figures 6 and 7, respectively. As Figure 6 shows, the modal strain energy method determined the location of damage in the bridge chord element with high accuracy. However, it is clear that the improved modal strain energy results were slightly better than Stubbs index, such that the improved index is slightly higher in damaged elements and lower in intact elements. Figure 7 shows that the modal strain energy method accurately predicts the severity of damage to bridge chord element.

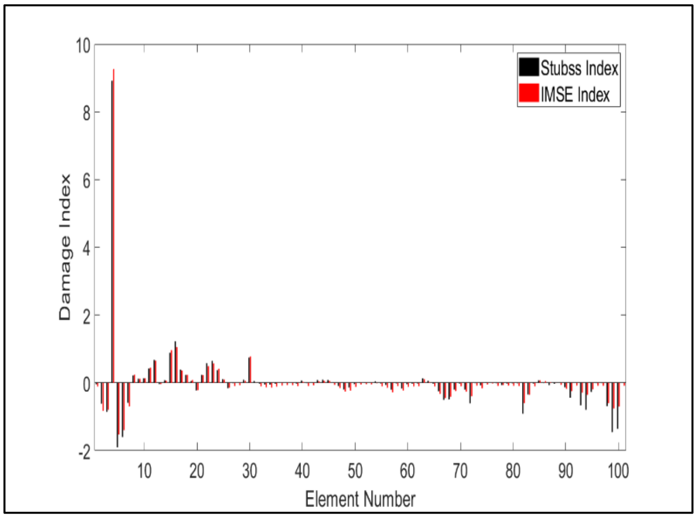

Figure 6: Damage localization results using Stubbs and IMSE indices in the first damage scenario

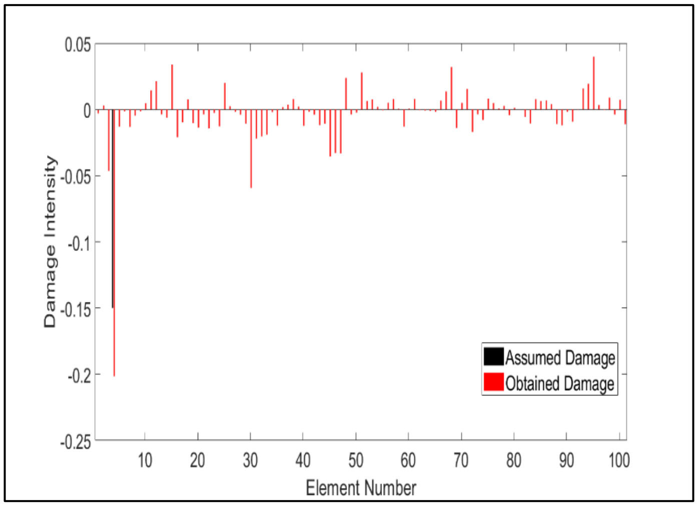

Figure 7: Damage severity estimation using modal strain energy method in the first scenario

3.3.2. second scenario

In this case, a hypothetical 20% damage is applied to element No.34 which connects the two bottom chords of the bridge. Figure 8 shows the damage localization and Figure 9 shows the damage quantification in this case. As Figure 8 shows, the improved method gives more accurate results for damage index. Figure 9 shows that the damage severity is predicted with an acceptable accuracy.

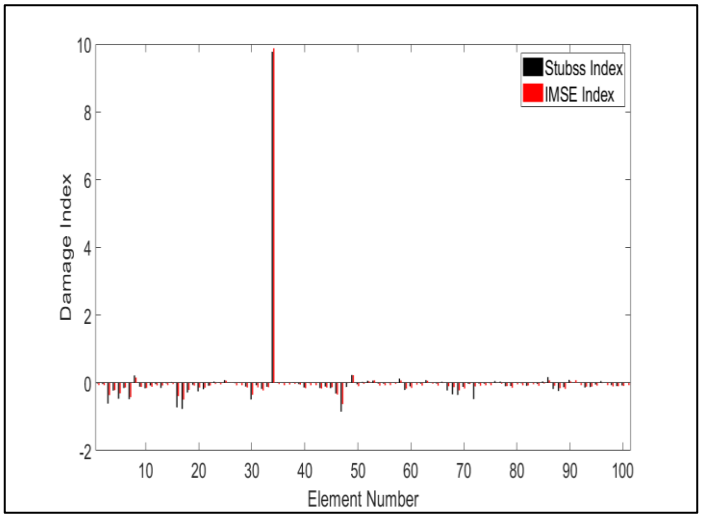

Figure 8: Damage localization results using Stubbs and IMSE indices in the second damage scenario

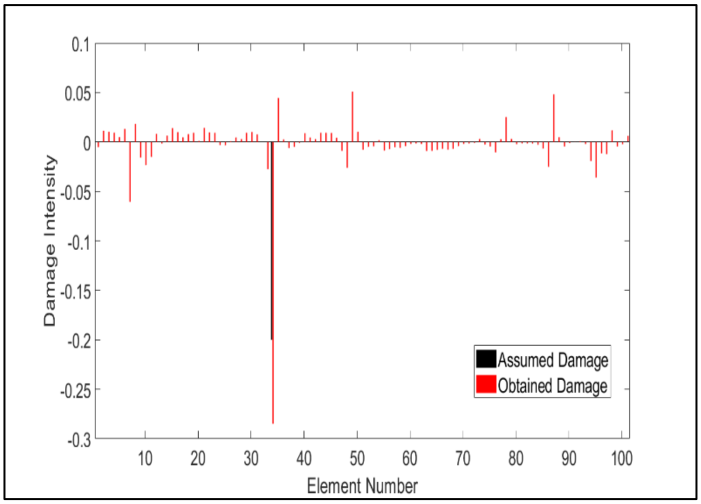

Figure 9: Damage severity estimation using modal strain energy method in the second scenario

3.3.3. Third scenario

In this case, a hypothetical 10 % damage is applied to the element No. 40 which is one of the diagonal members of the access bridge. The predicted location of the damage in this case is drawn in Figure 10, showing that the accuracy of the damage localization is improved using the IMSE index. Figure 11 also shows that the modal strain energy method accurately predicts the severity of damage for diagonal member of the access bridge.

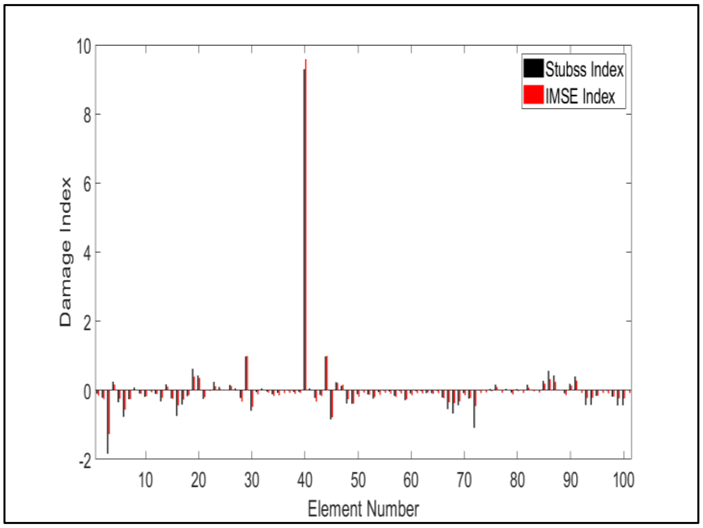

Figure 10: Damage localization results using Stubbs and IMSE indices in the third damage scenario

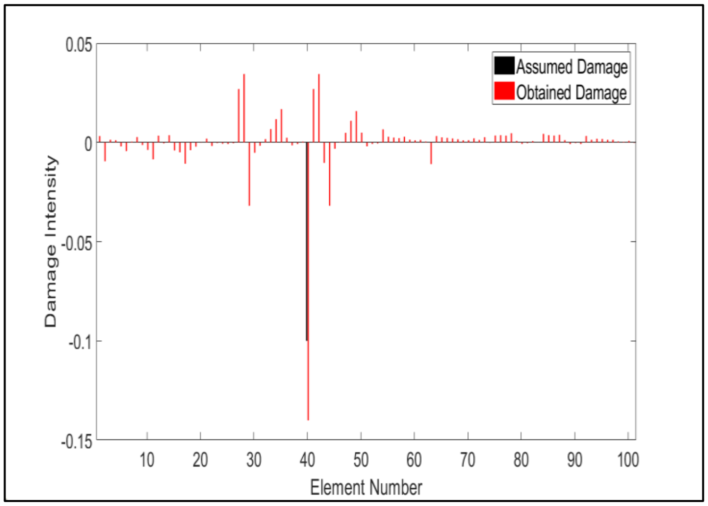

Figure 11: Damage severity estimation using modal strain energy method in the third scenario

3.3.4. Fourth scenario

In this case, a hypothetical 20% damage is applied to element No. 47 which is one of the inclined members of the access bridge. Figure 12 shows a slight improvement in damage localization using the improved method. Figure 13 shows that the modal strain energy method was able to accurately predict the severity of damage occurred in inclined members of the access bridge.

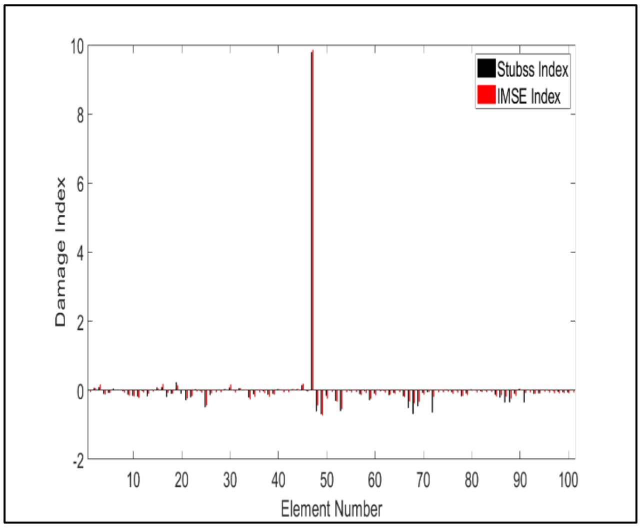

Figure 12: Damage localization results using Stubbs and IMSE indices in the fourth damage scenario

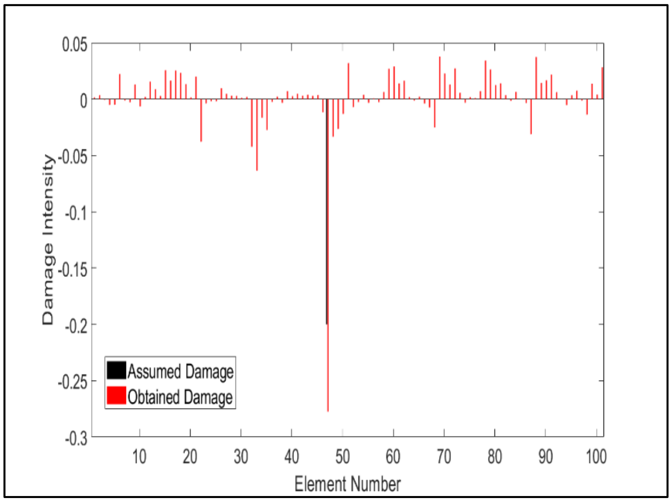

Figure 13: Damage severity estimation using modal strain energy method in the fourth scenario

3.3.5. Fifth scenario

In this case, it is assumed that member 70, as one of the inclined members connecting the lower chord to the upper chord, is damaged by 10%. Figure 14 shows a slight improvement of damage localization using the improved method. Figure 15 shows that the modal strain energy method was able to predict the severity of damage to the inclined member connecting the two chords, although the prediction accuracy was slightly reduced in comparison with the horizontal damaged element.

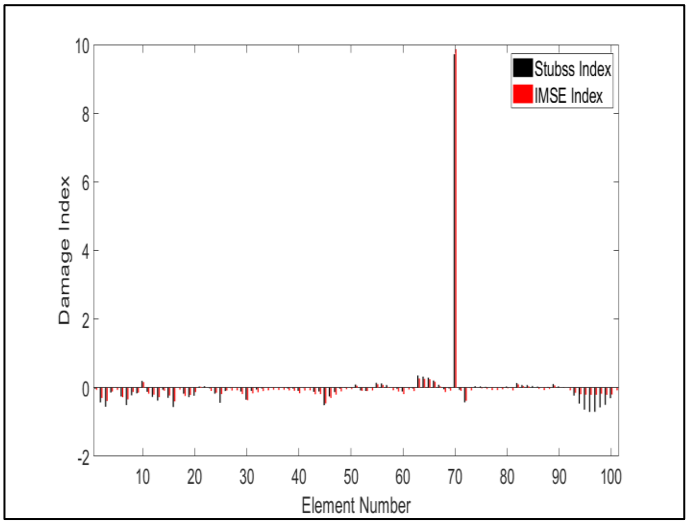

Figure 14: Damage localization results using Stubbs and IMSE indices in the fifth damage scenario

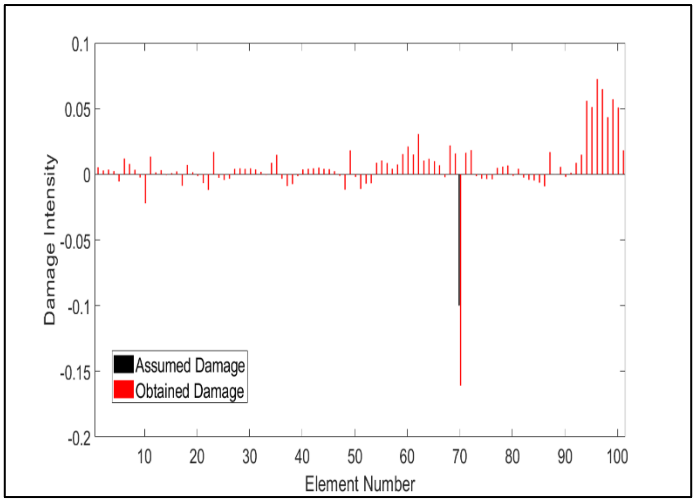

Figure 15: Damage severity estimation using modal strain energy method in the fifth scenario

3.3.6. Sixth Scenario

In this case, elements 4 and 47 (horizontal member and bracing member of the access bridge) are damaged by 15% and 20%, respectively. The results of the damage index in Figure 16 show that the modal strain energy method is able to predict the location of multiple damages with appropriate accuracy and again using the improved modal strain energy method has led to improved damage localization results. Figure 17 shows that the modal strain energy method has high accuracy in determining the severity of multiple damages.

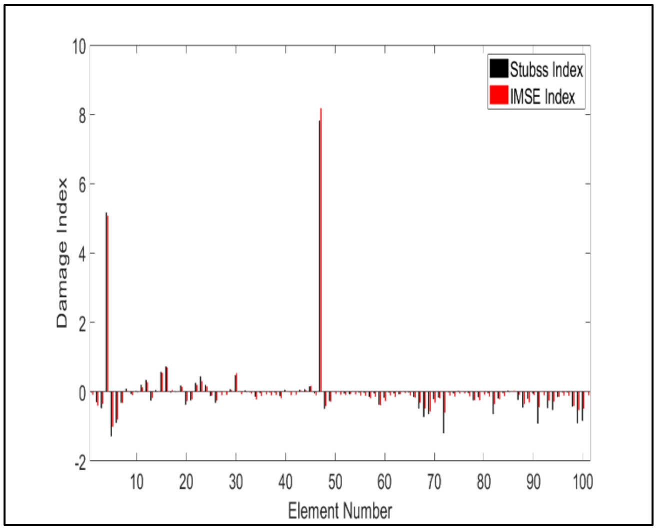

Figure 16: Damage localization results using Stubbs and IMSE indices in the sixth damage scenario

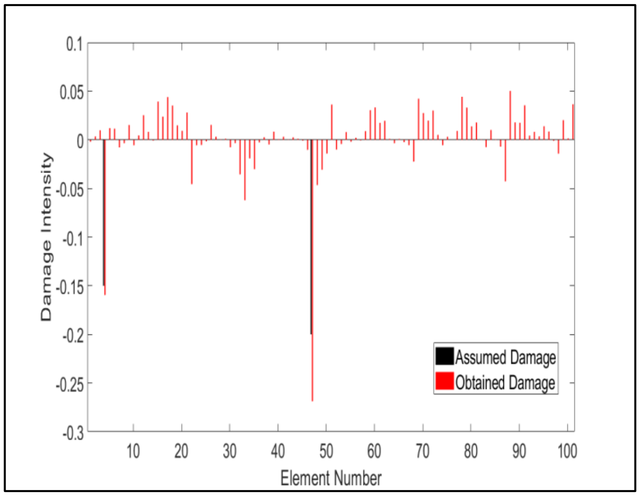

Figure 17: Damage severity estimation using modal strain energy method in the sixth scenario

4. Conclusion

As the service life of offshore structures expires, their structural health monitoring becomes important. Being a passage for staff and pipelines, access bridge that connects different offshore platforms is an important part of an offshore complex. However, it has received less attention in previous studies. In this research, using the modal strain energy method which is one of most appropriate non-destructive damage detection methods, single and multiple damages were identified at the access bridge of the Foroozan oil field in the Persian Gulf and the results of the two well-known modal strain energy-based damage indices, namely Stubbs and IMSE indices were compared. The hypothetical damage was applied to the elements that their damage was thought to have more negative effect on the structural integrity. For this purpose, the floor elements, the horizontal members of chords, the members connecting the two lower chords along with the elements connecting the lower chord to the top chord were selected as damaged elements. The results indicate the appropriate ability of the improved modal strain energy method to identify the severity and location of damage in the access bridge of offshore platforms. The method was also able to present acceptable performance in identifying both single and multiple damages. However, the accuracy of the method was higher in horizontal members than in the brace members. Also, the accuracy of damage detection in horizontal level was superior to its accuracy in inclined elements that connect lower and top chords. Also, the accuracy of damage identification increases by moving away from the supports. Finally, due to the fact that the improved modal strain energy method identifies the location of damage in structure with higher accuracy, the use of this method is recommended instead of the Stubbs index method.

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