



Structural health monitoring of Foroozan offshore platform using a novel modal strain energy damage index

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Received: 4 May 2021 / Accepted: 11 October 2021 / Published online: 9 February 2022
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Abstract

Being exposed to huge waves, repetitive wetting and drying as well as vessel collisions, members that are located in the splash zone of offshore platforms are prone to damage and failure. Providing the possibility of identifying and repairing these damages at an early stage, establishing a concise structural health monitoring system for these structures is of a great importance. The modal strain energy-based Stubbs index is one of the most successful vibrational methods for structural damage identification. In recent years, some modifications have been made on this method, one of which is considering natural frequencies for damage localization. By examining the original Stubbs index and an existing modified index, in this paper, a novel damage index is proposed to increase the accuracy of damage localization. Comparing the results of the Stubbs, IMSE (Improved Modal Strain Energy), and the new indices for damage localization in Foroozan platform which is located in Iran and Saudi Arabia water border in the Persian Gulf, this research shows that this novel method has been able to identify the location of hypothetical damage in the structure with higher accuracy. Also, single and multiple damages, with low and high severity, were predicted with appropriate accuracy by this method.

Keywords Offshore platforms · Splash zone · Damage identification · Modal strain energy · Stubbs index

1 Introduction

Occurrence of structural damages during the service life of the structure is obvious and inevitable. With the aim of increasing the safety and ensuring the current condition of the structure, structural damage identification is a vital task. By providing the possibility of repairing and replacing damaged elements, early detection of damage prevents general

failure of the structure. This in turn avoids the huge investment that may be incurred in rebuilding the structure. In any structural health monitoring system, first the dynamic characteristics are extracted from the recorded responses of the structure and then, structural damages could be identified by analyzing these characteristics, the most important of which are natural frequencies, mode shapes, damping or energy dissipation, stiffness and softness matrices of the structure, and frequency responses. These characteristics can be analyzed to reveal the abnormal behavior of the structure, which is a sign of damage. Due to their potential application in the prevention of failures and optimization of maintenance procedures, the development of strategies for evaluating health of structures has been studied by the international community [1]. The most common sources of damages in offshore platforms are corrosion, lamination, and unexpected phenomena such as storms or earthquakes. These damages can be revealed through geometric description (crack geometry) or changes in the energy dissipation properties of a system [2]. Common methods for damage identification are the visual inspection or localized experimental methods such as acoustic or ultrasonic methods, magnetic field methods, radiographs, eddy-current methods, and thermal

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field methods. A prerequisite for these experimental methods is that the severity of the damage is known in advance and that part of the structure to be inspected is fully accessible. Due to these limitations, experimental methods can only detect damage at or near the surface of the structure. Due to the limitations associated with the size of the structure, the location of possible damages, and the cost associated with the sensor array and signal processing, application of structural health monitoring techniques to civil engineering structures is not simple to be implemented [3]. The need for comprehensive and general damage identification methods that can be applied to any types of structures has led to the development of methods that are based on the changes in the dynamic properties of the structure.

In order to prevent possible failure of the structure, performing a damage detection technique in the early stages of its development is of great importance. Among the structural health monitoring methods, vibration-based damage identification technique (VBDIT) is one of the most common and most successful methods. The method that is based on changing the vibration properties of the structure in case of damage has several advantages such as the general and non-destructive nature and the potential to perform the process in an automatic manner. By considering the vibration behavior of the system and its physical properties, modal strain energy is one of the best modal parameters for describing structural damage because it is obtained by multiplying the stiffness matrix by the quadratic power of the mode shape. Extensive technical literature on the application of this method for damage identification in structures is another advantage of this method [4].

For structural systems that are founded on weak soil, considering the soil–structure interaction is required. Numerical analysis of the combined soil–structure system is performed using two sets of methods. The first one is the direct method where the combined system is discretized using the finite element method. The second one is the substructuring approach, where each component is separately modeled by semi-analytical or discrete models and subsequently combined using compatibility and equilibrium conditions at the common interfaces [5]. The spectra of wind and wave force have sufficient random excitation to drive offshore platforms at one or more of their natural frequencies. To measure the response of the structure, accelerometers can be used. Such determination can be performed one or two times in a year. A detected difference in the natural frequency of the structure between two successive measurements indicates a change in the mass or stiffness of the structure that is a sign of damage [6].

With the expiration of the service life of the first generation of offshore platforms and the occurrence of damage in these structures, structural health monitoring of these platforms has started since the 1970s. As one of the first

studies in this field, Vandiver [6] used the natural frequency changes to identify damage caused by a ship collision with an offshore tower. In another study, Cawley and Adams [7] identified structural damage using the difference between the natural frequencies of intact and damaged structures. Copolino and Rubin [8] identified the removal of an element of an eight-leg platform through finite element modeling of the structure and measuring its modal responses under the environmental stimulation. Shahriyar and Bouwkamp [9] used structural vibration information in an eight-legged steel offshore platform. Using natural frequencies and mode shapes of the structure, Hansen and Vanderplaats [10] identified damage location and severity in the structure. Using changes in mode shapes of the structure, Kim and Stubbs [11] proposed an algorithm for damage localization and quantification in jacket platforms and formulated a method for determining the modal parameters of the structure, which is known as damage index (DI) method. In the early stages of the development of the DI method, the Stubbs index was used as the most popular tool to determine the location of damage and as a result, the Stubbs index is often referred to as DI [12–14]. In this method, the condition of structural members is examined through a damage index obtained from modal and physical characteristics [15]. In the Stubbs index method, mode shapes are required before and after the occurrence of damage; however, the mass normalized mode shapes, which are used in many numerical and laboratory validations, are not necessary to calculate the damage index in this method. The possibility of using Stubbs index for damage identification in an offshore platform was studied by Kim and Stubbs [11] in which only the responses of damaged structure were used. Stubbs and Kim investigated the efficiency of using modal strain energy damage index for beam-like structures and determined the location of damage on a steel bridge [14, 16]. Salawu concluded that only the use of natural frequencies is not enough for damage localization, although it can be effective in general identification of the damage [17]. Comparing five damage identification techniques, namely 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 [18] concluded that the accuracy of the modal strain energy damage index method was superior to other methods. Preliminary reports have confirmed the appropriateness of the Stubbs index method for structures that generally act as beams or can be discretized into beam elements. Cornwell et al. [19] applied Stubbs index method to a plate-like structure marked with two-dimensional curvatures. Developing an improved, more accurate damage index for structures with high number of members, Kim and Stubbs [20] tested the performance of their index on a two-span beam. Proposing a method for damage localization in a planar element using the mode

shapes obtained by Rayleigh–Ritz method, Li et al. [21] demonstrated that this method has a high ability to detect single and multiple damages. A two-step method including the damage localization in the first step and damage quantification in the second step was proposed by Kim and Stubbs [22]. Ge and Lui [23] proposed a finite element model that used the dynamic properties of the structure including modal frequencies and mode shapes for damage localization and quantification. The application of Stubbs index for damage identification in composite laminated beams and plates was performed by Hu et al. [24]. Comparing different damage identification techniques, Alvandi and Cremona [25] concluded that the Stubbs index method has the best stability against noisy signals. Applying the modal strain energy method for damage detection in beams and plates, Shih et al. [26] concluded that this method can be used to detect damage in girder and bridge decks. Hu and Wu [27] developed a modal strain energy-based damage index for damage identification in aluminum plates. Loendersloot et al. [28] applied the Stubbs index method to composite plates with stiffeners. Hu et al. [29] used Stubbs index for damage identification in a hollow cylinder. Seyedpoor [30] proposed a two-step method for accurately detecting the location and severity of multiple damages in structural systems so that in the first step, the damage localization was performed and in the second step, using Particle Swarm Optimization algorithm, the severity of damage was determined using the results of the first step. Liu et al. [31] used modal strain energy difference in intact and damage modes for damage localization in an offshore wind turbine [31]. Wang et al. [32] 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. Li et al. [33] proposed a new damage index for damage localization in structures which was a modification on the original Stubbs index.

This extensive literature review shows that the modal strain energy method has been used in several cases to identify the location and severity of damage in different structures and has shown good results. Due to their harsh surrounding ocean environment, the possibility of collisions with vessels, falling objects, and high corrosion of the offshore environment, offshore platforms are more vulnerable to damage than other structures. Also, repairing and improving these structures after severe damage is more costly, time consuming, and difficult than structures located on land. Therefore, identifying structural damage in the early stages in these structures is of a great importance. Foroozan oil field, which is located on the water border of Iran and Saudi Arabia, is one of the oldest oil fields of Iran and is of great importance in the oil-dependent economy of the country. As a real case study, in this paper, three modal strain

energy methods [Stubbs, Improved Modal Strain Energy (ISME), and the novel formulation derived by authors] are used for damage identification in the Foroozan platform. For this purpose, in the next sections, first the modal strain energy method is reviewed, then the platform structure and the Foroozan oil field are introduced, and then by defining the various cases of damage to the Foroozan platform, the accuracy of this method in identifying hypothetical damages is examined.

2 Structural damage identification using modal strain energy

Modal analysis is the study of dynamic characteristics of a system. These can be defined comprehensively using three parameters, namely the natural frequencies, damping ratios, and mode shapes. Identifying these modal parameters results in full determination of the dynamic behavior of the structure. Modes are inherent properties of a structure and associated with structural resonances. They are independent of the load applied on the structure, while they depend on the geometrical properties, material properties, and the boundary conditions. Every system has set of natural frequencies which depends upon the material, material density, and damping of the system. Modal analysis is a key method for reliable study of structural behavior [34].

The modal strain energy damage index was first proposed by Kim & Stubbs [11] to find the location and severity of damage in an offshore platform. This index is based on changes in modal strain energy. The modal strain energy of a member is expressed as the product of the stiffness matrix multiplied by the quadratic form of mode shapes. In this method, the mode shapes before and after the damage are needed. Damage in a structure usually reduces the stiffness of the structure and 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 [20]:

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

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

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 shapes of the structure in intact and damage states, respectively. The Stubbs damage index is obtained from the following equation [20]:

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

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 $\beta_{ij} > 1$. 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. The main assumption is that the fraction of modal strain energy for the i th mode that is concentrated in the j th member for intact ($F_{ij} = K_{ij}/K_i$) and damaged ($F_{ij}^* = K_{ij}^*/K_i^* = F_{ij} \left(1 + \sum_{k=1}^{NE} A_{ik} \alpha_k + H.O.T\right)$) structures are much smaller than unity, then we have

$$1 = \frac{F_{ij}^* + 1}{F_{ij} + 1}. \quad (4)$$

Hence

$$1 = \frac{(K_{ij}^* + K_i^*)K_i}{(K_{ij} + K_i)K_i^*}, \quad (5)$$

$$1 = \frac{E_j^* \left(\phi_i^{*T} C_{jo} \phi_i^* + \frac{1}{E_j^*} \sum_{k=1}^{NE} \phi_i^{*T} C_k^* \phi_i^* \right) \frac{K_i}{K_i^*}}{E_j \left(\phi_i^T C_{jo} \phi_i + \frac{1}{E_j} \sum_{k=1}^{NE} \phi_i^T C_k \phi_i \right) \frac{K_i}{K_i^*}}. \quad (6)$$

And

$$\beta_{ji} = \frac{\left(\phi_i^{*T} C_{jo} \phi_i^* + \frac{1}{E_j^*} \sum_{k=1}^{NE} \phi_i^{*T} C_k^* \phi_i^* \right) \frac{K_i}{K_i^*}}{\left(\phi_i^T C_{jo} \phi_i + \frac{1}{E_j} \sum_{k=1}^{NE} \phi_i^T C_k \phi_i \right) \frac{K_i}{K_i^*}} = \frac{\left(\phi_i^{*T} C_{jo} \phi_i^* + \frac{1}{E_j^*} \sum_{k=1}^{NE} \phi_i^{*T} E_k^* C_k^* \phi_i^* \right) \frac{K_i}{K_i^*}}{\left(\phi_i^T C_{jo} \phi_i + \frac{1}{E_j} \sum_{k=1}^{NE} \phi_i^T E_k C_k \phi_i \right) \frac{K_i}{K_i^*}} = \frac{\left(\phi_i^{*T} C_{jo} \phi_i^* + \sum_{k=1}^{NE} \phi_i^{*T} C_{ko} \phi_i^* \right) \frac{K_i}{K_i^*}}{\left(\phi_i^T C_{jo} \phi_i + \sum_{k=1}^{NE} \phi_i^T C_{ko} \phi_i \right) \frac{K_i}{K_i^*}}. \quad (7)$$

Finally, the following relation is obtained:

$$\beta_j = \frac{\sum_{i=1}^{NM} (\Phi_i^{*T} C_{jo} \Phi_i^* + \sum_{i=1}^{NE} \Phi_i^{*T} C_{ko} \Phi_i^*) K_i}{\sum_{i=1}^{NM} (\Phi_i^T C_{jo} \Phi_i + \sum_{i=1}^{NE} \Phi_i^T C_{ko} \Phi_i) K_i}. \quad (8)$$

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 [20] where Z_j is the normalized damage index, $\bar{\beta}$ is the average, and σ_β is the standard deviation of β :

$$Z_j = \frac{\beta_j - \bar{\beta}}{\sigma_\beta}. \quad (9)$$

2.1 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. In order to improve the Stubbs's method, (33) used frequency information in determining the damage index. Eigen analysis for intact and damaged structures can be written as follows:

$$C \phi_i = \omega_i^2 M \phi_i, \quad (10)$$

$$C^* \phi_i^* = \omega_i^{*2} M^* \phi_i^*, \quad (11)$$

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:

$$\beta_j = \frac{\sum_{i=1}^m (\phi_i^{*T} C_j \phi_i^* + \omega_i^{*2} \phi_i^{*T} M \phi_i^*) \omega_i^2 \phi_i^T M \phi_i}{\sum_{i=1}^m (\phi_i^T C_j \phi_i + \omega_i^2 \phi_i^T M \phi_i) \omega_i^{*2} \phi_i^{*T} M \phi_i^*}. \quad (12)$$

Using Eq. 5, the above index can be normalized.

2.2 The proposed damage identification method

Damage detection using Stubbs index only requires the vibrational modes and the stiffness matrix. Some modifi-

cations have been performed on the original Stubbs index, one of which is suggested by [33]. Based on their study, due to the more accurate estimation of natural frequencies, the accuracy of damage detection is improved, especially in the presence of noise. In their modified form of damage index, the modulus of elasticity is not factorized from the stiffness matrix. Therefore, β_j does not present the fraction of modulus of elasticity in intact and damage structures.

We believe that this can somehow decrease the damage detection accuracy, especially for multi-damage cases. Therefore, replacing Eqs. 10 and 11 in Eq. 12, a new relation of damage index is formulated that compared with the available relations can detect the damage location with higher accuracy.

$$\beta_j = \frac{E_j}{E_j^*} = \frac{\sum_{i=1}^m (\phi_j^{*T} C_{jo} \phi_j^* + \sum_{j=1}^{ne} \phi_j^{*T} C_{jo} \phi_j^*) \omega_i^2 \phi_i^T M \phi_i}{\sum_{i=1}^m (\phi_j^T C_{jo} \phi_j + \sum_{j=1}^{ne} \phi_j^T C_{jo} \phi_j) \omega_i^2 \phi_i^{*T} M \phi_i^*} \quad (13)$$

$$\alpha_j = \frac{[\phi_i^T C_{jo} \phi_i]}{[\phi_i^{*T} C_{jo} \phi_i^*]} \frac{K_i^*}{K_i} \quad (15)$$

The superiorities of the upgraded equation (Eq. 13) over Eq. 12 are as follows:

1. The upgraded method (Eq. 13) has a much higher accuracy in damage detection than the IMSE method (Eq. 12).
2. In the upgraded method (Eq. 13), in addition to the stiffness matrix, the mass matrix also plays an important role in the formula and unlike IMSE index (Eq. 12), changes in the mass matrix can also be considered.
3. In the multi-damage cases, the IMSE method (Eq. 12) sometimes misdiagnoses. But the upgraded method (Eq. 13) accurately detects damage in multi-damage cases.

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

$$E_j^* = E_j(1 + \alpha_j) \quad (14)$$

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

3 Study area

Foroozan oil field is located in the Persian Gulf, about 100 km southwest of Kharg Island export terminal, on the water border of Iran–Saudi Arabia (Fig. 1.). The field, owned by the National Iranian Oil Company (NIOC), was discovered in 1966 and has 2.3 billion barrels of recoverable reserves. Foroozan 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.

3.1 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



Fig. 1 The location of Foroozan oil field in the Persian Gulf [35]

residential platform is a three-story platform for 42 people. A schematic diagram of the platform is shown in Fig. 2. The hydrocarbons produced in this field are separated into crude oil, associated gases, and water. Crude oil is transported through a 100-km 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 [35].

4 Applying hypothetical damage to structure and defining different damage scenarios

In this section, the modal strain energy method is used for damage identification in Foroozan platform. The hypothetical damage is applied by reducing the modulus of elasticity of the member in the finite element analysis. In order to show the accuracy of the damage identification of various variants of the modal strain energy method, different single and multiple damage scenarios have been defined. In this

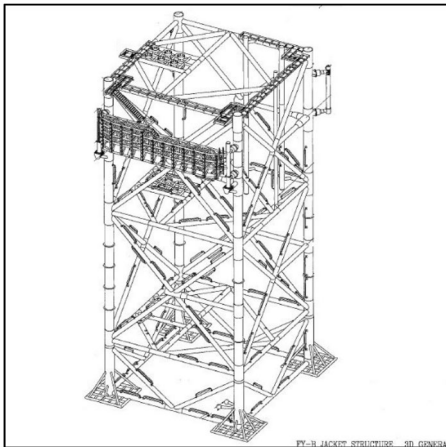


Fig. 2 Schematic view of Foroozan oil platform

method, structural modal information in the pre- and post-damage conditions are required for damage identification. For this purpose, after modeling the platform and defining the elemental stiffness and mass matrices and assembling them to achieve the global stiffness and mass matrices, the mode shapes and natural frequencies of the structure are extracted. The natural frequencies are then arranged in an 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. It should be noted that in the experimental studies, the structure is excited using an impulse hammer and the input force and the output acceleration are measured. Frequency response functions (FRFs) are recorded at different degrees of freedom [36]. Then, the natural frequency of the structure can be identified using available methods such as the peak picking method.

Table 1 shows the different scenarios of damage to the platform along with the first three natural frequencies of the damaged structure in each scenario. The geometric location of the damaged elements in different scenarios is also shown in Fig. 3. It should be noted that only a few first modes of the structure are considered in the calculations related to damage identification.

4.1 First scenario: 10% damage in element No. 58

In the first scenario, element No. 58, which is located below the free surface, is damaged by 10%. Figure 4 shows that although all three variants of the modal strain energy method have succeeded in damage localization, but the accuracy of the proposed method is much better than Stubbs index and improved modal strain energy method. An average error of 3.9%, 3.5%, and 3.02% are obtained for damage localization results by Stubbs, IMSE, and the present methods, respectively. Figure 5 shows that the damage severity is well estimated by the modal strain energy method.

Table 1 Different damage scenarios applied to Foroozan platform and the first natural frequencies of the structure in each scenario

Damage scenario	Damaged element	Damage severity (%)	Natural frequency (Hz)		
			1st	2nd	3rd
1	58	10	1.5441	1.6894	1.7449
2	78	1	1.5446	1.6902	1.7452
3	78	15	1.5446	1.6900	1.7452
4	100	10	1.5420	1.6898	1.7416
5	102	10	1.5425	1.6887	1.7446
6	106	10	1.5434	1.6899	1.7449
7	78 and 102	10 and 5	1.5436	1.6893	1.7449
8	78, 102, and 106	10, 5, and 5	1.5430	1.6892	1.7447

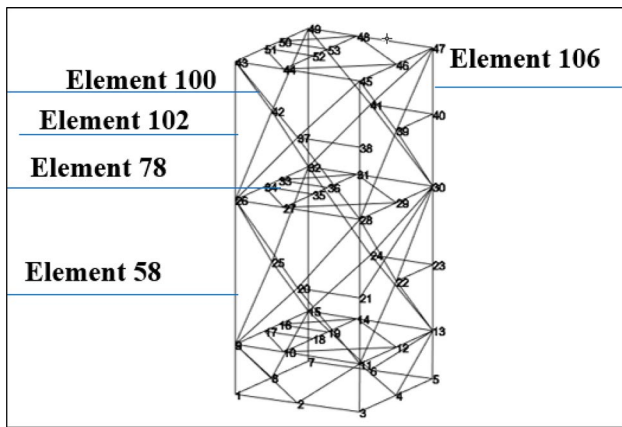


Fig. 3 Finite element model of Foroozan platform and the damaged elements

4.2 Second scenario: 1% damage in element No. 78

In the second scenario, element No. 78, which is below the water surface, is damaged by 1%. The purpose of this scenario is to control the accuracy of the method in identifying small damage in the early stages of damage. Figure 6 shows that although all methods have succeeded in identifying the location of the damage, the proposed method has been able to locate the damage with much greater accuracy and much less error. The average error in this case is 4.1%, 3.01%, and 1.15% for Stubbs, IMSE, and the present methods, respectively. Figure 7 shows that the damage accuracy is well estimated by the modal strain energy method. Therefore, the modal strain energy method has a good accuracy in identifying small damages.

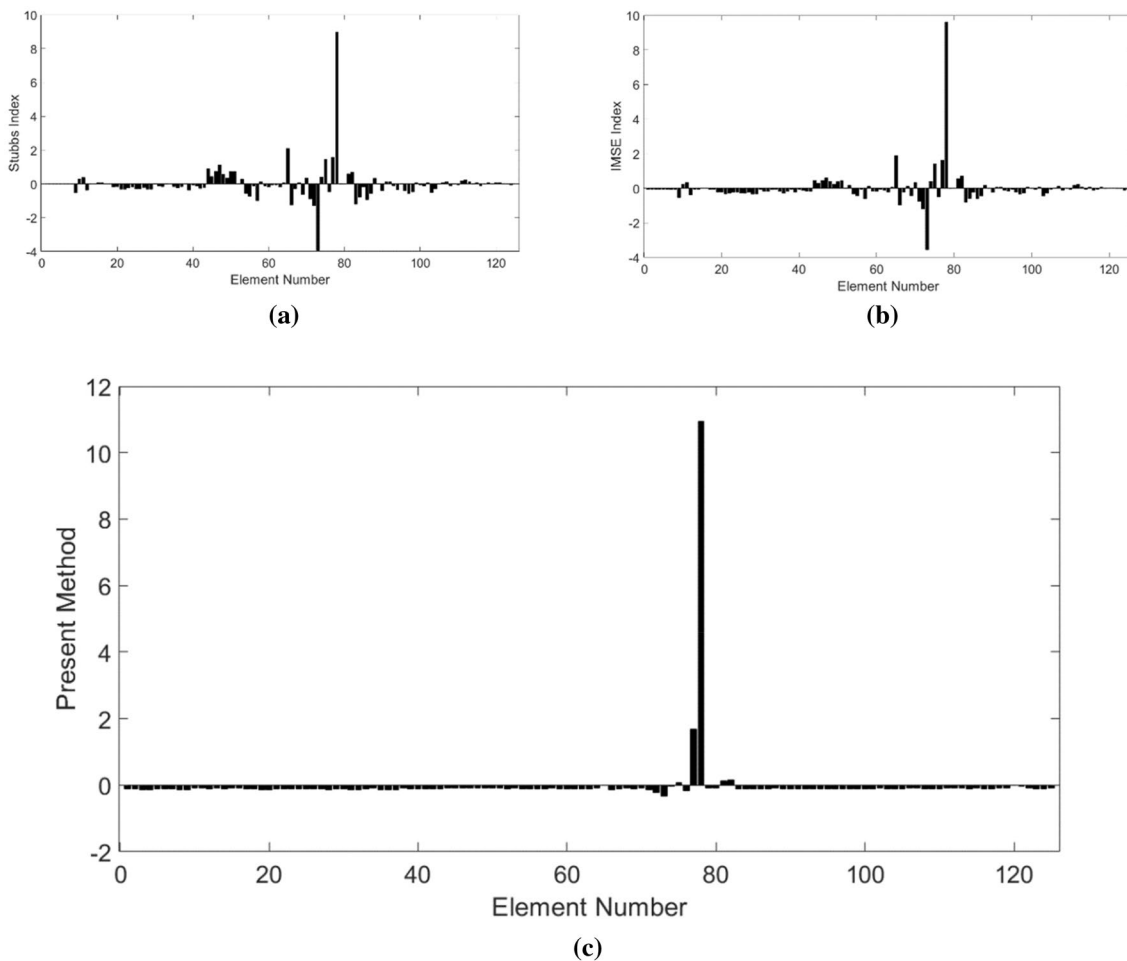


Fig. 4 Damage localization using different variants of the modal strain energy method in the first scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 5 Damage quantification using modal strain energy method in the first scenario

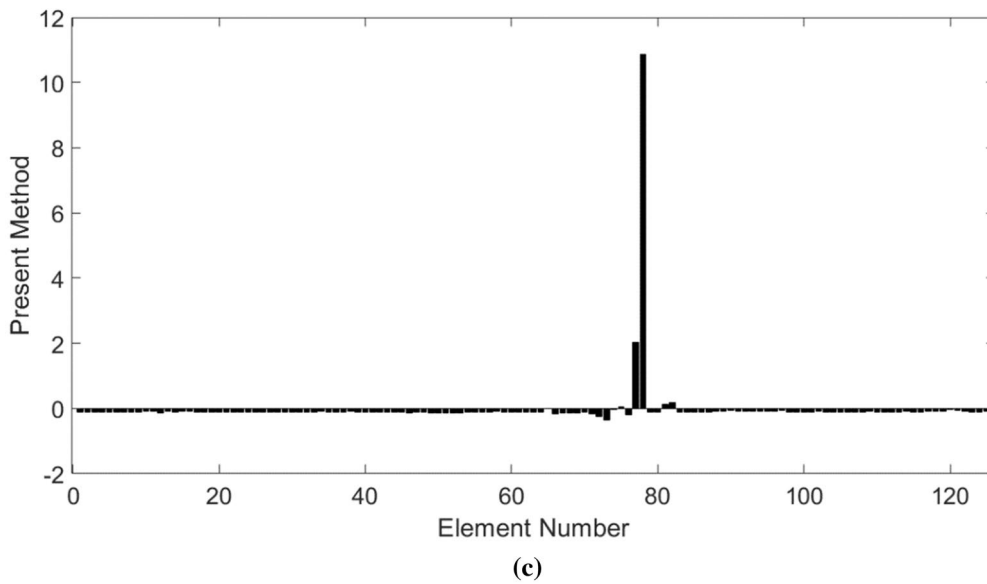
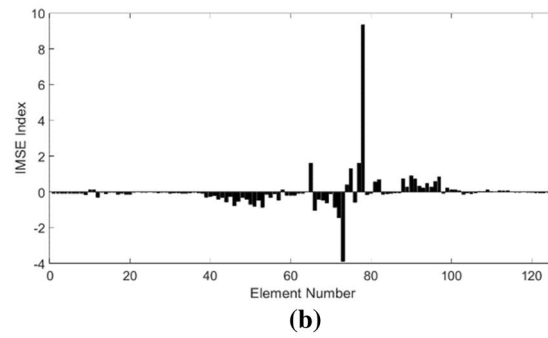
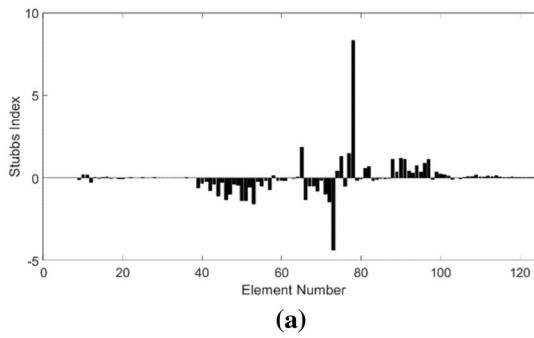
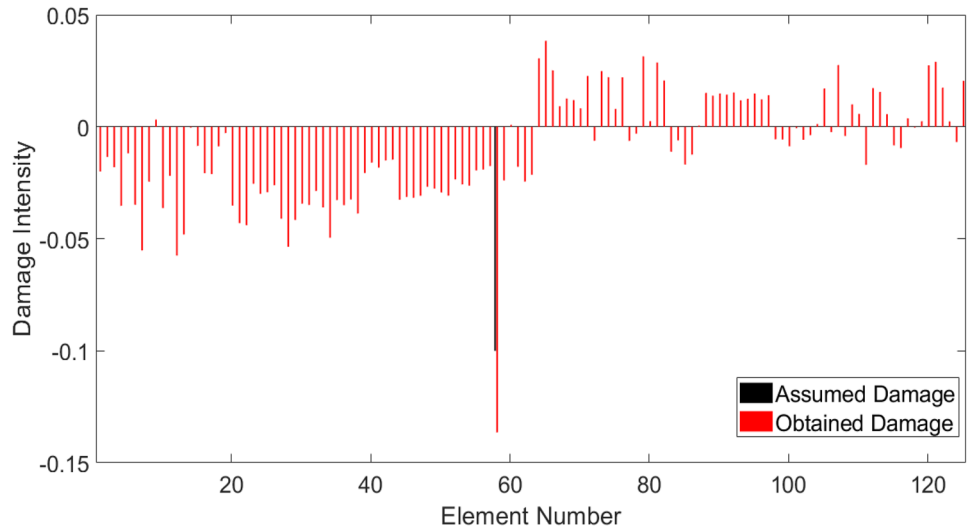
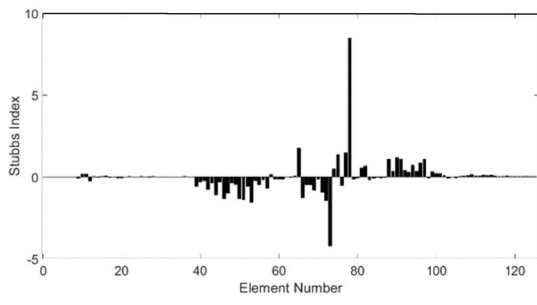
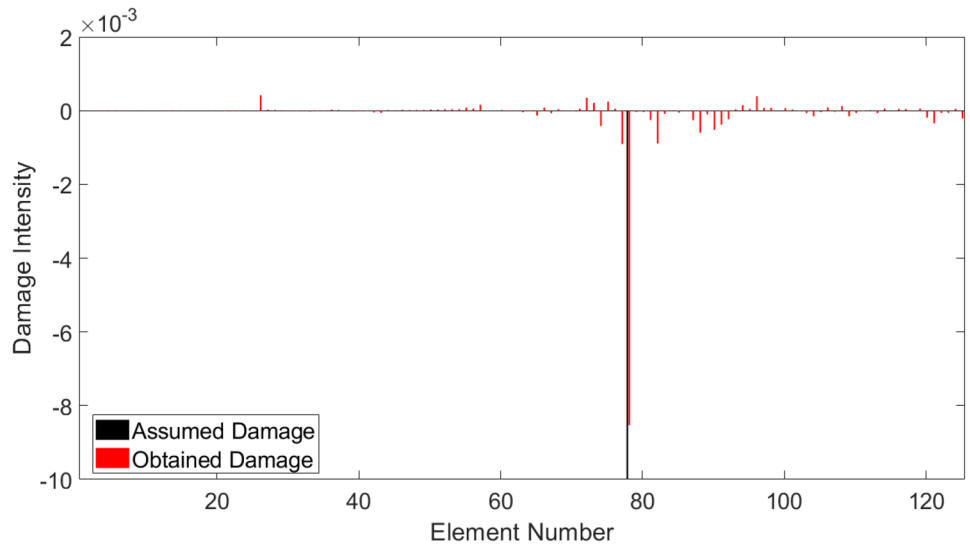
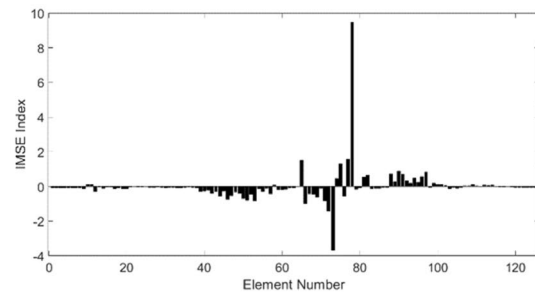


Fig. 6 Damage localization using different variants of the modal strain energy method in the second scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

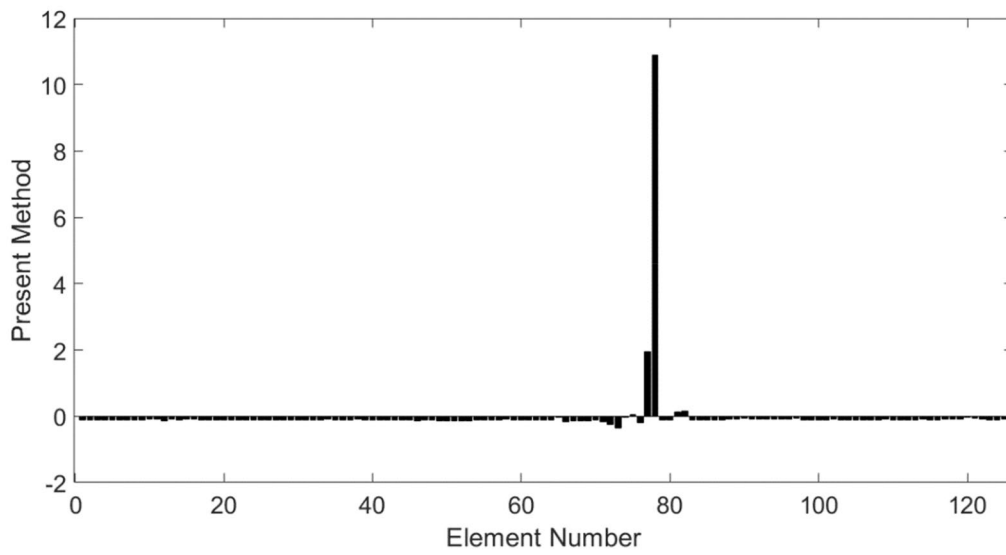
Fig. 7 Damage quantification using modal strain energy method in the second scenario



(a)



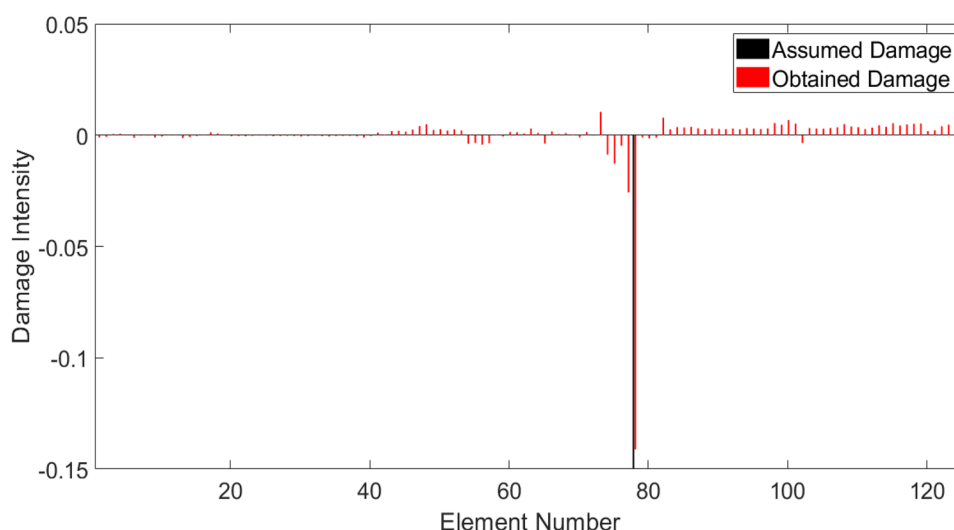
(b)



(c)

Fig. 8 Damage localization using different variants of the modal strain energy method in the third scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 9 Damage quantification using modal strain energy method in the third scenario



4.3 Third scenario: 15% in element No. 78

In this scenario, element No. 78 is 15% damaged. Figure 8 shows the much higher accuracy of the proposed method in damage localization compared to other variants of the modal strain energy method because it shows a higher index in the damaged element and less in other intact elements. The average error is 3.91%, 2.90%, and 1.14% for Stubbs, IMSE, and the present methods, respectively. Figure 9 shows that the severity of damage in this scenario is accurately determined, which indicates the accuracy of the modal strain energy method in identifying high severity damages.

4.4 Fourth scenario: 10% damage in element No. 100 (bracing member in splash zone)

Due to the fact that the elements located in the splash zone are more exposed to waves as well as successive wetting and drying which results in corrosion, in this scenario, element No. 100 which is located in the splash zone is exposed to a 10% hypothetical damage. Figure 10 shows that the location of the damage is appropriately predicted by all variants of the modal strain energy method, although again the proposed method is more accurate. The average error of 1.88%, 2.10%, and 2.23% are obtained for Stubbs, IMSE, and present methods, respectively. The comparison between the hypothetical damage intensity and the damage predicted by the modal strain energy method in Fig. 11 shows the appropriate accuracy of this method in identifying the severity of damage to bracing members located in the splash zone of the platform.

4.5 Fifth scenario: 10% damage in element No. 102

In this scenario, member No. 102, as one of the leg members of the platform, which is also located in the splash zone, is

damaged by 10%. As shown in Fig. 12, the proposed damage index has a higher accuracy in locating the damage than other methods. Average errors of 4.51%, 3.8%, and 3.39% are obtained for damage localization using Stubbs, IMSE, and the present methods, respectively. Figure 13 shows that the severity of the damage is estimated with a very good estimate for the leg member located in the splash zone.

4.6 Sixth scenario: 10% damage in Element No. 106

In this scenario, a 10% hypothetical damage is applied to element No. 106, which is a short leg element located in the splash zone. Figure 14 shows the damage index obtained in this case using different variants of the modal strain energy method. Again, this figure shows the higher accuracy of the proposed method for locating the damage. Average errors of 3.6%, 2.8%, and 2.16% are obtained for damage localization using Stubbs, IMSE, and the present methods, respectively. Also, as Fig. 15 shows, estimating the severity of damage in this scenario has good accuracy.

4.7 Seventh scenario: 10% damage in element No. 78 and 5% in element No. 102

In order to demonstrate the ability of the modal strain energy method to detect multiple damages, in this scenario, two elements of 78 (a horizontal under water element) and 102 (a vertical above splash zone element) are damaged. Figure 16 shows the superiority of the proposed method for damage localization. The figure shows that the Stubbs index and the improved method resulted in a higher damage index for the element with less damage (element number 102), but the proposed method is more successful in determining the element with more severe damage and shows less error in other members. The average error for Stubbs, IMSE, and the

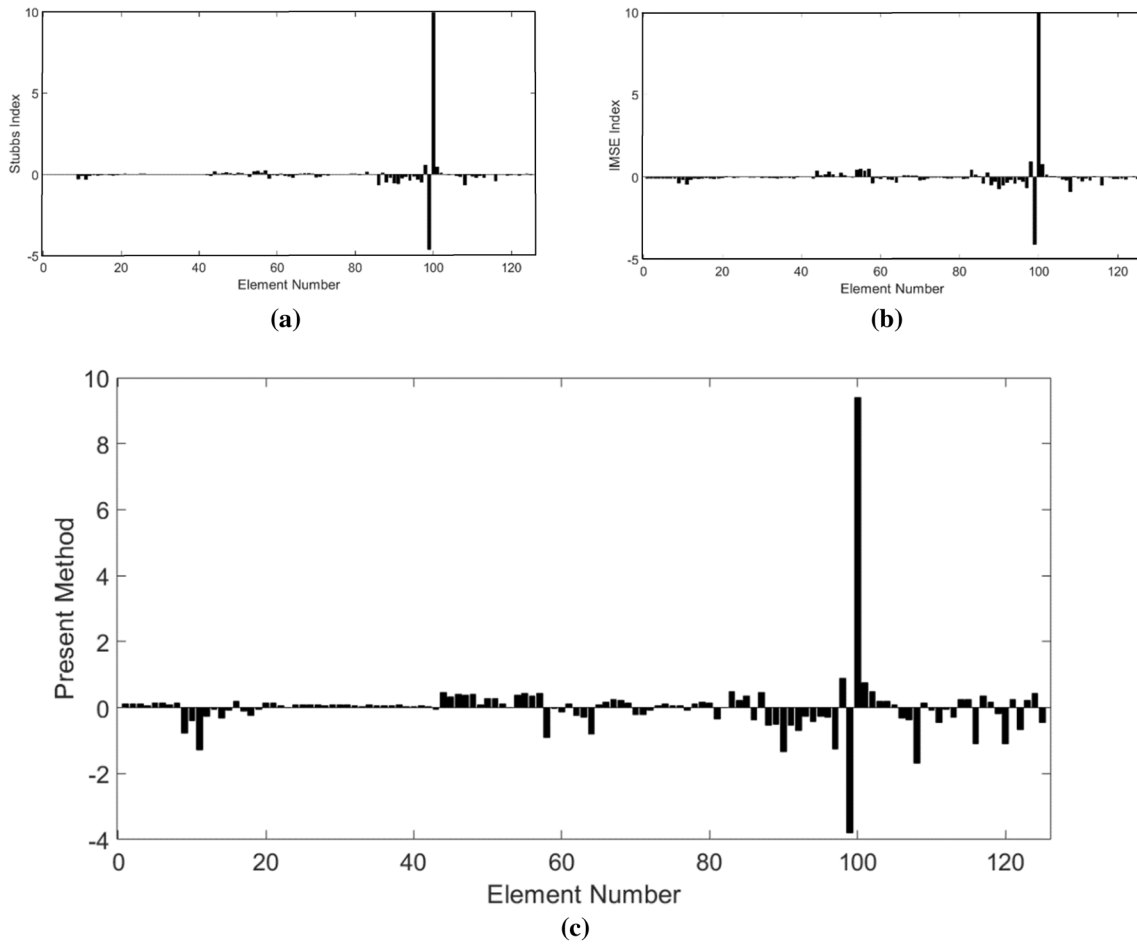


Fig. 10 Damage localization using different variants of the modal strain energy method in the fourth scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 11 Damage quantification using modal strain energy method in the fourth scenario

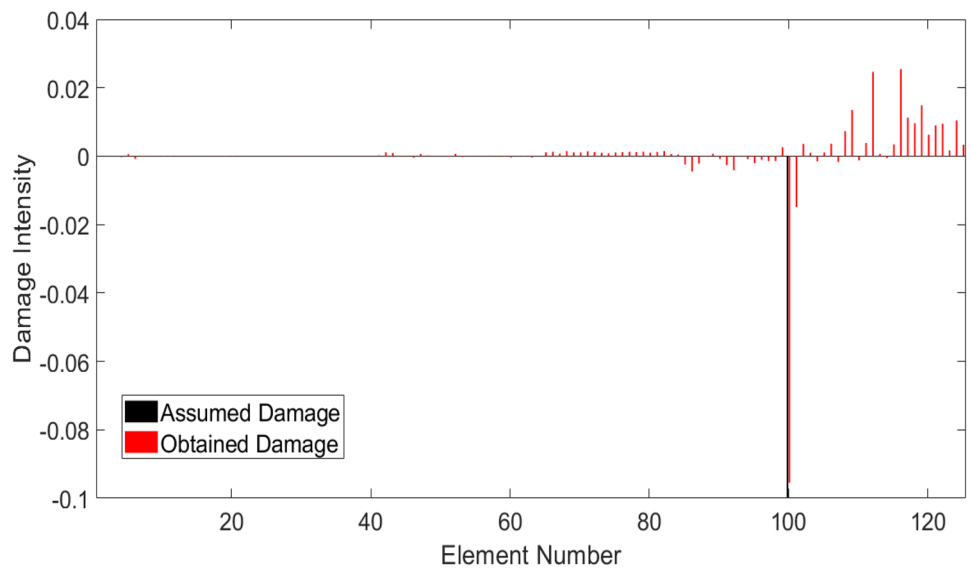


Fig. 12 Damage localization using different variants of the modal strain energy method in the fifth scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

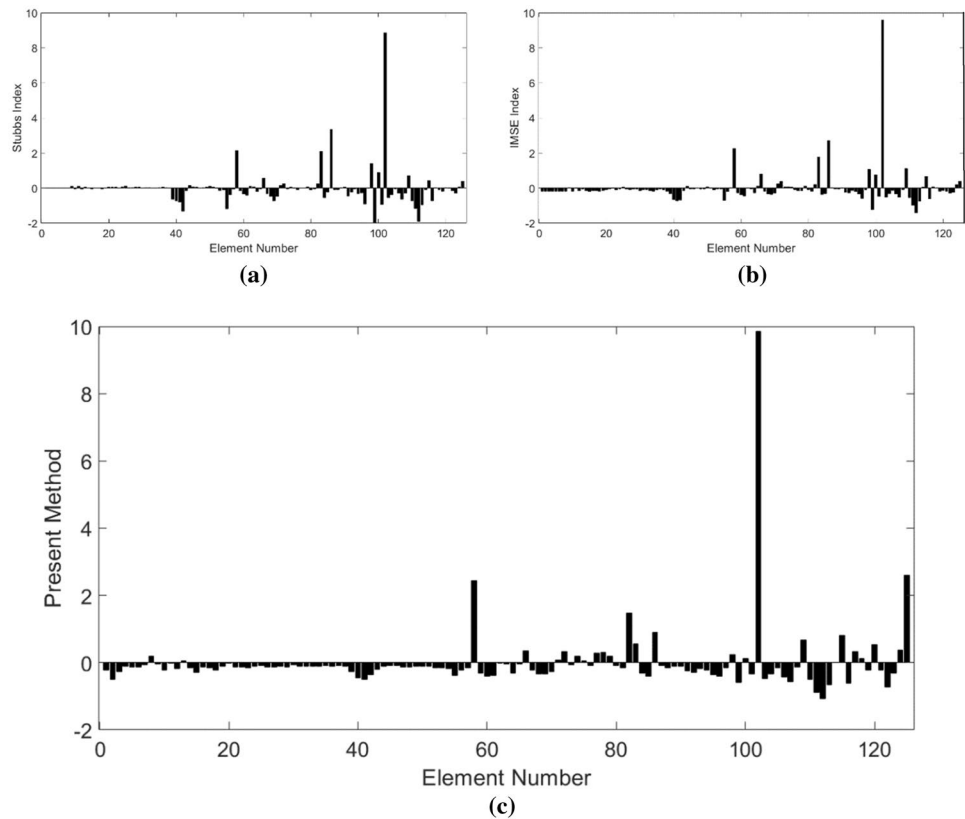
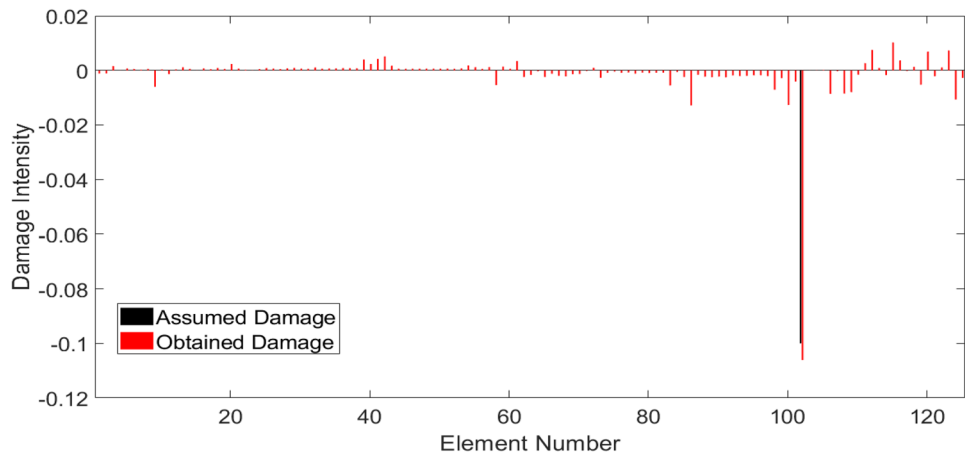


Fig. 13 Damage quantification using modal strain energy method in the fifth scenario



present method are 6.5%, 7%, and 3.46%, respectively, showing the higher accuracy of the proposed method. Figure 17 also shows that the severity of multiple damages is estimated with acceptable accuracy by the modal strain energy method.

4.8 Eighth scenario: 10% damage in element No. 78, 5% in element No. 102 and 106

The aim of this scenario is to show the ability of the method to identify more than two damaged elements in the

structure. Hence, three elements, including 78, 102, and 106, are damaged by 10%, 5%, and 5%, respectively. Figure 18 shows that between the three methods, the results of the proposed damage index are more accurate than the other existing methods. The average error for Stubbs, IMSE, and the present method are 8.19%, 7.95%, and 5.49%, respectively, showing the higher accuracy of the proposed method. Figure 19 also shows that the severity of multiple damages is estimated with acceptable accuracy by the modal strain energy method.

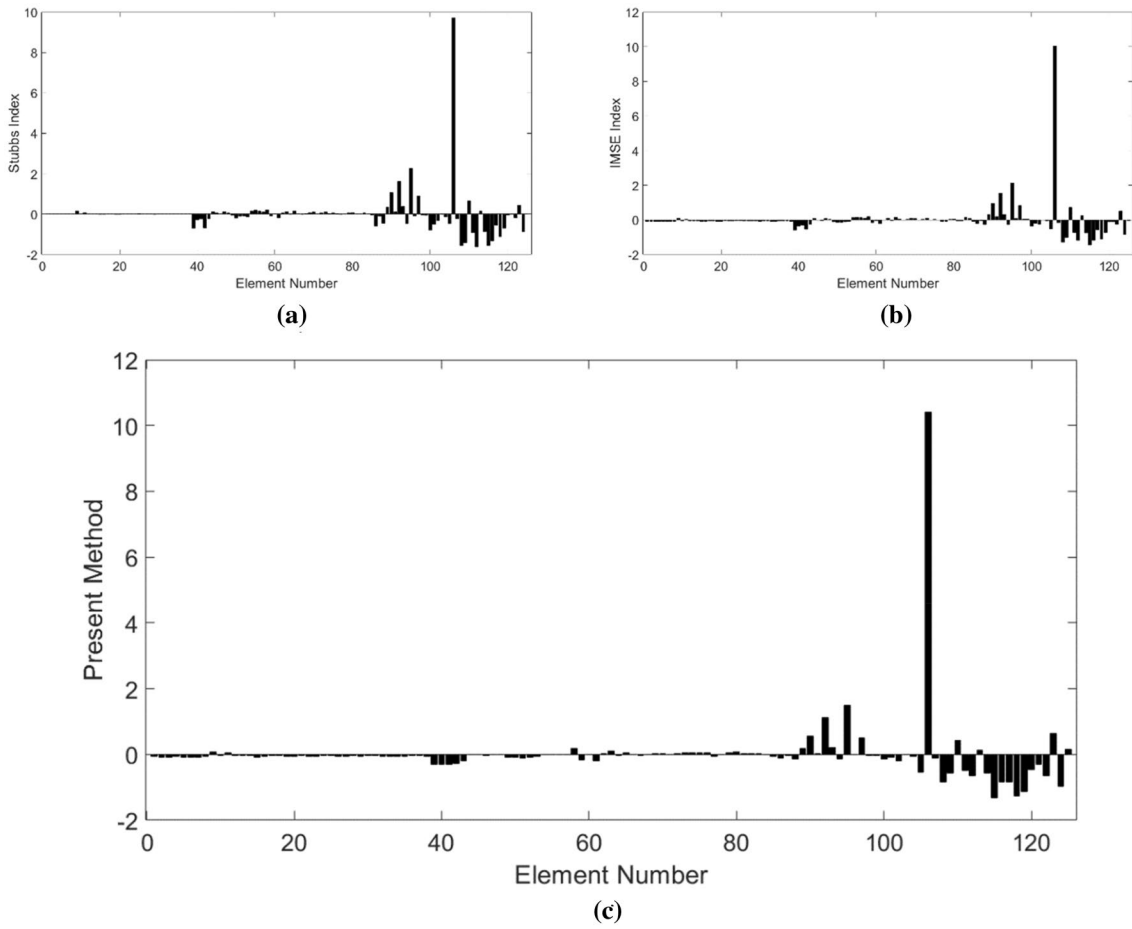
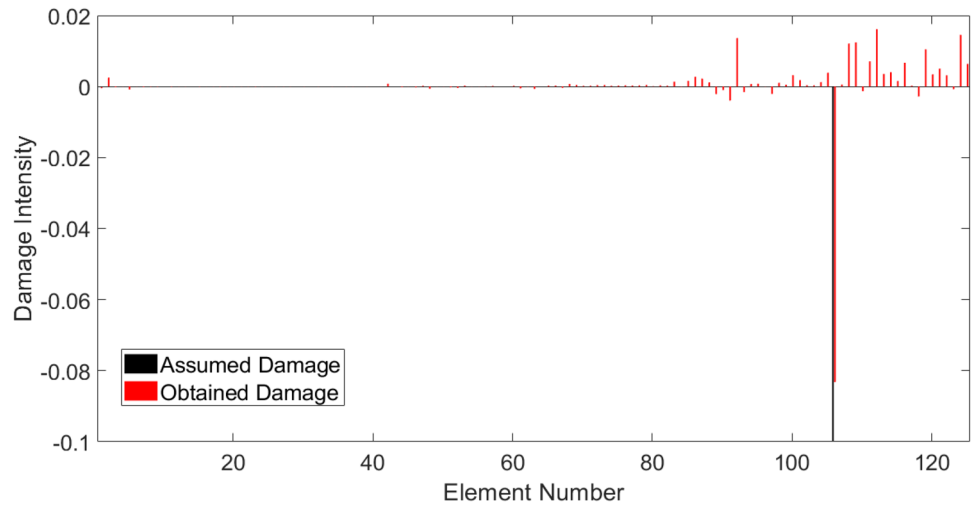


Fig. 14 Damage localization using different variants of the modal strain energy method in the sixth scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 15 Damage quantification using modal strain energy method in the sixth scenario



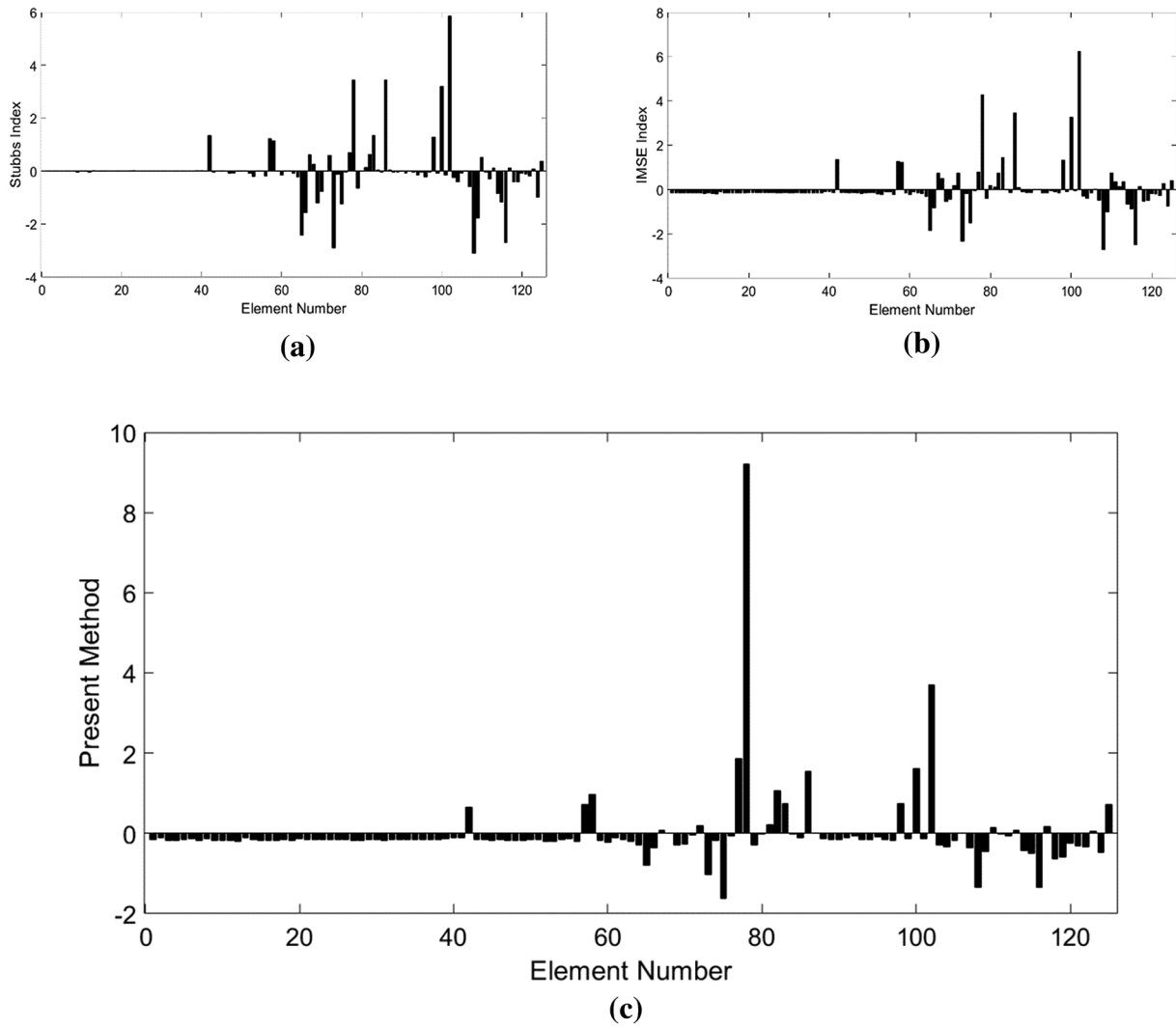
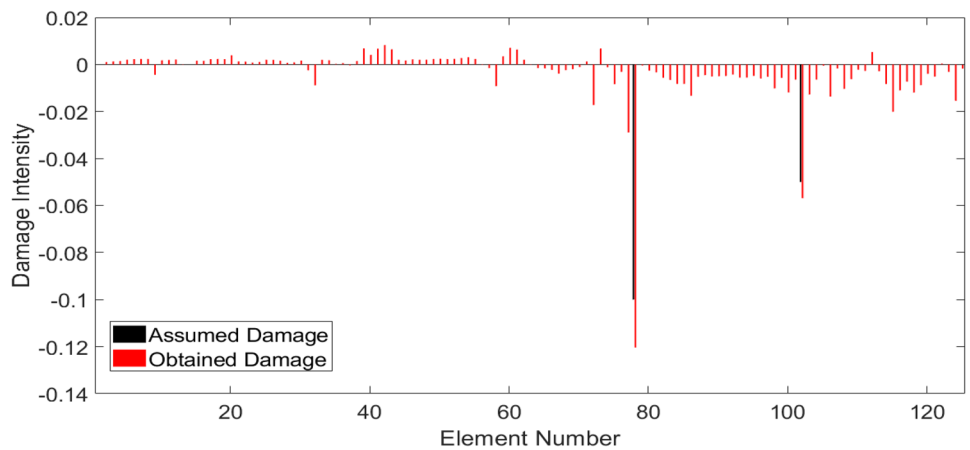


Fig. 16 Damage localization using different variants of the modal strain energy method in the seventh scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 17 Damage quantification using modal strain energy method in the seventh scenario



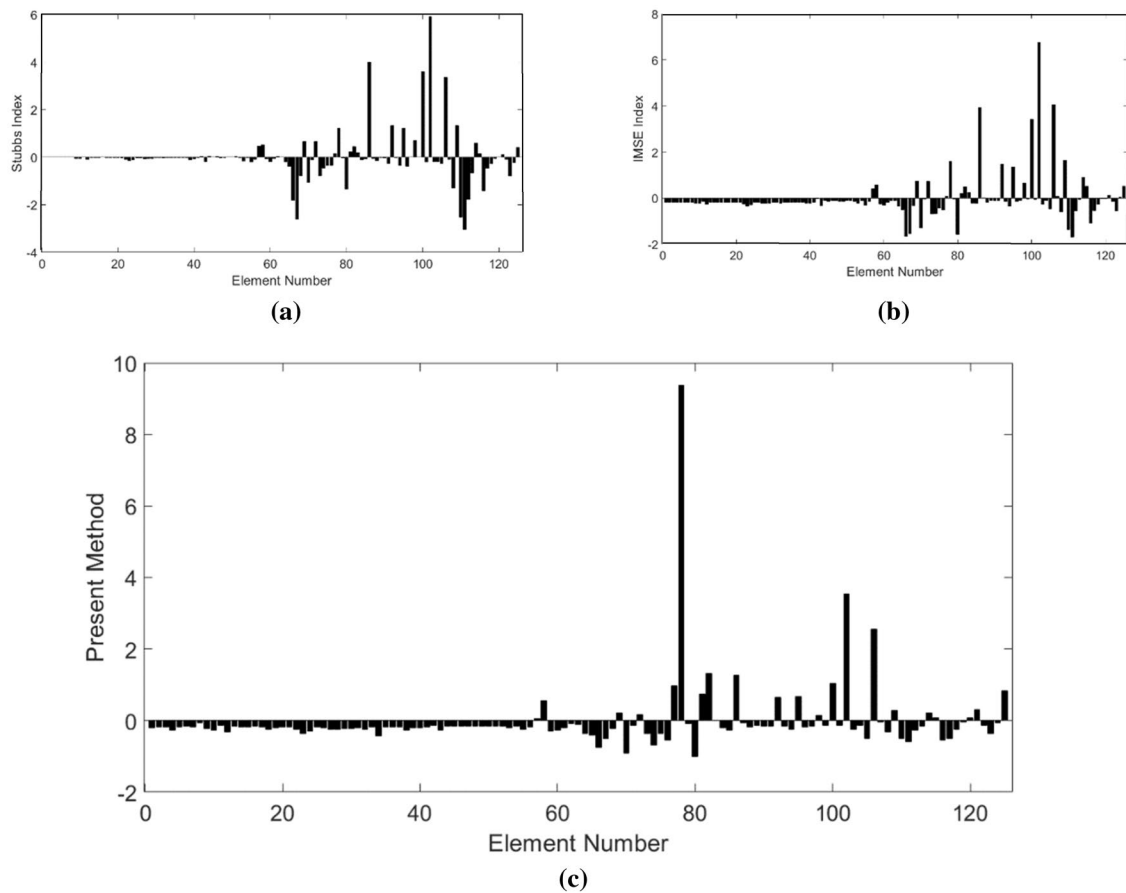
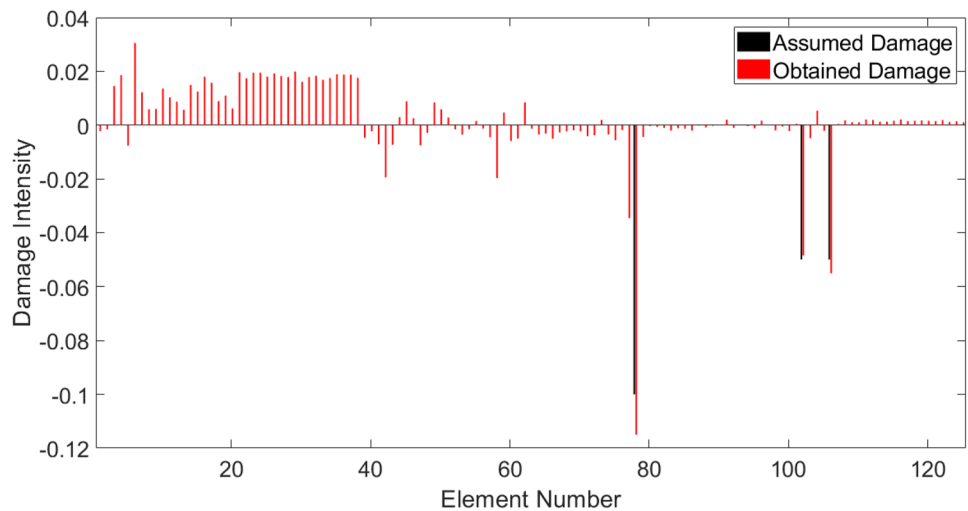


Fig. 18 Damage localization using different variants of the modal strain energy method in the eighth scenario. **a** Stubbs index, **b** IMSE method, and **c** proposed method

Fig. 19 Damage quantification using modal strain energy method in the eighth scenario



5 Conclusion

Offshore platforms are one of the most important and costly structures that are exposed to various damages due to their location in the harsh and corrosive environment of

the sea. The greatest amount of wave force is applied on the elements located in the splash zone where the wave hits the structure. Also, due to successive wetting and drying, it is more prone to corrosion than other members. Therefore, splash zone is a more probable place for structural

damage. In this study, the modal strain energy method is utilized for damage prediction in Foroozan offshore platform, one of the most important offshore infrastructures of Iran. In order to increase the accuracy of damage localization of this method, in this study, a novel modal strain energy damage index is proposed and its accuracy was tested on the considered offshore platform. One of the differences between the present study and other existing studies was the large number of members on the platform. The results showed that for almost all horizontal and inclined members, located in the splash zone and also for multiple damage cases, the proposed method is able to locate the damage in the structure with higher accuracy. Due to the fact that the splash zone is more prone to fatigue and corrosion, the focus of damage detection was placed on this area and it was found that the modal strain energy method is successfully able to identify the location and severity of damage in the elements located in the splash zone.

Acknowledgements The authors acknowledge the Iranian Offshore Oil Company for their valuable role in providing maps of the Foroozan platform.

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