



Sensitivity-based modal strain energy damage identification in an offshore catwalk to prevent environmental hazards

M. Alavinezhad¹ · M. Ghodsi Hassanabad¹ · M. J. Ketabdari² · M. Nekooei³

Received: 4 July 2021 / Revised: 15 December 2021 / Accepted: 15 December 2021 / Published online: 24 January 2022
© Islamic Azad University (IAU) 2022

Abstract

Catwalks are one of main components of each offshore complex. Their most important functionality is to provide connection between different parts such as the jackets and flare or between two neighboring jackets. Due to the catastrophic environmental and financial losses as well as the more importantly, loss of lives in case of the failure of an offshore platform and/or one of its elements, damage detection in this type of offshore structure is of a great importance. Such a concise damage identification can reduce the negative impacts of the failure of the structure on the marine habitat. Modal strain energy method is one of the most promising damage identifying methods which is based on variations in the dynamic characteristics of the structure. In this paper, a sensitivity-based modal strain energy damage identification technique is used to localize and quantify the assumed damages in an offshore catwalk structure. The finite element model of the structure is validated by comparing the outcomes of numerical and experimental modal analysis performed on the structure. This study shows that the implemented damage identification technique can be used to detect damages in real offshore truss structures with numerous members.

Keywords Offshore complex · Access bridge · Damage identification · Health monitoring · Sensitivity-based modal strain energy · Environmental hazards

Introduction

Steel jacket platforms are the most popular marine structure used for oil and gas extraction in regions with shallow depth, for instance in the Persian Gulf. Various operational, environmental and accidental are imposed on these structures during their life cycle. These loads may cause fatigue and crack in members and joints, element corrosion and perforation, and even collapsing of the platform or other types of damage. The access bridges attached to platforms are very significant in offshore oil and gas structures (El-Reedy 2015). High percentage of corrosion in the oceans and the

probability of various damages to the components of structures cause massive losses of life and property. Therefore, damage detection of these structures is very important.

Access bridges in platforms is usually hold long gas pips and so their damages can cause irreparable damage to the environment. Hence, damage detection in access bridges before destruction is necessary. Different methods have been introduced for marine structures' health monitoring, one category of which is non-destructive damage detection method with an advantage (maintaining the health of the structure). Among the non-destructive methods, using vibration-based damage detection in structures beside visual inspection can be considered as a perfect solution (Doebbling et al. 1996; Balageas 2006). In vibrational investigation of structures for damage identification, the modal characteristics of the structures are in terms of its mechanical characteristics. Variations in the mechanical response of the structures can be used to assess changes in their physical properties and as a result finding structural damage in early stages. Early damage detection reduces the maintenance costs and prevents the failure of the structure by providing the possibility of repairing or replacing the damaged components.

Editorial responsibility: Samareh Mirkia.

✉ M. Ghodsi Hassanabad
m.ghodsi@srbiau.ac.ir

¹ Department of Marine Industries, Science and Research Branch, Islamic Azad University, Tehran, Iran

² Department of Maritime Engineering, Amirkabir University of Technology, Tehran, Iran

³ Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran



Many researchers have been focused on the subject of condition monitoring of structures till now. Using the natural frequencies to indicate damage location by Cawley and Adams (1979) was one of the first attempts for structural damage detection. Shahrivar and Bouwkamp (1986) were studied the effect of damage in diagonal members of a jacket on modal properties of the deck. Their damage identification technique was based on vibrational properties of it. Hansen and Vanderplaats (1990) showed that using modal properties for structural damage identification is an effective method. Doebling et al. (1993) used modal strain energy in their study. In their research, a set of mode shapes in a structure vibration were extracted and its damages were identified by using some mathematical formulations. Kim and Stubbs (1995) showed that the frequencies and mode shapes of a structure change by damaging one or more component of that. They formulated a method and presenting an algorithm to determine the damage location and severity in the structure. Kim and Stubbs (1995, 1996) used modal strain energy technique for truss structures. They proved the effectiveness of their technique by localizing the damage and obtaining its severity in a steel bridge, correctly. In the study of Salawu (1997), damage location was attempted to obtain by only natural frequencies, but the author concluded that the location of damage cannot be obtained by only natural frequencies. Although it could be suitable in general damage identification. Farrar and Jauregui (1998) examined five damage detection methods on a truss bridge and derived that damage index obtained by modal strain energy technique has the highest precision for detecting damages. Kim and Stubbs (2002) developed an improved damage index formula with more accurate results in damage detection and confirmed the accuracy of that formula by a damaged two-span rod as a case study. Li et al. (2002) raised a numerical technique to determine damage location in a plane element applying the Rayleigh–Ritz vibrational modes and showed that this method able to detect single and multiple damages accurately. Yang et al. (2003) evaluated damages in marine structures using two damage indices [flexural modal strain energy change ratio (FMSECR) and compression modal strain energy change ratio (CMSECR)]. Considering the fragmentary modal data due to free and ambient vibrations induced by environmental phenomena such as irregular wind, Lekidis et al. (2004) introduced a FE (finite element) model updating method that could be integrated with an online monitoring system for recording response of the bridge. Merce et al. (2007) developed a FE model for the Clifton Suspension Bridge in UK to establish an updating process by ANSYS software. Establishing a 3D FE model of a real bridge in ANSYS with adjusting some design parameters, Xu-hui et al. (2008) concluded that the FE method by considering the basis of sensitivity concept and using ANSYS software is led to simplicity

and excellently updating of modal analysis. Deng and Cai (2010) used response surface method and genetic algorithm by a new practical FE model updating method for damage detection. Giles et al. (2011) conducted a study for identifying damage location at the second span of the Government bridge (Rock Island, USA) using the damage locating vector method (DLV). Along with performing experimental studies, Liao et al. (2012) developed a novel FE method in model updating based on the quasi-static generalized influenced line residual objection to improve the FE algorithm which was used. Modares and Waksanski (2013) fulfilled a historical review on sensors used for structural monitoring factors such as strain, vibration, displacement, fatigue, corrosion, temperature, cracking, settlement, tilt, water level and wind speed in the subject of structural health monitoring of steel bridges. Moradipour et al. (2013) quantified damage in members using modal strain energy technique and applied two-dimensional damage formulation in short and medium span bridges. To determine the severity and location of the damage, Budipripanto and Suzanto (2015) used the steel-truss steel railway bridge dynamic responses in healthy and damaged condition when under train dynamic load. Li and Hao (2016) studied current progresses in the topic of condition monitoring of structures, covering non-modal techniques for assessing shear joints in composite bridges, a user friendly graphical modal analysis toolkit, signal processing techniques for operational modal analysis, determination of the free span and support conditions of pipelines, investigation of the effects of uncertainty, noise and structural damage detection under dynamic loads (model updating) and damage identification techniques based on vibration. Chen and Omenzetter (2016) presented an estimation-based FE model updating process to analyze a real highway bridge structure using the results of operative modal investigation and showed that this procedure can appropriately update the models of complex and large-size of real structures. Asadollahi (2018) applied Bayesian model updating on a real large-scale bridge to achieve a more precise FE model for obtaining structure responses. Guo et al. (2018) studied on an offshore jacket structure with incomplete measured modal data using artificial neural network (ANN) technique for damage identification and concluded that rearrangement of the measurement points, increment the order of modal data, developing new damage detection indices and upgrading the neural network procedure are caused to better results in damage identification process. Alkayem et al. (2018) surveyed the technologies of FE model updating and developed algorithms in damage identification and then evaluated the common dynamic features applied to improve residuals in the goal function equation. Ding et al. (2019) studied on a large steel span bridge that was under construction process. They recorded the scaffold separation process condition and inspected changes in strain distribution. They also simulated



scaffold removal conditions of the bridge via the FE technique and investigated the recorded data in comparison with the strain in the girder. Altunisik et al. (2020) investigated earthquake responses of a timber bridge in a numerical and experimental study using FE updated method with linear dynamic time history analyses and investigated the effect of model updates on the responses by comparing with experimental data.

The abovementioned literature study revealed the modal strain energy method has been widely used as a suitable numerical tool for damage detection in marine structures. This review also showed that there are ongoing researches and modifications to increase the accuracy of this method. On the other hand, based on the best knowledge of the authors, there is not any publication on damage detection in offshore access bridges. This research aims at using modal strain energy technique for damage identification of an access bridge in Foroozan offshore complex (Fig. 1) that is located in Iran-Saudi Arabia water border in Persian Gulf and is operated by the Iran's Offshore Oil Company (IOOC). A sensitivity-based modal strain energy damage identification method is used in this study to locate and quantify hypothetical damages in an offshore cat walk. Along with this numerical study, an experimental modal analysis will be performed on the structure. The comparison between the first few frequencies of the experimental and numerical models will show the accuracy of the modal analysis performed in the numerical study.

Environmental impacts of failure of a platform

There are different phases in the oil and gas extraction in the oceans. Probing the location and geological specifications of well comprise the exploration phase. In the next phase, a steel platform is installed. The third phase is the production phase or extraction of oil and gas. Decommissioning phase is the final phase when the commercial life of all platform wells is terminated (Manfra et al. 2020).

Offshore platforms have both negative and positive impacts on marine environment. Investigating the environmental impacts of offshore platforms on the marine habitat is an emerging field of research. Hence, many of environmental impacts of offshore platforms are unknown. For offshore structure, various activities like emissions during construction, installation and disabling, physical impacts of the moorings, operations or maintenance and servicing logistics, can affect the marine habitat (Lu et al. 2014). Failure-induced elimination of platforms might result in ecological costs through the loss of flora and fauna and related ecosystem functions and services (Brigitte et al. 2019). Although elimination of structures decreases the environmental destructive impacts in the marine and returns the marine habitats to their pre-existing state, this can alter the current habitats that are formed around each offshore structure. Such a come back to the old state may no longer be possible nor desired (Lusseau et al. 2016).



Fig. 1 Foroozan oil complex (Anon., n.d.)

Offshore platform access bridge

The main performance of an access bridge which is also called catwalk is to provide a connection between two adjacent offshore structures. Having the length of about 30–49 m (100 = 160 ft.), the structure supports pipes or is used as pavement and path of materials movement (El-Reedy 2015). The various shapes of bridges are illustrated in Fig. 2.

Materials and methods

FE model updating

Structural model updating is a process in which the numerical model of the structure which is constructed based on the finite element method is modified using the experimental data that involve the dynamic characteristics of the structure (Meruane 2013). In this process, the parameters such as the mass, stiffness and damping are modified to obtain a better correlation between the numerical and experimental data (Jaishi and Ren 2006). Thus, performing any analysis on the updated model of the structure results in a better and more accurate prediction of the dynamic behavior of the real structure (Cha and Gu 2000). On the other hand, structural defects can be identified by comparing the differences between the updated model and the original model. Early and accurate detection of these defects can provide the possibility of repairing or replacing the damaged elements which in turn prevents the development of structural defects and initiation of large cracks. Therefore, it can be used as an applicable technique for the health monitoring, damage identification, control, evaluation and studying the behavior of structures.

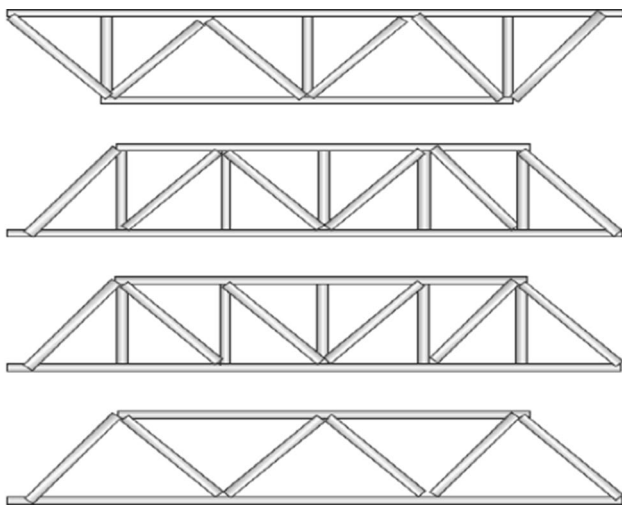


Fig. 2 Various shapes of catwalk (El-Reedy 2015)

Generally, all methods that have been developed since 1990s for finite element mode updating of structures can be categorized into two main groups including the direct methods and indirect or iterative methods (Friswell and Mottershead 1995; Hu et al. 2007). Direct methods directly update the structural mass and stiffness matrices in one step, ignoring the changes of the physical parameters. Despite their acceptable accuracy, the modified parameters obtained by this method don't have physical meaning and relating them to the corresponding elements in the main model is difficult. This leads to inaccurate detection of the damaged elements. In contrast, iterative methods that use the sensitivity and changes of the physical parameters for model updating of the structure, keep the physical.

Model updating technique in damage identification

In this technique of damage detection, the FE model of a healthy structure is modified by a mathematical model named model updating which is made an excellent correlation between FE model and the related damaged structure. Investigating all of FE model updating methods have been introduced till now, they can be categorized to two main methods, including the direct methods and iterative and indirect methods as shown in Fig. 3.

The model updating process in direct methods is performed using the modal characteristics. Direct methods are accurate and computationally efficient. Some of direct model updating techniques are the optimal matrix, matrix-update, Eigen structure assignment, error matrix (Alkayem et al. 2018). These methods have the following advantages:

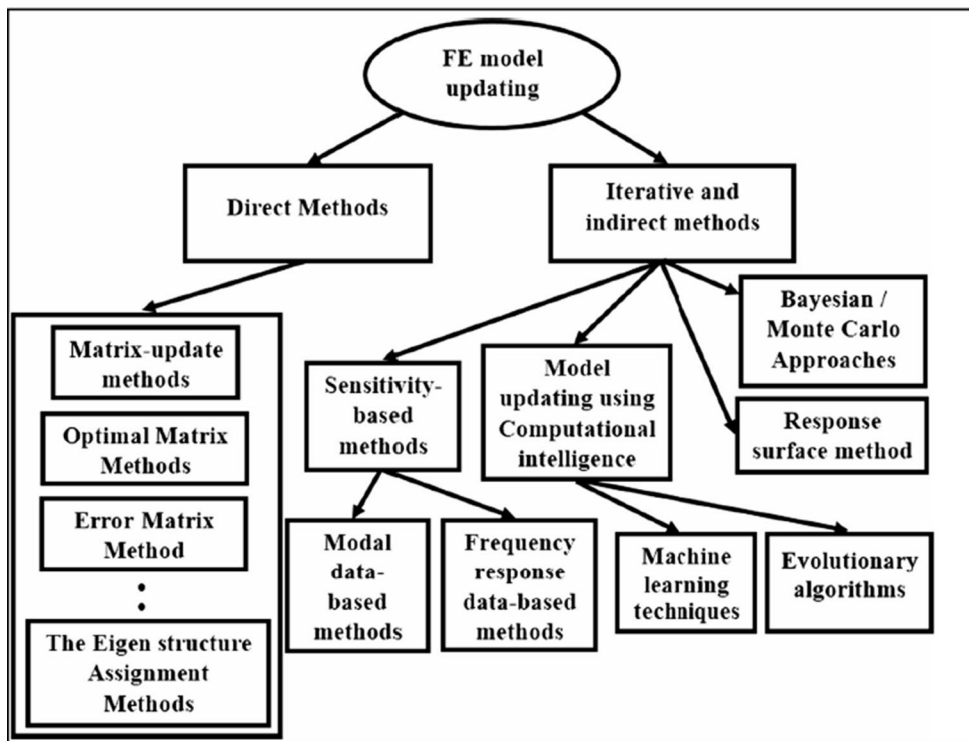
- In direct methods, iterative paradigms are not applied. Hence, these methods ensure fast convergence in computational process with acceptable accuracy.
- Structural physical parameters related to model updating are not consider in direct methods.
- The updated FE model results are matched with the precise measured data.

The limitations of direct methods that made them non-reliable are as follows:

- Accurate measurements are required for these methods. Also, they are very sensitive to noise.
- Measured and computed responses should be equivalent in size.
- These methods may yield unreal illustration of elements along the FE mesh. In other words, that methods may cause asymmetry in the matrices of the model.



Fig. 3 Finite element model updating approaches (Alkayem et al. 2018)



Hence, direct methods are not appropriate for damage identification. Indirect methods which are based on iterative computations can be good alternatives for damage detection.

One of the most common indirect methods are the sensitivity-based methods that place the measured data instead of some design data obtained by initial FE model of the undamaged structure. In these methods, a penalty function approach is used for optimization problem and undamaged structure. Accordingly, the sensitivity-based methods are only appropriate for small damages. The computational process of sensitivity-based methods is costly, because the main philosophy of these methods is to compute derivatives of modal properties or frequency response data (Alkayem et al. 2018). Different structural models updating methods are shown in Fig. 3.

Modal strain energy

Damage occurrence in a structure causes to vary some of its structural properties such as stiffness, natural frequencies, and mode shapes. 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 $c_{ir} = \frac{\{\phi_r\}^T [\Delta K] \{\phi_i\}}{\lambda_i - \lambda_r}$ ($i \neq r$), $\{\phi_i^d\}$ and $\{\phi_i\}$ are mode shape matrices at mode i for damaged and undamaged states, respectively, and md is the quantity of analytical mode shapes.

Changes of natural frequencies can be written as follows:

$$\lambda_i^d = \lambda_i + \Delta\lambda_i \tag{2}$$

where λ_i^d and λ_i are natural frequencies (eigenvalues) of i mode for damaged and undamaged states, respectively. Also, it can be obtained:

$$[K_n^d] = [K_n] + [\Delta K_n] = [K_n] + \alpha_n [K_n] (-1 < \alpha_n \leq 0) \tag{3}$$

where $[K_n^d]$ and $[K_n]$ are stiffness matrices of n th element of damaged and undamaged elements, and α_n is the coefficient of fractional reduction of n th elemental stiffness matrix. Applying Eq. (3) for all elements and collecting:

$$\sum_{n=1}^L [K_n^d] = \sum_{n=1}^L [K_n] + \sum_{n=1}^L [\Delta K_n] = \sum_{n=1}^L [K_n] + \sum_{n=1}^L \alpha_n [K_n] \tag{4}$$

Simplifying:

$$[K^d] = [K] + [\Delta K] = [K] + \sum_{n=1}^L [\Delta K_n] = [K] + \sum_{n=1}^L \alpha_n [K_n] \tag{5}$$

where K^d and K are structure stiffness matrices for damaged and healthy states, respectively.

Improved modal strain energy

To enhance the damage detection accuracy, a study by Shih et al. (2009) has been used in the present paper after some alterations. The structural damaged stiffness matrix was also adopted in the first place to achieve a more accurate modal strain energy equation. Notably, the strain energy obtained via this MSE formulation is expected to be more accurate while being more efficient in terms of computational and iteration costs, serving as an effective damage detection model (Moradipour et al. 2015).

The following equations are strain energies of the j th element in i th mode before and after damage, respectively:

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

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

The changes in MSE are:

$$\begin{aligned} \Delta \text{MSE}_{i,j} = \text{MSE}_{i,j}^d - \text{MSE}_{i,j} &= \frac{1}{2} \{\phi_i^d\}^T [K_j^d] \{\phi_i^d\} \\ &- \frac{1}{2} \{\phi_i\}^T [K_j] \{\phi_i\} \end{aligned} \quad (8)$$

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

$$\begin{aligned} \Delta \text{MSE}_{i,j} &= \frac{1}{2} \{\phi_i + \Delta\phi_i\}^T ([K_j] + \alpha_j [K_j]) \{\phi_i + \Delta\phi_i\} \\ &- \frac{1}{2} \{\phi_i\}^T [K_j] \{\phi_i\} \end{aligned} \quad (9)$$

Ignoring the higher order terms, the equation simplified to:

$$\begin{aligned} \Delta \text{MSE}_{i,j} &= \frac{1}{2} \alpha_j \{\phi_i\}^T [K_j] \{\phi_i\} \\ &+ \frac{1}{2} (1 + \alpha_j) [\{\phi_i\}^T [K_j] \{\Delta\phi_i\} + \{\Delta\phi_i\}^T [K_j] \{\phi_i\}] \end{aligned} \quad (10)$$

The following equation is obtained by composing Eqs. (1) and (10).

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

where $1 < i < 5$, and md is equal or less than number of degree of freedoms.

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

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

Final equation of modal strain energy changes of the j th element of the structure at i th mode is derived by neglecting the higher-order terms, as follows:

$$\begin{aligned} \Delta \text{MSE}_{i,j} &= \frac{1}{2} \alpha_j \{\phi_i\}^T [K_j] \{\phi_i\} \\ &+ \frac{1}{2} [\{\phi_i\}^T [K_j] \sum_{i=1}^L \alpha_i \sum_{r=1}^{md} \frac{\{\phi_r\}^T [K_i] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\} \\ &+ \sum_{i=1}^L \alpha_i \sum_{r=1}^{md} \frac{\{\phi_r\}^T [K_i] \{\phi_i\}}{\lambda_i - \lambda_r} \{\phi_r\}^T [K_j] \{\phi_i\}] (i \neq r) \end{aligned} \quad (13)$$

Damage localization

Damage localization is done using a method proposed by Shih et al. (2009). Alterations in modal strain energy are also updated with an improved formulation (Eq. (13)), so that the damage identification is of higher accuracy. An indicator of damage localizing named MSECR, which is shown in Eq. (14), is applied in this process. This parameter should be derived either for a single mode (as indicated in Eq. (14a) or several modes (as suggested in Eq. (14b) which is normalized for the first 5 mode shapes of element j). The resulting damage indicator is expected to localize the damage more accurately. The higher the amount of MSECR in an element, the more likely it is to potentially be a damaged element.

$$\text{MSECR}_{ij} = \frac{|\text{MSE}_{i,j}^d - \text{MSE}_{i,j}|}{\text{MSE}_{i,j}} \quad (14a)$$

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

in which $MSECR_j$ is the mean of $MSECR_{ij}$ for the first 5 mode shapes which is normalized by the maximum value of $MSECR_{i,max}$ in j th mode.

For damage localization by Eq. (14a), it can be selected an arbitrary mode from the first 5 modes. However, the selected mode of damaged structure should be equal to selected mode in healthy structure. It should be noted, the better results were obtained using Eq. (14b) than Eq. (14a), which is required all first 5 modes of both damaged and healthy structures.

Damage quantification

After detecting the damaged element out of the potential candidates figured out in the previous section, the process of quantifying the damage is handled by calculating the α values for relevant members. The aim is to find α value as the fractional reduction coefficient of elemental stiffness. If the element is indeed damaged, their corresponding α value will converge to the actual damage percentage, whereas for

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

the falsely suspected ones it converges to zero. It should also be noted that the exact value for each set of α 's could be calculated through a series of iterations.

The improved method is explained in the following paragraphs:

The following equation is obtained using Eq. (13) and neglecting the coefficient $\frac{1}{2}$ in it.

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

in which $MSEC'$ is derived from subtracting of damaged and healthy states. Thus:

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

where s is a chosen element for calculation the MSEC and t is a probable damaged element.

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

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

In so much as $MSEC_{ij}^d$ is a function of $[K_j^d]$ in theory, certainly it is expected more precise value for $MSEC_{ij}$ substituting K_j by K_j^d . Thus:

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

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

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

From Eqs. (17) and (19), yields:

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

From Eq. (16), (20) and Eq. (15), yields:

Simplifying

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

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

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

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

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

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

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

Results and discussion

Environmental hazards arising from failure of a platform

Persian Gulf is deemed one of the most significant areas of the world due to numerous geographical, political and financial reasons. In addition, the Persian Gulf is ecologically known to have an abundance of resources such as corals, fish, crustaceans and mollusks, and that is not to mention the fossil fuels like oil and gas. Various events such as the Kuwait–Iraq and Iran–Iraq war was in early 1990s and 1980s have led to petroleum and chemical contamination of the area. Development of the South Pars Gas Field (SPFG) has

been rendered a priority over the past 10 years thanks to its rich energy reserves. Environmental experts and authorities have, as a result, taken a great interest in oil exploration and gas wellbores and other relevant matters.

Ecosystems in the Persian Gulf, namely, coral reefs and local genetic resources are put in great risk if aquatic ecosystems are contaminated. Failure in this area has led to some species going extinct and the biodiversity of the region being depleted. Chemical hazardous substances move to the upper levels of food chain and threaten human health by the accumulation of chemicals in the bodies of these aquatic species (Safy et al. 2015).

Petroleum hydrocarbons and heavy metals are among the dangerous chemical contaminants that pose a threat to the aquatic environment when permeated into the ecosystems. Once infiltrated into the bodies of aquatic organism or eventually into the human body, they accumulate in the tissues of the hosts' body and create several issues. Karman and Reernik (1999) have calculated the ecological risk in benthic life, aquatic life, and food chain. Persian Gulf, especially in the recent times, has seen such pollutants entering its waters, particularly in coastal regions. The impacts of these hazards which are the consequence of release of ballast water, ship traffic, digging exploratory wells and operation of oils has led to significant issues to sea creatures, birds, and other creatures consuming them through food chain. Safy et al.

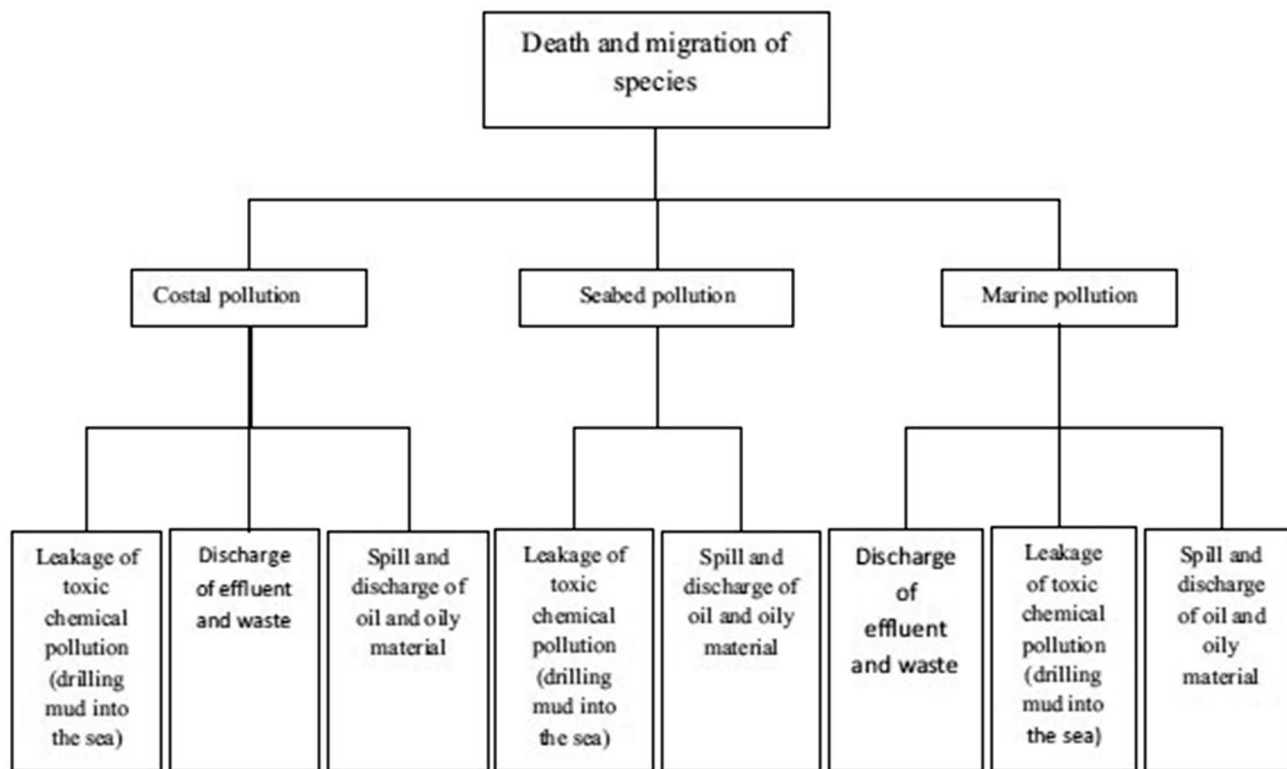


Fig. 4 The hazards of offshore, seabed and coastal contaminations (Safy et al. 2015)

(2015) consider the mass fatality of species such as dugongs, dolphins, turtles, and fishes among others to be a critical issue in the Persian Gulf area.

As displayed in Fig. 4, serious environmental hazard and death or migration of sea species is the eventual outcome of coastal, seabed, and offshore pollutions. Observations indicate that oil-fuel leakage and release of ballast water, fire in the sea, collapsed platforms, faulty leg system, and waste and wastewater discharge are the greatest threats to the offshore water. Almost all of these factors are the major causes of seabed contamination. Although offshore risks are not dissimilar to the environmental coastal ones, their extent and probability of occurrence may significantly vary in different places.

As previously mentioned, access bridges play a pivotal role in offshore platforms when it comes to determining the location of transmission pipes and the possibility of human passage. If bridge structure and/or transmission pipes are damaged, gas leakage and environmental hazards, such as damages to marine ecosystem and people present in the area cannot be ruled out. With the longevity of these platforms and the history of structural failures in the Persian Gulf, health monitoring is considered a crucial aspect of damage identification and preventing any potential environmental hazards.

Table 1 Characteristics of the catwalk structure

| Characteristics | Design data |
|---|-------------------|
| Front view | Triangular |
| Bridge width | 3.5 m |
| Bridge height | 4.5 m |
| Number of main rods | 3 |
| Main rods diameter, main rods thickness | 457 mm, 15.9 mm |
| Horizontal bracings diameter, thickness | 168.3 mm, 9.5 mm |
| Inclined horizontal bracings diameter and thickness | 219.1 mm, 9.5 mm |
| Inclined vertical bracings diameter, thickness | 219.1 mm, 15.9 mm |

Study area

As shown in Fig. 5, the structure studied is an access bridge located in Foroozan offshore complex, on the water boundary of Iran and Saudi Arabia, around 100 km southwest of Kharg isle export terminal. Belonging to the National Iranian Oil Company (NIOC), the field was originally operated with a production of 100,000 barrels a day back in 1987 but as of 2000, this rate plummeted by 60%. The Iranian Offshore Oil Company (IOOC) has embarked on reconstruction and redevelopment of the site aiming to raise the crude output of the field to 80,000 barrels a day. These activities



Fig. 5 The location of Foroozan oil field in the Persian Gulf (<https://www.iooc.co.ir>, 2020)

Fig. 6 Schematic of access bridge

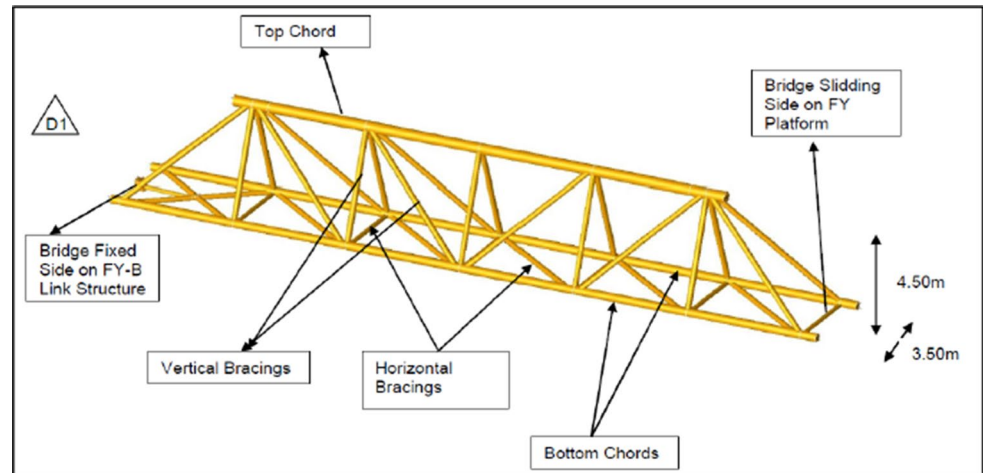


Fig. 7 3D view of the catwalk structure

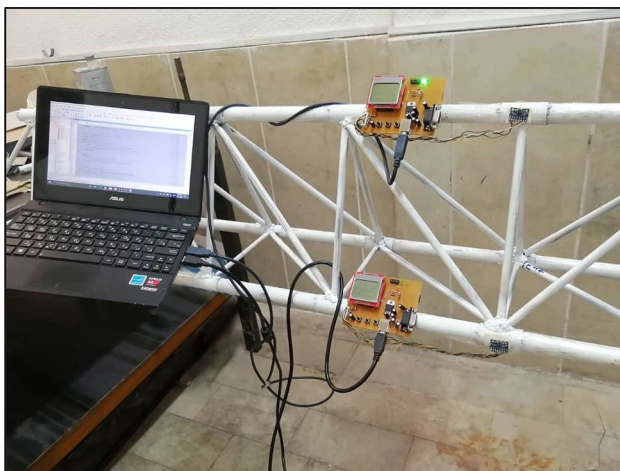
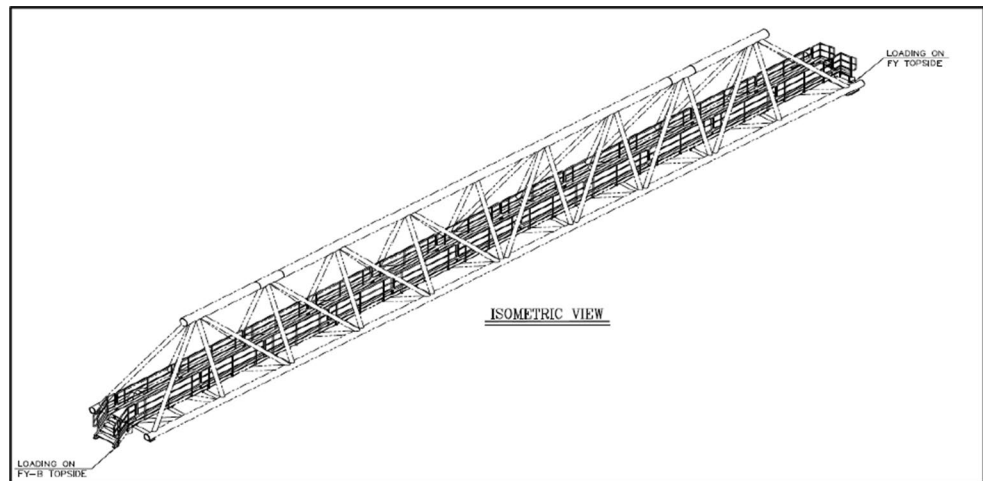


Fig. 8 Test setup instrumentation

include installing new offshore platforms. Two offshore production complexes, namely, FX and FZ, are responsible for processing the oil and gas produced in the Foroozan field.

Structural characteristics of the access bridge

This access bridge is designed to connect two platforms in Foroozan offshore complex. The length of this bridge is about 45.65 m. The cross section of this bridge is triangular. An overall dimension of the bridge is presented in Table 1 (Figs. 6, 7).

Description of the physical model and the test setup

In order to implement modal analysis experimentally, a 1:20 scaled model was built based on the drawings of the access bridge of Foroozan platform. A general view of the test



Fig. 9 Recorded acceleration signal

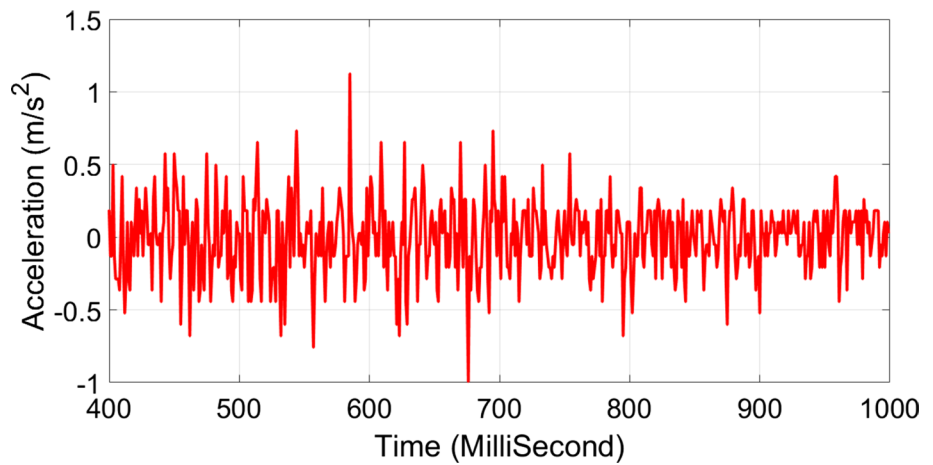


Fig. 10 Laboratory and numerical natural frequencies

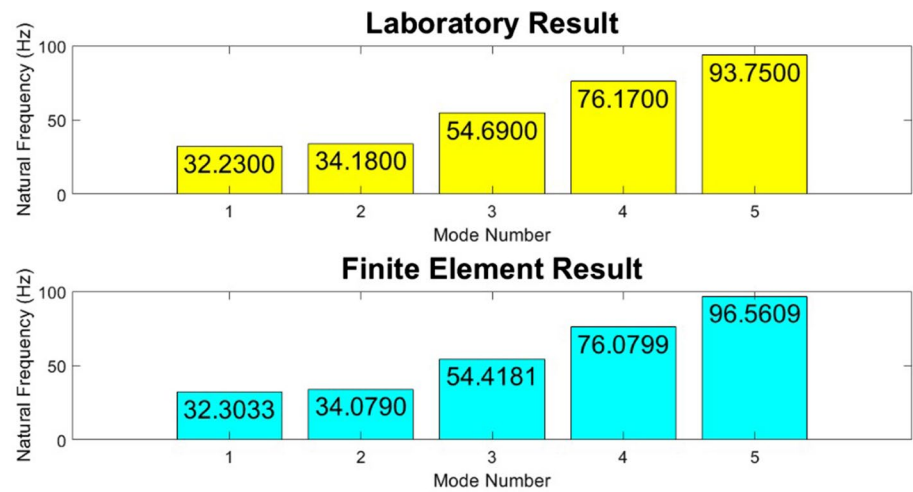


Table 2 Damage scenarios to access bridge with the first 3 natural frequencies

| Damage scenarios | Damage element | Damage severity (%) | Natural frequency (Hz) | | |
|------------------|----------------|---------------------|------------------------|-------------|------------|
| | | | First mode | Second mode | Third mode |
| 1 | 18 | 25 | 32.2920 | 34.0292 | 54.4096 |
| 2 | 23 | 10 | 32.3030 | 34.0737 | 54.4161 |
| 3 | 38 | 40 | 32.2999 | 34.0220 | 54.3965 |
| 4 | 48 | 15 | 32.3027 | 34.0449 | 54.3743 |

setup and instrumentation of the experiment is shown in Fig. 8. The excitation point was the left point of one of the lower chords (Fig. 11.). Two lightly assembled ADXL345 three-axis accelerometers were used to record the response of the structure. A computer was used for analysis of the raw data.

A sample of recorded data of acceleration that was recorded during one implemented test is shown in Fig. 9.

To obtain the natural frequencies experimentally, an experimental modal analysis procedure was performed. Natural frequencies obtained from Peak Picking method are shown in Fig. 10. As this figure shows, there is a good consistency between the numerical and laboratory natural frequencies. Therefore, the numerical program is well performed for modal analysis.

Damage scenarios

The intended hypothetical damage is applied through reduction of elasticity modulus in the finite-element code. In this paper, a variety of single and multiple damage scenarios are devised so that the efficiency of the modal strain energy technique to obtain the extent and the location of the damage is measured more accurately. It is worth noting that in this process, the structural modal information is also required both prior to and after the damage is inflicted. Natural frequencies and mode shapes are extracted after modeling the bridge and the relevant

properties are assigned. The natural frequencies are sorted in ascending order to identify the first mode shape, i.e., the one with the smallest frequency. The damaged structure natural frequencies in 3 modes and related damage scenarios are given in Table 2 in 4 scenarios. Figure 11 also displays the geometric location of the damaged elements. Worth noting the only the first few modes of each structure are taken into account for the calculations regarding damage identification.

Localizing damage and determining its severity in four scenarios

First scenario: damage in element No. 18

In this scenario, a horizontal member located in the bridge chord, namely, element No. 18, is subjected to a 25% damage. The extent and location of the damage are respectively presented in Figs. 12 and 13, with mode shapes of the structure obtained via the modal strain energy method both for

Fig. 11 Hypothetical damaged elements on FE model of the access bridge

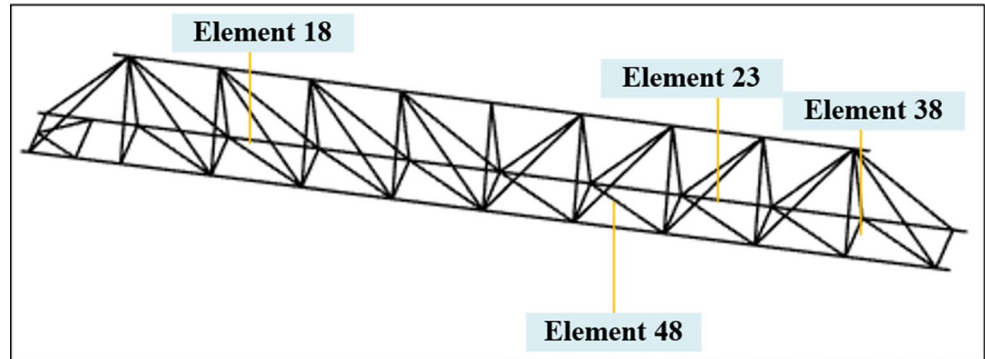


Fig. 12 Location of the damage in the first scenario

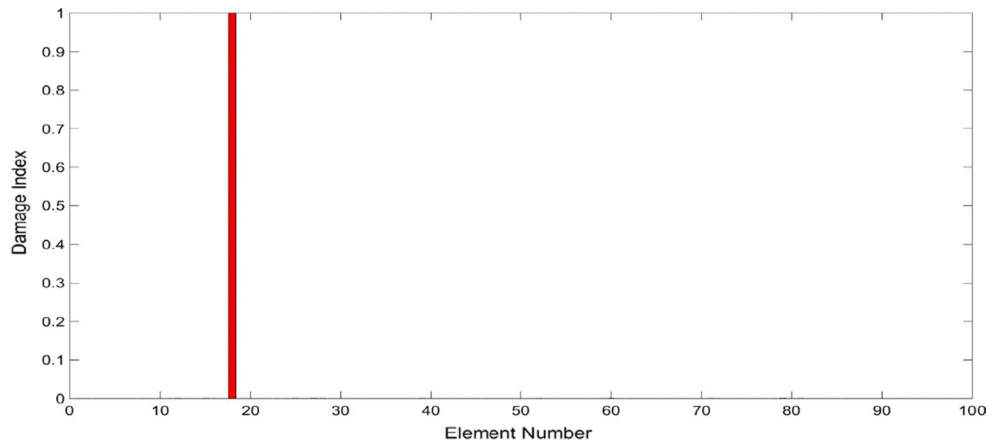
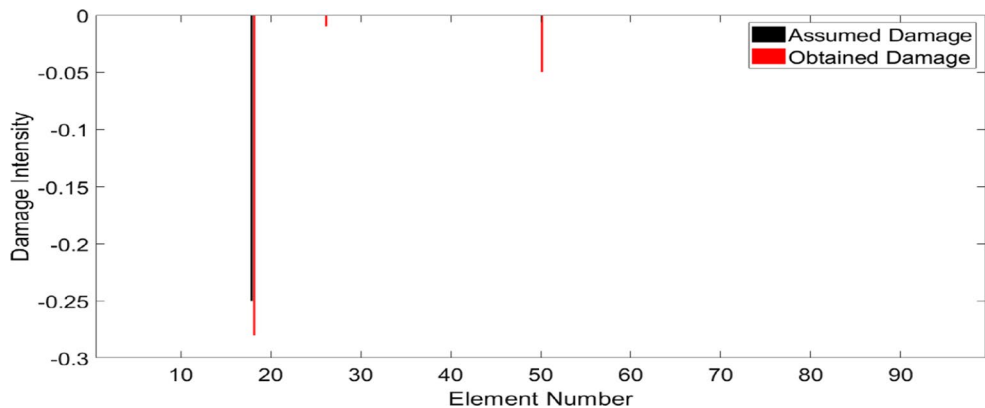


Fig. 13 Severity of the damage in the first scenario



the intact and damaged modes. As demonstrated in Fig. 12, sensitivity-based modal strain energy method is a precise indicator of the damaged elements. Figure 13 also implies that the extent of damage inflicted to bridge chord elements can be accurately estimated using modal strain energy technique.

Second scenario: early damage in element No. 23

Testing the capabilities of the modal strain energy for identifying damages in the early stages is crucial as well. For this purpose, a hypothetical damage amounting to 10% is applied a horizontal member in the bridge chord (element #23). The mode shapes for both the intact and damaged conditions are extracted. Figures 14 and 15 respectively, display the extent and location of damages. In addition, it can be inferred from Fig. 14 that this method is adept at identifying small damages. Likewise, Fig. 15 demonstrates the modal strain energy technique to reliably estimate the extent of damages inflicted to chord element.

Fig. 14 Location of the damage in the second scenario

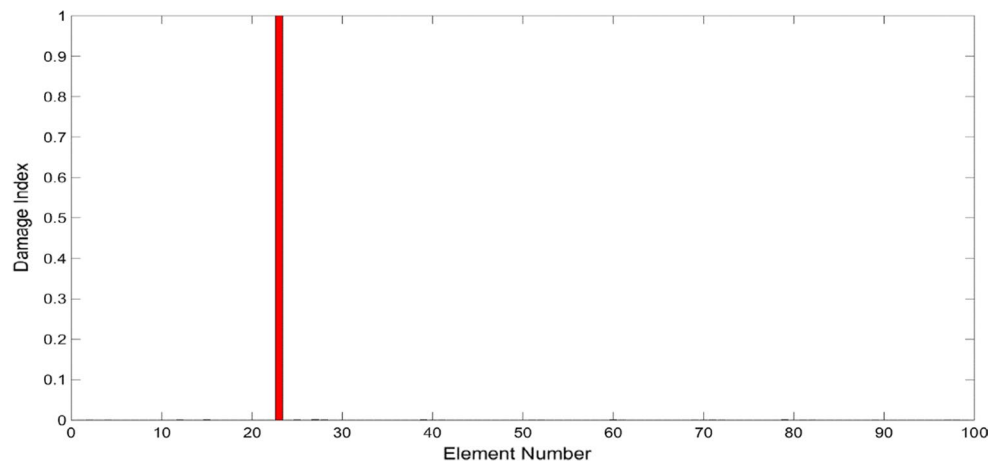
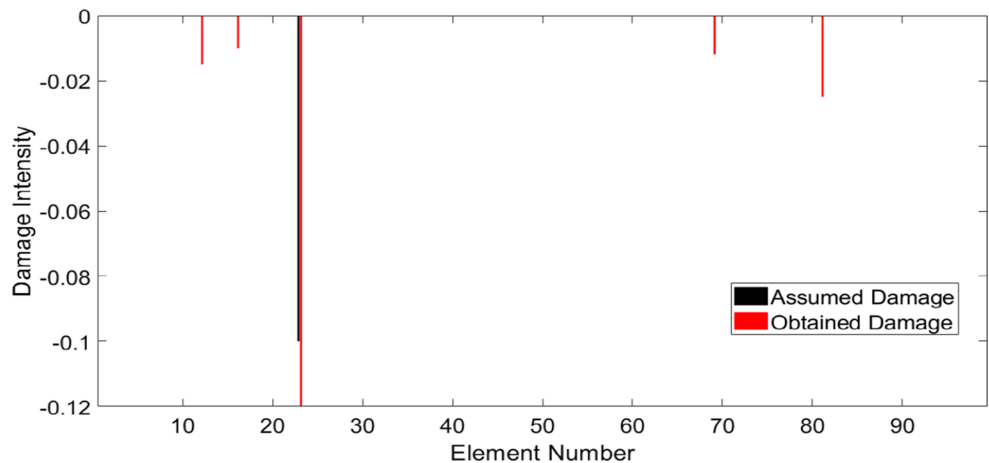


Fig. 15 Severity of the damage in the second scenario



Third scenario: damage in element No. 38

In the present scenario, a 40% damage is hypothetically applied to element No. 38 in order to further confirm the results of the second scenario. As displayed in Fig. 16, as the damage index increases, the modal strain energy method can offer a more precise identification of the damaged element. The accuracy with which the damage severity is estimated is also deemed acceptable as indicated in Fig. 17.

Fourth scenario: damage in element No. 48

In this scenario, an assumed damage amounting to 15% is inflicted to element No. 48, i.e., a member connecting the two lower chords. As displayed in Fig. 18, the modal strain energy is a fairly reliable indicator of damage localization in the access bridge. The modal strain energy method is also shown to be a precise measure for estimating the extent of damage in the diagonal member of the catwalk structure (Fig. 19).

Fig. 16 Location of the damage in the third scenario

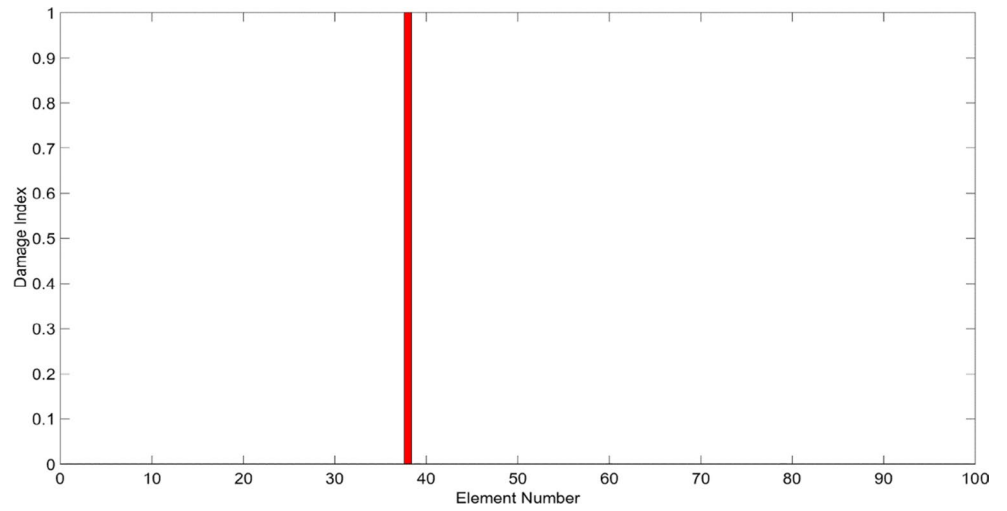


Fig. 17 Severity of the damage in the third scenario

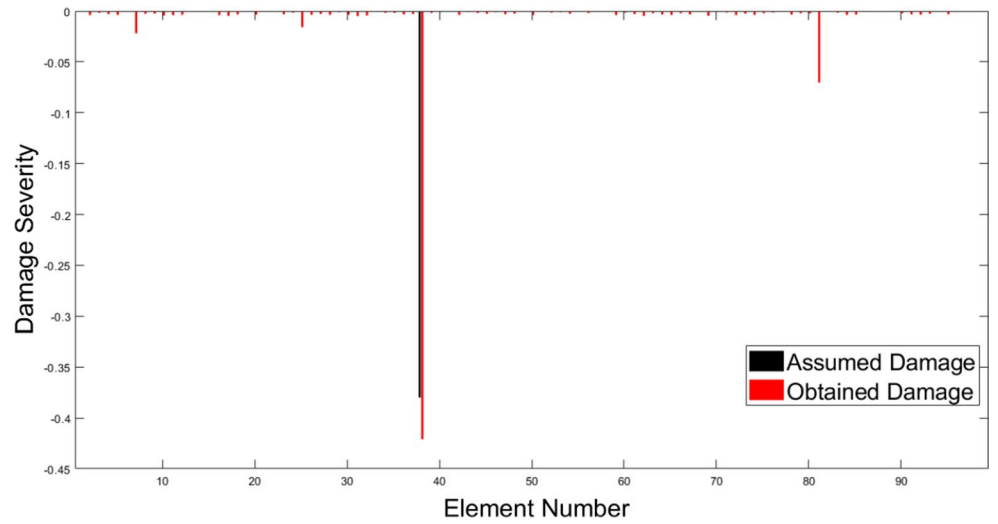


Fig. 18 Location of the damage in the fourth scenario

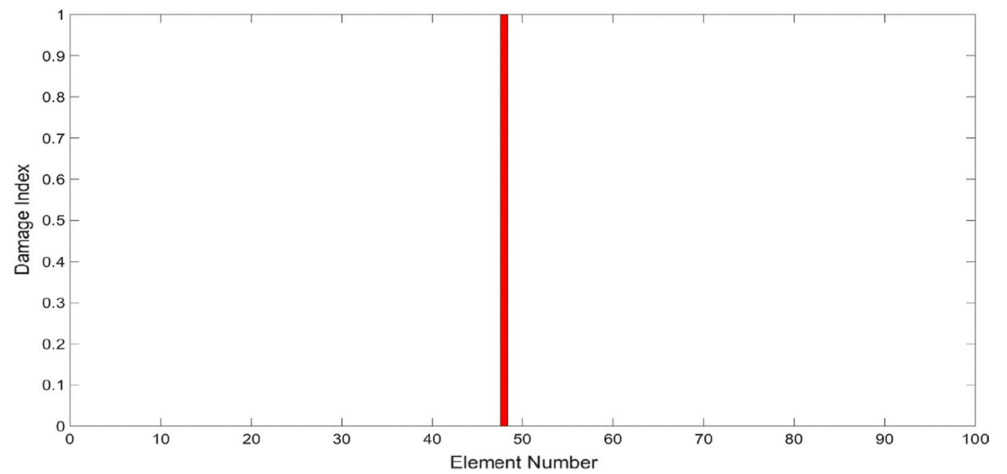
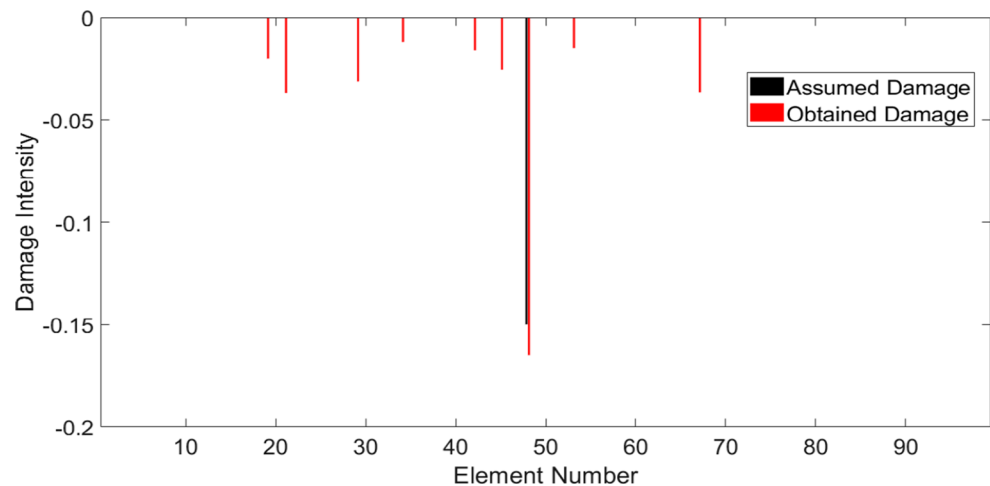


Fig. 19 Severity of the damage in the fourth scenario



Conclusion

In recent decades and with the development of coastal countries, the Persian Gulf ecosystem and especially its coasts have experienced devastating effects. The largest hydrocarbon resources in the world are located in this area, making this region one of the most significant centers of gas and oil production and also rendering the Persian Gulf the most important strategic highway in the world. On the other hand, these activities lead to aquatic mortality, destruction of valuable habitats, and disturbing the ecological balance. Compensation for these damages, especially in the field of biodiversity (species, genetics, habitat, and even aquatic behavior), would require huge sums of money and plenty of time to rebuild the stocks. A considerable portion of this pollution in offshore areas is caused by drilling operations, oil leakage from transmission pipes in the seabed and gas leakage from transmission pipes on access bridges in the air.

Access bridge that links different parts of offshore platforms is a significant part due to the necessity of sidewalks for pedestrian and supports for pipelines. Occurrence of failure in any of the elements of this sensitive structure results in huge negative impacts on the marine environment. This impact can be small like just the failure of a small member or huge like the gas leakage in the air and irreparable environmental damages. Although, to the best knowledge of authors, there is not any structural health monitoring study on this type of offshore structure. The present research that includes both experimental modal analysis and numerical damage identification process aimed at identifying the severity and location of damage in an offshore catwalk structure. The access bridge of the Foroozan offshore complex that is located on the Iran–Saudi Arabia water border was used as the case study. A hypothetical damage was applied to the elements whose impacts were thought to be more crucial

on the overall integrity of the structure. According to the results, sensitivity-based modal strain energy method, demonstrates a proper accuracy when it comes to identifying the extent and the location of damage in the catwalk structure of offshore platforms. It also proves to perform capably as a means to identify both single and multiple damages.

Acknowledgements The authors would like to thank the Iranian Offshore Oil Company (IOOC) for providing the drawings of the access bridge of Foroozan Oil complex. It is worth mentioning, the data provided in this article are not in conflict with the interests and laws of the organization concerned.

Author contributions Mehdi Alavinezhad: Conceptualization, Methodology, Formal analysis, Software, Investigation, Writing—original draft. Madjid Ghodsi Hassanabad, Mohammad Javad Ketabdari, Masoud Nekooei: Conceptualization, Supervision, Project administration, Resources, Writing—review and editing.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Alkayem NF et al (2018) Structural damage detection using finite element model updating with evolutionary algorithms: a survey. *Neural Comput Appl* 30:389–411
- Altunisik AC et al (2020) Finite-element model updating and dynamic responses of reconstructed historical timber bridges using ambient vibration test results. *J Perform Constr Facil* 34:04019085
- Anon., n.d. [Online]. Available at: <http://www.iooc.co.ir/>
- Anon., n.d. [Online]. Available at: <https://www.nsenenergybusiness.com/projects/forouzan-oil-field-expansion/>
- Asadollahi P (2018) Bayesian-based finite element model updating, damage detection, and uncertainty quantification for cable-stayed bridges. University of Kansas, Kansas
- Balageas D (2006) Introduction to structural health monitoring. In: *Structural health monitoring*. Wiley, London, pp 13–43

- Brigitte S et al (2019) Decommissioning of offshore oil and gas structures—environmental opportunities and challenges. *Sci Total Environ* 658:973–981
- Budipriyanto A, Susanto T (2015) Dynamic response of a steel railway bridge for the structure's condition assessment. *Proc Eng* 125:905–910
- Cawley P, Adams RD (1979) The location of defects in structures from measurement of natural frequencies. *J Strain Anal Eng Des* 14:49–57
- Cha PD, Gu W (2000) Model updating using an incomplete set of experimental modes. *J Sound Vib* 233:587–600
- Chen GW, Omenzetter P (2016) Finite element model updating of a prestressed concrete box girder bridge using subproblem approximation. In: *Proceedings of SPIE 9804, nondestructive characterization and monitoring of advanced materials, aerospace, and civil infrastructure*
- Deng L, Cai CS (2010) Bridge model updating using response surface method and genetic algorithm. *J Bridge Eng* 15:553–564
- Ding Y, Xiao F, Zhu W, Xia T (2019) Structural health monitoring of the scaffolding dismantling process of a long-span steel box girder viaduct based on BOTDA technology. *Adv Civ Eng* 2019:1–8
- Doebling S et al. (1993) Selection of experimental modal data sets for damage detection via model update.
- Doebling S, Farrar CR, Prime MB, Shevitz DW (1996) Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review. Los Alamos National Laboratory
- El-Reedy MA (2015) Introduction to offshore structures. In: *Marine structural design calculations*. Butterworth-Heinemann, pp 1–12
- Farrar CR, Jauregui DA (1998) Comparative study of damage identification algorithms applied to a bridge: II. *Numer Study Smart Mater Struct* 7:720–731
- Friswell MI, Mottershead JE (1995) *Finite element model updating in structural dynamics*. Kluwer Academic, Dordrecht
- Giles RK et al (2011) Structural health indices for steel truss bridges. *Civ Eng Top* 4:391–399
- Guo J, Wu J, Guo J, Jiang Z (2018) A damage identification approach for offshore jacket platforms using partial modal results and artificial neural networks. *Appl Sci* 8:8112173
- Hansen SR, Vanderplaats GN (1990) Approximation method for configuration optimization of trusses. *AIAA J* 28:161–168
- Hu SLJ, Li H, Wang S (2007) Cross-model cross-mode method for model updating. *Mech Syst Signal Process* 21:1690–1703
- Jaishi B, Ren WX (2006) Damage detection by finite element model updating using modal flexibility residual. *J Sound Vib* 290:369–387
- Kim JT, Stubbs N (1995) Damage detection in offshore jacket structures from limited modal information. *Int J Offshore Polar Eng* 5:58–66
- Kim JT, Stubbs N (2002) Improved damage identification method based on modal information. *J Sound Vib* 252:223–238
- Lekidis V, et al (2004) Investigation of dynamic response and model updating of instrumented R/C bridges. In: *13th World conference on earthquake engineering, Vancouver*
- Li J, Hao H (2016) A review of recent research advances on structural health monitoring in Western Australia. *Struct Monitor Mainten* 3:33–49
- Li YY, Cheng L, Yam LH, Wong WO (2002) Identification of damage locations for plate-like structures using damage sensitive indices: strain modal approach. *Comput Struct* 80:1881–1894
- Liao J et al (2012) Finite element model updating based on field quasi-static generalized influence line and its bridge engineering application. *Proc Eng* 31:348–353
- Lu S et al. (2014) Environmental aspects of designing multi-purpose offshore platforms in the scope of the FP7 TROPOS Project. Taipei, OCEANS 2014
- Manfra L et al (2020) Challenges in harmonized environmental impact assessment (EIA), monitoring and decommissioning procedures of offshore platforms in Adriatic-Ionian (ADRION) region. *Water* 12:2460
- Merce RN et al (2007) Finite element model updating of a suspension bridge using ANSYS software. *Inverse problems, design and optimization symposium, Miami*
- Meruane V (2013) Model updating using antiresonant frequencies identified from transmissibility functions. *J Sound Vib* 332:807–820
- Modares M, Waksanski N (2013) Overview of structural health monitoring for steel bridges. *Pract Period Struct Des Constr* 18:187–191
- Moradipour P, Chan THT, Gallage C (2015) An improved modal strain energy method for structural damage detection, 2D simulation. *Struct Eng Mech* 54:105–119
- Moradipour P, Chan T, Gallage C (2013) Health monitoring of short and medium-span bridges using an improved modal strain energy method. In: *5th International workshop on civil structural health monitoring, Japan*
- Salawu OS (1997) Detection of structural damage through changes in frequency: a review. *Eng Struct* 19:718–723
- Shahrivar F, Bouwkamp G (1986) Damage detection in offshore platforms using vibration information. *J Energy Res Technol* 108:97–106
- Shih HW, Thambiratnam DP, Chan TH (2009) Vibration based structural damage detection in flexural members using multi-criteria approach. *J Sound Vib* 323:645–661
- Stubbs N, Kim JT (1996) Damage localization in structures without baseline modal parameters. *AIAA J* 34:1644–1649
- Xu-hui H, Zhi-wu Y, Zheng-qing C (2008) Finite element model updating of existing steel bridge based on structural health monitoring. *J Cent South Univ Technol* 15:399–403
- Yang HZ, Li HJ, Wang SQ (2003) Damage localization of offshore platforms under ambient excitation. *China Ocean Eng* 17:495–504

