Using Refined Simplified Model for Damage Detection in Offshore Jacket Structures

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ABSTRACT

This work introduces a structural integrity assessment strategy for Jacket structures based on the finite element model updating and a novel simplified method. Hereof, model reducing and model updating procedure is established based on a optimization technique. Since the number of measured degrees of freedom is most of the time restricted in practice, this paper represents a methodology using the cross model cross mode method (CMCM) in combination with an iterative procedure which uses limited, spatially incomplete modal information. This research is an empirical study on a laboratory model of a jacket structure with the aim of establishing Refined Simplified FE Model (RSM) to conduct damage detection. In addition to elimination of uncertainty effects in the damage detection results, RSM technique is employed because of practical considerations and also this technique provides a fast damage zone diagnosis procedure. Also, improved reduction scheme is utilized based on static reduction scheme to carry out damage detection in jacket structure.

1. Introduction

Integrity monitoring of the marine structures is very important and undeniable. For more marine structures, numerous studies have been presented in damage identification field, such as [1-6]. Structural damage induces alterations in physical properties and modal characteristics of the jacket structure. These changes have long been applied to detect damage. Also, structural model updating is often utilized for structural integrity assessment (SIA): by calibrating stiffness parameters of FE models based on experimentally obtained information, structural damage can be determined [7]. In the damage diagnosis process, numerical models are employed to simulate the behavior of real structure. But errors from the numerical model and the modeler are inevitable, which reflect in the difference between the FE model and the experimental model. The uncertainty in the results between the numerical modal analysis and the experimental modal analysis is because of the assumptions made in defining numerous unknown or uncertain system properties [8, 9]. Accordingly, the validity of the adopted numerical models is necessary. Structural model updating improves a numerical FE model utilizing experimental modal data to produce a refined model that better predicts the dynamic behavior of a real structure. Among the damage diagnosis algorithm, the techniques based on the modal parameter identification along with vibration testing and model updating process have received increasing attentions of researchers [10-12]. As evidenced in the literature, because of the many practical challenges encountered in such techniques, efforts at further improving these techniques for marine structures were largely abandoned by the early 1980s [13]. In this regard, during recent years a few researchers have discussed about the SIA in fixed marine structures. But, despite of the aforementioned effort, there is not any research which directly focused on the effects of the mentioned challenges as the main objective of the study to circumvent these major problems along utilizing the concept of mentioned approaches for jacket structures. To summarize, the improvement of SIA methodologies for offshore jacket platforms is aiming to provide safety, cost saving (maintenance) as well as environmental benefits. But, the number of successful practical applications of Structural Integrity Monitoring (SIM) technologies is still limited. This research introduces a new technique to evaluate SIM system for offshore jacket platform and apply it to an experimental case study (SPD9 platform jacket

located of the Persian Gulf). In this study, reduction process includes the decrease of the members of the structural model (simplified platform model) and the reduction of degrees of freedoms (static reduction). In this regard, an optimization-based model reducing approach is presented to reduce the members of the structural model by preserving the properties of the structure dynamic behavior. Hence, the first target of the current study is to carry out FE model updating based on modal-domain method utilizing frequency response technique (FRT). The FRT directly utilizes the measured frequency response functions (FRFs) for FE model updating. Since the FRT has numerous advantages over the other updating methods, the work concentrates on this technique. An improved reduction technique (static reduction) associating the model updating process is also utilized. Improved reduction technique removes the bad effect of model reduction process on the proposed method. Moreover, this technique prevents the appearance of spurious modes in the frequency range of interest. It is worth mentioning, the considered technique of the both optimization-based model reducing and model updating process is established utilizing a Computational Intelligence (CI) method. This technique is called Refined Simplified Model (RSM) technique. In other words, we introduced the novel simplified method (RSM) in both model reducing (simplification) and model updating process (both procedures are performed simultaneously). Stated another way, the main aim of this work is to develop a SIA strategy for offshore jacket – type structures based on the FE model updating and a novel simplified technique which is less sensitive to both measurement and model uncertainties. RSM scheme can brings about a fast damage zone identification process and also, this simplification leads to a reduction in amount of calculations and expenses. The results demonstrate that the proposed methods provide reliable assesses of damage utilizing the measured incomplete modal data.

The Model Updating and Simplification Approach
Measured FRFs and mode shapes have been applied in FE model updating, by utilizing their features. Updating applying measured FRFs conquers both the problem caused by insufficient information, as measured information can be obtained at any number of frequency points, and the problem of introducing additional inaccuracies from modal analysis, as the measured FRF information are utilized directly. Also, the FRFs contain damping characteristics that otherwise have to be modeled when applying the measured modal properties approach. Another benefit of exploiting and applying measured FRF directly is that no pairing or matching of mode shapes is necessary [14]. The dynamic response of a multi degree damped structural system by a second-order matrix differential equation given by:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{Q(t)\} \tag{1}$$

Where $[M]$, $[C]$ and $[K]$ stand for mass matrix, damping matrix and stiffness matrix, respectively. Also, $\{U(t)\}$, $\{\dot{U}(t)\}$ and $\{\ddot{U}(t)\}$ represent the nodal displacement, velocity and acceleration vectors of the structure, respectively. Furthermore, $\{Q(t)\}$ is the forcing function vector. The damping matrix is assumed to be proportional and is defined in terms of mass and stiffness matrices as follows:

$$[C]=\chi[M]+\gamma[K] \tag{2}$$

Equation (1) could be rewritten as follows:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}-\{Q(t)\}=\{0\} \tag{3}$$

If it is presumed that:

$$\{U\}=\{U(\omega)\}e^{i\omega t} \tag{4}$$

By taking the appropriate derivatives, we have:

$$\{\dot{U}\}=i\omega\{U(\omega)\}e^{i\omega t} \tag{5}$$

$$\{\ddot{U}\}=-\omega^2\{U(\omega)\}e^{i\omega t} \tag{6}$$

Substituting Equations (5) and (6) into Equation (3), the equation may be presented in the frequency domain as follows:

$$\left(-\omega^2[M]+i\omega[C]+[K]\right)\{U(\omega)\}-\{Q(\omega)\}=\{0\} \tag{7}$$

$$[Z(\omega)]\{U(\omega)\}-\{Q(\omega)\}=\{0\} \tag{8}$$

In Equation (8), $[Z(\omega)]$ is the dynamic stiffness matrix of the structure. In Equation (7), $\{U(\omega)\}$ and $\{Q(\omega)\}$ are measured quantities. The drawback with Equation (7) is that FRFs are measured, instead of individual displacements and force. To fix this drawback, the excitation/ stimulation is presumed to be white noise, and hereupon the vector $\{Q(\omega)\}$ has a unit force magnitude at all frequencies, and the displacement is replaced by the FRFs. If the measured FRFs are applied into Equation (3), utilizing $[M]$, $[C]$ and $[K]$ from the FE model, then there will be an error that will depend on the accuracy of the FE model. This system error vector may be presented on the right hand side of Equation (8) and the resulting equation is:

$$[Z(\omega)]\{U(\omega)\}-\{Q(\omega)\}=\{\Omega(\omega)\} \tag{9}$$

Because of the difficulty in the check of the elements of the error vector, the Euclidean norm (∆), which is the square root of the sum of the squares of the error vector elements, is utilized [15]. If the error vector has zero elements, then (∆) will be equal to zero. The equation for ∆ is:

$$\Delta = \left(\sum_{i=1}^{\eta} \left| \Omega(\omega_i)^2 \right| \right)^{0.5} \tag{10}$$

Where, η is the number of frequency points. The structural element stiffness, mass, and damping matrices depend on the area (A), density (ρ), Poisson ratio (ν) and the modulus of elasticity (E) of each element. By changing one of these physical parameters, Δ can be minimized. The A, ρ, ν and E acquired by updating the FE model are thus known as updating parameters. A simplified platform model that represents the dynamic properties of jacket platform model and effectively reduces the computational effort has the potential to facilitate the structural damage detection steps. Hereof, there has been no research/ or work directly focusing on the damage detection based on simplified platform model as the main scope of the study. Although limited researchers have conducted studies on establishing simplified models for analysis and performance evaluation of the jacket platform [16, 17]. Accordingly, the reflection of model simplification effects on the dynamic performance of the jacket platform is considered as a perspective of this work for improving a SIM strategy for jacket structures based on the FE model updating. This simplification leads to a reduction in amount of calculations and expenses. For instance, many members of the initial platform model are replaced by a member in the simplified platform model, as shown in Figure 1. By imposing desired technique (FRT), a full accordance between the dynamic properties in both empirical and simplified model is gained. In other words, we introduced the novel simplified method (RSM) in both model reducing (simplification) and model updating process (both procedures are performed simultaneously), which is inspired by the computational intelligence algorithm. Based on the proposed scheme, new members created to be replaced in the desired position. Accordingly, properties of the removed members; including stiffness and mass features are equivalent to properties of the replaced members. Eventually, the RSM is produced.
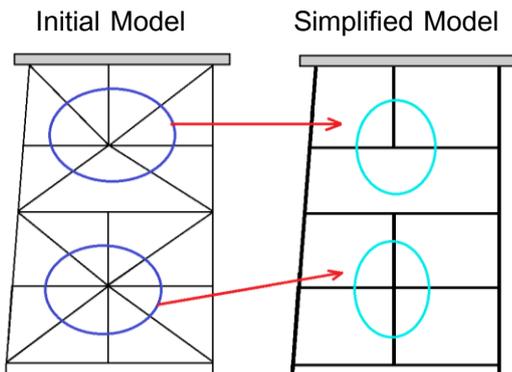

Figure 1: A diagrammatic sketch for creating a simplified platform model.

CMCM Method and Improved Reduction Algorithm Due to Incomplete Modal Data

The main framework of the algorithms being used in this study is based on the structure of the approach similar to CMCM [18]. In this section, this method introduce briefly. The eigensolution of the target system consists of the eigenvalues and eigenvectors. The ith eigenvalue and eigenvector associated with K and M is expressed as:

$$K\Phi_i = \lambda_i M\Phi_i \tag{11}$$

Where M and K is the mass matrix and stiffness matrix for the undamaged model and λ_i and Φ_i is the ith eigenvalue and eigenvector associated with K and M. In the development of the CMCM method, it is assumed that the stiffness and mass matrices of the structure denoted by K and M are obtained from a finite element model. Assume that the stiffness matrix K^* of the actual (experimental) model is a modification of K to be formulated as:

$$K^* = K + \sum_{n=1}^{N_e} \alpha_n K \tag{12}$$

Where K_n is the stiffness matrix corresponding to the nth element, N_e is the number of elements, and α_n are unknown correction factors to be determined. Herein, for simplicity in presentation, it is assumed that each element involves a parameter to be updated, such as the Young's modulus of each element. In most studies for the damage detection, particularly in relation to offshore structures usually changes in the mass matrix are negligible.so, it is assumed that:

$$M = M^* \tag{13}$$

Express the jth eigenvalue and eigenvector associated with K^* and M^* as:

$$K^*\Phi_j^* = \lambda_j^* M^*\Phi_j^* \tag{14}$$

It is assumed that a few of λ_j^* and Φ_j^* are known measurements available from modal testing. Premultiplying Equation (14) by $(\Phi_i)^t$ yields:

$$(\Phi_i)^t K^*\Phi_j^* = \lambda_j^* (\Phi_i)^t M^*\Phi_j^* \tag{15}$$

Where the superscript ''t'' is the transpose operator. Substituting Equations (12) and (13) into Equation (15) yields:

$$C_{ij}^{\int} + \sum_{n=1}^{N_e} \alpha_n C_{n,ij}^{\int} = \lambda_j^* \left(D_{ij}^{\int} \right) \tag{16}$$

After using a new index v to replace ij, Equation (16) becomes:

$$C_v^{\int} + \sum_{n=1}^{N_e} \alpha_n C_{n,v}^{\int} = \lambda_j^* \left(D_v^{\int} \right) \tag{17}$$

Where $C_{n,v}^{\int} = (\Phi_i)^{\int} K_n \Phi_j^*$, $\quad C_v^{\int} = (\Phi_i)^{\int} K \Phi_j^*$ and $D_v^{\int} = (\Phi_i)^{\int} M \Phi_j^*$. Rearranging Equation (17), one obtains:

$$\sum_{n=1}^{N_e} \alpha_n C_{n,v}^{\int} = f_v^{\int} \tag{18}$$

Where, $f_v^{\int} = -C_v^{\int} + \lambda_j^* D_v^{\int}$. When N_i modes are taken from the analytical (baseline) finite element model, and N_j modes are measured from the damaged structure, totally $N_v = N_i \times N_j$ equations can be formed from Equation (18). Equations formed based on Equation (18) are named CMCM equations because they involve two modes of two models. Rewriting Equation (18) in a matrix form, one shows:

$$C_{N_v \times N_e}^{\int} \alpha_{N_e \times 1} = f_{N_v \times 1}^{\int} \tag{19}$$

When N_v is greater than N_e, a least-squares technique can be taken to expect for α.

$$\alpha = (C^t C)^{-1} C^t f^{\int} \tag{20}$$

One of the simplest reduction schemes is static reduction (Guyan). The full scale model may have certain nodal freedoms specified as master freedoms. The remaining freedoms are slave freedoms. For dynamic analysis purposes the mass, stiffness and loading on the slave freedoms are condensed to these master freedoms. In matrix notation the overall matrices may be partitioned into master, slave and cross coupling terms.

$$\begin{bmatrix} [M_{mm}] & [M_{ms}] \\ [M_{sm}] & [M_{ss}] \end{bmatrix} \begin{Bmatrix} \ddot{U}_m \\ \ddot{U}_s \end{Bmatrix} + \begin{bmatrix} [K_{mm}] & [K_{ms}] \\ [K_{sm}] & [K_{ss}] \end{bmatrix} \begin{Bmatrix} U_m \\ U_s \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{21}$$

Where, the subscripts m and s refer to the master and slave coordinates, respectively. The technique then ignores the inertia terms in the second set of Equations. Neglecting the inertia terms for the second set of equations we have:

$$[K_{sm}]\{U_m\} + [K_{ss}]\{U_s\} = [T_s]\{U_m\} \tag{22}$$

By eliminating the slave DOF, we obtain:

$$\begin{Bmatrix} U_m \\ U_s \end{Bmatrix} = \begin{bmatrix} [I] \\ -[K_{ss}]^{-1}[K_{sm}] \end{bmatrix} \{U_m\} = [T_s]\{U_m\} \tag{23}$$

T_s is Guyan transformation matrix and I is identify matrix. The reduced Guyan mass and stiffness matrices are then given by [19]:

$$[M_R] = [T_s^T][M][T_s] \tag{24}$$

$$[K_R] = [T_s^T][K][T_s] \tag{25}$$

For larger marine structures, where it is necessary to reduce many slave DOF, this technique will not be as accurate as some of the more advanced approaches. Accordingly, improved reduction skill is probably the best practical process for solving large dynamic problems. Only the smallest frequencies are usually excited and for a typical jacket no more than 30 would normally be required. The process known as the Improved Reduction System (IRS) was presented by O"Callahan in 1989 [20]. This technique is an improvement over the Guyan static reduction scheme via introducing a term that includes the inertial effects as pseudo static forces. A transformation matrix T_i is applied to reduce the mass and stiffness matrices. It is defined as:

$$[T_i] = [T_s] + [S][M][T_s][M_R^{-1}][K_R] \tag{26}$$

$$S = \begin{bmatrix} [0] & [0] \\ [0] & [K_{ss}^{-1}] \end{bmatrix} \tag{27}$$

M_R and K_R are the statically reduced mass and stiffness matrices. The new reduced mass and stiffness matrices can be obtained by:

$$[M_{IRS}] = [T_i^T][M][T_i] \tag{28}$$

$$[K_{IRS}] = [T_i^T][K][T_i] \tag{29}$$

For this process, the rows and columns corresponding to the slave coordinates are eliminated from the mass and stiffness matrices one at a time; this allows the mass and stiffness matrices to adapt to the removal of a slave, and can possibly alter the DOF that will be removed. After each reduction, the DOF with the lowest K_{ii}/M_{ii} term is the slave which will be eliminated next [21].

Physical Model and Test Set up

A physical model was constructed of steel pipes that were welded together using argon arc welding to ensure proper load transfer. The experimental model is built of steel tubes, utilizing $34mm \times 3.5mm$ (outer diameter and thickness) section as 2 legs and $21mm \times 2.0mm$ section as all braces, and box cross section at the top with $40mm \times 20mm$ and $2mm$ thickness to simulate the upside structure. The 2D steel frame model structure has dimensions of $560mm$ (on the bottom) and $480mm$ (on the top) in width and has heights of $280mm, 285mm, 270mm$ and $270mm$ at the 1st, 2nd, 3rd and 4th storey, respectively, giving a total height of $1105mm$. The physical model along with test rig and FE model of the laboratory tested 2D steel frame jacket structure adopted for model updating is shown in Figure 2. The FE model presented in Figure 2 has 15 nodes and 29 elements with a total number of 45 degrees of freedoms. The mass density of the members is 7850 kg/m3 and the Young's modulus of steel is 207 GPa. The white noise signals were used as the input exciting signal. The instrumentation included two light uniaxial accelerometers (4508 B&K) in both the X and Y directions on each joint for response measurement and a load cell for measuring

the excitation force. The frequency sampling of the test setup was chosen to be 10 kHz, and the frequency range was 0-200 Hz. The recorded data were sent to the PULSE [22] software package for processing. The data required for calculating the FRFs were recorded by sensors that were fixed on the physical model joints. First tests are done on the undamaged structure. Then the tests are repeated in the same way for the damaged structure by removing the member of the model, as shown Figure 3.
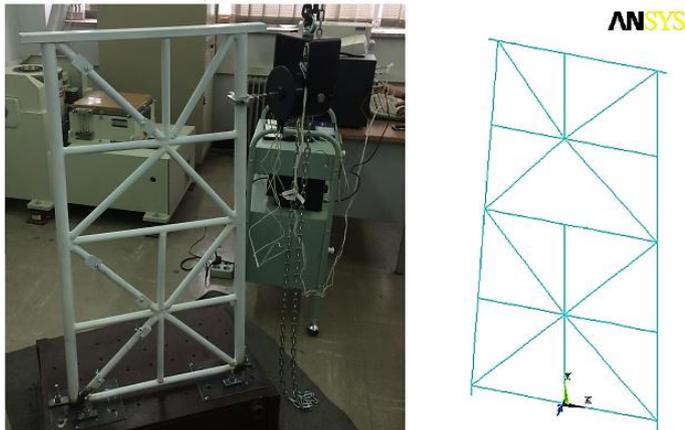

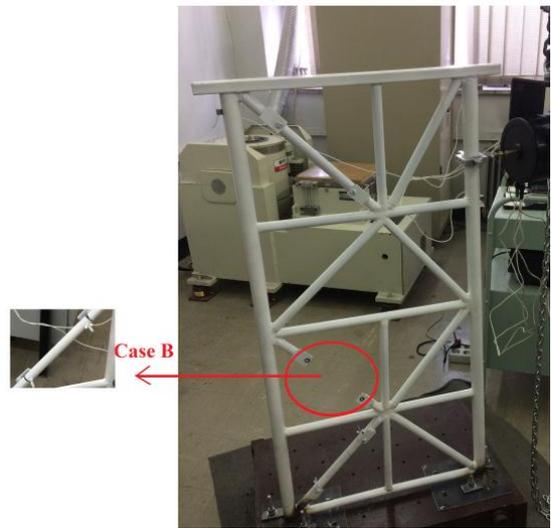**Figure 2: The physical model and FE model**

Figure 3: Experimental damage scenarios

Results and discussion
Refined simplified FE model of platform (RSM)

For production of perfect RSM, the obtained result from solving Equation 10 is presented in Figure 4 and Table 1. Moreover, Figure 5 and Table 2 imply the perfect correlation between the acquired natural frequencies of the RSM and experimental results.
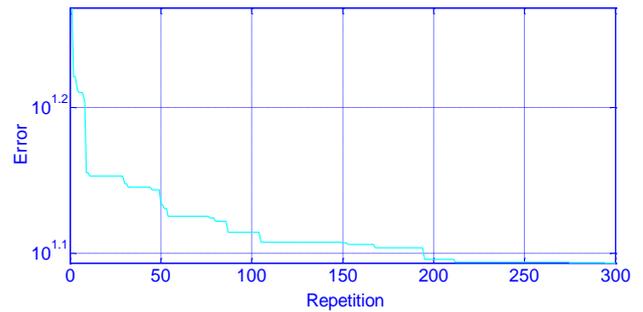

Figure 4: The convergence process obtained from solving the objective function.

Table 1: The obtained result from solving the objective function

Area (cm^2)	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
	11.61	6.02	3.461	11.61	5.53	6.02	5.33	6.72
Moment of inertia (cm^4)	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
	28.531	17.496	4.35	28.531	13.496	17.469	15.765	19.113

10.08 (Hz)   **45.83** (Hz)   **76.07** (Hz)
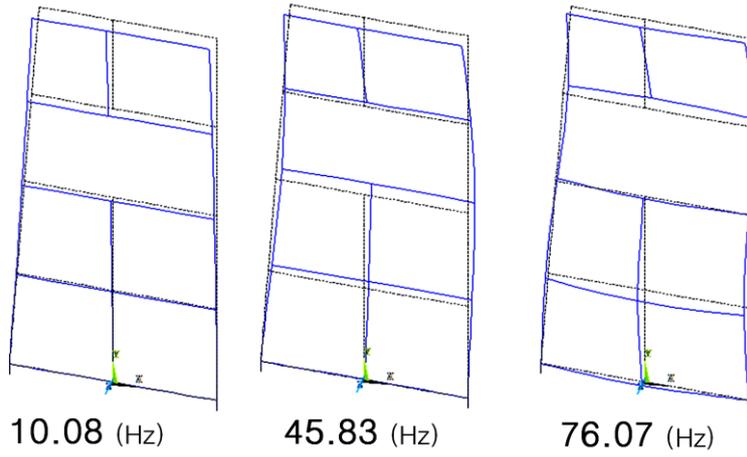
Figure 5: The first three mode shapes of the RSM.

Table 2: The first four natural frequencies.

Mode No.	1st	2nd	3rd	4th
Initial Model	16.49 (Hz)	58.03 (Hz)	91.75 (Hz)	143.25 (Hz)
Empirical Model	9.8 (Hz)	45.3 (Hz)	75.8 (Hz)	145 (Hz)
RSM	10.08 (Hz)	45.83 (Hz)	76.39 (Hz)	144.53 (Hz)

The updating and refining of the original FE model is required to minimize the numerical model error according to the experimental signatures. The ideas of the "*Modal Assurance Criterion*" (**MAC**) approach can be employed for this intention. A typical correlation criterion is the MAC which gives a single value between 0 and 1 for the mode shape concurrence. The MAC, between analytical mode φ_i

and experimental mode φ_j is expressed as:

$$MAC(\varphi_i,\varphi_j) = \frac{|\varphi_i^T \varphi_j|^2}{(\varphi_i^T \varphi_i)(\varphi_j^T \varphi_j)} \qquad (30)$$

Based on this factor, the MAC values always lie between 0 and 1, where values closer to 1 indicate a better agreement between the considered mode shapes. Results imply that the MAC values between the mode shapes of the RSM and the mode shapes of the tested physical model are all greater than 0.94, which represents that an effective RSM has been produced. The damaged structure has three damage elements, including element *A*, *B* and *C* (see Figure 6). For instance, element *B* in the damaged structure is equivalent with damage in "*Zone 3*" located in the RSM.
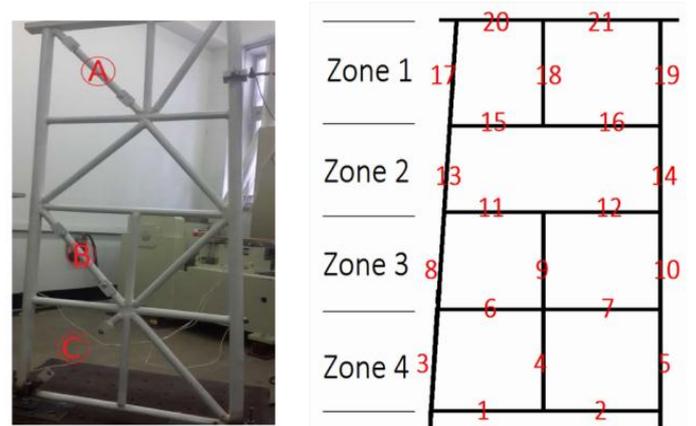

Figure 6: RSM and damaged model along with the locations of the damaged members and element number.

Damage detection using RSM

In the present work, damage identification strategy is applied on three damage cases to illustrate the applicability of the proposed technique for jacket structures. Three experimental tests were performed based on the exhibited scenarios in Figure 6. Damage identification results utilizing refined simplified FE model (RSM) and improved model reduction approach is shown in Figure 7 for case *B*.

As the first step, a without-iteration procedure is employed $(T = T^*)$ and also, the damage assessment utilizing only the three modes of the damaged model is checked. Shown in Figure 7 is the damage severity for case *B* when only the first three mode shapes of the damaged model are applied. Several members of the platform model as shown in Figure 7(a), are poorly estimated. In the next step, the iterative procedure is employed, T^* is always computed using the damaged model acquired from the previous

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iteration. So, employing the RSM and iterations develops the performance of the SIA process. Clearly, Member "9" of the refined simplified FE model represents the probable damage for members located on "*Zone* 3" of the damaged jacket platform (see Figure 6).
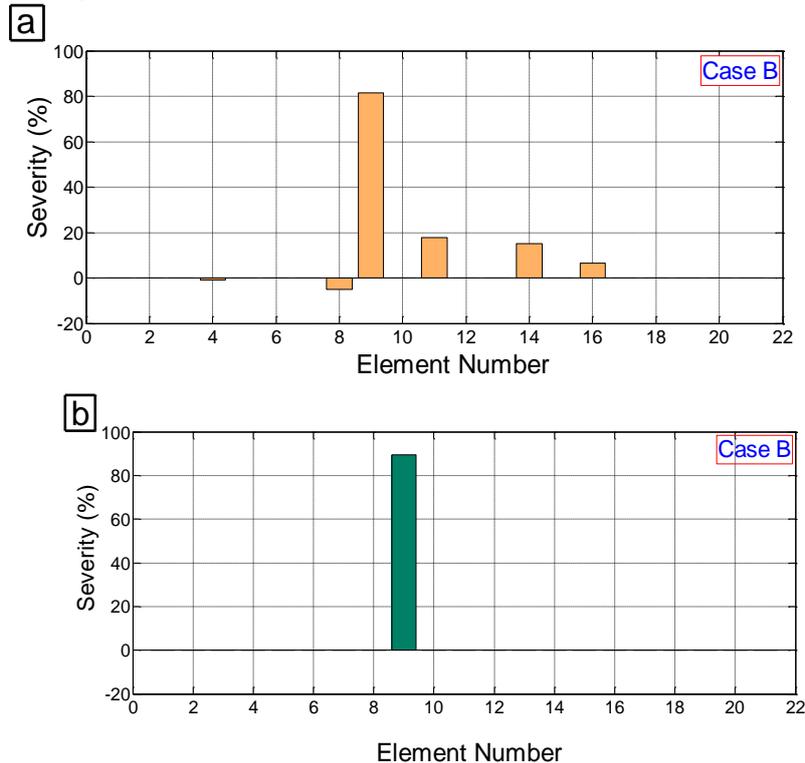

Figure 7: Damage detection results using RSM and improved model reduction approach: (a) without iteration (b) with iteration for case *B*.

Conclusions
This work develops a robust simplified method for SIM of offshore platform structures. Aiming at the restriction of the original CMCM method, which only uses baseline FE model; this study provides a useful damage diagnosis process by introducing a novel simplified methodology and successfully acquired damage indicator by using RSM. The first four natural frequencies which are acquired from the experimental modal analysis are 9.8, 45.3, 75.8 and 145 Hz, respectively, and after production of the RSM based on FRT and CI algorithm, the MAC factor to verify adjustment mode shapes obtained from RSM with mode shapes obtained from empirical model is also employed. In addition to elimination of uncertainty effects in the damage detection results, RSM technique is used due to practical considerations and also this technique provides a fast damage zone detection process. For the implementation of the proposed SIM technique, an improved reduction scheme (static reduction) is also applied to damage diagnosis procedure. This scheme removes the bad effect of model reduction process and prevents the appearance of spurious modes on the proposed SIA method. The findings of the study revealed that the proposed methodology is effective, practical and useful in the damage diagnosis of fixed offshore platforms.

List of Symbols

RSM	Refined Simplified Model
SIA	Structural integrity assessment
SIM	Structural integrity monitoring
CMCM	Cross model cross mode
FE	Finite element model
CI	Computational intelligence
DOF	Degrees of freedom

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