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Corrosion effects on structural behaviour of jacket type offshore structures

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Preliminary note

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The application of weight losses to investigate corrosion effects on structural behaviour of an offshore structure under wave loads is presented in this study. Weight losses of sections obtained during previous experimental studies are implemented in the model. The jacket type structural model is analysed in its intact and deteriorated forms to demonstrate corrosion effects. The ABAQUS finite elements program is utilized and the fluid structure interaction (FSI) technique is adopted when modelling the interaction between solid and fluid domains. Mode shapes, first three natural frequencies, displacements of selected points, and maximum stresses, are comparatively presented.

Key words:
ABAQUS, corrosion, finite elements, fluid structure interaction, offshore structures

Prethodno priopćenje

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Utjecaj korozije na izvanobalne konstrukcije

Ovaj rad obuhvaća primjenu gubitka masa kako bi se istražilo djelovanje korozije na ponašanje izvanobalnih konstrukcija pod utjecajem valova. Gubitci masa pojedinih dijelova koji su dobiveni iz prethodnih ispitivanja korišteni su u ovom modelu. Model rešetkaste konstrukcije analiziran je u ispravnom i u oštećenom stanju kako bi se pokazao utjecaj korozije. Pri analizi je korišten računalni program ABAQUS te metoda FSI (interakcija fluida i konstrukcije) koja prikazuje međudjelovanje konstrukcije s fluidom. U radu su uspoređeni modalni oblici, prve tri prirodne frekvencije, pomaci odabranih točaka i maksimalna naprezanja.

Ključne riječi:
ABAQUS, korozija, konačni elementi, interakcija fluida i konstrukcije, izvanobalne konstrukcije

Vorherige Mitteilung

Engin Gucuyen, R. Tugrul Erdem

Einfluss von Korrosion auf das Strukturverhalten von Offshorebauwerken

In dieser Arbeit wird durch die Anwendung von Massenverlust der Einfluss von Korrosion auf das Strukturverhalten von Offshorebauwerken unter Welleneinwirkungen untersucht. Im Model werden Massenverluste einzelner Elemente aufgrund vorheriger experimenteller Versuche angenommen. Die Gitterstruktur des Bauwerks ist in intaktem und in beschädigtem Zustand analysiert worden. Das Finite-Elemente-Programm ABAQUS ist angewandt und beim Modellieren ist die Fluid-Bauwerk-Interaktion berücksichtigt worden. Schwingungsformen, die ersten drei Eigenfrequenzen und maximale Spannungen sind zum Vergleich dargestellt.

Schlüsselwörter:
ABAQUS, Korrosion, finite Elemente, Fluid-Bauwerk-Interaktion, Offshorebauwerke

1. Introduction

Offshore jacket platforms have been extensively employed in the offshore oil and gas exploitation in complicated ocean environments. In addition to the traffic loads and environmental loads such as the wind, wave currents, and ice, offshore structures are subjected to other types of loads, including severe storms, corrosion, fire, explosions, etc., during their service life [1, 2]. Corrosion is an important strength degradation phenomenon that is widely encountered in offshore structures as a result of harsh environment. It is generally accounted for as a uniform corrosion wastage [3]. The corrosion in marine structures, which are generally made of various grades of steel and low alloy steel, is often very severe, not only under a sustained immersed condition, but also under general exposure to atmospheric conditions [4]. Classified according to different initiation mechanisms, the corrosion in metals assumes various forms: "uniform, pit, crevice, impact, cavity bubble, and galvanic couple corrosion" [5]. The most common forms are the uniform corrosion and pit corrosion. The uniform corrosion is caused by the complete exposure of metal surface to corrosive media, and it spreads at about the same rate in all parts [5]. When uniform corrosion occurs, the structural strength can be estimated relatively easily by deducting the weight loss per unit area from original values [6]. It should be noted that the loss of section, rather than the depth of pitting penetration, is important for the determination of structural strength [7].
Loads on offshore structures dominantly include environmental loads that can only be described by their statistical properties. Due to random changes in wind velocity and direction, the typical wave heights and periods also change randomly over time. However, these changes are sufficiently slow; the concept of sea state makes sense [8]. Only wave loads are adopted as environmental loads in this study. Wave forces acting on offshore structures dominantly contribute to total forces experienced by such structures, particularly in rough weather.
The studied models are composed of fluid and structure domains that interact with one another. When two or more physical systems interact, they become a coupled system. One example of a coupled system is the fluid-structure interaction (FSI), where a fluid and a structure are physical systems. The structure can be movable and/or deformable, and the fluid flow can be internal and/or external. Forces due to a moving fluid are applied as pressure on the structure, which will then be deformed. Coupling fluid dynamics and structure dynamics codes are difficult due to different domain discretization (fluid grids vs. FE-meshes) and different numerical approach for solving relevant equations. Numerical methods play an important role in predicting hydrodynamic motion and forces acting on offshore structures, and they are becoming increasingly interesting due to improvement of computational resources [9, 10].
A model similar to the one used in [11] is adopted in this study to determine the corrosion behaviour of offshore structures. The structure is modelled in two different conditions: intact and corroded, the objective being to compare corrosion defects on the structure. Both models are interacting with the offshore environment represented by the Linear Wave Theory. The Fluid Structure Interaction (FSI) technique is utilized to perform the analyses. Fluid domains and structure domains are modelled using the ABAQUS software for finite element modelling applications. Time histories of displacement of pick points, first three mode shapes, corresponding natural frequencies, and maximum stresses of mentioned models, are obtained according to wave loads, and are then compared to examine corrosion defects on offshore structures.

2. Material and method

The effect of external corrosion defects on structural behaviour of jacket type offshore structures is studied via a nonlinear numerical model based on the finite element method (FEM) using the ABAQUS analysis program [12]. Although 2D beam simplifications are generally implemented due to complexity of structures [13], the modelled structure is composed of 3D solid tubular members.
The structure adopted in the numerical study is an offshore platform 65 meters in height, and the sea depth is 55 m. The intact and corroded models are subjected to wave loads represented by the Linear Wave Theory. To model the corroded structure, the intact model is subjected to weight losses represented by pitting. The 10 % weight loss is applied by pitting the wall of members in the immersion zone according to [13]. The results obtained on small-scale specimens are generally considered to be directly applicable to full-scale structures. The reduction values are assumed to be 15 % for the splash zone, and 8 % for the atmospheric zone [14-16]. Displacements and stresses are obtained using the Explicit analysis. Modal analyses are carried out simultaneously to find natural frequencies. The finite element of the model is represented by the following matrices in Eqn (1).

$$[Ke]\{ue\}-\lambda[Me]\{ue\}=0 \tag{1}$$

where [Ke] and [Me] are the stiffness and mass matrices, {ue} is the generalized nodal displacement column, and λ is the square of natural frequency [17]. The Lanczos Method is utilized for solving matrices.

2.1. Fluid domain modelling

The fluid domain is modelled by the ABAQUS-CFD as shown in Figure 1. The dimensions of the domain are 45 x 55 x 45 m in directions x, y, and z, respectively. The fluid properties are chosen to represent the sea water, with the density of 1025 kg/m^3 and the dynamic viscosity of 0.0015 Ns/m^2.
The analysis is based on the boundary condition applied to fluid domain as fluid inlet velocities that represent the Linear Wave Theory, as given below [18].

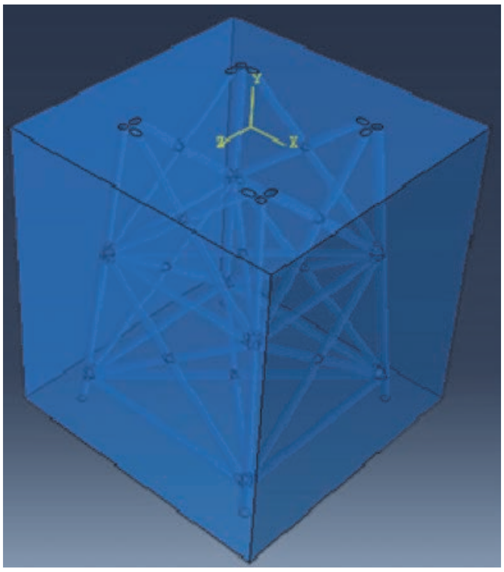

Figure 1. Fluid domain

$$\dot{u}_y = \frac{H}{2}\frac{gT}{L}\frac{\sinh(2\pi(y+d)/L)}{\cosh(2\pi d/L)}\sin\left(\frac{2\pi}{L}z - \frac{2\pi}{T}t\right) \tag{2}$$

$$\dot{u}_z = \frac{H}{2}\frac{gT}{L}\frac{\cosh(2\pi(y+d)/L)}{\cosh(2\pi d/L)}\cos\left(\frac{2\pi}{L}z - \frac{2\pi}{T}t\right) \tag{3}$$

Hydrodynamic wave forces acting on offshore structures are calculated using water particle velocities and accelerations in accordance with the wave theory determined by the wave height (H) and period (T), and the water depth in the zone where the structure is deployed (d). The water depth, wave period, and wave height, are three essential wave parameters that must be considered in the design of any offshore facilities [19]. It should be noted that the response of the seabed and its influence on the structure is neglected in this study when analysing the response of the structure to water waves [20]. Parameters taken into account in this paper are H = 2.5 m, T = 8 s and d = 55 m. The Linear Wave Theory is determined for these parameters and used in the analysis.

2.2. Structure domain modelling

In this study, the model similar to the one cited in literature [11] is evaluated to examine the effect of corrosion on structural behaviour of offshore structures using the same model, as presented in Figure 2. The structure is modelled under assumption that it is fixed to sea bed, as shown in Figure 2. Main dimensions on its top are 26 m × 26 m, while dimensions on the base are 36 m × 36 m. For convenience, the structure is modelled using the steel having the Young's modulus of $2.1 \cdot 10^{11}$ N/m^2. The Poisson's ratio is assumed to be 0.3, and the density value is 7850 kg/m^3.

The intact model, its joint, and the same joint for the deteriorated model, are given in Figure 2. The type of pitting corrosion is adjusted to the deteriorated structure of the model. Random pits are distributed along the structure to achieve the weight loss ratios of 10 %, 15 %, and 8 % in the immersion, splash, and atmospheric zones, respectively. In order to determine geometric properties of the intact structure, properties similar to [11] are utilized. Legs of the deck and legs of the jacket are 1.50 m in diameter and 0.016 m in thickness, while horizontal and vertical bracings measure 1.50 m in diameter and 0.014 m in thickness. Plain bracings are 1.20 m in diameter and 0.012 m in thickness.

Non-structural masses are defined as concentrated masses, and they are symmetrically located at four corner nodes. The loads acting on the structure are: dead weight, vertical deck loads with the total resultant value of 48 x 10^5 kg, and environmental loads including wave loads in the global z direction. The structural configuration consists of a template structure with four main legs.

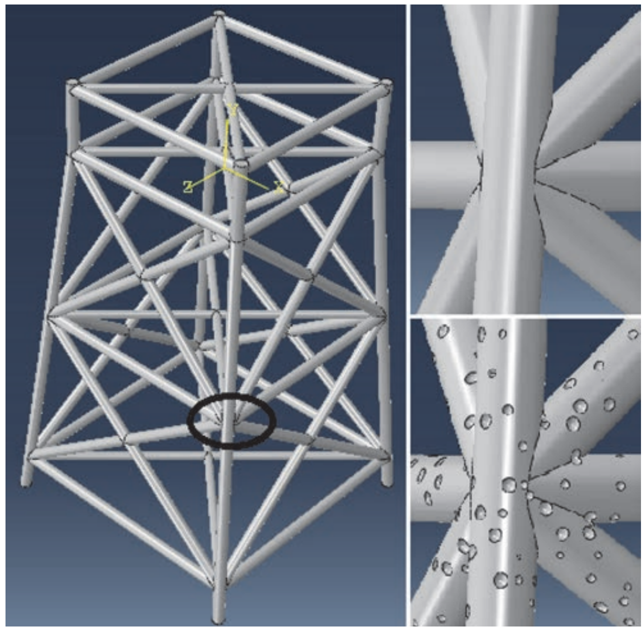

Figure 2. Joints of intact and deteriorated models

2.3. FSI Modelling

The FSI represents a class of multi-physics problems where the fluid flow affects compliant structures, which in turn affects the fluid flow. In the first step of the FSI, the problem is used to determine contact surfaces where the forces transfer from fluid to structure, and where deformations transfer from structure to fluid. Structural and fluid equations are solved independently. The finite elements program employs Eqn (4) as fluid solver [12].

$$k_f u_f = F_f(t) \tag{4}$$

Fluid forces that are transferred to structure are obtained by Eqn (4). In this equation u_f, given by Eqn (5), is calculated according to the pressure (p), velocity components ($\dot{u}_x$, $\dot{u}_y$, $\dot{u}_z$) and time (t).

$$u_f = \{p\ \dot{u}_x\ \dot{u}_y\ \dot{u}_z t\}^T \tag{5}$$

The equation of motion for structures, which is used by the finite elements program with regard to hydrodynamic forces, can be written as:

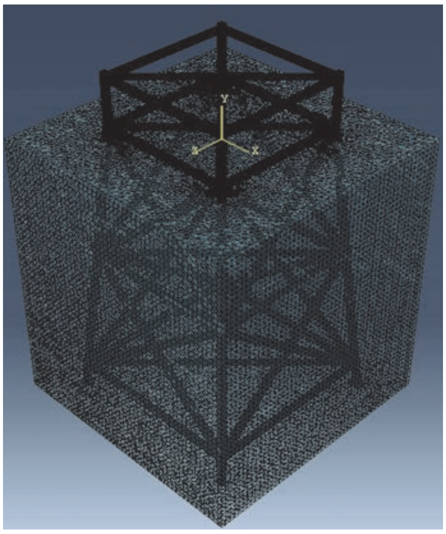

Figure 3. FSI model

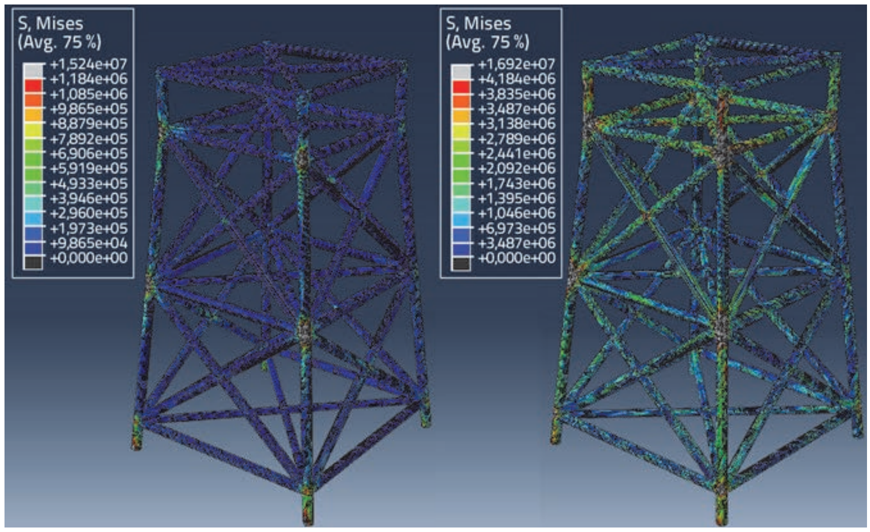

Figure 4. Stress distribution of intact and deteriorated models

$$m\ddot{u} + c\dot{u} + ku = F_f(t) \tag{6}$$

where m, c, k are the mass, stiffness and damping matrix, while u, $\dot{u}$ and $\ddot{u}$ represent displacement, velocity, and acceleration, respectively. The solutions from Eqn (6) produce displacements that will be transferred from structure to fluid. Interface loads and boundary conditions are exchanged after a converged increment. The FSI model is given in Figure 3.

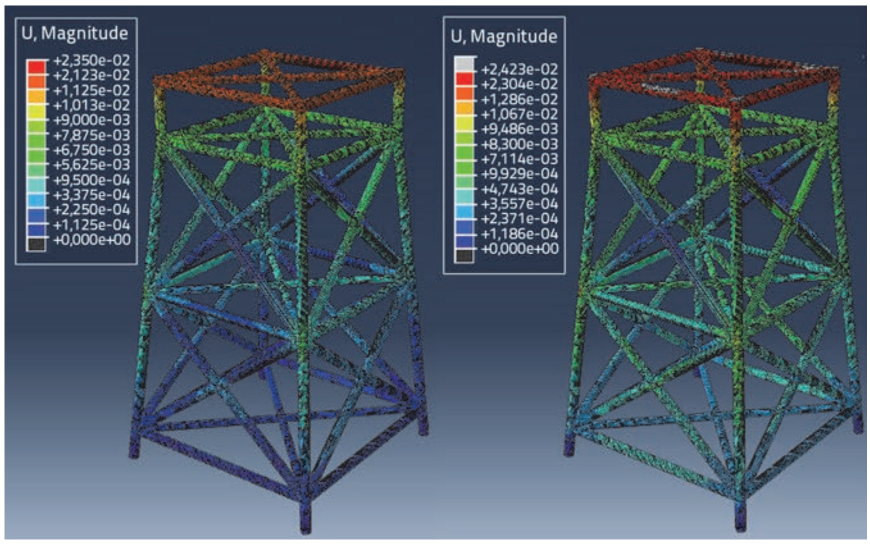

Figure 5. Displacement distribution of intact and deteriorated models

The fluid and structure domains interacting with each other are shown in Figure 3. This method is utilized for both intact and deteriorated models. The models are divided into small elements in the finite elements method so that complex models can be created and analysed. The 10-node modified tetrahedron elements (C3D10M), which are compatible with contact problems, are utilized in the model analyses. 232.423 nodes and 465.038 elements are derived for the intact model, while 247.989 nodes and 497590 elements are derived for the deteriorated model. The FC3D4 (4-node modified tetrahedron) type members that are suitable for FSI problems are used in the analyses for fluid domains. Fluid domains are made of 548.940 nodes and 3.176.250 elements for the fluid domain of intact model, and 561.914 nodes and 3.255.689 elements for the second model.

3. Numerical results

The jacket type model structure is analysed on two different models (with intact and deteriorated forms) to demonstrate the effect of corrosion on offshore structures. The ABAQUS finite element program is used in the analysis. Maximum stresses and displacements, first three mode shapes, and first three natural frequencies, are compared to examine corrosion defects on offshore structures, as shown in Figure 4.

Maximum Von-Misses stress values are $1.524 \cdot 10^7$ N/m^2 for the intact model, and $1.692 \cdot 10^7$ N/m^2 for the deteriorated model. It has been observed that stress values are getting higher in joint connections and supports for both models. The propagation of stress can be seen more clearly in deteriorated model when compared to the intact one. The displacement distribution of the models can be seen in Figure 5.

As expected, maximum displacement values are attained at the top of the structures. The displacement values of $2.350 \cdot 10^{-2}$ m and $2.518 \cdot 10^{-2}$ m are obtained at the pick points for the intact and corroded models, respectively. With regard to stress behaviour, displacement values of corroded model spread over

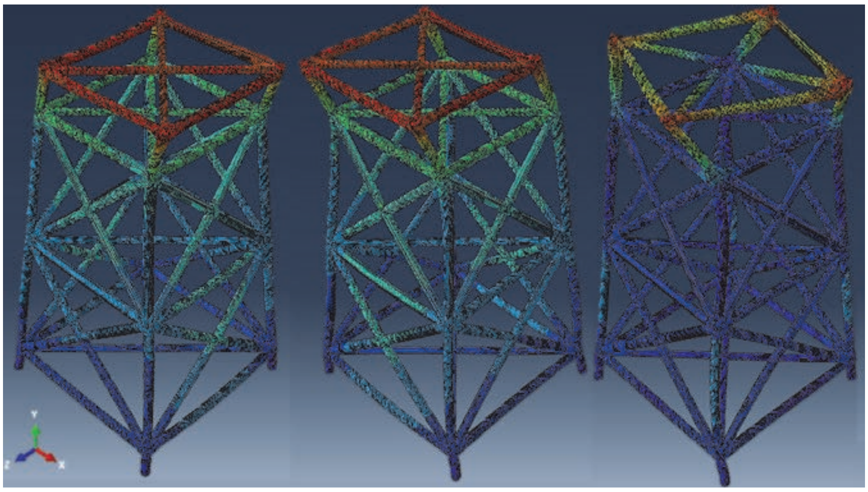

Figure 6. First three mode shapes of intact model

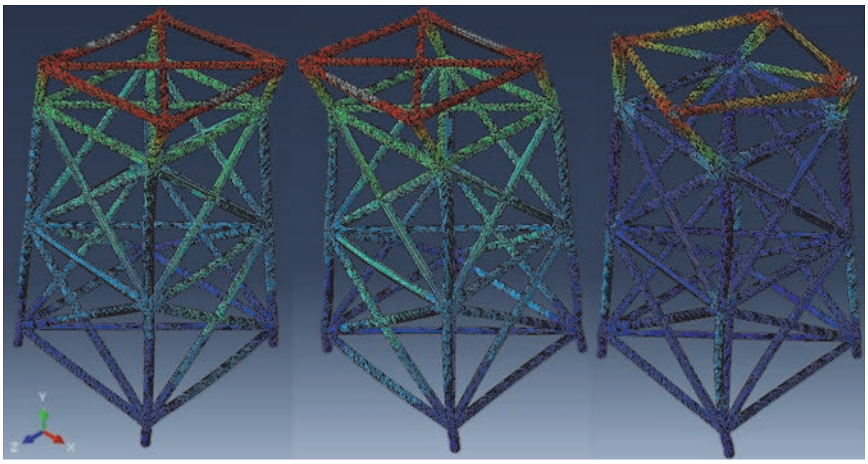

Figure 7. First three mode shapes of deteriorated model

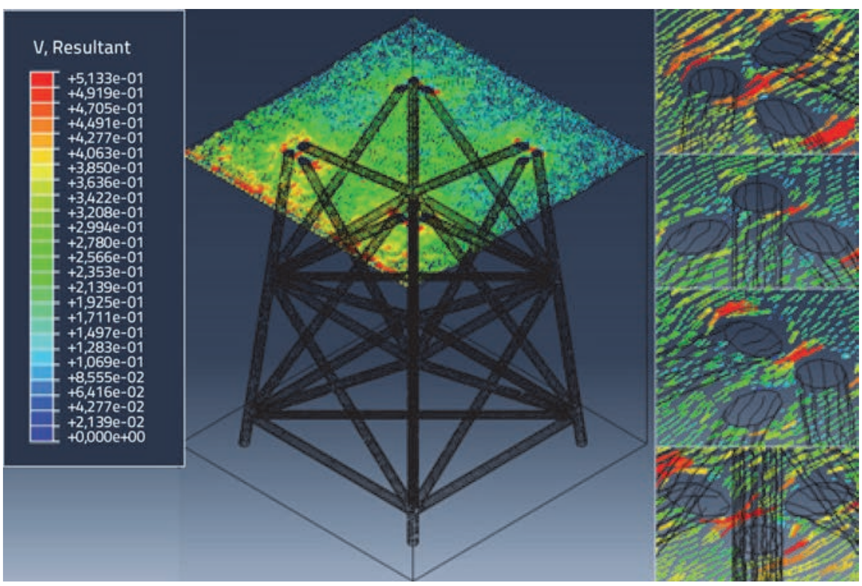

Figure 8. Velocity vectors around intact model

a greater area compared to the intact model.

As can be seen in Figure 6, first three mode shapes of the intact model are obtained by modal analysis using the ABAQUS finite element analysis program. Natural frequencies corresponding to the modes are 0.444 Hz, 0.446 Hz, and 0.517 Hz.

First three mode shapes of the deteriorated model are presented in Figure 7. Just like in the intact model, the first two nodes are bending modes, and the last one is the buckling mode. Natural frequencies corresponding to mode shapes are 0.471 Hz, 0.475 Hz, and 0.548 Hz.

Velocity vectors around the intact model are shown in Figure 8. A detailed presentation of vectors around the joint is given at a certain depth on the right side, starting clockwise from the top left joint. Wave forces transferred to the structure are calculated according to these velocities by the ABAQUS via the FSI.

4. Conclusions

The finite element program ABAQUS is utilized to define deterioration defects on the jacket-type offshore structures. In order to determine the defects, two types of the same model are studied: the intact model and the deteriorated model. Deteriorations are modelled as the pitting corrosion. It has been demonstrated in this study that corrosion deteriorations have a crucial effect on the structural behaviour of offshore structures.

From the perspective of displacements, the 6.67 % difference has been detected between the models. However, these values have been obtained under the Linear Wave Theory assumption; it is known that these values would be greater if other theories are used. The same situation has been observed according to Von Misses stresses. Greater values of Von Misses stresses have been obtained for the deteriorated model. The difference between the models is 11 % for the mentioned stresses. The maximum stress concentration occurs at the surf zone where the section attenuations increase. Horizontal bracings and joint connections on the main legs located in the surf zone are the most crucial members with regard to stresses. In the intact model, the displacement and stress distributions are uniform due to the absence of deterioration.

However, the same modal behaviour is observed between the models, where natural frequencies differ for each mode. Higher natural frequency values have been obtained for the deteriorated model due to weight losses caused by pitting. It is known that the natural frequency values that become closer to the external load frequency will cause resonance. This situation causes damage to the structure. It will be observed whether corrosion pitting causes such damage.

This study was conducted to examine structural behaviour of the mentioned models. Therefore the flow characteristics around structures were not studied, other than as shown in Figure 8. This study indicates that deteriorations due to corrosion cause structural imperfections. The stress behaviour is the most important parameter when the displacement, stress and natural frequency are compared, which is due to the fact that it causes fractions in accumulation zones. For this reason, these zones will be subjected to detailed analysis in future studies.

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