Received: *06.03.2022*
Accepted: 07.04.2022

A Comparative Study on Damaged Behavior of Offshore Jacket Structures

Engin GÜCÜYEN[1*], R. Tuğrul ERDEM[1]

[1]Manisa Celal Bayar University, Faculty of Engineering, Department of Civil Engineering, 45140, Manisa, Turkey

Abstract

In this study, the damage behaviour of the offshore jacket structures under environmental loads has been investigated. K-type and inverted K-type jacket structures have been used in order to compare the damage behaviours. A total of four structures such as one K-type, one inverted K-type and two damaged types of each one are modelled. Damage modelling has been performed in the form of a rupture in a leg. The examined models have 60 m height, three stories, cylindrical elements and they are angled-four-legged structures fixed to the seabed. Structures are affected by environmental forces including wind and wave effects as well as operational loads. The Eurocode velocity profile and the linear wave velocity profile have been used to calculate wind and wave forces, respectively. Abaqus finite elements software is utilized in the analyses. The force-displacement transfer between the structure and the marine environment has been performed by bidirectional fluid-structure interaction (FSI) analyses. In the bidirectional interaction analysis, modelling has been generated by CEL technique that is the combination of Eulerian-Lagrangian procedures. In this technique, the marine environment and the structure are created by Eularian and Lagrangian approaches respectively. In structural analysis, modal behaviours, frequencies, displacement and stress distributions for damaged and undamaged models have been obtained. The changes in the behaviour of different types of jacket structures have been investigated in the end.

Keywords**:** Coupled Eularian Lagrangian technique, offshore structures, damaged behaviour, environmental loads

Açık Deniz Kafes Sistem Yapıların Hasar Davranışları üzerine Karşılaştırmalı Çalışma

Özet

Bu çalışmada açık deniz kafes sistem yapılarının çevresel yükler altında hasar davranışları incelenmiştir. Hasar davranışlarının karşılaştırılması amacıyla K tipi ve ters K tipi kafes sistem yapılar çalışmada kullanılmıştır. Bir adet K tipi, bir adet ters K tipi model ve bunların hasarlı modelleri olmak üzere toplamda dört adet yapı modellenmiştir. Hasar modellemesi bir ayakta meydana gelen kopma şeklinde gerçekleştirilmiştir. İncelenen modeller 60 m yüksekliğinde, üç katlı, silindirik elemanlardan oluşan, açılı-dört ayaklı ve deniz tabanına sabitlenmiş yapılardır. Yapılar işletme yüklerinin yanında rüzgâr ve dalga yüklerini içeren çevresel kuvvetlerin etkisi altındadır. Eurocode hız profili ve Lineer dalga hız profili sırasıyla rüzgâr ve dalga kuvvetlerinin hesaplanmasında kullanılmıştır. Abaqus sonlu elemanlar yazılımı analizlerde kullanılmıştır. Yapı ve bulunduğu deniz ortamı arasındaki kuvvet deplasman aktarımı çift yönlü akışkan-yapı etkileşim (FSI) analizleri ile yapılmıştır. Modelleme, çift yönlü etkileşim analizinde Eulerian-Lagrangian yaklaşımlarının birleşimi (CEL) tekniği ile gerçekleştirilmiştir. Bu teknikte deniz ortamı Eulerian, yapı ise Lagrangian yaklaşımı ile modellenmiştir. Yapısal analizde ise hasarlı ve hasarsız modeller için modal davranışlar, frekanslar, deplasman ve gerilme dağılımları hesaplanmıştır. Sonuç olarak, farklı tipteki kafes sistem tipi yapıların hasar almaları durumunda davranışlarındaki değişimler ortaya çıkarılarak incelenmiştir.

Anahtar Kelimeler**:** Etkileşimli Eularian Lagrangian yöntemi, açık deniz yapıları, hasar davranışı, çevresel yükler

[*]*Corresponding Author,* e- mail: engin.gucuyen@cbu.edu.tr

1. **Introduction**

Today, with the developments in construction technologies, the construction of special structures has gained speed. Owing to the environment in which they serve, one of these types of structures that require sensitive work in modelling, assembly and use is offshore structures. These structures generally serve to meet fossil or renewable energy needs.

The structures fixed to the seabed consist of the platform on which the facility is located, the infrastructure carrying the platform and the foundation. While foundation in contact with the soil is effected by earthquake, infrastructure contacting with sea and air is effected by wave and wind. In addition, platform in contact with the air is under the effect of wind [1-3]. Infrastructure is most likely damaged due to its environment that is effected by wave, current and wind forces.

All unfavourable scenarios that may occur later during the construction phase should be taken into consideration, as they are difficult to access compared to those on land, adverse environmental conditions, and difficult assembly and disassembly. These negative scenarios can be listed as fatigue, corrosion, vessel impact, dropped object, design-fabrication-installation defaults and ice attacking cases [4, 5].

Damage scenarios can appear as member dents; reduce of section properties and removing primary members according to [6, 7]. Among these scenarios, removing members are utilized to model deterioration of four-legged jacket type offshore structures in the scope of this study. Some of the studies in the literature about the damage to the structures used in the study are included in this paragraph. Ship impact performance of different offshore structures including; monopile, tripod and jacket is studied by [8]. This study investigates the maximum collision-force, the damage area, the biggest bending moment of piles located at the seabed. It is seen that the jacket yields the minimum collision-force, damage field and nacelle acceleration as well as the medium bending moment and steel consumption between the three. In the present work [9], it is aimed to suggest an effective repair action for potential damages including hole and dent damage in elements and crack development and punching brace in joints. For this purpose, fifteen jacket platforms with different damages cases are modelled by Abaqus finite elements analysis software. Ultimate strength of damaged models and repaired ones are compared in the end. In this study [10], a reliability-based fracture mechanics approach is applied to perform fatigue reliability analysis of the welded tubular joints of jacket-type offshore wind turbine. The effects of corrosion, inspection and repair are taken into account. Fatigue damage of mentioned structures is studied by [11]. In their study, it is stated that the greatest damage is connected with the power production when the wind speed is slightly bigger than the rated wind speed at the hub. If the turbine is not in service wave loads become the reason of the fatigue damage under over speeded wind. Present structures are offers in offshore natural gas fields. Fire accidents because of the leakage of gas may end up with local damage and possible collapse of the structures [12]. Under the effect of vertical load, bearing capacity of the platform at high temperature is decreased in proportion to that at ambient temperature.

Fluid-structure interaction technique is widely used in determining the dynamic responses of structures subjected to environmental loads. Fluid-structure interaction analyses are classified as unidirectional and bidirectional. Bidirectional analysis is performed when the force is transferred from the fluid and the displacement is transferred from the structure. In both types, finite element method is the most widely used procedure. Finite element based fluid-structure interaction analyses are generated by Eularian approach [13], by Lagrange approach [14] or by both approaches Arbitrary Lagragian Eulerian (ALE) [15, 16] and by combination of Eulerian-Lagrangian techniques (Coupled Eulerian Lagrangian-CEL) [17, 18]. One of the finite element software used in interaction modelling is Abaqus [19]. In ALE and CEL analyses, the structure is modelled with Lagrangian and the fluid is modelled with Eulerian approaches.

In this study, CEL technique through Abaqus is utilized to model damaged-undamaged structures and their environment. Damaged and undamaged structures are exposed to the same environmental forces. Thus, damage conditions of K and inverted K type lattice systems have been investigated comparatively.

2. Materials and Method

Four models have been generated with damaged and undamaged cases of the two different type structures. K type structure modelled by Lagrangian technique and marine environment modelled by Eularin technique are seen in Figure 1.

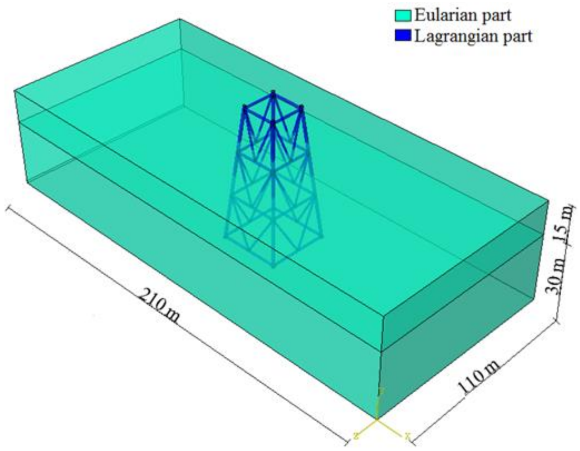

Figure 1. Structural model and environment

2.1. Structures under Consideration

In this study, three storey K and inverted K typed jacket structures with a constant story height of 20 m are modelled. Base dimensions of the structures are 27 m x 27 m. On the other hand, upper part dimensions are 15 m x 15 m. Dimensions of the Eularian part are seen in the Fig.1. While the carrier legs have a diameter of 1.20 m and a wall thickness of 0.012 m, other members have a diameter of 1.00 m and a wall thickness of 0.010 m. Nonstructural masses with 1.50×10^5 kg are distributed to the four sides on the upper part of the systems as lumped masses. The structures are modelled by using the steel material having the Young's modulus of 2.1 x1011 N/m^2, the Poisson's ratio of 0.3, and the density of 7850 kg/m^3. Finite element models of the structures are presented in Figure 2.

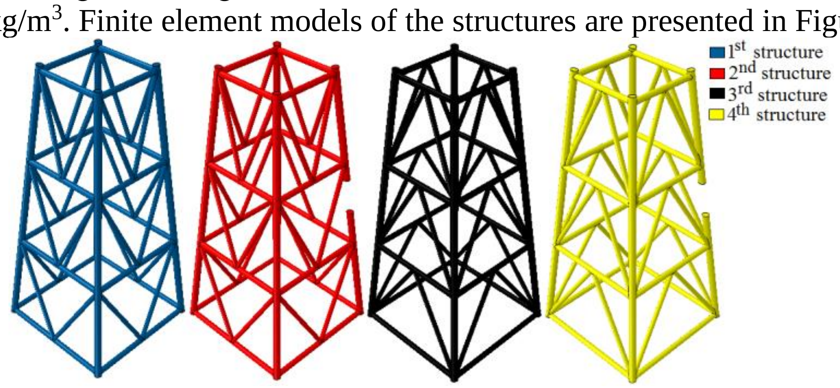

Figure 2. Structural models

As seen in the figure, the first structure is undamaged K typed, the second structure is damaged K typed, the third structure is undamaged inverted K typed, and the fourth structure is damaged inverted K typed models.

2.2. Environment under Consideration

Structures are under the effect of hydrodynamic wave and static wind forces due to their environment. Hydrodynamic forces can be calculated according to wave velocity (u) and acceleration (ú).

$$u = \frac{H}{2}\frac{gT}{L_w}\frac{\cosh[2\pi(z+d)/L_w]}{\cosh(2\pi d/L_w)}\cos\left(\frac{2\pi}{L_w}x - \frac{2\pi}{T}t\right) \tag{1}$$

The velocity value given by (Eq. 1) is calculated according to the wave theory that is determined according to the wave height (H), the wave period (T) and the water depth (d) where the structure is located. In this paper these parameters are adopted as follows, d=30 m, T=8 s and H=1.50 m. Value of the wave height (L_w) in the equation is calculated as 99.92 m according to Linear Wave Theory. Wave velocity is defined as input velocity in the numerical analysis. Sea water is identified as EOS material with the density of 1025 kg/m^3, dynamic viscosity of 1.50×10^{-3} Ns/m^2. Velocity of sound in sea water is 1560 m/s.

Wind force (F_a) which is the other environmental load effecting the structure is determined by (Eq.2) according to Eurocode velocity profile (u_a).

$$F_a = \int_{h}^{L-h} \frac{1}{2}\rho_a u^2_{a(y)} C_s A_{(y)}\, dy \tag{2}$$

In (Eq.2); A represents the cross sectional area of the member, ρ_a represents the mass density of air and C_s symbolizes the shape coefficient of the member that is 0.50 for cylindrical sections [20]. 222003 N and 145349 N are applied as wind load to third and the forth stories respectively.

3. CEL Based FSI Analysis

In this section, bidirectional fluid structure interaction analysis is generated according to CEL procedure via Abaqus. Abaqus uses following conservation of mass, momentum and energy equations for Lagrangian approach.

$$\frac{D\rho}{Dt} + \rho\nabla\cdot v = 0 \tag{3}$$

$$\rho\frac{Dv}{Dt} = \nabla\cdot\sigma + \rho b \tag{4}$$

$$\frac{\mathrm{De}}{\mathrm{Dt}} = \sigma : \mathrm{D} \tag{5}$$

In the equations, v, ρ, σ b and e stands for material velocity, density, Cauchy stress, the body force, and internal energy per unit volume respectively. Equations of conservation evaluated for Lagrangian approach are re-evaluated for Eularian approach by (Eq. 6) and thus (Eq.7) is obtained in general form.

$$\frac{D\varphi}{Dt} = \frac{\partial \varphi}{\partial t} + v \cdot (\nabla \varphi) \tag{6}$$

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot \Phi = S \tag{7}$$

In the equations, φ , Φ and S are randomly assigned solution variable, flux function and the source term respectively. Explanation of CEL technique is given more detailed by [21, 22]. Structures and the environments are created according to above mathematical definitions by Abaqus. Modelling steps are described as follows. Eulerian section is comprised of material assigned and unassigned (void) sections. Boundary conditions as well as structural mesh models are presented Figures 3-4.

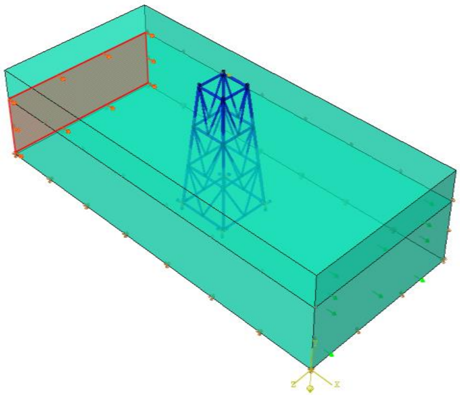

Figure 3. Boundary conditions

Figure 4. Mesh configurations of the Eularian-Lagrangian sections

In Figure 3, bottom of the Eularian section is defined as impermeable wall, the surfaces on the long side are defined as the far field, and the surfaces on the short side are defined as the inlet and outlet. (Eq.1) is utilized as inlet velocity. So, corresponding parameters as inlet surface are implemented to far fields. Mesh configuration of the finite elements model is seen in Figure 4. A 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains elements (S4R) are utilized in Lagrangian section. In addition, an 8-node linear eulerian brick, reduced integration, hourglass control elements (EC3D8R) are used in Eulerian section. Node distance in Lagrangian section is 0.01 m. In Eulerian section, this value is taken as 0.50 m. In this way, 10528593 nodes and 10451480 elements for the first structure and its environment, 10346032 nodes and 10190193 elements for the second structure and its environment, 9581020 nodes and 9534885 elements for the third structure and its environment, 9573715 nodes and 9506280 elements for the fourth structure and its environment have been constituted in the software.

The equation of motion which is utilized by the software under external forces (F) is presented below.

$$m^{NJ} \ddot{X}^{N} \big|_{t} = \left(F^{J} - I^{J} \right)\big|_{t} \tag{8}$$

In (Eq.8) m^{NJ} represents the mass matrix, F^J symbolizes the external applied load vector from Eulerian part, I^J symbolizes internal force vector generated by internal stresses of the members and it also represents the acceleration. I^J is determined from the single elements due to a global stiffness matrix which is not essential to be created. Coupled Eulerian-Lagrangian analyses are generated by the steps via Explicit integration rule presented by [19].

4. Results

Finite elements analyses are generated by 0.01 s time step and a total of 64 s which is the duration of eight wave period. Displacement values that change over time from maximum to minimum are obtained as second, fourth, first and third structures respectively. Maximum displacement values are presented in Table 1. Displacement values by time are shown in Figure 5.

Table 1. Analysis results

Structure	Max. displacement (m)	Max. stress (Pa)
1	0.713	1.291×10^7
2	0.965	1.676×10^7
3	0.664	1.175×10^7
4	0.851	1.421×10^7

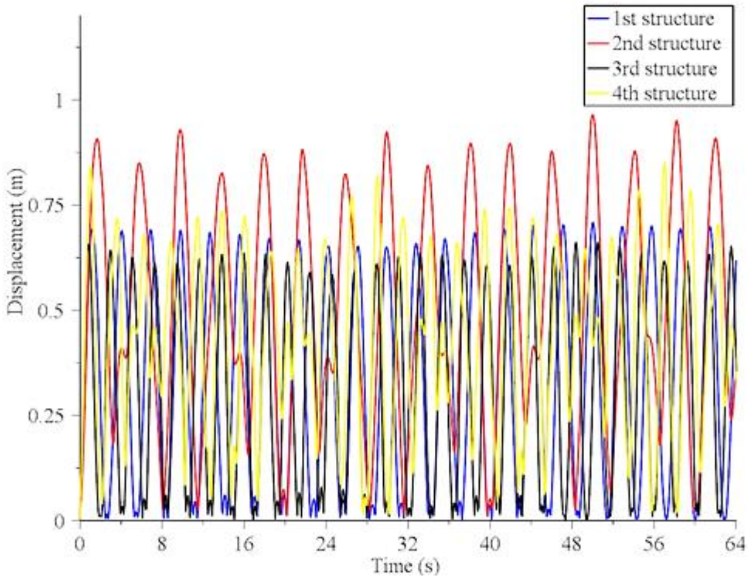

Figure 5. Time varying displacement values

Maximum Von-Mises stress values are also given in Table 1. According to the results, it is seen that maximum stress is obtained from the second structure. In addition to the stress and displacement values, the mode shapes of the structures and the related natural frequencies have been determined as well. Distributions of displacements and stresses with first mode shapes are comparatively presented for each structure between Figures 6-8.

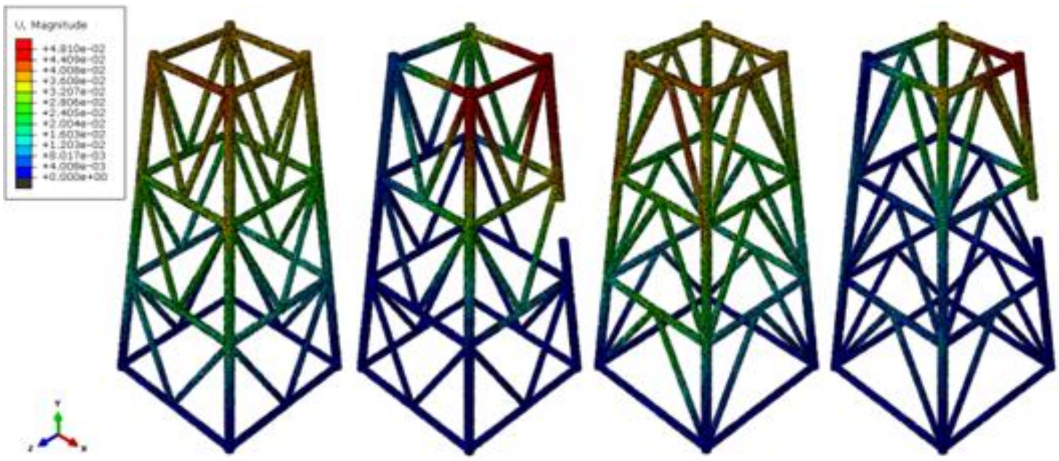

Figure 6. Displacement distributions of the structures

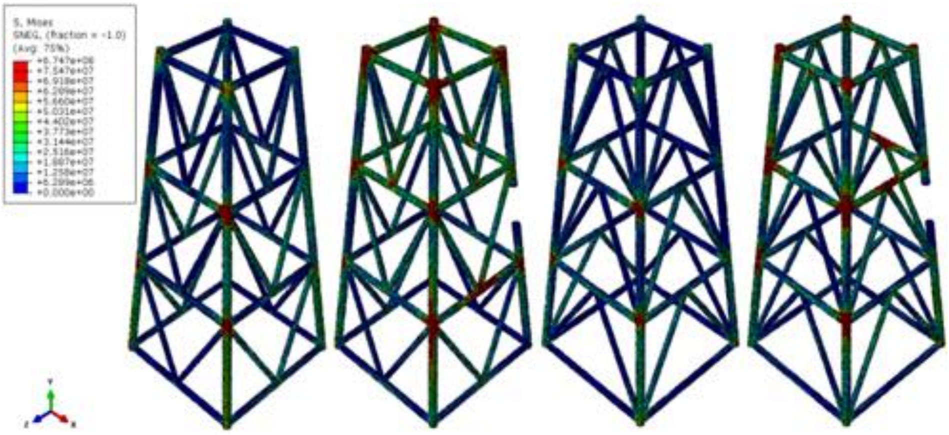

Figure 7. Stress distributions of the structures

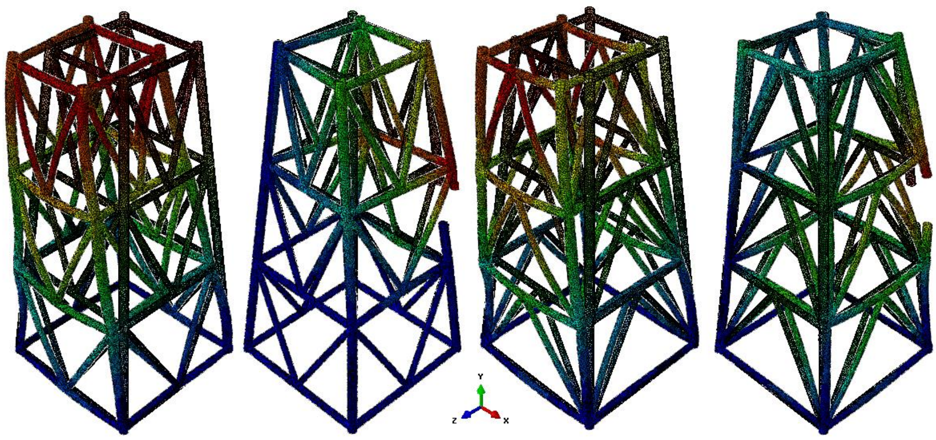

Figure 8. First mode shapes of the structures

First natural frequency values (ω_1) corresponding to mode shapes are given from first to fourth structures as follows, ω_1=2.895 rad/s, ω_1=1.004 rad/s, ω_1=3.199 rad/s, ω_1=1.879 rad/s. Flow environment surrounding the structure is also obtained as well as structural results. Structural displacement that changes by movement and free surface elevations of the wave are shown in Figure 9.

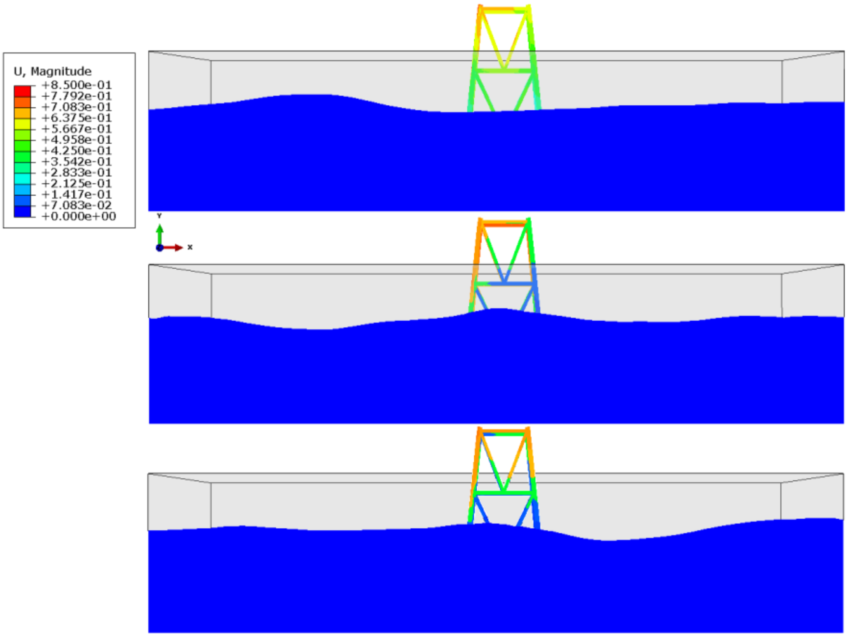

Figure 9. Coupled movement of fluid and structure

The effect of damage to the structural behaviour at a point in a certain leg has been examined through displacement, stress and mode shapes-natural frequency values. It has been determined that the damage has a significant effect on the outputs examined under environmental loads. The simulation of the wave force, which is the dominant force in offshore structures, is provided by using the CEL technique, which allows wave free surface modelling.

5. Conclusion

In this study, the effect of damage that may occur in the form of rupture in offshore jacket structures on the structural behaviour has been investigated on K-type and inverted K-type structures. It is comparatively presented in which structure type the rupture type damage becomes more effective.

When the structures are examined in terms of displacement, the displacement values reached the maximum in the damaged structures as expected. In the damaged second and fourth structures, a difference of 13.39% has occurred between the maximum displacements that has negative effects on the second structure. When the undamaged structures have been examined on the same output, there is a 7.379% difference between the first and third structures. When the structures of the same type have been investigated among themselves, there is a difference of 35.343% between the first and second structures and a difference is 28.162% between the third and fourth structures. It can be said that in terms of displacements that more negative situations may occur in the inverted K typed structure than the K typed structure.

When the maximum stresses are examined, it is obtained that the most unfavourable situation has emerged in the second structure. Thus, it can be said that the second structure is more sensitive to rupture type damages considering the displacement and stress values. As the displacement and stress distributions are investigated examined, it has been observed the values are diverged from the uniform distribution in case of damage. In addition, while the displacements are concentrated on the damaged feet, stresses are intensified on the undamaged feet.

Modal behaviour is determined over the first mode shapes of the structures. Besides, first natural frequency values have also been obtained from the software. Maximum value has occurred in the third structure having a structural undamaged inverted K typed modal.

As a result of the analysis, when all the outputs are examined, it has been observed that the damage in the form of rupture in one leg, which does not correspond to the wave movement, may cause negative results in the second structure (damaged K typed). It is anticipated that further studies on the subject will continue under different damage situations and locations.

6. References

[1] Asgarian B, Shokrgozar HR (2013). A new bracing system for improvement of seismic performance of steel jacket type offshore platforms with float-over deck. *Petroleum Science*, 10, 373–384.

[2] Gücüyen E, Yiğit ME, Erdem, RT, Gökkuş Ü (2020). Comparative analysis of tripod offshore structure. *Građevinar*, 72(11), 1021-1030.

[3] Gücüyen E, Erdem RT (2016). Açık deniz uzay kafes sistemin çevresel yükler altında akışkan-yapı etkileşimli analizi. *Dicle Üniversitesi Mühendislik Fakültesi Mühendislik Dergisi*, 7(3), 433-444.

[4] Zhu B, Sun C, Jahangiri V (2021). Characterizing and mitigating ice-induced vibration of monopile offshore wind turbines. *Ocean Engineering*, 219: 108406.

[5] Dehghania A, Aslani F (2019). A review on defects in steel offshore structures and developed strengthening techniques. *Structures*, 20, 635–657.

[6] Yang Y, Wu Q, He Z, Jia Z, Zhang X (2019). Seismic collapse performance of jacket offshore platforms with time-variant zonal corrosion model. *Applied Ocean Research*, 84, 268-278.

[7] Gücüyen E, Erdem RT (2014). Corrosion effects on structural behavior of jacket type offshore structures. *Građevinar*, 66(11), 981-986.

[8] Hao E, Liu C (2017). Evaluation and comparison of anti-impact performance to offshore wind turbine foundations: Monopile, tripod, and jacket. *Ocean Engineering* 130, 218–227.

[9] Mazaheri P, Asgarian B, Gholami H (2021). Assessment of strengthening, modification, and repair techniques for aging fixed offshore steel platforms. *Applied Ocean Research*, 110, 102612.

[10] Dong W, Moan T, Gao Z (2012). Fatigue reliability analysis of the jacket support structure for offshore wind turbine considering the effect of corrosion and inspection. *Reliability Engineering and System Safety* 106, 11–27.

[11] Ju SH, Su FC, Ke YP, Xie MH (2019). Fatigue design of offshore wind turbine jacket-type structures using a parallel scheme. *Renewable Energy*, 136, 69-78.

[12] Lin H, Luan H, Yang L, Han C, Karampour H, Chen G (2022). A safety assessment methodology for thermo-mechanical response of offshore jacket platform under fire. Process Safety and Environmental Protection, 160, 184-198.

[13] Martínez EL, Quiroga AG, Jardini AL, Filho RM (2009). Computational fluid dynamics simulation of the water – sugar cane bagasse suspension in pipe with internal static mixer. *Computer Aided Chemical Engineering*, 26, 683-688.

[14] Gücüyen E, Erdem RT, Gökkuş Ü (2016). FSI analysis of submarine outfall. *Brodogradnja/Shipbilding*, 67(2): 67-80.

[15] Korobenko A, Yan J, Gohari SMI, Sarkar S, Bazilevs Y (2017). FSI Simulation of two back-to-back wind turbines in atmospheric boundary layer flow. *Computers and Fluids*, 158, 167-175.

[16] Liu ZG, Liu Y, Lu J (2012). Numerical simulation of the fluid–structure interaction for an elastic cylinder subjected to tubular fluid flow. *Computers & Fluids*, 68, 192-202.

[17] Gücüyen E, Erdem RT (2019). Kompozit deniz yapısının dalga kuvvetleri altında incelenmesi. *DÜMF Mühendislik Dergisi* 10(3): 1125-1136. (In Turkish)

[18] Ji C, Cheng Y, Yang K, Oleg G (2017). Numerical and experimental investigation of hydrodynamic performance of a cylindrical dual pontoon-net floating breakwater. *Coastal Engineering*, 129, 1-16.
[19] Abaqus User's Manual, Version 6.12 (2015). Simulia, Dassault Systèmes Simulia Corp.
[20] Dyrbye C, Hansen SO (2004). *Wind loads on structures*, John Wiley & Sons, Ltd.
[21] Benson DJ, Okazawa S (2004). Contact in a multi-material Eulerian finite element formulation, *Computer Methods in Applied Mechanics and Engineering*, 193, 4277-4298.
[22] Reddy JN (2010). *Principles of continuum mechanics*, Cambridge University Press, New York, USA.