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Nonlinear response of fixed jacket offshore platform under structural and wave loads

Shehata E. Abdel Raheem *[1,2]

[1]*Taibah University, Medina, Saudi Arabia*
[2]*Civil Engineering Department, Faculty of Engineering, Assiut University, Egypt*

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Abstract. The structural design requirements of an offshore platform subjected to wave induced forces and moments in the jacket can play a major role in the design of the offshore structures. For an economic and reliable design; good estimation of wave loadings are essential. A nonlinear response analysis of a fixed offshore platform under structural and wave loading is presented, the structure is discretized using the finite element method, wave plus current kinematics (velocity and acceleration fields) are generated using 5th order Stokes wave theory, the wave force acting on the member is calculated using Morison's equation. Hydrodynamic loading on horizontal and vertical tubular members and the dynamic response of fixed offshore structure together with the distribution of displacement, axial force and bending moment along the leg are investigated for regular and extreme conditions, where the structure should keep production capability in conditions of the 1-yr return period wave and must be able to survive the 100-yr return period storm conditions. The result of the study shows that the nonlinear response investigation is quite crucial for safe design and operation of offshore platform.

Keywords: finite elements; fixed offshore platform; nonlinear response; wave-structure interaction

1. Introduction

The total number of offshore platform in various bays, gulf and oceans of the world is increasing year by year, most of which are of fixed jacket-type platforms located in 100 *ft* (32 *m*) to 650 *ft* (200 *m*) depth for oil and gas exploration purposes. The analysis, design and construction of offshore structures compatible with the extreme offshore environmental conditions is a most challenging and creative task. Over the usual conditions and situations met by land-based structures, offshore structures have the added complication of being placed in an ocean environment where hydrodynamic interaction effects and dynamic response become major considerations in their design (Haritos 2007). Offshore Jacket Platforms are normally designed using one of the following offshore design codes: API RP2A WSD (American Petroleum Institute 2000), API RP2A LRFD (American Petroleum Institute 1993) or ISO 19902 (International Standards Organization 2007). API RP2A-LRFD and ISO 19902 codes are limit state design based approaches for design of steel jacket platforms. Working Stress Design by American Petroleum Institute uses a common factor of safety for material. Static nonlinear analysis, i.e. pushover

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*Corresponding author, Associate Professor, E-mail: shehataraheem@yahoo.com

Institute uses a common factor of safety for material. Static nonlinear analysis, i.e. pushover analysis, is widely utilized in current offshore standards such as API, ISO and DNV (Det Norske Veritas 1977, 1999) to evaluate nonlinear behavior and ultimate capacity of offshore platforms against environmental wave loading. In this method, the jacket platform is subjected to the site specific design wave load, i.e., 100-yr wave and the corresponding load pattern is increased monotonically until the collapse of the structure is exhibited.

Dynamic analysis is particularly important for waves of moderate heights as they make the greatest contribution to fatigue damage of offshore structures. The dynamic response evaluation due to wave forces has significant roles on the reliable design of the offshore structure (Barltrop and Adams 1991, Hallam *et al.* 1978). In the design and analysis of fixed offshore structures many nonlinear physical quantities and mechanisms exist that are difficult to quantify and interpret in relation to hydrodynamic loading. The calculation of the wave loads on vertical tubular members is always of major concern to engineers. The analysis of wave effects on offshore structures, such as wave loads and corresponding responses, are of great importance to ocean engineers in the design, and for the operational safety of offshore structures, especially recently when such studies are motivated by the need to build solid marine structures in connection with oil and natural gas productions (Eicher *et al.* 2003). The effects of various wave patterns on offshore structure have been investigated by numerous researchers in the past (Chakarabarti and Tam 1975, Raman *et al.* 1977, Au and Brebbia 1983, Zhu 1993, Zhu and Moule 1994). The influence of hydrodynamic coefficients depends on the wave period and the variation is nonlinear between the different wave heights with the same wave period (Gücüyen 2012). Chandrasekaran *et al.* (2004) conducted a parametric study on the influence of hydrodynamic coefficients in the response behavior of triangular TLPs in regular waves. Gudmestad and Moe (1996) compared the API's and North Sea Design Practice approaches relevant to the selection of appropriate values for the coefficients used in the calculation of the hydrodynamic loads. Mendes *et al.* (2003) developed a numerical model for the prediction of combined wave-current loading. Others investigated the effect of the free surface fluctuations on the loading (Hahn 1995, Yang and Tung 1997).

In this study, nonlinear analysis is formulated for reliable evaluation of a fixed Jacket platform response due to structural and wave loads. A three dimensional finite element model (Abdel Raheem *et al.* 2012) is employed to determine displacements and stresses in a steel jacket under combined structural and wave loadings. The analysis considers various nonlinearities produced due to change in the nonlinear hydrodynamic drag force. The structure is discretized using the finite element method, wave plus current kinematics (velocity and acceleration fields) are generated using 5th order Stokes wave theory, and the wave force acting on the member is calculated using Morison's equation. Numerical results are presented for various combinations of typical sea states. Natural periods and corresponding mode shapes of the system are calculated. The nonlinear wave kinematics and the nonlinearity due to waves interacting with the structure is the most important factor. The wave induced loads on fixed offshore platform for Storm Sea states are governed by the nonlinear drag term of the Morison equation and variations in wave height. Moreover, the structural response of fixed jacket platforms subjected to extreme loads structures is a function of the behavior of their components in the nonlinear range of deformations. A parametric study of varying certain parameters of the wave and current loads such as current and/or wave incidence angle is conducted to study their effects on the internal forces distribution and platform displacement under various combinations of wave loading conditions.

2. Environmental loads

Water force can be classified as forces due to waves and forces due to current. Wind blowing over the ocean's surface drags water along with it, thus forming current and generating waves. The forces induce by ocean waves on platform are dynamic in nature. However, it is the accepted practice to design shallow water platforms by static approach. As a water depth increases and platforms become flexible, dynamic effect becomes significant.

2.1 Waves and hydrodynamic loads

Regular wave theories used for calculation of wave forces on fixed offshore structures are based on the three parameters water depth (d), wave height (h) and wave period (T) as obtained from wave measurements adapted to different statistical models, Fig. 1. Wave plus current kinematics (velocity and acceleration fields) are generated using 5th order Stokes wave theory, the forces on individual structural elements are calculated using Morison equation, based on hydrodynamic drag and mass coefficients (C_d , C_m) and particle velocity and acceleration obtained by the 5th order Stokes wave theory. The hydrodynamic force vector is calculated in each degree of freedom. According to Morison's equation, the intensity of wave force per unit length on the structure is calculated. The response analysis is performed in time domain to solve the dynamic behavior of jacket platform as an integrated system using the iterative incremental Newmark's Beta approach. Stokes 5th order wave is defined by providing wave height and period in the input data with the wave type specified as Stokes in the Sap2000 options (Computers and Structures Inc. 1995).

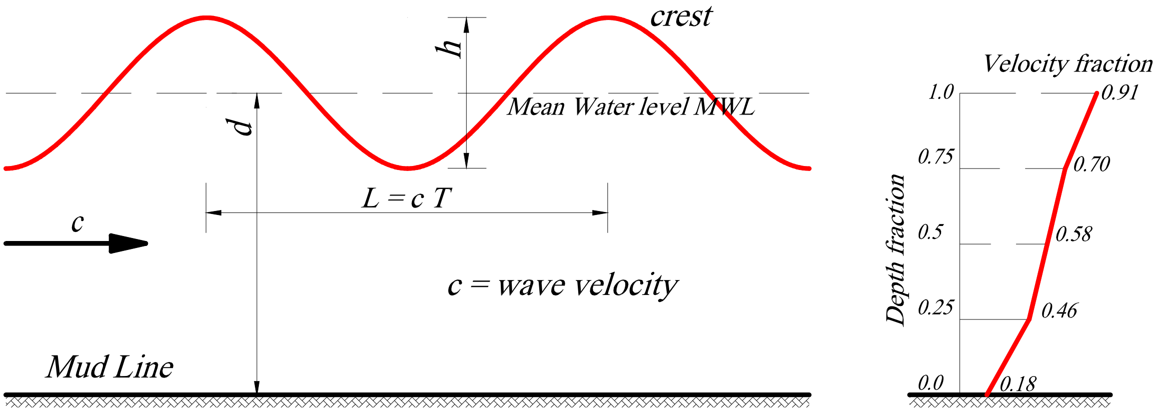


Fig. 1 wave coordinate system and typical wind and tidal current profile

2.2 *Current loads*

The wave induce an orbital motion in the water in which they travel, and these orbits are closed but experience a slight drift forward to wind surface effects. The current is actually induced by wave. A current in the wave direction tends to stretch the wavelength, typical wind and tidal current profile that shown in Fig. 1 is consider in this study (American Petroleum Institute 2000, Haritos 2007).

2.3 Wind loads

When a structure is placed in the path of the moving air so that wind is stopped or is deflected from its path, then all or part of the kinetic energy is transformed into the potential energy pressure. Wind forces on any structure therefore result from the differential pressure caused by the obstruction to the free flow of the wind. These forces are functions of the wind velocity, orientation, area, and shape of the structural elements. Wind forces on a structure are a dynamic problem, but for design purposes, it is sufficient to consider these forces as an equivalent static pressure.

3. Jacket platform structural model

The studied platform is a fixed Jacket-Type platform currently installed in the Suez gulf, Red sea, 1988 shown in Fig. 2, The offshore structure is a four legs jacket platform, consists of a steel tubular-space frame. There are diagonal brace members in both vertical and horizontal planes in the units to enhance the structural stiffness. The Platform was originally designed as a 4-pile platform installed in 110 feet (110' = 33.5 m) water depth. Standard Steel Material A36 was used platform jacket fabrication: density is 0.2836 lb/in^3; Young's modulus is 29×10^6 psi; Poisson's ratio is 0.30; shear modulus is 11.5×10^6 psi; yield strength is 36000 psi and ultimate tensile strength is 58000 psi.

4. Finite element analysis procedures

A finite element analysis is carried out under different types of wave loading. The structural model concentrates on the accurate description of load deformation characteristics of the legs. The legs are modeled by equivalent beam elements. For the present analysis, dead loads include all fixed items in the platform deck, jacket, and bridge structures. Live loads are defined as movable loads and will be temporary in nature. A uniformly distributed live load of intensity 50 psf "0.245 t/m^2" is applied to Helideck area; 200 psf "0.978 t/m^2" is applied to production deck area and cellar deck area. The water depth in the location of installed platform is 110' (33.5 *m*). Regarding to the information of waves height with the returning period of 1-yr for studied zone, a fifth order stokes wave theory with the height of 17 *ft* and the period of 6.5 sec used. A 100-yr return wave with the height of 26 *ft* and the period of 8 sec was selected for safety checks; contour for horizontal velocity for 100-yr return period wave storm conditions is shown in Fig. 3. The C_d and C_m values are considered as per API (2000) to be 0.65 and 1.6, respectively. The same values of wave parameters are applied in three directions ±0°, ±45° and ±90° (X, XY, and Y) with the associated current parameters having the same direction of wave application.

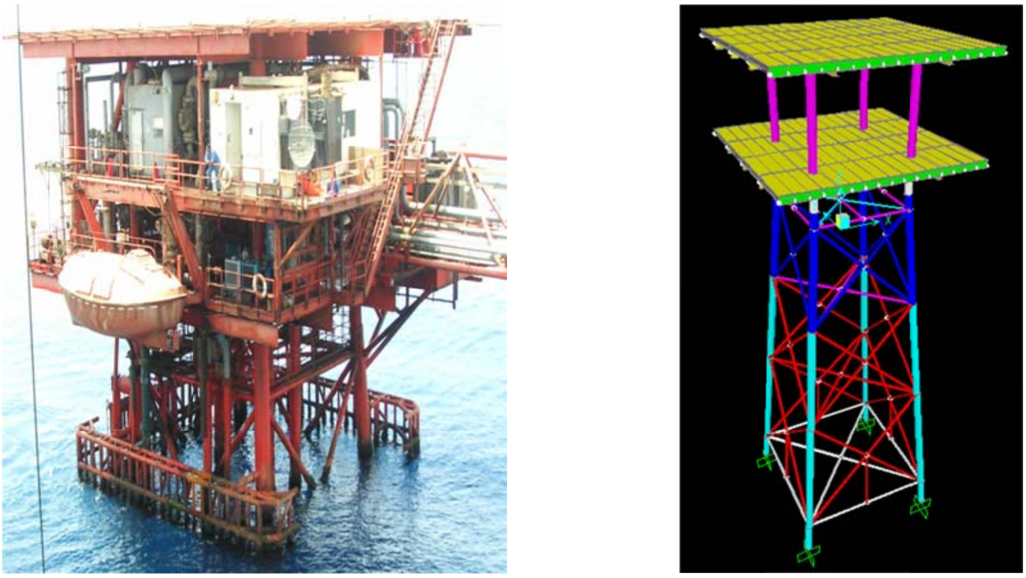


Fig. 2 Fixed steel offshore platform photo in site and finite element model based on as Built drawings

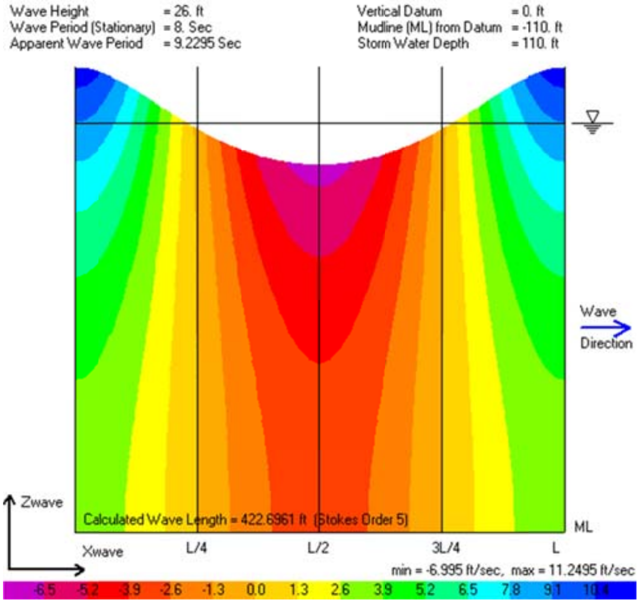


Fig. 3 Contour for horizontal velocity for 100-yr return period wave storm conditions

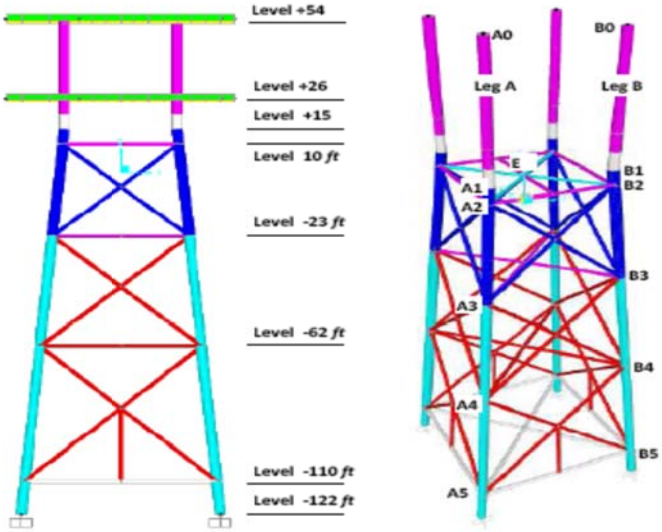


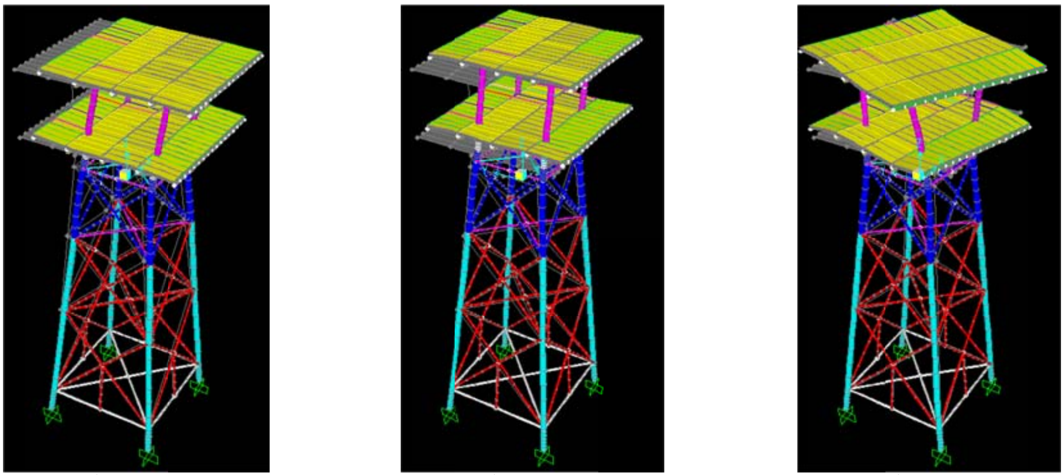
Fig. 4 Finite element model and selected nodes for measured responses

5. Numerical results and discussions

To provide a more accurate and effective design, a finite element model is employed herein to determine the internal forces and displacements in an offshore leg under combined structural and wave loadings. The vertical structural load is essentially a static load, while the lateral wave loading fluctuates in time domain and directly affected by the incident wave angle. The module in this study is classical steel platform was built in 1988 at Gulf of Suez in Egypt. A 3D finite element model had been generated for the platform based on as built drawings using SAP2000 computer software package (Computers and Structures Inc. 1995). Secondary members that are not expected to contribute much to the structure strength are not included in the model simulation (i.e. ladders, grating, etc.) but their loads were reflected to the model. The right hand Cartesian system is used with the Z-axis vertically upwards and the origin is located at the Mean Water Level (MWL), 3D beam element is used to model jacket legs, bracing, beam for heli-deck/main-deck, shell element is used to model the heli-deck/main-deck. The finite element model and selected nodes for measured responses are shown in Fig. 4. Fixed base boundary conditions are used at 10 *ft* below the mud line/seabed of pile length.

The natural periods and corresponding vibration mode shapes are computed by Eigen values analysis; the first three dominant vibration modes are shown in Fig. 5 and the natural period values and corresponding vibration mode for the first six vibration modes are listed in Table 1. The first and second modes are sway modes in y- and x- directions with slight different natural periods. The third mode is dominated by torsional vibration mode. While the higher modes from fourth to sixth modes are local vibration modes of bracing or couple higher order global sway model with local bracing vibration mode.

The nonlinearities considered is this study; cover the structure system geometrical nonlinearity (large displacement and P-Δ), material nonlinearity, wave nonlinear input. Effect of geometrical nonlinearity on structural response is compared to that using linear formulation, the geometrical nonlinearity effects on various response demands not exceed five percentage. However the material nonlinearity is checked, the structure system displays elastic behavior. The wave load calculations are based on the requirements presented in the American Petroleum Institute references. It generates loads on the structure resulting from waves, current flow, buoyancy and wind. Wave plus current kinematics (velocity and acceleration fields) are generated using 5th order Stokes wave theory. The horizontal components of the wave velocity and acceleration fields are multiplied by a wave kinematics factor that is intended to account for direction spreading and irregularity of the wave profile. The wave force acting on the member is calculated using Morison's equation. The size of a member used to calculate the wave load force is based on the section assignment, the specified marine growth.



1st Sway-Y 1st Sway-X 1st torsion

Fig. 5 First three global mode shapes of the steel fixed platform jacket model

Table 1 Natural period and vibration mode for the offshore platform

Modes	1st mode	2nd mode	3rd mode	4th mode	5th mode	6th mode
Period (sec)	0.622	0.616	0.472	0.253	0.252	0.251
Vibration mode	1st Sway-Y, global mode	1st Sway-X, global mode	1st Torsion, global mode	Horizontal bracing local mode	Vertical bracing local mode	2nd Sway-Y, global mode and vertical bracing local mode

Table 2 lists the wave loading parameter values for 1-yr return period wave for operating conditions and for 100-yr return period wave for safety conditions. The straining actions and deflection results are investigated for jacket only because the main important part in platform, which is subjected to all environmental load and high costs to install it. A parametric study of varying certain parameters of the wave, current loads to study their effects on the internal forces distribution and platform displacement under various combinations of structural and wave loadings is investigated, Table 3.

Table 2 Wave loading parameter values

Definitions	water depth ft	LAT ft	HAT ft	tide ft	$H_{max.}$ ft	T_p sec
1-yr return period wave for operating conditions	110'	-6'	6'	3'	17'	6.5
100-yr return period wave for safety conditions				5'	26'	8

Table 3 different load combinations

Load Combination	Description
Comb01	DL + LL "Reference case"
Comb02	DL + LL + (Wave + Wind) $_{1\text{-yr}}$+ Wave/Wind/Current incidence angle 00.0^{o}.
Comb03	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Current incidence angle 45.0^{o}.
Comb04	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Current incidence angle 90.0^{o}.
Comb05	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Current incidence angle 135.0^{o}.
Comb06	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Current incidence angle 180.0^{o}.
Comb07	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Wave/Wind/Current incidence angle 45.0^{o}.
Comb08	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Wave/Wind/Current incidence angle 90.0^{o}.
Comb09	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Wave/Wind/Current incidence angle 135.0^{o}.
Comb10	DL + LL + (Wave + Wind) $_{1\text{-yr}}$ + Wave/Wind/Current incidence angle 180.0^{o}.
Comb11	DL + LL + (Wave + Wind) $_{100\text{-yr}}$ + Wave/Wind/Current incidence angle 00.0^{o}.
Comb12	DL + LL + (Wave + Wind) $_{100\text{ - yr}}$ + Current incidence angle 45.0^{o}.
Comb13	DL + LL + (Wave + Wind) $_{100\text{ - yr}}$ + Current incidence angle 90.0^{o}.
Comb14	DL + LL + (Wave + Wind) $_{100\text{- yr}}$ + Current incidence angle135.0^{o}.
Comb15	DL + LL + (Wave + Wind) $_{100\text{- yr}}$ + Current incidence angle 180.0^{o}.
Comb16	DL + LL + (Wave + Wind) $_{100\text{ - yr}}$ + Wave/Wind/Current incidence angle 45.0^{o}.
Comb17	DL + LL + (Wave + Wind) $_{100\text{ - yr}}$ + Wave/Wind/Current incidence angle 90.0^{o}.
Comb18	DL + LL + (Wave + Wind) $_{100\text{- yr}}$ + Wave/Wind/Current incidence angle135.0^{o}.
Comb19	DL + LL + (Wave + Wind) $_{100\text{- yr}}$ + Wave/Wind/Current incidence angle 180.0^{o}.

5.1 Displacement response of the structure

To have a better understanding of the behavior over the entire height of the platform jacket, the analysis was conducted for a 110 *ft* water depth for the maximum wind and wave forces. Although time series deflections of the platform were estimated, only the maximum deflections to each wave and wind forces are extracted. The deflection responses U_1, U_2 and U_{abshz} (absolute horizontal displacement is calculate as square root of the summation of square of U_1 and U_2) along the platform jacket height to the wave loading of 1-yr and 100-yr return period conditions are shown in Figs. 6 and 7, respectively. It should be noted that the responses considered are the deflections U_1 and U_2 in global X- and Y- directions, respectively.

The jacket displacement U_1 is dominated by the first sway mode of vibration in wave direction and increases nonlinearly along the height of the platform jacket, while the deformation; U_2 dominated by second sway mode of vibration. For the 1-yr return period wave for operation conditions, the platform jacket displays maximum deflection demands for the coincidence of the wave; current and wind directions "***Comb02***" in the wave direction of 0.116 *ft* and 0.063 *ft* at platform heli-deck level (+54 *ft*) and jacket - deck connection level (+10 *ft*). The displacement responses decrease slightly as the current incidence angle deviate from the wave direction and this reduction reaches at maximum 14.5 % for current incidence angle of 180 degree "***Comb06***". While the wave incidence angle has significant effect on the displacement demands, this effect reaches 62 % reduction in the U_1 and U_{abshz} displacement responses "***Comb10***".

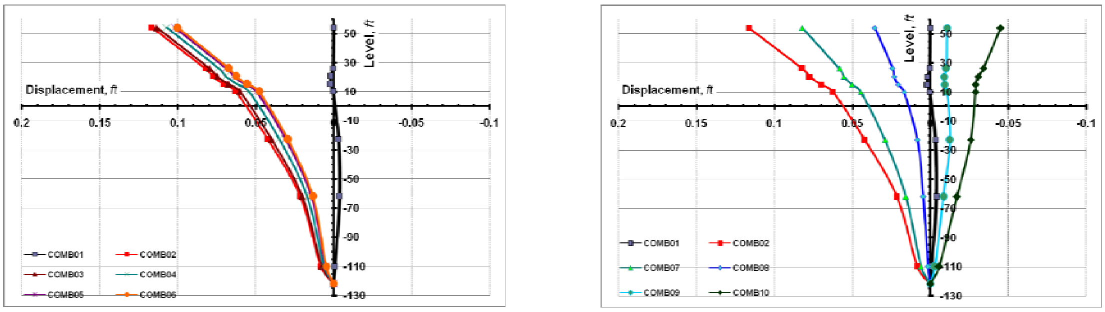
For the 100-yr return period wave for storm/extreme conditions, the platform jacket displays maximum deflection demands for the coincidence of the wave; current and wind directions "***Comb11***" in the wave direction of 0.165 *ft* and 0.109 *ft* at platform heli-deck level (+54 *ft*) and jacket - deck connection level (+10 *ft*). The displacement responses decrease slightly as the current incidence angle deviate from the wave direction and this reduction reaches at maximum 32 % for current incidence angle of 180 degree "***Comb15***". While the wave incidence angle has significant effect on the displacement demands, this effect reaches 57 % reduction in the U_1 and U_{abshz} displacement responses "***Comb19***".

For the current incidence angle 90 degree "***Comb04*** and ***Comb13***", the displacement response U_2 is significantly amplified, however it is effect on the absolute horizontal displacement is negligible due to its small value, while for the wave incidence angle 90 degree "***Comb08*** and ***Comb17***", the displacement response U_2 is significantly amplified and its contribution to the absolute horizontal displacement reach 50 % .

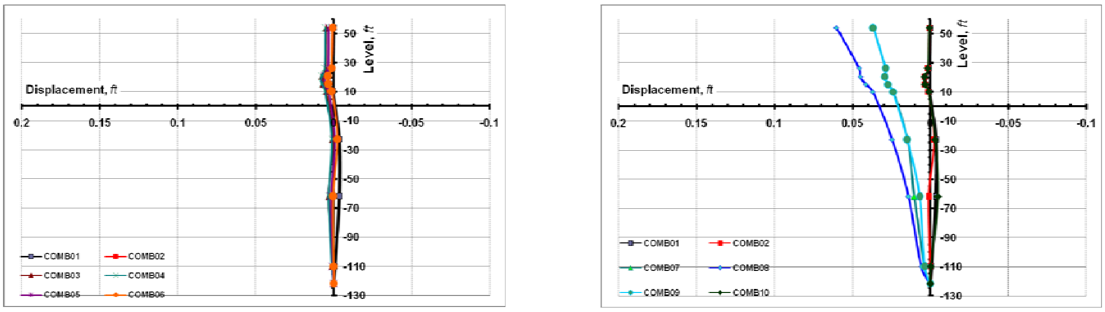
Large inter-story drift of the jacket leg is not allowed for the jacket platform to satisfy the drilling and production requirements. Both the maximum deck acceleration and the maximum deck to top of jacket displacement were important response parameters affecting the performance of equipment, vessels, and pipelines. On one hand, low maximum deck acceleration was desirable for the vessels and equipment, but on the other hand, a small deck-to-top of shaft displacement was desirable for the risers and caissons.

From analysis results, the displacement response is investigated for the critical nodes; node A_1 of jacket – deck connection level (+10 *ft*) and; node E of center of horizontal bracing at level (+10 *ft*) and node A_0 of jacket top (heli-deck level +54 *ft*). A comparison of the maximum displacement at all nodal points for various load combinations could indicate the current incidence angle; wave incidence angle and load conditions. Figs. 8 and 9 show the horizontal displacements at jacket-deck connection level and at jacket level (+10 ft) for different loads combinations. While the structural dead and live vertical loads are kept constant for all combinations, the upward force

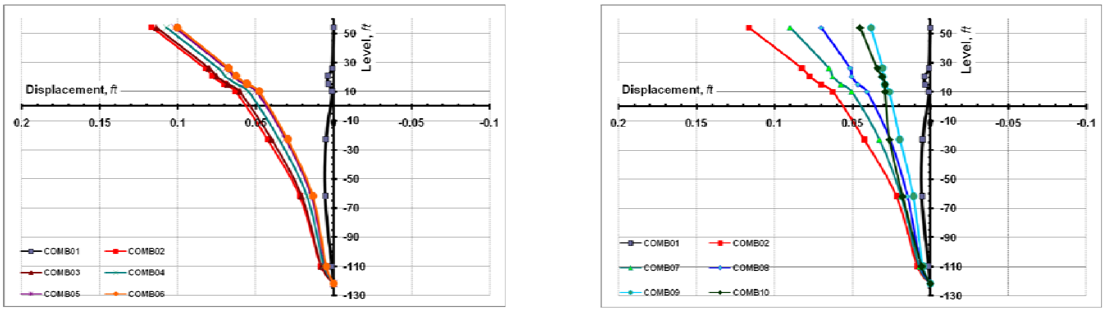
of buoyancy for 100-yr return period wave is greater than that of 1-yr return period wave, so the displacement (U_3 direction) of node E_2 (center intersection joint of horizontal bracing) much less for the 100-yr load combinations than for the 1-yr load combinations due to reduction of vertical force effect as resultant of buoyancy and structural forces. The results indicate that the current incidence direction has a slight effect on the horizontal displacement response, while the wave incidence direction plays a significant effects on the displacement response value and directions. The 100-yr return period wave display 42% and 73% higher displacement demands compared to that of 100-yr return period wave at node A_0 of jacket top (heli-deck level +54 *ft*) and node A_1 of jacket – deck connection level (+10 *ft*), respectively.



U_1 for Leg A



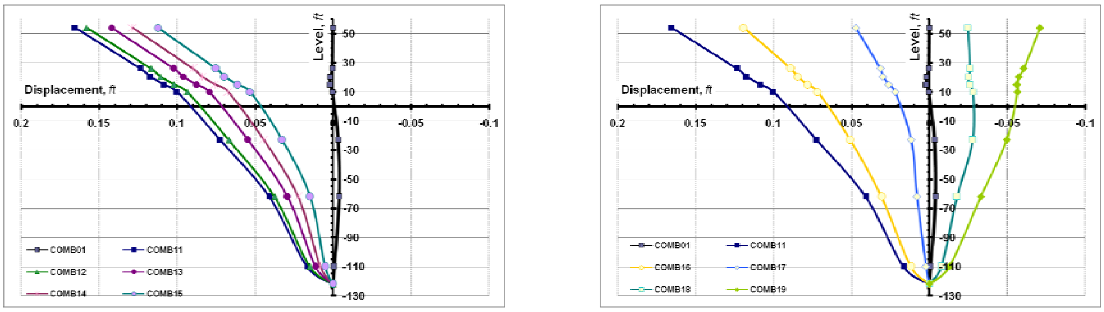
U_2 for Leg A



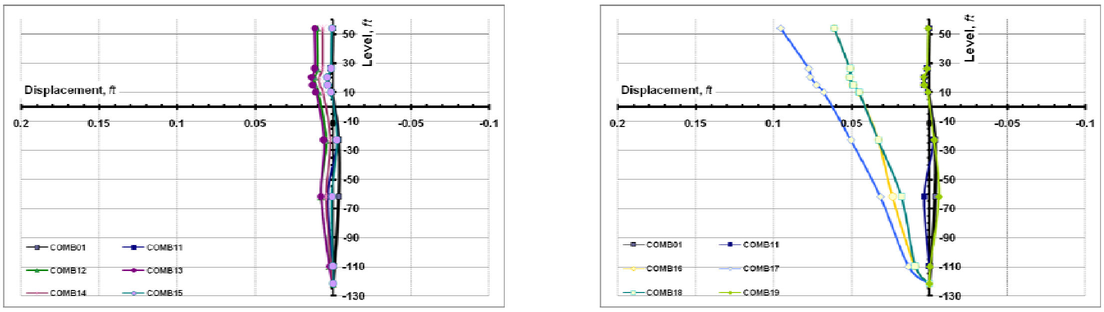
$U_{Abs\ hz}$ for Leg A

(a) Current Incidence angle effect (b) Wave, wind and current Incidence angle effect

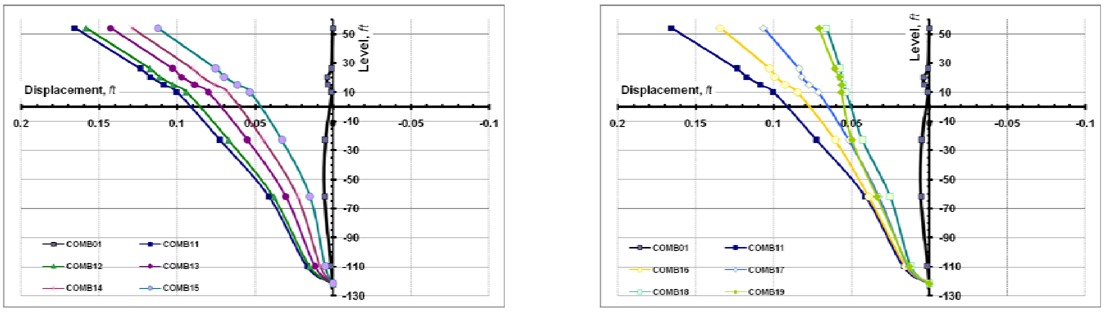
Fig. 6 Displacement with respect to jacket levels for 1-yr operating conditions



U_1 for Leg A



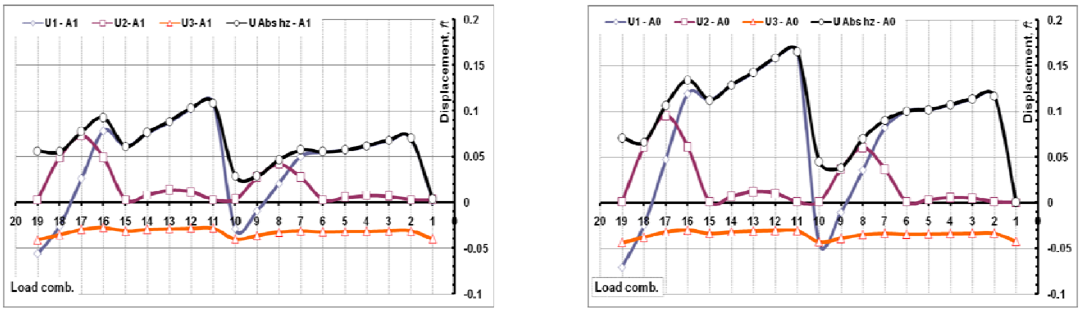
U_2 for Leg A



$U_{Abs\ hz}$ for Leg A

(a) Current Incidence angle effect (b) Wave, wind and current Incidence angle effect

Fig. 7 Displacement with respect to jacket levels for 100-year safety conditions



(a) Node A_1 (b) Node A_0

Fig. 8 The variation of displacements of jacket node A_1 and A_0

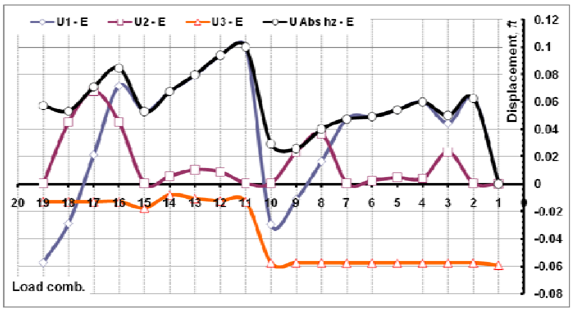
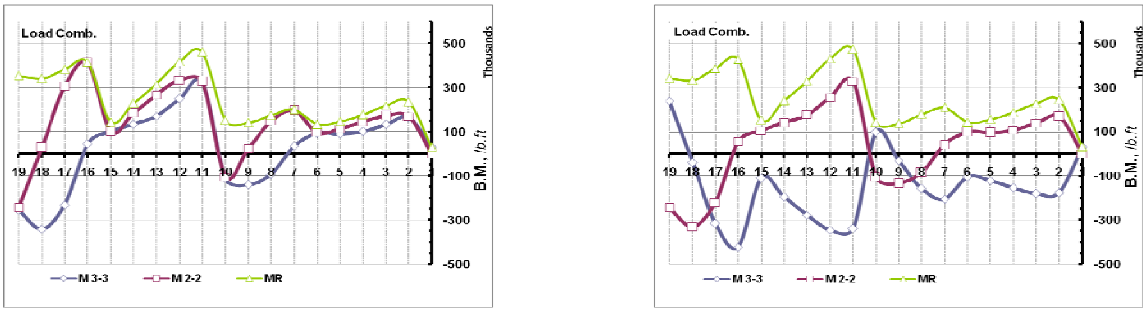


Fig. 9 Displacement variation of jacket center node E_2 at level (+10 ft)

5.2 Bending moment and axial force responses

Figs. 10 and 11 show a comparison of the maximum bending moments at critical levels along jacket leg. As the bending moment is generally concentrated at the connection points between the different structural systems, the biggest value can be expected to occur at the fixed base of the structure, however, the bending moment response at level (10 *ft*) displays comparable values and reach 235×10^3 *lb.ft* and 262×10^3 *lb.ft* for 1-yr and 100-yr return period wave conditions, respectively. The results indicate that the current/wave incidence direction has a slight effect on the bending moment demands for 1-yr return period wave (***Comb02 – Comb11***), while the current incidence direction plays a significant effects on the bending moment demands value and directions, reach 68% for incidence angle of 180 degree (***Comb11 – Comb15***). The 100-yr return period wave display 93% and 22% higher bending moment demands compared to that of 100-yr return period wave at fixed base of the jacket (level -122 *ft*) and of jacket – deck connection level (+10 *ft*), respectively. The effects of wave/current on forces demands decrease for the measured response at higher levels along jacket.

Fig. 12 shows a comparison of the maximum axial force at critical levels along jacket height. It is important in the design of platform leg to determine the location of maximum axial force because the jacket diameter wall thickness can be reduced below locations of maximum stresses.



(a) Fixed base boundary conditions

(b) Jacket – deck connection level (+10 *ft*)

Fig. 10 Bending moment response with load combinations

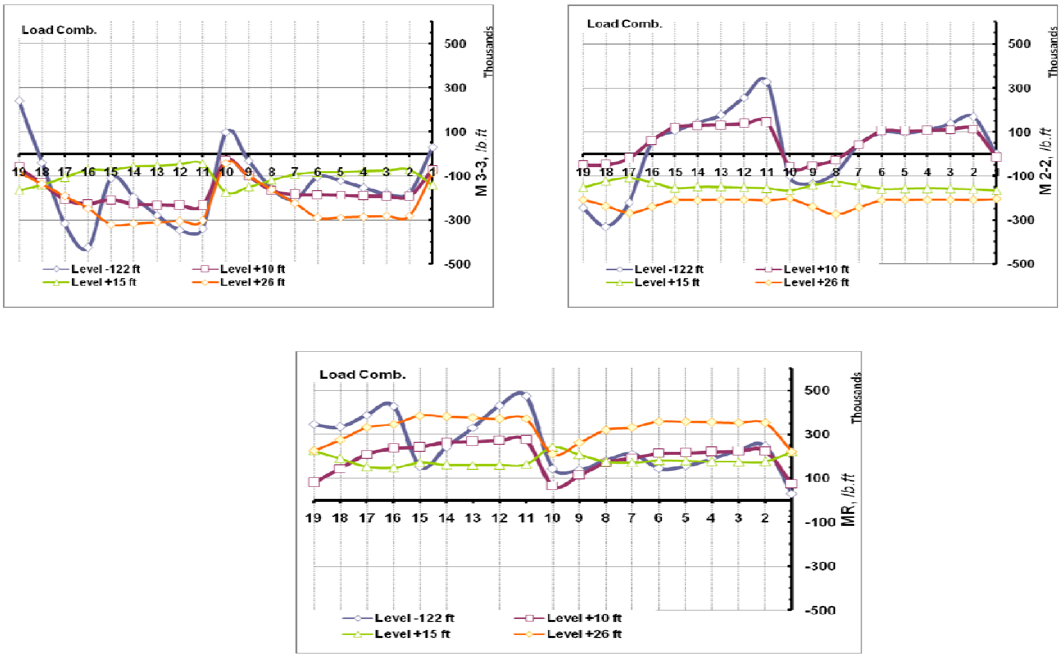


Fig. 11 Bending moment response with load combinations for different levels

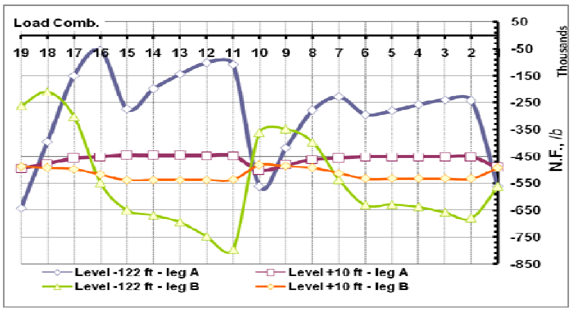


Fig. 12 Normal force response "N.F." with load combinations at different nodes

6. Conclusions

Safe and cost effective design of offshore platforms depends to a large extent on the correct assessment of response demands which is expected to be encountered by the structures during its life span. However, the functioning of the drilling operation takes place during fair weather window, the structure as a whole need to withstand extreme design conditions. The extreme design conditions are site specific. It is crucial to reduce the overall response of a jacket platform subjected to environment loads. In general, the reduction of dynamic stress amplitude of an offshore structure by 15% can extend the service life over two times, and can result in decreasing the expenditure on the maintenance and inspection of the structure.

The periodic inspection and monitoring of offshore platforms for certification needs the study of the responses of structures owing to wave and wind forces. A finite element formulation has been developed for the nonlinear response of a fixed offshore platform jacket. Where, three-dimensional beam element incorporating large displacement, time dependent wave forces is considered. The time dependent wave force has been considered as a drag component of the wave force, which is a function of second-order water particle velocity; hence the nonlinearity due to the wave force has been included.

The offshore structural analysis is used to obtain platform displacement response under varying external loadings. The deflection of the platform is studied for individual and combined wind and wave forces. Offshore platform jacket displacement, axial forces, bending moments, and natural modes and frequencies of free vibration are evaluated. A comparison of the maximum displacement at all nodal points for various wave and current incidence angles is introduced. The results indicate that the current incidence direction has a slight effect on the horizontal displacement response, while the wave incidence direction plays a significant effects on the displacement response value and directions. The displacement response, U_1 increases nonlinearly with the height of the platform jacket, but there is a significant curvature to the displacement response, U_2 along the platform height. The results indicate that the current/wave incidence direction has a slight effect on the bending moment demands for 1-yr return period wave, while the current incidence direction plays a significant effects on the bending moment demands value and directions. The 100-yr return period wave display 93% and 22% higher bending moment demands compared to that of 100-yr return period wave at fixed base of the jacket (level -122 *ft*) and of jacket – deck connection level (+10 *ft*), respectively. The effects of wave/current on forces demands decrease the measured response at higher levels. Large inter-story drift of the jacket leg is not allowed for the jacket platform to satisfy the drilling and production requirements. Both the maximum deck acceleration and the maximum Deck to top of jacket displacement were important response parameters affecting the performance of equipment, vessels, and pipelines. On one hand, low maximum deck acceleration was desirable for the vessels and equipment, but on the other hand, a small deck-to-top of shaft displacement was desirable for the risers and caissons. Nonlinear analysis is required for a realistic determination of the behavior of structures and to obtain an economical and rational structural design. The results of these investigations highlight the importance of accurately simulating nonlinear effects in fixed offshore structures from the point of view of safe design and operation of such systems.

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