# Nonlinear Analysis of Offshore Structures under Wave Loadings

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**SUMMARY:**

The structural design requirements of an offshore platform subjected 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 wave loading is presented, the structure is discretized using the finite element method, wave force is determined according to linearized Morison 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 one year return period wave and must be able to survive the 100 year 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: Offshore, Sea wave, Nonlinear Analysis, Finite Element Analysis, 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 30 m to 200 m depth for oil and gas exploration purposes. Fixed offshore platforms are subjected to different environmental loads during their lifetime. These loads are imposed on platforms through natural phenomena such as wind, current, wave, earthquake, snow and earth movement. Among various types of environmental loading, wave forces loading is dominated loads. According to API-RP2A 1997 (2.2) [1-3], environmental loads, with the exception of earthquake, should be combined in a manner consistent with the probability of their simultaneous occurrence during the loading condition being considered. In addition DNV 1980 (5.2.4) [4] suggests that loads due to earthquake normally need not be considered to act simultaneously with other environmental loads. It is necessary to design an offshore structure such that it can respond to moderate environmental loads without damage and is capable of resisting severe environmental loads without seriously endangering the occupants. The standard design of the structure is carried out using the allowable stress method. However, it is important to clarify the effects on nonlinear responses for an offshore structure under the severe wave conditions.

Offshore structures may be analyzed using static or dynamic analysis methods. Static analysis methods are sufficient for structures, which are rigid enough to neglect the dynamic forces associated with the motion under the time-dependent environmental loadings. On the other hand, structures which are flexible due to their particular form and which are to be used in deep sea must be checked for dynamic loads. Dynamic analysis is particularly important for waves of moderate heights as they make the greatest contribution to fatigue damage and reliability of offshore structures. The dynamic response evaluation due to wave forces has significant roles on the reliable design of the offshore structure [5].
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, especially recently when such studies are motivated by the need to build solid offshore structures in connection with oil and natural gas productions. The effects of various wave patterns on offshore structures have been investigated by numerous researchers in the past [6 - 17].

This research summarizes the nonlinear dynamic analysis of a 3-D model of a typical Jacket-Type platform, which is installed in Suez gulf, Red sea, 1988 and presents the numerical investigation on dynamic behaviour of an offshore structure under wave loads. Wave loading is applied to a full jacket structure by Stokes 5th order wave methods with gravity loads also present. The analysis considers various nonlinearities produced due to change in the nonlinear hydrodynamic drag force. The wave forces on the elements of the offshore structure are calculated using Airy's wave theory and Morison's equation. Numerical results are presented for various combinations of typical sea states. Natural periods and mode shapes of the system are calculated. 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.

## 2. DESIGN CODES OF PRACTICE

The majority of the world's platforms have been designed according to the different editions of Recommended Practice by The American Petroleum Institute (API), which until 1993 has been in Working Stress Design (WSD) format. The 20th edition (1993) was also issued in Load and Resistance Factor Design (LRFD) format, and was in 1997 supplemented with a section on re-qualification of offshore structures. American Petroleum Institute (API) RP2A-LRFD, 1993 provisions provide characterization of environmental load and design requirement for fixed offshore platform for use in design, describe analytical methods to determine the forces induced in the platform system by ground motions, and give guidance for sizing and configuring steel elements for the design forces. The consideration of environmental loads are consist earthquake loads in terms of earthquake ground motions, wind, wave and current loads. Design methods for structures, members or components under static loads to avoid failure, collapse, buckling are well defined in codes and standards, such equivalent codes in other countries, whilst for offshore structures the design code used almost invariably is API RP2A (API 1993).

## 3. SEA 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/or platforms become flexible, dynamic effect assume significance.

### 3.1. Waves and hydrodynamic loads

Several theories for the description of the shape and kinematics of regular waves exist. 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, **Figure 1**. Wave forces on individual structural elements can be calculated using Morison equation, based on hydrodynamic drag and mass coefficients ($C_d$, $C_m$) and particle velocity and acceleration obtained by the chosen wave theory. Water particle kinematic is evaluated using Airy's linear wave theory. This description assumes the waveform whose wave height; $h$ is small in comparison to its wavelength; $L$, and water depth; $d$. 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; **Figure 2**. 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. Stokes waves were applied as distributed loads to the submerged members of the offshore structure using normal offshore design procedures.

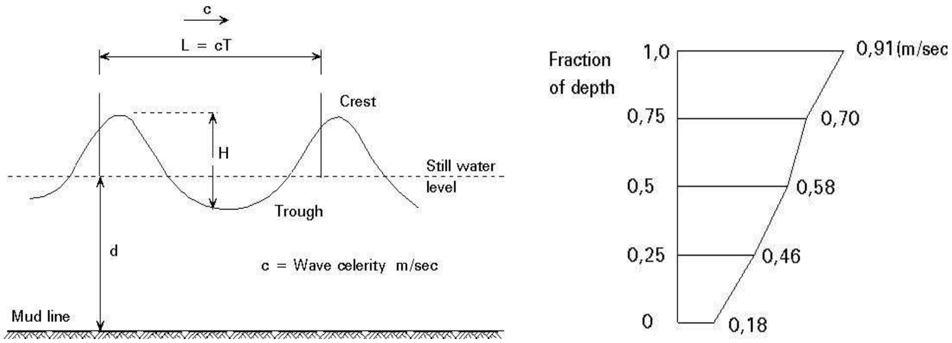


**Figure 1** wave co-ordinate system and typical "Wind and Tidal" Current Profile

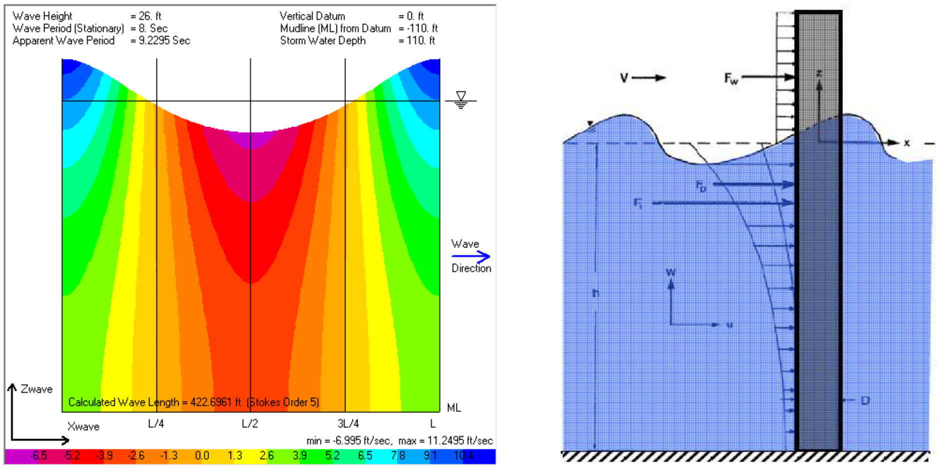

Wave Height = 26. ft
Wave Period (Stationary) = 8. Sec
Apparent Wave Period = 9.2295 Sec
Vertical Datum = 0. ft
Mudline (ML) from Datum = -110. ft
Storm Water Depth = 110. ft
Calculated Wave Length = 422.6961 ft (Stokes Order 5)
min = -6.995 ft/sec, max = 11.2495 ft/sec

**Fig. 2** 100 year return period wave for safety conditions and hydrodynamic wave loading

### 3.2. 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. (API Recommended practice 2A-LRFD)

### 3.3. Wind loads

Wind possesses kinetic energy. 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 are a dynamic problem, but for design purposes, it is sufficient to consider these forces as an equivalent static pressure.

## 4. JACKET PLATFORM STRUCTURAL MODEL

The studied platform is a fixed Jacket-Type platform currently installed in the Suez gulf, Red sea, 1988 shown in **Figure 3**, 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.

- The Top side structure consists of Helideck 50'x50' at ELevation, EL. (+54') & Production deck 50'x50' at EL. (+26'); Top of jacket at EL (+12.5').
- The Jacket consists of 4 legs with 33 inch Outer Diameter (33" O.D.) & 1 inch Wall Thickness (1"W.T.) between EL. (+10' ) and EL. (-23' ) and (33" O.D. x 0.5" W.T.) between EL. (-23' ) and EL. (-110' ).
- In the splash zone area that is assumed to extend from EL. (-6') to EL. (+6') LAT. (Lowest Astronomical Tide).
- The jacket legs are horizontally braced with tubular members (8.625" O.D. x 0.322" W.T.) at elevations (+10'); (10.75" O.D. x 0.365" W.T.) at elevations (-23'); (12.75" O.D. x 0.375" W.T.) at elevations (-62’) and (14" O.D. X 0.375" W.T.) at elevations (-110’).
- In the vertical direction, the jacket is X-braced with tubular members (12.75" O.D. x 0.844" W.T.) from EL. (+10') to EL. (-23’) and (12.75" O.D. x 0.375" W.T.) from EL. (-23’) to EL. (-110’). The platform is supported by 4 piles (30" O.D. x 1.25" W.T.).

**Figure 3** Sketch map of the platform model

## 5. ANALYSIS PROCEDURES

A finite element analysis is carried out under different types of wave loading. The hull of jack up is relatively stiff compared to legs, so the structural model concentrates on the accurate description of load deformation characteristics of the legs. The legs are modeled by equivalent beam elements. Focus has been on the underlying mechanisms of the global structural response. 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 intensity of 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 one year 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-years return wave with the height of 26 ft and the period of 8 sec was selected for the type of analysis that is normally used for safety checks. The wave force is expressed using the Morison equation and the nonlinear relative-velocity squared drag term is replaced by an equivalent linearized drag term.

The design force of most platforms is dominated by waves. A wave height of 1 or 100 years return period is the commonly used design criterion, which was extended by employing the combination of the 100-year wave with the 100-year wind. American Petroleum Institute (API RP 2A) recommends the following formula to calculate wind force on offshore structures, The 100 year return period sustained wind at 30 feet above LAT (lowest astronomical tide) shall be 70 mph (mile per hour), the wind may act in any direction. The variation of wind speed with height is taken as varying with height according to the power law.

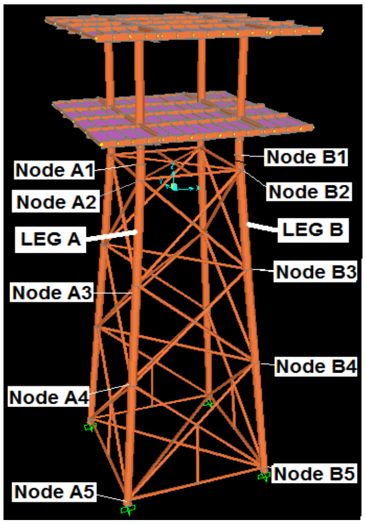


**Figure 4** Finite element model

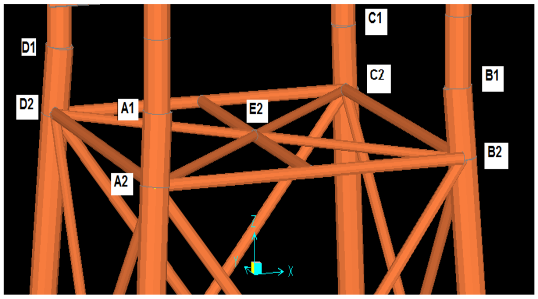


**Figure 5** Jacket - deck connection nodes at level (+10 ft)

$$V_Z = V_{30} \ (Z/30)^{X}$$

Where $V_Z$ = Velocity at height $Z$ feet (*ft/sec*); $V_{30}$ = Velocity at height 30 feet (*ft/sec*); Z is Height above LAT, (feet); $X = 0.125$; $V_Z$ shall not be less than V30. The wind loads on the topsides and exposed part of the jackets shall be calculated based on the topsides layout configurations to determine the shape coefficients.

## 6. NUMERICAL RESULTS AND DISCUSSIONS

The natural frequencies and vibration mode shapes are computed by eigenvalue analysis. The values of natural frequencies are shown in **Table 1** for up to the six mode of vibration. The stress distribution within such a large structure is a dominant factor in the design procedure of an offshore structure. 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 is directly affected by the incident wave angle. The module in this study is classical steel platform was built in 1988 at Gulf of Suez, Egypt, **Figure 3**. A 3D model had been generated for the platform using SAP 2000 computer software package. 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 Main water Level (MWL) as shown in **Figures. 4** and **5. Table 2** lists the properties of the studied. Different load combinations are applied to platform as shown in **Table 3**. The straining actions and deflection results are investigated for jacket only because the main important part in platform, which is supported under sea, water and 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. 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 ±$0^o$, ±$45^o$ and

±90$^o$ (X, XY, and Y) with the associated current parameters having the same direction of wave application, **Table 3**.

**Table 1** Natural period and vibration mode

| Modes | 1st mode | 2nd mode | 3rd mode | 4th mode | 5th mode | 6th mode |
|---|---|---|---|---|---|---|
| Natural period (sec) | 0.902 | 0.897 | 0.734 | 0.281 | 0.277 | 0.267 |
| Vibration mode | 1st Sway-X | 1st Sway-Y | 1st Torsion | 2nd Sway-X | 2nd Sway-Y | 2nd Torsion |

**Table 2** wave loading parameter values

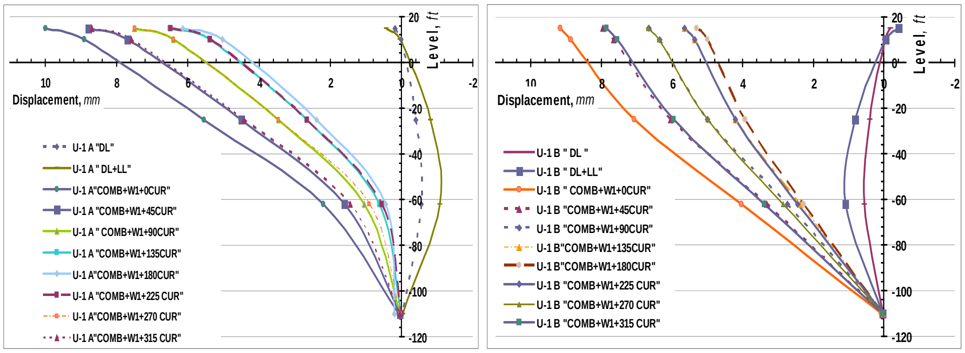
| Definitions | Water depth (MSL) ft | LAT (MSL) ft | HAT MSL) ft | tide (ft**)** | $H_{max.}$ (ft) | $T_p$ (sec) |
|---|---|---|---|---|---|---|
| 1-year return period wave for operating conditions | 110' | -6' | 6' | 3' | 17' | 6.5 |
| 100 year return period wave for safety conditions | | | | 5' | 26' | 8 |

**Table 3** different load combinations

| **Load combination** | **Description** |
|---|---|
| 1 | Dead Loads |
| 2 | Comb " Dead Load + Live load " |
| 3 | Comb+ ( Wind + wave ) $_{1\ year}$+ currents hitting 00.0 deg. |
| 4 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 45.0 deg. |
| 5 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 90.0 deg. |
| 6 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 135 deg. |
| 7 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 180 deg. |
| 8 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 225 deg. |
| 9 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 270 deg. |
| 10 | Comb+ ( Wind + wave ) $_{1\ year}$ + currents hitting 315 deg. |
| 11 | Comb+ ( Wind + wave ) $_{100\ year}$ + currents hitting 00.0 deg. |
| 12 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 45.0 deg. |
| 13 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 90.0 deg. |
| 14 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 135 deg. |
| 15 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 180 deg. |
| 16 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 225 deg. |
| 17 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 270 deg. |
| 18 | Comb+ ( Wind + wave ) $_{1\ 00year}$ + currents hitting 315 deg. |

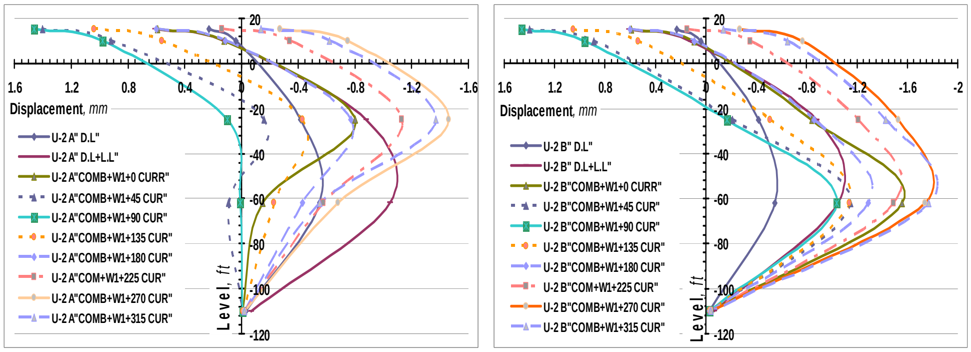
## 6.1. Displacement response of the structure

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. Even though time series deflection of the platform were estimated, only maximum deflection to each wave and wind forces are extracted. The deflection responses along the platform jacket height to the wave loading of 1 year and 100 year return period are shown in **Figures 6 and 7**. It should be noted that the response considered are deflection in global X- direction; $U_1$ and Y-direction; $U_2$. **Figure 6** shows the platform deflections; $U_1$ dominated by the first sway mode of vibration in wave direction; **Figure 6 (a, b)** and **Figure 7 (a, b),** while the deformation; U2 dominated by second sway mode of vibration as shown in **Figure 6 (c, d)** and **Figure 7 (c, d).** The maximum platform deflection in the wave direction is 1.0 *cm* and 1.8 *cm* at jacket – deck level for 1 year and 100 year return period wave and wind loadings, respectively. The displacement responses attain its peak values for the coincidence of the wave; current and wind directions, decrease as the current direction deviate from that from the wave incidence direction as shown in **Figures 6 and 7**. 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.



(a) U$_1$ for Leg A

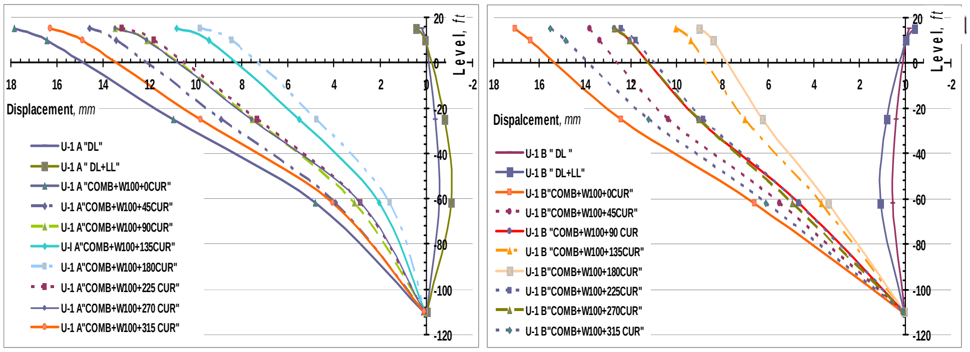
(b) U$_1$ for Leg B



(c) U$_2$ for Leg A

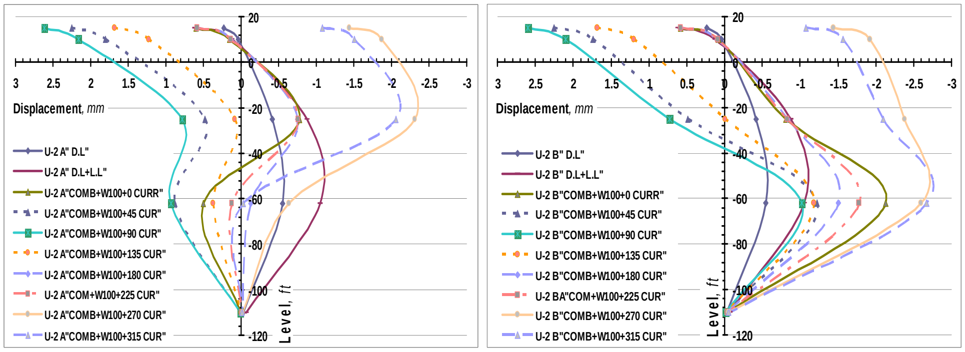
(d) U$_2$ for Leg B

**Figure 6** Displacement with respect to jacket levels for 1-year operating conditions.



(a) U$_1$ for Leg A

(b) U$_1$ for Leg B

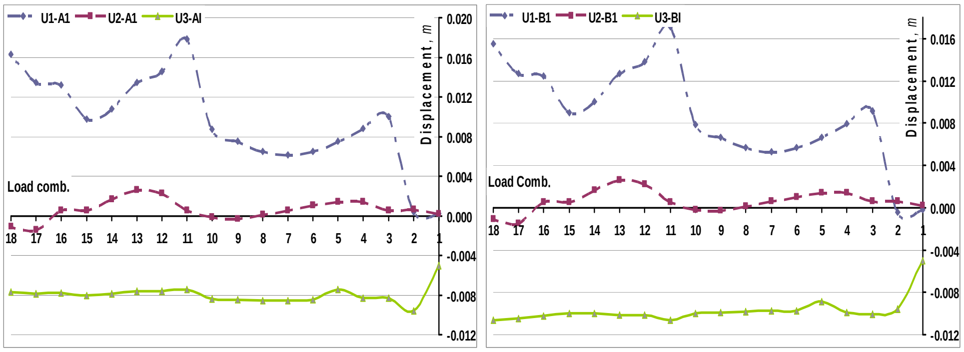


(c) U$_2$ for Leg A

(d) U$_2$ for Leg B

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

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, it can be observed that the critical nodes for displacement responses are at jacket - deck connection and at jacket level (+10 ft). A comparison of the maximum displacement at all nodal points for various current incidence angles is introduced. **Figures 8 and 9** show the horizontal displacements at jacket-deck connection level and at jacket level (+10 ft) for different loads combinations, the results indicate a significant effect of the current incidence direction



(a) Node $A_1$ (b) Node $B_1$

**Figure 8** The variation of Displacements of jacket node $A_1$&$B_1$ at "jacket-deck" connection

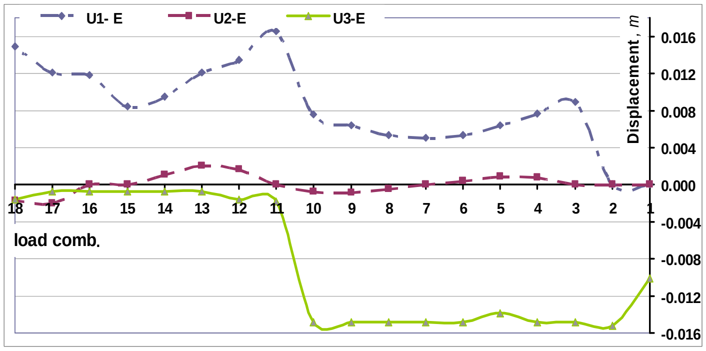


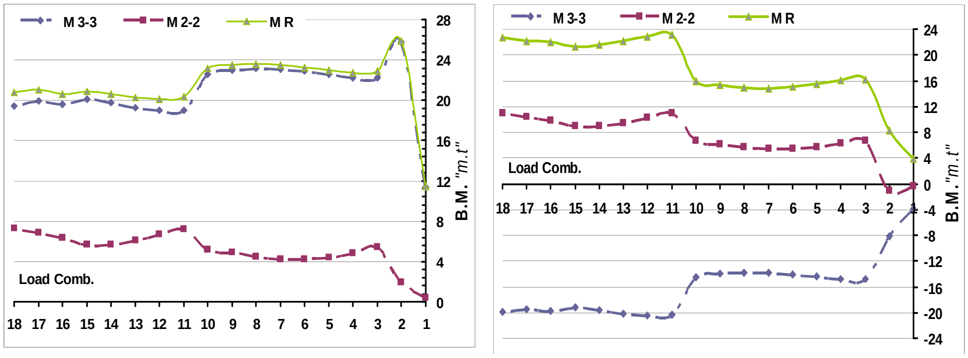
**Figure 9** The variation of Displacements of jacket center node $E_2$ at level (+10 ft)

## 6.2. Bending moment responses

**Figures 10 and 11** show a comparison of the maximum bending moments at critical nodal points. 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 top of the structure. The bending moment at node $A_1$ due to 100 year wave show an inverse pattern compared to those at node $A_2$ (i.e., the maximum value decreases). This phenomenon can be explained because the node $A_1$ locates at deck – jacket level at member span, while the node $A_2$ locate at connection joint, the moment direction at both nodes has opposite direction, so the wave loading has inverse effect on the peak values response.

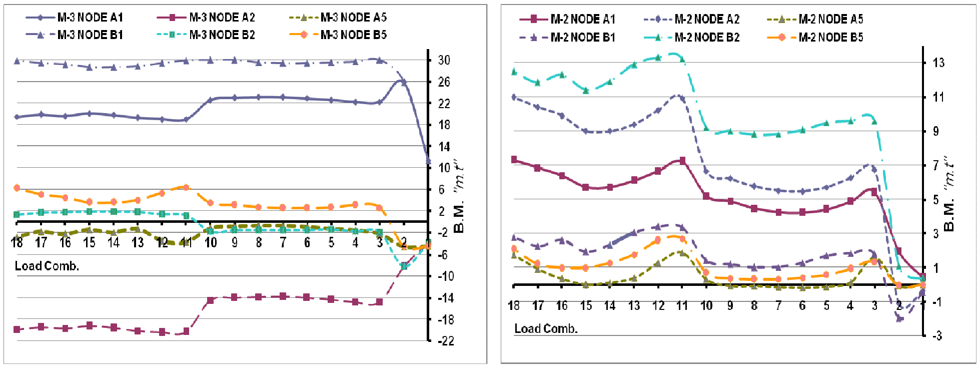
## 6.4. Axial force response of the platform leg

**Figure 12** shows a comparison of the maximum axial force at critical nodal points along jacket height. It is important in the design of platform leg to determine the location of maximum bending moment because the pile/jacket diameter wall thickness can be reduced below locations of maximum stresses.



(a) Node $A_1$ (b) Node $A_2$

**Figure 10** the variation of the bending moment response with the variation of loadings



(a) $M_{3-3}$ (b) $M_{2-2}$

**Figure 11** Bending moment response with load combinations for different nodes

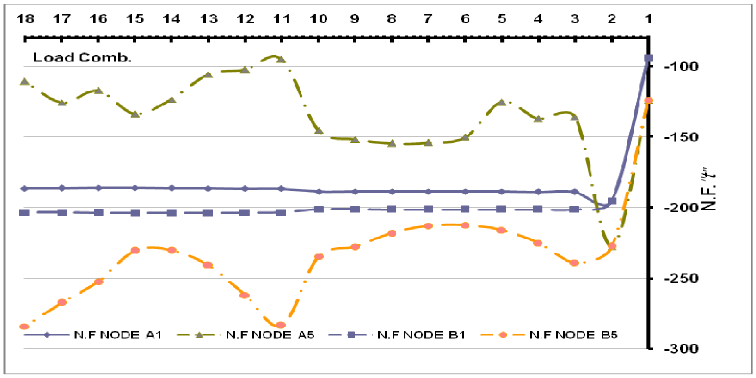


**Figure 12** Normal Force responses "N.F." with load combinations for different nodes

## 7. 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 current incidence angles is introduced. The results indicate a significant effect of the current incidence direction. 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. 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.

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