Effects of Sea Water Level Fluctuations on Seismic Response of Jacket Type Offshore Platforms

M. Rad, M. Dolatshahi Pirooz, and M. Esmayili

Abstract**—**To understand the seismic behavior of the offshore structures, the dynamic interaction of the water-structure-soil should be assessed. In this regard the role of the water dynamic properties in magnifying or reducing of the effects of earthquake induced motions on offshore structures haven't been investigated in precise manner in available literature. In this paper the sea water level fluctuations effects on the seismic behavior of a sample of offshore structures has been investigated by emphasizing on the water-structure interaction phenomenon. For this purpose a two dimensional finite element model of offshore structures as well as surrounded water has been developed using ANSYS software. The effect of soil interaction with embedded pile foundation has been imposed by using a series of nonlinear springs in horizontal and vertical directions in soil-piles contact points. In the model, the earthquake induced motions have been applied on springs and consequently the motions propagated upward to the structure and surrounded water. As a result of numerical study, the horizontal deformations of the offshore deck as well as internal force and buckling coefficient in structural elements have been recorded and controlled with and without water presence. In part of study a parametric study has been accomplished on sea water level fluctuations and effect of this parameter has been studied on the aforementioned numerical results.

Keywords**—**Fluid-Structure Interaction, Jacket, Sea Water Level, Seismic Loading.

I. INTRODUCTION

THE analysis of the response of superficial structures to seismic activity has eeen the object of a large number of publications so far. Due to scientific background of structural engineers, the effects of earthquakes on structures were initially analyzed on the basis of quasi static force models. Moreover most of these works were limited to consider plane frame structures.

In the study of offshore structures under seismic action a special attention must be given to interaction of the structure with the surrounding water. Indeed, intense ground shaking due to seismic loadings may cause fixed offshore structures to undergo large deformations.

Non linear effects play a very important role during seismic loadings. Venkataramana & Kawano (1995) have studied the non-linear response of offshore structures in random seas, to inputs of earthquake ground motions. They take into account the hydrodynamic damping effects in the earthquake response. Their study shows that the hydrodynamic damping force is higher in waves and, furthermore, sea waves generally reduce the seismic response of offshore structures. However they didn't consider the pile-soil interaction in their study [1].

To understand the behavior of these structures under extreme environmental conditions we are, therefore, confronted with the analysis of problems of fluid structure interaction. Such problems involve a certain degree of complexity, since they demand the simultaneous use of adequate structural and fluid-flow models.

For typical offshore structures located in a seismically active region, earthquake loading should also be considered in the dynamic analysis. Earthquake motions are generated through numerous random phenomena and are essentially random in nature. Several methods are available for the dynamic analysis of structures on land subjected to earthquake ground motions. However, these methods cannot be directly applied to offshore structures due to the presence of surrounding water and sea waves. Penzien et al (1972) have presented a stochastic method of analysis of fixed offshore towers due to random sea waves and strong motion earthquakes. They observed that the hydrodynamic drag effects become important with increasing tower period or water depth [2]. Bea (1979) developed the design criteria for offshore platforms subjected to these loads and compared his results with onshore building structures [3]. Most of researchers didn't consider the fluid-structure-soil interaction simultaneously and in some researches which modeled this kind of interaction the effects of pile-soil structure or the nature of fluid had been neglected.

The modeling of fluid-structure-soil interaction is a complicated process so there are a few researchers which developed a complete model considering fluid-structure-soil interaction. Therefore the main goal in this paper is developing a finite element model in ANSYS software which has capability of modeling fluid-structure-soil interaction. We apply the applicable approach which can model the fluid environment. The soil-structure interaction would be modeled

---

M. Rad is with Department of Civil Engineering, Tehran University, Iran (phone: 0098-9124404541; e-mail: meysam_rad@ yahoo.com).

M. Esmayili is with Department of Railway Engineering, Iran University of Science and Technology, Iran (m_esmaeili@iust.ac.ir).

M. Dolatshahi Pirooz is with Department of Civil Engineering, Tehran University, Iran (e-mail: mdolat@ut.ac.ir).

using p-y and t-z elements. After presenting the finite element model, the seismic response of jackets in offshore structures and the effects of sea water level fluctuations on this response will be evaluated via the presented finite element model. Also the axial and bending behavior of jacket members will be studied

II. PLATFORM DESCRIPTION

The frame which selected for modeling is a jacket of a recently designed and installed offshore platform in Persian Gulf. This platform had already been designed in accordance with API criteria. The platform was fabricated with pipe sections. Details of frame and the sections of frame members are shown in figure 1. As shown in this figure the overall height and width of jacket frame is about 69 and 32 meter respectively [4].

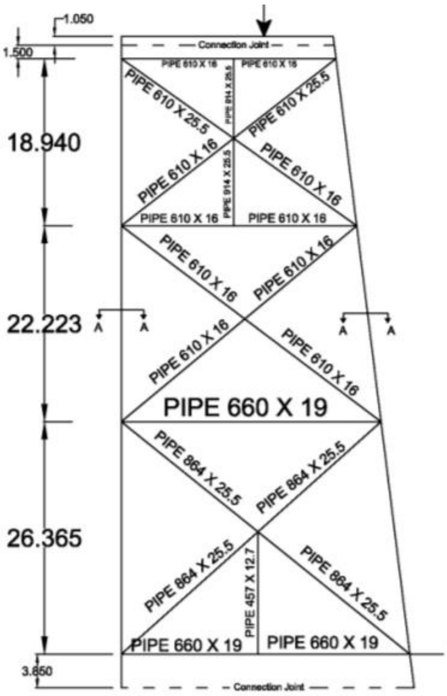

Fig. 1 Frames Fabrication Drawing

The leg section is a composite section which is compound of steel and grout material. Figure 2 shows the leg and pile section of modeled frame.

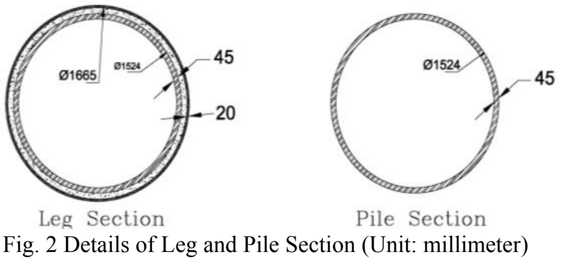

Fig. 2 Details of Leg and Pile Section (Unit: millimeter)

The characteristics of steel material of all sections, including portal and strut sections, are same. They grade of steel material is S355 which means that the yield strength is 355 MPa. The grout was made of seawater and cement type II (with Water/Cement weight ratio of 39% and 1.98 t/m3 density).

Based on the hydrodynamic information in Persian Gulf, the height of splash zone in region which the studied platform have been constructed is about 8 meter. It should be mentioned that the reference level in technical drawings is L.A.T (Low Astronomical Tide). Figure 3 shows the reference level and the splash zone with respect to jacket.

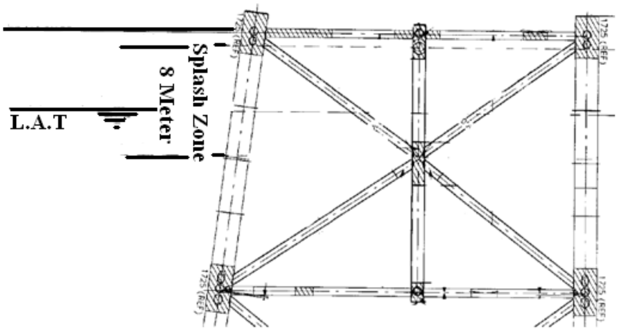

Fig. 3 Sea Water Level Fluctuations

III. FINITE ELEMENT ANALYSIS

Modeling jacket type offshore platforms is a fluid-structure-soil interaction problem. So for applying correct process, both interactions should be considered. Fluid-structure interaction is required for many applications such as biomedical (elastic artery modeling for stent design) and civil engineering. Fluid-structure interaction (FSI) is the interaction of some movable or deformable structure with an internal or surrounding fluid flow. Fluid-structure interactions can be stable or oscillatory. The interaction due to earthquake is an oscillatory interaction. In oscillatory interactions, the strain induced in the solid structure causes it to move such that the source of strain is reduced, and the structure returns to its former state only for the process to repeat [5].

Addition to considering the fluid-structure interaction, the interaction between jacket piles and soil is very important. The behavior of pile foundations under earthquake loading is an important factor affecting the performance of many essential structures such as offshore platforms. Analysis and design procedures have been developed for evaluating pile under seismic loading. Dynamic p-y analysis is an equivalent modeling method that has a long history of development and application to seismic and offshore problems (e.g. Matlock et al. (1970) Kagawa and Kraft (1980) and Nogami et al. (1992)). One such method which will be used throughout this paper is the beam on nonlinear Winkler Foundation (BNWF) model, where the soil-pile interaction is approximated using parallel nonlinear soil-pile p-y springs (Matlock, 1970) [6]. Also the BNWF analysis in seismic problems includes viscous dashpots with nonlinear p-y springs to model the effects of radiation damping.

In this section we would mention the properties of finite element approach of modeling the fluid-structure-soil interaction. We used finite element software ANSYS to model fluid-structure-soil interaction. In the following sections the procedure of modeling and our assumptions will be discussed. On the other hand the reason of this approach would be mentioned.

A. Characteristics of Finite Element Model

One of the most applicable finite element tools for modeling this interaction is ANSYS. The ANSYS fluid-structure interaction solution provides the analysis industry's most flexible and advanced coupled structural fluid physics analysis tool.

The portals, struts and pile were modeled using BEAM188 elements which take into consideration hydrodynamic loading and fluid-structure consideration. This element is suitable for analyzing slender to moderately stubby/thick beam structures and is based on Timoshenko beam theory

The material of whole members was nonlinear. We applied bilinear diagram to define nonlinear properties of steel material. This approach was based on the proposed model of Keyvani-Barzegar which approved via Zayas experimental studies [7] , [8]. The Elasticity module and Poisson ratio of steel material were assumed 2.088E+011 Pascal (N/m^2) and 0.3 respectively. The deck weights were modeled using concentrated mass elements MASS21. This is a point element having up to six degrees of freedom.

One of the basic process in the finite element analysis is meshing the model. There are two areas which have different characteristics and should be meshed:

- The water which is located outside the jacket. Regarding the geometry of this area, the mapped mesh was applied. The mesh elements were quadratic. For optimizing the duration of analysis and the accuracy of results, and based on the geometry of model, the element length of structure were assumed one meter. Therefore the size of each mesh is about 1*7 meter.
- The water which is located inside the jacket. Regarding the shape of this area, the free mesh was applied for these parts. The mesh elements were triangular. The smart size of mesh in ANSYS software was chosen 8 for optimizing run time and result accuracy.

B. Modeling of Fluid-Structure Interaction

The fluid was modeled using FLUID29 elements. FLUID29 is used for modeling the fluid medium and the interface in fluid-structure interaction problems. Typical applications include sound wave propagation and submerged structure dynamics. The element has the capability to include damping of sound absorbing material at the interface. The element can be used with other 2-D structural elements to perform unsymmetric or damped modal, full harmonic response and full transient method analyses. The fluid element was defined inside and outside the jacket to model the fluid-structure interaction between jacket and surrounded environment. Figure 4 shows the frame which modeled in fluid environment.

The element is defined by four nodes, the number of harmonic waves, the symmetry condition, a reference pressure, and the isotropic material properties. The reference pressure is used to calculate the element sound pressure level (defaults to 20x10-6 N/m^2). The speed of sound ($\sqrt{k / \rho_0}$) in the fluid is input of fluid element where k is the bulk modulus of the fluid (Force/Area) and ρo is the mean fluid density (Mass/Volume). In this paper the speed of sound and water density were assumed 1420 m/s and 1000 kg/m3 respectively. The dissipative effect due to fluid viscosity is neglected, but absorption of sound at the interface is accounted for by generating a damping matrix using the surface area and boundary admittance at the interface. Experimentally measured values of the boundary admittance for the sound absorbing material may be input as material property (MU). MU = 0.0 represents no sound absorption and MU = 1.0 represents full sound absorption. The selected values of MU for various part of model will be described in next part [9].

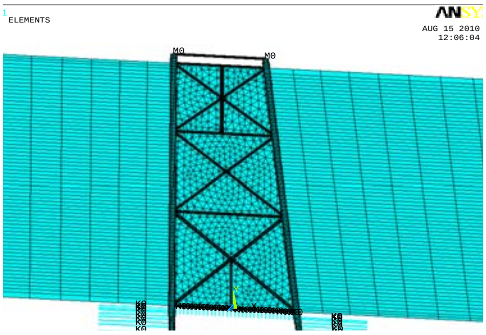

Fig. 4 The finite element model of Frame in ANSYS

C. Boundary condition

After defining the fluid elements it's necessary to introduce boundary conditions. Concerning that the frame was located in marine environment, we introduce the absorbing boundary far from the model to absorb incoming waves. Three boundary conditions were defined here:

- Far field boundary: the boundary which is located far from model to absorb the incoming waves. In this boundary the value of MU was set to 1 which means the fully absorption.
- The bottom boundary: the boundary which present the interface surface between soil and fluid. The value of MU was set to 0.8 based on the Chopra recommendations [10].
- Surrounded fluid: the fluid which located inside and outside the jacket. The value of MU was set to 0 which means no absorption.
- The water surface: this boundary is the interface between sea water and air. So in this model, the pressure were assumed zero along this boundary.

D.Modeling of Soil-Structure Interaction

Nonlinear p-y elements and t-z elements which consider the pile skin friction were implemented in the ANSYS program for dynamic analyses of the pile. For this study API recommendations were applied to model nonlinear p-y and t-z elements. The p-y curve was calculated based on the following equation [11]:

$$p = 0.5 p_u (y / y_c)^{0.33} \qquad (1)$$

In equation (1) p denotes actual lateral resistance (KPa), y denotes actual lateral deflection (mm), y_c is equal to $2.5\varepsilon_c D$ (mm) and p_u is the lateral bearing capacity. It should be mentioned that ε_c is the strain which occurs at one-half the maximum stress on laboratory undrained compression test of undistributed soil samples. The value of this parameter was obtained based on the site investigation in Persian Gulf. The value of p_u for soft and hard clay was calculated based on the API recommendations.

The nonlinear t-z elements were modeled based on the data which presented in table 1. This table was exerted from API manual. In this table z denotes local pile deflection (mm), D is pile diameter (mm), t is mobilized soil pile adhesion (kPa) and tmax denotes maximum soil pile adhesion which is equal to f.(2πD).

TABLE I

T-Z CURVE FOR CLAYS

z/D	t/tmax
0.0016	0.30
0.0031	0.50
0.0057	0.75
0.0080	0.90
0.0100	1.00
0.0200	0.70 to 0.90
∞	0.70 to 0.90

The f is a unit skin friction capacity which is computed based on the following equation for adhesive and granular soils [3]:

$$Adhesive \quad Soils : \begin{cases} f = \alpha c \\ \alpha = 0.5\psi^{-0.5} \quad ; \psi \le 1 ; \psi = \dfrac{c}{p_0'} \\ \alpha = 0.5\psi^{-0.25} \quad ; \psi > 1 ; \end{cases} \qquad (2)$$

$$Granular \quad Soils : f = K \,.\, p_0 \,.\tan \delta \qquad (3)$$

In these equations, α and ψ are dimensionless factors, c is a undrained shear strength of soil and p_0' is effective overburden pressure of each layer. K is coefficient of lateral earth pressure which is assumed one in this paper and δ is a friction angle between the soil and pile wall which is assumed 30 for dense sand.

For modeling the nonlinear elements in ANSYS software, we apply COMBIN39. This element is a unidirectional element with nonlinear generalized force-deflection capability that can be used in any analysis. The element has longitudinal or torsional capability in 1-D, 2-D, or 3-D applications.

Input motion

The record of TABAS earthquake was used for modeling the seismic loading. The maximum acceleration of earthquake in longitudinal direction is about 0.3g. the linear method was used for baseline correction. Also for decreasing the duration of analysis, we consider the 5% to 95% of earthquake energy based on the arias criteria. Figure 5 shows the time history of seismic loading in longitudinal direction. It should be noted that the seismic loading were assumed in both vertical and longitudinal directions. The maximum acceleration of earthquake in vertical direction is also 0.1g.

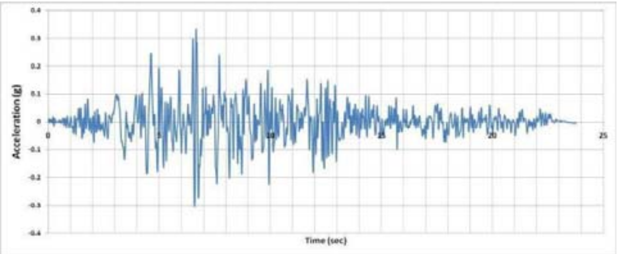

Fig. 5 The acceleration history of Tabas earthquake in longitudinal direction

IV. RESULTS AND DISCUSSION

For studying effects of sea water level fluctuations on seismic response of jacket, three models were defined based on the environmental condition of Persian Gulf:

- Model 1: in this model the sea water level considered in the highest level
- Model 2: in this model the sea water level was assumed equal to L.A.T.
- Model 3: in this model the sea water level was assumed equal to probable lowest level of sea water.

For analyzing the effects of sea water level fluctuations on seismic response, initially the deck displacement of jacket is analyzed here. Figure 6 shows the deck response of frame in these three models.

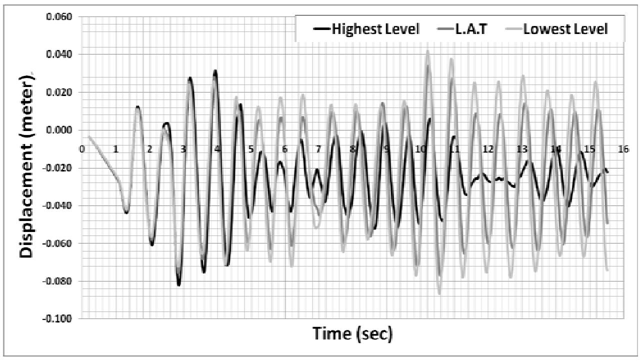

Fig. 6 The effects of fluid-structure interaction on jacket response

As this figure shows, increasing the sea water level have considerable effects on deck displacement especially after 5 seconds. With increasing the time of earthquake the energy of earthquake would be increased. So the higher earthquake energy and higher sea water level could lead in lower deck displacement.

For further analysis on hydrodynamic damping effects, we divided the duration of seismic loading into three equal parts. After that the root mean square (RMS) of time history of deck displacement for each model and each part of seismic loading were calculated. Table 2 summarizes these results.

TABLE II
RMS VALUES OF DISPLACEMENT HISTORY OF DECK DURING EARTHQUAKE

Case	0-5.17	5.17-10.34	10-15.52
I	0.039	0.029	0.027
II	0.038	0.035	0.038
III	0.037	0.038	0.044
Ratio(I/ II)	1.036	0.816	0.711
Ratio(III/ II)	0.980	1.086	1.181

Table 2 presents the ratio of each model proportion to second model which sea water level was assumed L.A.T. As results of this table shows, in the first part of seismic loading, the lower height of sea water leads in decreasing the jacket response. But after five seconds, the higher water level would decreased the jacket displacement which means that the hydrodynamic damping due to water-structure interaction needs enough time during earthquake to affect jacket response.

For studying the variations of axial load in jacket members, we studied the time history of axial force of whole members of jacket including horizontal braces, X-braces and portal members. For further analysis, first the RMS value (root mean square) of time history of axial force was calculated. Then for checking buckling criteria, the RMS of each time history was presented in Figure 7. It should be noted that each value was normalized based on the buckling force of jacket members. In this figure the HB, XB and L represent horizontal brace, X-brace and main leg respectively. Also the suffix 1, 2 and 3 and these abbreviations means upper, middle and lower part of jacket.

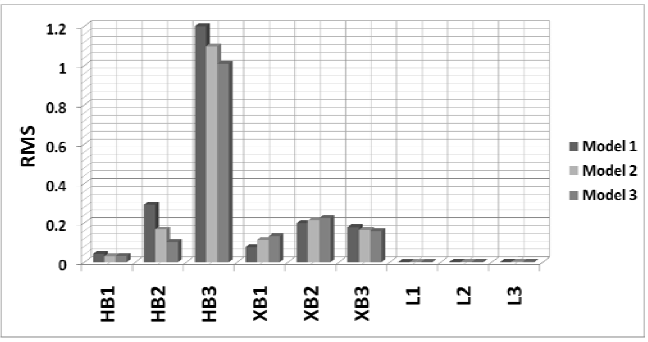

Fig. 7 The RMS value of time history of axial force (normalized respect to buckling load)

As figure 7 shows, the higher water level (model 1) produced high axial forces in horizontal braces. This situation is more critical in middle and lower part of jacket (HB2, HB3) which the hydrodynamic pressure of water increases with increasing water depth. In contrast these members, the lower water increase the axial force of X-braces especially in middle part of jacket (XB2). On the other hand the water fluctuations don't axial force of portal members considerably and so these members don't sensitive to water level fluctuations.

For detailed analysis of axial force variations during earthquake, we divided the time of seismic loading into three equal part same as the procedure which was applies for analyzing deck displacement. Table 3 summarizes the RMS ratio of three models for three parts.

TABLE III
THE RMS RATIO OF AXIAL FORCE OF JACKET MEMBERS DURING EARTHQUAKE

	Ratio(I/ II)			Ratio(III/ II)		
Member	0-5.17	5.17-10.34	10-15.52	0-5.17	5.17-10.34	10-15.52
HB1	1.974	1.341	1.389	0.970	1.042	1.157
L1	0.980	0.980	0.992	1.006	1.022	1.033
XB1	1.023	0.592	0.314	0.993	1.161	1.330
HB2	1.769	1.750	1.764	0.610	0.620	0.624
L2	0.989	0.922	0.924	1.005	1.054	1.080
XB2	1.137	0.890	0.776	0.931	1.040	1.179
HB3	1.146	1.145	1.145	0.920	0.920	0.919
L3	1.005	0.774	0.778	0.999	1.112	1.164

The results of table 3 show that increasing the sea water level could decrease the axial force of portal members in upper part of jacket. But in horizontal braces decreasing the level of water could possibly the axial force and axial stresses of member. Horizontal braces which located in middle part of jacket have been affected more than others.

Water level fluctuations level has considerable effects on axial forces of X-braces especially in the last part of seismic loading. The axial force of these members decreased or increased in analytical models after five seconds which means that the time hydrodynamical damping and fluid-structure interaction have considerably effects on seismic behavior of jacket.

V.CONCLUSION

One of the most limitations in the modeling process of jacket type offshore platforms is considering the fluid-structure interaction effects into the analysis procedure. In this paper we tried to introduce finite element model not only have capability to model soil-pile interaction but also could analyze the fluid-structure interaction under various loading especially seismic loadings.

After introducing the model, we showed the effects of sea water level fluctuations during seismic loading. Two output time histories are important for us. First time history is displacement of deck which has the critical responses during seismic loading, and second is the axial force of members which plays main role of stability of structural.

Our studies showed that the effects of sea water level fluctuations on response of jacket are very important and neglecting these effects during procedure of designing jackets could possibly destructive effects especially in seas that have affected by tidal phenomenon and the sea water level changes are very considerable. On the other hand the results showed that the sea level changes have various effects on strut and portal members of jacket. In some parts of seismic loading could increase or decrease the axial forces regards to type of jacket member and the level of it. It should be issued that introducing this phenomenon (sea water level fluctuations) in procedure of analyzing and designing of jacket can lead in optimizing the scheme of jacket type offshore platforms.

REFERENCES

[1] K.J. Venkataramana, and K. Kawano, "Nonlinear dynamics of offshore structures under sea wave and earthquake forces", Sadhana, parts 2-4, 1995,pp 501-512, India

[2] J. Penzien , M. K. Kaul, B. Berge, "Stochastic response of offshore towers to random sea waves and strong motion earthquakes", Computer Structures Jr,1972, pp. 733-756.

[3] R.G. Bea, "Earthquake and wave design criteria for offshore platforms". J. Struct. Div, Am. Soc.,Civ. Eng., 1979, 105(ST2): 401-419.

[4] S. A. Anagnostopoulos, "Wave and earthquake response of offshore structures: Evaluation of modal solutions", J. Struct. Div., Am. Soc. Cir. Eng., 1982, 108(ST10): 2175-2191.

[5] Technical Drawing, "SPD10, BS10 & FSP10 Platforms Field Layout, Drawing No. Sp9/10-PO-IL-D-9640, National Iranian Oil Company

[6] H.J. Bungartz, M. Schäfer, "Fluid-structure Interaction: Modeling, Simulation, Optimization", Springer-Verlag, 2006, ISBN 3-540-34595-7.

[7] H. Matlock, "Correlations for design of laterally loaded piles in soft clay", Proc. 2nd Annual Offshore Technology Conference, 1970, pp. 577-594.

[8] K. Kayvani, F. Barzegar, "Modeling of Tubular Members in Offshore Steel Jackets under Severe Cyclic Loading", UNICIV Report No. R-324, School of Civil Engineering, The University of New South Wales, December 1993, ISBN No. 858412918.

[9] V.A. Zayas, E.P. Popov, and S.A. Mahin, "Cyclic inelastic buckling of tubular steel Braces", Report No. UCB/EERC-80/16, Earthquake Engineering Research Center, University of California, Berkeley, CA, 1980.

[10] Release 11.0 Documentation for ANSYS, Copyright © 1995-2002.

[11] A. K. Chopra, "Earthquake Response Analysis of Concrete Dams .Advanced Dam Engineering for Design, Construction and Rehabilitation", Von Nostrand Reinhold, 1988.

[12] American Petroleum Institute, Recommended practice for planning, designing and constructing fixed offshore platforms. API Recommended Practice 2A (RP -2A). 21st ed, 2000.