Jack-up's leg structural analysis

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Jack-up structural failures are usually found in leg structures due to cracks in connections between tubular members of leg structures. It is important that the structural model accurately reflects the complex mechanism of the jack-up's leg structure. A number of different modeling techniques can be used to depict the leg of a jack-up structure. The purpose of this paper is to describe a balanced approach to the modeling of jack-up's leg structure through numerical calculations for a jack-up unit subjected to long term loading in drilling condition. The study of the physical problem is aided by detailed analysis of the jack-up's leg structure. This paper describes a fully detailed model of leg, hull/leg connections and hull/spud can connection with the leg structure using Finite Element Analysis (FEA). The internal member forces and moments determined from the FEA are stored for input to the post processing programs which insure satisfaction of the individual elements against American Petroleum Institute (API RP 2A-WSD) design criteria.

ان المنصات البحرية تستخدم في مجال التنقيب والحفرلزيت البترول والغاز الطبيعي بعيدا عن الشواطئ. يوجد طلب متزايد لاستخدام الحفار الرافع في ظروف جوية قاسية ومياه عميقة نسبيا. يتكون الحفار الرافع من بدن مثلثي عائم يرتكز علي ثلاثة ارجل شبكية. الانهيارات الانشائية بالرافع توجد عادة في التكوينات الانشائية في ارجل الرافع نتيجة الشروخ في الوصلات بين الاضلاع الانبوبية للأرجل. انه من المهم ان يعكس النموذج التصميمي الانشائي التقنية المركبة للتكوين الانشائي الخاص بأرجل الرافع. ويمكن استخدام طرق مختلفة من تقنيات النموذج التصميمي لتصف التكوين الانشائي الخاص برجل الحفار الرافع. هذا البحث يصف نموذج تصميمي تفصيلي كامل لرجل الحفار الرافع و طبيعة الوصلات بين بدن الرافع ورجل الرافع وكذلك طبيعة الاتصال بين رجل الرافع والتنك السفلي الخاص بتثبيت الرافع بقاع البحر باستخدام طريقة العنصر المحدد. ويتم الحصول علي القوي الداخلية للاعضاء والعزوم من طريقة العنصر المحدد ويتم استخدامها كمدخلات لبرنامج تحليل النتائج لفحص كل عضو علي حدة طبقا لمعايير التصميم.

Keywords: Jack-up, Leg structures, Structural model, Finite element analysis

1. Introduction

Jack-up drilling platforms are used for the exploration, drilling and work-over of offshore oil and gas fields. There is a steadily increasing demand for the use of jack-up units in deeper water and harsher environments. Confidence in their use requires jack-up analysis techniques to reflect accurately the physical processes involved. Typical units consist of a buoyant triangular barge resting on three independent lattice legs. There has been a growing trend to use self elevating "jack-up" drilling units for offshore exploration of hydrocarbons at deep water sites [1]. Originally designed for use in shallow waters, they are now being used in deeper locations. They have the major advantage of being re-usable so helping marginal field development. Jack-up drilling platforms contribute to a significant part of offshore engineering activities around the world. The application of the platform is continuously being extended towards deeper waters and harsher environments. Designs have been developed for operation in areas with maximum wave heights of 30m and water depths well beyond 130 m; these are of significant importance within the offshore industry.

Typical units consist of a buoyant triangular barge resting on three independent lattice legs, with the weight of the deck and equipment equally distributed [2]. Large end bearing shells called "spud cans" located at the bottom of the legs rest on the sea bed when the unit is jacked-up. The legs are moved up and down through the hull utilizing a rack and pinion jacking system. Each corner or chord of the lattice leg has a rack attached to it. The pinions are housed in the jacking houses on the deck [3].

Before a jack-up can operate at a given site, an assessment of its capacity to withstand a design storm, usually for a 50-year period, must be performed. In the past with jack-ups used in relatively shallow and calm waters, it has been possible to use overly simplistic and conservative analysis techniques for this assessment. However as jack-ups have moved into deeper and harsher environments, there has been an increased need to understand jack-up behavior [4]. The publication of the 'Guidelines for the Site Specific Assessment of Mobile Jack-Up Units' is an example of the offshore industry's desire both to standardize and to develop jack-up assessment procedures [2]. In calculating wave loading on jack-ups deterministic regular wave theories, such as Airy and stokes waves, together with the Morison equation are still widely used.

2. General consideration

The interaction between leg and hull influences the stress distribution, so the most heavily loaded portion of the leg is normally between the upper and lower guides and in way of the lower guide. The stress levels in these areas depend on the design type of the jack-up. A specific jack-up design concept, see figs. 1 and 2, can be described by the combination of the following components:

1. With or without fixation system,
2. fixed or floating jacking system,
3. opposed or unopposed pinions.

In units having fixation systems the transfer of moment between the leg and the hull is largely by means of a couple due to vertical loads carried from the chord into the fixation or jacking system.

Where a fixed or floating jacking system is fitted (and there is no fixation system) the transfer of moment between the leg and the hull is partly by means of a couple due to horizontal loads carried from the chords into the upper and lower guides. In this case and when the chord/guide contact occurs between bracing nodes significant local chord bending moments are normal.

If the jacking system has unopposed pinions local chord moments will arise due to:

1. The horizontal pinion load component (due to the pressure angle of the rack/pinion).
2. The vertical pinion load component acting at an offset from the chord neutral axis.

In this work, the floating jacking system is considered, Where a fixed or floating jacking system is fitted the transfer of moment between the leg and the hull is partly by means of a couple due to horizontal loads carried from the chords into the upper and lower guides [5] see Figure 1. In this case and when the chord/guide contact occurs between bracing nodes significant local chord bending moments are normal. The guide structure should be modeled to restrain chord member horizontally only in the direction in which guides contact [6].

Only the analyses of the jack-up in drilling and survival condition are considered in this paper; however the general analysis method is applicable to all load cases. The method of the analysis is divided into a number of stages. The procedure for analysis of jack-up structure is illustrated in fig. 2.

3. Basic design data

3.1. Jack-up's leg model description

A lattice structure assembled with tubular members is normally adopted for the leg structure in deep waters to reduce the wave forces on the structure to a minimum. The triangular column lattice structure for a jack-up rig consists of three chords, horizontal braces and diagonals.

3.2. Model definition

The model definition file consists of:

1. Definition of the type of analysis, the mud-line elevation and water depth.
2. Member sizes (member groups and sections)
3. Member joints definition
4. Soil data
5. Joint coordinates

6. Distributed load surface area definition
7. Wind area definition
8. Member and /or group overrides
9. Subsection on general concept of the analysis
10. Description of Airy wave through the structure
11. Loading directions of the waves
12. Details of the hydrodynamic leg-modeling procedure
13. Consideration of gravity loads and buoyancy
14. Importance of leg buoyancy
15. Emphasis of the effects contributed from Spudcan during the analysis
16. Finally, the load cases, which will include dead and live loading, environmental loading, crane loads, etc… [7]

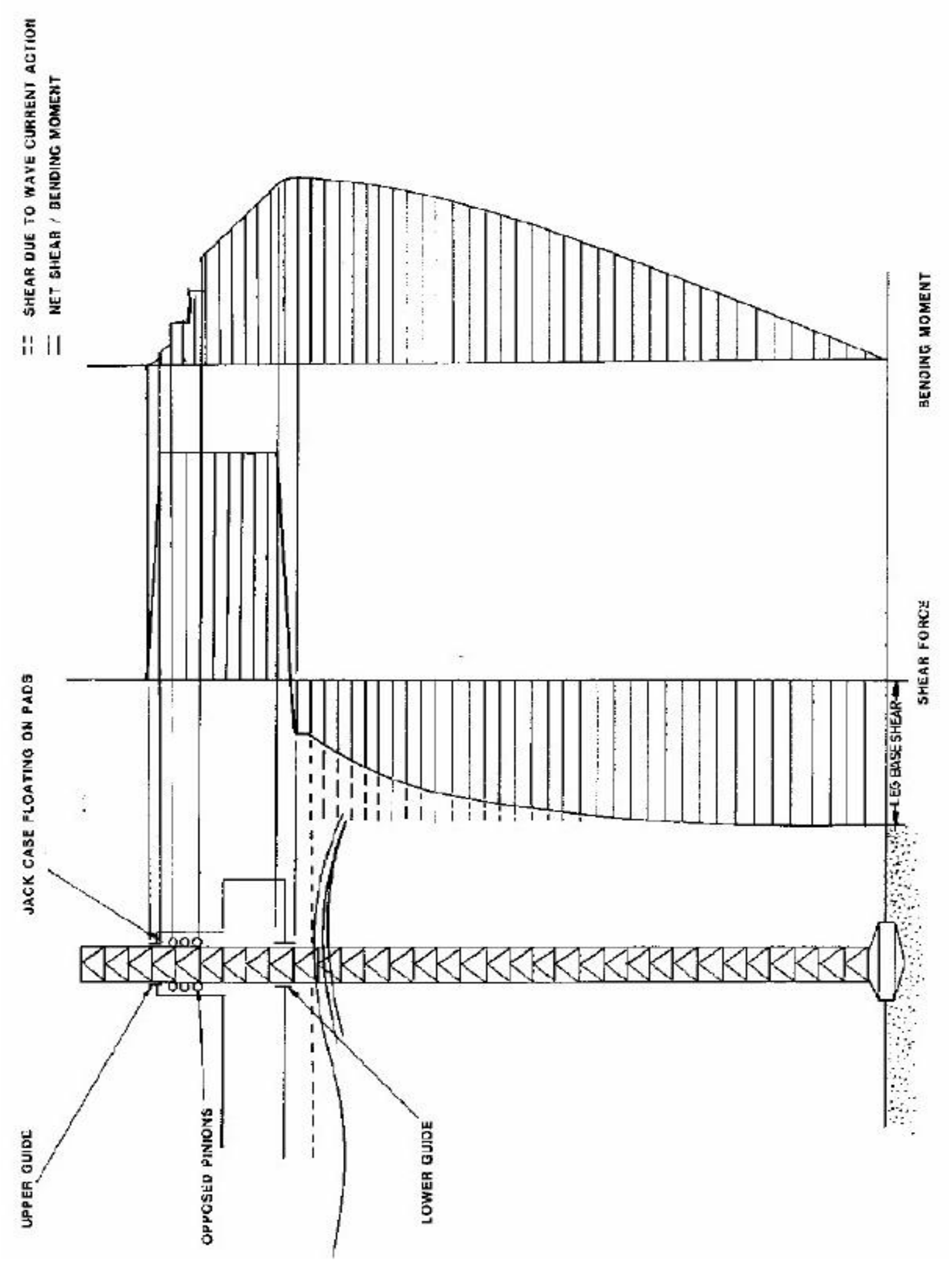

Fig. 1. Leg shear force and bending moment - jack-ups without a fixation system and having a floating jacking system [6].

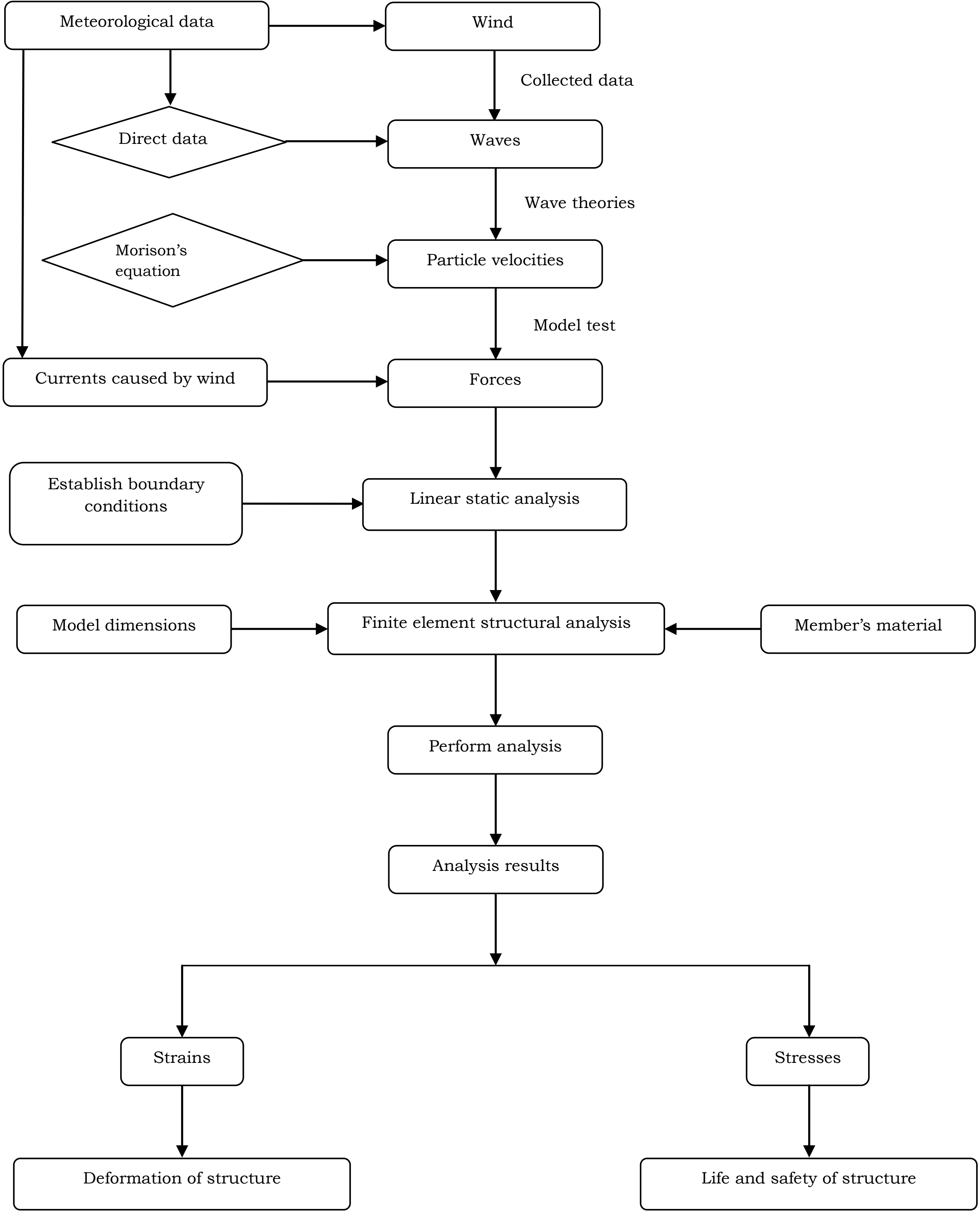

Fig. 2. Sequence analysis of jack-up's leg structure.

3.2.1. Material properties

All components of the chord members are made from steel with minimum yield strength of 686.7 N/mm^2. The horizontals and diagonals are constructed from steel with minimum yield strength of 441.45 N/mm^2. Other steel properties are assumed as follows:

Young's modulus E = 200,000 MPa
Shear modulus G = 80,000 MPa
Density ρ = 77008.5 N/m^3
Poisson's ratio υ = 0.3

3.2.2. Water level

The site-specific data for a site located in the Red-Sea is considered in determination of water level see fig. 3 [8]. The water levels used for the determination of the base case are shown in table 1.

3.2.3. Environmental loading acting on leg structures

The environmental conditions are described by a set of parameters for definition of:

a. Waves
b. Current
c. Wind
d. Water depth
e. Bottom condition [8, 9]

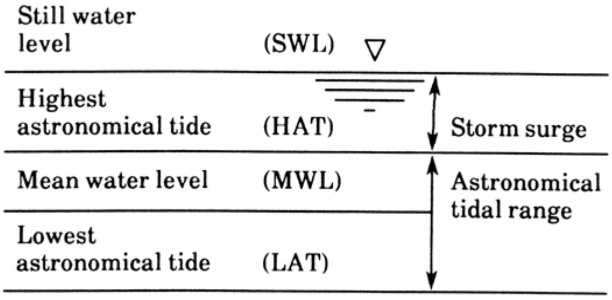

Fig. 3. Schematic showing the determination of water level [8].

Table 1

1. Water depth (LAT)	73 m
2. Tidal rise (MHWS) and positive storm surge	2 m
3. Wave crest height	7 m
4. Max water level	75 m
5. Minimum air-gap	8 m

Morison's formula is used to derive the wave and current forces on tubular members of leg structures in sea water. The hydrodynamic forces are calculated on the basis of the static assumption and only horizontal forces are considered for the wave direction in each horizontal level of leg structure assuming that the current and wind directions are identical to the waves.

The external loads are shown in fig. 4 and the axial forces and the lateral forces can be treated separately as shown in the figure for the purposes of strength calculations.

3.2.3.1. Wave and current forces idealization and determination The wave-current loading on the leg and spudcan structures above the mud-line may be applied as distributed or nodal loads. Where nodal loads are used the application should reflect the distributed nature of the loading.

Wave profile is taken as Airy wave (approximation to facilitate spreadsheet implementation) applicable for deep water for wave height H = 2 ζ_a, wave amplitude ζ_a, wave length L, and water depth d. Airy waves are sinusoidal, whereas higher order waves have a pronounced peak at their maximum surface elevation for results of linear wave theory (Airy wave) see ref. [9].

The vertical profile of currents is conventionally shown as decreasing with depth as a parabolic function. Recent studies in the ocean and on actual deep water projects indicate, however, that in many cases, the steady–state current velocities just above the seafloor are almost as high as those nearer the surface [11].

The current velocity is to include components due to tidal current, storm surge current and wind driven current. In stead of defensible alternative methods, the vertical distribution of current velocity in still water and its modification in the presence of waves as shown in fig. 5 are recommended, where:

$$V_C = V_t + V_S + V_W \{(h-z)/h\} \quad \text{for } z < h \qquad (1)$$

$$V_C = V_t + V_S \quad \text{for } z > h \qquad (2)$$

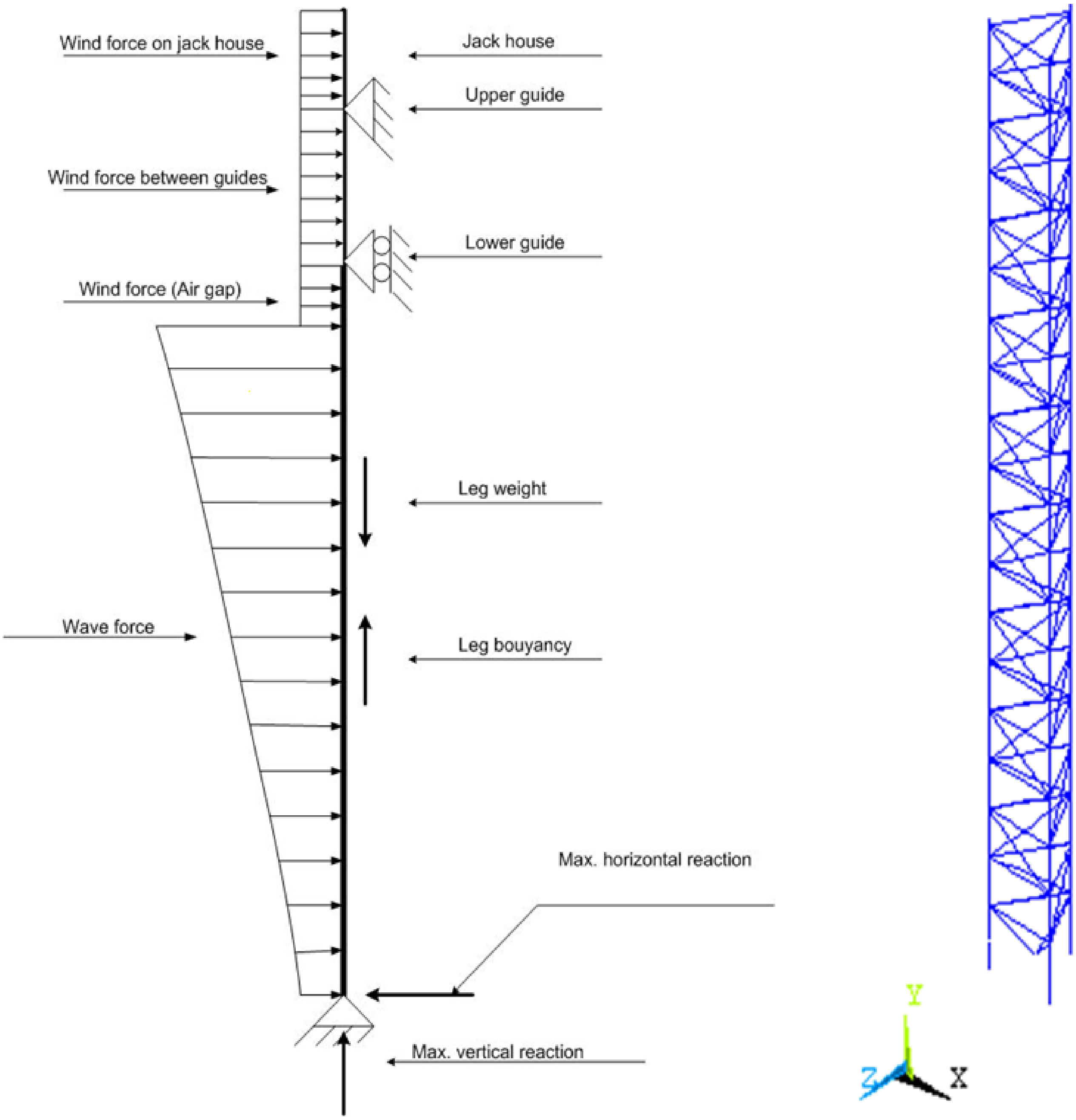

Fig. 4. Schematic describing the calculation model for the design structural analysis (Forces acting on leg structures when grounded to sea bed).

where V_C is the current velocity, V_t is the component of tidal current velocity in the direction of the wind, V_S is the component of storm surge current and V_W is the wind driven current velocity.

In the presence of waves, the current velocity profile is to be modified, such that the current velocity at the instantaneous free surface is a constant [7].

When calculating the drag force on submerged parts of the structure due to current and wave, the following equation may be used [12]:

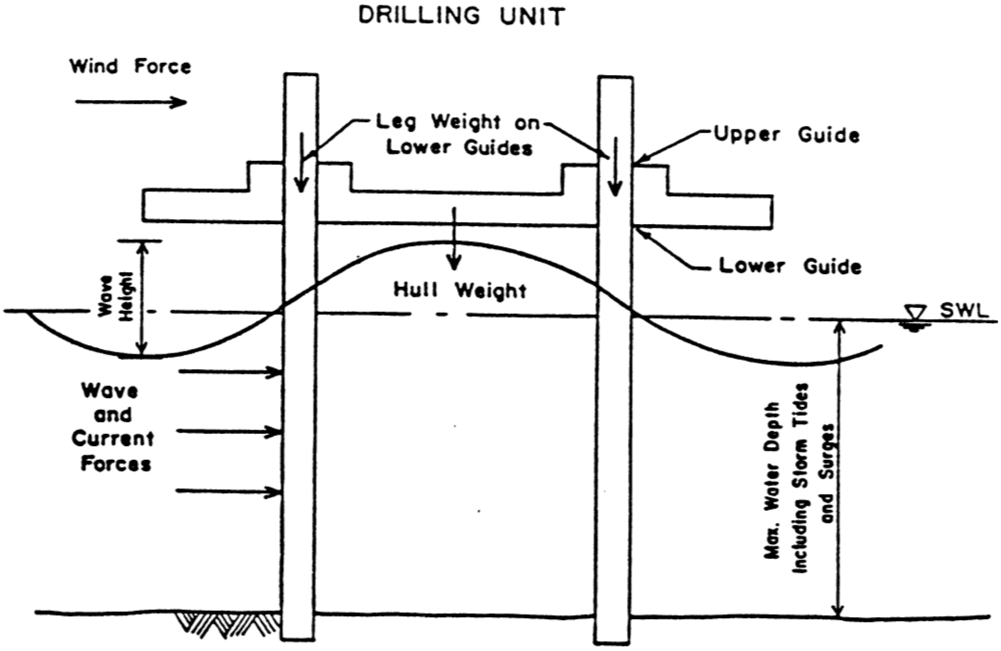

Fig. 5. Environmental forces and hull weight on schematic jack-up [15].

$$F_D = \left(C/2\right) D C_D U_C \left|U_C\right| , \qquad (3)$$

where F_D is the wave and current drag force vector per unit length along the member, acting normal to the axis of the member and U_C is the Component of the current velocity vector, V_c, normal to the axis of the member .

All of the above values are to be taken in a consistent system of units, C_D being dimensionless. Drag coefficients in steady flow vary considerably with section shape; Reynold's number and surface roughness are to be based on reliable data obtained from literature, model or full scale tests. The effect of Airy waves and current should be considered in Morison's equation.

The Morison's inertia force formulation is [6]:

$$\Delta F_{inertia} = \rho C_M A \dot{u}_n , \qquad (4)$$

where $\dot{u}_n$ is the fluid particle acceleration normal to member and $\Delta F_{inertia}$ is the inertia force (per unit length) normal to the member axis and in the direction of $\dot{u}_n$.

The hydrodynamic force acting normal to the axis of a cylindrical member, as given by Morrison's equation, is expressed as the sum of the force vectors indicated in the following eq. [7]:

$$F_W = F_D + \Delta F_{inertia} , \qquad (5)$$

where F_W is the hydrodynamic force vector per unit length along the member, acting normal to the axis of the member and F_D is the drag force vector per unit length.

(a) Wind force idealization and calculation

The wind loading on the legs above and below the hull may be applied as distributed or nodal loads. Where nodal loads are used, a sufficient number of loads should be applied to reflect the distributed nature of the loading [6].

The wind force for each component, F_{wi} may be computed using the formula [6]:

$$F_{wi} = P_i A_{wi} , \qquad (6)$$

where P_i is the pressure at the centre of the block and A_{wi} is the projected area of the block considered. The pressure P_i shall be computed using the formula:

$$P_i = 0.5\,\rho\,(V_{ref})^2\,C_h\,C_s\,, \qquad (7)$$

where V_{ref} is the 1 minute sustained wind velocity at reference elevation (normally 10m above MWL) and C_h may be derived from the wind velocity profile [6];

$$V_z = V_{ref}\,(Z/Z_{ref})^{1/N}\,. \qquad (8)$$

Where V_z is the wind velocity at elevation Z and N should be taken as 10 unless site specific data indicate that an alternative value of N is appropriate.
Hence,

$$C_h = (V_z/V_{ref})^2 = (Z/Z_{ref})^{2/N}, \text{ but always } >1.0. \qquad (9)$$

The height is the vertical distance from the still water surface to the centre of area of the block considered. Blocks which have a vertical dimension greater than 15 m shall be sub-divided, and the appropriate height coefficients applied to each part of the block [6].

(b) Wind force on hull structure
By treating the hull structure as a single block, the force on the hull structure can be written in the form:

$$Force = 0.5\rho V_{ref}^2 A_{hull} C_h C_s\,. \qquad (10)$$

where A_{hull} is an effective area of the hull.
The corresponding moment about the SWL is:

$$Moment = 0.5\rho V_{ref}^2 A_{hull} Z_{hull}\,, \qquad (11)$$

where Z_{hull} is the effective moment arm. We can calculate an effective area and moment arm from the numerous contributions of the projected areas of the blocks making up the hull structure.

3.2.4. Soils Data

For the selected site; Belayim 113M4 Gulf of Suez in Egypt, the stiffness of the footings was based on an assumed G/Su ratio of 50, where G is the soil shear modulus and Su is the un-drained shear strength of soil beneath the footings (taken as 200 k.Pa). A reduced value of 60 k.Pa was assumed for the un-drained shear strength in the horizontal direction. Poisson's ratios for clay and sand were taken as 0.5 and 0.3, respectively [13]. Vertical, horizontal and rotational spring stiffness values were calculated as 532 MN/m, 106 MN/m and 15684 MN.m/rad, respectively.

The soil profile below the mud-line was taken from borehole records as indicated in ref. [14] and shown in table 2.

3.2.4.1. Loading conditions Load cases define the loads considered for the assessment of the jack-up unit. 50-year environmental data were considered see fig. 5 which shows environmental forces on schematic model of jack-up. Fig. 4 shows environmental forces on schematic model of one leg of jack-up and table 3 shows condition of expected storm [15]. The full set of loading effects was as follows:

a. Dead loads including buoyancy
b. Variable loads
c. 50-year wave and current loads
d. 50-year wind loads [13]

3.2.5. Load Application

3.2.5.1. Self weight, variable and drilling load

Depending on the initial positions of the legs with respect to guide clearances, and the operation of the jacking and fixation systems (if fitted); see table 4, 5 and 6 which show weight calculation data.

Table 2
Summary of soil layer characteristics [14]

Depth [m]	Soil Description
0.0 to 5.0	Siliceous carbonate COARSE SAND, very gravelly
5.0 to 9.0	Siliceous carbonate GRAVEL, very sandy
9.0 to 16.7	Siliceous carbonate fine to medium sand, clay, with gravel

Table 3
Environmental storm condition

Operating water depth	75.00	meter
Maximum wind velocity	70.00	knots
ht	7.00	meter
Maximum current velocity	15.00	Knots
Expected additional load (fore leg)	545.0	M.T.

Expected additional load (aft leg)	620.0	M.T.

Table 4
Weight calculations

Item	Weight (MT)	Centre of gravity			
		Longitudinal		Transverse	
		LCG (M)	Moment (MT-M)	TCG (M)	Moment (MT-M)
Platform basic weight	4712	20.59	97020.08	0.76	3.562
Variable load	2200	17.78	39116	-0.21	-4.67
Total weight	6912	19.61	136136.08	0.45	3.095

Table 5
Distribution coefficient of jack-up legs

Leg position	Distribution equation	Value of distribution coefficient
Fore leg	$C_f = \frac{LCG - 12.00}{37.00}$	0.2035
Aft leg (starboard)	$C_S = \frac{49.80 - LCG}{75.60} + \frac{TCG}{37.00}$	0.4104
Aft leg (port)	$C_a = \frac{49.80 - LCG}{75.60} - \frac{TCG}{37.00}$	0.3861

Table 6
Jack-up leg load calculation

Leg number	1	2	3
Leg position	Fore	Starboard	port
Platform weight		6912	
Distribution coeff.	0.2035	0.4104	0.3861
Static load on leg	1407	2837	2669
Additional leg load	545	620	620
Total load on leg	1952	3457	3289

The method of transferring the loading from (and to) the deck box to the legs, as indicated in offshore guidelines see [12], critical to the typical design of the jack-up are

- Utilization and design of guides (e.g. with respect to number: flexibility, positioning, supporting length and plan(s), gaps, etc...)
- Utilization of braking systems in gearing units.
- Utilization of chocking systems.
- Utilization of holding and jacking pins.

It is noted that an F.E model with distributed hull stiffness and loading will incorporate hull sagging effects if the hull and variable gravity loading is 'turned on' with the unit defined in its initially undeflected shape at the operating air-gap. It should be verified that the amount of hull sagging moment arising is applicable, given the operating procedures pertaining to the unit. It may be necessary to apply corrections to the final results for any discrepancies in the hull sag induced loadings [6].

3.2.5.2. Buoyancy was automatically included for all tubular members below SWL. It was necessary to apply chord buoyancy manually. This was achieved by utilizing buoyancy elements. The diameter of the spherical shaped buoyancy elements was calculated to give the same internal dry volume per meter as that of the chord [13].

4. Design structural analysis method applied to jack-up's leg structure

The platform and the corresponding structural platform's leg are corresponding to 75 m water depth, air gap of 8m, 5m spudcan penetration and return period of 50 years. The jack-up's leg structure is a solid lattice structure consisting of chords, horizontal braces and diagonal braces. It composed of 208 elements. The horizontal braces are arranged at a fixed spacing. The description of the element used is a uniaxial element with tension-compression, torsion, and bending capabilities. The element has two nodes each of them has six degrees of freedom: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. This element is based on the 3-D beam element, and includes simplifications due to its symmetry and standard pipe geometry. The input data the geometry, node locations, and the coordinate system for this element are shown in fig. 6 and fig. 7. The element input data include two or three nodes, the pipe outer diameter and wall thickness, stress intensification and flexibility factors and thickness, corrosion thickness allowance, insulation surface area, axial pipe stiffness and the isotropic material properties.

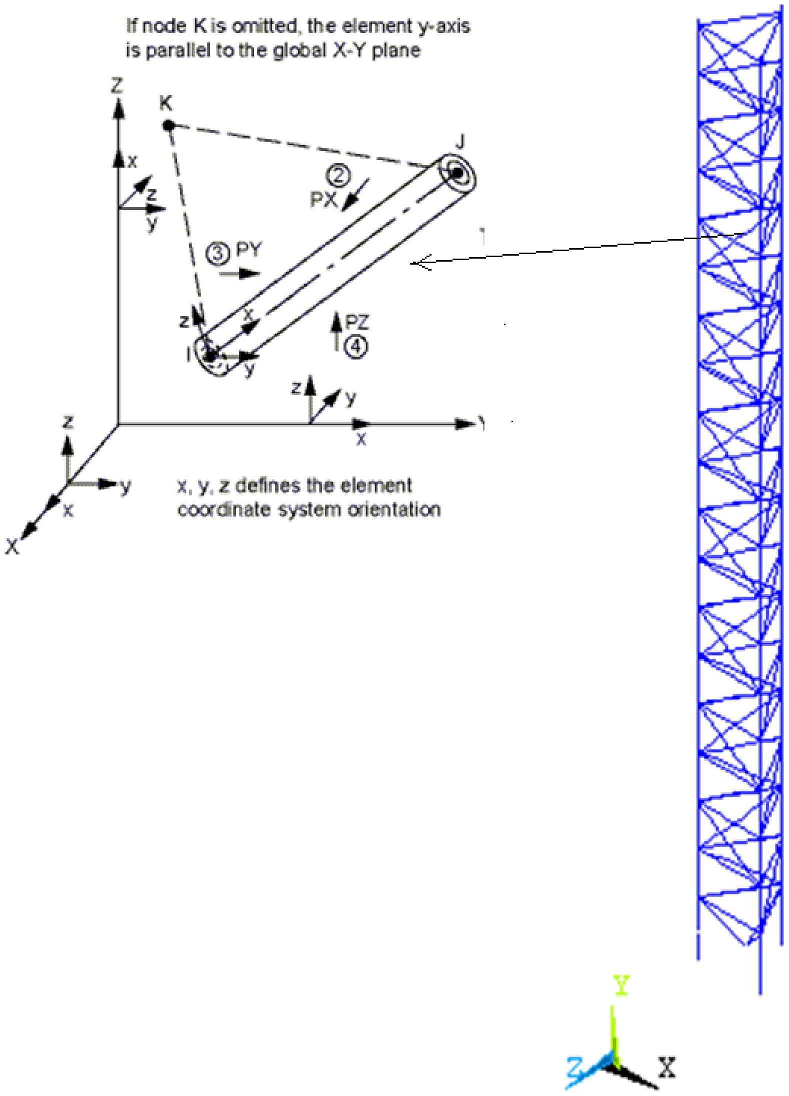

Fig. 6. Element geometry.

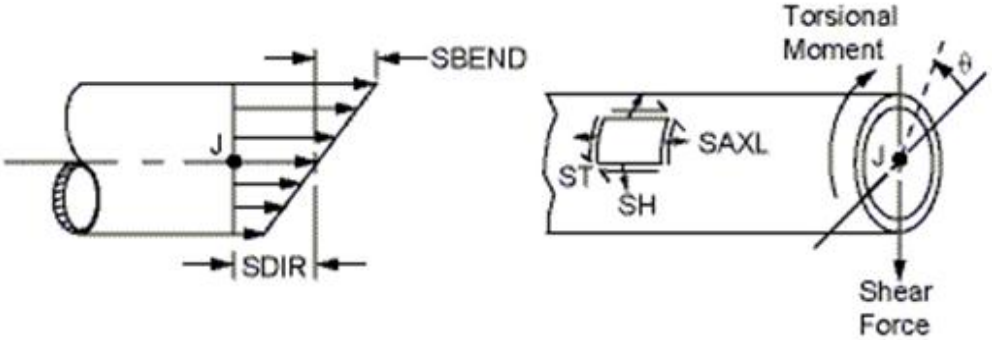

Fig. 7. Element stress output.

Modeling of the hull-leg interaction is therefore essential to both static and dynamic structural analyses of the jack-up. It is important that hull-leg interaction be simulated realistically in the mathematical model for purposes of design assessment. The hull-leg connection modeling is of extreme importance to the analysis since it controls the distribution of leg bending moments and shears carried between the upper and lower guide structures and the jacking or fixation system. For jack-ups with a fixation system, the leg bending moment will be shared by the upper and lower guides, the jacking and the fixation systems. Normally the leg bending moment and axial force due to environmental loading are resisted largely by the fixation system because of its high rigidity [16, 17]. Depending on the specified method of operation , the stiffnesses, the initial clearances and the magnitude of the applied loading a portion of the environmental leg loading may be resisted by the jacking system and the guide structures. For detailed leg structural design, the upper and lower guides should be modeled to restrain the chord member horizontally only in directions in which guide contact occurs. The normal lower guide position relative to the leg may be derived using the sum of leg penetration, water depth and air gap. Since the main concern is load effects at the base of the structure, the deck-leg (between upper and lower guide) connection is simplified and modeled as rigid. Hull leg-connection can be idealized as a roller support assumed at the level of the lower guide see fig. 4 [6, 17].

For independent leg jack-up units, the seabed reaction point for horizontal and vertical loads at each footing shall be situated on the geometric vertical axis of the leg/spudcan, at a distance above the spudcan tip equivalent to:

a. Half the maximum predicted penetration (when spudcan is partially penetrated), or

b. Half the height of the spudcan (when the spudcan is fully or more than fully penetrated) [6].

So, in our case the height of spudcan is 5.8 m and penetration is 7.6 m and the reaction point is at 3 m above the base of spudcan. The spudcan-foundation interface should normally be modeled as a pin joint unless there is justification for using fixity.

4.1. Hull/leg interaction and modeling

The barge of a jack-up in the elevated mode is typically supported by the legs through jacking units and leg guides. Under the action of wind and wave loads, leg bending is resisted by both horizontal forces in the guides and vertical forces (and partially horizontal forces) from the jacking systems. Proper modeling of the hull-leg interaction is therefore essential to both static and dynamic structural analyses of the jack-up [1].

To better represent the hull-leg interaction of detailed model representing each of the legs by a frame structure and the hull by a three-dimensional finite element model with special attention paid to the determination of the pinion stiffness and representation of the leg guides. Through this analysis, realistic load distributions between the legs and the hull structure can be obtained. Furthermore, the effects of the pinion stiffness, leg guide length and hull flexibility on the structure's natural periods, displacement response, and pinion loads and guide reaction can also be assessed [1].

4.2. Upper and lower guides

The guide structures should be modeled to restrain the chord member horizontally only in directions in which guide contact occurs [16]. The upper and lower guides may be considered to be relatively stiff with respect to the adjacent structure, such as jack case, etc. the normal lower guide position relative to the leg may be derived using the sum of leg penetration, water depth and air gap. It is however recommended that at least two positions are covered when accessing leg strength: one at a node and the other at the mid-span. This is to allow for uncertainties in the prediction of leg penetration and possible differences in penetration between the legs [13]. The jack-up leg considered is attached to the hull by guides (reacting horizontal loads) and gear pinions (reacting vertical loads). The moment is reacted partly by differential horizontal loads in the guides and partly by differential vertical loads in the gear pinions.

4.3. Fixation system

The fixation system should be modelled to resist both vertical and horizontal forces [17]. The model can simulate the local moment capacity of the fixation system arising from its finite size and the number and location of the supports [6].

4.4. Shock pad

Floating jacking systems generally have two sets of shock pads at each jack case, one located at the top and the other at the bottom of the jack house. Alternatively shock pads may be provided for each pinion. The jacking system is free to move up or down until it contacts the upper or lower shock pad. In the elevated condition, the jacking system is in contact with the upper shock pad and in the transit condition it is in contact with the lower shock pad. The stiffness of the shock pad should be based on the manufacturer's data and the shock pad should be modelled to resist vertical force only [6].

4.5. Structural modeling

It is important that the structural model accurately reflects the complex mechanism of the jack-up's leg. A number of different modeling techniques can be used to depict the leg of jack-up structure. The recommended techniques are summarized below giving a fully detailed model of leg and hull/leg connections.

4.5.1. Single detailed leg model

The model consists of a detailed leg, hull/leg connection and modeling of leg-spudcan connection. This model is to be used in conjunction with the reactions at the spudcan or the forces and moments in the vicinity of lower guide see fig. 8 [15]. The results from this model can be used to examine the leg strength and the adequacy of the jacking system or the fixation system.

The coordinates of the joints for this model are to be defined by the intersection of the chord and brace centerlines. For joints where there is more than one brace, it is unlikely that there will be one common point of intersection between the braces and chord. In this instance, it is usually sufficient to choose an intermediate point between the chord/brace centerline intersections.

4.5.2. Support at seabed reaction point

Support at footing is taken as simple support (knife edge) to be treated as the worst condition which generates large stresses upon the detailed leg model. However, several cases are to be treated for comparing (example between footing spring and footing pin edge).

5. API acceptance criteria

The main purpose of structural analysis is to synthesize a structure in such manner that a satisfactory level of reproducing the actual response of the structure to some applied load is obtained. In undertaking such a task, engineering judgment is applied as a means to

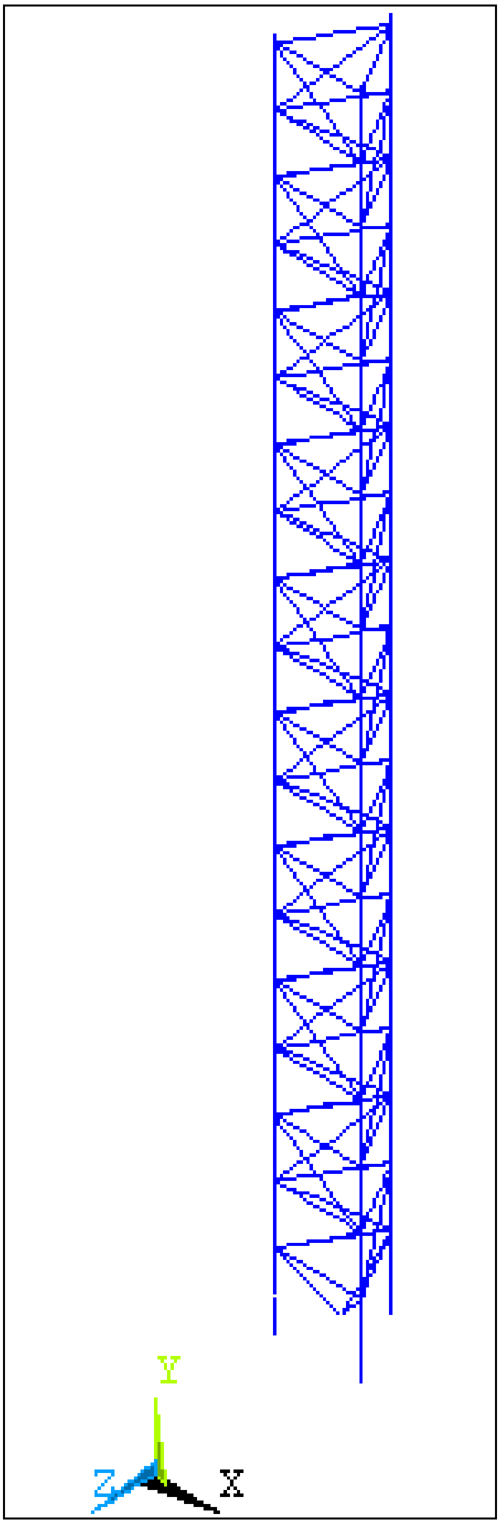

Fig. 8. Finite element model of jack-up's leg.

achieve a practicable solution to the physical problem at hand. It is necessary to check in detail the maximum stress in the leg chord and leg bracing. These generally occur at the leg connection to the hull [3]. The internal member forces and moments determined from the finite element analysis are stored for input to the post processing programs which check the individual elements. All bracing members are checked as beam columns against an appropriate code such as API Recommended Practice 2A-WSD (RP 2A-WSD) [18]. The stress in the chord members include the axial and bending stresses plus the additional effects of saddle stresses induced from the bearing of the guide system. The estimated stresses are compared to the design allowable stresses and the ultimate strength capacity. The diagonal braces and horizontal struts are also checked for compression capacity by comparing estimated stresses against the design allowable stresses and the ultimate strength capacity see figs. 9:16 [15]. In the static strength analysis the following modes of failure are considered;

- Excessive yielding
- Punching shear
- Buckling
- Brittle fracture

The possibility of buckling is considered for all slender structural members. The possibility for brittle fracture should be considered in connection with the selection of grade of material to be used [8, 19].

API acceptance criteria covered are:

a) Structural strength,
b) overturning stability,
c) foundation capacity (sliding displacement and punch-through) and
d) horizontal deflection.

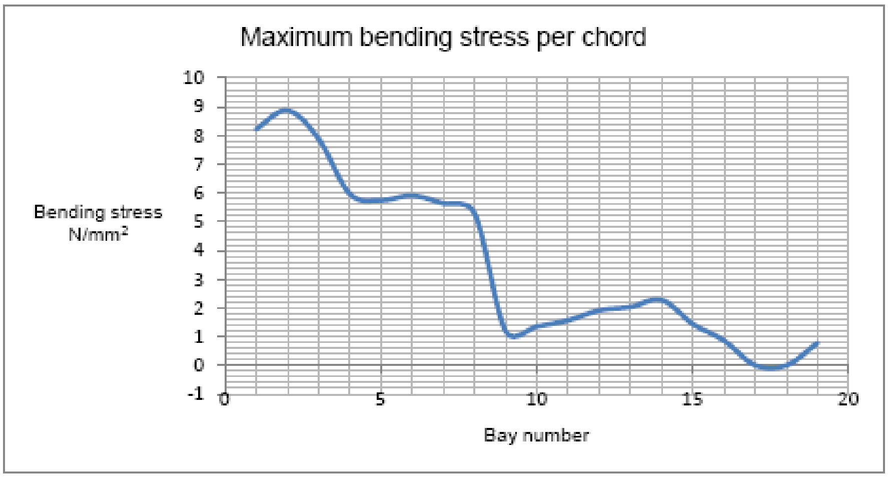

Fig. 9. Maximum bending stress per chord.

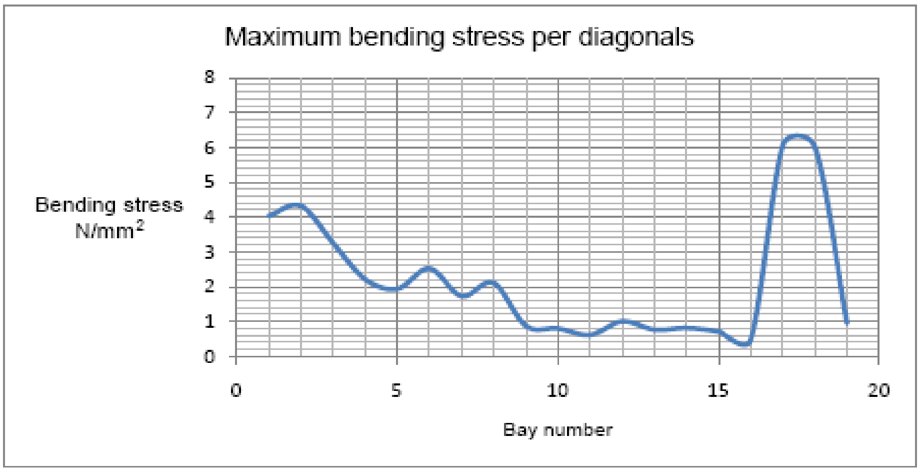

Fig. 10. Maximum bending stress per diagonals.

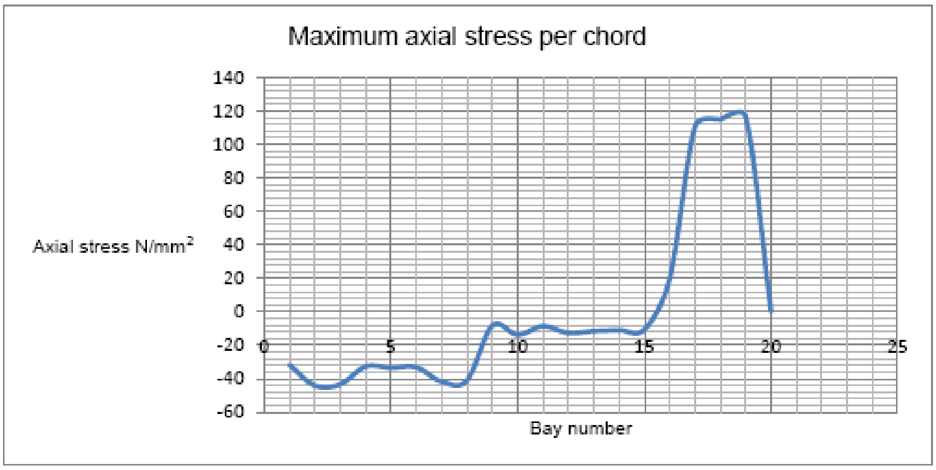

Fig. 11. Maximum axial stress per chord.

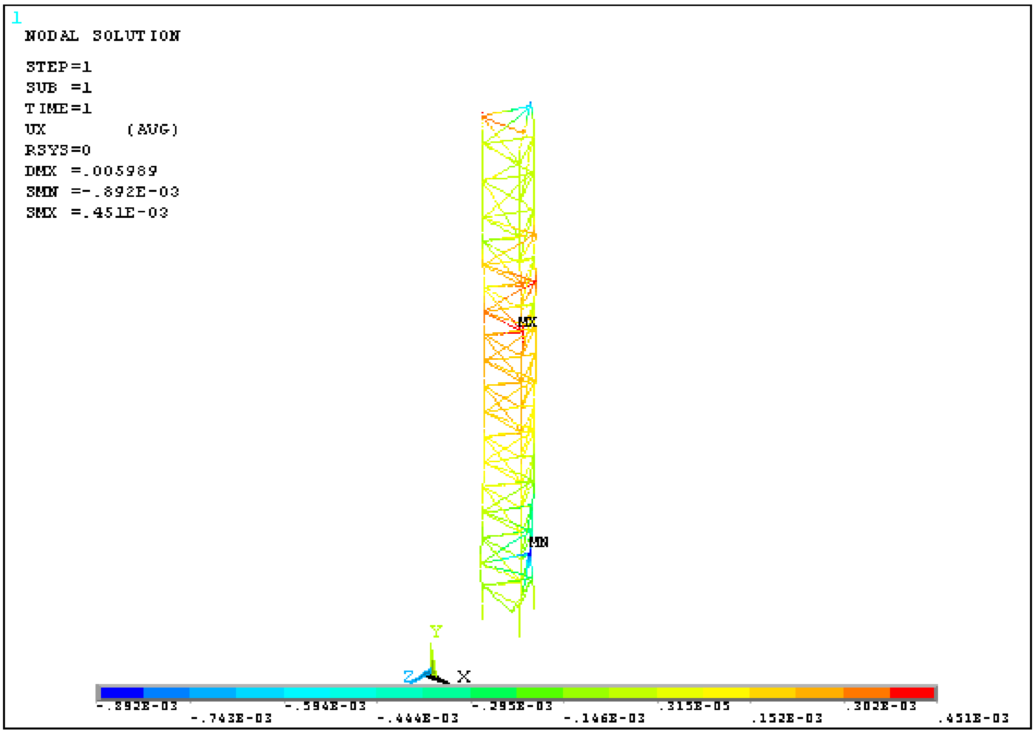

Fig. 12. DOF solution (X-component of displacement) (Units- meter).

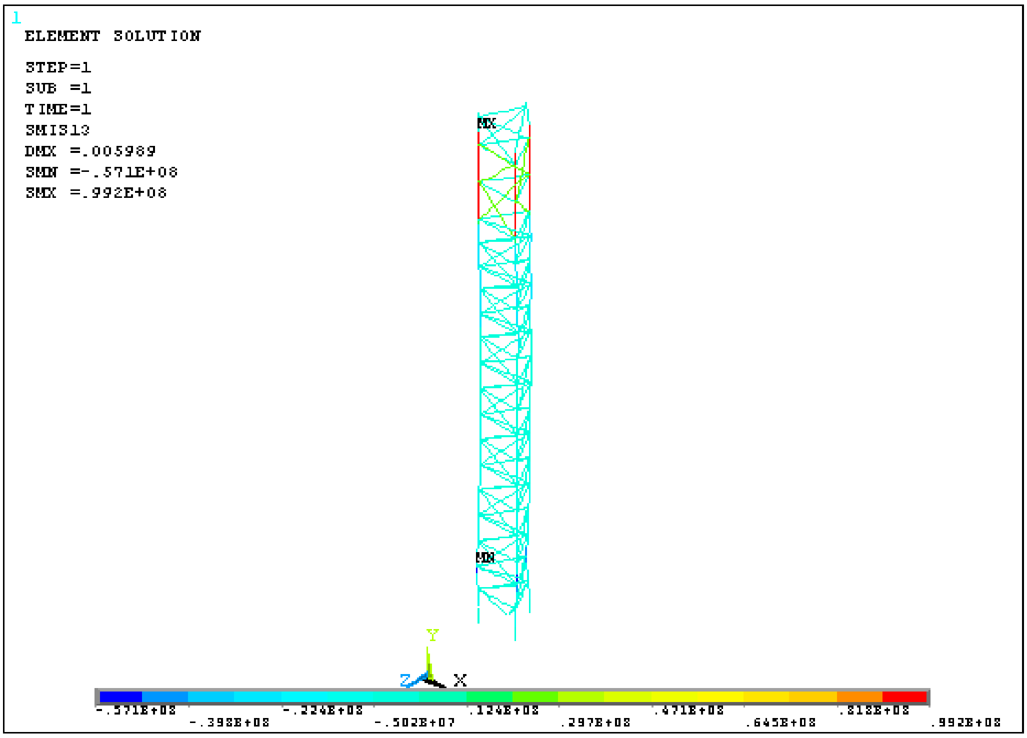

Fig. 13. Element solution (axial stress) (Units – Newton-Meter).

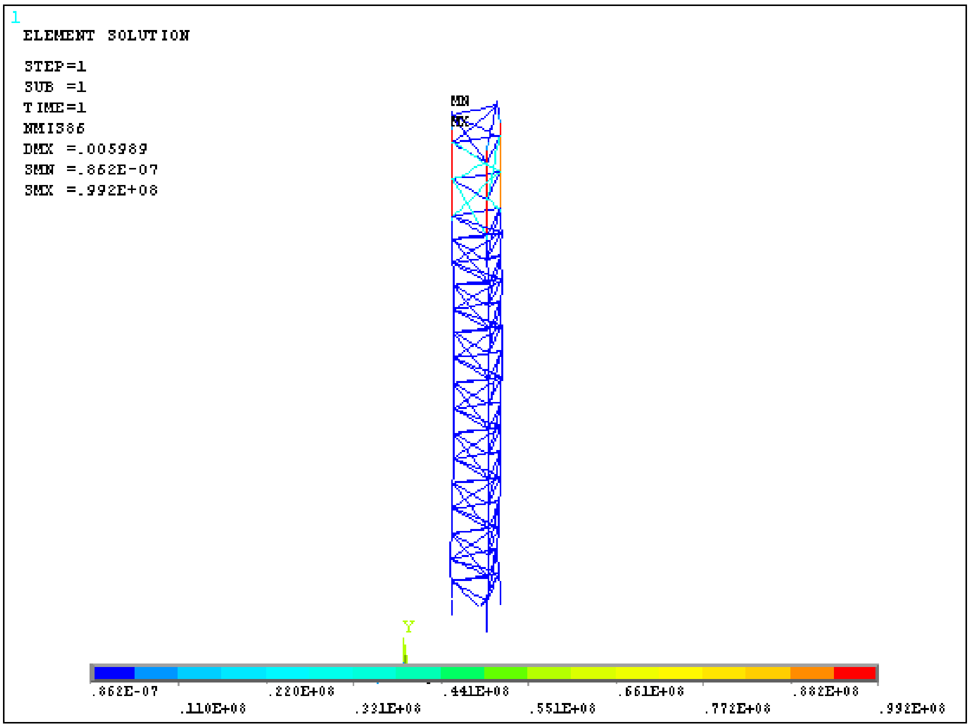

Fig. 14. Element solution (maximum principal stresses) (Units – Newton-Meter).

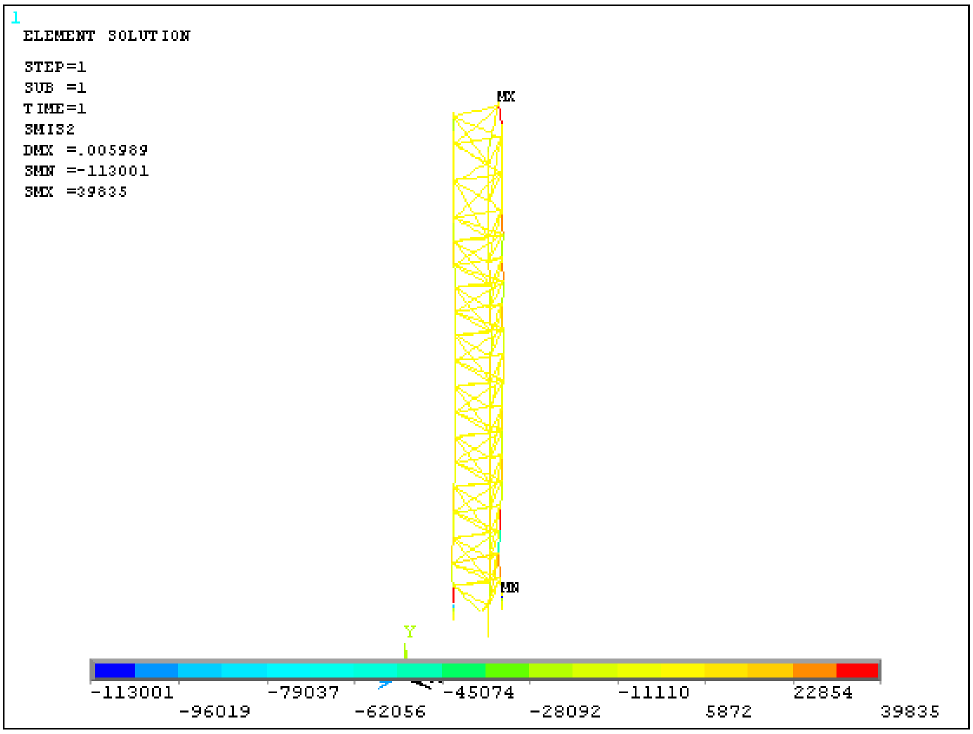

Fig. 15. Element solution (member force in Y-direction for node I and J) (Units – Newton-Meter).

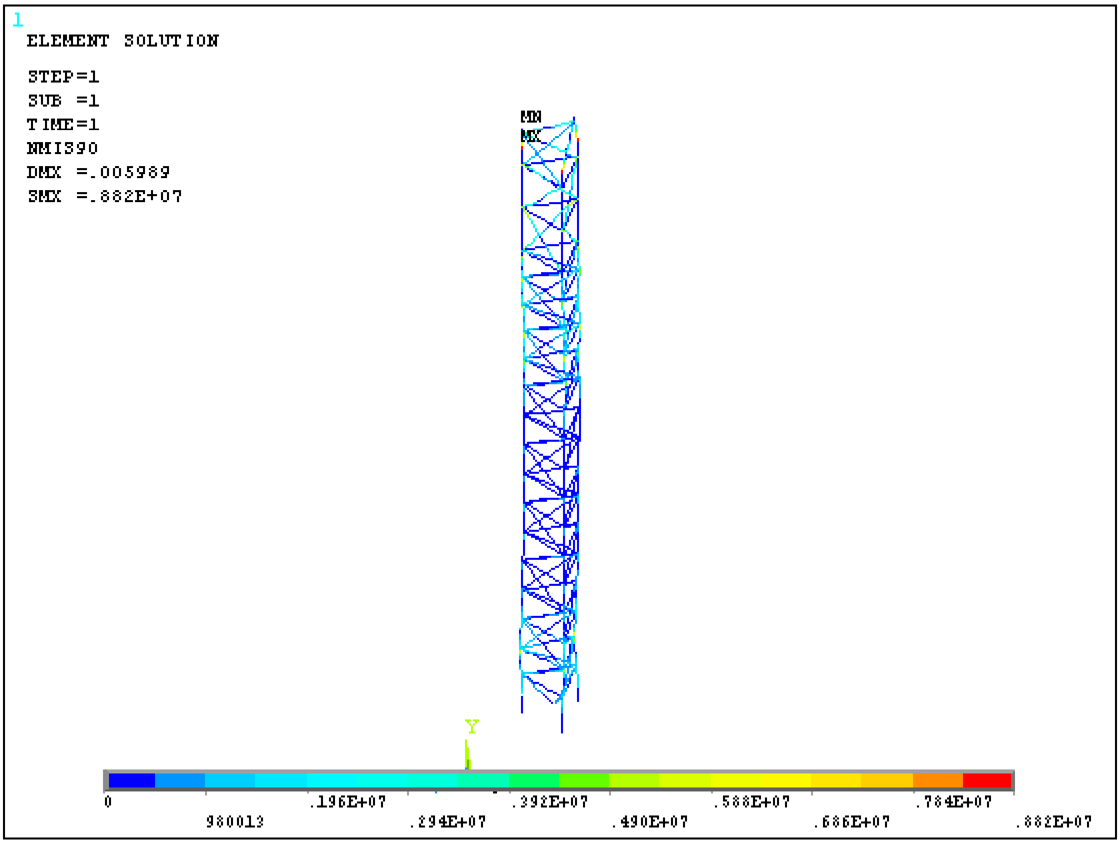

Fig. 16. Element solution (maximum bending stress at the outer surface) (Units – Newton-Meter).

6. Conclusions

a. The ratio of the diameter and length of each structural member is adequately small, and the ratio of cross section area of chord and brace is adequately large. Therefore, the bending moment (M) is taken up by the axial force in the chord structural members, and the shear force (F) is taken up by horizontal and diagonal brace structural members which confirm the indicated in Guidelines for site specific assessment of mobile jack-up units see ref. [6]. The shear rigidity of each structural member by itself is small as compared to the triangular column lattice structure. Therefore, the shear force (F) is taken up by the axial force in each member.

b. Regarding the axial stress on the chord, the bending moment of the leg is taken up only by the axial rigidity of the chord.

c. The bending stress of the chord and diagonals, except for the part between the upper and lower guides and the spud tank at the lower part, is not to exceed 6 N/mm^2, which is a small value and therefore can be neglected.

d. The maximum axial stress occurs on the chord between the upper and lower guides due to the pinion and bending moment, therefore this part has to be considered in design.

Nomenclature

A	is the cross section area of the member, m^2,
A_{wi}	is the projected area of the block considered,
C	is the constant in the Morrison equation and may be taken as 1.025,
C_D	is the drag coefficient,
C_h	is the height coefficient,
C_M	is the inertia coefficient,

C_s	is the shape coefficient depend on the type of member or structure,
D	is the projected width of the member, m,
d	is the still water depth, m,
E	is the Young's modulus, MPa,
$\Delta F_{inertia}$	is the inertia force (per unit length) normal to the member axis and in the direction of $\dot{u}_n$,
F_D	is the wave and current drag force vector per unit length along the member, acting normal to the axis of the member,
F_W	is the hydrodynamic force vector per unit length along the member, acting normal to the axis of the member,
G	is the Shear modulus, MPa,
h	is the reference depth for wind driven current, m, (h may b taken as 5 m),
H	is the wave height, m,
L	is the wave length, m,
P_i	is the pressure at the centre of the block,
U_C	is the component of the current velocity vector, V_c, normal to the axis of the member,
$\dot{u}_n$	is the fluid particle acceleration normal to member,
V_C	is the current velocity, m/s,
V_{ref}	is the 1 minute sustained wind velocity at reference elevation (normally 10m above MWL),
V_S	the component of storm surge current, m/s,
V_t	is the component of tidal current velocity in the direction of the wind, m/s,
V_W	is the wind driven current velocity, m/s,
V_z	is the wind velocity at elevation Z, and
z	is the distance still water level under consideration, m.

Greek symbols

ρ	is the fluid density, N/m^3,
υ	is the Poisson's ratio, and
ζ_a	is the wave amplitude, m,

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