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Investigation on the Overturning Stability of a Jack up Mobile Offshore Production Unit by Site-Specific Analysis to Find a Solution to Avoid the Failure of Its Leg Lattice Structure

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Abstract: The site-specific assessment analysis has been performed on a three legged drill rig with spud cans to investigate the failure of the leg lattice structure of the legs of a Jack-up Rig which is being converted from Mobile Offshore Drilling Unit (MODU) to Mobile Offshore Production Unit (MOPU). The failure of legs is quite common because of the increased elevated loads for a MOPU and also being a fixed platform and cannot be regularly jacked up & down due to severe wave conditions. Unless a proper assessment and analysis is done, it is found dangerous to put the vessel into operation.

The authors in this paper have enunciated a proper procedure for the assessment of failure and a system and correct analysis procedure has been shown by taking into consideration the overturning stability of the unit, preload requirements and the structural integrity of the legs and the leg holding system (pinions) under storm loading. The hull strength has been considered to be completely rigid since the jack-up MOPU under the study has been continuing to maintain the Class Certificate. The research has been done for the jack-up MOPU in elevated condition without giving consideration to the relative displacements with respect to the adjacent fixed platform structure with which the MOPU will be connected with a walkway bridge.

The Finite Element Method is used to determine the stresses and strains in various joint sections of the leg lattice by modelling the entire rig structure in SACS modelling and FE analysis software which is extensively used in offshore industry. A very cost effective solution has been identified of changing a portion of the leg with a high strength material and increased thickness to encounter for the failure at higher wind loads. Comparative studies have been done with existing rig being converted, after modifications as suggested and taking entirely new rig with higher cost, indicating that the proposed solution is very versatile, cost effective and time saving solution by meeting the fundamental axiom of finding the solutions to the yesterday's problems with tomorrow's technology.

Keywords: Overturning Stability, Pinion Stiffness Jack Up Rig, Mobile Offshore Drilling Unit (MODU), Mobile Offshore Production Unit(MOPU), Stress, Displacement, Chord Pipes, Bracing Pipes, Leg Penetration, Metallurgical Analysis.

NOMENCLATURE

H [m]	***Wave Height***
D [m]	***Water Depth***
T [sec]	***Wave Period***
g [m/sec^2]	***acceleration due to gravity***
E [N/mm^2]	***elastic modulus of the material***

Greek Conventions

σ_y ***[N/mm^2]***	***yield stress of the material.***
ρ ***[kg/m^3]***	***density of material***

I. INTRODUCTION

Description of the Vessel under study: The Jack-up under this study is a CFEM T-2000-C design of independent-leg jack-up unit. Built in 1981 as a Mobile Offshore Drilling Unit (MODU), it is being converted to a Mobile Offshore Production Unit (MOPU).

The jack-up has three square Z-braced truss legs with internal cross span-breaker bracing. Each leg has two diagonally opposed driven chords and two diagonally opposed un-driven chords. The driven chords are of the split-cylinder type with a centre-plate and opposed (double-sided) racks. The un-driven chords are cylindrical.

The legs will be elevated and lowered by means of an electrically powered rack-and-pinion jacking system having 12 pinions per leg, with six pinions per driven chord arranged in opposed pairs in three-high floating-type jacking units. Each three-high jacking unit has elastomeric shock-pads at its top and bottom. The pinions will be under the brake once the hull has been elevated to the required air-gap and the braked pinions support the weight of the hull.

Each leg is fitted with a tank-like spud can footing which bears on the seabed when the jack-up is in elevated mode. The spud cans are free-flooded with seawater before being lowered to the seabed, prior to elevating the hull. The legs are guided through the hull by rigid guide structures located near the base of the hull and near the top of the jack-frames. The jack-frames are of the open truss type. The hull is of a barge-like construction, roughly triangular in plan, with a leg at each corner. The following pictures (Fig. 1) show the outboard profile and plan views respectively of the Jack-up MOPU.

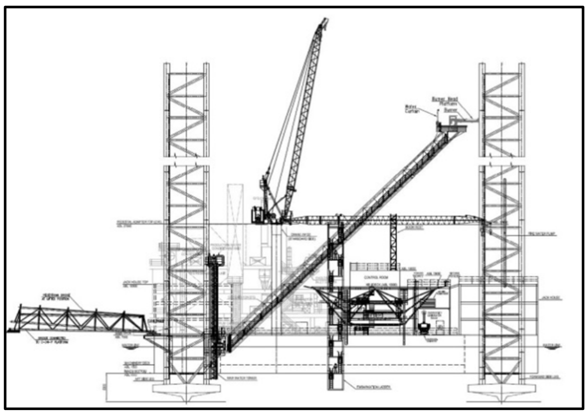
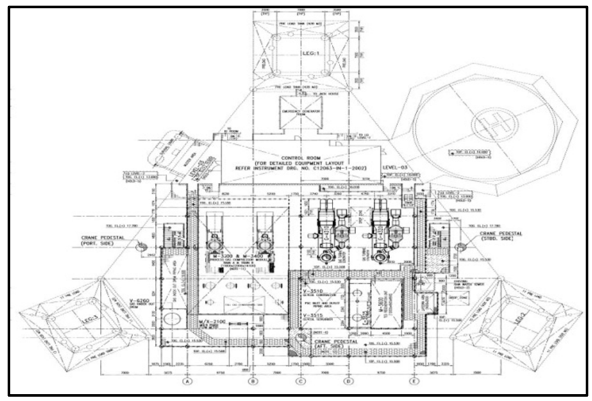

Fig-1: Outboard Profile & Plan Views

The Principal particulars of the vessel are as indicated below.

Length of Hull (m)	71.97 m
Breadth of Hull (m)	83.10 m
Depth of Hull (m)	7.00 m
Leg Length (m)	128.85 m
Longitudinal Leg Spacing (m)	55.40 m
Transverse Leg Spacing (m)	63.97 m
Leg Chord Spacing (m)	7.00 m
Leg Bay Height (m)	4.05 m
Spudcan Effective Diameter (m)	13.28 m
Distance from Spudcan Tip to maximum bearing Area (m)	1.54 m

II. SCOPE OF WORK

In this research work, the failure analysis of Leg Lattice structure of Jack-up rigs has been carried out by conducting both metallurgical analysis and mechanical analysis, to predict the causes and modes of structure failures. Metallurgical examination has been carried out by collecting the sample pieces of bracing & chord pipes from the rig when the rig was dry docked on a barge, assuming that there might be some micro-structural changes in the materials of tubular members such as chord pipes, bracing pipes and joint cans of the welded joints, to identify if there is any lead to failure of these elements. It includes the activities such as determination of material composition, macroscopic examination and microscopic examination. Specimens have been collected from corroded and failed regions of the Rig's Leg Lattice structure to carry out the metallurgical examination. The picture below (Fig-2) shows the rig being towed for conducting study on the failure and for repairs into a shipyard.

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Fig-2: Rig with legs elevated and floating condition

III. APPROACH TO THE PROBLEM

For conducting the mechanical analysis, the FE Analyses have been done to evaluate the causes of failure, location of high stress concentration factors etc. by using the SACS software. The analyses have also been done on the rig under study, and an existing rig built newly with versatile materials and strength. Finally, recommendations have been made for future versatile designs to meet the elevated loads. All the relevant rules and guidelines published in ABS rules for building & classing offshore installations (Ref#1), SNAME Guidelines site specific analysis T&R 5-5A (Ref#2) and ABS rules on working Stress Design, RP-2A, WSD (Ref#3) have been used for generating the FE models and giving proper inputs for analysis.

IV. SPECIFICATIONS FOR ANALYSIS

A. Elevated Loads

Table-1 below shows the specifications of elevated loads for calculation of leg reserve length estimation and for carrying out the Rig Elevated Analysis.

Table-1: Elevated Loads

Elevated lightship	5617 tons
Variable weight	1250 tons
Leg Self weight	2190 tons
ENVIRONMENTAL CONDITIONS:	
Water depth	50 m
Wind Speed	191.88 km/hr (103.6 knots)
Wave Height	13.42 m
Wave Period	12.00 sec
Spud can penetration	3.75 m
Current speed varies with height as below.	
0.00 m	0.0 m/s
47.0 m	0.257 m/s
50.0 m	0.514 m/s

Table-2 below shows the specifications of pinion characteristics.

Table-2: Pinion Characteristics

Number of pinion pairs per leg	6
Holding Capacity (ABS Value) Per Pinion	400 tons
Holding Capacity (ABS Value) Per Pinion Pair	800 tons
Equivalent Stiffness Per Pinion Pair	26,640 (tonne/m)

Fig-3 below shows the Rig in elevated condition in the repair yard.

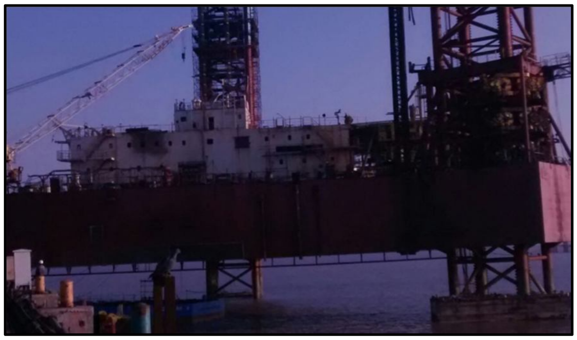

Fig-3: Rig in elevated condition

V. OVERALL METHODOLOGY

Modelling of the jack-up has been based on drawings of the Rig understand, which is the CFEM T-2000-C design, as well as information provided for this study regarding the unit's conversion to a MOPU. A Finite Element (FE) model has been generated in SACS software to analyse the leg lattice structures using "finite element techniques". The site specific geotechnical investigations have been carried out in accordance with SNAME TR 5-5A (Ref#2). For Stress calculations, guidelines given in API RP-2A WSD (Ref#3). Fig-4 below shows the 3D model developed for FE analysis.

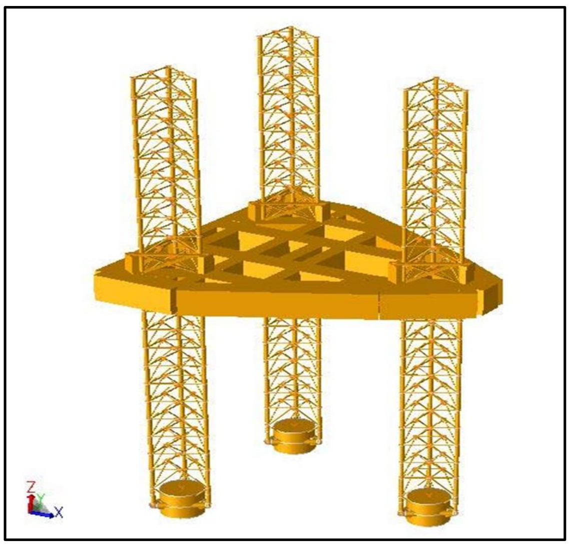

Fig-4: Three Dimensional FE Model of the Rig

The objective of the analysis is to verify that structural reliable supports the total elevated load in a specified environment for storm conditions throughout its life cycle. The leg strength has been evaluated considering all relevant, realistic load conditions and combinations.

ABS Guidance Notes for Dynamic Analysis of Self elevating Drilling Units(Ref#5) have been used for defining the boundary conditions and load cases. The mathematical calculations have been verified by using the structural FE model analysis. A high degree of accuracy in the analytical method has been used.To investigate its validity and verify the accuracy, due to the structure complexity, certain conventions have been adopted in constructing the actual structure of legs for global analysis, as given in some examples in technical papers (Ref#6,7). The results are compared with the results of "Detailed structural analysis" of a lattice structure using the general purpose structural analysis program, SACS.

A. Boundary & Load Conditions

Leg is assumed to be pinned 3.75m below the sea bed (based on leg penetration analysis) which brings more realistic behavior of the legs under the action of environmental and elevated loads. Sequence of fixity input on each joint is shown below is F_x, F_y, F_z, M_x, M_y, M_z. The fig-5 below shows the boundary condition for the model.

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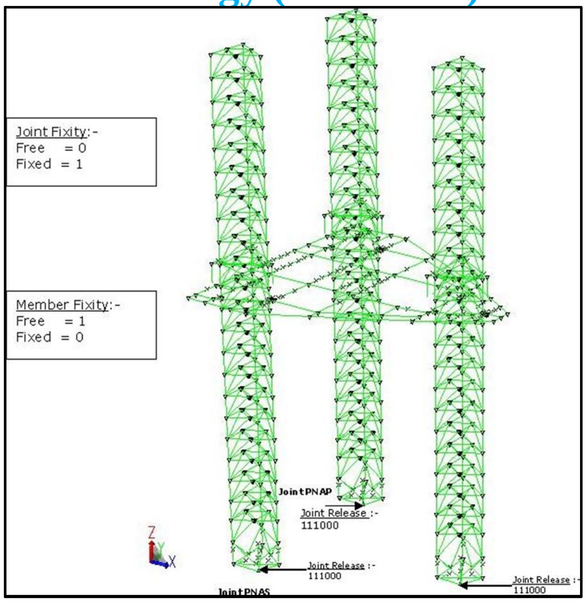

Fig-5: Boundary and Load Conditions

The calculations for the drag coefficients on members, leg hull interface, and pinion stiffness have been discussed in the technical papers already published by the same authors (Ref#13,14 & 15). All sample calculations and tabulated values have been shown in these papers.

B. Crest Height Calculation

Considering a water depth of 35m being the depth at which the rig under study has to be deployed, the wave theory selection and corresponding crest height calculations have been done as shown below.

Depth (D) = 35 m
Height (H_{max}) (As per specs) = 17.38 m Wave Period (T) (As per specs) = 14.0 s
Wave Theory (As per API graph) = Stream 7
Crest Water Depth (output) = 47.08 m
Trough Water Depth = 29.07 m
Crest Height = 47.08-35 = 12.08 m
Trough Depth = 29.70-35 = -5.30 m

Wave theory selection for particular location depends on water depth, wave height and time period associated with same.

Wave Height = 13.416 m
T_{ass} = 12.0 sec
Water Depth = 50.0 m
H/gT^2 = 0.0095
D/gT^2 = 0.0354

For present location, depend on above parameter, stream function theory of 5^{th} order is selected. Refer Fig-6 below.

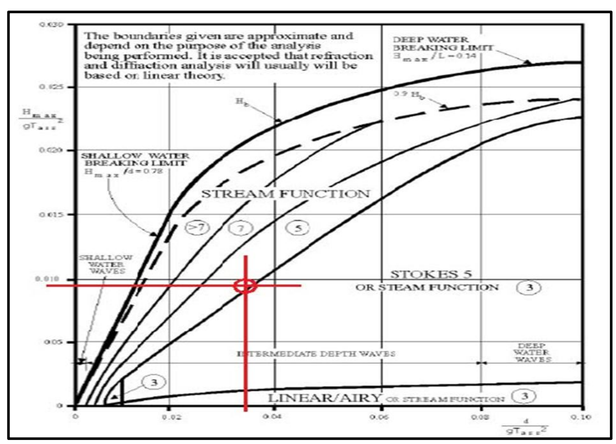

Fig-6:Stream Function Wave Theory

C. Leg Reserve Length Estimation

Table-3 below shows the leg reserve length calculation.

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Table-3: Leg Reserve Length Estimation

Total leg length	124.00 m
Penetration	3.75 m
Water Depth	50 m
Wave Crest Elevation	9.24 m
Air gap	3.275 m
Hull depth	7.0 m
Jack house height	5.084 m
Leg Reserve Length	45.651m

D. Loading Combination

Environmental loads such as wind, wave and current is applied on structure in respective direction. Fig-7 below showstypical environmentalload application scenario. P-delta loads have been included in analysis using respective load cases. Elevated load, variable load, buoyancy load and leg weight are considered as P-delta load cases. Inertial loads due to dynamic action of waves are considered along with environmental loads.

Loading Combination has been considered for wind angles of 0^0, 30^0, 65.56^0, 90^0, 144.44^0, 150^0, 180^0have been considered in storm condition. All load combinations are similar as mentioned below:

Load combination = LTSH (Elevated Lightship) + VRIA (Variable Load) + LEG (Leg Self Weight) + ENVR (Wave, Current and Wind Load) + INERTIA (Dynamic loads) + PDELTA + BUOY (Buoyancy Load).

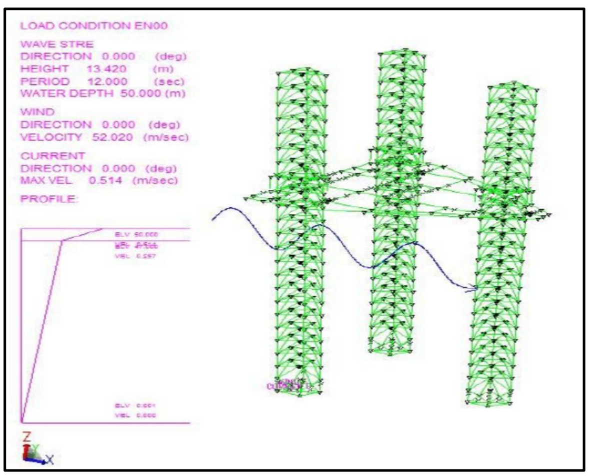

Fig-7: Environmental Load application scenario

VI. GOVERNING EQUATIONS

Ultimate vertical / horizontal / rotational capacity interaction function for spud cans in sand and clay is given by the following formula. (This is the formula for fully or partially penetrated spud cans).

$$\left[\frac{F_H}{Q_H}\right]^2 + \left[\frac{F_M}{Q_M}\right]^2 - 16(1-a)\left[\frac{F_V}{Q_V}\right]^2\left[1-\frac{F_V}{Q_V}\right]^2 - 4a\left[\frac{F_V}{Q_V}\right]\left[1-\frac{F_V}{Q_V}\right] = 0$$

For shallow embedment for sand value of ‘a’ tends to zero, then the yield interaction formula takes the following form.

$$\left[\frac{F_H}{Q_H}\right]^2 + \left[\frac{F_M}{Q_M}\right]^2 - 16\left[\frac{F_V}{Q_V}\right]^2\left[1-\frac{F_V}{Q_V}\right]^2 = 0$$

Q_v = The gross ultimate vertical bearing capacity of the soil beneath the spud can.

= Net preload reaction + $W_{BF,O}$+ B_S

F_v= the gross vertical force acting on the soil beneath the spud can due to applied load case including the efforts of backfill during preloading and spud buoyancy

F_H = the horizontal force applied to the spud can due to the applied load case.

F_M= the bending moment applied to the spud can due to the applied load case.

VII. DETAILS OF DESIGN & ANALYSIS

In view of the orientation of site specific location of the rig, the model has been analysed by taking the heading most critical storm loading directions 0 to 180 degrees with respect to rig heading. The environmental parameters in the directions of 180 deg to 360 degree are quite less when compared to those in 0 degree to 180 degree. On account of the same and the symmetry of the rig about longitudinal centre line only 0 to 180 degree headings were modelled and analysed. Since the response of the jack up to the environmental loads is non-linear due to P-Delta effects and non-linear spud can-soil stiffness, the jack ups response have to be calculated under the action of factored environmental loads as enunciated in the SNAME T&RB 5-5A, Section 8.1.3. The non-linearity due to P-Delta effects have been considered in the Natural Frequency analysis the non-linearity caused by the reduction in effective spud can contact area due to P-Delta effect is accounted by means of a reduced soil static rotational stiffness calculated based on a realistic spud can soil interaction model up of compression only elements. The output of these natural frequency analysis are the natural frequencies and mode shapes only which are further used as inputs to the regular extreme wave time domain analysis to calculated the wave loading including the dynamic inertial contribution from each modes.

A. Spud Can Vs. Tip Penetration Calculation

Based on the soil data collected for site specific for the rig, it comprises of 11.5m of very soft to soft clay overlaying 8.5m medium to fine grained sand up to a depth of 21.0m. This is underlain by a 9.0m thick layer of very dense sand to a depth of 30.0m below the seabed surface. The soil stratum is modeled using specified design parameter and BOR log chart of soil. The friction angle of soil is reduced by 5 degree for the friction angles between 30 deg to 40 deg. as suggested for large diameter spud cans in ISO & SNAME. Vertical bearing capacity is calculated at various spud can tip penetrations below seabed using bearing capacity solutions given in ISO 19905-1.

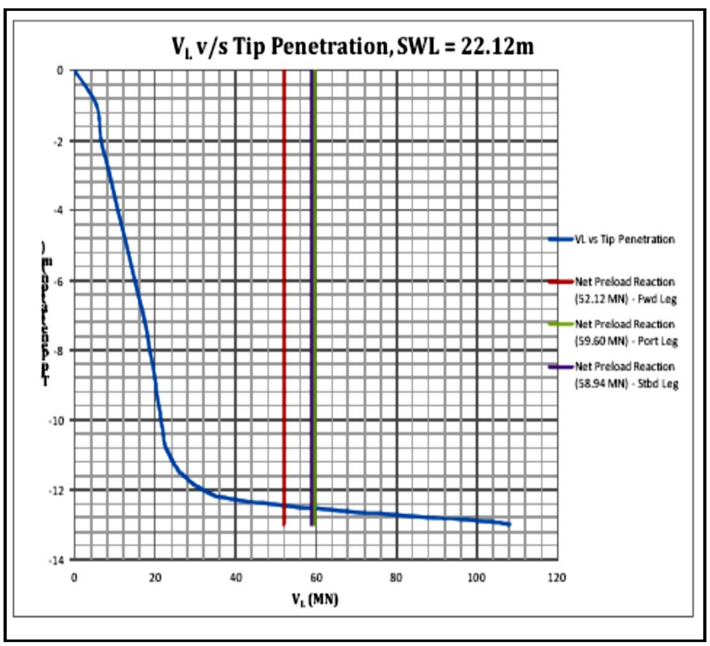

Fig-8: Spud Can Reaction vs. Tip Penetration

The total ultimate vertical bearing capacity is then converted to available structural spud can reaction V_L by deducting submerged weight of backfill during preloading, Wbf0 and adding soil buoyancy of spud can below bearing area B_s. The following formula from ISO 19905-1 has been used.

$V_L = Q_v - W_{BF,O} + B_S$

A graph of V_L vs. spud can tip penetration is plotted as shown above (Fig.8)

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VIII. SUMMARY OF RESULTS

The most critical storm loading directions will be missed by analysing storm directions in 30 degree intervals. The usual approach, particularly for a jack-up with four chorded legs is to analyse storm directions in 15 degree intervals.

With the results obtained from the analysis on the model frequencies, UC values of tubular members, preload reaction and minimum preload requirement etc, in the present case, through FE analysis it has been noticed that the cracks may be developed in some tubular members where stress concentration factors are found to be high. In high cycle fatigue situations, materials performance is normally characterized by the S-N Curve. The graph depicts of a cyclical stress (S) against cycles of failures (N). Failure due to repeated loading is called fatigue. Fatigue failures are often caused by the degradation of metal surface. A rough surface finish, a scratch or oxidation will provide an initial crack. Those cracks will propagate after cyclical loading and eventually lead to fatigue failure. It has been noticed some critical members are failing.

For avoiding the failure situation, a very cost effective modification solution has been suggested, i.e., by increasing the thickness of the chord pipes from existing 36mm to 65mm and material quality with high strength steel from existing AH36 to DQ70. This has to be done in the leg area of about 30m length which is mostly interfacing with hull for most of deployment locations and water depths. With this modification it has been noticed that it meets the complete overturning stability and minimum UC values and the failure of members have been avoided. This suggestion is most cost effective and takes less time for repairs and conversions, so that instead of building entirely new rig, conversion of existing rigs with this low cost modification and still meeting 100 year wave & storm conditions is a good solution.

The modification suggested is as shown in the figure below (Fig.9)

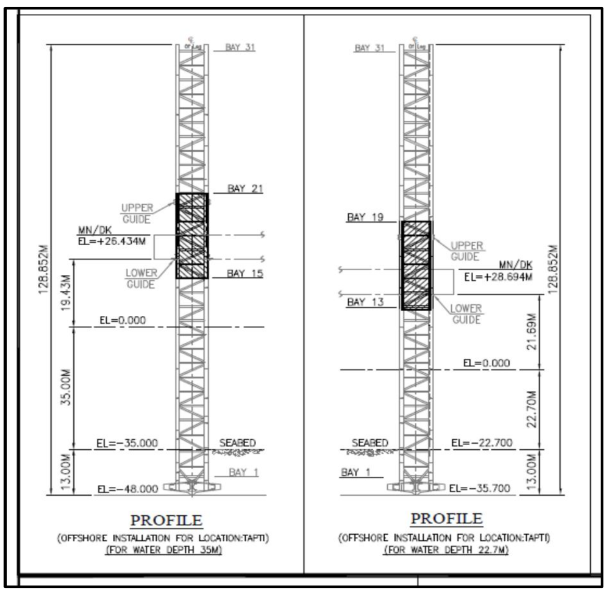

Fig.9: Suggestion for Leg Modification.

A comparison has been made with the existing rig which is being converted without modifications of leg and its failure to sustain the new regulations of 100 years wave & storm conditions as one part and the suggestions made for chord pipes and bracings to meet the criteria without failure on the second part and a third case of building entirely new rig with higher scantlings and full length of the chord and bracings built with higher thickness and high strength steels to meet the new regulations. In other words, with the same FE model by changing the dimensions of the chord & bracings with new thickness and high strength materials, the analysis have been done and the values have been noted. Another modern rig which if built with advanced materials and preload capacities which can withstand the higher elevated loads has also been considered for comparing the results obtained.

The results of the analysis are presented here in the form of comparative graphs with the three different analyses. The comparative studies made have been shown in the graphs below for four different scenarios by comparing the model frequencies of three rigs, Member UC values, Preload Reaction Check & Preload Capacity Check. All the comparative studies have been shown in the form of graphs (Fig. 10,11,12 & 13) which are self-explanatory.

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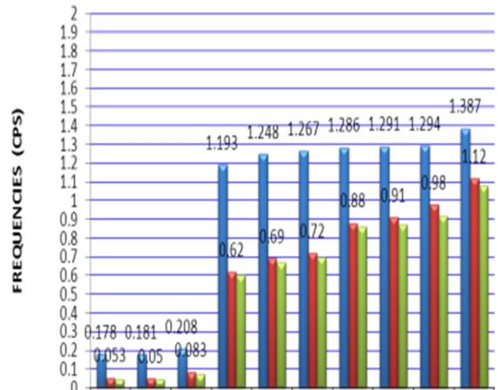
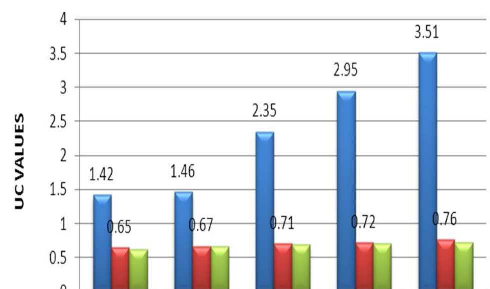


	1	2	3	4	5	6	7	8	9	10
EXISTING RIG	0.178	0.181	0.208	1.193	1.248	1.267	1.286	1.291	1.294	1.387
RIG WITH MODIFICATIONS SUGGESTED	0.053	0.05	0.083	0.62	0.69	0.72	0.88	0.91	0.98	1.12
MODERN RIG AVAILABLE	0.043	0.046	0.073	0.6	0.67	0.7	0.86	0.87	0.92	1.08

CRITICAL MODES

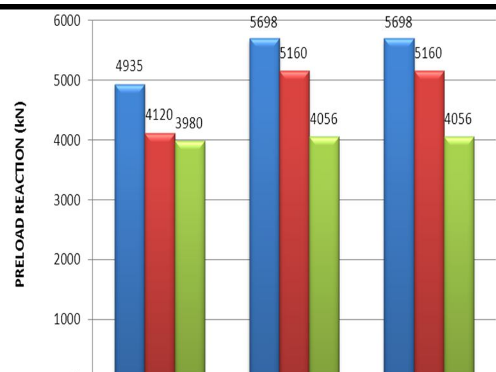
Fig-10: Comparative Study of Model Frequencies



	1	2	3	4	5
EXISTING RIG	1.42	1.46	2.35	2.95	3.51
RIG WITH MODIFICATIONS SUGGESTED	0.65	0.67	0.71	0.72	0.76
MODERN RIG AVAILABLE	0.62	0.67	0.69	0.71	0.72

CRITICAL NODES

Fig-11: Comparative Study of UC Values



	FWD LEG	AFT PORT LEG	AFT STBD LEG
EXISTING RIG	4935	5698	5698
RIG WITH MODIFICATIONS SUGGESTED	4120	5160	5160
MODERN RIG AVAILABLE	3980	4056	4056

Fig-12: Comparative Study Report of Preload Reaction

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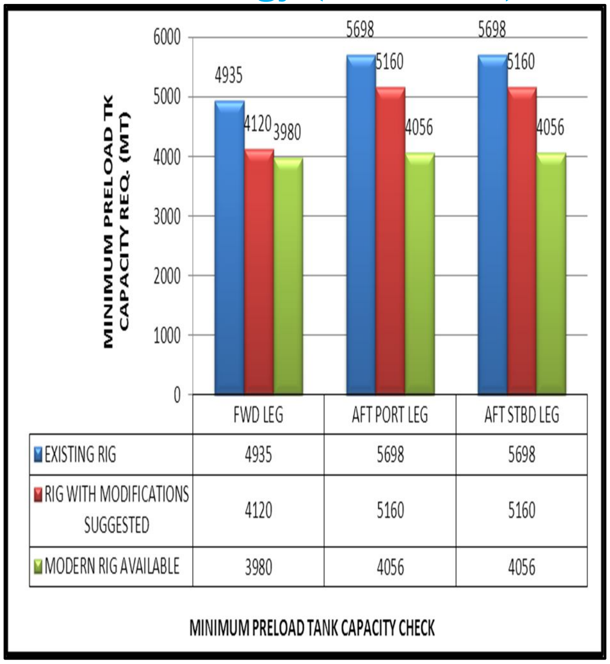

Fig-13: Comparative Study Report of minimum Preload Capacity

IX. CONCLUSIONS

In the present case, through FE analysis it has been noticed that the cracks may be developed in some tubular members where stress concentration factors are found to be high. Pinion Holding capacity is not found to be adequate. (4800 tons per leg or 400 tons per pinion). Additional preload capacity is required. MEMBER UC VALUES found to be Insufficient. Maximum UC Values from all leg members in SACS output is 1.35 for leg chord member, 1.45 for diagonal members and 1.13 for horizontal members.

With the new modifications suggested as shown in the figure-9 above, the overturning check, pinion stiffness and holding capacity are found to be satisfactory and all member UC values are les than 0.7. Hence, the suggested solution is most cost effective, time saving and can be adopted with a proper check on analysis.

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[15]Bh.Nagesh, Prof. I.N. NiranjanKumar, Dr Manu Korulla – Technical Paper on "AN INVESTIGATION INTO THE FAILURE OF PINION HOLDING CAPACITY, JOINT CANS OF A LEG STRUCTURE, AND PRELOAD TANK CAPACITY OF A JACK-UP RIG BY USING FINITE ELEMENT METHOD". International Journal of Science &Technowledge (IJST), Vol-4, Issue-8 (August-2016). ISSN:2321-919X, pp 17-25 (August-2016 journal).

ABOUT THE AUTHORS

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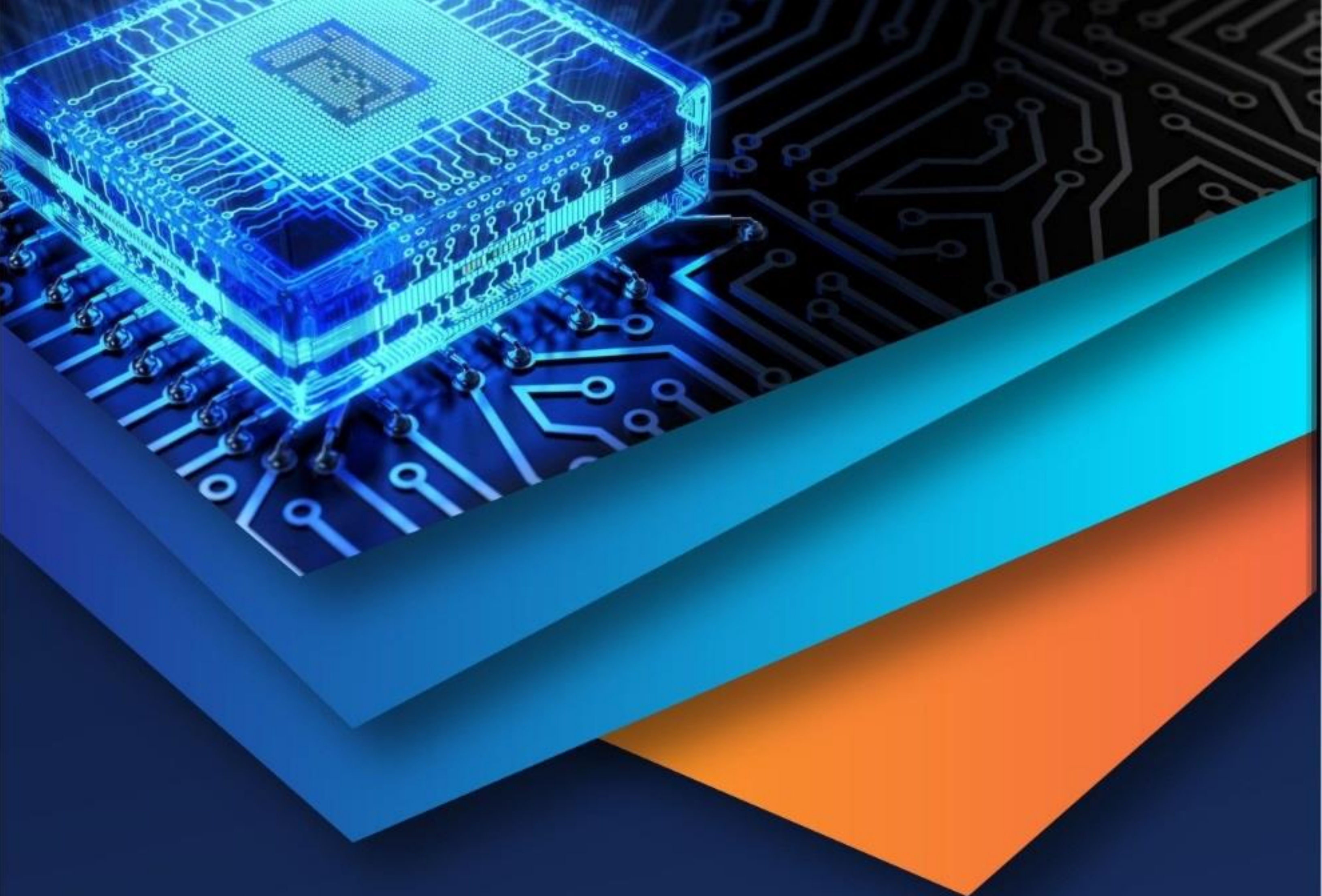

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