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Oil and Gas Industry Onshore Rig Structure Design Study

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Abstract—*Oilfield offshore and onshore drilling rig structures are center part of oil and gas exploration because the rig derrick and mast structures are essential piece of equipment for both onshore and offshore drilling, completion, and services. Different types of offshore and onshore rig derrick and mast structures have reviewed briefly. The major differences and similarities are also discussed. Different types of onshore land drilling rig structures along with design codes and standards are reviewed with more details. Then, the land rig mast structure design base, detailed engineering calculations, and finite element analysis-FEA are addressed based upon the code, standard, and engineering literature. Finally, the onshore design challenges, manufacturing recommendations, future innovative approaches and expectations, and some conclusions are presented.*

Keywords— oil and gas, offshore, onshore, derrick, mast, failure, structure, design, finite element analysis, study, load, stress, fatigue, reliability, seismic, frequency, buckling, static, dynamic, linear, non-linear.

1. INTRODUCTION OF OIL AND GAS INDUSTRY RIG DERRICK AND MAST STRUCTURE

1.1 **Overview of Oil and Gas Industry Offshore Structure**s

Oil and gas industry offshore structures have developed rapidly over the decades. It has been driven by the needs to exploit deeper waters as a result of depletion of shallow water easy-to-reach fields, buoyed by a generally continually rising price of oil and gas. These needs for deep-water developments and a desire to continue to exploit depleting shallow water reserves have created new forms of offshore structures for production, such as production semi-submersibles, tension leg platforms in various shapes and sizes, monohulls (ship-shaped units), spars, monotowers, and production jack-ups. Jackets have continued to be exploited in a variety of ways by using different construction methods, all aimed at speeding up design, fabrication and installation. The offshore structures can be categorized into fixed as shown at Fig.1 below and floating. Subsea completions can also consider as structures placed on the seafloor to support equipment as shown at Fig.2 numbered item 9) and 10) below.

There are many different types of oilfield facilities from which offshore drilling operations take place. These include bottom founded drilling rigs (jack-up barges and swamp barges), combined drilling and production facilities either bottom founded or floating platforms, and deep water mobile offshore drilling units including semi-submersibles and drillships. They are capable of operating in water depths up to 3,000 meters (9,800ft). In shallower waters the mobile units are anchored to the seabed, however in deeper water (more than 1,500 meters (4,900ft) the semi-submersibles or drillships are maintained at the required drilling location by using dynamic positioning technology.

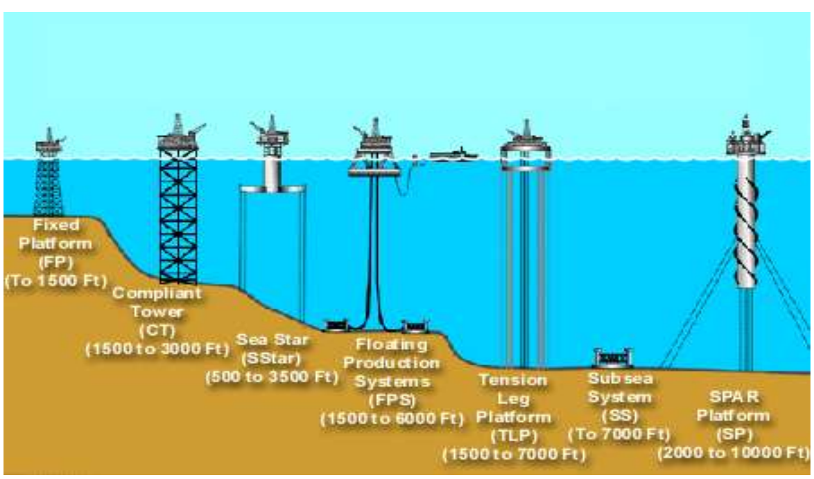

Fig.1: Different types of offshore fixed platforms [1]

Offshore drilling is a mechanical process where a wellbore is drilled below the seabed by utilizing various offshore platform structures, including various derrick types for platforms, jack-ups, semi-submersibles, and drillships.

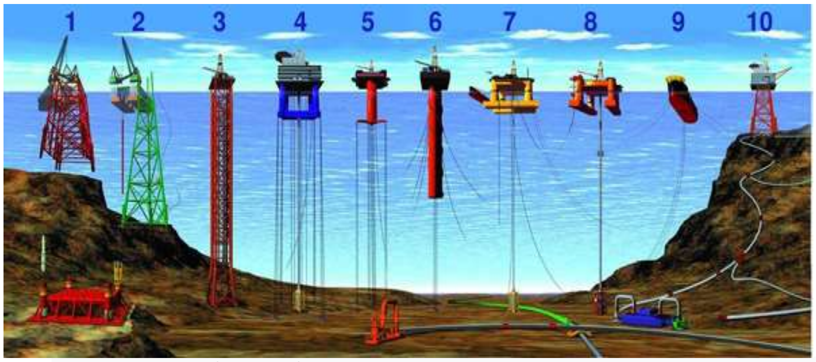

Fig.2: 1, 2) conventional fixed platforms; 3) compliant tower; 4, 5) vertically moored tension leg and mini-tension leg platform; 6) spar; 7, 8) semi-submersibles; 9) floating production, storage, and offloading facility; 10) sub-sea completion and tie-back to host facility [2].

An offshore platform, oil platform, or offshore drilling rig is a large structure with facilities for well drilling to explore, extract, store, and process petroleum and natural gas that lies in rock formations beneath the seabed. Many oil platforms also contain facilities to accommodate their workforce. Most commonly, oil platforms engage in activities on the continental shelf, though they can also be used in lakes, inshore waters, and inland seas. Depending on the circumstances, these platforms may be fixed to the ocean floor, consist of an artificial island, or float [3]. The remote subsea wells may be connected to a platform by flow lines and by umbilical connections. These sub-sea solutions may consist of one or more subsea wells or of one or more manifold centers for multiple wells.

There are many similarities between offshore and onshore drilling structures. The major differences are with BOPs on land surface verses subsea, and special considerations to minimize weight that needed to be supported by the offshore platform structures, The platform drilling rigs themselves are essentially of the same type and construction as land based rigs. Depending on the size and capacity of the particular platform, in case of insufficient size to support the complete drilling package, plus all of the equipment, materials, and liquids necessary for the drilling operation; the use of a tender vessel was often required. The tender vessel, usually a barge, semisubmersible or ship, would maintain station alongside the platform, and all of the necessary manpower, electrical power, mud pumping capacity, equipment and materials stored or located on the tender vessel are transferred to the platform rig as required. With the advent of extended-reach and new horizontal drilling technologies, enabled by steerable drilling technology, a significant number of wells could be drilled from a single platform to maximize oil recovery. Platform drilling rigs were deployed onto these large platforms.

1.2 Oil and Gas Industry Offshore and Onshore Structures Differences and Similarities

Petroleum industry onshore structures include all kinds of oil and natural gas drilling rigs. Drilling Rigs are one of the most important pieces of oilfield equipment structure and are used during a number of stages throughout their life cycle of oil and gas fields. Land drilling rigs can be of different sizes, power capabilities and used in different applications.

Oil and natural gas drilling rigs are used not only to identify geologic reservoirs but also to create wells that allow the extraction of oil or natural gas from those reservoirs. Primarily in onshore oil and gas fields once a well has been drilled to reach the desired reservoir after the cementing of all the casings has been completed, the drilling rig along with its related equipment and materials will be moved off of the well, the drilling site. The smaller rigs, such as a service rigs, workover rig or completion rig, including coil tubing and wireline mast that are purpose-built for remaining completion operations will be moved on to the well site to get the well ready for the production. This frees up the drilling rig to drill another well and streamlines the operation as well as allowing for specialization of certain services, i.e. completions vs. drilling.

There are two main categories of oilfield drilling structures: derrick and mast. Mast and derrick are used to support load from hoisting system and drilling load. However, they are different. A derrick is a semi-permanent structure of square or rectangular cross-sections having members that are latticed or trussed on all four sides. This kind of structure must be assembled in the vertical or operation position, as it includes no erection mechanism. It may or may not be guyed. A derrick is normally used on offshore rigs and they can be divided into two categories; stationary derricks and dynamic derricks as shown on Fig. 3 below, fixed and floating. A stationary derrick is used on offshore fixed structures and jacked up rigs, whereas a dynamic derrick is used on a floating rig, and it is subjected to marine stress [4].

Fig.3: Stationary Derrick and Dynamic Derrick [4]

The onshore mast structure used to support the crown block and the drilling string. Masts are usually rectangular or trapezoidal in shape and offer a very good stiffness, and important to land rig mast is that it can be laid down when the rig is moved as shown on the Fig. 4 below. They suffer from being heavier than conventional derricks and consequently are not usually found in offshore environments, where weight is more of a concern than in land operations.

Fig.4: Onshore Land Drilling Rig Mast Structures [4]

Referring to the API definition, a mast is a structural tower comprised of one or more sections assembled in a horizontal position near the ground and then raised to the operating position. If the unit contains two or more sections, it may be telescoped or unfolded during the erection procedure. Generally, these masts are assembled on the ground in a horizontal position and then are raised by using the draw works or by using hydraulic cylinders as shown on the Fig.5 below. Some masts use telescopic sections and are assembled in a vertical position. Masts are normally used on land rigs; and they are rarely used on offshore rigs.


Fig.5: Left, the Mast Raised by using the Drawwork and Right, Mast Raised by Hydraulic Cylinders [5]

The onshore masts structures include Cantilever Masts and Substructures, Folding Masts, Telescoping Masts, and Bootstrap Masts, and they are also used on various oil and gas well completion rig and service rig applications as shown on the Fig. 6 below.

Fig.6: Onshore Completion and Service Rig Structures-Benchmark Wireline Masts

1.3 Types of Onshore Drilling Rig Structures

Originally, drilling rigs were built with wood, permanent immovable derrick structures, with derricks built on site and left behind after the wells were completed. Once manufacturers began fabricating rigs from steel, this traditional wooden derrick rig became much less common. Drilling rigs were manufactured today have a stronger structure with a smaller footprint and the capability to be moved or adjusted without being dismantled even the largest drilling rigs made from steel are designed to be taken apart and moved once the drilling at a site is completed.

Rotary drilling rigs are used for most drilling operations today. The hole is drilled by rotating a bit and applying a downward force. Generally, the bit is turned by rotating the entire drill string, using a rotary table or a top drive at the surface, and the downward force is applied to the bit by using heavy thick walled pipe, called drill collars, in the drill string above the drill bit. The cuttings generated by drilling are lifted to the surface by circulating a drilling mud fluid down the drill string, through the bit, and up the annular space between the hole and the drill string. The cuttings are separated from the drilling fluid at the surface.

Rotary drilling rigs can be classified as land rigs and marine rigs. The main features of land rigs are portability and maximum operating depth. Land rigs are built so that the derrick/mast can be moved easily and reused for drilling new holes. The various rigs components are skid-mounted so that the rig can be moved in units and connected easily. Today most drilling rigs utilize rotary drilling, with drilling mud/fluid powering the drill string. Many manufacturers of land-based drilling rigs will label their drilling rigs as cantilevered masts (also called a jackknife). The jackknife, or cantilever, derrick/mast is assembled on the ground with pins and then raised as a unit using the rig-hoisting equipment, such as drawwork. The portable mast which is suitable for moderate depth wells usually is mounted on wheeled trucks of trailers that incorporate the hoisting machinery, engines, and derricks as a single unit. The telescoped portable mast is raised to the vertical position and then extended to full height by hydraulic pistons on the unit as shown at Fig. 5 above.

Masts are prefabricated and assembled on site with large pins, and can be erected as a single working unit, and laid down when it's time to move the rig. Masts have helped improve the portability of both large and small drilling rigs in recent years. The rig masts are primarily found on land-based (onshore) drilling rigs because the land-based drilling rigs are onshore setups for drilling oil and gas wells and are capable of drilling up 30,000 feet. Each type of drilling rig is capable of different depths, often depending on overall rig size, lifting capacity, horsepower, number of mud pumps, and pipe choice. For onshore land-based oil and gas drilling rig structures, there are many sizes available, depending on which manufacturer and model is chosen.

Land-based drilling rigs are classified by their maximum drilling depth and portability. There are many types of onshore rigs available today. These onshore drilling rigs can be divided into two categories: mobile and conventional. While almost all onshore rigs can be moved, the term "mobile" more refers to the effort it takes to physically move the entire system from one location to the next location.

The mobile drilling rigs are included truck mounted and trailer-mounted. Truck mounted drilling rigs are made to be mounted into the bed of a truck; this setup includes the mast, drawworks, tools, and mud pumps. Truck-mounted drilling rigs are mobile units that are used in semi-level or uneven ground for drilling purposes that offer a quick set-up process. Heavy-duty truck-mounted drilling rigs can also be useful drilling in remote areas; the off-road capabilities often make the difference between making a site productive and dormant. They are utilized for extracting oil or natural gas by drilling wells, but they are also useful for geothermal drilling. Many truck-mounted drilling rigs are capable of drilling up to 10,000 feet and can be equipped to operate in extreme climates like the Arctic or in desert conditions. They can also be equipped with hydraulic stabilization legs and outriggers to help stabilize the truck on uneven ground.

Fig.7: Jereh ZJ40 Truck-Mounted Drilling Rig in Turkey

The trailer-mounted rigs are highly versatile. They can be easily set up and relocated to drill multiple wells in an area. Trailer-mounted drilling rigs are often used for oil, natural gas, or water well drilling. This type of drilling rig can be a small, towable system, or large, tractor-trailer-sized rig. The trailer-mounted rig can hold the mast, drawworks, and mud pumps. Smaller systems are often used for water well drilling and they typically do not drill deeper than 1,000 feet; larger drilling rig systems are used for oil and gas drilling and extraction and the larger systems can have a maximum drilling depth of about 6,000 to 13,000 feet and they can operate in extreme climate conditions as shown on the Fig. 8 below.

Fig.8: Jereh Truck/Trailer Mounted Workover Rig

Conventional drilling rigs are sometimes called walking drilling rigs; skid-mounted drilling rigs are the most powerful and larger than many other types of drilling rigs. This type of drilling rigs are mobile rigs, but the entire mast and substructure move together short distances to the next location without being disassembled to drill a "cluster" of wells. Because the entire mast and substructure must move together, skid-mounted drilling rigs require more structural reinforcement. This increases the weight and overall design complexity of the structure. They require a small work site and can be installed or moved quickly for oil and natural gas drilling and extraction. Many drilling rigs in the Arctic are skid-mounted for easy movement from wellhead to wellhead. Most skid-mounted drilling rigs can drill anywhere between 13,000 and 30,000 feet, depending on manufacturer and model as shown on the Fig.9 below.

Fig.9: Jereh Conventional Skid- Mounted Drilling RigS

2. Review of Rig Structure Design

2.1 Abbreviations and Acronyms

The abbreviations and acronyms are defined as the followings:

- DNV: Det Norske Veritas (formally DNVGL)
- AISC, American Institute of Steel Construction (AISC)
- ABS: American Bureau of Shipping
- API: American Petroleum Institute
- ASCE: American Society of Civil Engineers
- AS: Australian Standard
- BS: British Standard
- NORSOK: NORSOK Standards are Developed By The Norwegian Petroleum Industry
- ISO: International Organization for Standardization
- FEA: Finite Element Analysis

Glossaries of Terms are explained as the followings:

- DNV: Formerly DNV GL, is an international accredited registrar and classification society headquartered in Høvik, Norway.
- NORSOK: NORSOK Standards are developed by The Norwegian Petroleum Industry.

2.1 Importance of Oil and Gas Rig Mast Structures

Drilling derrick/mast structures are a very important part of the drilling rig; however, these structures are often overlooked because of their static nature. Many drilling activities take place on the drilling rig, with most of the activity being on the drill floor. The supports for all of these activities and working drilling load are the structures. The derricks and masts are the tower structures that are the characteristic images of drilling rigs and are the most important rig structures.

Safety on the drilling rig is of utmost importance. The drill floor is a dangerous place when the rig is operating. Everyone who is working on the rig must always be aware of the surroundings, activities, potential overhead risks and escape paths from their location. Awareness and proper personal protective equipment (PPE) for the situation are essential to preventing injuries. Therefore, rig operators must have proper training and a broad working knowledge of drilling structures and their function to assist the drilling rig operator to conduct daily safe drilling operation, including operational inspection, maintenance and storage are all critical part of safe operational procedures.

A well maintained rig mast structure is very important for its safe operations. Any damage due to wear, corrosion, incidental impact or other means can have detrimental effects on the operation of the drilling rig structures. This can be as simple as a short shutdown time for repair or a catastrophic failure resulting in equipment damage and personal injury. Regular inspection intervals with a pre-planned procedure are essential for keeping the structure in good working condition. Oftentimes drilling rigs are stored for long periods. This does not exclude them from regular inspection and maintenance; otherwise they may not be in good working condition when needed. The manufacturer of the structures will also provide guidance on maintenance and inspections. However, the industry-standard guidance provided in this area will ensure that the drilling rig mast structures remain in working order.

Because a rig mast structure free of any defect, from engineering design, manufacturing, fabrication, welding, commissioning , final testing, and regular inspections and maintenance, plays critical role to ensure its safety and integrity, life cycle structural integrity management of onshore rig mast structures is indeed the best approach.

Based on relevant experiences with the rig mast structure hazards, accidents and means to control the associated risks, rig mast structure risks can be categorized from a technical and physical as well as human and organisational point of view. There are many literatures about the structural integrity management of onshore rig mast structures in the oil and gas energy sector. In general, rig mast structural risk relates to extreme environmental and accidental events, as well as structural degradation can be controlled by use of adequate design criteria, inspection, repair and maintenance as well as quality assurance and control of the engineering processes. With an emphasis placed upon a quantitative design approach for dealing with a life cycle approach especially relating to crack degradation phenomena. The current status of risk and reliability methodologies to aid decisions in the safety management of novel and mature onshore rig mast structures are not focus of this article. The holistic approaches and life-cycle structural integrity management are important for the oilfield rig mast structure to operate in a safe and optimal condition to contribute to success of the oil and gas industry.

2.2 Review of Current Offshore and Onshore Rig Mast Structure Design Standards and Codes

The currently engineering design standard, code and literature review looks at published materials relating to the both offshore and onshore rig mast structures. The most common oilfield rig structure engineering design codes and standards are listed below:

- API Specification 4F, Specification for Drilling and Well Servicing Structures
- API Specification 7K, Design and Manufacture of Drilling and Well-Servicing Equipment
- API RP 2A-LRFD 1st Edition, Recommended Practice for planning, designing, and constructing fixed offshore platforms-Load and Resistance factor design, July 1993
- AISC, American Institute of Steel Construction (AISC) -1989 Specification for Design of Steel Structures
- AISC 335, 1989, Specification for Structural Steel Buildings Allowable Stress Design and Plastic Design
- ABS Guide for the Certification of Drilling Equipment System
- NORSOK standards- N-004 (2013), Design of Steel Structures
- DNV-OS-C101, Design of Offshore Steel Structures, General (LRFD Method), April 2011
- DNVGL-OS-C201, Structural Design of Offshore Unite-WSD Method
- ISO 19901-3 (2014) and -2 (2017) (en), Petroleum and Natural Gas Industry-Specific Requirements for Offshore Structures-Part 3: Topside Structure
- BS ENISO 19901-2, -6,-7 and B/525/12- Design of Offshore Structures
- BS 5950, Structural Use of Steelwork in Building
- AS4100, Steel Structures
- ASCE (2006), Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05
- ASCE (2000), Design of Latticed Steel Transmission Structures

Current oil and gas industry practice is implemented in both offshore and onshore rig structure related codes mentioned above, as well as by many classification societies, and the available codes and standards can be characterized by:

- Design methodologies, criteria formulated in terms of allowable stress, safety factor, load and resistance factor, serviceability, reliability, and safety limit states, considering payloads, environmental and accidental loads

- Semi-probabilistic methods for ultimate strength design which have been calibrated and/or factored by reliability or risk tolerance level analysis methodology, and state of the art methods for linear and non-linear structural analysis.
- Explicit accidental impact or collapse design criteria to achieve damage-tolerance for the system and fatigue or corrosion design checks depending upon consequences of failure (damage-tolerance) and access for with state of the art of non-destructive test or examination methods of regular inspections.
- Global and local structural analysis by finite element static and dynamic analysis methods for ultimate strength and fatigue design checks, including non-linear analyses to demonstrate damage tolerance in view of inspection planning and progressive failure due to accidental damage or experiencing impact load.
- Asset life cycle management feature with strong correlations and links between design, welding, machining, manufacturing processes, assembling, testing, QA &QC, inspection, condition monitoring, maintenance and repair, and services.

Drilling rigs' structure design practices are designed mainly according to the API 4F (2013) standard because The API 4F Specification provides us a tried and tested guideline for rig design. This standard has been always the main reference since and is still to be considered in all design practices in the future. With an abundance of other reference codes and standards available as mentioned above, our design engineers need to take informed and innovative approaches to refers to other standards relevant to the specific parts of the design project process to make sure the structure engineering design indeed following the current best practices.

2.3 The Oilfield Rig Structure Design Bases

As shown from Fig.1 to Fig.9 above, offshore rig structures differ from onshore structures in many ways both in terms of their pre-service and in-service characteristics. From engineering and manufacturing point of views, all offshore structure components are designed, fabricated, assembled, tested and commissioned onshore, then transported to an offshore site, and then finally installed. Therefore, the engineering design criteria, stresses and loads variables, manufacturing processes, construction methods, material specifications and corrosion requirements, risk and reliability analysis, and the acceptable construction tolerances applicable to offshore rig structures substantially differ from those applicable to onshore rig structures.

As we all know that both offshore and onshore rig structures are designed to resist functional gravity loads and the site-specific wind and seismic forces. However, the offshore rig structures are subjected to additional complex forces associated with pre-service construction, transportation, installation, and the in-service wave, wave drift, current and ice. Because specific functional requirements and the site characteristics define a set of given design parameters that need to be incorporated into design, these parameters are often identified as "independent variables".

Offshore rig structures should be designed to minimize both the excitation forces and the response of the structure to these excitation forces. A rig structure can be designed to optimize functional buoyancy forces and hydrostatic pressure and to minimise the excitation forces associated with wind, water wave, flow current, seismic event and ice. Because the component member-sizes of an offshore rig structure, their configuration and arrangement directly influence the magnitude of these forces, they are often defined as "dependent variables"

The study of dependent variables in developing an offshore structure configuration is not limited to minimize the excitation forces alone. Additional requirements often dictate trade-offs to meet several conflicting requirements. One such requirement is to have natural periods that would preclude resonant response of the structure to excitation forces. Another requirement for floating structures is to maintain positive metacentric height to ensure desirable stability characteristics [6].

In order to develop a solution to meet a specific need for cost effective offshore rig structure, many engineers and scientists are tasked to develop innovative offshore structures or component systems to suit for cost-effective development of marginal oil and gas fields. The process of developing such an innovative structure that meets various offshore oilfield requirements have already been discussed in detail in many literatures in public domain with several examples. Many of these structures are already operating in offshore oilfields today and many innovative concepts are in various stages of development.

The main purpose of this paper is to focus on onshore rig structure design with holistic approaches in developing a concept for a particular need and a set of prescribed requirements.

2.4 Onshore Rig Mast Structure Design Bases

Onshore Land drilling rigs are composed of four main systems including the hoisting, power generation, mud circulation, and well control systems. Because the rig structure is a matter of interest within this study, the rest of systems are out of the scope of this paper and will not be addressed further. Hoisting system is composed of the following units:

- Mast and substructure
- Crown Assembly and Travelling Block Equipment
- Rotary Table or Top Drive

As depicted from Fig.4 to Fig.9, there are various masts structures used in oilfield. Masts are major land rig structural latticed towers of rectangular cross section with an open face (API Specification 4F, 2013). These towers are generally composed of one or more separate parts which are connected to each other in a horizontal position and then, the whole mast structure is erected to a vertical working position with hydraulic cylinders. Masts are mostly employed in onshore drilling rigs, while derricks are utilized in offshore drilling rig units and normally refer to steel derrick towers with different geometries. The masts have one open side to allow the travelling block/top drive to move freely along the height of the mast for drilling pipe tripping-in or tripping-out.

As demonstrated in from Fig.4 to Fig.9, a mast substructure is a structure platform under the mast tower which is used for supporting the entire drilling floor, including mast, drill pipes and tools, hoisting drum winch and drawwork, oil well dog house, driller's cabin, and many other drilling equipment. In general, a mast substructure provides the structure support for the whole rig working area, referred to as drill floor along with the working personnel. For a guyed mast, the substructure is also used as anchor points of guy-lines as shown on Fig. 5, Fig.7 and Fig. 8 above.

The American Petroleum Institute (API) provides standards for the operation, manufacture, and design of drilling and service rigs. The API 4F standard outlines a set of general guidelines for the design of drilling and service rigs, both on and offshore, for a range of environments and weather conditions. The API 4F facilitates the broad availability of proven, sound engineering, and operational practices. The API 4F standard itself is also reviewed and revised every five years to ensure a current knowledge on engineering design practices and new challenges.

API 4F also offers a limit on allowable stresses on components, safety factors on all structural components for different environmental conditions. It formulates information on acceptable materials and quality control methods during the manufacturing of the rig structure. These conditions provide a level of confidence that the rig will function safely in its intended environment.

Another major component of any rig structure design is the loading on the mast due to wind. Wind pressure loading on complex rig structures can be difficult to calculate. API 4F provides a simple method of calculating wind load on a large steel rig structure through a wind pressure analysis on individual members. With each new edition of 4F, the new wind loading requirements increase the calculated load on the rig structure. This leads to more stringent conditions for the stabilizing the rig structure package to combat overturning and sliding and generally requires a larger rig footprint. For instance, a rig designed to the 2nd Edition of 4F would likely require some structural reinforcement and increased stability structure to meet the 3rd Edition requirements, and even more stiffening structures needed to meet 4th Edition.

Load combinations: Onshore rig mast structure shall be designed based on the load combinations according to the API 4F (2013) standard. In general, a drilling rig structure includes the following types of loads:

Dead Load: they could include the weight of crown, traveling block hook, top drive and guide rail, racking platform and mast. Besides weight of the mast, other loads are applied on mast through the guy-lines or other structure beam member.

Working Load/Maximum Rated Static Hook Load: it is the weight of the travelling equipment and a static load applied to the travelling equipment and it might contain the static hook load and hoisting rope work force.

Rated Setback Load: the rated setback load is the maximum weight of tubular goods that can be supported by the substructure in the setback area according to the API 4F (2013) standard.

Wind Load: application of the wind load on the rig structure should conform to the Section 8.3 of the API 4F (2013). Therefore, the wind environments should be considered when analyzing the structure. Tt includes three kinds of wind speed and three kinds of the wind direction. In order to more comprehensive comparison, the direction of wind can be divided into front wind, back wind and lateral wind with reference to the mouth direction of the well. The wind load is applied to all the nodes bearing the wind load.

Equipment Load: the weight of the equipment attached to the drill rig mast structure as well as their working moment is exerted to the rig mast structure. Based on the Section 4.7 of the ASCE 7 (2006), an impact factor should be applied on the equipment weights to allow for ordinary impact conditions in applications containing unusual vibration and impact forces**.** Top drive toque is good example of the equipment load.

Top Drive Torque: The guide rail of top drive is connected with the reaction torque beam on the mast, top drive torque is passed to the mast by the reaction torque beam, the point of action are the junction points of top drive guide rail and reaction torque beam.

Seismic Load: Section 8.5 of the API 4F (2013) addresses the Earthquake Loads imposed upon the drilling rig structures. This load case is not a dominant environmental load case in most regions of the world. Because the drilling process is carried out in a very short period of time, exposure of the rig mast structure to the seismic loads is considered unlikely case. However, design of drilling rigs for seismic loads have recently been a routine procedure and for fixed offshore platforms the provisions of ISO 19901-2 (2017) are utilized. In land drilling rig mast structures, the API Specification 4F (2013) does not provide the design methodology for seismic loads and engineers can refer to the local seismic design standards for the seismic analysis and design of rig mast structures.

Design calculation steps are list of following steps:

1. To determine the actual length of column: The rig mast tower structure is fixed at bottom end and free at another end. Hence for buckling calculations total length of tower will be considered as:

L = actual length of rig mast column.

2. Determine end fixity factor from the manner of support of the ends. Because here one end is fixed and another end is free, we took K = fixity factor = 2.

3. Compute the effective length: Effective length (L) = effective length of the rig mast tower

4. To calculate moment of Inertia. Moment of Inertia about X axis is given by:

$$I_{xx} = [\frac{bd^3}{12} - \frac{b1d1^3}{12}] \quad (1)$$

5. To calculate radius of gyration: r = radius of gyration:

$$r = \text{radius of gyration} = \sqrt[2]{\frac{Ixx}{A}} \quad (2)$$

6. To calculate slenderness ratio:

$$S.\ R. = \frac{\text{Effective length(L)}}{r} \quad (3)$$

7. To calculate critical ratio of the rig Mast tower: Critical ratio is given by:

$$Cc = \sqrt[2]{\frac{2\times\pi^2\times E}{\sigma y}} \quad (4)$$

Where,

Cc = critical ratio

E = modulus of elasticity of column material

σy = yielding strength

8. To calculate buckling stress, As Cc is greater than S.R. we use Johnsons parabolic formulae

Buckling Stress is given by:

$$\sigma = \sigma y = [1 - \frac{\sigma y\times(S.R)^2}{4E\pi^2}] \quad (5)$$

9. To Calculate factor of safety, F.S [7]

$$F.S = \left\{1 - \frac{(S.R)^2}{2\times Cc^2}\right\}\left(\frac{\sigma y}{\sigma}\right) \quad (6)$$

Where,

Cc = Critical ratio

σy = Yielding strength

σ = Stress of the Rig Mast Tower [7]

For the Steel Latticed Mast Tower, the design of tension members, the design tension stress on the net section of concentrically loaded members is taken to be the yield stress Fy, but if the bolted connection is eccentric to the centroid of an angel, the design stress on the set section is 0.9Fy. The unconnected leg of an angel connected by one leg may be considered fully effective unless it is wider than the connected leg, in which case it should be assumed to have the same width as the connected leg [8] [9].

The design of compression members, the design compression stress Fa on the gross cross-section area, or on the reduced area where specified, of axially loaded compression members shall be:

$$\text{Fa} = \left[1 - \frac{1}{2} \times \left(\frac{K\left(\frac{L}{r}\right)}{Cc}\right)^2\right] Fy \qquad K \times \frac{L}{r} \leq Cc \qquad (8)$$

$$Fa = \frac{\pi^2 \times E}{\left(\frac{KL}{r}\right)^2} \qquad \frac{KL}{r} > Cc \qquad (9)$$

$$\text{Cc} = \pi \sqrt{\frac{2E}{Fy}} \qquad (10)$$

Provided the largest width-to-thickness ratio w/t is not greater than [10]:

$$\left(\frac{w}{t}\right) lim = \frac{80}{\sqrt{Fy}} \qquad (11)$$

Where,

Fy = guaranteed minimum yield strength

L = unbraced length

r = radius of gyration

K = effective length coefficient

KL/r = largest effective slenderness ration of any unbraced segment of member

w = distance from edge of fillet to extreme fiber

t = thickness

After completion of all stress, deflection, safety factor calculations, the finite element analysis-FEA should be conducted to make sure the calculation results converging with FEA outcomes and actively seek continuous engineering design improvement.

2.5 The Finite Element Analysis of the Onshore Rig Mast Structure

SolidWorks and its simulation premium and ANSYS were used for 3D design modeling and finite element analysis-FEA. Detailed structural modeling and design procedure of the onshore steel drilling rig mast structures is outlined in the followings.

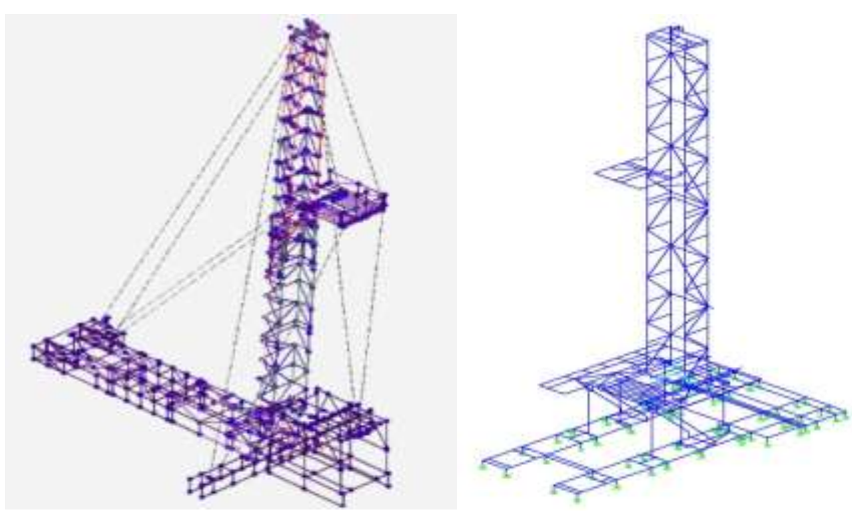

Fig.10: Onshore Land Rig Mast and Substructure (left with guyline and right without guyline [11])

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The onshore land rig mast simplified general structural layouts for FEA are shown as Fig.10 above. Because the mast and substructure of the land drilling rig are modeled for finite element analysis and design purposes, the geometrical information of these structures is not the focus of the paper.

Drilling pipes and doghouse/cabins are modeled solely for absorbing the wind loads imposed upon the structure without having a structural role. The substructure can be constructed of several parts. The substructure surface which is normally located at the height of 7-9 meters above ground is used as the drilling floor; therefore, the columns of the substructure can transfer the loads to the ground firmly. As the results, the sub-structural elements at the ground level can provide the entire structure with the required stability either in erection position or in in-place stages.

Because the most important rig structure is the mast structure, the rig mast structure FEA would be discussed in more details. The mast can be divided into four separate parts, including the Top, Mid-top, Mid-low, and Lower parts as represented in Fig.11 below.

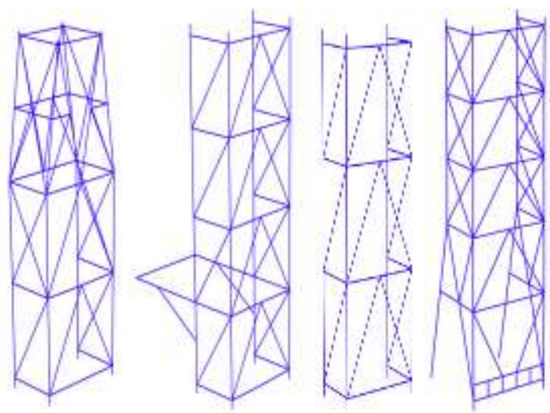
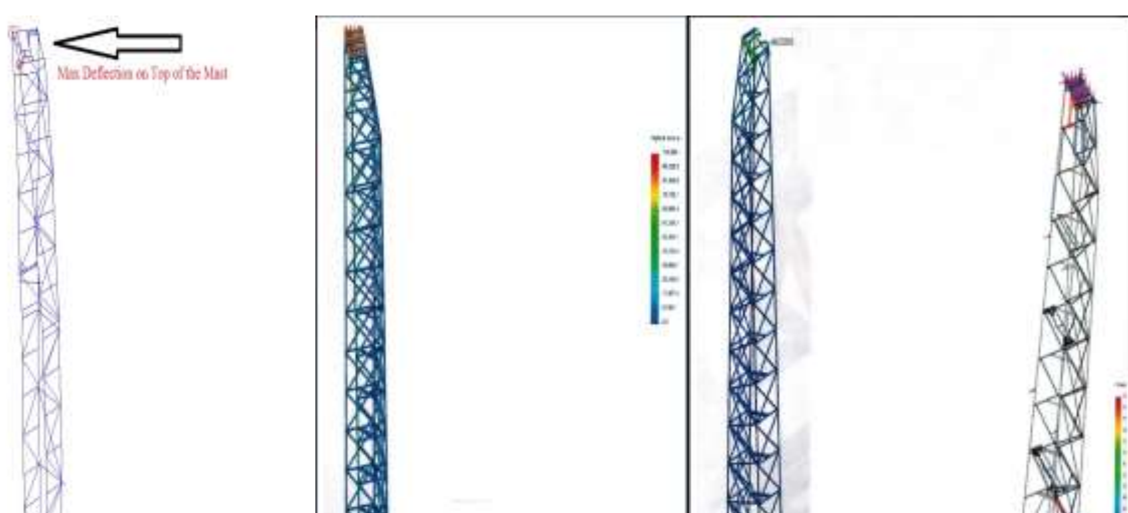


Fig.11: Divided Rig Mast for Aiming Design Telescoping and Folding Mast (Left to Right: Top, Mid-Top, Mid-Low, and Lower [12])

With proper divided the mast structure into separate sections as shown on Fig.11 above, we can achieve more flexible design, such as telescoping rig mast and folding rig mast. This division feature can reduce the overall length of the rig mast structural parts for transportation purposes and thus conforms to the local transportation rules.

For simplicity of the finite element analysis, the main rig mast structure FEA iterations are conducted as shown on Fig.12 below based upon the different of load, stress, deflection, and required mast structure safety level until the outcomes meet engineering design intents and compliance with related codes. As expected, the maximum deflections would be at top end of rig mast structure.



3. CHALLENGES FOR ONSHORE RIG MAST STRUCTURE DESGIN

3.1 Challenges for Rig Mast Structure Design

The followings are listed some challenges related to engineering design to facilitate better manufacturing processes, quality control, testing, commissioning, maintenance & repair, and mast structure life-cycle management.

- There are many competing factors need to put into consideration during design phase such as the budget, project timeline, material availability, manufacturing process, welding engineering design, rig mast erection design and operational control, safety features and monitoring, and quality control & inspection, commissioning, operational and load test, and engineering document and control.
- In addition to API specification 4F as the main code for the rig mast structure design, there are so many related standards out there as the design references as described on previous section 2.2 "Review of Current Offshore and Onshore Rig Mast Structure Design Standards and Codes". Because most design codes and standards do not have more detailed specifications or specifically requirements for each appropriate rig mast structure application, this could point out or direct engineering design in different design focus, such as: minimum design load for buildings, for latticed steel transmission structures. Moreover, API 4F is mainly based upon the Allowable Stress Design methodology while AISC and ASCE had adapted the Load and Resistant Factor Design Method. All these factors have leaving the design engineer to decide the best way to proceed based on their knowledge and experience. Therefore, there are in needs to have more research done and incorporate research and test findings into a main stream design code or standard to guide engineering design to safe guard public and environment safety.
- Onshore rig mast structure safety and reliability are the very important during the engineering design process to mitigate any potential failure through the entire life –cycle of the rig mast structure. Even a statically well designed drilling rig mast structure may have poor dynamic characteristics, which can cause earlier structure failure of the drilling rig mast that has been working under harsh environment condition or under vibrating severely operational condition.

Because there are many structure failure causes for an oilfield rig mast, the better engineering designs to overcome or eliminate these structural failure causes have presented a big challenge for engineers. A summary root cause of rig mast structure failure is listed below:

- Rig mast structural failures normally develop in a sequence of technical and physical operational events. Therefore, any structural damage can cause progressive structural failure.
- The main cause of actual structural failures is abnormal resistance or accidental or abnormal loads due to human errors negligence, and omissions.
- Design errors with wrong material as a structural deficiency can lead to a crack, fatigue or overload damage to the rig mast structure.
- Fabrication imperfections, such as cracks or shaft misalignment, can also affect the structure strength, such as a poor l welders' performance, environmental conditions, can lead to a normal structural property or with the imperfection weldment size caused by using a wet electrode, or another careless fabrication error.
- Some initial fatigue failure of a brace in a rig mast structure was due to lack of fatigue design checks, fabrication defects as well as the poor quality control measures, such as inadequate inspection and inappropriate load testing.

3.2 Manufacturing Processes and Practices Recommendations for Rig Mast Structures

The manufacturing and fabrication quality are one of the main design assumptions. Deviations in the manufacturing and fabrication quality are one of the reasons for reduced correlation between observed failures and the probability for failure given by the finite element analyses- FEA.

Besides differences between the features of different structures, the manufacturing and fabrication processes might induce additional uncertainties, especially regarding the local geometry that affect fatigue performance. Hence, it is crucial to update the design model to as build model to reflect the real world scenarios to predict crack growth based on the particular features of each structure and according to inspections during fabrication and operations.

The QA&QC during and after manufacturing and fabrication could address concerns of material and geometry, especially tolerances relating to misalignment, possible crack or defects and other damages that could occur. It is noted that weld defects are primarily related indirectly to specification of welding procedure and environment. So, the Non-Destructive Exam-NDE inspections play an important role to detect welding defect or crack due to wet electrodes or other deviations from standard welding procedures.

Fig.13: Rig Mast Structure Manufacturing Recommended Practices with Jigs, Template Support, Reinforcement, Bracing/Gusset, and QA&QC

As shown at Fig. 13 above from left to right, many special fabrication jigs, layout templates, reinforcements, and proper managed QA&QC are needed to ensure rig mast structure integrity. Moreover, proper engineering document control with regarding to the geometry, dimension, proper alignments, and potential crack or defect inspection and repair play an important role in case of miscommunication or misuse manufacturing, fabrication, and welding standard operational procedures.

Full penetration welding, proper welding procedure specifications (WPS) and welding procedure data sheet (WPDS), and all welding consumables should be used and should comply with American Welding Society or Canadian Welding Bureau or equivalent. All welders who perform the welding must be a qualified welder as per international standards. The post welding treatment might be needed depending on the design intent and the application requirements.

There are many machining, geometry fitting, and safety feature control processes commissioning and testing involved before and after manufacturing and post welding to properly prepare and get the final rig mast structure manufactured to meet the engineering design specifications. Each subassembly load testing and commissioning step along with manufacturing sequence and quality control are also critical to ensure the overall integrity and high quality product of rig mast structure.

3.3 Discussions

There are many differences and similarities between offshore and onshore drilling structures. However, the engineering design and manufacturing principles are fundamentally the same. Special attentions must give to the major differences, unique applications, load and load combinations, stresses, failure model, and safety and environment impact and consequences.

The complexity in design of offshore and onshore associated rig structure continues to demand the critical analysis of all operating loads and constraints. These critical analyses may include static linear and non-linear analysis, buckling analysis, natural frequency analysis, seismic and dynamic analysis. These analyses validate that offshore and onshore rig structures meet all operating conditions with safety and integrity during their life-cycle. By designing, analyzing, simulating the working conditions and characteristics of structural models, engineers can improve and optimize their structural designs to ensure overall engineering integrity. Integrated FEA tools allow engineering design to create and check structural models to ensure design code compliance.

Onshore rig mast structural integrity and reliability life-cycle management should start from engineering design, analysis, manufacturing and fabrication processes, assembling, testing, commissioning, inspection, monitoring, maintenance, service, and repair, QA& QC and regular inspection to control or eliminate any crack or damage before and after installation and operation.

To prevent inadequate design and inspection, fatigue, overload or impact damages, crack developing into failures for the rig mast structures, the holistic risk focused, reliability centered, safety oriented approaches needs to be yet further researched and developed.

4. Conclusions

This oil and gas industry onshore rig mast structure design study is conducted and combined with my personal successful working experiences through over several dozen rig structure engineering design, finite element analysis-FEA, manufacturing, fabrication, welding, commissioning, QA& QC, have concluded some insights with regarding to the following areas:

- In addition to API specification 4F as the main code for the rig mast structure design, there are in needs to have more research done and incorporate research and operational test findings into a main stream design code or standard to guide engineers with systematic approach to ensure adequate engineering design to safe guard public and environment safety, instead of spending much time searching and referencing from different codes with different approach and design focus as shown on section 2.2 mentioned above.
- The novel onshore land drilling rig mast structure design has to meet demands of development of industry trends, such as walking rig and fully automatic rig, which has resulted in enhanced structure and welding strength with high level of reliability and safety. Therefore, innovative onshore rig mast structure engineering design needs to provide for a safer and cleaner work environment than that of a conventional rig, deliver significant life-cycle cost savings, have a very small footprint with compact general layout, and become lighter with high level of mobility to facilitate rig easily moving across thawed gravel roads, narrow bridges, and frozen tundra with short set-up time and high operational efficiency and reliability.
- A properly modeled FEA can provide great insights to help investigation any stress concentration spot and create innovative solution to reinforce or eliminate the weakest link in order to meet engineering design intents and specifications. Moreover, the design, modeling, and analysis of today's complex onshore rig mast structures represent a major capital investment in oil and gas production. Using advanced engineering design software and finite element analysis tools, engineers can design and analyze complex offshore and onshore structural systems with confidence to ensure compliance with industry design codes and meet local operating conditions from static and dynamic load, wind, and seismic loads.
- All necessary well-developed and tested welding procedure specifications and welding procedure data sheets are needed to guide proper welding processes from start to finish. High quality of workmanship for welding, machining, manufacturing, assembling, testing, and proper quality control procedures and processes are crucial to ensure high quality and reliability of rig mast structures.
- Material fatigue is considered the most common cause of structural failure for in-service structural component, subassembly, frame, and/or equipment. Therefore, rig mast structure life-cycle fatigue and reliability based design and inspection management along with proper calculations of load and load combination, stress, wind force, level of deflection, vibration and fatigue level, welding strength are all important for the integrity of a rig mast structure.

5. References

[1] Kabir Sadeghi. (2007). An Overview of Design, Analysis, Construction and Installation of Offshore Petroleum Platforms Suitable for Cyprus Oil/Gas Fields, GAU J. Soc. & Appl. Sci., 2(4), 1-16, 2007.

[2] Oil States Industries, Inc. (15 December 2008). "Types of Offshore Oil and Gas Structures", courtesy of Oil States Industries with license to NOAA Ocean Explorer: Expedition to the Deep Slope. National Oceanic and Atmospheric Administration. Retrieved from 23 May, 2010.

[3] Ronalds, BF (2005). "Applicability ranges for offshore oil and gas production facilities". Marine Structures. 18 (3): 251–263.

[4] DrillingFormulas.Com January 12 (2016). What are Differences between Mast and Derrick. Retrieved from http://www.drillingformulas.com/what-are-differences-between-mast-and-derrick/

[5] Introduction Land Rigs. (2015). International Association of Drilling Contrctors, IADC Drilling Manual. Retrieved from https://www.iadc.org/wp-content/uploads/2015/08/preview-rt.pdf

[6] Cuneyt Capanoglu. (2005). Novel and Marginal Field Offshore Structures, Handbook of Offshore Engineering, Chater 2.1, 2005.

[7] Pritibala B. Pekhale and Prof.P.V. Deshmukh. (2017). Stress Analaysisi of Mast Structure for Water-Well Drilling Machine. IJARIIE-ISSN(0)-2395-4396, Vol-3-Issue-6-2017.

[8] Guid for Design of Steel Transmission Towers, ASCE Manual 52, 2nd Ed., American Society of Civile Engineers, New York, 1988.

[9] Design of Latticed Steel Transmission Towers ANSI/ASCE Standard 10-90, American Society of Civile Engineers, New York, 1991.

[10] Edwin H. Gaylord, JR., Charles N. Gaylord., James E. Stallmeyer. (1997). Structural Engineering Handbook., 4th Edtion., ISBN 0-07-023724-7, TA 635.S77, page: 30-5, 1997.

[11] Design Strudy for API 4F Transition from ASD to LRFD, Phase-2 Final Report, (2016). Stress Engineering Service Inc. SES Document No.; 1102926-EN-RP-0001 (Rev B) 9 August 2016.

[12] Salatin Reza. July (2018). Optimization of Onshore Steel Drilling Rigs Using the Convergence Rate Approach Integrated Metaheuristic Serch Algorithms. The Graduate School of Natural and Applied Science of Middel East Technical University.

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