COMPLIANT TOWER PLATFORMS: A GENERAL GUIDANCE FOR ANALYSIS, CONSTRUCTION, AND INSTALLATION

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ABSTRACT

Offshore structures are complicated structures requiring the consideration of different aspects both for design and construction procedures. The compliant structures are one of the offshore structures used in oil and gas industry. This type of structures requires special considerations during their design procedure. However, construction of such structures has share similarities with conventional steel jacket structures. The aim of this paper is to present a general guidance about the design and construction of compliant towers. Moreover, design and analysis methods of the structure along with the required data for design of piles with respect to code provisions are provided. In addition to that, the fabrication, assembly and erection, loadout, transportation, launching methods are also discussed. Furthermore, corrosion protection methods are also submitted in this paper.

Keywords: Offshore, Design, Compliant Tower, Oil and Gas

INTRODUCTION

By the beginning of the 1970s, the ongoing search of oil and gas field in open seas lead the operators to explore deeper waters in order to cope with the increase in demand of hydrocarbons to fulfill needs of developing the world. When deepwater conditions combined with harsh weather conditions are reviewed, fixed jacket platforms with excessive dimensions were needed to obtain desired stiffness and strength of required structures. Such platforms were expensive and lead operators in search of new solutions to reduce developments cost. This challenge opened a new era in offshore construction. As a result of that, a new type of structures called compliant structures had been evolved. This kind of structures are fixed at their base to the seabed but also free to move with lateral forces. The compliant mechanism of the structure provides mobility to the structure to dissipate destructive forces. Stability of the structures is either provided with large buoyancy forces or guylines. The structures are generally designed with natural vibration frequencies different from the ones of waves to reduce the amplification of forces. Additionally, piles of such structures should have the sufficient length to cope with loads (Patel and Witz, 1991).

The construction technique used for the conventional fixed platforms can be implemented to be used for such structures. The compliant tower structures are divided into two groups; guyed towers and freestanding compliant towers. Vertical and lateral stability of free-standing compliant towers are provided with floatation devices. On the other hand, the vertical and lateral stability of guyed tower are provided by guylines. One such example of the free-standing concept is adopted by Petronius platform in the Gulf of Mexico. The guyed concept is used on the Lena platform in the Gulf of Mexico. In this paper, freestanding type compliant towers are investigated. The guyed type of compliant towers are out of the scope of the paper.

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DESIGN OF COMPLIANT TOWERS

Design methods used for offshore platforms are different according to the type of structure. For instance, the fixed jacket platforms are highly rigid structures with insignificant displacements. Due to that reason, more forces accumulate inside members. Therefore, the design of the member should focus on to limit stresses in members instead of controlling displacements (Petrowiki.org, 2018).

Loads

Offshore platforms are different kind of engineering works due to their unique placement and uses. Due to the environment, they are placed in; there are different types of loads applied to the structures. Most of the loads are generally lateral loads. The design of the structures is based on these loads and strength of the material used for construction.

The load acting on offshore structures can be classified into following categories:

i. Dead Loads
ii. Live Loads
iii. Environmental Loads

i. Construction and Installation Loads
ii. Accidental Loads

The dead loads and live loads are gravity loads applied to the structure. Environmental loads are consist of different loads like wind forces, wave forces, earthquake loads, ice and snow loads and marine growth. Furthermore, lifting forces, loadout forces, transportation forces and launching, upending forces can be classified as construction and installation forces. Lastly, rare occurring forces like impact forces can be listed under accidental loads. In spite the fact that, earthquake forces are treated as accidental loads for onshore construction conditions, earthquake forces are considered as environmental loads for offshore structures. Loads values for design are based on studies carried on available data. U.S (API) and Norwegian (NORSOK) code provisions suggest the design should be carried out according to 100 years data. On the other hand, British standards (BS) suggest 50 years of or more for design.

The Analysis of Compliant Towers

The compliancy means flexibility. Therefore, compliant towers are designed as floating structures fixed at the bottom to the seabed. In addition to that, that floating design means that, the structure is allowed to displace more under wave actions in order to reduce the impact of environmental forces like wind, waves and currents. Since the displacements are the high dynamic response of such structures, they are highly important for design considerations. Due to that reason, the geometric nonlinearity is an important aspect for the analysis of such structures. Previous studies carried out on such structures considered the design as a rigid body with one or two angular degrees of freedom. Although, the structures is assumed to be flexible, very few studies considered it as such and when it is analyzed like that either it is designed as lumped-mass or using finite element methods (Adrezin, Bar-Avi and Benaroya, 1996).

The time period between large waves is approximately 13 seconds during hurricane conditions (Offshore-mag.com, 1999).The natural period of primary modes of the structure should be reasonably higher than those of seastate in order to prevent an increase in environmental forces due to resonance. To achieve that, mass and stiffness characteristic of compliant towers are adjusted accordingly to regulate natural vibrations of the structures with respect to the frequencies of wind and waves. In general, compliant towers with flexing jackets or tubes have a natural period of 30-33 seconds. On the contrary, platforms in shallow

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water conditions only have 3-4 seconds (Offshore-mag.com, 1999). Fig. 1. Illustrates the modal shapes of Baldplate Compliant Tower.

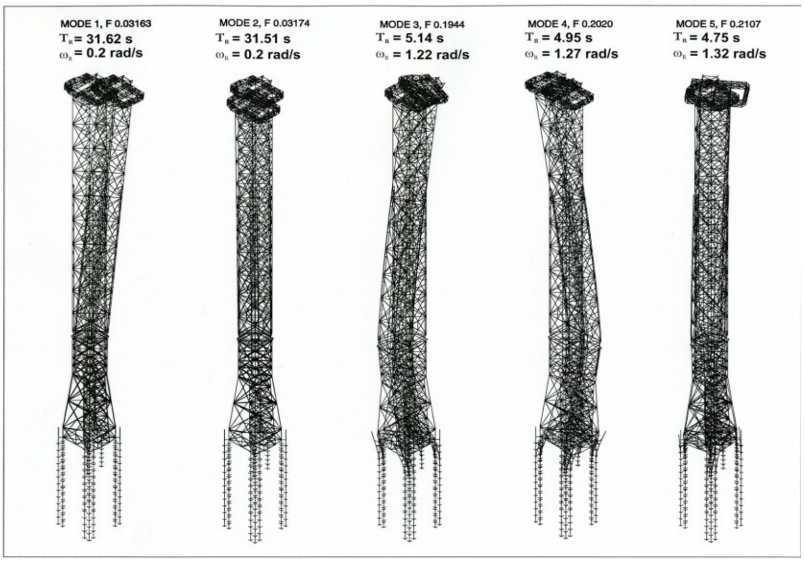

Fig. 1. Modal shapes of Baldplate Compliant Tower (Clauss, Lee and Kosleck, 2004)

Moreover, a topographical survey of the offshore site is needed before platform installation. In addition to that, a hydrographical survey of the area also needs to be carried out. Windrose diagram for wind velocities along with the dominant direction of the wind and its duration should be known for design. Additionally, as the open sea is more prone to extreme weather conditions, cyclonic tracking data of past storms with their direction, peak velocities and period are also needed for calculations. Furthermore, in order to determine the sea-state conditions, tide data, wave data, tide tables, local currents, rainfall, temperature, humidity and seabed conditions that are known as oceanographic data is a necessary part of data collection. Seismicity levels and ground acceleration values should also be accounted for the design purposes. Structural data of similar buildings constructed close to the proposed structure also gives a hint about the conditions of the site to aid engineers during the design phase. Finally, soil investigation report is necessary for building such structures.

The analysis of offshore structures is a challenging task. During the design of offshore structures, many disciplines like geotechnical, structural, naval architecture as well as metallurgy are all involved. The tower structures are designed to cope with different phases of the structure like execution, installation and service stages. The different analysis involving different conditions of the structure during its life are required listed as follows (Sadeghi, 2001):

i. In-place analysis
ii. Earthquake analysis
iii. Impact analysis
iv. Temporary analysis
v. Load-out analysis
vi. Transportation analysis
vii. Lift/Launch analysis
viii. Upending/Up-righting analysis
ix. In-place analysis
x. Earthquake analysis
xi. Impact analysis
xii. Temporary analysis
xiii. Load-out analysis
xiv. Transportation analysis
xv. Appurtenances analysis
xvi. Un-piled stability analysis
xvii. Pile and conductor pipe drivability analysis
xviii. Installation analysis
xix. Cathodic protection analysis
xx. Fatigue analysis

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Software Used in Offshore Design Industry

Due to recent developments and increased usage of computer software for designing structures, there are a wide variety of software that can be used for structural analysis. The several of these software are Bentley SACS (Bentley.com, 2018), DNV GL (DNV GL, 2018), SESAM, NSO and FASTRUDL/ISYMOST (Principia-group.com, 2018). Apart from these specific software designed for use in offshore industry, the other software like Dlubal RFEM and RSTAB and CSI SAP2000 (Csiamerica.com, 2018) can also be used for structural analysis of offshore structures (Software, 2018). In addition to that detailing software like Tekla Structures (Tekla, 2018) can be useful during the fabrication stage.

Methods Used for Design of Compliant Towers

Just like all steel structures, verification of structural elements for comparing characteristic resistances with design forces and stresses are needed to determine the member sizes. These include the check strength of members with the yield strength of the material, overall stability conditions of the structure and buckling resistances with respect to the limits of the element. In addition to design checks, members of the structure should also be verified against corrosion, fatigue, temperature effects for durability reasons.

The fatigue is an important aspect of the design and greatly affects the durability of the structure throughout its lifetime. The fatigue analysis is available in API RP 2a and DNV RP C203 in detail. Additionally, American Bureau of Shipping (ABS) provides good information on Fatigue Assessment of Offshore Structures.

The design of the members of the structures can be calculated either Allowable Stress Method or Limit State Method.

To use Allowable Stress Method, the loads are used without any factors and characteristic strength of the members are calculated using coefficients. Table 1. Demonstrates the coefficients used for resistance to stress.

Table 1. Coefficients used for resistance to stress (Chandrasekaran, 2018)

Condition	Axial	Strong Axis bending	Weak axis bending
Normal	0.60	0.66	0.75
Extreme	0.80	0.88	1

Normal and extreme cases shown on the table are for regular operation of the structure without closure and extreme conditions, which structure could face during its lifetime.

Moreover, Limit State Method was the preferred method of design for European and Norwegian codes (NORSOK, ISO, DNV etc.). However, such method of design is also adopted recently by American Petroleum Institute (API). The Limit state method is divided into further categories. These are Ultimate Limit State (ULS), Fatigue Limit State (FLS), Progressive Collapses Limit State (PLS) and Serviceability Limit State (SLS).

Ultimate Limit States (ULS) are used to check whether the structural resistance is sufficient with proper reserved resistance. Furthermore, Fatigue Limit State (FLS) is to check the probable failure under cyclic loading conditions. Progressive Collapse Limit State is used to check the structure for accidental or unusual loading occurrences. Lastly, Serviceability Limit State reflects the ability of structure under normal usage. Table 2. Presents the load factors for Limit State Design (Chandrasekaran, 2018). In this Table P is for permanent loads, L is for live loads, D is for deformations, E represents environmental loads, and A is for accidental loads.

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Table 2. Load factors for Limit State Design

Limit State	Load Categories				
	P	L	D	E	A
ULS (normal)	1.3	1.3	1.0	0.7	0.0
ULS (extreme)	1.0	1.0	1.0	1.3	0.0
FLS	0.0	0.0	0.0	1.0	0.0
PLS (accidental)	1.0	1.0	1.0	1.0	1.0
PLS (post-damage)	1.0	1.0	1.0	1.0	0.0
SLS	1.0	1.0	1.0	1.0	0.0

Due to the variability of loading conditions of offshore structures, the process of designing continues until sufficiently safe and economical sections are achieved. As the process is demanding, the proper initial sizing of the members is an important part of the design. The previously built structure is a good example for initial sizing of members.

Design of Pile Foundations

Compliant towers are generally fixed to the seabed by using open driven piles. Driven piles are generally placed in their position using external forces exerted to the pile during placement. Because of that, the pile wall thickness should be enough to resist axial and lateral loads in addition to the stresses during the driving procedure. Moreover, the piles of the compliant tower are exposed to cyclic and static loading and these loads are axial and lateral forces. Therefore, the piles should be designed accordingly by considering such load effects. The design of piles is based on soil investigation carried on site. The drilling ships are often preferred for investigation but manned submersibles are also used in some cases. In general, CPT tests are used for soil investigation. However, there are some other methods like field vane test and pressure meters can also be employed. The entire test should comply with universal standards like ASTM, BS etc. The design of pile system for structures for offshore use are under provisions of API RP-2A. The API provisions for sizing of piles are based on Allowable Stress Method. This method does not include pile penetration. However, alternate methods like limit state design can also be implemented for the design procedure. Additionally, API included factors of safety for design. The factors are based on 100-year storm wave effects and environmental conditions.

FABRICATION

The materials used for the construction of offshore structures like compliant towers should comply with ASTM A572 and ASTM A6 standards. The materials used can be classified into different groups. In Table 3, the groups are listed with respect to their usage in offshore platforms (El-reedy, 2017).

Table 3. Materials to Select the Structure

Steel group	Yield strength	Charpy toughness	Structural element
I	220-275 MPa	20J	Primary/secondary bracing, legs, piles, conductor panels boat landing, walkways and stiffeners
II	280-395 MPa	35J	Joint cans, legs, stiffeners, pilling with thick walls
III	400-450 MPa	45J	Legs and bracing in area of high collision

It should be noted that most of the platforms are built using members made up with group I steel. Low hydrogen welding process are required when group II steels are preferred for construction.

Durability is an important aspect of offshore design considering the harsh marine environment. Structural steel material is prone to corrosion. The risk of corrosion is more critical in splash zone during high currents and cold-water conditions due to the high dissolved oxygen content of cold water. In splash zone, water evaporates leaving salt residue on steel. Therefore, fabrication of offshore tower platforms is important in order to keep the structure in good condition. The performance of the structure should be able to cope with both service and extreme loads. Joints of the structure are primary elements of the structure. 3D truss formation of compliant towers results in complex geometric shapes. Due to that reason, special care is needed during welding of the structure. Fabrication of offshore structures should follow provisions of codes. An example of such codes is AISC for design, fabrication and erection of steel for buildings (El-Reedy, 2017). ISO 19902 contains information on materials, welds, preparation of welds and inspection. On the other hand, API RP2A and ISO 19902 shows guidance for fabrication. Moreover, welding of high strength steels and normal steel with a carbon content greater than 41% should be welded using low hydrogen electrodes (El-Reedy, 2017). Full penetration welds should be adopted and fillet welds should be avoided. However, fillet welds for sealing are permitted according to provisions provided in codes like DNV and API.

Fabrication should be followed by non-destructive testing (NDT). These include radiographic testing, ultrasonic testing and magnetic particle testing. In addition to that, steel also should be tested by tensile tests, bend tests, Charpy V-notch tests and hardness tests.

The compliant tower structures are more slender and less complex structures compared to deep water fixed platforms. Therefore, the fabrication is simpler and making quality control of the structure easier leading to more economic structures. Reduced complexity also benefits the long-term performance of the structure. For instance, the Baldplate platform has a base width of 90ft increasing to 140ft at the mudline. On the other hand, fixed platforms in similar depths have base widths exceeding 400ft (Offshore-mag.com, 1999). As a result of that, the shop fabrication is easier with increased safety during fabrication.

JACKET ASSEMBLY AND ERECTION

During the fabrication, the components of the jacket are fabricated as flat trusses. The jacket assembly is composed of assembly of joints, members, boat landing and other necessary components of the jacket. The jackets that are fabricated for deep waters can be made up of several parts. A care should be given to weld most of the structure in shop in order to maintain higher quality welding. There are several objectives to be cared during the assembly and the erection of the jacket. First of all, there should be an easy access around the jacket during the assembly and the erection to have a proper control over the structure. It is a good practice to reduce the number of temporary structures like scaffolding, walkways etc. Furthermore, Sub-assembly of main elements should be carried out including the maximum amount of secondary items. It is essential to align critical areas (launch runners, conductor guides and pile sleeves) during assembly of the jacket. Before starting to weld, dimensional control of assembly parts is essential. This is later followed by a pre-weld inspection. After the welding non-destructive tests should be carried out to verify the structure. Coating or painting should be applied to required areas prior to the erection. After necessary checks and removal of the temporary supports, the jacket is ready for transportation and lifting. The assembly of jackets frames is always a challenge for the assembly crew as it requires precise

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planning for proper field layout and temporary supports. In addition to that, the jackets having a base of 50 meters or more are prone to thermal changes (El-Reedy, 2017).

TRANSPORTATION, LOADOUT AND INSTALLATION

The jacket assembled at a yard onshore must be transported to the site. The installation of compliant towers is mostly handled by launch barges. In general, launch barges are grounded at the dock with water ballasts placed sufficient to hold it steady even with high tides. However, for heavy jackets, deepwater conditions or with changing tides, the barge is kept in floating condition. In such conditions, the barge is maintained ballasted at a proper level near the shore. This can be best done by computer-controlled ballasting (Gerwick, 2007). Fig. 2. Shows the loadout of a jacket onto launch barge.

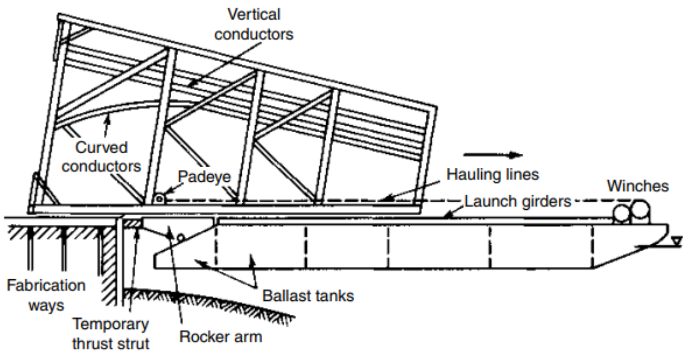

Fig. 2. Loadout of a jacket onto launch barge (Gerwick, 2007)

There are several provisions available to loadout and transportation procedure of jackets. One such are presented in API RP2A. After the loadout of the jacket onto the barge, tie-downs are installed before entering to open sea. It should be noted that these tie downs are major structural elements during the transportation of the jacket and should be designed accordingly to the needs. Tie down hooks should be designed for inertial forces. The inertial forces depend on the duration of the transportation. In addition to that gravity loads and wind loading also exist during the transportation.

The following criteria can be used for designing tie-downs as listed below (Gerwick, 2007)

i. Single amplitude roll 20 degrees,
ii. Single amplitude pitch 10 degrees,
iii. Roll or pitch period, 10s, double amplitude,
iv. Heave force, 0.2g.

Furthermore, since the speeds of barges used during the transportation is slow, towing routes should be selected considering the duration of the transport to avoid storms and heavy traffic areas. In addition to that, the route can be configured to benefit from currents. Therefore, the engineer must have an environmental report showing the worst seastate conditions during that time of the year throughout the course of the intended route (Sadeghi, 2007a).

As it is mentioned in earlier in the previous section**,** the structural members of jackets are designed to withstand transportation, lifting/launching stresses. The launching and installation procedure starts with driving of piles in the seabed. In general, for the installation of compliant towers, foundation leveling piles are installed followed by docking piles to guide the jacket at the base before the launch of the base. It should be noted that during that operation the jackets must be designed to support itself under such conditions.

The installation of the Baldplate platform was started by driving 12400-ton skirt piles to a depth of 430ft. After the preparation of the base, the jacket was launched and lowered. The

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tower legs were attached to the base by using docking pins. After the installation of the jacket, the deck was transported to the location followed by installation of facilities (Offshore-mag.com, 1999).

CORROSION PROTECTION

The offshore structure platforms built in open seas like compliant towers are exposed to seawater during their lifetime. The cathodic protection of the structure to remain durable during service life is under the responsibility of structural engineer (El-Reedy, 2017).

There are many different types of corrosion, which can occur on such structures. These can be listed as atmospheric corrosion, splash zone corrosion, crevice corrosion, intergranular corrosion, galvanic corrosion etc. Typical rates of corrosion for bare steel in the splash zone and submerged zone are 0.15mm/year and 0.07mm/year respectively. This rate can be more in areas with abrasive carrying tides. In addition to that, it has been found out that many structures in service are corroded by marine growth on structures. (Gerwick, 2007). The offshore structures can be divided into three different zones according to corrosion control measures. These are atmospheric zone, splash zone and submerged zones. (Singh, 2017). The atmospheric zone is the upper deck of the structure situated above the splash zone. The atmospheric zone of the structure is generally protected by coatings applied to members, as the members are not in frequent contact with seawater. The splash zone is in between submerged part and upper deck. The splash zone is intermittently in or out of water during the service life of the structure. Therefore, the corrosion control of this zone requires different methods. The submerged part of the structure is always below seawater level. This part of the structure is protected by cathodic protection as it is always in an electrolyte (seawater).

There are three different cathodic protection methods, which can be adopted for offshore structures. These are sacrificial, impressed current and hybrid systems. Sacrificial methods use more reactive metals like zinc or aluminum alloys for protection. Furthermore, impressed current systems use inert anodes, which require an external power source for protection. On the other hand, hybrid system uses both of the systems in combination.

A well-designed combination of cathodic protection methods along with proper coatings maintains the structure in top condition during its service life. It should be noted that proper care should also be given in fabrication phase to maintain good quality welds throughout the structure as the weld points are critical areas for corrosion.

WAVE ANALYSIS AND FURTHER INFORMATION

For extra data on the ecological information together with important equations and the information required for outline and examination of such structures as well as the damage evaluation, the guidelines, information and suggestions given by (API, 2010), (Sadeghi, 1989, 1998, 2004, 2007b, 2008 and 2013), (US Army Coastal Engineering Research Center, 1980), (US Army Corps of Engineers, 2002), Muyiwa and Sadeghi, 2007), (Sadeghi and Nouban, 2010, 2011, 2016, 2017), (Sadeghi and Aleali, 2008) (Nouban and Sadeghi, 2013 and 2014), (US Army Corps of Engineers, 2011), (Nouban, 2016), (Nouban et al., 2016) and (Nouban et al., 2017) may be utilized.

CONCLUSION

The aim of this paper is to discuss the information needed for design and construction of compliant towers. To design a compliant tower, it is necessary to collect data for the suggested site. This information includes topographical survey, hydrographical survey, wind rose diagram, cyclonic tracking data, oceanographic data, seismicity levels and structural data of structures in close proximity.

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