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PROJECT WORK

DEPARTMENT OF CIVIL ENGINEERING

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Contents

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FATIGUE STUDIES ON STRUCTURAL STEEL USED FOR FLOATING OFFSHORE RENEWABLE ENERGY SUPPORT PLATFORM

A PROJECT REPORT

submitted by

AMRUTHA K

VML21CESC01

to

the APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology

In

Structural Engineering and Construction Management

Department of Civil Engineering

Vimal Jyothi Engineering College
Chemperi

APRIL 2023

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DECLARATION

I undersigned hereby declare that the project report "Fatigue Studies on Structural Steel Used for Floating Offshore Renewable Energy Support Platform", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Dr. M. Saravanan, Principal Scientist, CSIR-Structural Engineering Research Centre and Mrs. Margaret Abraham, Assistant Professor, Vimal Jyothi Engineering College. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea orfact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This project report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Place: Chemperi

Date: 4th May 2023

Amrutha K

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VIMAL JYOTHI ENGINEERING COLLEGE, CHEMPERI

CERTIFICATE

This is to certify that the report entitled, **'FATIGUE STUDIES ON STRUCTURAL STEEL USED FOR FLOATING OFFSHORE RENEWABLE ENERGY SUPPORT PLATFORM'** submitted by **Ms. AMRUTHA K** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Structural Engineering and Construction Management is a bonafide record of the project work carried out by her under our guidance and supervision. This project report in any form has not been submitted to any other University or Institute for any purpose.

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PROJECT COMPLETION CERTIFICATE

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I profound my sincere thanks to my parents, who always pray for my progress and extend their moral and financial support for my welfare.

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ABSTRACT

Energy demand has been increasing nowadays. Wind energy is considering as a remarkable renewable energy source to be implemented in power systems. Offshore wind turbine simultaneously helps the reduction of greenhouse gas emissions, an increase in energy security and diversity, creates jobs, and promotes sustainable development. Location of multiple wind turbine on large floating structure offshore offers the advantages of no land usage and probably a more reliable wind resource. Dueto the cyclic loading of wind and waves the fatigue damage occurs mainly in substructure steel and mooring chain used for anchorage in the floating offshore wind turbine. Hence, it is necessary to study the fatigue behavior of structural steel used in renewable offshore wind turbine and mooring chain used for anchorage.

In this study, Experimental fatigue life evaluation was conducted on an IS2062 grade E350 transverse butt weld joint specimens at different stress ranges used for semisubmersible floating offshore wind turbine support structure. Also, evaluated the mechanical properties and fatigue life evaluation of mooring chain of U3 grade at stress range used for anchoring the offshore wind turbine support structures. The fatigue life of the substructure steel and mooring chain of U3 grade steel specimen was predicted using experiments. From S-N curve data obtained from experiment on an IS2062 grade E350 transverse butt weld joint specimens at different stress ranges are compared with the S-N curve in IS 800: 2007 with detail category number 83. With decrease in applied stress range number of cycles to failure is observed to be more.

Key words: *Mooring chain, S-N curve, Offshore wind turbine, Fatigue, U3,*
IS 2062 E350, Cyclic loading.

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CONTENTS

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Signature Not Verified

Principal.VJEC

Signature Not Verified

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Signature Not Verified

Principal.VJEC

Signature Not Verified

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LIST OF TABLES

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LIST OF FIGURES

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
ASME	American Society for Mechanical Engineers
ABS	American Bureau of Shipping
DOE	Department of Energy
FOWT	Floating Offshore Wind Turbine
HCF	High cycle fatigue
IWRC	Independent wire core
FWTs	Floating wind turbines
TLP	Tension-leg platform
LCF	Low cycle fatigue
MW	Megawatt
NREL	National Renewable Energy Laboratory
SIF	Stress Intensity Factor
UTM	Universal Testing Machine
WSC	Wire-stand core

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NOTATION

N_i	Fatigue crack initiation life
N_p	Fatigue crack propagation life
N_t	Total fatigue life
f_t	Design normal stress range
f_{fn}	Normal strength of the detail for $5x10^6$
N_{sc}	Fatigue life

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Demand for renewable energy is rising quickly, and this trend is expected to continue globally in the future. Due to the increase in pollution, the use of renewable energy sources gets on increasing. Renewable energy can be generation of electricity from ocean-based resources which increased environmental awareness, energy security and depletion of land-based resources are driving the dependence on renewable energy technologies. The long-standing energy issues that developing countries are currently facing may be solved by renewable energy sources and technology. The energy crisis in India can be solved by using renewable energy sources such as wind, solar, geothermal, ocean, biomass, and fuel cell technologies. Renewable energy can be both offshore and onshore renewable energy. onshore wind energy is the power that's created by wind turbines positioned on land propelled by the natural movement of the air. Wind energy has gained wide acceptance across the globe and its ultimate focus is on the development of offshore wind farms. Due to the negative effects of changing wind speeds, changes in wind direction and speed can make it difficult for wind farms to consistently produce power and as a result impact both nature and people.

Several people have issues with the loudness and how wind farms look in the landscape. Also, some people are concerned that onshore wind farms could endanger birds. Due to planning restrictions that frequently apply to onshore turbine tip heights, which don't apply to offshore turbines, onshore wind farms typically produce less electricity than their offshore counterparts (referred to as their "capacity factor"). Compared to an onshore wind turbine offshore wind turbine produce an average output of 3.6 MW offshore power; an onshore wind turbine typically produces between 2.5 and 3 MW which is less as compared with offshore power generation. Due to this disadvantage renewable energy moves from onshore to offshore renewable energy. The presence of vast resources of wind in oceans encourages research to move offshore. Offshore wind technology is a booming industry that can decrease the energy crisis and climate-change problems. Electricity is produced by offshore wind farms using the wind that blows across the water. Due to the higher wind speeds, greater consistency, and lack of physical interference from the land or

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man-made objects, they are thought to be more efficient than onshore wind farms. Offshore wind farms are more productive and offshore installations need fewer turbines to produce more amount of energy as compared with onshore wind farms due to higher wind speeds and consistent wind directions in an offshore wind turbine. Oceans provide the perfect location to build wind farms in terms of scale and openness. Hence, more wind farms are being built which makes more clean, sustainable energy can be produced. In the case of a floating wind turbine, more challenges occur as fatigue damage occurs in the substructure structural steel part used in the floating offshore wind turbine and mooring chain used in offshore wind turbines.

Support structures of offshore wind turbine are exposed to high dynamic load caused by wind, waves and operation. The support structures have to resist an extreme number of load cycles during their design life. Therefore, fatigue resistance becomes relevant for providing secure service time and economic design. There are different challenges facing the wind energy sector including aerodynamic and hydrodynamic effects, soil-structure interaction, design optimization, environmental factors related to harsh operating conditions, excessive costs associated with manufacturing, installation, building, operation, and maintenance. There are physical asset management challenges due to the remote location of these structures in deeper waters as well as life performance challenges due to higher wind loads and lower fatigue performance at the welds. Fatigue damage was caused due to cyclic behavior of mechanical loading. Due to the cyclic loadings of wind and waves, the fatigue phenomenon is inevitable. Understanding the fatigue approaches of different guidelines and the applied procedures is crucial for having a good view of fatigue life prediction in design. One of the primary methods for fatigue design is the S-N curve. The use of fracture mechanics, which is used to estimate and anticipate the propagation of fatigue cracks, is also advised by several standards.

1.2 OFFSHORE RENEWABLE ENERGY

Nations around the world are grappling with issues related to how to best meet the rising demand for energy. A variety of new, sustainable energy production technologies has been created as a result of increased knowledge of how the burning of fossil fuels, which contributes to climate change and ocean acidification, affects our climate. Due to rising costs, concerns about oil spill risks, and worries about the security of energy supply from unstable or potentially hostile neighbors have led to the development of a range of new, sustainable, energy production

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technologies. Several nations have now established definite goals for the percentage of energy must supply from renewable sources. Offshore renewable energy involves the generation of electricity from ocean-based resources. Which include wind turbines located offshore in the oceans and marine-based energy sources including waves, tides and salinity and thermal properties Offshore renewable energy has the potential to be a significant source of future global electricity production, reduce carbon emissions, decrease dependence on energy importation and stimulate economic growth in coastal and remote areas.

Fig. 1.1 Offshore Renewable Energy (sources: California Energy commission)

Fig. 1.2 Offshore wind in Vietnam at a crossroads (sources: Global Wind Energy Council)

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1.3 OFFSHORE WIND TURBINE

According to the water depth of the offshore environment, two types of foundation systems for offshore wind turbines have been proposed, one is fixed foundations (for depths up to 50 m) and the other one is floating platforms with mooring systems (for deeper waters). Floating offshore wind turbines provide more access to deeper water than conventional fixed-bottom wind turbines, which expands the viable area for wind energy development, reduces visibility from shore, and can potentially be located in areas with a higher and steadier wind characteristic. For sites near the UK coast, the water depth is usually between 20 m to 50 m, and fixed foundations would be the preferred choice due to the lesser cost. However, while the water depth can be up to hundreds of meters on sites further away from the coast and where the wind resources are greater than near shore, floating systems should be used in this condition.

1.3.1 FIXED BOTTOM OFFSHORE WIND TURBINE

Fixed wind turbines are attached to foundations (pile, concrete, etc.), which are themselves fixed to the continental shelf. With a floating installation, it becomes possible to operate wind turbines installed at depths greater than 50 meters.

For fixed offshore wind turbines gravity foundations are used at shallow depths of 30 m and consist of large, steel, or concrete bases that rest on the seabed. Suction bucket foundations are also made from steel or concrete and are installed using the pressure difference generated between the inside of the bucket and the water surrounding it without any use of mechanical force. Monopile foundations are used at shallow depths of 30 m and consist of a pile that is driven into the seabed. Monopiles are typically less costly than other foundation types and are the most used. Tripod fixed bottom foundations are used at transitional depths of 20 m to 80 m and consist of three legs connecting to a central shaft that supports the turbine base. Each leg has a pile driven into the seabed, which creates a wide foundation that allows for the piles to be placed at a shallower depth in the seabed than monopile foundations. Jacket foundations are also used at transitional depths of 20m to 80m and feature a lattice framework that comprises three to four anchoring points driven into the seabed.

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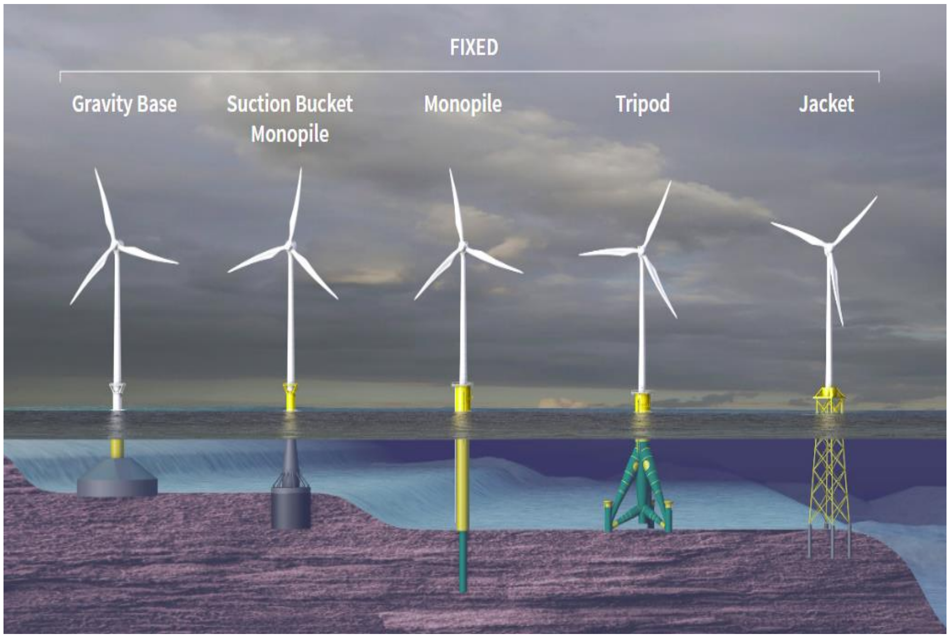

Fig. 1.3 Fixed offshore wind turbine (source: https://tethys.pnnl.gov/)

1.3.2 FLOATING OFFSHORE WIND TURBINE

Floating offshore wind energy is an emerging technology that provides access to new wind generation sites allowing for a diversified wind supply in future low-carbon electricity systems. floating offshore wind, based on floating structures rather than fixed structures, offers new opportunities and alternatives. Basically, it opens the door to sites further offshore by allowing the deployment of wind turbines in larger and deeper offshore areas with higher wind potential. Figure 1.4 shows the floating offshore wind turbine.

There are four types of the floating offshore wind turbines that are given below.

- Spar-buoy type
- Tension-leg platform type (TLP)
- Semi-submersible type (Column stabilized)
- Pontoon-type (Barge-type)

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Principal.VJEC

1.3.2.1. Spar-buoy type

A cylinder with low water plane area ballasted to keep the centre of gravity below the centre of buoyancy. The foundation is kept in position by catenary or taut spread mooring lines with drag or suction anchors. The spar buoy types of foundation are deeper water than the 100 meters above. Floating spar-buoy offshore wind turbines are one of the best design concepts that have the potential to effectively harvest energy in deep waters. The spar -type platform with either a catenary or taut mooring system maintains its stability by lowering the center of mass with regards to the center of buoyancy using the structure, significantly contributing to the roll, pitch and displacement. Mooring lines are utilized to prevent drifting and limit the surge and sway motions.

1.3.2.2. Tension leg platform (TLP)

This type of floating assets is highly buoyant with central column and arms are connected to tensioned tendons which secure the foundation to the suction or piled anchors the depth in the water are 50 m to 60 m depending upon the ocean conditions. The stability of the tension leg platform (TLP) is utilized by its excess buoyancy as well as the vertical tendons that are anchored to the seabed.

1.3.2.3. Semi-submersible type

The semi-submersible concept was originally developed for use in the offshore oil and gas industry where a large drill deck was needed. Semi- submersible floating offshore wind turbines typically consist of a number of vertical columns joined by cross braces or pontoons. The semi-submersible types are a number of large columns linked by connecting bracings or submerged pontoons. The columns provide the hydrostatic stability, and pontoons provide additional buoyancy. The foundation is kept in position either by catenary or taut type spread mooring lines and drag anchors. It can be used in the water depths to be about 40 m to 50 m.

1.3.2.4. Barge type

Barge platform achieves stability using their distributed buoyancy, taking advantage of the large water plane area. One of the most common types of barge platforms used in offshore wind industry is Ideol. The floating platform has a large surface area in contact with the water, which is precisely what gives it stability. Like boats, it is made to move to avoid overstressing and stresses

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on the structure. To minimize these movements, the platform is usually fitted with heave plates, which are surfaces below the waterline. For barge platforms a catenary mooring system is typically utilized to prevent drifting. It is also possible to use abandoned vessels as a floating platform for wind turbines.

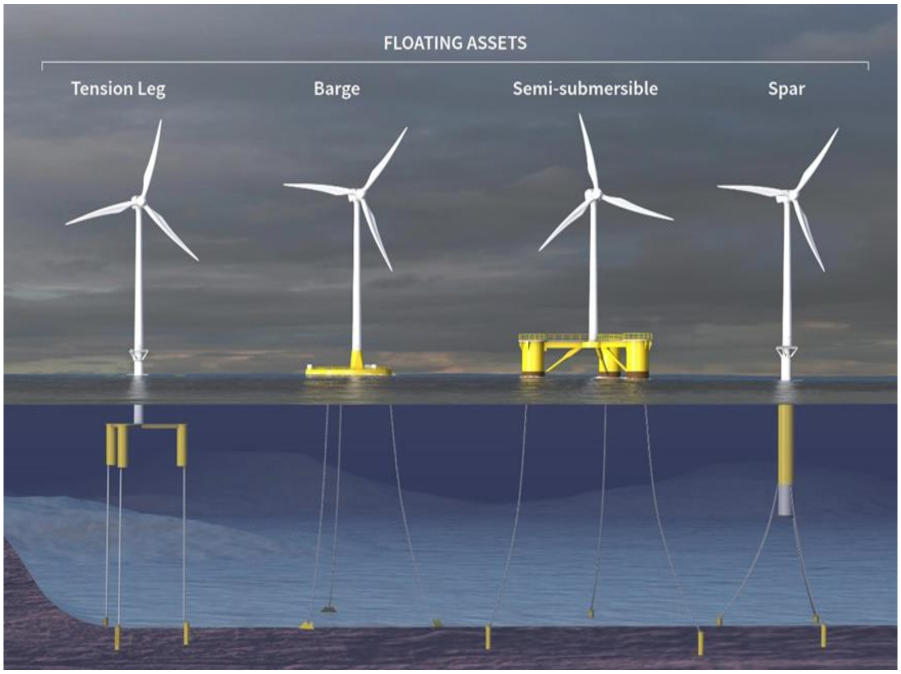

Fig. 1.4 Floating offshore wind turbine (source: acteon.com)

1.4 TYPES OF FLOATING WIND TURBINE SYSTEMS

1.4.1 EOLINK

Eolink floating wind turbine is a solitary point securing framework innovation. The licensed construction of this French organization situated in Plouzané is a semi-submarine drifting frame with a 4 poles pyramidal design. The construction upholds the turbine by 2 upwind and 2 downwind poles. It gives more freedom for the cutting edges and a disseminates pressure. Dissimilar to the vast majority of the floating wind turbines, the turbine turns around its single securing point to confront the breeze. The rotate point guarantees the mechanical and electrical connection between the turbine and the ocean bottom. Eolink lattice associated its initial 1/tenth scale demonstrator of the 12 MW wind turbine in April 2018. Figure 1.5 shows the floating wind turbine single-point mooring eolink.

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Fig. 1.5 Floating wind turbine single point mooring eolink (sources: Centrale Nantes SEM-REV)

1.4.2 IDEOL'S

Ideol's engineers have developed and patented a ring-shaped floating foundation based on a central opening system (Damping pool) used for optimizing foundation wind turbine stability. As such, the sloshing water contained in this central opening counteracts the swell-induced floater oscillations. Foundation-fastened mooring lines are simply attached to the seabed to hold the assembly in position. This floating foundation is compatible with all wind turbines without any modification and has reduced dimensions of floating wind turbine from 36 to 55 meters per side for a wind turbine between 2 MW and 8 MW. This floating foundation allows for local construction near project sites. The construction of this project, France's first offshore wind turbine with a capacity of 2 MW, was completed in April 2018 and the unit installed on site in August 2018. For the month of February 2020, it had an availability of 95% and a capacity factor of 66%. Figure 1.6 shows the IDEOLS offshore wind turbine.

Fig. 1.6 IDEOL'S offshore wind turbine

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1.4.3 Volturn U.S

Volturn U.S is North America's first floating grid-connected wind turbine. It was lowered into the Penobscot River in Maine on 31 May 2013 by the University of Maine Advanced Structures and Composites Center and its partners. During its deployment, it experienced numerous storm events representative of design environmental conditions prescribed by the American Bureau of Shipping (ABS) Guide for Building and Classing Floating Offshore Wind Turbines in 2013. The Volturn US floating concrete hull technology can support wind turbines in water depths of 45 m or more. With 12 independent cost estimates from around the U.S. and the world, it has been found to significantly reduce costs compared to existing floating systems. The design has also received a complete third-party engineering review. In June 2016, the UMaine-led New England Aqua Ventus I project won top tier status from the US Department of Energy (DOE) Advanced Technology Demonstration Program for Offshore Wind. This means that the Aqua Ventus project is now automatically eligible for an additional $39.9 Million in construction funding from the DOE, as long as the project continues to meet its milestones. Figure 1.7 shows the Volturn US floating offshore wind turbine.

Fig. 1.7 Volturn US floating offshore wind turbine

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1.5 MOORING CONCEPTS

Mooring is the process of fixing the floating structure to the seabed. For a floating wind turbine, the most important aspect of the mooring system is to control the mean offset of the FWT within an acceptable limit. A floating structure in open water experience the environmental load caused by wind, waves, current and ice. The mooring system designed to withstands the environmental loads, such that the strength and fatigue requirements are met by all mooring components. Mooring lines adsorb dynamic loads and transfer load to seabed. Floating offshore wind industry mainly utilizes three different mooring concepts. These are catenary, taut-line, and tension leg. These methods depend on weather conditions, depth, size of the platform and costs. The mooring system characteristics have a large impact on the floating structures static stability and dynamic response to environments loads. Fatigue failure is one of the critical failure modes of offshore permanent mooring systems.

1.5.1 Catenary mooring

Catenary mooring systems consist of long chains and steel ropes/wires with the mooring system in a horizontal position at the seabed. Wires are applied to limit the pre-tensioning and reduce costs and chain is used to obtain the catenary effect. The foundation is limited to vertical motion as anchors may be misplaced and vertical component of the tension is assumed to be zero at the anchored. In order to keep the floating structure within its boundary conditions the mooring system is pre-tensioned. Lower pre-tensioning results is lower maximum tensions in the line but offsets of the boundary condition are higher, hence it has to be tuned appropriately

1.5.2 Taut-mooring system

In the taut-mooring system, the mooring lines have a linear shape from the anchor to the floating structures. This configuration depends on the axial elasticity of the line to provide the required restoring force to the structure. Compared to a catenary mooring system, it has higher linear stiffness and the attached anchor is exposed to both a vertical and horizontal force. The lines are pre-stressed with an angle between 30 degree and 40 degrees to the horizontal plane.

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1.5.3 Tension leg mooring

A tension leg mooring system is vertically moored with vertical tendons or tethers withstanding large tensile loads. These are anchored by suction piles, driven piles, or a template foundation. Platforms moored with this type of configuration are favorable in deep waters (>300 m)

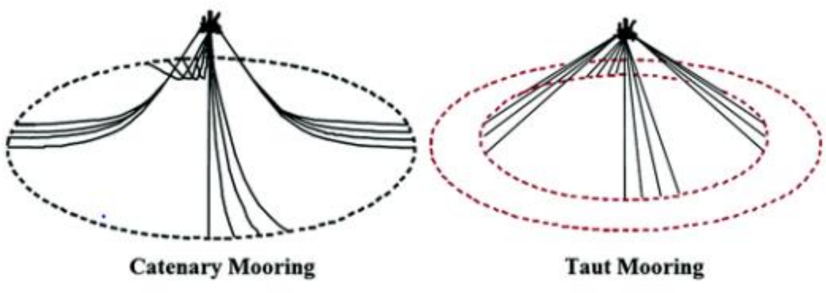

Fig. 1.8 Mooring system (sources: https://corewind.eu)

1.6 FATIGUE

According to ASTM E1823-2013, fatigue is defined as follows, "The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points, and which may culminate in cracks or complete fracture after a sufficient number of fluctuations". The number of cycles required to initiate a fatigue crack is the fatigue crack initiation life N_i. The number of cycles required to propagate a fatigue crack to a critical size is called the fatigue crack propagation life, Np. The total fatigue life, N_t is the sum of initiation and propagation lives.

$$N_t = N_i + N_P$$

Also, Fatigue is defined as initiation, propagation of crack in a material due to cyclic loading. When a material undergoes initiation of fatigue crack it grows a small amount with each loading cycle. The crack will continue to grow until it reaches a critical size, which occurs when the stress intensity factor of the crack exceeds the fracture toughness of the material finally producing rapid propagation and typically complete fracture of the structure. The process of fatigue consists of three stages:

- Initial fatigue damage leading to crack nucleation and crack initiation.

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- Progressive cyclic growth of a crack (crack propagation) until the remaining uncracked cross section of a part becomes too weak to sustain the loads imposed
- Final, sudden fracture of the remaining cross-section

Fig. 1.9 Fracture of an aluminium crank arm. Dark area of striations: slow crack growth. Bright granular area: sudden fracture

1.7 DIFFERENT FORMS OF FATIGUE FAILURE

Fatigue failure is caused by cyclic loading at loads well below the ultimate tensile strength of materials. For a material to undergo fatigue damage material should change permanently due to applied cyclic loading Fatigue failure occur in many different forms like mechanical fatigue, creep fatigue, thermo-mechanical fatigue, corrosion fatigue, rolling contact fatigue, and fretting fatigue. Fatigue failure depends on other factors besides cyclic loads and temperature which include the oxidizing environment, embrittlement, structural deformation, strain rate, and frequency of the applied load. Fatigue failures may be classified as high-cycle and low-cycle fatigue failures. Under high cycle fatigue loading, crack growth is normally controlled by the range of stress intensity ΔK rather than the magnitude of maximum or minimum stress intensity. HCF requires a high number of loading cycles to reach fatigue failure mainly due to elastic deformation. Low-cycle fatigue (LCF) is characterized by its high-stress amplitude and low frequency. In this case, stress produces both elastic and plastic strains. The fatigue strength of materials is highly sensitive to various internal and external factors. External factors include the part's shape, size, surface finish, and service conditions, while internal factors include the material's composition, microstructure, purity, and residual stress. A small change in these factors can cause fluctuations or significant changes in the material's fatigue performance. Understanding the impact of various factors on fatigue strength is crucial in fatigue research.

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1.8 TYPES OF FATIGUE

i) High cycle fatigue

High cycle fatigue is probably the most difficult phenomenon to handle within solid mechanics and is by consequence the main cause of failure of mechanical components in service. The difficulty comes from the early stage of damage which initiates defects at a very small micro or nano scale under cyclic stresses below the engineering yield stress. Fatigue phenomenon corresponding to relatively small stress amplitude which induces large numbers of cycles to failure (greater than 10^4) is high cycle fatigue.

(ii) Low cycle fatigue

Elasto-plasticity corresponds to stresses above the yield stress which induce lower number of cycles to failure (smaller than 10^4). The corresponding fatigue phenomenon is called low cycle fatigue. Low cycle fatigue may occur when structures are subjected to heavy cyclic loadings which induce irreversible strains on small or large scale, giving rise to damage up to crack initiation and propagation.

(iii) Endurance limit

Endurance limit is a region where stress amplitude is very less, and any number of cycles will not lead to failure. The number of cycles is in between the range of 10^6 to 10^{10}. The stress amplitude at which it occurs is one-half of endurance strength. There are many materials, such as austenitic stainless steels, for which endurance strength point is not well defined.

1.9 FATIGUE LOADING HISTORIES

Structural components are subjected to a variety of load (stress) histories. The simplest of these histories is the constant amplitude cyclic stress fluctuation. This type of loading usually occurs in machinery parts such as shafts and rods during periods of steady-state rotation. The most complex fluctuating load history is a variable amplitude random sequence. This type of loading is experienced by many structures, including offshore drilling rigs, ships, aircraft, bridges, and earthmoving equipment.

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1.10 FACTORS AFFECTING FATIGUE LIFE

1. **Effect of stress concentration**

The conventional method of measuring fatigue strength involves using carefully processed smooth specimens. However, in reality, mechanical parts often have various forms of gaps such as steps, keyways, threads. These notches result in stress concentration, causing the maximum actual stress at the root of the notch to be much greater than the nominal stress of the part. As a result, the fatigue failure of the part often initiates from these notches.

2. **Cyclic stress state**

Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxial, in-phase, or out-of-phase shear stress, and load sequence.

3. **Air or Vacuum**

Certain materials like metals are more prone to fatigue in air than in a vacuum. Depending upon the level of humidity and temperature, the lifetime for metals such as aluminium or iron might be as much as 5 to 10 times greater. This is mostly because of the oxygen and water vapour in the air which will aggressively attack the material and so encourage the propagation of cracks. Other environments such as oil or seawater may perform better than air, but they will also be worse than a vacuum.

4. **Grain size**

For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse-grained alloy.

5. **Direction of loading**

For non-isotropic materials, fatigue strength depends on the direction of the principal stress. In certain conditions, a limited number of instances of overloading may not cause damage to the material. Due to the effects of deformation strengthening, crack tip passivation, and residual compressive stress, the material is also strengthened, thereby improving its fatigue limit.

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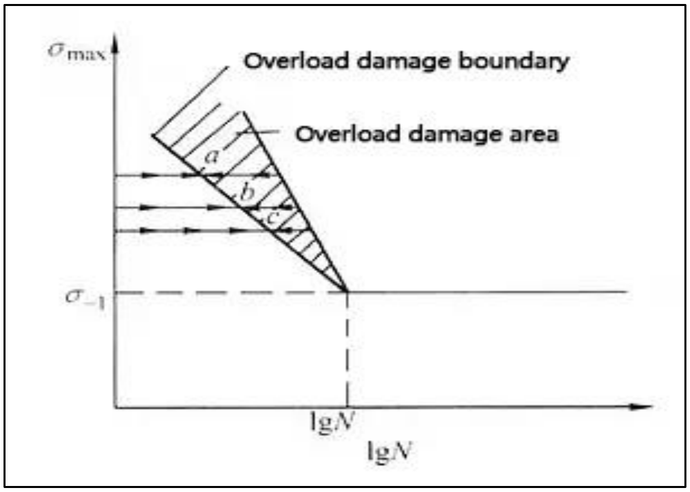

Fig. 1.10 Overload damage boundary: sources (https://www.machinemfg.com/)

6. Effect of heat treatment on microstructure

The effect of heat treatment on fatigue strength is largely the effect of microstructure, as different heat treatments result in different microstructures. Although the same composition of materials can achieve the same static strength through various heat treatments, their fatigue strength can vary greatly due to different microstructures.

7. Surface quality

Surface roughness cause microscopic stress concentrations that lower the fatigue strength. Compressive residual stresses can be introduced in the surface by e.g., shotto increasing fatigue life. Such techniques for producing surface stress are often referred to as peening, whatever the mechanism used to produce the stress. Low plasticity burnishing, laser peening, and ultrasonic impact treatment can also produce this surface compressive stress and can increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue.

8. Residual stresses

Welding, cutting, casting and other manufacturing processes involving heat or deformation can produce high levels of tensile residual stress, which decreases the fatigue strength.

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9. Environment

Environmental conditions can cause erosion, corrosion, or gas-phase embrittlement, which all affect fatigue life. Corrosion fatigue is a problem encountered in many aggressive environments.

10. Temperature

Extreme high or low temperatures can decrease fatigue strength.

1.11 CHARACTERISTIC OF FATIGUE FAILURES

The following characteristics are common to fatigue in all materials:

- The process starts with a microscopic crack called the initiation site, which then widens with each subsequent movement.
- Failure is essentially probabilistic. The number of cycles required for failure varies between homogenous material samples.
- The greater the applied stress, the shorter the life
- Damage is cumulative, materials do not recover when rested.
- Fatigue life is influenced by a variety of factors, such as temperature and surface finish in complicated ways.
- Some materials (e.g., steel and titanium alloys) exhibit an endurance limit or fatigue limit; a limit below which repeated stress does not induce failure, theoretically, for an infinite number of cycles of load. Most other non-ferrous metals like aluminum and copper alloys exhibit no such limit and even small stress will eventually cause failure. As a means to gauge fatigue characteristics of such materials, fatigue strength is frequently determined, and this is typically the stress level at which a component will survive 10 million loading cycles.

1.12 FATIGUE LIFE CURVE

The American Society for Testing and Materials defines fatigue life, N_f, as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature

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occurs. Fatigue life is affected by cyclic stresses, residual stresses, material properties, internal defects, grain size, temperature, design geometry, surface quality, oxidation, corrosion, etc. For some materials, notably steel and titanium, there is a theoretical value for stress amplitude below which the material will not fail for any number of cycles, called a fatigue limit, endurance limit, or fatigue strength Fatigue curves are used to determine the number of allowable cycles. The fatigue curve is also known as the S – N diagram, because one axis represents stress, S, and the other axis represents number of cycles, N. Each material group has its own fatigue curve based on test results and is shown in ASME Section VIII, Division 2, Annex 3-F.

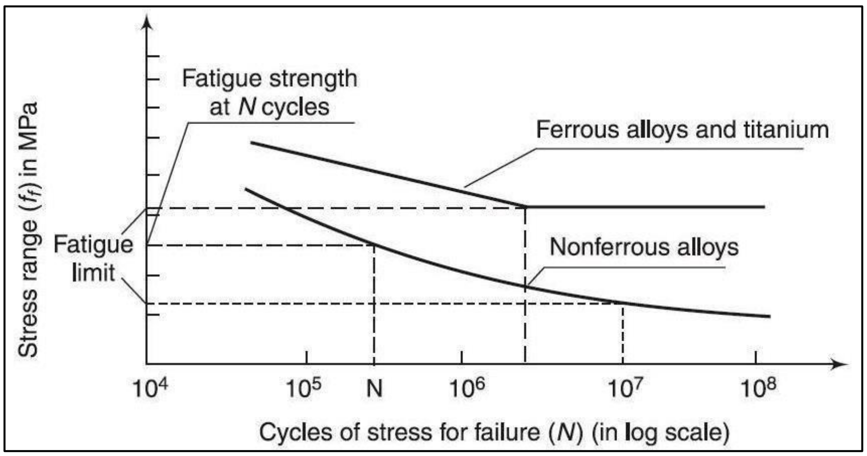

Fig. 1.11 Typical S-N curve for ferrous and non-ferrous alloys (Sources: ResearchGate)

The fatigue curves can be used in several ways as follows:

- If the number of cycles is known, then you can determine the maximum allowable alternating stress that corresponds to that number of cycles. As long as the actual stress is less than this value, then the design is acceptable.
- If the actual alternating stress is known, then you can determine the maximum number of allowable cycles based on that stress. If this quantity is greater than the actual number of cycles designed for, then the design is acceptable. As an alternative, the design life can be determined by this method, given the allowable number of cycles.

Engineers use a number of methods to determine the fatigue life of a material. One of the most useful is the stress-life method, which is commonly characterized by an S-N curve, also known as a Wohler curve. This method is illustrated in the figure 1.11. It plots applied stress (S) against component life or the number of cycles to failure (N). As the stress decreases from some

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high value, component life increases slowly at first and then quite rapidly. Because fatigue like brittle fracture has such a variable nature, the data used to plot the curve will be treated statistically. The scatter in results is a consequence of the fatigue sensitivity to a number of test and material parameters that are impossible to control precisely.

1.13 OBJECTIVES OF THE PROJECT

- Identification of materials used for support structure and mooring in floating offshore renewable energy wind turbines.
- Fatigue life evaluation of IS2062 Grade E350 steel welded specimens at different stress ranges used for offshore wind turbine support structure.
- Evaluation of mechanical properties of mooring chain used for anchoring the offshore wind turbine support structure.
- Fatigue life evaluation of mooring chain of U3 Grade used for anchoring the offshore wind turbine support structures.

1.14 SCOPE OF THE PROJECT

- Develop S-N curves for steel used in offshore wind turbine support structure.
- Develop S-N curve for mooring chain used for anchoring the offshore wind turbine support structure.

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CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The literatures that are more relevant to the study are summarized in the chapter. The literatures are mainly related to previous studies on fatigue in offshore wind turbines.

2.2 LITERATURE REVIEW

Kim et al. (2014) studied on mooring design procedure of semi-submersible floating offshore wind turbines. The offshore environmental data of Jeju south sea was collected from Korea Hydrographic and Oceanographic Administration (KHOA) such as wave height, wave period, current speed, current direction, wind direction, and wind speed. The water depth in Jeju offshore area was taken as 120m. Semi-submersible floating wind turbine system was considered as a mooring system based on Offshore Code Comparison Collaborative Continuation (OC4) DeepCWind platform and the National Renewable Energy Laboratory (NREL) 5 MW class wind turbine. A catenary mooring system made of studless chain was selected and design criteria such as how large the nominal sizes, long the mooring lines, and how far the anchor points was located was discussed. Nominal sizes of mooring chain links D85, D95, D105 was taken into consideration. Time domain analysis was performed to determine the safe overall length of mooring lines. Strength of mooring lines were evaluated in terms of ultimate limit state and fatigue limit state. It was found that 100 years return period, and 50-year fatigue design life was assumed while design the mooring chain.

Hong et al. (2015) investigated the effect of mooring system on the dynamics of a SPAR buoy-type floating offshore wind turbine. Through experiments, the effects of important floating platform parameters on the dynamics of a SPAR buoy were investigated. As scaled model responses with large motion as the wave frequency approaches one of the natural frequencies in regular wave tests. Since the scaled models were dynamic response around the natural frequencies is practically quite important. Hywind of National Renewable Energy Laboratory (NREL) with 5 MW power wind turbine. The effect of the platform parameters mooring line spring constant and locations of the COG and fairlead on the natural frequencies and damping coefficient were

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examined. As the results dynamic response of model to wave become nonlinear. So, the scale model dynamic response around the natural frequencies is practically quite important.

Nejab et al. (2015) discussed about different study on TLP, spar and semi-submersible floating wind turbine. Analyzed the fatigue damage of drivetrains in land-based and stochastic dynamic load effect. Designed power taken as NREL 5MW and the fatigue damage in mechanical components was compared for different environmental conditions. large damage occurs in the spar wind turbines due to which large waves induced axial force on the main shaft. This paper mainly identifies the most drivetrain-friendly floating offshore wind turbine. Here they applied dynamic load which obtained through a de-coupled analysis approach for wind turbine gearbox analysis. They identified fatigue damage of gear and bearings in floating wind turbines which is compared with fatigue damage of the land-based turbine in different environmental conditions.

Xutian Xue et al. (2018) studied T-N curves, S-N curves, and fracture mechanics approach using the fatigue analysis of a semi-submersible mooring system was considered. Crown section of the mooring chain had prone to more fatigue damage than compared with the bend and weld sections without considering the stress concentration factor. A parameter study was carried out to examine the impact of initial crack shape, critical crack depth and initial crack sizes on the fatigue life of a mooring chain was also conducted in detail with the help of the FM approach. Studied four column ring pontoon semi-submersible with 16 mooring lines operated at the Gulf of Mexico is considered. Two types of mooring systems namely catenary and taut mooring systems with four cases were designed for the semi-submersible. Each mooring line consists of a 6-inch R4 grade studless bottom chain, 267 mm polyester rope, and a 150 m long 6-inch R4 grade studless top chain. The length of bottom chain is 210 m and top chain was 150m long. The wear and corrosion rate of mooring chains was assumed to be 0.5 mm per year. The variation in mooring tension caused by wave frequency motion is calculated by a dynamic method.

Lin Chen et al. (2018) discussed about the fatigue load estimation of a spar-type floating offshore wind turbine considering wave-current interactions in fatigue analysis. Analytical wave-current interaction models based on Airy's theory considering the current effects are applied for generating the flow fields. Hence based on a spar-type FOWT and the wave-current interaction model, numerical simulations have been performed for three cases with only waves, and current without and with interactions. The comparison of the structural responses showed that the curre[illegible]d wave

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current interactions can have significant influences on FOWT tower and cable responses. If the current tends to increase the cable tension, neglecting the current and wave-current interactions leads to overestimate of the cable fatigue life. Considered steel chain cable for mooring with Poisson ratio 3.324. It was observed that the NREL offshore 5 MW baseline wind turbine supported on the OC3-Hywind spar-buoy was used here for obtaining the structural responses which was further used for fatigue analysis.

Igwemezie et al. (2019) collected current trends in the offshore wind energy sector and material requirements for fatigue resistance improvement in large wind turbine support structures. Global energy from wind power will rise due to rapid reduction in the cost of wind energy. With advance in turbine technology, efficient and optimized turbine support structure. Considered the status of wind turbine (WTs) and the economic perception of extra-large wind turbines (XL-WTs). And also presented some critical structural integrity concerns relating to XL steel plates which need to be evaluated to enable technical and cost-effective decisions to be made for the design of next generation WT support structures. TMCP steels are reported to be well situated for XL-WTs. The reduced alloying-elements in this steel will give the steel high weldability and this property will be good for thick sections in XL-WT design.

Jacob et al. (2019) discussed about experimental and numerical study on residual stress effects on fatigue crack growth behaviour of S355 steel weldments and Fatigue crack growth tests were conducted on S355 G10+M structural steel which was widely used in the fabrication of offshore structure. Examine the influence of residual stresses on near threshold fatigue crack growth behavior of the material and numerical model has been built up in ABAQUS. The experimental results from fatigue crack growth tests in air have shown that the specimen orientation with respect to the weld geometry plays a significant role in fatigue crack behavior of the material. Also, observed that data collated from the different literature are on different ranges of medium to high strength structural steel tested on different specimen geometries with different load level and specimen thicknesses.

Zarandi et al (2020) conducted an experimental and numerical study of the mooring chain under residual stresses and implications for fatigue life. Two measurement techniques were conducted such as Elastic-plastic finite element simulation of the proof loading and the computed residual stresses were compared to the experimental measurements. The critical damage parameter was

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employed to estimate fatigue crack initiation life of corroded mooring chains subjected to various service load levels considering the effect of residual stresses. Residual stresses in offshore mooring chains were measured for the first time. The mooring chain links with 114 mm nominal diameter (D) and made of steel grade R4 were selected for the residual stress measurements.

Stanislav Seitl et al. (2020) studied the comparison of fatigue crack propagation behaviour in steel grades S235, S355 and a steel from old crane way. The comparison of these steel grades was done by fatigue crack propagation tests. The fatigue properties were discussed and recommendations for the use of the steel were stated. The fatigue crack propagation was characterized by mean of crack growth curves experimentally determined on compact tension specimens. The experimentally obtained results are discussed. The results show that it was preferable to use the S235 steel for replacement of the structural components in the cases where the fatigue crack growth was the decisive parameter for the service life. Also, fatigue crack growth rates in S355 and S235 steels were higher than in steel from old crane way under the stress intensity factor range in which old steel was more resistant to the growth of long fatigue cracks.

Moghaddam et al. (2020) discussed about the structural integrity assessment of floating offshore wind turbine support structures. A framework was proposed to simulate fatigue crack growth from multiple corrosion pits at critical spots of the Spar-type floating support structure to examine the status of the crack during several years of operation. Mooring chain system for Hywind Scotland 5 MW NREL tower taken under consideration. Experiments on S355 and S690 steel grade to examine the effect of the ratio on fatigue crack growth and results show that the fatigue crack growth power law constants are similar for tests with positive non-zero R ratios.

Yoan Chevillote et al. (2020) discussed studed on the basis fatigue characterization of polyamide mooring ropes for floating offshore wind turbines. About Yarn-on-Yarn abrasion test and final failure criteria was carried out. Abrasion resistance gets increased by the addition of aspecially developed coating from yarn-on yarn loading abrasion tests and finally fatigue life can be increased

Mathern et al. (2021) was identified and categorized the challenges and future trends related to the use of concrete for support structures of future offshore wind projects. Different types of support structures, consisting of either steel or concrete (reinforced or prestressed) were used as support structures for the offshore wind turbine. Gravity-based foundations made of concrete, similar to those used for onshore wind turbines were a commonly used solution in the very first

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offshore wind farms situated in very shallow waters. The majority of support structures for offshore wind turbines are made of steel and most of those are monopiles. The main advantage of using concrete for these particularly exposed parts was the increased robustness and reduced amount of required maintenance compared to steel alternatives. Concrete substructures have usually built from normal-strength concrete (mainly concrete of strength class C45/55) in order to satisfy the requirements of building standards. There was now a trend towards the use of higher-strength concrete, as new concepts that are being developed often rely on high-strength concrete characteristic compressive strength (f_{ck}) higher than 50 MPa However, recent studies highlight the potential benefits of using concrete for offshore structures in general and for offshore wind turbines. Since concrete structures have lower production costs and better durability and fatigue resistance when compared to offshore wind turbine steel support structures.

Li et al. (2021) studied the dynamics of a Y-shaped semi-submersible floating wind turbine and also considered the comparison of concrete and steel support structures in floating offshore wind turbine. The results indicated that the steel structure with a lower center of gravity exhibits advantages in platform pitch motion alleviation. The steel structure was also subjected to lower pitch-induced tower base loads and nacelle acceleration than its concrete counterpart. However, an opposite trend was found in the wave-frequency responses, leading to an insignificant difference of tower base loads and nacelle acceleration between the two structures. In order to make a better understanding of the dynamic behavior of the two models, time-domain coupled multi-body simulations were performed by using the offshore horizontal axis wind turbine simulator FAST. The platform motion was validated with this model tests and the wind turbine dynamic responses including tower-based fore-aft bending moment and nacelle acceleration was calculated. The differences between the concrete and steel platform were addressed and discussed in detail.

Farr et al. (2021) discussed about the potential environmental effects of deep water floating offshore wind energy facilities and potential mitigation measures for the occurred effects. Find out six different ideas about potential environmental effects of deep water floating offshore wind energy which are changes to atmospheric and oceanic dynamics due to energy removal and modification, electromagnetic field effects on marine species from power cables, habitat alterations to benthic and pelagic fish and invertebrate communities, underwater noise effects on marine species, structural impediments to wildlife and changes to water quality. Give review of 89

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articles explain about the mitigation measures to be taken for reducing the risk to the marine environment.

Yang et al. (2021) discussed about the investigation on mooring breakage effects of Barge Type Floating offshore wind turbine with a power of 5MW using FAST and AQWA (F2A) technique. Carried out a Dynamic modelling approach of mooring lines and calculated tension occurring in the mooring lines. Failure occurs in mooring line causing a wide damage in the floating offshore wind turbine. Hence it calculates the breakage occurring in mooring and to identify the dynamic response of the rotor platform in floating offshore wind turbines. Correct behavior on usage of 5MW floating offshore wind turbine subjected to FAST and AQWA(F2A) technique when a mooring was subjected to a sudden breakage followed by IEC 61400-3 standard.

Lone et al. (2021) carried out fatigue assessment of offshore mooring chain considering the effects of mean load and corrosion. Reduction of the mean load gives an increase in fatigue life whereas the corrosion experienced by used chain have a significant negative impact. The parameters were estimated empirically from mooring chain test data includes new and used chain with various mean load and with different degrees of corrosion. The fitting capacity model was then used for fatigue calculation for the mooring system of semi-submersible platforms. The used chains have been retrieved after operation of eight different platforms in North Sea. Studied on 76 mm studless chain of R3 and R4 grade steel which has high fatigue performance of high strength and large diameter studless chain.

Mendoza et al. (2022) carried out on analysis of fatigue test data for retrieved catenary type mooring chain links subject to pitting corrosion effect and fatigue resistance of mooring lines was empirically estimated based on S-N curves. Data from fatigue testing of both new and used samples from several offshore floating unit chain links were considered. Tension–tension fatigue tests of full-scale, studless chain links were conducted to produce the fatigue data. The fatigue tests were conducted for various stress range values and for one or more mean stress levels with mean stress in the range of 10% to 18% of MBL.

Pillai et al. (2022) studied the anchor loads for shallow water mooring of a 15 MW floating wind turbine based on part II synthetic and novel mooring systems. The influence of synthetic and novel mooring tethers on anchor loads and platform dynamics in shallow water was evaluated. The mooring line tensions of the taut mooring system are considered with the resulting taut system had

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a mooring line angle of 25° with the seabed and pretension of 1600 kN. Taut moorings must balance the mooring radius against the anchor's vertical holding capacity and the mooring angle can be further optimized. The taut moored system limits excursions compared to the catenary systems and limits them to within ±15 m in surge and within ±10 m in sway. These excursions are primarily a result of the flexibility of the polyester rope component that makes up the majority of the mooring line.

Danial H et al. (2022) carried out review of fatigue damage assessment in offshore wind turbine support structure. The survey of the specific offshore steel shows that the fatigue lifetime does not have good agreement with the S-N curve of guidelines due to the inhomogeneity of the material and different mechanical properties. The fracture mechanics method used for geometry function would be very useful to approximate the fatigue crack growth rate and J-integral was a criterion to determine the orientation and along with of the fatigue crack and define the plastic behavior of the fatigue crack tip zone. Different mechanical properties associate fatigue behavior, and the nonlinear models can consider two important mechanical parameters fatigue resistance and fatigue ductility behavior. The innovative methods in the fatigue area like PhyBal method could provide accurate fatigue results with three specimens to reduce the test cost from which one specimen would be prone to load increase test and two of them are subjected to constant amplitude loading with load ratio R=-1.

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CHAPTER 3

TYPES OF OFFSHORE WIND TURBINE AND MATERIAL USED FOR SUPPORT STRUCTURE AND MOORING

3.1 GENERAL

The existing literature studies to understand the material used for the support structure and mooring chain in the floating offshore renewable energy wind turbine. Mainly it will be focused on fatigue damage occurs in the support structure and mooring chain in the offshore wind turbine. The substructures are economically limited to a maximum water depth of 40 m to 50 m. The deep offshore environment starts at water depths greater than 50 m.

3.2 DIFFERENT TYPES OF TOWERS USED IN OFFSHORE WIND TURBINE

Different types of wind turbines projects based on different power-carrying capacities and different substructures are given below:

3.2.1. HYWIND

The Hywind design consists of a slender, ballast- stabilized cylinder structure. The spar-type floater has a low water plane area that minimizes wave induced loading, and a simple structure that minimises production cost. It can be used with any qualified offshore wind turbine. The mooring system consists of three mooring lines were connected to the hull by means of bridles that prevent excessive rotation about the vertical axis (yaw motion). The mooring system has inherent design redundancy, with adequate reserve strength in case of a mooring line failure. The 2.3 MW Hywind demo was installed in Norway in 2009 - the world's first full scale floating offshore wind turbine. The unit is located at a water depth of 200 m and10 km off Norway's west coast. It has been thoroughly inspected after the first and second years in service, and no signs of deterioration, damage, or wear connected to being on a floater have been reported. Statoil now considers the design to be technically verified. The floater design has been optimized and up scaled for deployment with multi-megawatt turbines in the 3 MW to 7 MW range. The next step will be to test the design in a pilot farm with four to five units. Figure 3.1 shows Hywind turbine.

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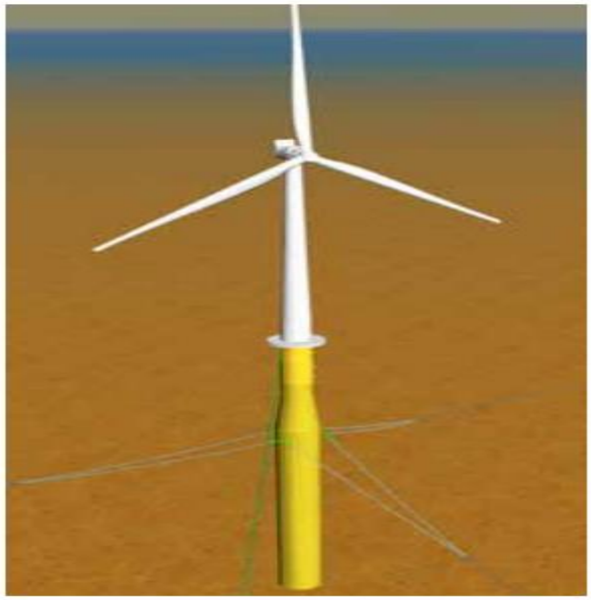

Fig.3.1 Hywind turbine (source: www.ewea.org)

3.2.2. WINDFLOAT

The WindFloat design consists of a semi-submersible floater fitted with patented water entrapment (heave) plates at the base of each column. The plate improves the motion performance of the system significantly due to damping and entrained water effects. This stability performance allows for the use of existing commercial wind turbine technology. In addition, WindFloat's closed loop hull trim system mitigates average wind induced thrust forces. This secondary system ensures optimal energy conversion efficiency following changes in wind velocity and directions. The mooring system employs conventional components such as chain and polyester lines to minimise cost and complexity. Through the use of pre-laid drag embedded anchors, site preparation and impact are minimised.

In 2011, WindFloat was installed off the Portuguese coast. The turbine equipped with a 2 MW Vestas wind turbine and the installation started producing energy in 2012. Figure 3.2 shows Windfloat wind turbine with semi-submersible floater.

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Fig. 3.2 WindFloat turbine with semi-submersible floater (source: www.ewea.org)

3.2.3. BLUE H TLP

The Blue H has been the pioneer in developing deep water floating foundation technology for offshore wind turbines, designed to unlock the vast potential of offshore wind at an economical cost at 2004.The submerged deepwater platform consists of a hollow body. This provides the buoyancy, by being held “semi-submerged” under water by chains or tethers connecting the buoyant body to a counterweight that lies on the seabed with the buoyant body held semi-submerged in the water, the necessary uplifting force is created, keeping the chains constantly tensioned. In 2007, Blue H technologies installed the first test floating wind turbine in Italy. It generated 80 kW and after a year of testing and data collection it was decommissioned. Blue H Engineering is now executing the design, engineering works and related applied research for the development of a generic 5 MW model, based on proven Tension Leg Platform technology. This will offer a more stable floating foundation for commercially available 5-7 MW wind turbines. The manufacturing demonstrator is planned for 2015 and the commercial model is planned for 2016.

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Fig. 3.3 Deepwater platform (source: www.ewea.org)

3.2.4. FLOATING HALIADE 150

Alstom has been developing its floating Haliade 150 with 6 MW based on a tension stabilised concept. The most suitable configurations are Tension Leg Buoy for water depths between 50 m to 80 m, or TLP for water depths between 80 m to 300 m.

Alstom R&D activities started with the Azimut Offshore Wind Energy 2020 Project [2010-2013], jointly with Acciona & Gamesa, and with an objective to develop know-how for constructing large scale marine wind turbines and develop 15 MW floating offshore wind turbines overcoming financial and technical challenges. A partnership between b_Tech and the MIT has been developing know how to model tension leg platforms (TLP's) and developing robust and reliable tools to design TLPs. A grant has been awarded by the US Department of Energy to work on energy cost reduction through advanced control strategies for energy improvement. Figure 3.4 shows the floating Haliade turbine with 6 MW.

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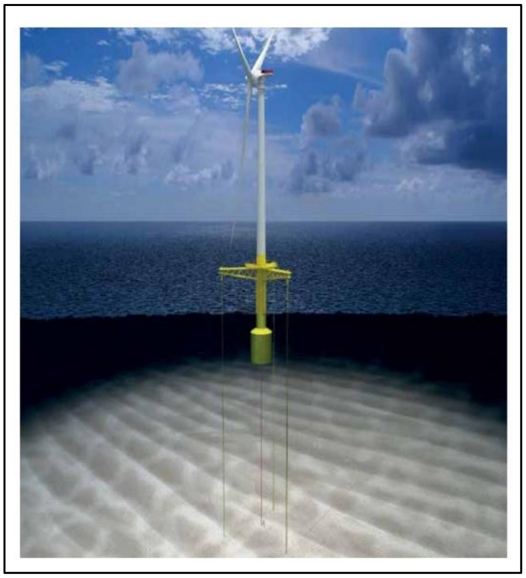

Fig. 3.4 Floating Haliade 150 turbine with 6 MW (source: www.ewea.org)

3.2.5. WINFLO

Using a semi-submersible unit concept,wind turbine specifically designed for offshore floating specifications (sea and moving conditions) and an anchoring system with few constraints suitable to all types of seabed. After two periods of successful tank tests (2010 & 2011), the Winflo life sized demonstrator will be tested in sea conditions in 2013. After a one-year testing period, it will be followed by a pilot farm built in 2016. The machine will be manufactured in pre-series and marketed from 2016 onwards. The programme is coordinated by Nass & Wind Industrie, a major player in the offshore wind sector, in close partnership with DCNS, an international ship building and marine renewables company, and Vergnet, experienced in turbine engineering and manufacturing for harsh environments. The consortium also includes two experienced scientific partners: IFREMER (Sea Research Institute) and the university ENSTA-Bretagne. Officially recognised by the Pôle Mer Bretagne in 2008, WINFLO has also been guaranteed the financial support from the ADEME, the French Environment and Energy Management Agency, under a state investment programme.

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Fig. 3.5 Winflo project (source: www.ewea.org)

3.2.6. PELASTAR

PelaStar is a tension-leg platform (TLP) integrating proven TLP technology. It is widely used in the offshore oil and gas industry and is being adapted for the offshore wind industry.

PelaStar's features include:

• Simplicity of design – an optimised steel structure with no mechanical systems.

•Minimal motions and accelerations at the turbine – there are no pitch, roll, or heave that degrades performance and increases wear on components.

•Efficient quayside assembly, turbine testing, and partial commissioning reduces offshore work, weather delays, and the need for expensive offshore equipment.

•The tendons, with their vertical orientation under the hull, create a compact footprint that reduces the risk of underwater interferences.

•Technology focused on reducing the cost of energy has produced the lowest capital costs for floating designs.

The PelaStar TLP is designed to support 5 MW to 10 MW turbines in 50m to 200m water depths. Model testing at 1:50 scale was completed in 2011. A full-scale, 6 MW turbine demonstration is planned for 2015, with a multi-unit pilot project following in 2017.

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Fig. 3.6 PelaStar with tension-leg platform (source: www.ewea.org)

3.2.7. IDEOL

Based on a concrete hull built in partnership with major civil engineering companies, IDEOL scales from small to very large wind farms. On-site construction, high local content and versatile construction methods are used, depending on site conditions and local procurement options. IDEOL has developed and patented the Damping Pool system. Its floating foundation can be used with any commercial offshore wind turbines, without modification. Damping Pool enables reduction of floater motions by using the hydrodynamic properties of water mass entrapped into a central well. Oscillations are, by design, opposed to the excitation force generated by the waves. IDEOL is currently working with partners on the construction and installation of two commercial scale demonstrators in 2014.

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Fig. 3.7 IDEOL (source: www.ewea.org)

3.2.8. HEXICON ENERGY DESIGN

The Hexicon Energy Design is based on a floating platform which incorporates existing and verified offshore technologies and applications. The towers are installed directly onto the platform, enabling the installation of wave generator applications.

Fig. 3.8 Hexicon Energy Design (source: www.ewea.org)

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1.Centralized swivel system enabling the entire platform to turn around its axis and align itself automatically with the wind while moored

2.Turbines with proven track record

3.Propulsion and dynamic positioning by use of thrusters

4.Tension mooring system (no anchor chains)

5.Protective hull system

6.Electric feeder cable and swivel hook-ups, including the substation, are located above water surface

7.Docking and service facilities located at rear of platform, including heliport designated area

8.24/7 management, surveillance, maintenance and accommodation area

3.2.9. HIPRWIND – EU PROJECT

The HiPRwind project is creating and testing novel, cost effective approaches to Deepwater offshore wind energy developments. In order to gain real sea experience and data, a fully functional floating megawatt scale wind turbine will be deployed at an ocean test site off the coast of Spain and used as an experimentation platform. This installation is approximately on a 1:10 scale of the future commercial floating wind systems for deep offshore. As the world 's first large scale, shared access real sea research and test facility, HiPRwind will facilitate the study of new floater designs, installation methods, control engineering solutions and grid integration aspects of deep-water wind. R&D includes high reliability power electronic components, new concepts for large rotors, control systems, condition and structural health monitoring. Built in active control features will reduce dynamic loads on the floater to save weight and cost compared to existing designs. R&D results will be shared with the offshore wind technology community.

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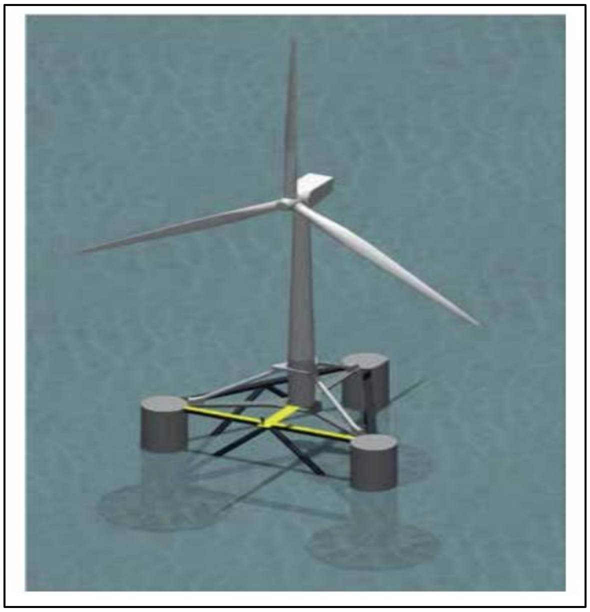

Fig. 3.9 HiPRwind project (source: www.ewea.org)

3.2.10. ZEFIR TEST STATION

The ZEFIR Test Station is an international research facility that will be used for the testing of offshore wind turbines in deep waters. It is located off the coast of Ametlla de Mar, and it will be constructed in two phases. The first will consist of the installation of a maximum of four wind turbines anchored to the seabed at a distance of 3.5km from the coast, with a total power output of no more than 20 MW, whilst the second will involve a maximum of eight floating wind turbines that will be installed around 30km from the coast, which together will provide a maximum power output of 50 MW.

Goals:

• To reduce the costs of building offshore wind farms and develop technologies enabling them to be installed in deep waters.

• To conduct research into these applications.

• To increase the understanding of the science and technology behind wind energy by the industrial sector associated with the research centres involved.

• To create new opportunities for the businesses participating in the project.

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• To establish a leading international centre that can attract investment from the sector

. • To create an environment for promoting university training programmes that attract people into R&D.

• To ensure that Catalonia, and Tarragona in particular, become an international hub for offshore wind energy.

• To raise awareness of the project's environmental impact and its location in the Gulf of Sant Jordi, off the coast of L'Ametlla de Mar.

The first phase of the ZÈFIR project will enable Spanish manufacturers to test their prototype offshore wind turbines, with the advantage of easy access as they will be located relatively close to the coast on water navigable all year round.

3.2.11. SATH

One of several Spanish designs now heading for – or in – the water, the SATH (Swing Around Twin Hull) being developed by engineering outfit Saitec is to be installed as a "medium-scale" prototype in the Cantabrian Sea in the first quarter of this year.

3.2.12. SEATWIRL

Sweden-based SeaTwirl stands apart from other concepts now floating out by being a vertical-axis design. It is engineered to rotate as one unit, from blade-tip down the length of its axle, turning a direct-drive permanent-magnet generator, with seawater drawn into the structure through the shaft by centrifugal force, and then released during low-wind periods to maintain the turning momentum like a figure 3.10 skater pirouetting. So that the turbine works as a flywheel. The 1:6 demonstrator, based on a 10MW design built around conjoined cylindrical pre-stressed concrete hulls anchored to the seabed via a single-point mooring system that allows the unit to 'weathervane' to face the wind, will undergo a 12-month testing programme version as part of the so-called BlueSATH project.

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Fig. 3.10 Belgium's Colruyt Group and Norway's Norsea to finance installation of first 1MW S2 unit off Norway in 2020

Table. 3.1 Gives the outlines of the deep offshore wind designs and projects.

No	Project name	Company	Type of floater	Turbine size (MW)
1.	Hywind (2016)	Statoil	Spar buoy	3.7 MW
2.	Windfloat (2017)	Principle power	Semi-submersible	5-7 MW
3.	DeepCWind Floating Wind (2017)	NREL, MARIN, Technip, Advanced Structures and composites center (AEWC)	Design of one or more full-scale floating wind turbine platforms.	2 MW
4.	Kabashima Island, Kyushu (2013)	Ministry of Environment, Kyoto University, Fuji Heavy Industries	Spar	100 MW
5.	Deepwind (2016)	EU project	Floating and rotating foundation plus vertical wind turbine	5 MW

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6.	Blue H TLP (2016)	BlueH	Submerged deepwater platform	5-7 MW
7.	Advanced floating turbine (2014)	Nautica windpower	Buoyant tower and downwind turbine	5 MW
8.	IDEOL (2015)	IDEOL	Concrete floater	5-6 MW
9.	FLOTTEK (2014)	Consortium led by Gamesa, including Iberdrola	Tension leg turbine platform	2 MW
10.	Pelagic power (2015)	W2power	Hybrid wind and wave energy conversion plant	2-3.6 MW
11.	WINFLO (2016)	Nass and wind/DCNS	Semi-submersible	2-5 MW
12.	Vertiwind(2016)	Technip /Nenuphar/EDF	Semi-submersible	2 MW

3.3 CONCRETE SUPPORT STRUCTURE MATERIAL USED IN OFFSHORE WIND TURBINE

The material used for the support structure in floating offshore renewable energy wind turbines is steel and concrete (reinforced and prestressed) substructures.

The use of concrete support structures for offshore wind turbines offers many potential advantages over towers comprised of only steel, including greater durability, a longer lifespan, increased local labor opportunities, and much quieter installation. An additional challenge for concrete foundations is the longer production time relative to steel structures. This problem could be addressed by prefabricating concrete foundations.

3.3.1. Gravity-based foundation

Gravity-based foundations made of concrete similar to those used for onshore wind turbines were a commonly used solution in the very first offshore wind farms situated in very shallow waters. Recent studies highlight the potential benefits of using concrete for offshore structures and concrete structures have lower production costs and better durability and fatigue resistance. The cost of concrete structures is also more predictable as steel material prices are very

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volatile, with price fluctuations that are several times larger than those of cement. The significant weight of the gravity base foundations is distributed across the large base area and provides stiffness and overturning stability. The hollow base is in general built of concrete with a steel shaft. The structure is floated to the site and ballasted by filling the hollow concrete base with sand; see Figure 3.11. The foundation is suitable for a large variety of soil conditions but viable at locations with stiff sediments near the seabed or shallow bedrock. The gravity base foundation is normally equipped with shallows skirts for increased bearing and sliding capacity and to prevent undermining by scour. High-rise pile caps are usually made of concrete or of a combination of steel and concrete. The cap is supported by a large number of piles. This type of substructure has been used in several wind farms in China and Japan.

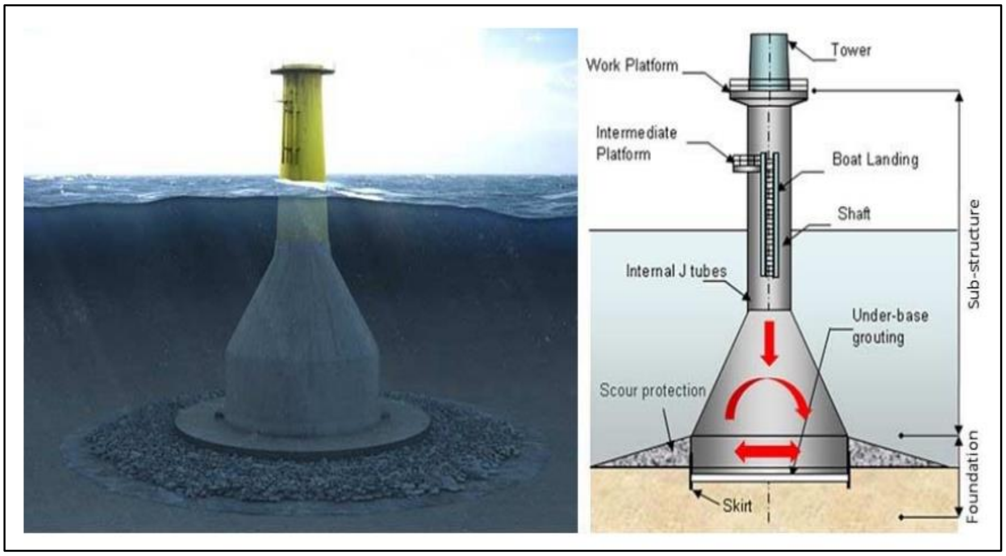

Fig. 3.11 Gravity Base Foundation (Seatower) for Offshore Wind turbines. (Source: SPARREVIK et al (2019) From Research to Applied Geotechnics)

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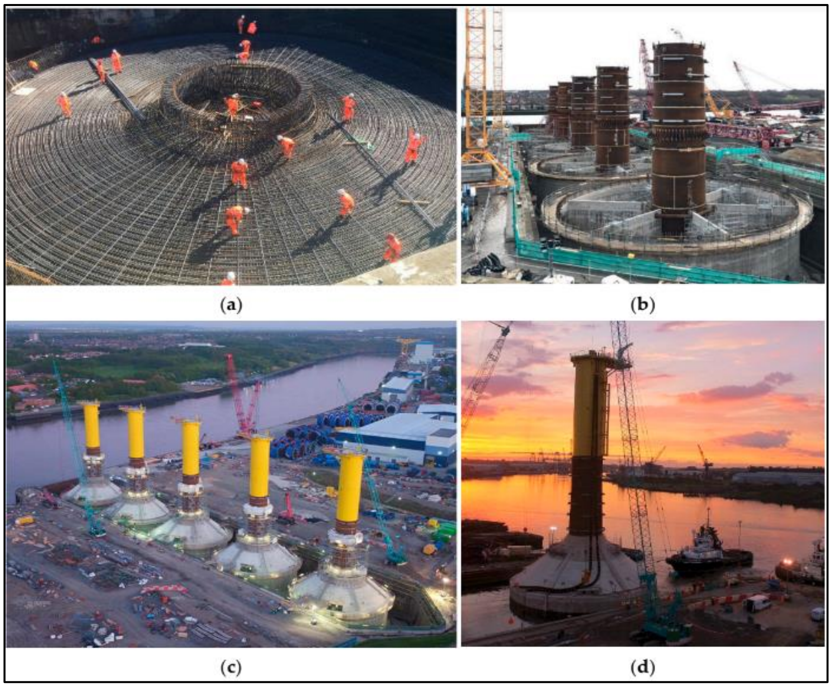

Fig.3.12 Construction of gravity-based concrete substructures for the Blyth Offshore Demonstrator Project: (a) reinforcement placing, (b,c) construction of the concrete base and steel shaft of the substructures in the dry dock. (Source: Alexandre Mathern et al. 2021)

3.3.2 Multi-Leg concrete substructures

New concepts for concrete multi-leg substructures, following the example of steel tripod and jacket substructures, are being developed. These types of substructures can be supported by piles or suction buckets which can consist of either steel or concrete. One such example is Figure: 3.13 (a) HyConCast substructure with tubular concrete members shown in grey and cast-iron connections shown in blue, (b) connection detail of the HyConCast substructure, which consists of a hybrid substructure with tubular elements, made of high-strength concrete, that is connected by thin-walled joints consisting of ductile cast iron. The advantage of this concept is that the uniaxially loaded braces are made of prestressed concrete, whereas the knots subjected to bending are made of cast iron.

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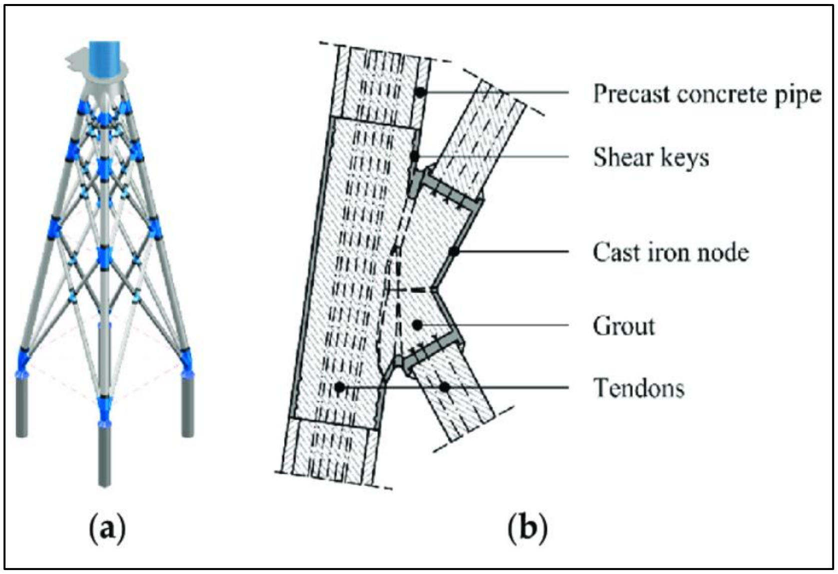

Fig. 3.13 (a) HyConCast substructure with tubular concrete members shown in grey and cast-iron connections shown in blue, (b) connection detail of the HyConCast substructure. (Mathem -2021) (researchgate.net)

3.4 STEEL STRUCTURES

3.4.1 Monopile foundation

Monopiles, also called mono-tower structures, which is cylindrical steel tubes that are driven down into the seabed. They usually consist of two parts; the monopile is the bottom part which is hammered into the ground, and a transition piece mounted on top of the monopile. The connection between the monopile and the transition piece is often a grouted connection, where a special concrete is injected between the two pieces fixing them to each other.

The monopile is a simple construction and extends effectively the turbine tower underwater and into the seabed as illustrated in Figure 3.14. The majority of offshore wind parks in Europe are supported by monopile foundations. The monopile consists of a steel pile with a diameter between 3.5 and 5.5 m driven or drilled up to 40 m into the seabed. Monopile were used extensively in near and offshore environments up to water depths of 25 m. For the installation of monopiles only small preparations of the seabed are necessary. For water depths larger than 25 m lattic steel structures are used.

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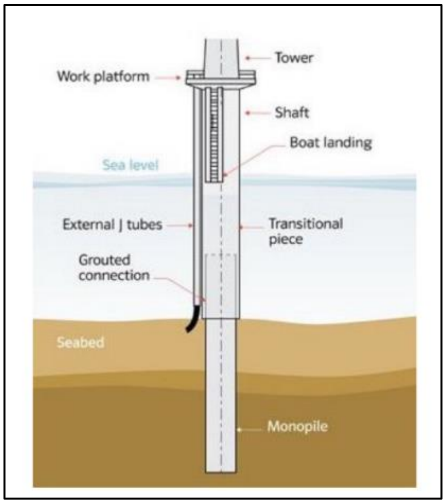

Fig. 3.14 Monopile foundation with help of steel support structure

3.4.2 Tripod support structure

Tripod structures are supported by three legs mounted on the sea bottom. They have a steel column in the center, where the turbine tower is mounted on top. Piles or suction buckets are used to fix the legs to the bottom. Similar to the other concepts, the tripod structure has platforms and boat landings for the crew to board the structure. An example of the structural layup of a tripod structure is shown in Figure.3.15.

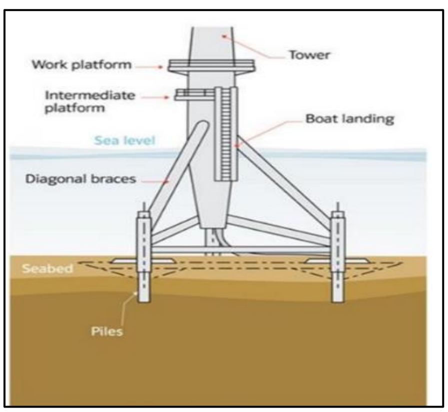

Fig. 3.15 Structural layup of a tripod structure (Johannessen -2018)

3.4.3 Jacket support structures

Jacket structures are bottom-fixed structures with multiple legs. The most common types have three or four legs, which are supported by bracing extending from one leg to another. The

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braces are connected to the legs at nodes and are designed to carry axial loads in tension or compression. A mount for the tower is placed on top of the jacket, where a transition piece results in a circular cross-section for the connection. The jacket structure is fixed to the bottom using piles, which are either driven before or after the jacket is placed on the bottom. An example of a jacket structure is shown in Figure.3.16. They are considered more expensive to manufacture than monopiles, due to the many joints of tubes in different angles. The development of these structures is driven by the need for reducing costs.

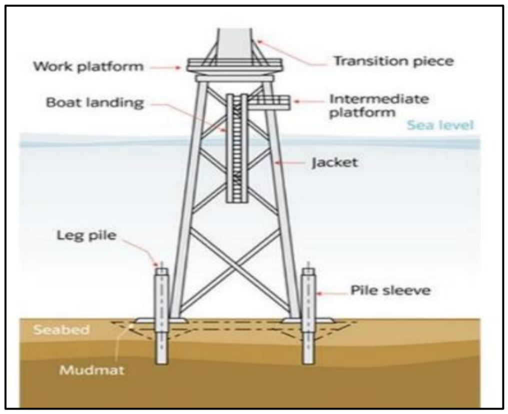

Fig. 3.16 Jacket steel support structures

3.5 DIFFERENT TYPES OF MOORING CHAINS USED IN OFFSHORE WIND TURBINE

Today have variety of fiber rope can be considered for use in mooring system such as polyester, aramid, HMPE and nylon in which growth of cracks occurs during dynamic loading and is an important design criterion for mooring lines. Mooring systems maintain a dynamic floating structure within their predefined geographical area, with a specified tolerance. Historically, mooring systems have been a great importance within the oil and gas industry. In recent years, it has also seen a rise in the renewable energy sector.

3.5.1 Wire rope

Wire rope consists of individual wires wound in helical pattern to form a strand. Multi-strand or single-strand construction are used in offshore mooring, shown in Figure 3.17. Multi-strand consists of 12, 24, 37, or more wire per strand. Multi-strand contains fiber or metallic. Independent wire rope core (IWRC) and wire-strand core (WSC) are two types of metallic core.

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IWRC is the most common core filling for heavy marine application. Two constructions of wire rope are used for permanent mooring, six-strand, and spiral-strand construction. Six-strand construction is typically used in applications with short design lives less than 8 or 10 years. While spiral strand construction is designed to be used in application from 10 to 30 years, depending on the level of corrosion protection. Six-strand wire is traditionally used due its low elastic stiffness, cost, and ease of handling. The disadvantages are low service life, the individual wires are galvanized, providing corrosion protection for about 8 years and due to its construction, it rotates under load. This construction-induced rotation can induce permanent twist into anchor leg system, and changes in tension can induce cycles of rotation, resulting in torsional loading of the chain that could result in undesired stresses and reduction of the estimated fatigue life. Spiral-strand wire is supplied either unsheathed or sheathed with a service life ranging from 10 to 30 years, respectively. Unsheathed spiral-stand wire requires care during installation. Re spooling the wire rope from a shipping reel into an installation reel, deploying it over s stern roller, or using grippers to support the wire during deployment can cause result-in loose wires at the socket. In addition, careful handling of the socket during installation is important. Single-strand ropes are more common in large permanent installation. The wires are wound as a helix with each layer wrapped in a different direction. This provides torque balancing, preventing the rope from twisting when under load. The spiral strand is more fatigue resistant than the multi-strand rope. Corrosion resistance is enhanced by either sheathing with a polyurethane coating, adding zinc filler wires, or using galvanized wires

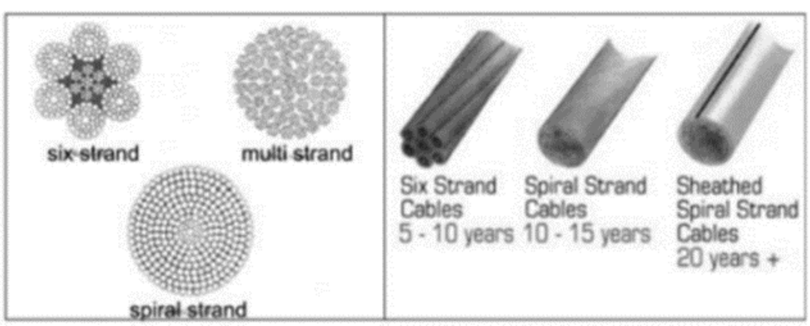

Fig.3.17 Wire rope used for mooring of multi-strand or single-strand construction (Brown,2005 Journal of Ocean Engineering) (source: www.elsevier.com)

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3.5.2 Polyester rope

Polyester has now been used in permanent mooring systems and has been an enabling technology for extending mooring design to ultra-deep water. Polyester ropes are not fully elastic, this means that the ropes undertake plastic deformation and will have a permanent change in length. Polyester, as a material and mooring component has been studies extensively by the industry and all major societies. There have been issued various design guideline and detailed manufacturing and testing procedures to ensure suitability for offshore mooring. Polyester has developed an excellent track record for long-term performance, other than for its susceptibility to damage by contact with sharp or abrasive and objective. This requires well-defined installation equipment and procedure. Polyester rope has light weight and high elasticity. Its high elasticity allows the use of taut mooring system in deep and ultradeep water without need for catenary compliance to limit dynamic tensions. Figure 3.18 shows the cross-section of a polyester rope construction.

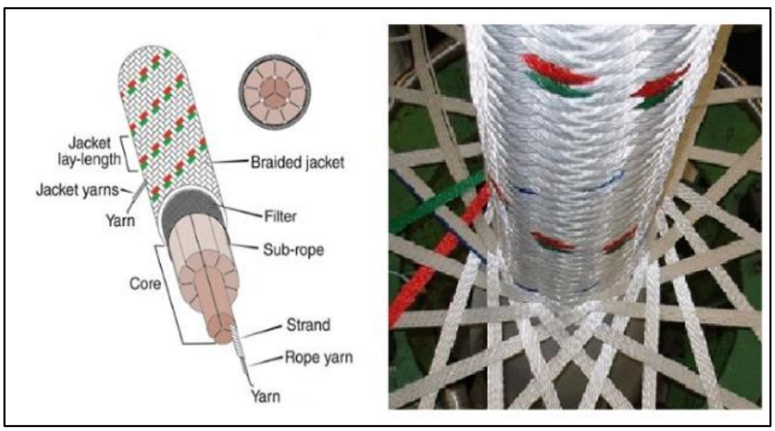

Fig. 3.18 Cross-section of a polyester rope (Deep Sea Mooring, 2020)

Advantages of polyester rope:

- Reduced vessel offset
- Smaller mooring footprint
- Improved vessel payload capacity
- Excellent fatigue properties

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3.5.3 Steel wire

Steel wires are commonly used in engineering application such as crane, lifts and offshore mooring line. Every class of steel wire are suit for different purpose. Steel wire also have several types of cross section. The extensive use of steel wire rope for load bearing elements is mainly due to the strength offered by steel coupled with the flexibility of rope construction, rope geometry and wire that can be suited to the required application (Beltran, 2006). In tensile load, the steel wire subjected to bending and torsion moment, frictional and bearing load and tension. The distribution of stress resulting from the loading is determine by the elongation and rotation of wire steel rope. Steel wire have been using a long time for a mooring line of offshore platform. The weight of steel give restoring force for the platform. When in deep-water, this steel wire rope has reach nature limitation. In this research, will focus on the 1+6 rope structure. Steel wire also have three basic component that is wire, strand and core.

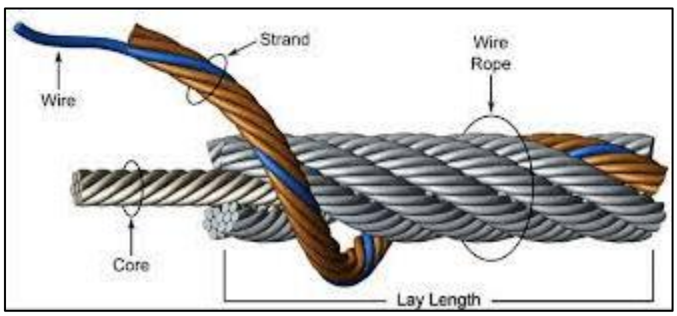

Fig. 3.19 steel wire rope (source: https://www.ehsdb.com/wire-ropes.php)

3.5.4. Nylon

For pilot farms of floating wind turbines (FWTs) in shallow-water between 50 m and 100 m, the application of nylon as a mooring component can provide a more cost-effective design. Indeed, nylon is a preferred candidate over polyester for FWT mooring because of its lower stiffness and a corresponding capacity of reducing maximum tensions in the mooring system. The use of nylon has, however, not been well proven appropriate for permanent mooring application due to its poor wet fatigue characteristics.

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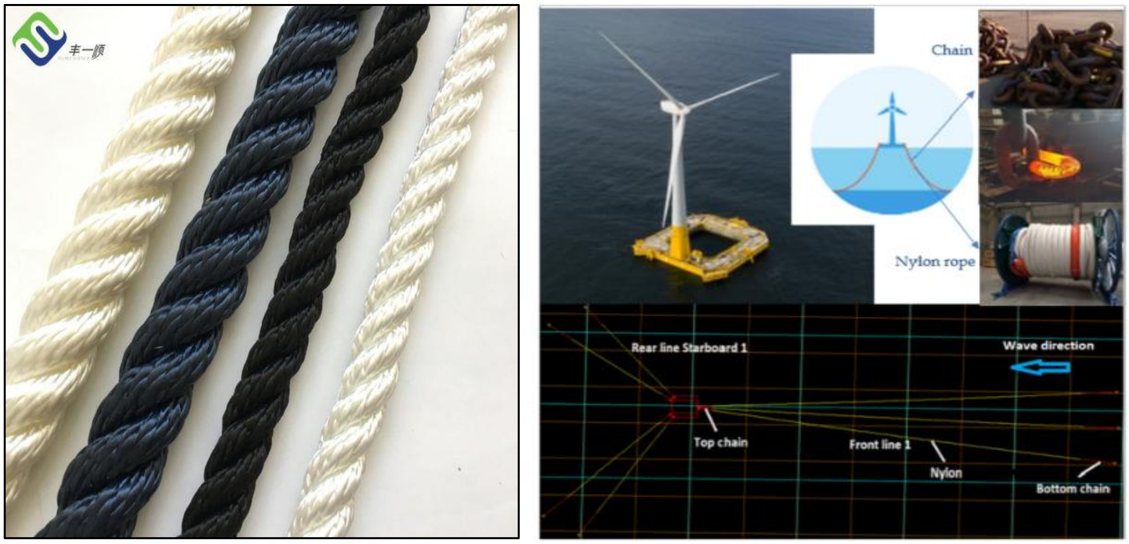

Fig. 3.20 The FLOATGEN FWT principal parameters and mooring components (Berhault, 2017) and the Orcaflex model of the floating structure attached to its mooring lines (Spraul et al., 2017; Pham et al., 2019) – down (source: www.elsevier.com)

3.5.5. Synthetic fibre ropes

Synthetic fibre ropes are lighter and more elastic than chain and steel wires, this makes fibre ropes easier to handle. The light weight of the ropes combined with the buoyancy makes the weight in water negligible for many instances. This provides the moored structure with an enhanced payload capacity with respect to the traditional mooring systems. The synthetic fibre ropes are composed as illustrated in Figure 3.21, with a braided jacket as the outer layer. This is to provide resistance against damage since the ropes are easier damaged than its steel counterparts. For this reason, the synthetic ropes are not allowed to touch the seabed, and the lines must always be in tension because temporary slack may decrease the line strength.

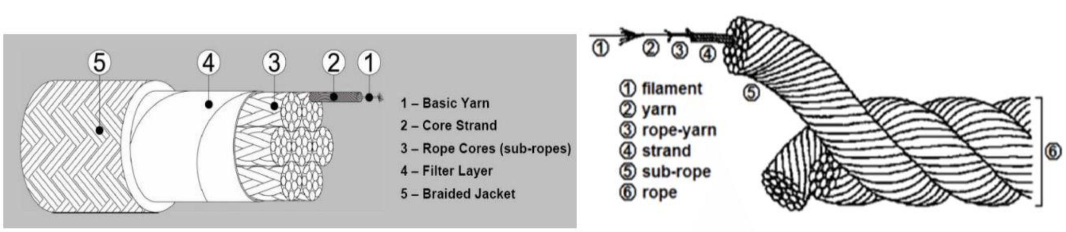

Fig.3.21 Typical marine synthetic rope (Amran et al. (2016)) (source: researchgate.net)

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3.5.6. Chains

Chains are the most common mooring line to till date. The extensive use of chains for mooring lines have made the limitations and applications of chain well documented. There are two different chain types that are much used, studded and stud-less chain. Studded chains have a higher capacity than the stud-less, and the stability of the links are also improved. But the added weight of each link for studded chain are a negative factor in terms of cost and weight of each link. The two-chain links are seen in Figure 3.22. Chains have been very popular to use in mooring systems that shall have a long-life span. This is due to steels high breaking strength and the fact that it is heavy and have good properties when it comes to wear and tear.

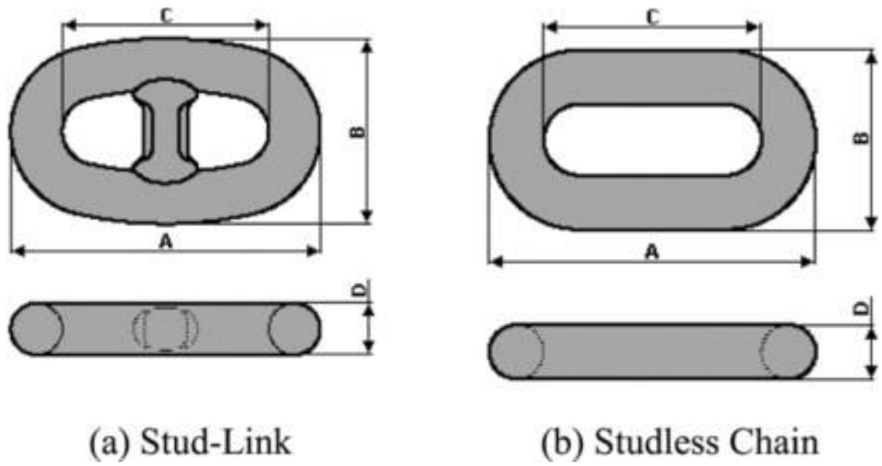

Fig. 3.22 Mooring chain showing both stud-link and stud-less chain (Brown, Journal of Ocean Engineering (2015)) (source: www.elsevier.com)

Permanent moorings have recently preferred to use open link, or studless chain (Fig. 3.22 b). Removing the stud reduces the weight per unit of strength and increases the chain fatigue life. The expense of making the chain less convenient to handle.

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Table 3.2 Material used for mooring chain and offshore wind turbines.

AUTHOR'S NAME	OFFSHORE WIND TURBINES	POWER	MATERIAL USED FOR MOORING
Hyungjun Kim et al. (2013)	Semi-submersible	5 MW	Chain mooring
Sinpyo Hong et al. (2015)	Spar buoy-type floating offshore wind turbines	5 MW	Synthetic mooring lines
Zi Lin et al. (2015)	Combined study		Elastic Polyester mooring
Lin Chen et al. (2018)	Spar-buoy type floating offshore structure	5 MW	Chain mooring
Yuanchuan Liu et al. (2019)	Semi-submersible	5 MW	Chain mooring
Kun Xu et al. (2020)	Semi-submersible floating wind turbines	5 MW	Chain and Synthetic fiber rope
Yang yang et al. (2021)	Barge-type floating offshore wind turbine	5 MW	Cables like mooring
Yuan Ma et al. (2021)	Spar floating offshore wind turbine	5 MW	Chain mooring
Pillai et al. (2022)	Semi- submersible	15 MW	Synthetic and Novel mooring
Kang Sun et al. (2022)	Spar buoy-type	5 MW	Chain mooring
Giulio Ferri et al. (2022)	Semi-submersible	10 MW	Chain and synthetic lines
Hoa Nguyen et al. (2022)	Spar type floating offshore wind turbines	5 MW	Cables mooring
Philip Alkhoury et al. (2022)	Barge type	10 MW	Chain mooring
Yajun Ren et al. (2022)	Multi-column tension leg platform	5 MW	Synthetic fiber rope

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Chenglin Zhang et al. (2022)	Semi-submersible	5 MW	Chain mooring
Xiaoqian Wing et al. (2022)	Full Submersible floating wind turbine	5 MW	Carbon-fiber-reinforced polymer (CFRP)
Yang Zhou et al. (2023)	Semi-submersible	25 GW	Chain and Synthetic fiber rope

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CHAPTER 4

FATIGUE LIFE EVALUATION OF THE WELDED STEEL SPECIMEN USED FOR FLOATING OFFSHORE WIND TURBINE SUPPORT STRUCTURES

4.1 GENERAL

The fatigue life of high-strength steel used for floating offshore wind turbine support structures are studied. In order to predict the fatigue behaviour and to evaluate the life estimation under cyclic loads, fatigue tests were carried out on IS2062 E350 grade steel. The E350 grade steel has been used in the substructures of floating offshore wind turbines. Fatigue testing is a process of subjecting a material or a structure to repeated loading and unloading cycles in order to simulate the stresses it would experience during normal use over time. The goal of fatigue testing is to determine the point at which the material or structure will fail due to repeated loading and to measure the properties of the material or structure under those conditions.

For the fatigue design of offshore wind turbine support structures, safe-life methodology in which the fatigue strength is based on a stress-life (*S*-*N*) approach that relates the number of cycles (*N*) and the constant stress range (*S*) likely to cause fatigue failure for specific categories of welded connection details or components, is generally used. Three different concepts of *S*-*N* curves are developed and referred to in the literature and standards. They are: (a) nominal stress *S*-*N* curve, (b) hot spot *S*-*N* curve and (c) notch stress *S*-*N* curve. DNVGL-RP-C203: "Fatigue design of offshore steel structures" gives *S*-*N* curves for tubular joints in (a) air, (b) seawater with cathodic protection and (c) free corrosion, i.e., without corrosion protection. Traditionally, S355 steel conforming to EN10025 is the main structural steel typically used for wind turbine support structures. The equivalent Indian grade of steel for S355 is Grade E 350 conforming to IS 2062: "Hot Rolled Medium and High Tensile Structural Steel - Specification".

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4.2 EXPERIMENTAL STUDIES

4.2.1 FATIGUE LIFE EVALUATION OF TRANSVERSE BUTT WELD JOINT

Fatigue life of IS 2062 Grade E 350 steel identified for floating offshore support structures has been taken up. Before taking up the fatigue studies, mechanical properties were determined by carrying out tension tests on three specimens as per ASTM E 8M - 16a. The average yield strength and ultimate tensile strength of the material were 338 MPa and 494 MPa respectively. The percentage elongation was 27.3. The modulus of elasticity was 200 GPa. ASTM E 466 - 21: "Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials" has been followed in preparing the test specimens and carrying out the fatigue tests. The overall size of the transverse butt weld specimens used in the present studies are 500 mm × 32 mm × 16 mm. The tests were carried out under constant amplitude sinusoidal cyclic loading at various values of maximum stress which were decided as a percentage of yield strength of the material.

Fatigue tests were carried out at a maximum stress value equal to 95%, 85%, 80% and 75% of the yield strength of the material. The stress ratio was kept as 0.10. The corresponding maximum and minimum stress values were 321.10 MPa and 32.11 MPa; 304.20 MPa and 30.42 MPa;287.30 MPa and 28.73 MPa; 270.40 MPa and 27.04 MPa; 253.50 MPa and 25.35 MPa respectively. The corresponding stress range values were 288.99 MPa, 273.78 MPa, 258.57 MPa, 243.36 MPa and 228.15 MPa. Three specimens were tested at each stress range using ±500 kN capacity Universal Testing Machine (UTM). The test frequency was maintained in the range of 10 Hz to 15 Hz. Figure 4.1 shows the set-up for fatigue test on transverse butt weld joint specimen of Grade E 350 steel. Figure 4.2 shows the close-up view of the fatigue test on transverse butt weld specimen. Figure 4.3 shows the close-up view of the specimen after failure.

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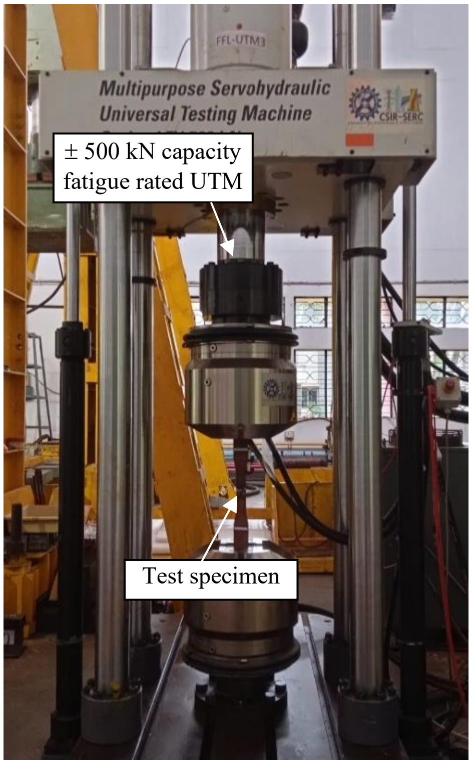

Fig. 4.1 Set-up for fatigue test on transverse butt weld specimen of a Grade E 350 steel

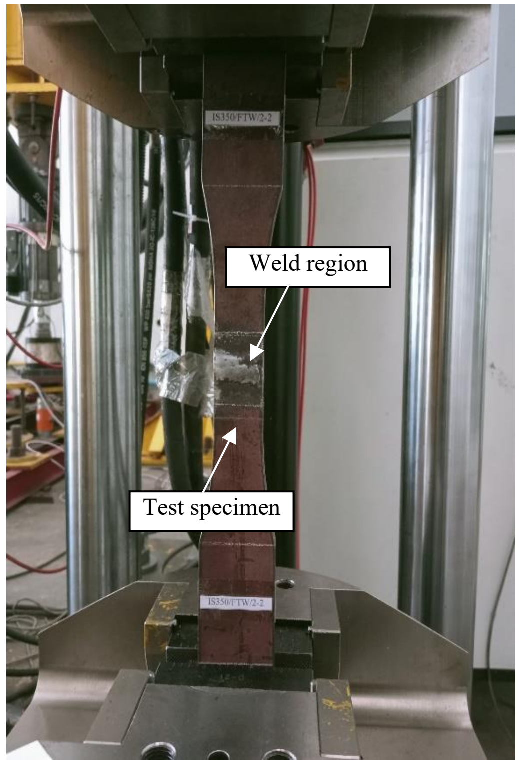

Fig. 4.2 Close-up view of the fatigue test set-up

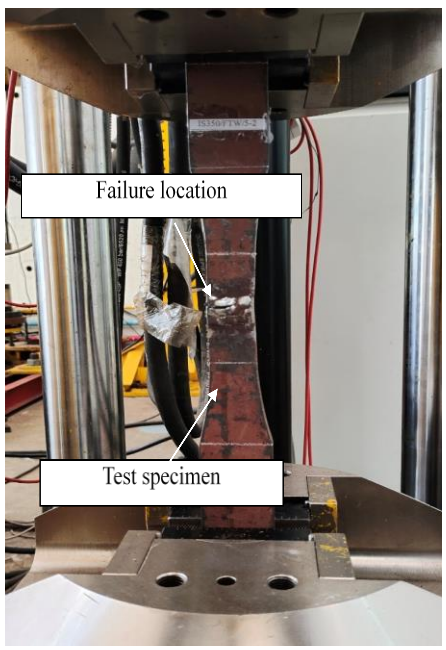

Fig. 4.3 Close-up view of the specimen after failure

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4.2.2 FATIGUE LIFE PREDICTION

To successfully conduct an evaluation of the fatigue of steel structures, it is necessary to evaluate the fatigue life of every structural component. Predicting the fatigue life of a component is using stress range and number of cycles for generating S-N curves as per IS 800: 2007. Figure 4.4 shows the standard *S-N* curves for each detail category for normal stress range given IS 800:2007

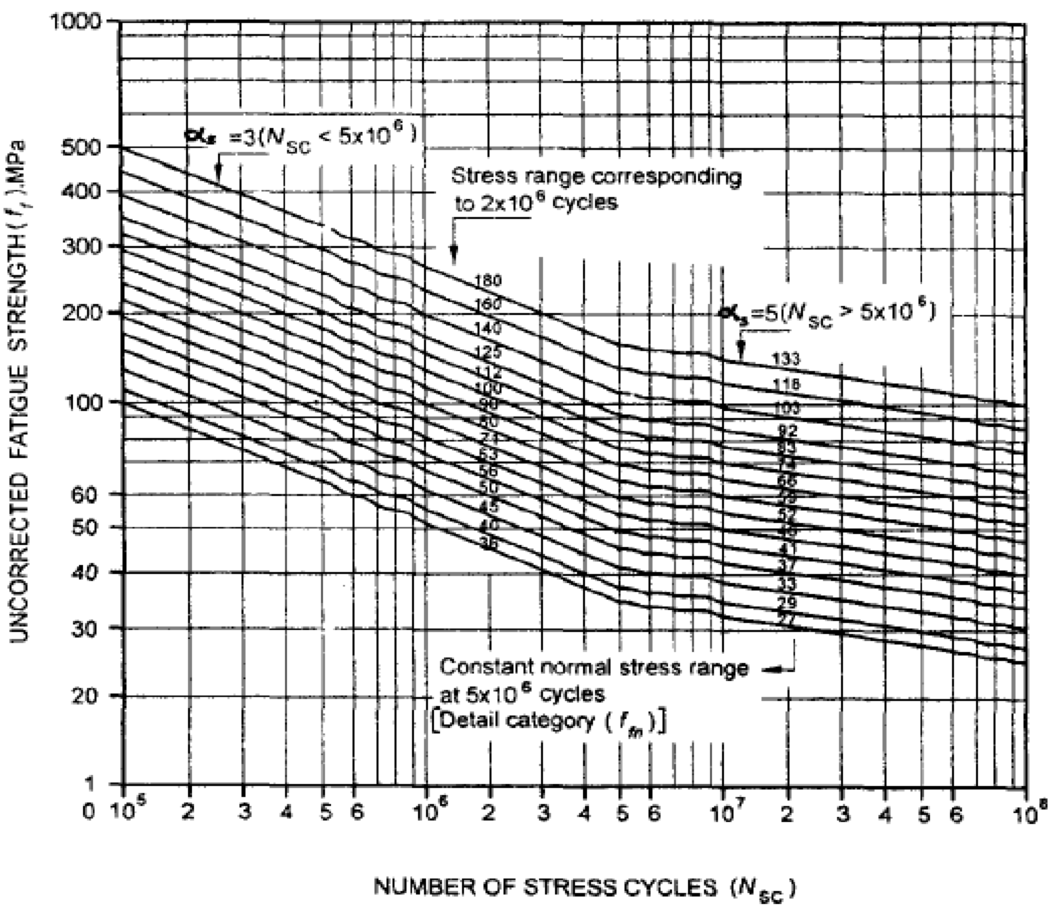

Fig. 4.4 S-N curves for normal stress as per IS 800: 2007

These curves are constructed by experimental results of numerous specimens at different stress range and determining the number of cycles to fail are of the specimen. Fatigue resistance decrease with an increase in the number of stress amplitude. By varying the stress amplitude, the number of cycles to failure also varies allowing different points on the curve to be plotted, the higher the stress amplitude the fewer cycles it takes to reach failure and vise versa.

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The fatigue design provisions given in IS 800:2007 for constructional details are discussed. The detail category in IS 800:2007 designated by a number which represents the fatigue strength of the constructional detail at 5 x 10^6 cycles in N/mm^2. The fatigue strength of the standard detail category for normal stress range is given below.

When $N_{sc} \leq 5x10^6$

$$f_t = f_{fn} \sqrt[3]{\frac{5x10^6}{N_{sc}}}$$

When$5x10^6 \leq N_{sc} \leq 5x10^8$

$$f_t = f_{fn} \sqrt[5]{\frac{5x10^6}{N_{sc}}}$$

Where,

f_t -design normal stress range

f_{fn}– Normal strength of the detail for $5x10^6$

N_{sc}- Fatigue life

Fatigue life evaluation of specimens considering as material with machine gas-cut edges with draglines or Manual gas-cut material as per IS 800:2007 is carried out. The constructional Detail for the specimens and the corresponding detail category is 83. The details as per IS 800:2007 for normal stress range is given figure 4.5 as detail category 83.

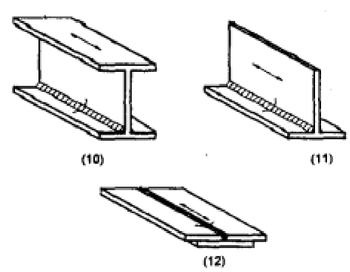
83		**Welded plate I-section and box girders with continuous longitudinal welds** (10) & (11) : Zones of continuous automatic butt welds made from one side only with a continuous backing bar and all welds not having un-repaired stop-start positions. (12) : Zones of continuous longitudinal fillet or butt welds carried out from both sides but containing stop-start positions. For continuous manual longitudinal fillet or butt welds carried out from both sides, use Detail Category 92.

Fig. 4.5 Detail category 83 as per IS 800:2007 for normal stress range.

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CHAPTER 5

FATIGUE LIFE EVALUATION OF U3 GRADE STEEL USED IN MOORING SYSTEMS

5.1 GENERAL

A mooring chain of U3 grade steel specimen is taken for the study. Tensile test and fatigue test we conducted in Fatigue & Fracture Laboratory, CSIR-SERC Chennai to obtain material properties of the specimen. To evaluate mechanical properties of mooring chain of U3 grade steel, tension tests were carried out at room temperature. Based on these results to the study, fatigue life evaluation was carried out as these material for developing S-N curves. The gauge length for both round specimens is taken as 9 mm. The two primary factors to affect fatigue reliability are the materials fatigue strength and the applied cyclic loading.

5.2 MOORING CHAIN

The stud link mooring chain of 40 mm diameter of U3 grade steel used to anchor the floating offshore wind turbine structures. Mooring chain used for the study was 1.5 m. R3 grade of steel is used for internationally considered for mooring chain as per DNV-OS-E301. The equivalent grade of R3 steel in corresponding to Indian steel as U3 grade.

5.2.1 MANUFACTURING PROCESS

Chains are welded on automatic flash butt welding machines. The weld area is trimmed all around the weld on specially designed machines to give a smooth weld. Studs are hydraulically pressed in the link.

5.2.2 Heat treatment

To ensure required physical properties and homogeneous grain structure, all chain is heat treated in automatic controlled furnaces.

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5.2.3 Inspection and testing

Proof and break load testing of each chain and accessories was carried out on 500 tonnes capacity horizontal testing machine. Visual link by link inspection and dimensional check-up is done after proof load testing.

Magnetic particle test was carried out on forged and machined components to ensure flawless components.

Tensile tests and impact tests were performed on each batch of finished chain and accessories to comply with the requirements of the specifications. Testing is certified by classification societies as required by the customer.

5.2.4 Painting and Packaging

Chains and accessories are generally coated with bitumen. If desired these can be supplied in electro zinc plated or hot dip galvanized condition. Chains are bundled and tied with wire ropes and loose items are packed in wooden boxes.

The stud link U3 grade mooring chain obtained from the manufacturer is given below figure 5.1.

Fig. 5.1 U3 grade of studded mooring chain of 9 links

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5.2.5 Fabrication

The mooring chain obtained from manufacturers were sent for the fabrication and test specimen were fabricated. The mooring chain ordered for the project work from manufacturers has a total length of 1.5 m and has a 40 mm diameter with 9 links included. The fabrication team cut off the stud portion and made the mooring chain studdles. They also separated all links of the studded portion and made the mooring chain studless. They separated all links of the mooring chain via machine cutting. The vertical portion of the links were cut off and the horizontal straight portion was obtained and fabricated for the tension testing as per ASTM E8 “Standard Test Methods for Tension Testing of Metallic Materials” and as per ASTM E466-15 “Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials” for fatigue test specimen were fabricated with the AutoCAD drawing which is based on the ASTM Standard condition which given to the fabrication team. Figure 5.2 shows the straight portion extracted from the chain link through machining process.

Fig. 5.2 straight portion of mooring chain

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Table 5.1 Mechanical properties of U3 grade mooring chain from manufacturers**.**

Grade	**Heat Treatment**	**Tensile strength (N/mm2)**	**Yield stress(N/mm2)**	**Elongation (%) min**	**R.A. (%) min**
U3	Quenched and tempered	Min .690	410	17	40

5.3 EVALUATION OF MATERIAL PROPERTIES.

An experimental study for tension tests is carried out by three-rounded tension test specimens. The test specimen possess a solid circular cross-section for tension test on 16 mm grip diameter, 160 mm overall length, and a gauge length of 9 mm diameter specimens fabricated using U3 grade steel mooring chain used in offshore. The test was carried out by using ASTM E8 "Standard Test Methods for Tension Testing of Metallic Materials". The details of dimensions drawing from AutoCAD depending on ASTM E8 standards and the specimen detail drawing are shown in figure 5.3 respectively.

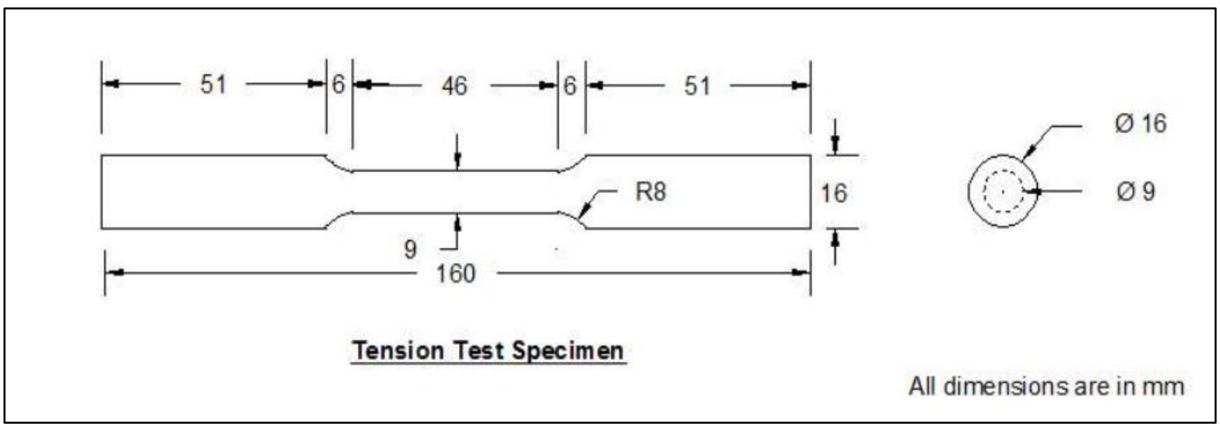

Fig. 5.3 Details of dimensions for tensile test round specimen

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Fig. 5.4 Tension test specimen

5.4 EXPERIMENTAL SETUP

The static tensile test on U3 grade mooring chain specimen was tested using Universal Testing Machines (UTMs) of 500 KN capacity at the Fatigue and Fracture Laboratory of CSIR-SERC. The tests were carried out under monotonic loading till failure of U3 grade steel specimen. By gradually increasing the tensile load, the specimen will be elongated. The extensometer used to measure 25 mm elongation of the specimen. Here three specimens' tensile test were compared to determine the yield strength, ultimate tensile strength, percentage of elongation and location of failure. To measure strain in the U3 grade steel specimen extensometer used. The test specimen was correctly marked before testing. Grip of 50 mm provided, and gauge length marked correctly for the determination of elongation shall be in accordance with the product specifications for the material being tested. The marking made before testing are shown in the figure 5.5. The testing machine shall be set up in such a manner that zero-force indication signifies a state of zero force on the specimen. Figure 5.6 shows the Universal Testing Machine with tensile specimen included extensometer on the specimen and set the reading to zero and provided at the centre portion of gauge length. Change in length is obtained from reading recorded from extensometer. With the increase in load at some point, the load pointer remains stationary. Load corresponding to this indicated the yield point. With further increase in load the pointer goes backward and specimen break. The load before this breaking is the ultimate load. The load at the breaking of the specimen is called as the breaking load. As shown in figure 5.8 below, once load crosses the ultimate stress (ultimate load) necking starts to form in the specimen. Figure 5.9 shows broken point.

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Fig. 5.5 Mark made before testing the specimen.

Fig. 5.6 Universal Testing Machine with tensile specimen included extensometer.

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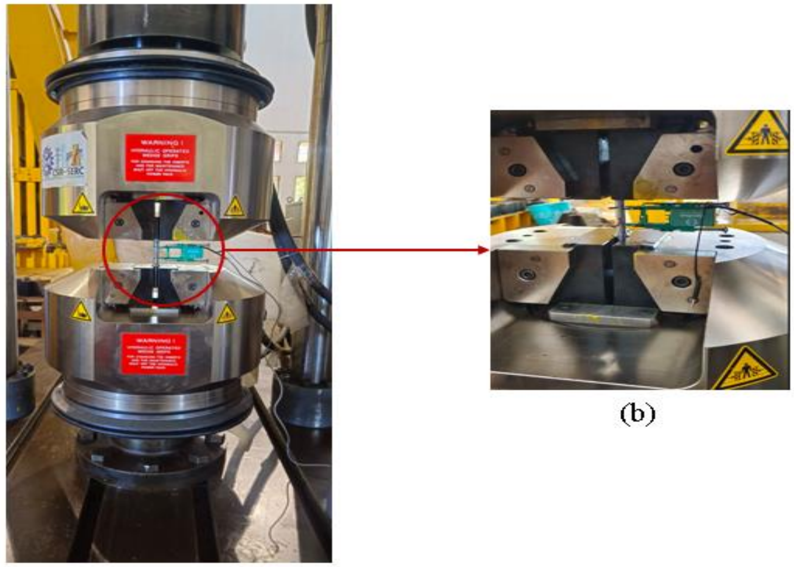

(a) (b)

Fig. 5.7 Test specimen with extensometer

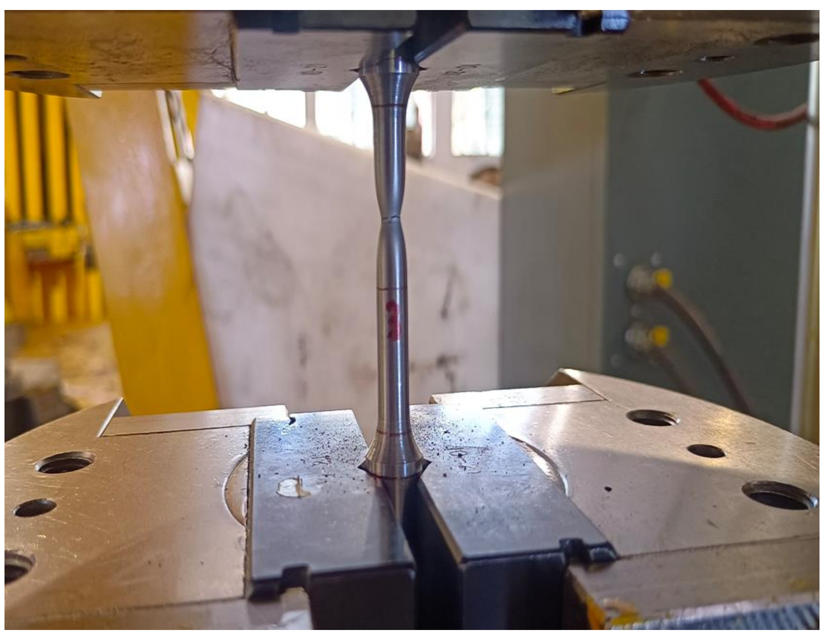

Fig. 5.8 Necking of steel specimen under tensile load

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Fig. 5.9 Broken point

5.5 Results and Discussion

The specimens were tested until failure load. The tension test results for the mooring chain of U3 grade steel specimens are given in table 5.2 and stress-strain curve for specimens are given in below figure 5.10, figure 5.11, figure 5.12.

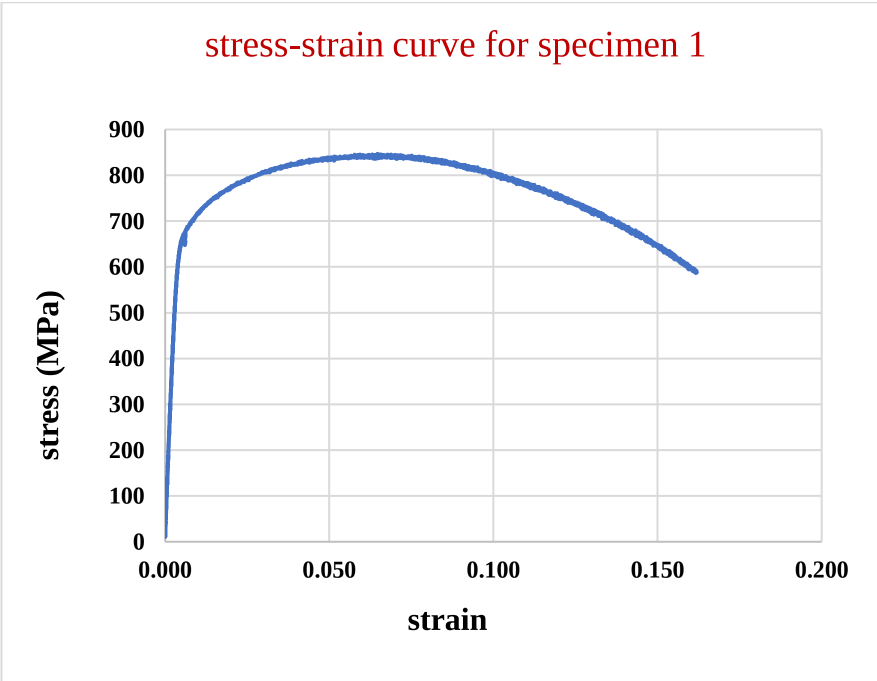

Fig. 5.10 stress strain curve for specimen 1

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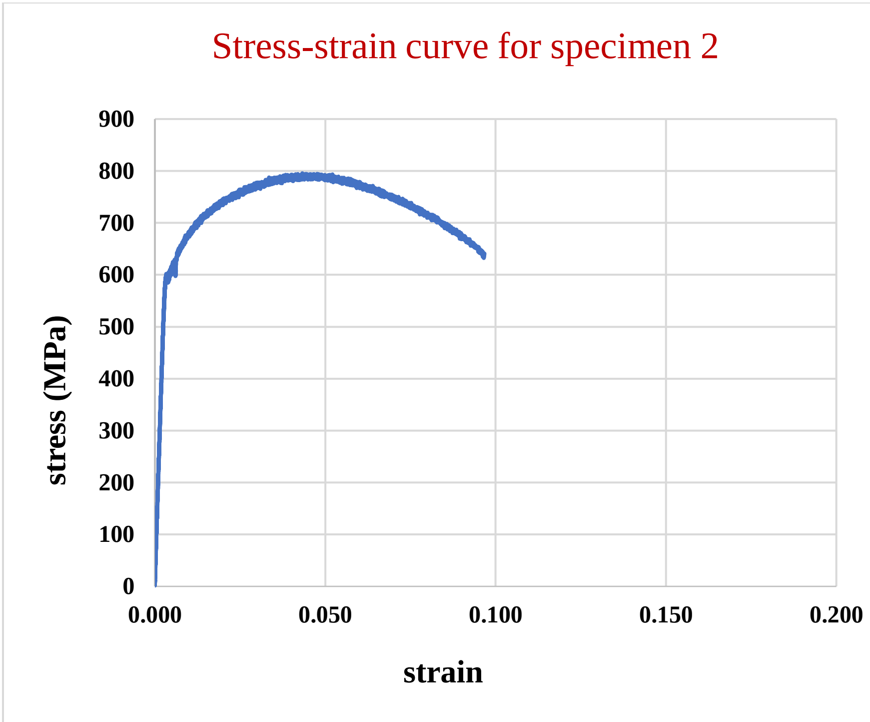

Fig. 5.11 stress strain for specimen 2

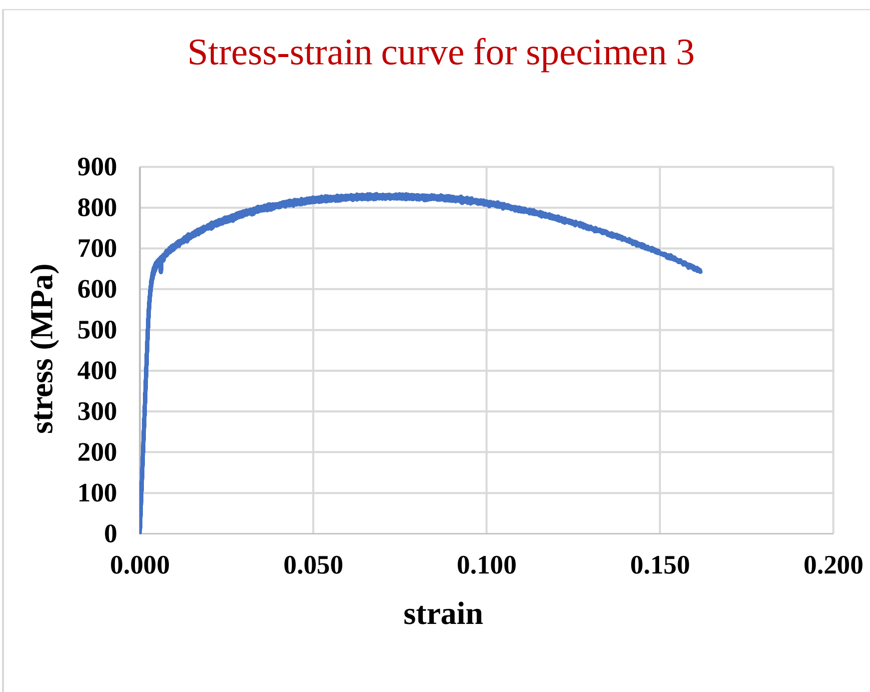

Fig. 5.12 stress strain curve for specimen 3

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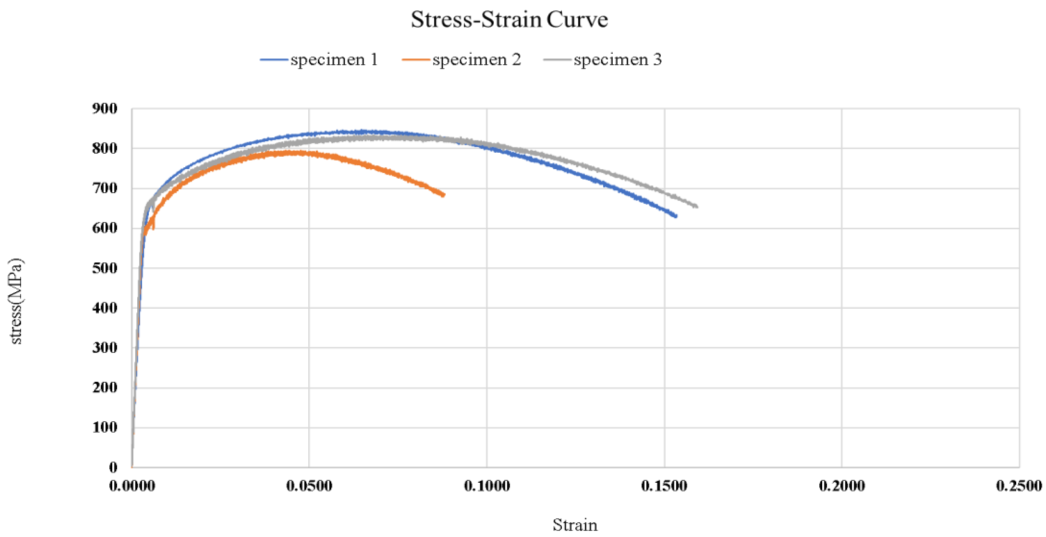

Fig. 5.13 Combination of stress strain curves

Table 5.2 Tension test result on U3 grade steel specimen

Specimens	**Ultimate tensile strength (N/mm2)**	**Yield strength (MPa)**	**Elastic modulus (GPa)**	**Percentage of elongation (%)**	**Percentage of reduction in area (%)**
Specimen 1	847.19	664	210.219	17.39	69.1
Specimen 2	795.54	612	211.256	16.39	55.5
Specimen 3	833.69	669	224.644	16.39	69.1

5.6 FATIGUE STUDIES ON MOORING CHAIN OF U3 GRADE STEEL

ASTM E 466 - 21: "Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials" has been followed in preparing the test specimens and carrying out the fatigue tests.

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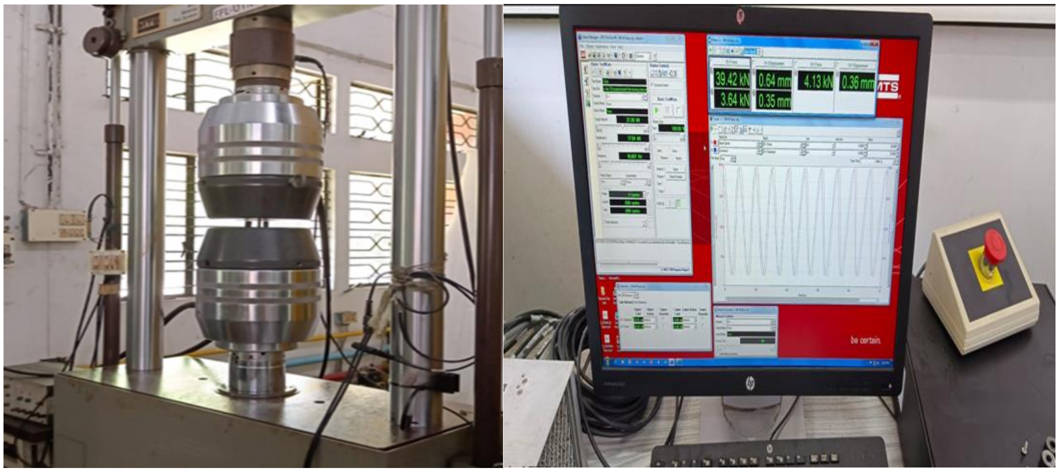

Fig. 5.14 Experimental setup

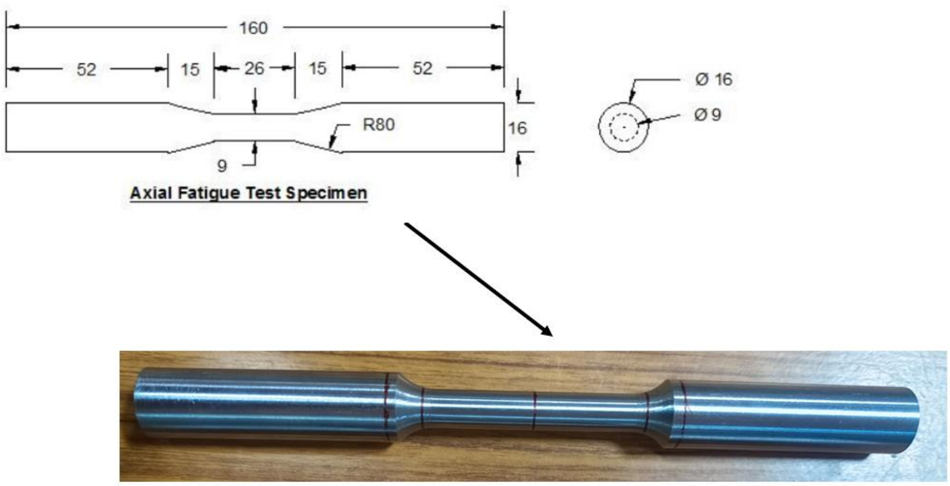

Fig. 5.15 Test specimen

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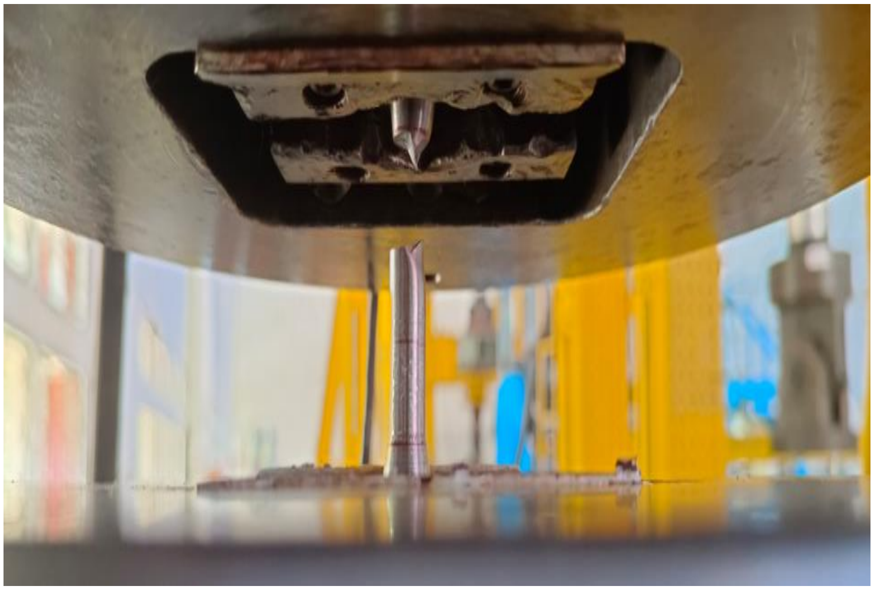

Fig.5.16 Fatigue damage of test specimen

5.7 FATIGUE LIFE PREDICTION

S-N curves describe the fatigue properties of different materials. These curves are found empirically through fatigue tests and show the number of cycles to failure N, as a function of the cyclic stress S applied to the specimen. The fatigue life design for offshore structures is commonly based on the use of S-N curve diagram, which will thus be used in the following.

The following equation can be used for the component capacity against tension fatigue:

$$n_c(s) = a_D s^{-m}$$

Where n_c is the number of cycles at a certain stress, S is the stress range in MPa, a_D is the intercept parameter of the S-N curve and m describes the slope of the S-N curve. The parameters for design S-N curves for fatigue of different mooring line materials are given in the offshore standards DNV-OS-E301. For S-N fatigue curve parameters for stud chain intercept parameter taken as 1.2×10^{11} and slope of S-N curve as 3 as per offshore standard DNV-OS-E301.Figure 5.17 shows design S-N curve as per offshore standard DNV-OS-E301.

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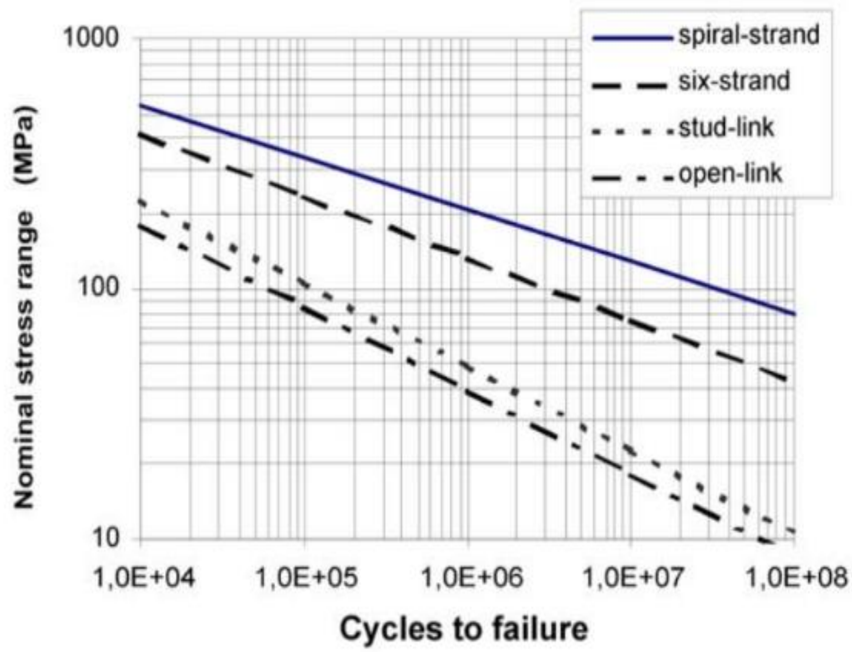

Fig. 5.17 Design S-N curve

5.8 RESULT OF FATIGUE TEST ON U3 GRADE MOORING CHAIN

Table. 5.3 Result of fatigue test on U3 grade mooring chain

Specimen no.	Maximum stress (MPa)	Minimum stress (MPa)	Stress range (MPa)	Number of cycles to failure
Specimen 1	583.5	58.35	525.15	41032 cycles
Specimen 2	583.5	58.35	525.15	64,296 cycles

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CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 EVALUATION OF FATIGUE LIFE PREDICTION OF TRANSVERSE BUTT WELD SPECIMENS

For the development of the S-N curve for transverse butt weld specimen were carried out at maximum stress value equal to 95%, 85%,80%, and 75% of the yield strength of the material.

The no of cycle to failure for transverse butt weld specimen of IS2062 Grade E350 steel with different stress ranges are given in table 6.1. It can be seen that the fatigue life reduced with increase in the stress amplitude of cyclic load. Figure 6.1 shows the close-up view of the specimen final failure.

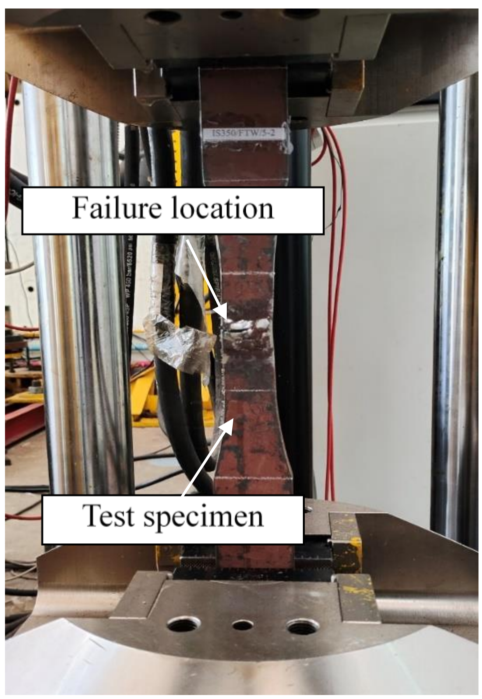

Fig. 6.1 Close-up view of the specimen after failure

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Table 6.1 Results of fatigue tests carried on transverse butt weld specimens of IS 2062 Grade E350 steel

Specimen no.	**Maximum stress (MPa)**	**Minimum stress (MPa)**	**Stress range (MPa)**	**Number of cycles to failure**
1	321.10 (95% σ_y)	32.11	288.99	49,246
2				79,896
3	304.20 (90% σ_y)	30.42	273.78	91,166
4				72,850
5				94,659
6	287.30 (85% σ_y)	28.73	258.57	1,29,189
7				1,15,849
8				1,33,531
9	270.40 (80% σ_y)	27.04	243.36	90,832
10				1,75,686
11				97,200
12	253.50 (75% σ_y)	25.35	228.15	1,19,943
13				85,531
14				1,63,576

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6.2 COMPARISON OF EXPERIMENTAL RESULT WITH IS 800: 2007 DETAIL CATEGORY 83

Figure 6.2 shows the S-N curves of IS2062 E350 grade transverse butt welded specimens corresponding with the S-N curve given in IS 800:2007. IS 2062 grade E350 welded flat specimen's samples tested for different stress ranges are not satisfying according to the codal provision detail category 83 as per IS 800:2007 due to problems in welded region.

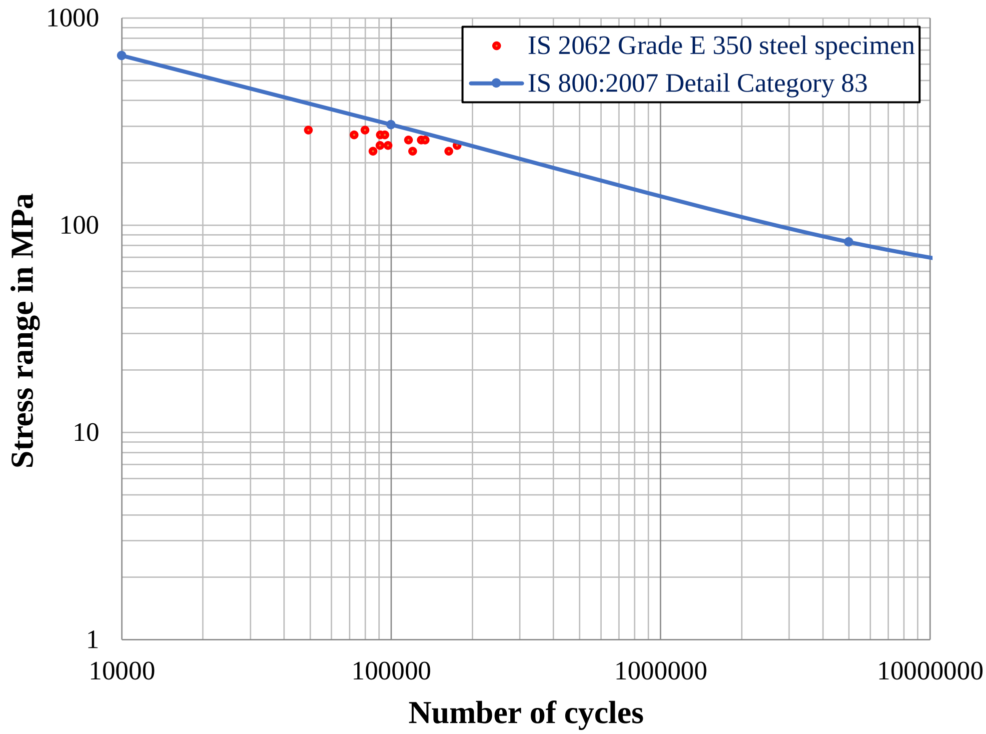

Fig. 6.2 S-N curves showing experimental results and IS 800:2007 standards.

With decrease in applied stress range, number of cycles to failure is observed to be more. From S-N curve data obtained from experiment is compared with the S-N curve given in IS 800:2007 for constructional detail number 12 with detail category number 83. It is observed that all the specimen fails to satisfy the requirement of S-N curve given in IS 800:2007 due to defect in welding.

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Table 6.2 Comparison of experimental results and IS 800:2007 codal results.

STRESS RANGE (MPa)	**NO OF CYCLES FROM EXPERIMENT**	**NO OF CYCLES AS PER IS 800: 2007**
288.99	49246	118456
288.99	79896	118456
273.78	91166	139315
273.78	72850	139315
273.78	94659	139315
258.57	129189	165375
258.57	115859	165375
258.57	133531	165375
243.36	90832	198361
243.36	175686	198361
243.36	97200	198361
228.15	119943	240737
228.15	85531	240737
228.15	163576	240737

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6.3 FATIGUE LIFE EVALUATION OF U3 GRADE STEEL USED IN MOORING SYSTEMS

Table 6.3 Result of a fatigue test on U3 grade mooring chain

Specimen no	Maximum stress (MPa)	Minimum stress (MPa)	Stress range (MPa)	Number of cycles to failure
Specimen 1	583.5	58.35	525.15	41032 cycles
Specimen 2	583.5	58.35	525.15	64,296 cycles

6.4 COMPARISON OF EXPERIMENTAL RESULT WITH OFFSHORE STANDARD DNV-OS-E301

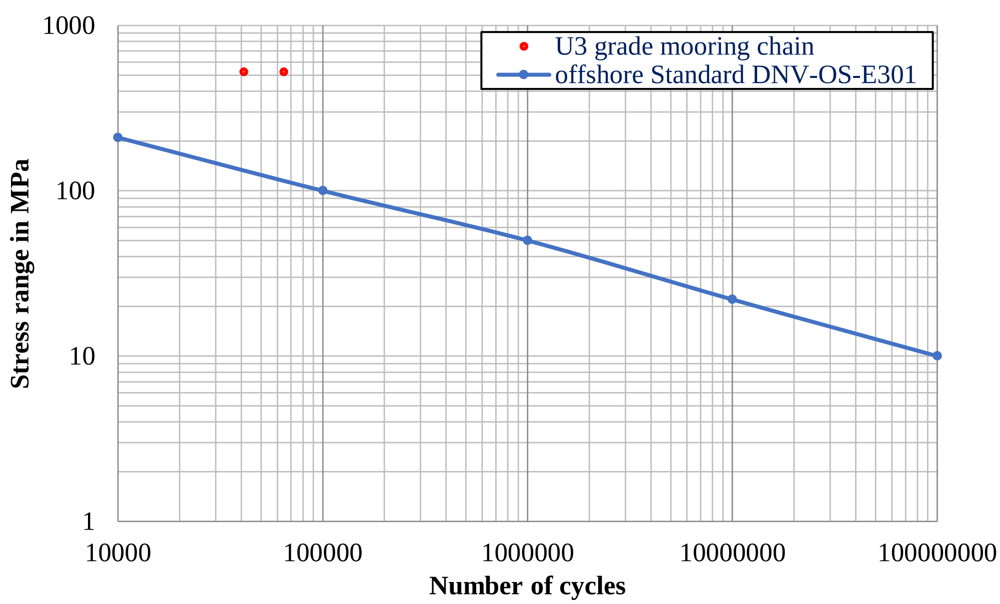

Fig. 6.3 Comparison of S-N curve of U3 grade mooring chain with offshore standard DNV-OS-E301

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CHAPTER 7

SUMMARY AND CONCLUSION

7.1 SUMMARY

Material properties of the offshore renewable energy support steel structural and U3 grade mooring chain used for anchorage were found out by tension test and fatigue test. S-N curve developed for transverse butt weld specimens was carried out at maximum stress value equal to 95%, 85%,80%, and 75% of the yield strength of the material. The no of cycles to failure for transverse butt weld specimens of IS2062 Grade E350 steel with different stress ranges find out. Fourteen specimens were taken into consideration for evaluation of the fatigue life of transverse butt weld specimens at different stress ranges and also five U3 grade mooring chain specimens were fabricated for tension test and fatigue test. Hence, from S-N curve data obtained from the experiment is compared with the S-N curve given in IS 800:2007 for constructional detail number 12 with detail category number 83. Similarly, S-N curve for the U3 grade mooring chain used for anchorage purposes is also carried out based on offshore standard DNV-OS-E301.

7.2 CONCLUSIONS

- Different materials used for support structure and mooring in floating offshore renewable energy wind turbines are identified and the availability of material find out.
- With decrease in applied stress range, number of cycles to failure is observed to be more. From S-N curve data obtained from experiment is compared with the S-N curve given in IS 800:2007 for constructional detail number 12 with detail category number 83. It is observed that all the specimen fails to satisfy the requirement of S-N curve given in IS 800:2007 due to defect in welding.
- Mechanical properties of mooring chain used for anchoring the offshore wind turbine support structure are estimated and compared with the manufacturer data.
- Mooring chain of U3 Grade used for anchoring the offshore wind turbine support structures evaluated and number of cycles to cause fatigue damage also find out with experiments. And from S-N cures data obtained from the experiment is compared with the S-N curve given in offshore standard DNV-OS-E301. It is observed that all the specimens satisfied the condition of offshore standards.

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This is to certify that the Report entitled "**PARAMETRIC STUDY OF RIBBED SLAB WITH CLOSED RIBS**" is a bonafide record of project done by **Mr. IRSHAD ASHRAF C P** , under our supervision andguidance, in partial fulfilment of the requirements for the award of Degree of Master of Technologyin Civil Engineering of the **APJ Abdul Kalam Technological University (KTU)**. This project report in any form have not been submitted to any other university or institute for any purpose.

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This is to certify that the report entitled, **'FATIGUE STUDIES ON STRUCTURAL STEEL USED FOR FLOATING OFFSHORE RENEWABLE ENERGY SUPPORT PLATFORM'** submitted by **Ms. AMRUTHA K** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Structural Engineering and Construction Management is a bonafide record of the project work carried out by her under our guidance and supervision. This project report in any form has not been submitted to any other University or Institute for any purpose.

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This is to certify that the Report entitled "**STRENGTHENING OF SEVERELY DAMAGED RCC COLUMN THROUGH CAST IN SITU VS PREFABRICATED SOLUTION METHOD**" is a bonafide record of project done by **Mr. SANJAY A**, under our supervision and guidance, in partial fulfilment of the requirements for the award of Degree of Master of Technology in Civil Engineering of the **APJ Abdul Kalam Technological University (KTU)**. This project report in any form have not been submitted to any other university or institute for any purpose.

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This is to certify that the report entitled, **'EVALUATION OF J-INTEGRAL FOR WELDED STRAIGHT PIPES WITH CIRCUMFERENTIAL THROUGH-WALL NOTCH UNDER FLEXURAL LOADING'** submitted by **Ms. RAJULA K P** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Structural Engineering and Construction Management is a bonafide record of the project work carried out by her under our guidance and supervision. This project report in any form has not been submitted to any other University or Institute for any purpose.

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This is to certify that the Report entitled "**ANALYSIS OF COUPLED COMPOSITE COLUMN**" is a bonafide record of project done by **Mrs SAHALA SHERIN**, under our supervision and guidance, in partial fulfilment of the requirements for the award of Degree of Master of Technology in Civil Engineering of the **APJ Abdul Kalam Technological University (KTU)**. This project report in any form have not been submitted to any other university or institute for any purpose.

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This is to certify that the Report entitled "**STRUCTURAL PERFORMANCE ENHANCEMENT OF BEAM THROUGH COLUMN CONNECTION**" is a bonafide record of project done by **Ms. SNIGDHA P.**, under our supervision and guidance, in partial fulfilment of the requirements for the award of Degree of Master of Technology in Civil Engineering of the **APJ Abdul Kalam Technological University (KTU)**. This project report in any form have not been submitted to any other university or institute for any purpose.

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