STRUCTURAL INTEGRITY ASSESSMENT FOR LIFE EXTENSION AND RETROFITTING OF AGING OFFSHORE PLATFORMS

A Dissertation Submitted
in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF TECHNOLOGY

in
Structural Engineering
by
PRANJAL GUPTA
(2K23/STE/507)

Under the Supervision of

PROF. SHILPA PAL

DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
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Bawana Road, Delhi- 110042
MAY, 2026

M.Tech (Structural Engineering)
Pranjal Gupta (2K23/STE/507)
May 2026

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CANDIDATE'S DECLARATION

I, **Pranjal Gupta**, M. Tech (Structural Engineering) student, having **Roll no: 2K23/STE/507**, hereby certify that the work which is being presented in the dissertation entitled "**Structural Integrity Assessment for Life Extension and Retrofitting of Aging Offshore Platforms**" in the partial fulfilment of the requirements of the award of the Degree **Master of Technology in Structural Engineering**, submitted in the **Department of Civil Engineering, Delhi Technological University** is an authentic record of my work carried out under the supervision of **Prof. Shilpa Pal**, Professor, Department of Civil Engineering, Delhi Technological University, Delhi.

The matter present in this dissertation has not been submitted by me for the award of any other degree of this or any other institute.

Pranjal Gupta

PRANJAL GUPTA

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

(PROF. SHILPA PAL)

(Signature of Supervisor) **(Signature of Examiner)**

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CERTIFICATE

I hereby certify that the Project Dissertation titled "**Structural Integrity Assessment for Life Extension and Retrofitting of Aging Offshore Platforms**" which is submitted by **PRANJAL GUPTA**, **2K23/STE/507**. **Department of Civil Engineering**, **Delhi Technological University**, Delhi in partial fulfilment of the requirement for the award of the **Degree of Master of Technology**, is a record of the project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Shilpa Pal
29/5/26

Place: Delhi
Date: May 29, 2026

PROF. SHILPA PAL
(Professor and Supervisor)
Department of Civil Engineering

ABSTRACT

Hydrocarbons continue to play an important role in meeting global energy demand. In India, offshore oil and gas facilities, especially in the western offshore region, contribute significantly to domestic production and energy security. However, many fixed jacket platforms in fields such as Mumbai High are now operating beyond their actual design life and are exposed to long-term deterioration due to wave loading, corrosion, fatigue, accidental damage, and changing operational requirements. These factors make periodic reassessment and re-certification essential to ensure the continued structural integrity and safe operation of aging offshore platforms.

The present study focuses on the structural reassessment of an existing fixed jacket-type offshore platform based on the recommendations of the American Petroleum Institute (API) for life extension assessment. Site-specific metocean data for the Gulf of Kutch, including wave, wind, and current conditions corresponding to both operating and extreme storm environments, are considered during the analysis. A global linear in-place structural analysis is performed using SACS v24 to evaluate the adequacy of jacket members and tubular joints under combined operational and environmental loading conditions. Member and joint utilization checks are performed in accordance with API RP 2A, 22nd Edition, Working Stress Design, 2014 provisions to identify overstressed structural components.

For loading conditions where the platform does not meet the prescribed acceptance criteria, a nonlinear ultimate strength assessment is performed using static pushover analysis to capture the actual structural response under extreme environmental loading. Incremental wave loading is applied until structural collapse to investigate the failure sequence, redistribution of internal forces, and ultimate collapse behaviour of the jacket system. The Reserve Strength Ratio (RSR), also referred to as the Collapse Load Factor (CLF), is evaluated to determine the residual strength and redundancy of the platform.

The study also examines strengthening and retrofitting techniques for overstressed subsea tubular joints, which remain one of the major challenges in rehabilitation of aging offshore structures. Retrofit schemes using ring stiffeners and friction-grip clamp systems are evaluated for strengthening deficient joints and facilitating member replacement without extensive modification to the existing structure. To investigate local joint behaviour in detail, Component-Based Finite Element Analysis (CBFEA) is carried out using IDEA StatiCa 26.0. Detailed finite element models of tubular joints incorporating ring stiffeners and clamp arrangements are developed to evaluate stress distribution, load transfer mechanisms, and structural performance under applied loading conditions.

The results of the study indicate that the adopted reassessment and strengthening approach improves both global and local structural performance of the aging jacket platform. From the in-place analysis, 20 tubular joints are found overstressed under extreme storm loading. After grout filling, most of the joints meet the unity check requirement and for remaining critical joints retrofitting procedures are performed. The pushover analysis shows adequate global reserve strength, with the minimum RSR obtained as 1.80 against the required value of 1.60, and the maximum RSR obtained as 3.20. For the proposed mechanical friction-grip clamp, all IDEA StatiCa checks remain within allowable limits, with maximum bolt utilization of 87.2%, weld utilization of 76.8%, and first buckling factor of 43.85. The ring stiffener model also shows improvement in local stress distribution, with the equivalent stress in members reducing from 355.3 MPa to 286.9 MPa. These results confirm that targeted retrofitting using ring stiffeners and friction-grip clamp systems can improve the residual capacity and support the life extension of the existing offshore jacket platform.

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I, PRANJAL GUPTA, would like to offer a special thanks to all those who have contributed to the successful completion of this thesis.

I express my deepest gratitude to my supervisor Prof. Shilpa Pal, Delhi Technological University. She introduced me to the world of research from scratch, my time with her has helped me to grow in many ways. Her comments at every stage of my writing and instances on perfection has helped this dissertation to come out in this sense. It is not only the careful supervision but also her personal affection that has given me lot of confidence to proceed smoothly with my work. Words cannot express my gratitude to my supervisor for patiently helping me to think clearly and consistently by discussing every point of this dissertation with me. It is my privilege to work with her in my post-graduation.

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PRANJAL GUPTA
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LIST OF ABBREVIATIONS AND SYMBOLS

API = American Petroleum Institute
API-RP-2A = American Petroleum Institute Recommended Practice 2A
API-RP-2SIM = Structural Integrity Management of Offshore Structures
AISC = American Institute of Steel Construction
ASD = Allowable Stress Design
ASTM = American Society for Testing and Materials
CBFEA = Component-Based Finite Element Analysis
CHS = Circular Hollow Section
CJP = Complete Joint Penetration
CLF = Collapse Load Factor
DTU = Delhi Technological University
FEM = Finite Element Method
GMNA = Geometrically and Materially Nonlinear Analysis
ISO = International Organization for Standardization
LAT = Lowest Astronomical Tide
LQ = Living Quarters
MLW = Mean Low Water
NORSOK = Norwegian Standards for Offshore Structures
RSR = Reserve Strength Ratio
SACS = Structural Analysis Computer System
SIM = Structural Integrity Management
SMR = Strengthening, Modification and Repair
UC = Unity Check / Utilization Check
WSD = Working Stress Design
C_d = Drag coefficient
C_m = Inertia coefficient
FE_{XX} = Tensile strength of weld electrode
Rn_{slip} = Nominal slip resistance of preloaded bolt
$|U|$ = Bolt utilization in tension
Ut_s = Bolt utilization in shear / slip
Ut_t = Bolt utilization in tension
Ut_{ts} = Combined bolt utilization in tension and shear
σ_{Ed} = Design equivalent stress / von Mises stress
σ_{cEd} = Design contact stress

CHAPTER 1

INTRODUCTION

1.1 GENERAL

One of the most significant developments of the twentieth century was the discovery and large-scale utilization of petroleum resources, which transformed global industrial growth, transportation, and energy production. The widespread applications of oil and natural gas have made hydrocarbons an essential part of modern civilization. Initially, oil exploration activities were primarily concentrated in onshore regions during the early twentieth century. However, with the rapid increase in global energy demand and depletion of easily accessible onshore reserves, exploration activities gradually expanded toward offshore regions, particularly in shallow and intermediate water depths during the mid-twentieth century [1].

In today's geopolitical scenario, offshore oil and gas production plays a significant role in meeting the increasing global energy demand as most of the subsea reserves are undiscovered. Fixed offshore steel jacket platforms are widely used for hydrocarbon exploration and production in shallow and moderate water depths due to their structural efficiency and economic feasibility[1], [9]. There are around 10,000 fixed offshore jacket type platforms currently operational worldwide. In India, there are over 200 fixed jacket type offshore installations are located in the western offshore field, particularly in the Mumbai High South, Mumbai High North, Bassein, Tapti, Heera, Mukta, and Neelam where offshore infrastructure contributes substantially to domestic oil and gas production [13].

The Mumbai Offshore Basin located along the west coast of India is one of the most productive hydrocarbon-bearing offshore basins in the nation. Exploration activities in the basin began during the early 1960s, and the first major oil discovery was made in the Mumbai High field in 1974. Subsequent exploration and development activities led to several significant oil and gas discoveries, including Heera, Neelam, Panna, Mukta, and Bassein fields as shown in the Figure 1.1 [15].

Most offshore jacket platforms were actually designed for an operational life of approximately 25 years in accordance with API RP 2A guidelines [3]. However, many existing offshore platforms are presently operating beyond their intended design life and are continuously subjected to harsh metocean conditions such as waves, wind, currents, corrosion, and cyclic loading effects. Long-term exposure to such conditions may result in structural deterioration, fatigue damage, overstressed tubular joints, and reduction in reserve strength capacity [2], [13]. In addition, installation of new facilities and changes in metocean criteria further increase the necessity for reassessment of existing offshore structures.

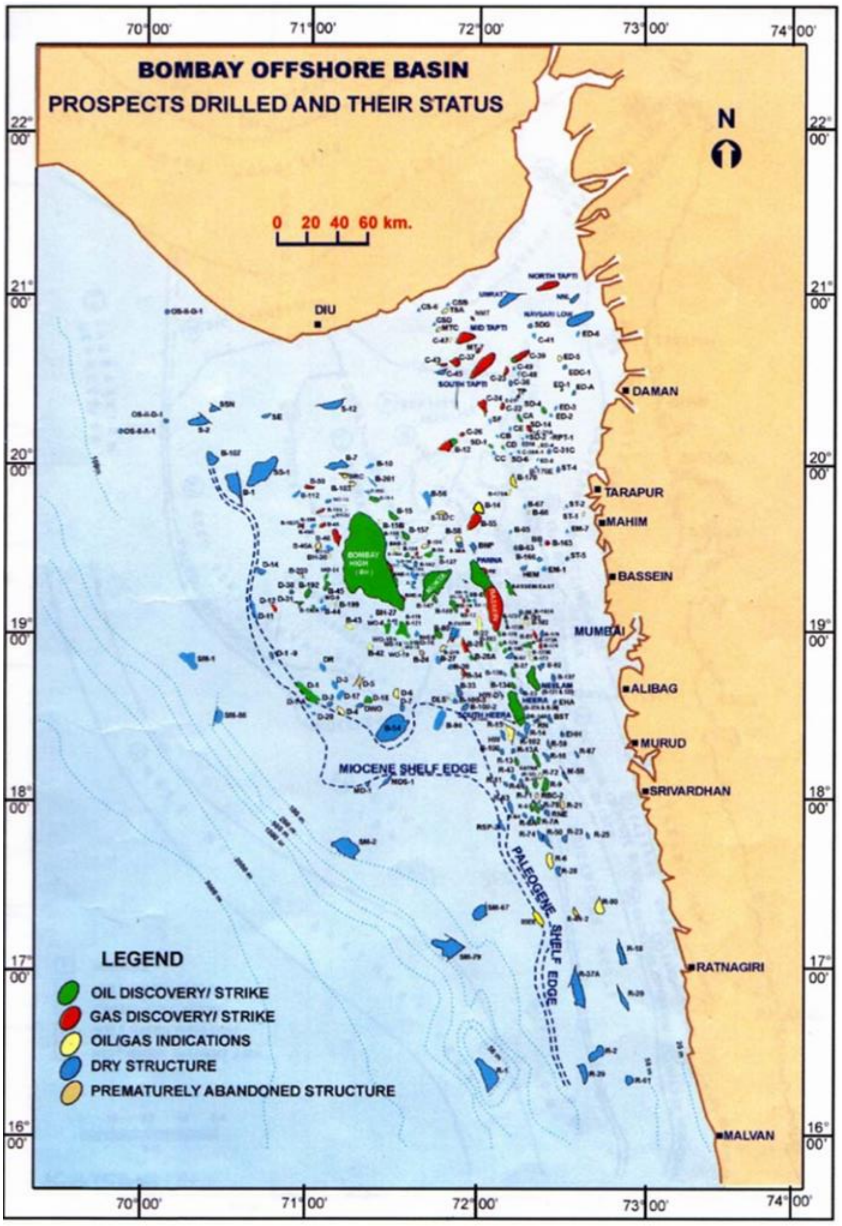


Fig. 1.1. Mumbai Offshore Basin showing drilled prospects and hydrocarbon discoveries in the western offshore region of India [15]

1.2 FIXED OFFSHORE STRUCTURE

Jacket-type offshore platforms are among the most commonly used fixed offshore structures for hydrocarbon production in shallow and intermediate water depths. These structures generally consist of a three-dimensional tubular steel space frame, commonly referred to as a jacket, which supports the topside facilities including drilling equipment, production units, and accommodation decks, as shown in Figure 1.2. The subsea structure can be 4, 6, or 8-legged configuration based on method of installation top side requirements and metocean loading data. The jacket structure is rigidly connected to the seabed using tubular steel piles driven either through the jacket legs or through external skirt pile sleeves provided near the base of the structure [1].

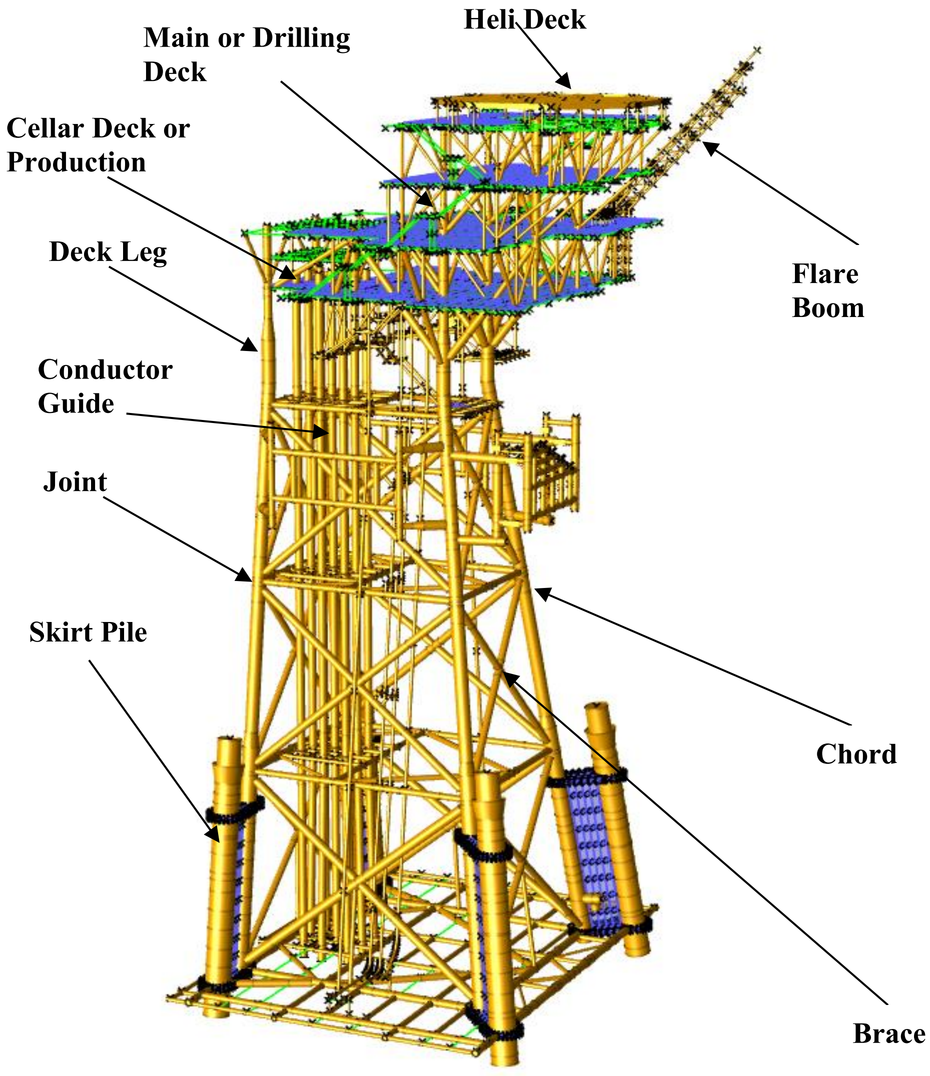


Fig. 1.2. Fixed Template Type Platform

Fixed steel jacket platforms are considered economically suitable for installation in water depths of up to approximately 500 m due to their high structural stiffness and reliable load-carrying capacity under severe environmental conditions. The design philosophy of such structures is primarily based on achieving adequate global stiffness and minimizing structural deflections under wave, wind, and current loading. In offshore structural design, the natural period of the fixed type jacket platform is generally maintained significantly lower (4 seconds) than the dominant ocean wave periods (4 to 24 seconds) in order to avoid resonance effects and excessive dynamic amplification. Therefore, the configuration of the jacket framing system and foundation arrangement is carefully selected to ensure satisfactory structural performance under environmental loading conditions [1].

1.2.1 TUBULAR JOINTS

Tubular joints, also refer as joint Can form the most important components of fixed offshore jacket platforms, as they facilitate the transfer of forces both axial and moment between interconnected tubular members within the jacket framing system. Offshore jacket structures are generally fabricated using circular hollow section (CHS) steel members connected through complete joint penetration (CJP) welded joints due to their excellent hydrodynamic characteristics, lower hydraulic drag, high strength-to-weight ratio, higher plastic collapse capacity, uniform sectional properties, and superior torsional resistance[1]. According to API RP 2A-WSD, tubular joints are classified based on their geometric configuration and load transfer mechanism into T-, Y-, K-, and X-type joints, shown in Figure 1.3 [3]. These joints are extensively used in offshore jacket platforms for efficient load distribution under complex environmental loading conditions. Tubular joints are formed by the intersection of tubular members at a common connection region where load transfer takes place between the structural members. In a typical tubular joint, the primary member is referred to as the chord member, while the intersecting secondary members are known as braces. The structural behaviour and strength of offshore jacket platforms are significantly influenced by the performance of these tubular joints, as they represent critical stress concentration regions within the structure [1].

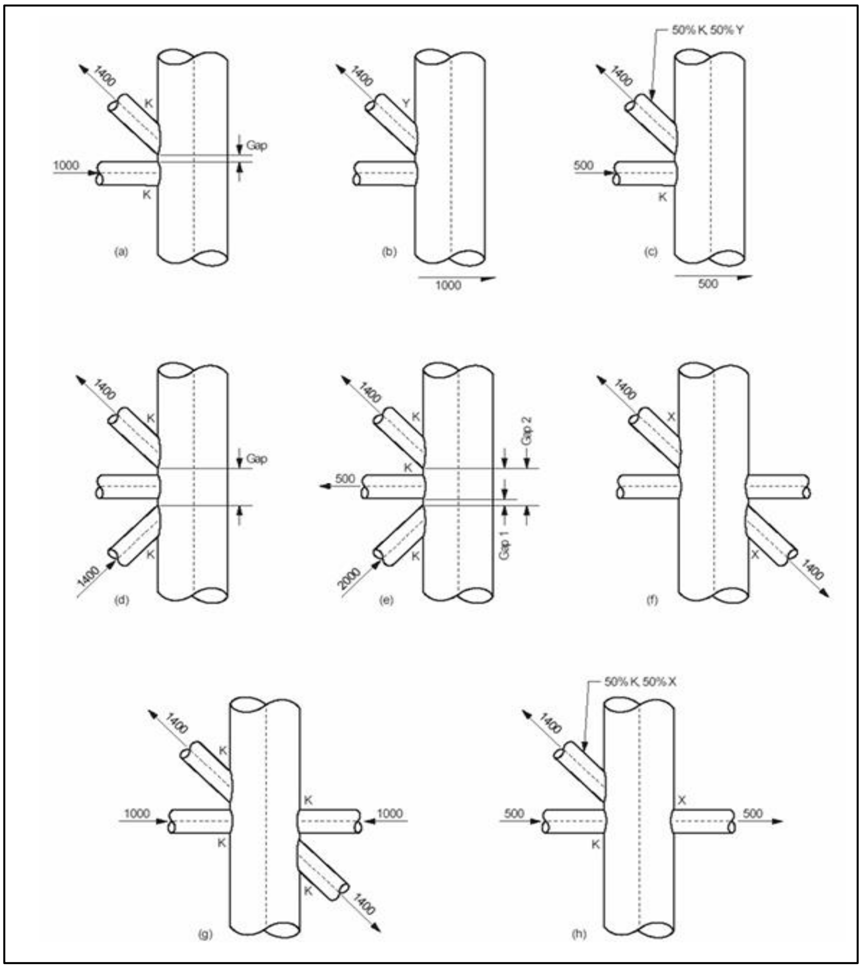


Fig. 1.3. Joint Classification on the Basis of Geometry [3]

Tubular joints may also be classified according to the manner in which forces are transferred through the joint region. In balanced K-joints, the axial load from one brace is counteracted by the opposing load from the adjacent brace, thereby minimizing the transfer of shear forces through the chord member. However, in unbalanced T- or Y-joints, the radial load from the brace is transferred directly to the chord in the form of beam shear, resulting in higher local stresses in the joint region, as shown in Figure 1.4. In X-joints, the load is transmitted across the chord through opposing brace members connected on opposite sides of the joint. The load transfer mechanism significantly influences the stress concentration, fatigue behaviour, and ultimate strength characteristics of offshore tubular joints [3].

Offshore tubular joints are continuously subjected to cyclic wave and wind loading throughout the operational life of the platform. Due to the presence of welded connections and geometric discontinuities, these joints are highly susceptible to fatigue

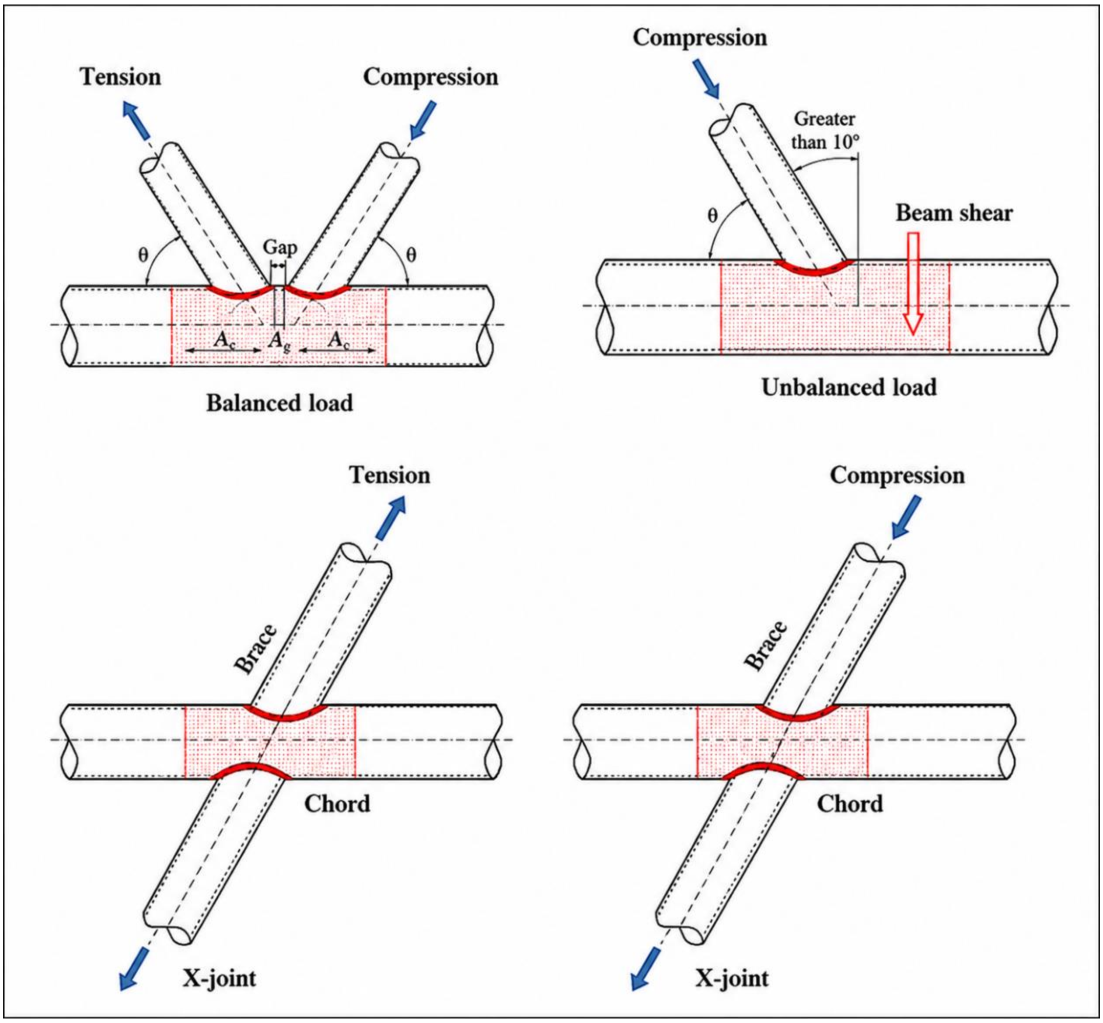


Fig. 1.4. Joint Classification on the Basis of Load Path [1]

damage and crack initiation at hotspot locations, particularly near the weld toe region. Over prolonged service periods, fatigue cracks may propagate through the brace and chord thickness, thereby reducing the structural integrity and residual strength of the platform. Therefore, periodic inspection, reassessment, and strengthening of tubular joints become essential for ensuring the safe operation and life extension of aging offshore jacket platforms [2], [13].

1.2.2 FATIGUE AS A CRITICAL LIMIT STATE

Fatigue needs particular attention in aging offshore jackets because the structure is almost continuously subjected to cyclic loading. Even when the platform is operating normally, waves and currents repeatedly stress the tubular members and welded joints. Fatigue cracks generally initiate at stress concentration regions, especially near welded tubular connections, where local stress flow is disturbed, as shown in the Figure 1.5. API RP 2A-WSD treats fatigue and tubular joint performance as important design and assessment considerations for fixed offshore platforms [3]. Fatigue becomes more significant in life-extension assessment because the probability of crack development increases with service time, and multiple cracks may become relevant in aging structures [16]. A fatigue crack may first appear as a local defect, but once it grows, it can reduce member stiffness, alter load distribution, and increase demand on nearby members. For this reason, fatigue should not be treated only as a local joint issue. It must also be connected to the overall redundancy and reserve capacity of the jacket system.

Fig. 1.5. Cracked Tubular Joints
Ref: https://madcon.com/

1.2.3 RETROFITTING AND STRENGTHENING REQUIREMENT

When structural assessment indicates that a member, tubular joint, or any part of the jacket no longer has adequate capacity, retrofitting or strengthening becomes necessary. The deficiency may arise from corrosion loss, fatigue cracking, inadequate joint capacity, member overstress, reduced reserve strength, increased topside loading, or changes in the environmental design basis. In aging jacket platforms, such problems rarely occur in isolation. A fatigue crack at a welded tubular joint, for example, may begin as a local defect, but with time it can influence stiffness, load redistribution, and the reserve capacity of the surrounding structural system. Ersdal [16] indicates that inspection and repair act as important safety barriers in life-extension assessment, especially because damage in one component may increase demand on adjacent members through load redistribution and continued fatigue loading.

API RP 2SIM [4] treats strengthening, modification, and repair is segment of the broader structural integrity management process, where assessment findings are linked with mitigation and continued-service decisions. NORSOK N-006 [10] follows a similar logic and identifies mitigation measures such as strengthening, grouting of members or joints, provision of new braces, use of stiffeners or brackets, reduction of wave actions by marine-growth removal, structural instrumentation, and storm unmanning where required. Dier [17] further explains that SMR of offshore steel installations should be selected only after proper assessment, since inappropriate or unnecessary SMR schemes may become costly and ineffective in offshore conditions. The report also classifies the main SMR techniques into welding, clamp technology, grout filling, weld improvement, remedial grinding, member removal, bolting, composite repair, and other mechanical connection methods, as shown in Figure 1.6 [17]. Therefore, retrofitting should not be viewed simply as a repair activity after damage has occurred. Rather, it forms part of the continuing structural integrity process used to maintain adequate safety and serviceability during the extended life of an offshore jacket platform.

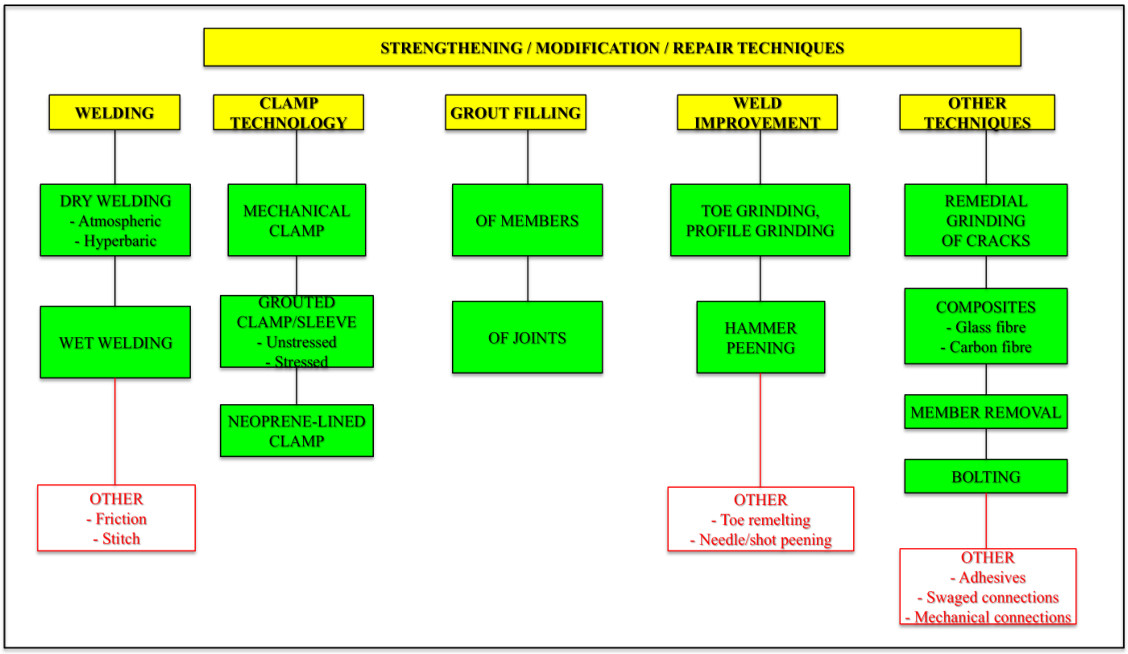


Fig. 1.6. SMR Techniques [17]

1.3 PROBLEM STATEMENT

Many offshore jacket platforms are now required to operate beyond the life for which they were actually designed. This creates a difficult engineering problem because the structure may have accumulated fatigue damage, corrosion, accidental defects, additional topside loading, and uncertainty in inspection or repair records. Although tubular joints and welded connections are known to be fatigue-sensitive regions, the safety of an aging platform cannot be judged only by studying these local details. The global behavior of the jacket, its reserve strength, damaged-condition capacity, inspection reliability, and repair feasibility must also be considered as part of structural assessment. Existing literature on offshore reassessment and life extension shows that continued safe operation requires a systematic evaluation of both component-level and system-level performance [13], [16].

Most available studies on subsea tubular joint strengthening focus on grouted clamp connections, while comparatively limited work is available on friction-grip clamp systems for strengthening deficient offshore tubular joints [17], [19]. Thus, the central problem addressed in this study is to determine whether the existing jacket platform has adequate residual strength for life extension and whether targeted retrofitting can improve the performance of overstressed tubular can joints.

1.4 OBJECTIVES OF THE STUDY

The objective of the study is to carry out the structural reassessment of an existing fixed jacket-type offshore platform for life extension, using current offshore industry practices and API-based assessment procedures. The study aims to evaluate the platform under present operating and extreme environmental loading conditions, considering site-specific metocean data for the Gulf of Kutch. The objectives of the study are as follows:

- To perform global linear static (in-place) analysis of the jacket platform using SACS v24 under operating and extreme storm loading conditions.
- To evaluate the adequacy of jacket members and tubular joints in accordance with API RP 2A, 22nd Edition, Working Stress Design provisions.

- To carry out nonlinear ultimate strength assessment using static pushover analysis for extreme load condition to determine the Reserve Strength Ratio (RSR), or Collapse Load Factor (CLF).
- To examine suitable strengthening and retrofitting techniques for deficient subsea tubular joints, particularly ring stiffeners and friction-grip clamp systems.
- To investigate the local behaviour of strengthened tubular joints using Component-Based Finite Element Analysis in IDEA StatiCa 26.0.

1.5 LIMITATIONS OF THE STUDY

The study is based on the reassessment of a specific configuration of fixed jacket-type offshore platform and, therefore, the results may not be directly applicable to all offshore structures without considering differences in geometry, water depth, soil condition, loading environment, material properties, and operational history.

The global structural analysis is carried out using available structural data and assumed or provided metocean conditions. The pushover analysis is limited to nonlinear static ultimate strength assessment. Dynamic collapse analysis, nonlinear time-history analysis, accidental ship impact analysis, and seismic reassessment are not included. The foundation system is considered only to the extent required for the global structural model, while detailed geotechnical reassessment of piles and soil-structure interaction is not covered.

The retrofit study is limited to selected strengthening schemes, mainly ring stiffeners and friction-grip clamp systems for deficient tubular joints. The IDEA StatiCa-based local joint analysis is used to evaluate connection behaviour and strengthening effectiveness, but it is not a substitute for full experimental validation or detailed project-specific offshore repair design.

1.6 THESIS ORGANIZATION

Chapter 1 introduces the background of offshore jacket platforms, tubular joints, fatigue, need for structural reassessment, and retrofitting techniques. It also presents the problem statement, objectives, scope, limitations, and organization of the thesis.

Chapter 2 reviews previous studies, codes, and guidelines related to offshore jacket platforms, structural assessment, fatigue and corrosion damage, tubular joints, pushover analysis, reserve strength, and repair or strengthening techniques.

Chapter 3 explains the adopted methodology, including structural modelling, metocean loading, load combinations, in-place analysis using SACS, pushover analysis, and local joint assessment using IDEA StatiCa.

Chapter 4 presents the results of member checks, joint utilization, critical load cases, pushover analysis, Reserve Strength Ratio, and performance of proposed strengthening schemes such as ring stiffeners and friction-grip clamps.

Chapter 5 summarizes the major findings of the work and concludes on the structural adequacy, life-extension feasibility, and effectiveness of the proposed retrofitting measures. It also provides recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The literature on aging offshore jacket platforms mainly deals with three connected issues: assessment of existing structures, fatigue damage in welded tubular joints, and selection of suitable repair or strengthening techniques. Offshore jacket platforms are exposed to wave, current, wind, corrosion, marine growth, and operational changes over a long service life. Because of this, member capacity, joint strength, fatigue life, and reserve strength may no longer remain the same as assumed during actual design. Existing codes such as API RP 2A, API 2SIM, ISO 19902, and NORSOK N-006 provide the basis for structural reassessment and life extension [3]-[5], [10]. Alongside these codes, several studies have discussed reserve strength, repair methods, grouted clamps, and ring stiffened tubular joints. The present review is therefore categorized into structural assessment, fatigue damage, pushover and reserve strength, SMR techniques, grouted clamps, ring stiffeners, and friction-grip clamp-based retrofitting.

2.2 STRUCTURAL ASSESSMENT OF OFFSHORE PLATFORMS

Nallayarasu (2009) discussed the basic framework for structural assessment of existing offshore structures. The module explains that assessment is usually required when a platform is intended to operate beyond its actual design life, when its loading or operating condition changes, when damage or deterioration is detected, or when the structure has to be checked against updated design requirements. This is directly relevant to the present study, since the selected fixed jacket platform is being reassessed for continued operation under current metocean and operational loading conditions [1].

The assessment process includes platform selection, categorization, condition assessment, design basis verification, analysis checks, and consideration of mitigation measures. The module also emphasizes that assessment should be based on as-built drawings, inspection history, present structural condition, planned modifications, updated design basis, degradation history, prediction of future deterioration, and maintenance or inspection strategy. This supports the approach adopted in the present work, where the platform is first evaluated through global in-place analysis and then checked further through ultimate strength assessment when required [1].

Structural integrity analysis may be carried out in stages. A design-level analysis is generally simpler and more conservative, while ultimate strength analysis is more refined and is used when design-level checks do not provide sufficient confidence. In the ultimate strength approach, the environmental load is increased gradually until collapse, and the corresponding load multiplier is interpreted as the reserve strength or redundancy of the system. This concept is consistent with the pushover analysis carried out in the present study for evaluating the Reserve Strength Ratio of the jacket platform [1].

API RP 2 SIM (2014) provides a structural integrity management framework for existing offshore structures. The standard links inspection, assessment, mitigation, repair, and continued operation into one decision-making process. This is relevant to the present study because the work does not stop at identifying overstressed members and joints through in-place analysis. It further evaluates reserve strength through pushover analysis and then considers retrofitting measures for critical joints.

API RP 2SIM also discusses strengthening, modification, and repair methods that may be adopted when assessment indicates inadequate structural capacity [4]. The SMR selection may broadly include damage removal, load reduction, local strengthening, and global strengthening. Damage removal may involve component removal or crack removal, while load reduction may include reduction of gravity loads or hydrodynamic loading.

Local SMR techniques include member grouting, joint grouting, structural clamps, welding, bolting, adhesives, epoxy grouts, and cold forming, as shown in Figure 2.1, for more severe deficiencies, global SMR may be adopted through leg-pile annulus grouting or external bracing. This classification is useful for the present study because the proposed strengthening work mainly falls under local SMR, particularly through ring stiffeners and friction-grip clamp systems [4].

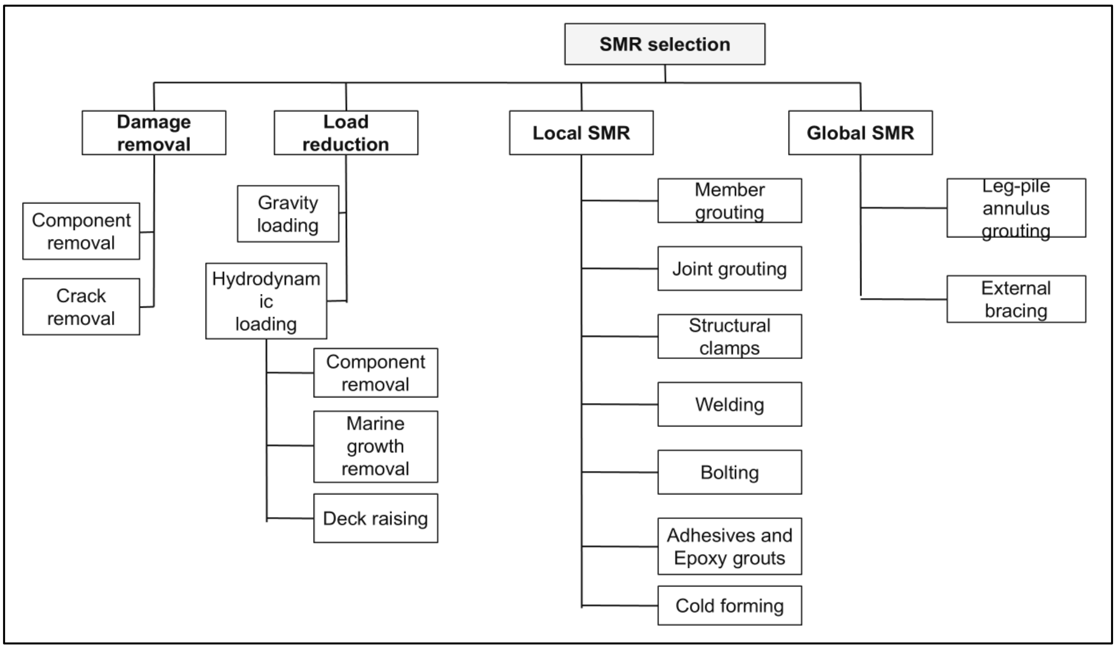


Fig. 2.1. SMR Technique Selection Process [4]

NORSOK N-006 (2008) provides guidance for assessing the structural integrity of existing offshore load-bearing structures and is intended to be used along with other NORSOK standards such as N-003, N-004, and N-005. The standard treats mitigation as part of the assessment process, as shown in Figure 2.2, where the structure is first assessed in its "as-is" condition and, if acceptance criteria are not satisfied, suitable mitigation alternatives are considered [10] .

For fatigue-related deficiencies, NORSOK N-006 recommends measures such as reducing loading, strengthening the structure to reduce stress levels, grouting to reduce stress concentration, applying fatigue improvement techniques, and carrying out controlled in-service inspection so that cracks can be detected before they become through-thickness defects. For minor fatigue cracks, grinding may be used if the crack is completely removed within permissible limits, while hammer peening may be applied at locations where no cracking is present. However, if through-thickness cracks are detected, more robust mitigation measures such as bolted clamps or bolted and grouted clamps should be considered. This guidance is relevant to the present study because the reassessment of the jacket platform is followed by the evaluation of strengthening schemes for deficient tubular joints [10].

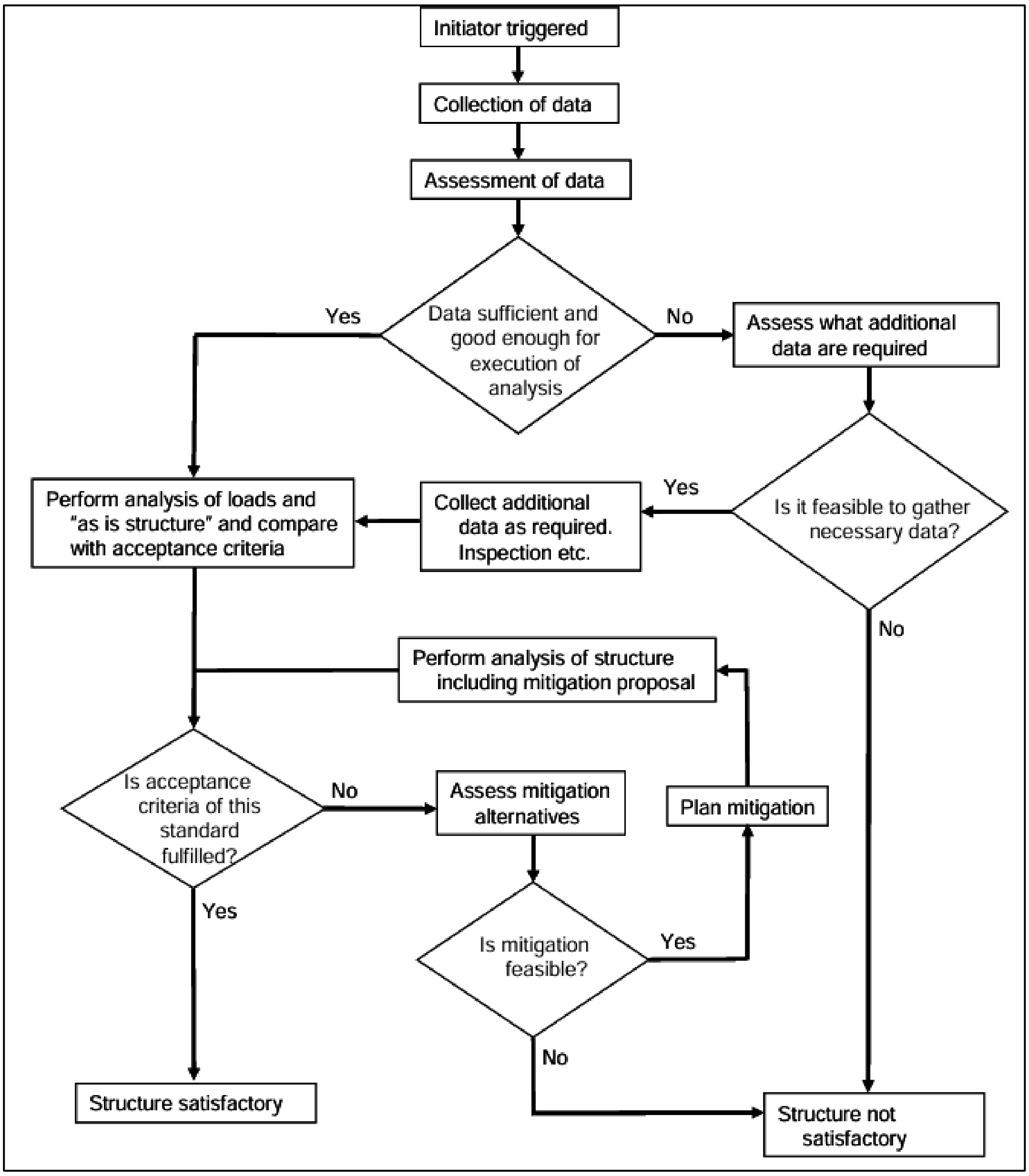


Fig. 2.2. Flow sheet of the structural assessment process [10]

2.3 RETROFITTING, STRENGTHENING AND REPAIR TECHNIQUES

Dier (2004) presented a detailed assessment of repair techniques for ageing and damaged offshore steel structures. The report was prepared by MSL Services Corporation for the Minerals Management Service (MMS) with the objective of reviewing available repair methods, industry experience, design considerations, offshore implementation issues, and possible diver less repair technologies. The work is useful because it does not treat repair only as a structural design problem. It also considers practical offshore constraints such as access, installation time, equipment requirement, cost, inspection after repair, and reliability of the selected technique.

The report is divided into two major parts. The first part discusses the overall process of strengthening, modification and repair, including assessment initiators, selection of SMR schemes, design considerations, and implementation planning. The second part explains individual repair techniques in detail, covering their description, limitations, design approach, fabrication and installation issues, and previous offshore applications. The repair methods discussed include member removal of members and joints, weld improvement methods, remedial grinding, bolting, FRP composite repair, and other miscellaneous mechanical connection techniques as presented in Table 2.1 [17].

Dier also compared the applicability of different SMR techniques and their inter-relationship as shown in the Figure 2.3, for common offshore damage scenarios such as fatigue cracks, non-fatigue cracks, dents, corrosion, inadequate reserve strength, and inadequate fatigue strength. The comparison is useful in the present study because strengthening of deficient tubular joints is not selected only on the basis of strength demand. Factors such as underwater execution, load transfer mechanism, installation feasibility, and post-installation inspection are also important. A summarized comparison of SMR applicability and practical performance is presented in Table 2.2 [17].

Table. 2.1. Comparison of SMR Techniques [17]

Repair / Strengthening Option	**Static Strength Design Basis**	**Fatigue Design**	**Equipment Requirement**	**Offshore Execution Time**	**Yard Fabrication Cost**	**Additional Weight Impact**	**Hydrodynamic Load Impact**
Dry hyperbaric welding	Applicable	Applicable	High	Very lengthy	High	Nil	Nil
Wet underwater welding	Applicable	Applicable	Medium	Rapid	Nil	Nil	Nil
Weld-toe profiling	Not applicable	Applicable	Low	Moderate	Nil	Nil	Nil
Corrective grinding	Applicable	Applicable	Low	Moderate	Nil	Nil	Nil
Impact peening	Not applicable	Applicable	Low	Rapid	Nil	Nil	Nil
Preloaded mechanical clamping	Case-specific	Case-specific	Medium	Rapid	High	Medium	High
Non-preloaded grouted clamping	Case-specific	Case-specific	Medium	Moderate	Medium	Medium	Medium
Preloaded grouted clamping	Case-specific	Case-specific	Medium	Lengthy	High	Medium	High
Elastomer-lined clamping	Case-specific	Case-specific	Medium	Moderate	High	Medium	High
Internal grout infill	Case-specific	Case-specific	Low	Rapid	Low	High	Nil
Bolted repair connection	Applicable	Applicable	Low	Moderate	Low	Low	Low
Member replacement	Not applicable	Not applicable	Medium	Rapid	Nil	Nil	Nil
Composite wrap repair	Case-specific	Case-specific	Low	Rapid	Medium	Low	Low

Table. 2.2. Application of SMR Techniques [17]

SMR option	Fatigue crack repair	Non-fatigue crack repair	Dent / local indentation	Corrosion / metal loss	Low static strength member	Low static strength joint	Low fatigue strength under high loads	Low fatigue strength under fabrication defect
Dry welding repair	Applicable (1)	Applicable	Applicable (3)	Applicable (3)	Applicable (1)	Applicable (1)	Not suitable	Applicable
Underwater wet welding	Not suitable (2)	Applicable	Applicable (3)	Applicable (3)	Applicable (1)	Applicable (1)	Not suitable	Applicable
Toe profile improvement	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Applicable	Not suitable
Corrective grinding	Applicable	Applicable (1)	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable
Hammer peening treatment	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Applicable	Not suitable
Preloaded mechanical clamp	Applicable	Applicable	Not suitable	Applicable	Applicable	Not suitable	Applicable	Applicable
Non-preloaded grouted clamp	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable
Preloaded grouted clamp	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable
Elastomer-lined clamp	Not suitable	Applicable	Not suitable	Applicable	Not suitable	Not suitable	Not suitable	Not suitable
Member grout infill	Not suitable	Not suitable	Applicable	Applicable	Applicable	Applicable (4)	Applicable (4)	Not suitable
Joint grout infill	Not suitable	Not suitable	Applicable	Not suitable	Applicable	Applicable (4)	Applicable (4)	Not suitable
Bolted repair system	Not suitable	Applicable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable
Member replacement	Applicable (5)	Applicable (5)	Applicable (5)	Applicable (5)	Not suitable	Not suitable	Applicable (5)	Applicable (5)
Composite wrap / patch	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable	Applicable

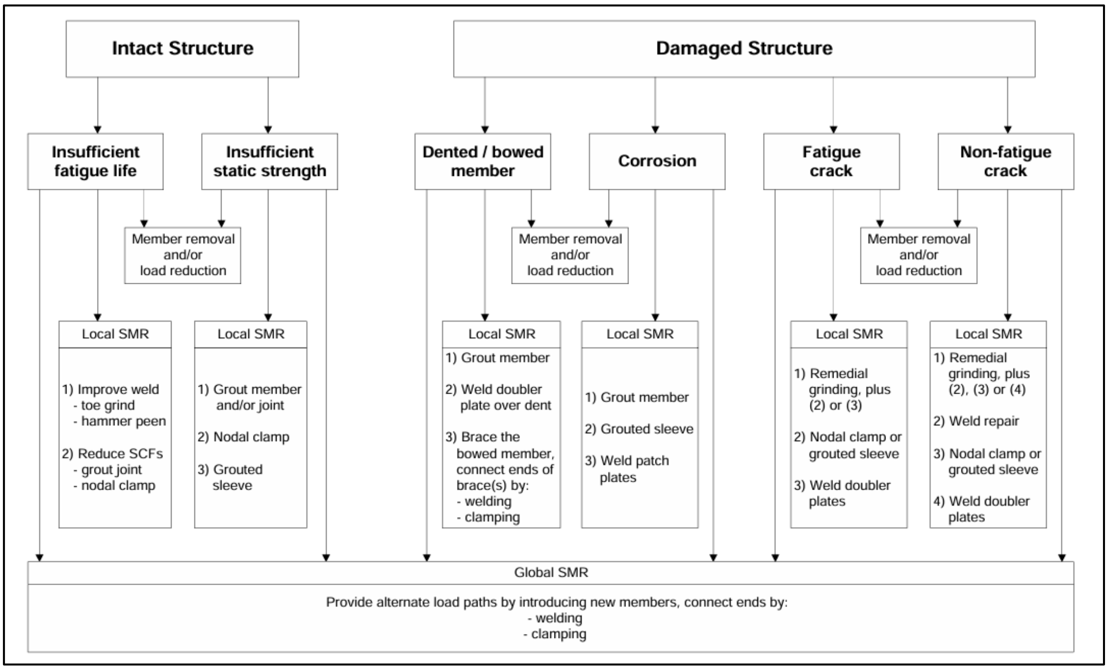
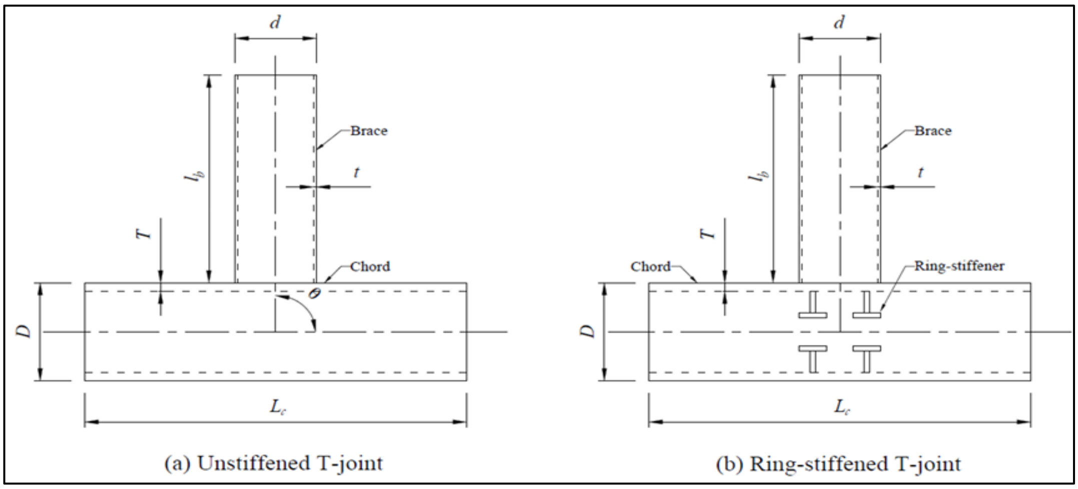


Fig. 2.3. Interrelationship between scenarios, SMR schemes and SMR Techniques [17]

2.4 STRENGTHENING OF TUBULAR JOINTS

Ragupathi (2021) investigated the ultimate strength behavior of tubular joints strengthened with internal ring stiffeners. The study is useful because it deals with a very practical problem in offshore jacket design: sometimes the chord wall does not have enough capacity to resist the brace load, but increasing the chord thickness is not always convenient from fabrication or availability point of view. In such cases, internal ring stiffeners can improve the local stiffness of the chord and reduce deformation around the brace-chord intersection, as shown in the Figure 2.4. Ragupathi carried out experimental work on 1:8 scale tubular T-joints and also developed nonlinear finite element models to study unstiffened, plain ring-stiffened, and flanged ring-stiffened joints. The work further proposed a capacity enhancement factor which can be used along with API RP 2A equations for calculating the strength of ring-stiffened T/Y joints. This reference is directly relevant to the present study because ring stiffeners are considered as one of the strengthening options for deficient tubular joints identified during reassessment [18].

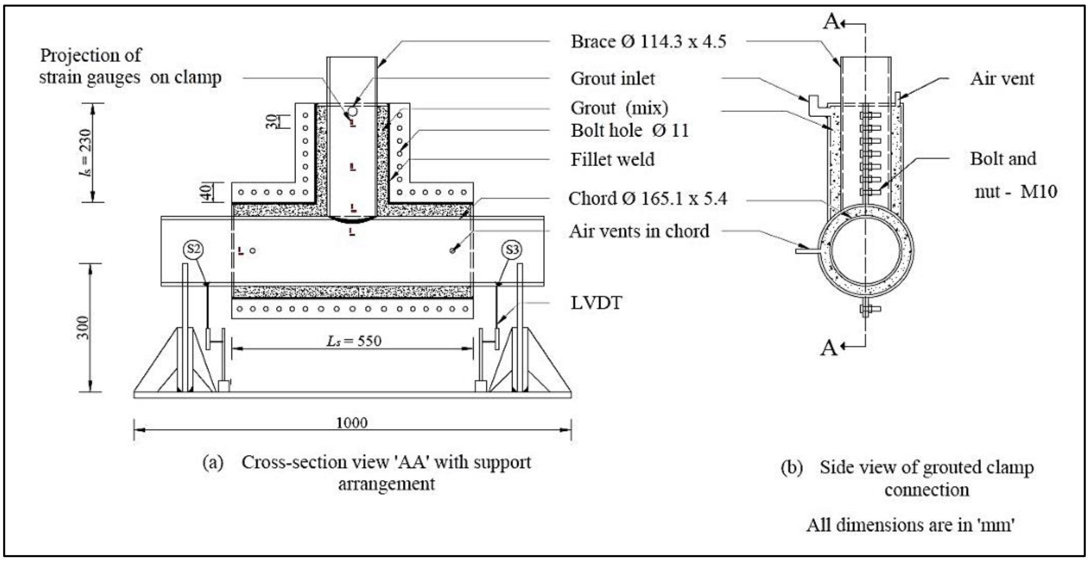


(a) Unstiffened T-joint

(b) Ring-stiffened T-joint

Fig. 2.4. Geometric definition of Unstiffened, Ring-Stiffened and Internal Ring Stiffener [18]

Chellappan (2022) studied cracked tubular joints strengthened using grouted clamp connections. The work is closely related to aging offshore platforms, where fatigue cracks may develop at welded tubular joints after long exposure to cyclic wave and wind loading. Chellappan focused on how cracks reduce the strength of tubular joints and how grouted clamps can help restore or improve their load-carrying capacity. The study included experimental testing and nonlinear finite element analysis of uncracked joints, cracked joints, and cracked joints strengthened with grouted clamps, as shown in the Figure 2.5. It also proposed reduction factors for cracked joints and enhancement factors for grouted clamp-strengthened joints under axial and moment loading. This is important for the present work because it gives a strong reference for clamp-based strengthening. However, the focus of Chellappan's work is mainly on grouted clamps, while the present study further looks toward friction-grip clamp systems as an alternative local retrofitting solution [19].



(a) Cross-section view 'AA' with support arrangement

(b) Side view of grouted clamp connection

All dimensions are in 'mm'

Fig. 2.5. Schematic diagram of the grouted clamp connection [19]

Dier (2004) reviewed structural clamps as an important strengthening, modification and repair technique for ageing or damaged offshore steel structures. In general, clamps are fabricated in two or more segments and bolted around an existing tubular member or joint. Their main purpose is to transfer load across a damaged or deficient region, strengthen an under-capacity member or joint, or provide a connection for an additional member. The report also highlights that the behaviour of clamps depends strongly on the interface condition, such as steel-to-steel contact, grout, or elastomer, and whether bolt pretension is used to generate contact pressure. The general clamp terminology, including saddle plate, flange, stiffener, cap plate, split and stud bolts, shown in the Figure 2.6 [17]. For mechanical friction clamps, the load transfer is achieved mainly through friction between the clamp saddle and the existing tubular member. The required friction is developed by tightening long stud bolts, which generate radial pressure at the steel-to-steel interface. This makes the system useful where immediate load transfer is required, especially for member strengthening or for connecting new members. However, the method is sensitive to fit-up accuracy, surface condition, weld protrusions and geometric tolerance. Therefore, mechanical friction clamps are generally more suitable for relatively regular tubular members rather than complex nodal joints [17].

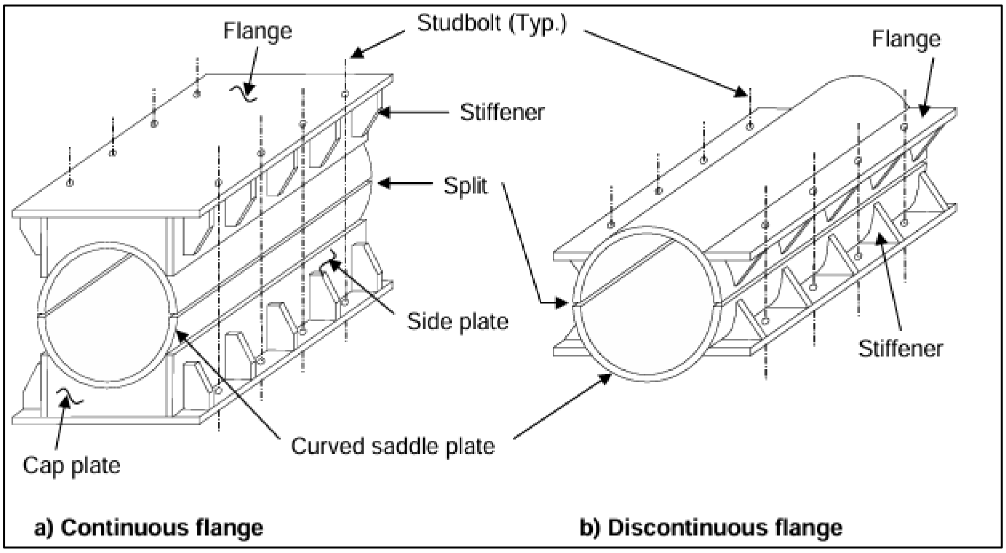


Fig. 2.6. Clamp Terminology [17]

2.5 RESEARCH GAP

Earlier, offshore platform assessments were often carried out using highly conservative assumptions. While this approach is safe, it can sometimes indicate a need for strengthening even when the platform still has sufficient reserve capacity. Such interventions are extremely expensive. Therefore, ultimate strength analysis is used to reduce unnecessary conservatism and obtain a more realistic estimate of the platform capacity utilizing the reserve strength.

These works provide a strong basis for understanding local joint strengthening using the grouted clamp, but the available literature is still limited on friction-grip clamp systems for deficient offshore tubular joints, particularly in terms of bolt pretension, frictional load transfer, contact behaviours, and local stress distribution. Therefore, the present study attempts to bridge this gap by combining global reassessment of an aging fixed jacket platform with local strengthening evaluation of overstressed tubular joints using ring stiffeners and friction-grip clamp systems.

CHAPTER 3

ASSESSMENT METHODOLOGY

3.1 GENERAL

The methodology adopted in the present study is developed to assess the structural adequacy and strengthening requirement of an existing fixed jacket-type offshore platform. Unlike a new design problem, the assessment of an existing offshore platform has to deal with the structure in its present condition, including its geometry, loading history, environmental exposure, possible deterioration, and future operational requirement. Therefore, the methodology is arranged in a step-by-step manner, starting from metocean data collection and SACS model development, followed by in-place analysis, ultimate strength assessment, pushover analysis, identification of critical members and joints, and finally local connection-level strengthening evaluation as listed below.

3.2 STRUCTURAL ASSESSMENT AND RETROFITTING FRAMEWORK

- The study begins with the collection of the environmental load data, including wave, current, wind and marine growth parameters, are adopted from the Environmental Data Report for Indian Western Offshore Region [8].
- Preparation of an independent three-dimensional SACS model of the fixed jacket-type offshore platform.
- The platform geometry, member sections, material properties, support conditions, deck levels and appurtenance details are defined in the structural model.
- The loads are applied in the SACS model, including structural self-weight, live loads, skid loads, and environmental loads. The environmental loads are applied for different approach directions so that the critical loading direction, maximum base shear, and maximum overturning moment can be identified for assessment.
- The global structural assessment is carried out using SACS in accordance with API RP 2A-WSD provisions for member and tubular joint checks [3].
- Linear in-place analysis is performed to evaluate the adequacy of jacket members and tubular joints under combined gravity and environmental loading.

- Operating and Extreme loading condition and their load combinations are considered to identify overstressed members and joints.
- Nonlinear pushover analysis is carried out to evaluate the Reserve Strength Ratio and understand the collapse behaviour of the jacket system.
- Local strengthening schemes using ring stiffeners and friction-grip clamp systems are developed for deficient tubular joints.
- The strengthened connection behaviour is further evaluated using CBFEA feature in IDEA StatiCa to study stress distribution, load transfer, bolt force and local utilization.

3.3 OVERVIEW OF SACS AND IDEA STATICA SOFTWARE

In this study, two software tools are used for two different parts of the work. Structural Analysis Computer System (SACS) is used for the global structural assessment of the offshore jacket platform, while IDEA StatiCa is used for checking the selected strengthened connections in more detail at local level. In this way, the study connects the global behaviour of the offshore structure with the local behaviour of the retrofit connection.

Bentley SACS 2024 is used to prepare the global three-dimensional model of the fixed jacket platform. The model includes the jacket legs, bracings, horizontal framing, deck framing, conductors and support conditions. Gravity loads, live loads, equipment loads and metocean loads due to wave, current and wind are applied in the model. The software is used to carry out in-place analysis for operating and extreme storm conditions. From this analysis, member utilization ratios, joint utilization ratios and critical load directions are obtained. These results help in identifying the members and tubular joints that require further attention. Pushover analysis is also carried out in SACS to study the reserve strength and collapse behaviour of the jacket [20].

IDEA StatiCa 26.0 is used for the local assessment of selected tubular joints and strengthening details. The forces obtained from SACS are taken as input for the connection model. This helps in studying the behaviour of ring stiffeners and friction-grip clamp arrangements under the applied loading. The software is useful for checking stress distribution, plate utilization, bolt forces, contact pressure and load transfer in the strengthened connection. This is particularly relevant for friction-grip clamp systems, where the performance depends on bolt pretension, contact between surfaces and frictional resistance [21].

3.4 MODELLING OF JACKET STRUCTURE

The analyzed structure is a four-legged fixed jacket type platform located in the Mumbai High field.

- The platform is installed in a mudline of EL -79.50 m.
- The jacket is assumed to be supported by a piled foundation system, with the piles providing fixity at the seabed level.
- The topside consists of two deck levels, cellar deck at EL +15.30 m with respect to MLW and main deck at EL +23.00 m with respect to MLW.
- The main deck has a plan dimension of 20 m X 28 m and cellar deck framing has a plan dimension of approximately 15 m X 28 m.
- The subsea jacket substructure consists of four main chords, refer as columns and 4 horizontal framing levels at EL +2.0 m, EL -21.0 m, EL -50.0 m, and EL -79.5 m as shown in the Figure 3.1.
- The total vertical height of the subsea jacket is 85 m and total inclined length 85.4 m.
- The overall SACS model of the offshore platform is shown in Figure 3.1.

3.5 MODELLING ASSUMPTIONS

The following modelling assumptions were adopted for developing the SACS model:

- The pile stubs are assumed to be fixed at mudline level for the purpose of global structural analysis.
- Conductor shielding effects are considered for both orthogonal and diagonal loading directions based on the spacing-to-diameter ratio (S/D). The increase in effective diameter due to marine growth is also included while calculating the S/D ratio.
- Conductors are included in the model to account for environmental loading due to wave and current action. But their structural stiffness is neglected in the global analysis.
- For in-place analysis, the wave position is selected to produce the most critical structural response for each environmental loading direction. The governing wave

position is identified by reviewing global responses such as base shear, overturning moment, member forces, and joint utilization.

- The drag effect of sacrificial anodes is accounted for by suitably increasing the effective marine growth thickness in the hydrodynamic model.
- Hydrodynamic coefficients, including drag coefficient C_d and inertia coefficient C_m, are assigned separately for smooth and rough tubular members as per B.5.3.1.2.8.2, API RP 2A provisions.
- Additional wall thickness provided in the splash zone as corrosion allowance is not considered as it impacts the strength and stiffness calculation.
- Jacket legs are assumed to be flooded in the analysis model.

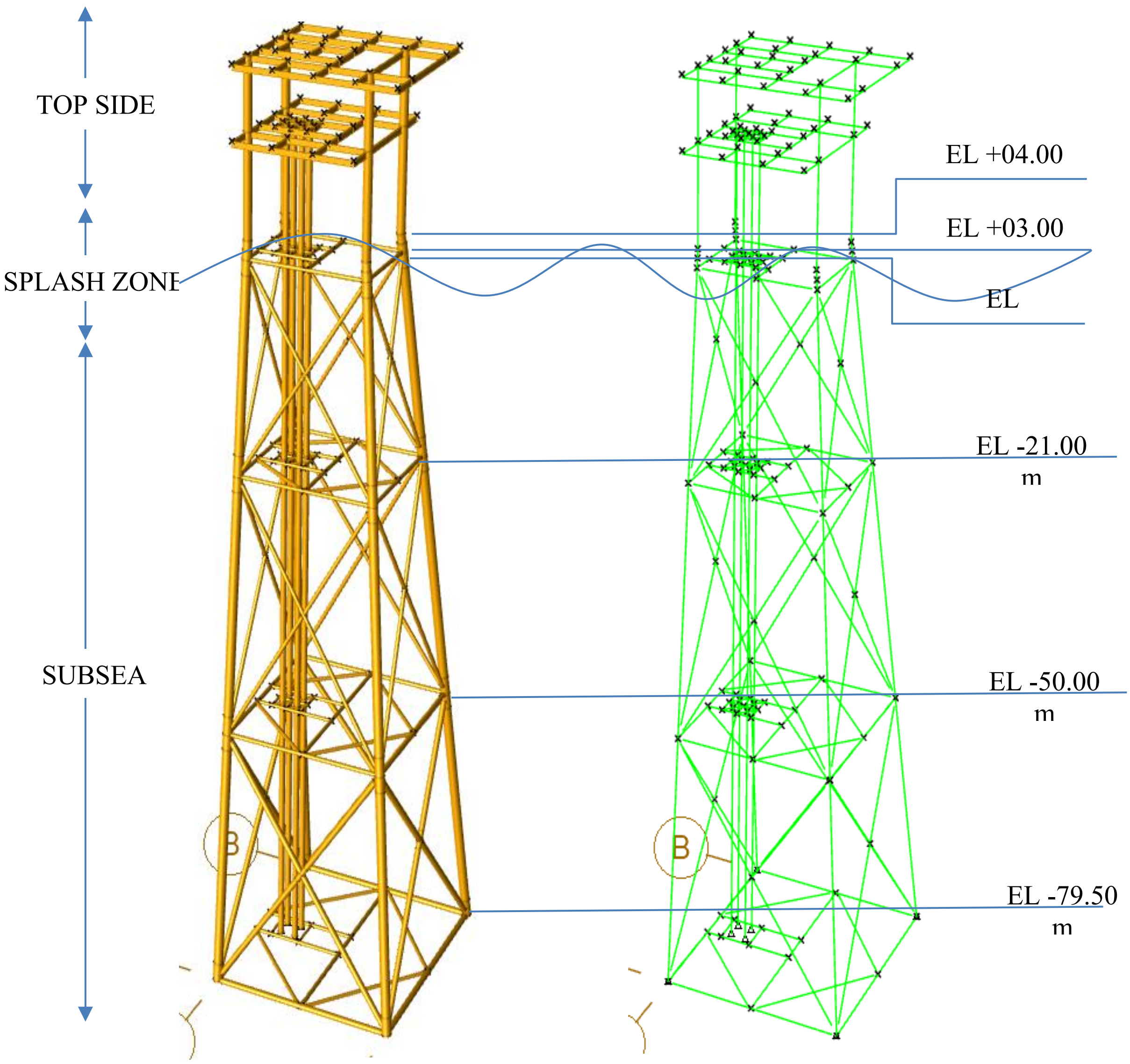


Fig. 3.1. Render and Line View of the Jacket Model

- The design water depth for operating and storm conditions is calculated as:

$$\text{Water Depth} = 76.00 + LAT + 0.5AT + \text{Storm Surge}$$

where LAT = Lowest Astronomical Tide and AT = Astronomical Tide.

- Effective length factors are assigned to jacket members based on their type and end restraint condition. The assigned values are given below in Table 3.1:

Table. 3.1. Member wise Effective Length Factor

Member Type	**Effective Length Factor (k)**
Jacket legs	1.0
Jacket braces	0.9
X-braces, longer segment length	0.9

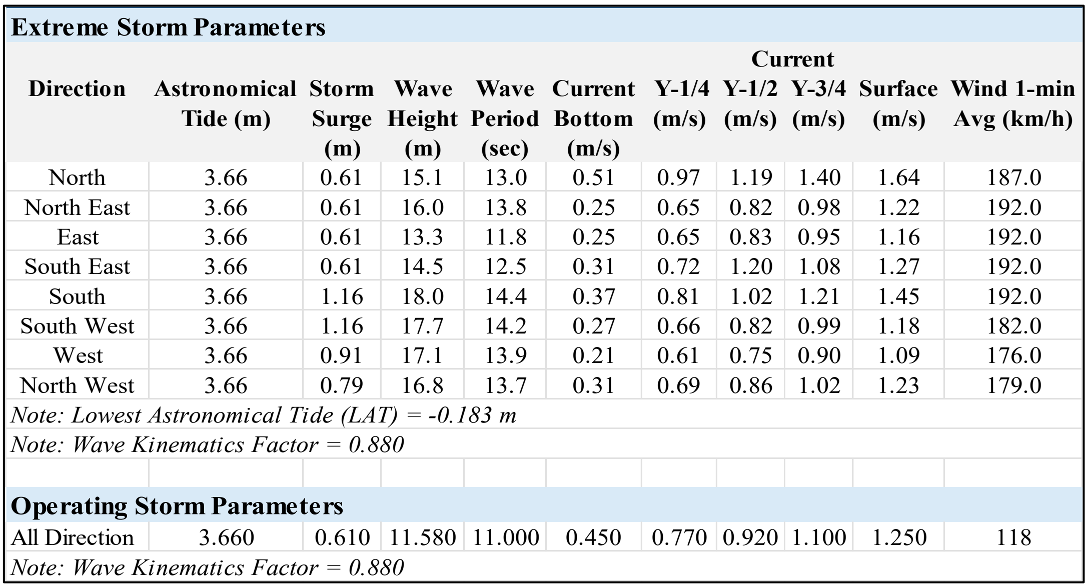
3.6 ENVIRONMENTAL LOAD CALCULATION METHODOLOGY

Environmental loads form the main lateral loading on a fixed offshore jacket platform. The adopted procedure follows the general API RP 2A approach, where wind loads are evaluated from exposed projected areas, while wave and current loads are calculated from hydrodynamic forces acting on submerged tubular members [3].

3.6.1 COLLECTION OF LOAD DATA

The environmental load data used for the present reassessment were taken from the Metocean Data Report for Indian Western Offshore Region based on Mumbai High Data [8]. The document provides indicative metocean parameters for the west coast offshore region, including operating and extreme storm wave height, wave period, current profile, wind speed, astronomical tide, storm surge, Lowest Astronomical Tide (LAT), and wave kinematics factor AS summarized in Table 3.2.

Table. 3.2. Environmental load data [8]



Extreme Storm Parameters										
						Current				
Direction	**Astronomical Tide (m)**	**Storm Surge (m)**	**Wave Height (m)**	**Wave Period (sec)**	**Current Bottom (m/s)**	**Y-1/4 (m/s)**	**Y-1/2 (m/s)**	**Y-3/4 (m/s)**	**Surface (m/s)**	**Wind 1-min Avg (km/h)**
North	3.66	0.61	15.1	13.0	0.51	0.97	1.19	1.40	1.64	187.0
North East	3.66	0.61	16.0	13.8	0.25	0.65	0.82	0.98	1.22	192.0
East	3.66	0.61	13.3	11.8	0.25	0.65	0.83	0.95	1.16	192.0
South East	3.66	0.61	14.5	12.5	0.31	0.72	1.20	1.08	1.27	192.0
South	3.66	1.16	18.0	14.4	0.37	0.81	1.02	1.21	1.45	192.0
South West	3.66	1.16	17.7	14.2	0.27	0.66	0.82	0.99	1.18	182.0
West	3.66	0.91	17.1	13.9	0.21	0.61	0.75	0.90	1.09	176.0
North West	3.66	0.79	16.8	13.7	0.31	0.69	0.86	1.02	1.23	179.0
Note: Lowest Astronomical Tide (LAT) = -0.183 m										
Note: Wave Kinematics Factor = 0.880										
Operating Storm Parameters										
All Direction	3.660	0.610	11.580	11.000	0.450	0.770	0.920	1.100	1.250	118
Note: Wave Kinematics Factor = 0.880										

3.6.2 LOAD CLASSIFICATION

In the present study, the load application procedure in SACS was developed with reference to the Bentley SACS weight feature modelling workflow. The loads were grouped into surface loads, live loads, equipment loads, miscellaneous/appurtenant loads, anode loads, inertia loads and environmental loads. Surface and live loads were applied through defined deck surfaces, equipment loads were applied using footprint weights, and appurtenant loads were applied through member, joint and anode weight definitions. Environmental loads were generated using SEASTATE by defining wave, current, wind and dead/buoyancy parameters. Finally, the basic load cases were combined to form operating storm and extreme storm load combinations for structural assessment. Basic loads are shown in the Table 3.3.

Table. 3.3. Basic Load / Weight Groups used in SACS

Load Group	Type of Load	Magnitude Used in Model	Method of Application in SACS	Description
AREA	Deck area dead load	Cellar deck: 0.50 kN/m²; Main deck: 0.75 kN/m²	Surface Weight	Pressure load applied on defined deck surfaces
LIVE	Deck live load	Cellar deck: 2.50 kN/m²; Main deck: 5.00 kN/m²	Surface Weight	Live load applied on cellar and main deck surfaces
EQPT	Equipment load	SKID1: 1112.05 kN; SKID2: 667.23 kN; SKID3: 444.82 kN; SKID4: 155.587 kN	Footprint Weight	Equipment weights distributed through skid/footprint arrangement
MISC	Miscellaneous deck load	Walkway: 2.773 kN/m; Crane: 88.964 kN; Firewall: 15.00 kN	Member / Joint Weight	Miscellaneous loads applied as distributed or concentrated loads
LPAD	Lifting padeye load	2.00 kN per padeye joint	Joint Weight	Padeye load applied at selected joints
WKWY	Boat landing / jacket walkway load	1.50 kN/m	Member Weight	Distributed walkway load applied to selected members at boat landing level
ANOD	Anode load	2.50 kN per anode, 2 anodes per member	Anode Weight	Anode weight applied to jacket members, including buoyancy and wave load option
DEAD	Structural self-weight / dead-buoyancy load	Generated from model geometry, section properties and material density	SACS / SEASTATE	Self-weight and buoyancy-related effects generated by SACS

3.6.3 METOCEAN/ENVIRONMENTAL LOAD DATA

The metocean data were adopted from the Environmental Data Report for Indian Western Offshore Region [8]. Since fixed jacket platforms are mainly governed by lateral environmental loading, the data were applied direction-wise in SACS for eight approach directions: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°, as shown in the Figure 3.2. For each direction, the corresponding wave height, wave SACS for eight approach directions: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° time period, current velocity profile, wind speed and still water depth were used to generate the environmental load cases.

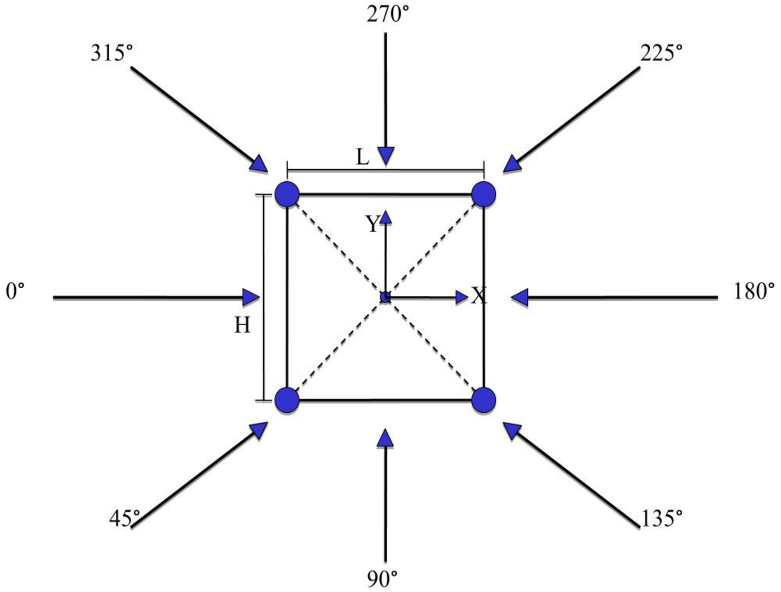


Fig. 3.2. SACS load direction

3.6.4 STORM WAVE LOAD

Wave loading on a fixed offshore platform is basically dynamic, because the water particle velocity and acceleration change continuously with time. For many jacket-type platforms in conventional water depths, the wave action may be reasonably represented by equivalent static wave forces for design and reassessment purposes. This simplification is acceptable when the structure is relatively stiff and its dynamic amplification is not significant.

For deterministic static wave analysis, API RP 2A [3] gives a systematic procedure for calculating wave and current forces on fixed offshore platforms. For each wave approach direction, the analysis begins with the selection of design wave height, associated wave period, storm water depth and current profile. These parameters are then used to obtain wave kinematics and hydrodynamic forces on the submerged tubular members. Refer the Figure 3.3.

In the present study, this procedure is followed through SACS, where the wave, current, water depth, marine growth, hydrodynamic coefficients and blockage factors are defined to generate environmental loads.

The wave-force calculation procedure may be summarized as follows [3]:

- The design wave height, associated wave period, storm water depth and current profile are selected for the required wave direction.
- The apparent wave period is evaluated by considering the interaction between wave and current. This accounts for the Doppler effect caused by the current.
- A suitable wave theory is selected based on the wave height, water depth and apparent wave period.
- Wave kinematics, mainly water-particle velocity and acceleration, are calculated using the selected wave theory.
- The horizontal components of wave-induced velocity and acceleration are modified using the wave kinematics factor.
- The specified current profile is corrected using the current blockage factor to obtain the effective local current profile.
- The corrected current velocity is combined vectorially with wave-particle kinematics to obtain the local fluid velocity and acceleration.
- Marine growth is considered by increasing the effective diameter of submerged tubular members.
- Drag and inertia coefficients are selected based on member size, surface roughness, marine growth condition, orientation and hydrodynamic parameters.
- Conductor shielding effects are included where conductor groups are present.
- Hydrodynamic models are defined for risers, conductors and other appurtenances.
- Local wave-current forces are calculated for members, conductors, risers and appurtenances using Morison’s equation.
- Finally, the global wave-current force is obtained by summing the local forces acting on all relevant components.
- The overall calculation sequence is presented schematically in Figure 3.4.

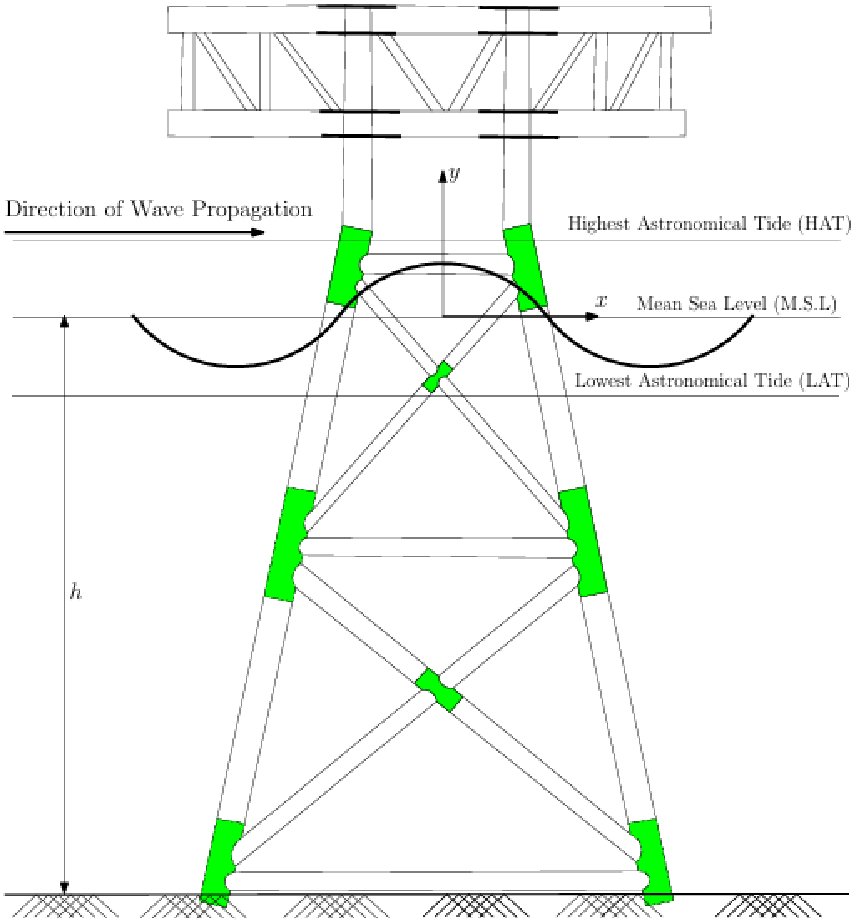


Fig. 3.3. Wave Load action on the Jacket Structure [3]

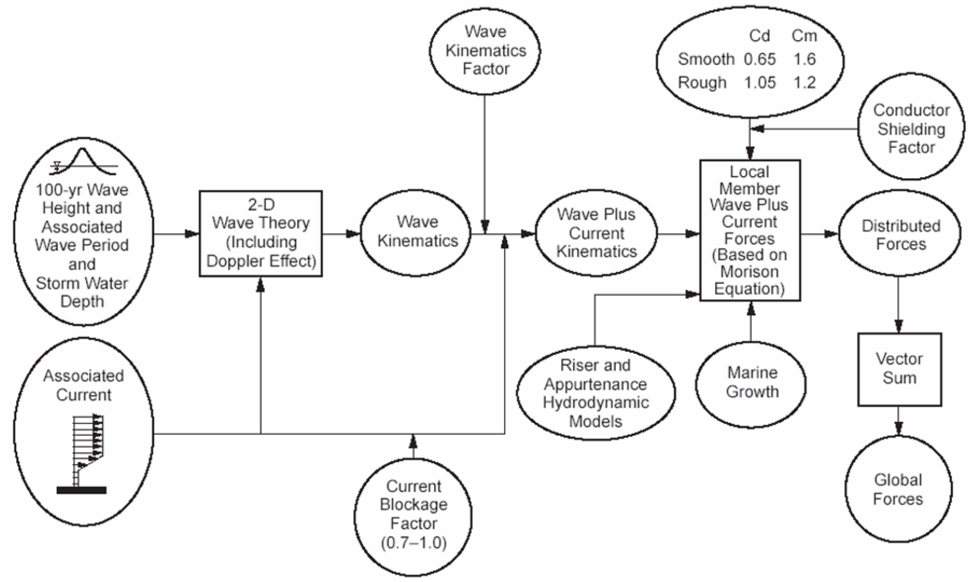


Fig. 3.4. Procedure for Calculation of Wave Plus Current Forces for Static Analysis [3]

3.6.5 WAVE THEORY SELECTION

The calculation of wave kinematics, mainly water-particle velocity and acceleration, depends on the wave theory adopted for the analysis. Different wave theories are available like Linear/Airy, Stokes, Stream Function and Cnoidal wave theory, the choice is usually governed by water depth, wave height, wave period, and the level of accuracy required.

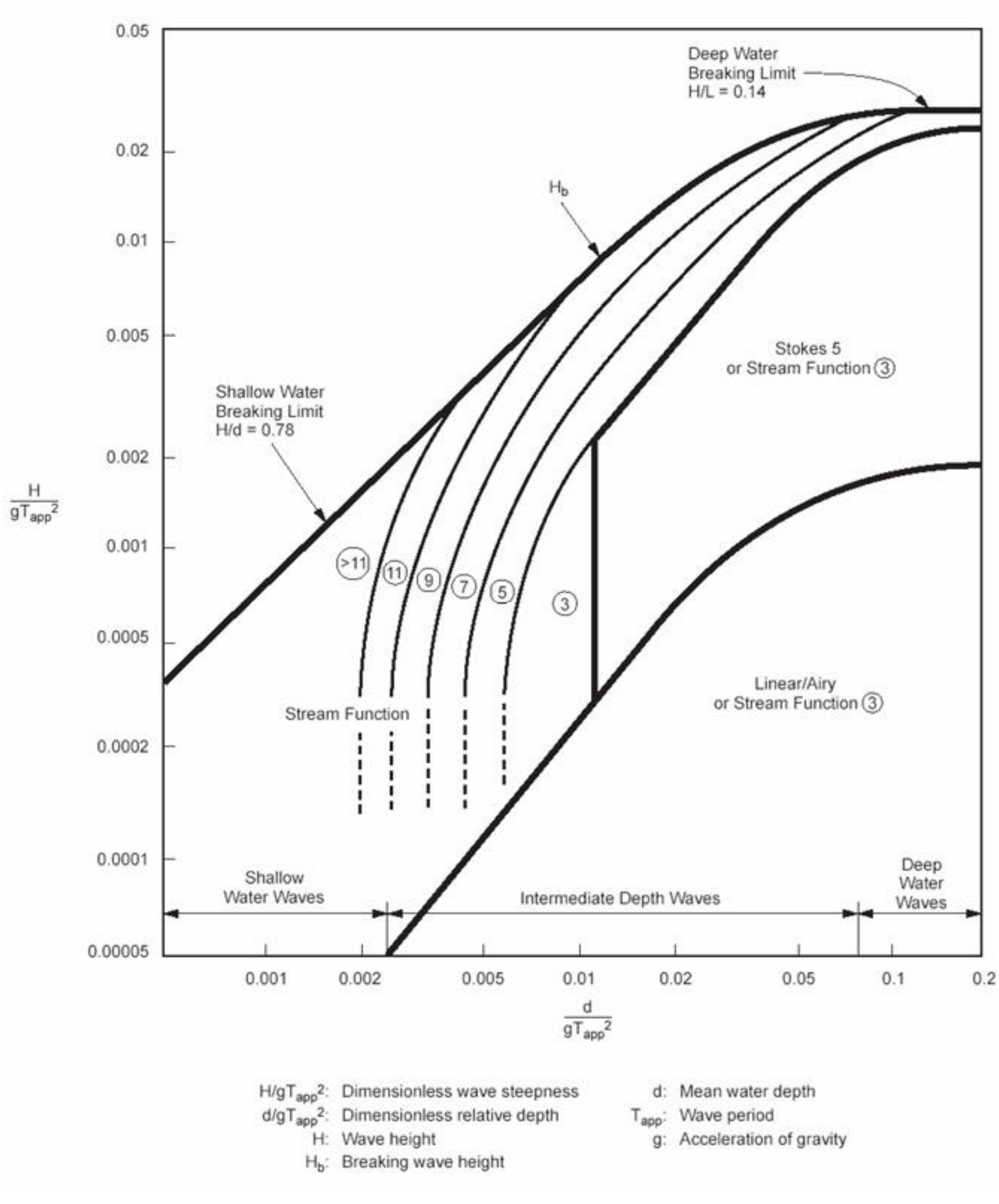


Figure.3.5 Regions of Applicability of Stream Function, Stokes V, and Linear Wave Theory [3]

For offshore jacket analysis, the selected wave theory should realistically represent the wave condition at the site. A theory suitable for deep water may not be appropriate for shallow-water or highly nonlinear wave conditions. API RP 2A recommends selecting the wave theory using a wave theory selection chart based on the non-dimensional parameters d/gT$^{\wedge 2}$ and H/gT$^{\wedge 2}$ as shown in the Figure 3.5, where d is water depth, H is wave height, T is wave period, and g is gravitational acceleration [3].

3.6.6 MORISON EQUATION

For slender tubular members of an offshore jacket, wave force is commonly evaluated using Morison's equation. This approach is applicable when the wavelength is large compared with the member diameter, generally when the wavelength-to-diameter ratio is greater than about 5. Under this condition, the member does not significantly disturb the incoming wave field, and the total hydrodynamic force can be represented as the combination of drag force and inertia force.

As per API RP 2A [3], the wave-current force per unit length acting normal to a cylindrical member may be written as:

$$f = f_D + f_I$$

$$f = \frac{1}{2}\rho C_D D \mid U \mid U + \rho C_M \frac{\pi D^2}{4} \frac{\partial U}{\partial t}$$

where,

f = total hydrodynamic force per unit length acting normal to the member,

f_D = drag force component per unit length,

f_I = inertia force component per unit length,

ρ = mass density of seawater,

C_D = drag coefficient,

C_M = inertia coefficient,

D = effective diameter of the tubular member, including marine growth,

U = water particle velocity normal to the member axis due to combined wave and current action,

$\mid U \mid$ = absolute value of the normal water particle velocity, and

$\frac{\partial U}{\partial t}$ = water particle acceleration normal to the member axis.

3.6.7 WAVE LOAD CALCULATION

The maximum wave height is observed for the 180° direction, where the 100-year wave height reaches 18.00 m with a corresponding period of 14.40 s. The still water depth varies from 78.26 m to 78.81 m, depending on the direction-wise storm surge. Storm wave load for eight approach directions: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° is calculated in tabulated in the Table 3.4.

$$\text{Water Depth} = 76.00 + LAT + 0.5AT + \text{Storm Surge}$$

Table. 3.4. Extreme Storm and Operating Storm Wave Load Data

Wave Data								
Direction	**0°**	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
100-year wave maximum height, m	15.09	16.77	17.07	17.68	18	14.48	13.26	16.00
100-year wave period, sec	13.0	13.7	13.9	14.2	14.4	12.5	11.8	13.8
Still water depth, m	78.26	78.44	78.56	78.81	78.81	78.26	78.26	78.26
1-year wave maximum height, m	15.58	15.58	15.58	15.58	15.58	15.58	15.58	15.58
1-year wave period, sec	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
Still water depth, m	78.3	78.3	78.3	78.3	78.3	78.3	78.3	78.3

3.6.8 STORM CURRENT LOAD

Current load is considered because the steady movement of seawater produces drag force on the submerged parts of the jacket, including legs, braces, conductors, risers and other appurtenances. Unlike wave loading, which varies with time and includes both velocity and acceleration effects, current loading is mainly associated with fluid velocity. Current load contribution is normally included through the drag component of Morison’s equation. In the present analysis, the current profile is defined along the water depth, with separate velocity values at the bottom, intermediate levels and free surface. The environmental data report provides current speeds at bottom, $Y/4$, $Y/2$, $3Y/4$ and surface levels for operating and extreme storm conditions [8].

For current load calculation, the specified current profile is first corrected using the current blockage factor, which accounts for the reduction in effective current velocity caused by the obstruction of the jacket structure. The corrected current velocity is then applied along the selected environmental approach direction. For conservative storm load generation, the current direction is generally taken parallel to the wave direction so that the combined hydrodynamic effect is properly represented.

The current-induced drag force per unit length on a tubular member may be expressed as:

$$f_c = \frac{1}{2}\rho C_D D_{eff} \mid U_c \mid U_c$$

Where,

f_c = current drag force per unit length,

ρ = seawater density,

C_D = drag coefficient,

D_{eff} = effective member diameter including marine growth,

U_c = corrected current velocity normal to the member axis.

Marine growth is included by increasing the effective diameter of submerged members:

$$D_{eff} = D + 2t_m$$

In SACS, the current profile is defined in the SEASTATE module along with current direction, current stretching option, blockage factor, marine growth and hydrodynamic coefficients. The software then calculates member-level current forces and combines them with other environmental effects for global analysis. The SACS load workflow also defines current loading through the environmental loading module, where current velocity, current direction, blockage option and stretching method are specified before load generation.

3.6.9 CURRENT LOAD CALCULATION

The current velocity profile was applied at different water-depth levels, from seabed to surface. As expected, the current velocity generally increases toward the free surface, which increases the wave-current force contribution on the upper jacket members. Storm current load for eight approach directions: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° is calculated in the Table 3.5 for extreme storm and in Table 3.6 for operating storm condition.

Table. 3.5. Extreme Storm Current Profile

Elevation	Current Speed (m/s)							
	Direction of Approach							
	0°	45°	90°	135°	180°	225°	270°	315°
Bottom	0.51	0.31	0.213	0.27	0.37	0.31	0.25	0.25
Y-1/4	0.97	0.69	0.609	0.66	0.81	0.72	0.65	0.65
Y-1/2	1.19	0.86	0.75	0.82	1.02	1.2	0.83	0.82
Y-3/4	1.4	1.02	0.9	0.99	1.21	1.08	0.95	0.98
Surface	1.64	1.23	1.09	1.18	1.45	1.27	1.16	1.22

Table. 3.6. Operating Storm Current Profile

Elevation	Current Speed (m/s)							
	Direction of Approach							
	0°	45°	90°	135°	180°	225°	270°	315°
Bottom	0.45							
Y-1/4	0.77							
Y-1/2	0.92							
Y-3/4	1.1							
Surface	1.25							

3.6.10 WIND LOADS

Wind load is considered for the exposed portion of the offshore platform, mainly the deck, equipment, helideck, handrails, crane, piping, and other topside facilities above the water level. Although wave and current loads generally dominate the jacket substructure, wind load contributes to the global lateral force and overturning moment of the platform [1].

As per the API RP 2A approach, wind speed is normally specified at a reference height of 10 m above sea level. If the wind force is required at another elevation, the reference wind speed is extrapolated using a power-law profile:

$$V_z = V_{10}\left(\frac{z}{10}\right)^{1/8}$$

where V_z is the wind speed at elevation z, V_{10} is the wind speed at 10 m reference height, and z is the height above the reference water level. In the present study, the wind speed values are taken from the adopted metocean data and applied along the same environmental approach directions used for wave and current loading.

The wind pressure is calculated from the dynamic pressure of air:

$$q_z = \frac{1}{2}\rho V_z^2$$

The wind force on a projected area is then calculated as:

$$F_w = q_z C_s A$$

where F_w is the wind force, $q_z$is the wind pressure, C_s is the shape coefficient, and A is the exposed projected area normal to the wind direction. For global jacket and deck analysis, a shape coefficient close to 1.0 is commonly adopted unless a more specific component-wise coefficient is required from API RP 2A [3].

For orthogonal wind directions, the wind force components may be written as:

$$F_x = q_z C_s A_x$$

$$F_y = q_z C_s A_y$$

where A_x and A_y are the projected wind areas normal to the X and Y directions, respectively.

Wind loads were applied in SACS using wind load areas defined between the cellar deck and main deck region. The direction-wise design wind speeds were converted into m/s and used for extreme and operating storm load generation. The highest design wind speed considered is 53.30 m/s, which is used for the 180°, 225°, 270° and 315° directions as calculated in Table 3.7.

Table. 3.7. Extreme & Operating Wind Speed

Storm Condition	**Design Wind Speed (m/s)**							
	Direction of Approach							
	0°	**45°**	**90°**	**135°**	**180°**	**225°**	**270°**	**315°**
Extreme Condition in m/s	51.94	49.72	48.89	50.56	53.33	53.33	53.33	53.33
Operating Condition	32.78	32.78	32.78	32.78	32.78	32.78	32.78	32.78

3.6.11 HYDRODYNAMIC PARAMETERS

The hydrodynamic coefficients were assigned separately for smooth and rough tubular members. Smooth members represent clean tubular surfaces, while rough members represent members affected by marine growth calculated in Table 3.8a and Table 8b.

Table. 3.8. Hydrodynamic Coefficients

Member Surface Condition	Drag Coefficient, C_d	Inertia Coefficient, C_m
Smooth tubular members	0.65	1.6
Rough tubular members	1.05	1.2

The following additional hydrodynamic parameters were considered:

Parameter	Magnitude
Wave kinematics factor	0.88
Current blockage factor, end-on	0.8
Current blockage factor, diagonal	0.85
Current blockage factor, broadside	0.8
Lowest Astronomical Tide, LAT	−0.183

3.6.12 MARINE GROWTH PROFILE

Marine growth was included because it increases the effective diameter and surface roughness of submerged tubular members, which directly affects wave and current forces. Thickness of marine growth calculated in Table 3.9.

Table. 3.9. Elevation wise Marine Growth

From Elevation, m	To Elevation, m	Density KN/m^3	Marine Growth Thickness on Radius, mm
3	−60.00	14	100
−60.00	-79.5 or Mudline	14	50

3.6.13 METOCEAN LOAD CASES

There are sixteen load cases, eight load cases for each loading direction for both operating and extreme load case utilizing the sea-state method tabulated in Table 3.10.

Table. 3.10. Metocean Load Cases

Load Case	Condition	Direction	Loads Included
P000	Operating storm	0°	Wave + Current + Wind + Dead/Buoyancy
P045	Operating storm	45°	Wave + Current + Wind + Dead/Buoyancy
P090	Operating storm	90°	Wave + Current + Wind + Dead/Buoyancy
P135	Operating storm	135°	Wave + Current + Wind + Dead/Buoyancy
P180	Operating storm	180°	Wave + Current + Wind + Dead/Buoyancy
P225	Operating storm	225°	Wave + Current + Wind + Dead/Buoyancy
P270	Operating storm	270°	Wave + Current + Wind + Dead/Buoyancy
P315	Operating storm	315°	Wave + Current + Wind + Dead/Buoyancy
E000	Extreme storm	0°	Wave + Current + Wind + Dead/Buoyancy
E045	Extreme storm	45°	Wave + Current + Wind + Dead/Buoyancy

E090	Extreme storm	90°	Wave + Current + Wind + Dead/Buoyancy
E135	Extreme storm	135°	Wave + Current + Wind + Dead/Buoyancy
E180	Extreme storm	180°	Wave + Current + Wind + Dead/Buoyancy
E225	Extreme storm	225°	Wave + Current + Wind + Dead/Buoyancy
E270	Extreme storm	270°	Wave + Current + Wind + Dead/Buoyancy
E315	Extreme storm	315°	Wave + Current + Wind + Dead/Buoyancy

3.6.14 LOAD COMBINATIONS

Load Combinations as per API code are tabulated in the Table 3.11. There are sixteen load combinations for operating storm conditions and for extreme storm conditions tabulated in Table 3.12. The environmental load factor of 1.0 is there for both operating and extreme load cases, while the live load factor is taken as 0.75 in extreme storm combinations.

Table. 3.11. Load Combination as per API RP 2 Working Stress Design

Load Category	**Normal Operating Case**	**Hydro-Test Case**	**Extreme Storm case**	**Tension Pullout case**	**Seismic Case**
Gravity Loads					
Structural Dead Loads	1.00	1.00	1.00	0.90	1.00
Mechanical Equipment	1.00	1.00	1.00	0.90	1.00
Piping & Bulks	1.00	1.00	1.00	0.90	1.00
Electrical Equipment	1.00	1.00	1.00	0.90	1.00
Instrumentation	1.00	1.00	1.00	0.90	1.00
Operating Fluids	1.00	-	1.00	-	1.00
Hydro-test Fluids	-	1.00	-	-	-
Live Loads	1.00	(0.50)	-	-	0.50
Drilling Loads					
Drilling Equipment	1.00	1.00	1.00	0.90	1.00
Supplies	1.00	-	-	-	0.50
Hook Loads	1.00	-	-	-	-
Rotary Loads	-	-	1.00	-	-
Environmental Loads					
Operating Wind	1.00	1.00	-	-	-
Extreme Wind	-	-	1.00	1.00	-
Operating Wave+Current	1.00	1.00	-	-	-
Extreme Wave+Current	-	-	1.00	1.00	-
Seismic Loads	**-**	**-**	**-**	**-**	1.00

Table. 3.12. Load Combinations Prepared in SACS

Load Combination	**Storm Condition**	**Direction**	**LOAD FACTOR**				
			AREA	**EQPT**	**LIVE**	**MISC**	**OP/EX**
OPR-01	Operating	0°	1	1	1	1	1
OPR-02	Operating	45°	1	1	1	1	1
OPR-03	Operating	90°	1	1	1	1	1
OPR-04	Operating	135°	1	1	1	1	1
OPR-05	Operating	180°	1	1	1	1	1
OPR-06	Operating	225°	1	1	1	1	1
OPR-07	Operating	270°	1	1	1	1	1
OPR-08	Operating	315°	1	1	1	1	1
STM-01	Extreme	0°	1	1	0.75	1	1
STM-02	Extreme	45°	1	1	0.75	1	1
STM-03	Extreme	90°	1	1	0.75	1	1
STM-04	Extreme	135°	1	1	0.75	1	1
STM-05	Extreme	180°	1	1	0.75	1	1
STM-06	Extreme	225°	1	1	0.75	1	1
STM-07	Extreme	270°	1	1	0.75	1	1
STM-08	Extreme	315°	1	1	0.75	1	1

3.7 DESIGN AND ANALYSIS PROCEDURE

The design and analysis procedure adopted in the present study is based on a staged assessment approach. First, the jacket platform is checked using linear in-place analysis to identify the adequacy of members and tubular joints under gravity and environmental loading. If the structure does not fully meet the design-level acceptance criteria, it is further assessed through nonlinear pushover analysis to understand the reserve strength and collapse mechanism of the platform. This approach is consistent with the structural assessment philosophy discussed by Nallayarasu [1].

3.7.1 IN-PLACE ANALYSIS

In-place analysis is carried out to evaluate the structural adequacy of the offshore jacket platform under its installed condition. In this analysis, the jacket, deck, piles, conductors, appurtenances and applied loads are considered together in the global SACS model. The main objective is to check whether the platform can safely resist the combined effects of dead load, live load, equipment load, wind, wave and current.

The in-place analysis is performed using a linear static approach in SACS. Member utilization ratios and tubular joint utilization ratios are obtained as the main output. The members are checked for axial force, bending, shear and combined stress interaction, while tubular joints are checked for punching shear and joint capacity in accordance with API RP 2A-WSD [3]. Components with utilization ratio greater than the permissible limit are treated as critical and are considered for further assessment.

3.7.2 PUSHOVER ANALYSIS

Pushover analysis is carried out to evaluate the ultimate reserve strength of the jacket platform beyond the linear design-level check. In a conventional in-place analysis, the structure is checked member by member using allowable stress criteria. This is useful for identifying overstressed members and joints, but it may not fully represent the actual system capacity of an offshore jacket. A jacket platform generally has redundancy, and after local yielding or member overstress, the load may redistribute to adjacent members. Pushover analysis is used to study the global collapse behaviour of the structure.

In the present study, nonlinear pushover analysis is performed using the SACS Collapse module. Gravity loads are applied first, followed by incremental environmental loading in the selected wave direction. The environmental load is gradually increased until the structure reaches collapse or a limiting failure condition. During this process, the analysis accounts for material nonlinearity, geometric nonlinearity, member yielding, stiffness degradation and load redistribution. The failure sequence, critical members, collapse load and reserve strength of the platform are then obtained from the analysis, refer the Figure 3.6.

The main output of pushover analysis is the Reserve Strength Ratio (RSR) [12], which represents the ratio of collapse environmental load to the design environmental load. It may be expressed as,

$$RSR = \frac{\text{Collapse Environmental Base Shear Load}}{\text{Design Environmental Base Shear Load}} = \frac{V_{collapse}}{V_{design}}$$

Where $V_{collapse}$ is the base shear at collapse and V_{design} is the base shear corresponding to the design environmental load. Wahab et al. [2] discussed pushover analysis as an important tool in the condition assessment and life-extension evaluation of aged fixed offshore platforms, since it helps in estimating reserve capacity and identifying whether strengthening or repair is actually required.

In this study, pushover analysis is used after the in-place. If overstressed members or joints are observed in the design-level analysis, the pushover analysis helps to judge whether these local overstressed affects the overall collapse resistance of the platform. This makes the assessment more rational and avoids unnecessary strengthening based only on conservative linear analysis results.

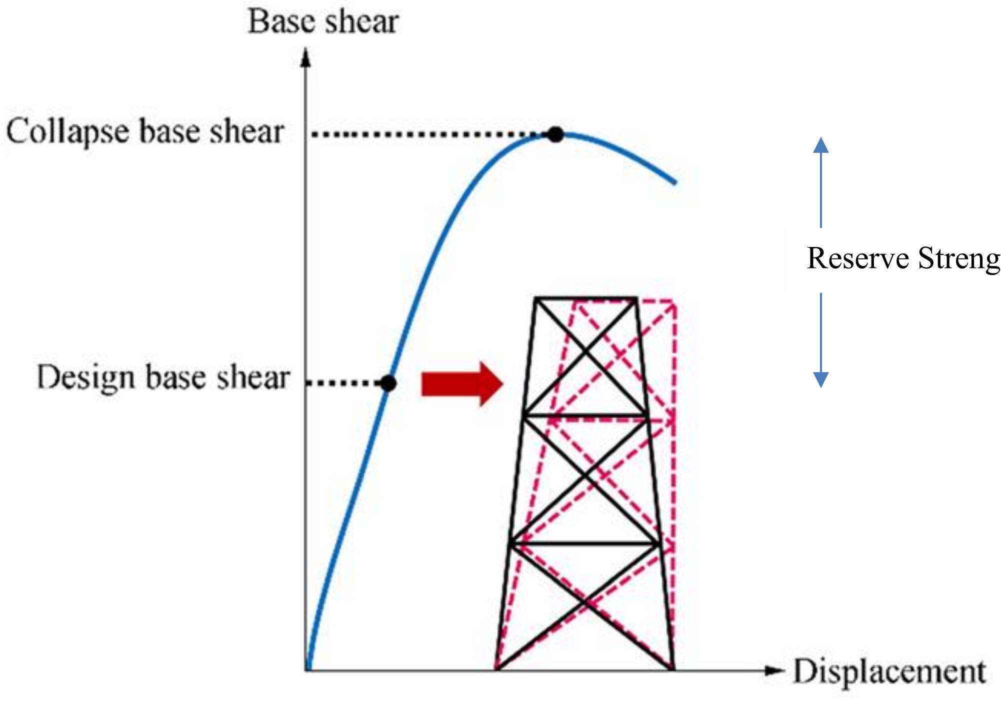


Fig. 3.6. Base Shear from Pushover Analysis [2]

3.7.3 ANALYSIS PROCEDURE OF JACKET STRUCTURE

The analysis procedure for jacket structure adopted in this study is summarized below:

- A three-dimensional SACS model of the fixed offshore jacket platform is developed using the available geometry, member sections, material properties and support conditions.
- Gravity loads, deck loads, equipment loads, appurtenance loads and environmental loads due to wave, current and wind are applied in the model.
- Operating and extreme storm load combinations are prepared for the selected environmental approach directions.
- Linear static analysis is carried out in SACS to check the installed condition of the platform.
- Member utilization ratios and tubular joint utilization ratios are reviewed as per

API RP 2A-WSD provisions.

- Critical members and overstressed tubular joints are traced from the SACS results.
- Nonlinear pushover analysis is performed to evaluate reserve strength, collapse behaviour and load redistribution of the jacket platform.
- Critical tubular joints are selected for local strengthening study.
- Connection-level assessment is carried out in IDEA StatiCa using forces obtained from the SACS analysis.
- Strengthening schemes such as ring stiffeners and friction-grip clamp systems are evaluated for deficient tubular joints.
- Final assessment is made by combining global SACS results with local connection design results.

3.7.4 ANALYSIS PROCEDURE FOR MECHANICAL FRICTION CLAMP CONNECTION

The analysis procedure for mechanical friction clamp connection adopted in this study is summarized below:

- Identify the critical tubular member or joint from the global SACS analysis.
- Extract the governing axial force, shear force, bending moment and torsion.
- Select the clamp location based on available length, surface condition and member geometry.
- Decide the preliminary clamp size, saddle plate, stiffeners, flange arrangement and number of stud bolts.
- Calculate the required slip resistance at the clamp-member interface.
- Check available friction resistance against the applied slip demand.
- Verify that bolt tightening does not cause local crushing or excessive hoop stress in the tubular member.
- Check clamp plates, stiffeners, flanges and bolts for strength and serviceability.
- Model the final arrangement in IDEA StatiCa to study bolt forces, contact pressure, stress distribution and local utilization.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter presents the results of global structural assessment and local connection-level evaluation of the fixed jacket-type offshore platform. The SACS results are discussed through member utilization, tubular joint unity checks, grout-filled joint strengthening, and pushover analysis. Based on the critical joints identified from the global analysis, local retrofitting studies are carried out using mechanical friction-grip clamp and ring stiffener arrangements. The performance of these strengthening schemes is assessed using Component-Based Finite Element Analysis in IDEA StatiCa by reviewing equivalent stress, local deformation, bolt utilization, weld utilization, slip resistance, and buckling behavior. The results presented in this chapter provide the basis for evaluating the structural adequacy of the existing platform and the effectiveness of the proposed strengthening measures for life extension.

4.2 IN-PLACE ANALYSIS RESULTS

In-place analysis was performed in SACS for operating and extreme load combinations. Unity check results for topside and jacket members were reviewed using the SACS UC-check colour contour option.

4.2.1 EXTREME VS OPERATING MEMBER UNITY CHECK

Extreme load combinations showed higher utilization compared to operating conditions due to increased environmental loading. Most members were found within the allowable UC limit in the operating condition. Higher UC values were observed mainly near deck beams, beam-column intersections, and brace connection regions. Members/joints with UC greater than 1.0 were identified for further detailed assessment and strengthening checks.

The colour legend represents member utilization:

- Red: UC ≥ 1.00
- Orange/Yellow: High utilization
- Green/Grey: Safe utilization range

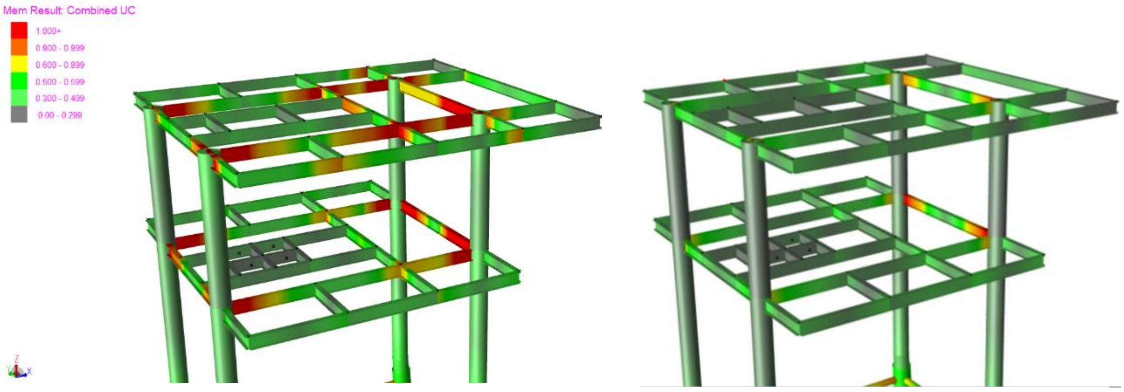


Fig. 4.1. Top-Side Member UC in Extreme vs Operating Condition

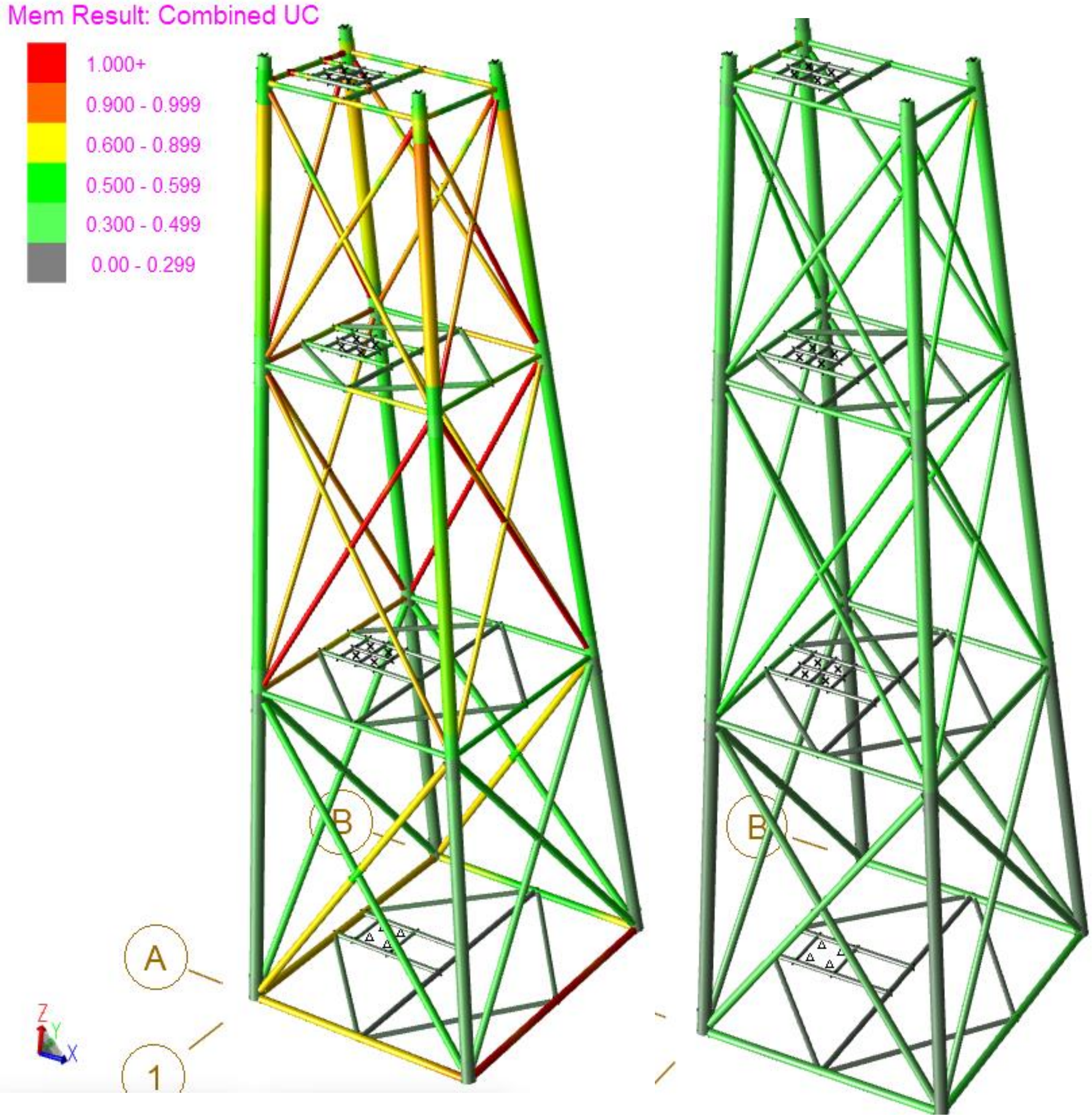


Fig. 4.2. Jacket Member UC in Extreme vs Operating Condition

4.2.2 OPERATING VS EXTREME JOINT UNITY CHECK

Joint unity check results were evaluated for both operating and extreme environmental load combinations. The jacket structure consists of a total of 107 tubular joints, out of which 20 joints were found to be overstressed under extreme loading conditions. A comparative assessment of joint utilization under operating and extreme storm conditions is presented in Fig. 4.3.

The colour legend represents joint utilization:

- Red: UC ≥ 1.00
- Blue: UC = 1.00
- Green: UC < 1

The comparison of operating and extreme load conditions indicates that extreme environmental loading governs the joint unity check values, with selected tubular joints exceeding the permissible UC limit and requiring further reassessment.

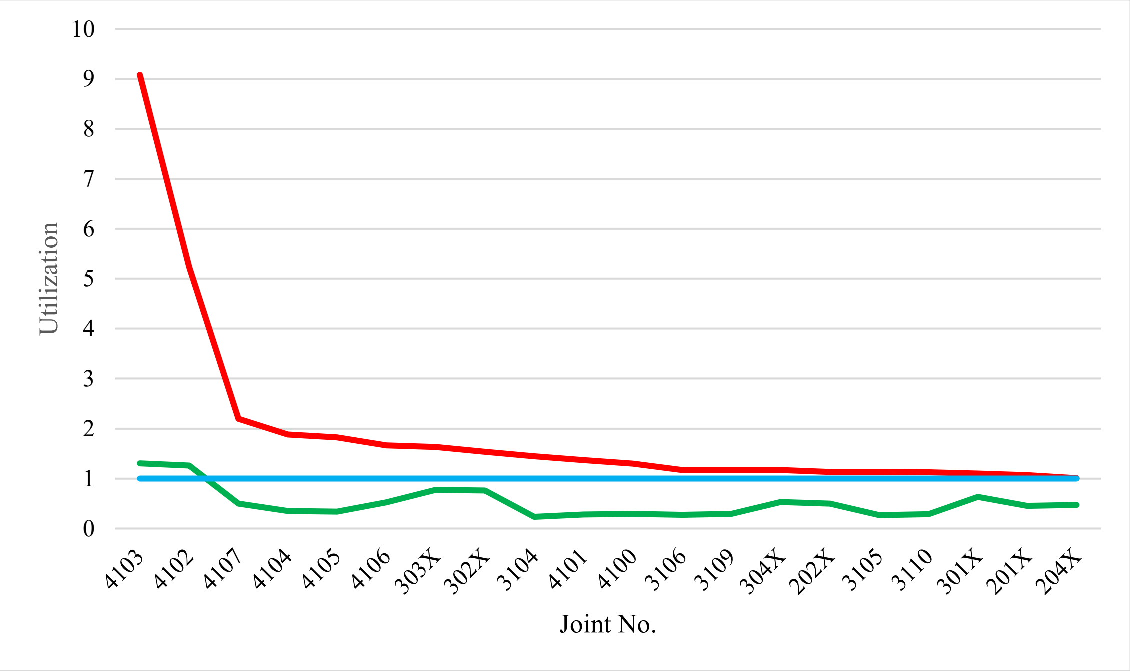
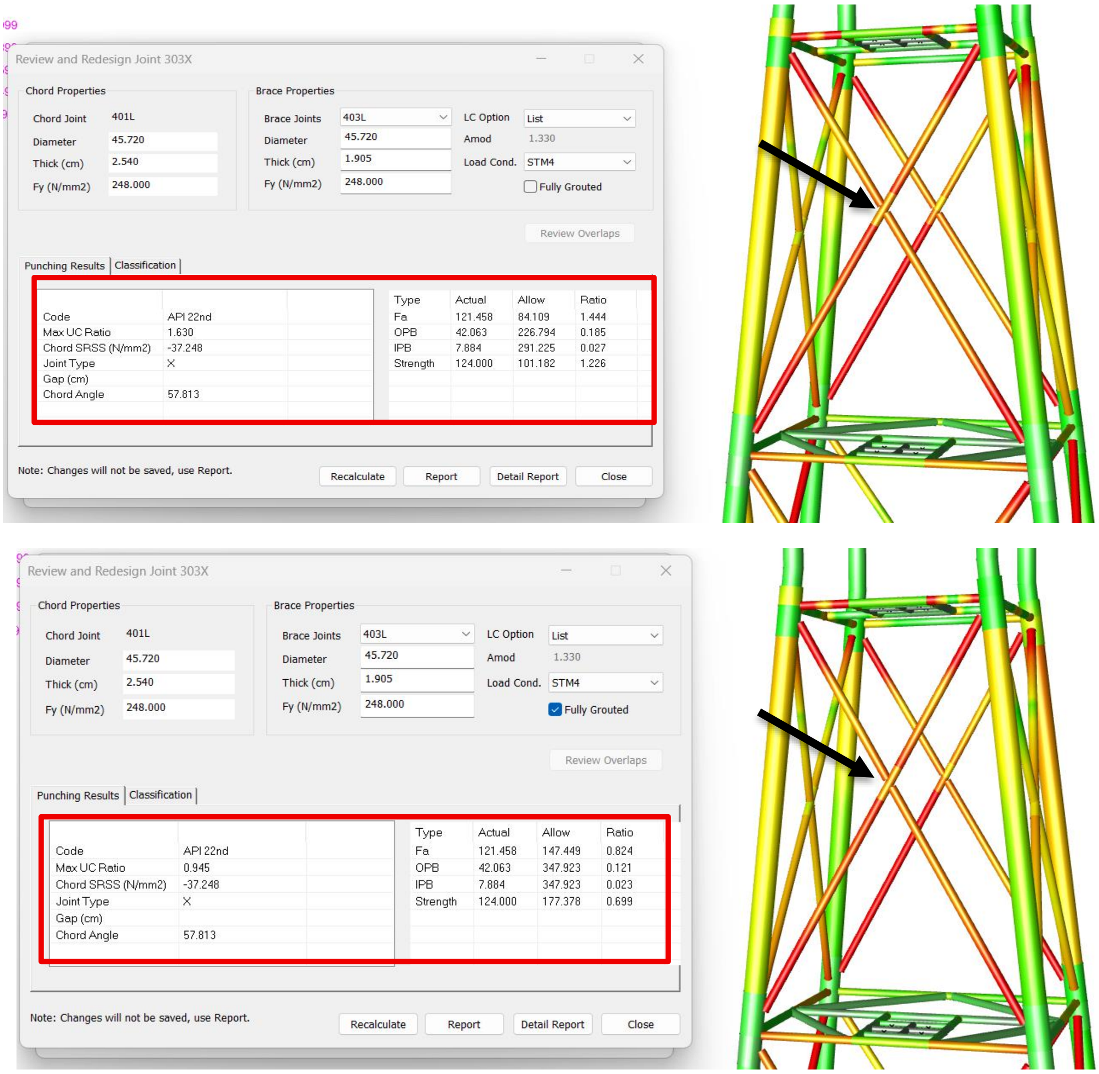


Fig. 4.3. Jacket Member UC in Operating vs Extreme Condition

4.2.3 STRENGTHENING OF THE MEMBER USING GROUT FILLED JOINT

The overstressed tubular members identified during the in-place analysis are initially strengthened using grout-filled joint. In this method, annular space is assumed to be filled with high-strength grout to improve overall joint capacity.

For Joint 303X, grout filling reduced the utilization ratio from 1.63 to 0.945 as shown in the Figure 4.4. Similarly, strength assessment is carried out for other overstressed joints. Most joints satisfied the allowable utilization limit after grout filling, while a few critical joints required additional retrofitting techniques for further strengthening.



Review and Redesign Joint 303X

Chord Properties
Chord Joint: 401L
Diameter: 45.720
Thick (cm): 2.540
Fy (N/mm2): 248.000

Brace Properties
Brace Joints: 403L
Diameter: 45.720
Thick (cm): 1.905
Fy (N/mm2): 248.000
LC Option: List
Amod: 1.330
Load Cond.: STM4
☐ Fully Grouted

Punching Results

Code	API 22nd
Max UC Ratio	1.630
Chord SRSS (N/mm2)	-37.248
Joint Type	X
Gap (cm)	
Chord Angle	57.813

Type	Actual	Allow	Ratio
Fa	121.458	84.109	1.444
OPB	42.063	226.794	0.185
IPB	7.884	291.225	0.027
Strength	124.000	101.182	1.226

Note: Changes will not be saved, use Report.

Review and Redesign Joint 303X

Chord Properties
Chord Joint: 401L
Diameter: 45.720
Thick (cm): 2.540
Fy (N/mm2): 248.000

Brace Properties
Brace Joints: 403L
Diameter: 45.720
Thick (cm): 1.905
Fy (N/mm2): 248.000
LC Option: List
Amod: 1.330
Load Cond.: STM4
☑ Fully Grouted

Punching Results

Code	API 22nd
Max UC Ratio	0.945
Chord SRSS (N/mm2)	-37.248
Joint Type	X
Gap (cm)	
Chord Angle	57.813

Type	Actual	Allow	Ratio
Fa	121.458	147.449	0.824
OPB	42.063	347.923	0.121
IPB	7.884	347.923	0.023
Strength	124.000	177.378	0.699

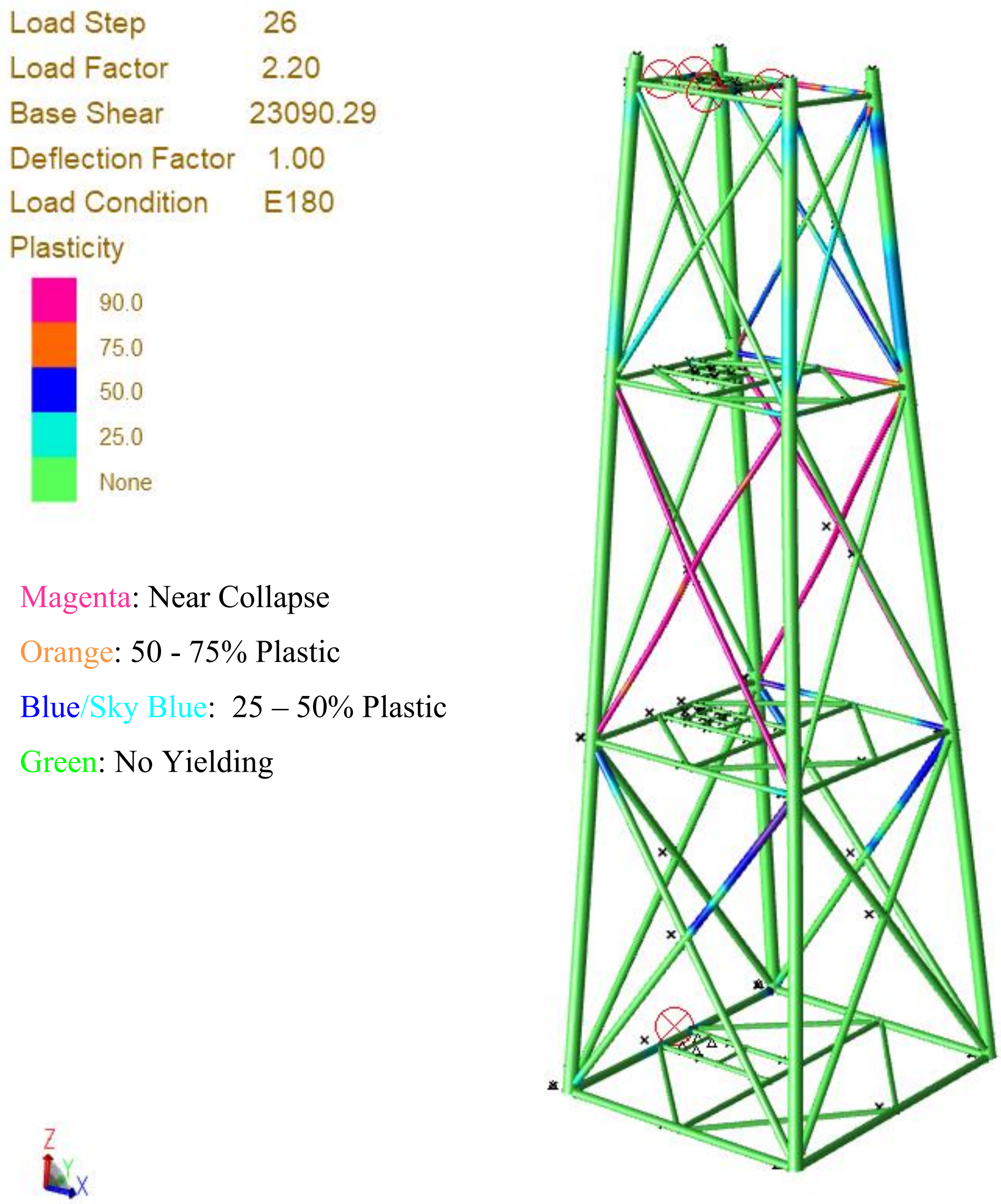
Note: Changes will not be saved, use Report.

Fig. 4.4. Joint 303X UC before and after Grouting

4.3 PUSHOVER ANALYSIS RESULTS

As per API RP 2A, the minimum required RSR for a high exposure category platform is 1.60 [3]. The pushover analysis results indicate that the obtained RSR values are equal to or greater than 1.60 for all load cases. No member or joint showed plasticity at 100% environmental loading; therefore, the jacket structure is robust enough to resist the extreme design environmental load without collapse.

Figure 4.5 shows the pushover collapse mechanism of the jacket structure for load condition E180 at the pre-collapse stage. The maximum load factor or RSR achieved prior to collapse was 2.20 with corresponding collapse base shear of 23090.29 kN. In similar way, load factors for remaining load sequences are evaluated in the Table 4.1 and presented graphically in the Figure 4.6.



Magenta: Near Collapse

Orange: 50 - 75% Plastic

Blue/Sky Blue: 25 – 50% Plastic

Green: No Yielding

Fig. 4.5. Pushover Deformed Shape for Load Sequence E180 at Pre-Collapse Condition

Table 4.1. Reserve Strength Ratio/Load Factor for Different Load Sequences

Load Sequence	**Storm Condition**	**Direction**	**RSR/LF**
STM-01	Extreme Storm	0°	3
STM-02	Extreme Storm	45°	2.5
STM-03	Extreme Storm	90°	2.7
STM-04	Extreme Storm	135°	1.8
STM-05	Extreme Storm	180°	2.2
STM-06	Extreme Storm	225°	2
STM-07	Extreme Storm	270°	3.2
STM-08	Extreme Storm	315°	2.3

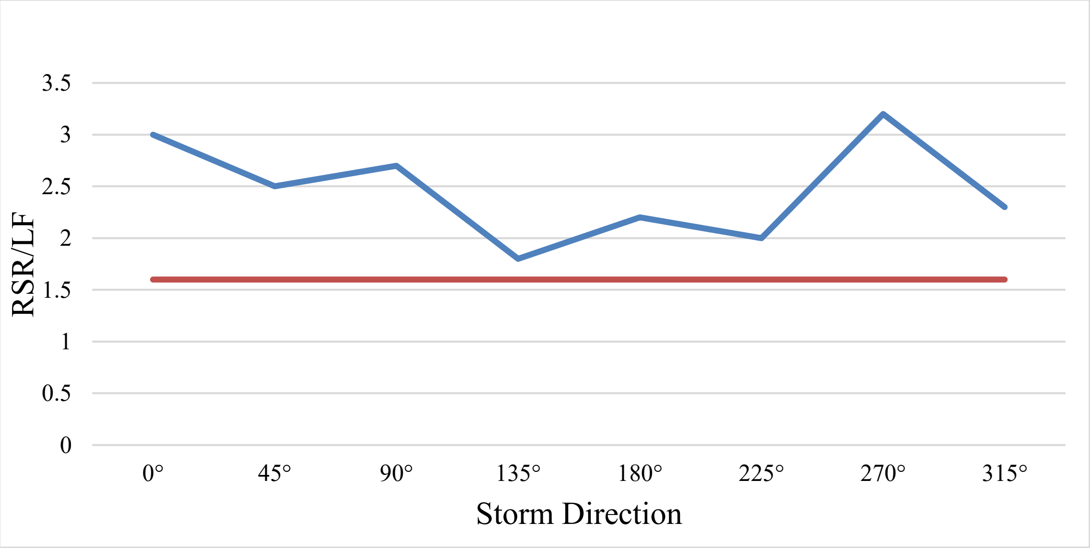


Fig. 4.6. Reserve Strength Ratio/Load Factor against Storm Direction Plot

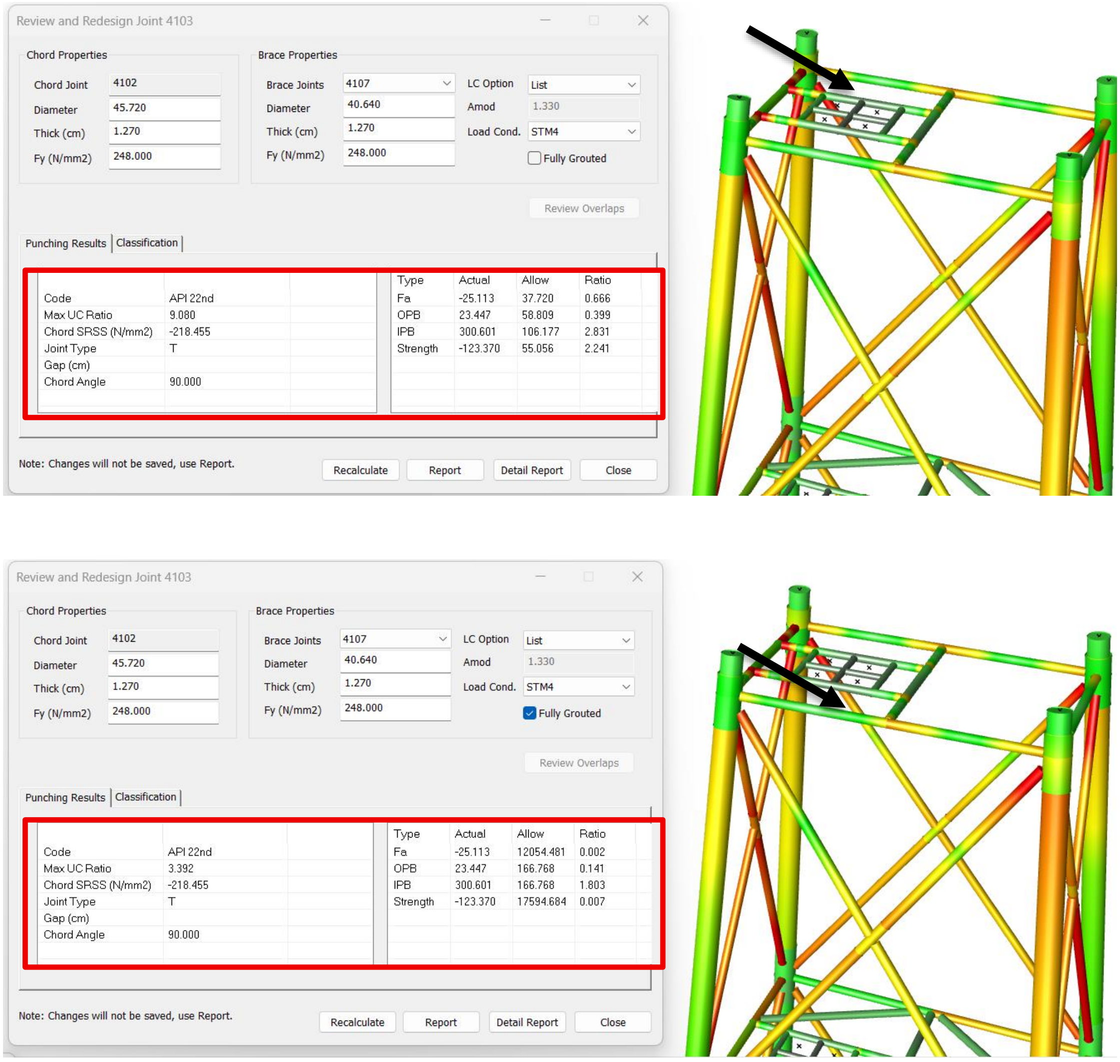
4.4 STRUCTURAL EVALUATION OF THE CRITICAL JACKET CONNECTION FOR RETROFITTING

4.4.1 MECHANICAL FRICTION CLAMP

As discussed in Section 4.1, 20 joints were found to have UC values greater than 1.0. These joints were first checked by considering grout filling inside the tubular section. After this strengthening check, 18 joints satisfied unity check except the joint no. 4103 and 4102. Joint 4103 was the most critical joint, as shown in Fig. 4.7. Under extreme load condition STM4, its UC value was 9.08. After grout filling, the UC reduced to

3.40. Although the reduction was considerable, the joint still did not meet the allowable limit.

In order to ensure the structural adequacy, replacement of both the existing chord and brace members with larger bore tubular sections is proposed. To connect the new tubular members, a mechanical friction-grip clamp arrangement is adopted. This method is suitable for offshore strengthening work as it reduces the need for extensive underwater welding and provides better installation control. For analysis, the connection was modelled as a T-type tubular joint. The clamp arrangement along with a splice connection is used to connect the replaced tubular members as shown in the Figure 4.8.


Review and Redesign Joint 4103

Chord Properties
Chord Joint: 4102
Diameter: 45.720
Thick (cm): 1.270
Fy (N/mm2): 248.000

Brace Properties
Brace Joints: 4107
Diameter: 40.640
Thick (cm): 1.270
Fy (N/mm2): 248.000
LC Option: List
Amod: 1.330
Load Cond.: STM4
☐ Fully Grouted

Code	API 22nd
Max UC Ratio	9.080
Chord SRSS (N/mm2)	-218.455
Joint Type	T
Gap (cm)	
Chord Angle	90.000

Type	Actual	Allow	Ratio
Fa	-25.113	37.720	0.666
OPB	23.447	58.809	0.399
IPB	300.601	106.177	2.831
Strength	-123.370	55.056	2.241

Note: Changes will not be saved, use Report.

Review and Redesign Joint 4103

Chord Properties
Chord Joint: 4102
Diameter: 45.720
Thick (cm): 1.270
Fy (N/mm2): 248.000

Brace Properties
Brace Joints: 4107
Diameter: 40.640
Thick (cm): 1.270
Fy (N/mm2): 248.000
LC Option: List
Amod: 1.330
Load Cond.: STM4
☑ Fully Grouted

Code	API 22nd
Max UC Ratio	3.392
Chord SRSS (N/mm2)	-218.455
Joint Type	T
Gap (cm)	
Chord Angle	90.000

Type	Actual	Allow	Ratio
Fa	-25.113	12054.481	0.002
OPB	23.447	166.768	0.141
IPB	300.601	166.768	1.803
Strength	-123.370	17594.684	0.007

Note: Changes will not be saved, use Report.

Fig. 4.7. Joint 4103 UC before and after Grouting

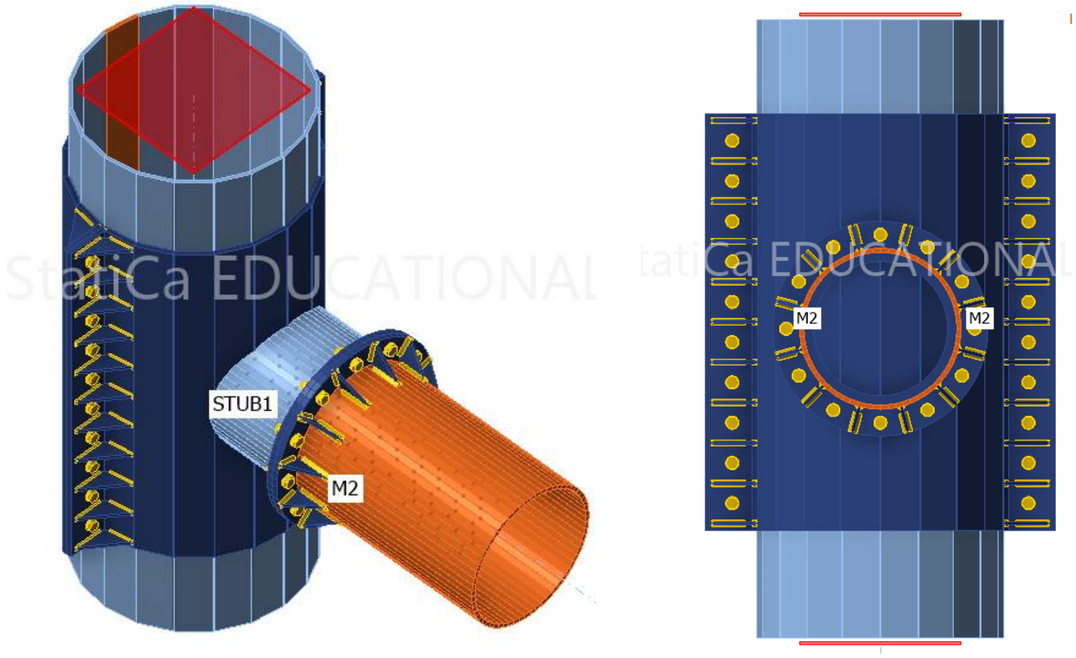


Fig. 4.8. Render view of Mechanical Friction Clamp and Splice Connection

Clamp jacketing is proposed because the joint is located in the splash zone, where corrosion is severe due to repeated wetting, drying, and salt exposure. The clamp acts as an additional protective cover around the tubular member, reducing direct contact with seawater.

4.4.2 MATERIAL PROPERTIES

Material Properties are used for FEM analysis are tabulated below in the Table 4.2.

Table 4.2. Material Properties of Structural Components

Material / Component	**Cross-section / Item**	**Property**
A36 tubular member	1 - CFRegP460×20	Yield strength = 248.2 MPa
A36 tubular member	2 - CHS600×16	Yield strength = 248.2 MPa
A572 Gr.50 steel plate / clamp component	3 - CFRegP480×20	Yield strength = 344.7 MPa
A490 bolt	Ø25 mm bolt	Yield strength = 896.3 MPa
A490 bolt	Ø25 mm bolt	Ultimate strength = 1034.2 MPa
A490 bolt	Ø25 mm bolt	Gross area = 507 mm²
E70xx weld electrode	Fillet welds	Electrode strength = 482.6 MPa

4.4.3 DESIGN CODE SETTINGS

Allowable Stress Design method as per AISC 360-22 is used for design verification, code settings are tabulated in the Table 4.3.

Table 4.3. Design Code Settings

Item	Value	Reference
Friction C_{off} in slip-resistance	0.33	AISC 360-22 – J3.9
Limit plastic strain	0.05	
Distance between bolts [d]	2.66	AISC 360-22 – J3.4
Deformation at bolt hole at service load is design consideration	Yes	AISC 360-22 – J3.11
Local deformation check	Yes	
Local deformation limit	0.03	CIDECT DG 1, 3 – 1.1
Geometrical nonlinearity (GMNA)	Yes	Analysis with large deformations for CHS joints

4.4.4 SAFETY FACTORS CALCULATION – ASD

Allowable stress for steel (AMOD) is evaluated based on API RP2A WSD [3], the basic allowable stress may be taken as:

$$S_b = \frac{F_y}{FS} = \frac{F_y}{1.60} = 0.625F_y$$

where F_y is the yield strength of steel plate and FS is the factor of safety. Taking $FS = 1.60$. For the 100-year extreme storm condition, a one-third increase in allowable stress (AMOD) is considered. So, the allowable stress for steel member becomes:

$$S = 1.33 \times 0.625F_y = \frac{F_y}{1.2}$$

Similarly for bolts, Taking $FS = 2.0$,

$$S_b = \frac{F_y}{2.0} = 0.5F_y$$

For the 100-year extreme storm condition, a one-third increase in allowable stress (AMOD) is considered. So, the allowable stress for bolts becomes:

$$S = 1.33 \times 0.5F_y = \frac{F_y}{1.5}$$

Modified allowable stress design safety factors adopted for the connection checks in IDEA StatiCa are tabulated in Table 4.4:

Table 4.4: Modified Safety Factors

Check Components	ASD Safety Factor, Ω
Tensile and shear strength, bolts	1.5
Combined tensile and shear strength, bolts	1.5
Bearing at bolt holes	1.5
Fillet welds	2.0
Material safety factor	1.2
Slip-resistant joint	1.5

4.4.5 LOAD EFFECT

Under extreme load condition STM4, member forces extracted for clamp design are tabulated below in Table 4.5:

Table 4.5. Load Effect

Load Effects	Member	N [kN]	My [kNm]	Mz [kNm]
LC STM4	M2 / End	-394	451	35

4.4.6 CHECK SUMMARY

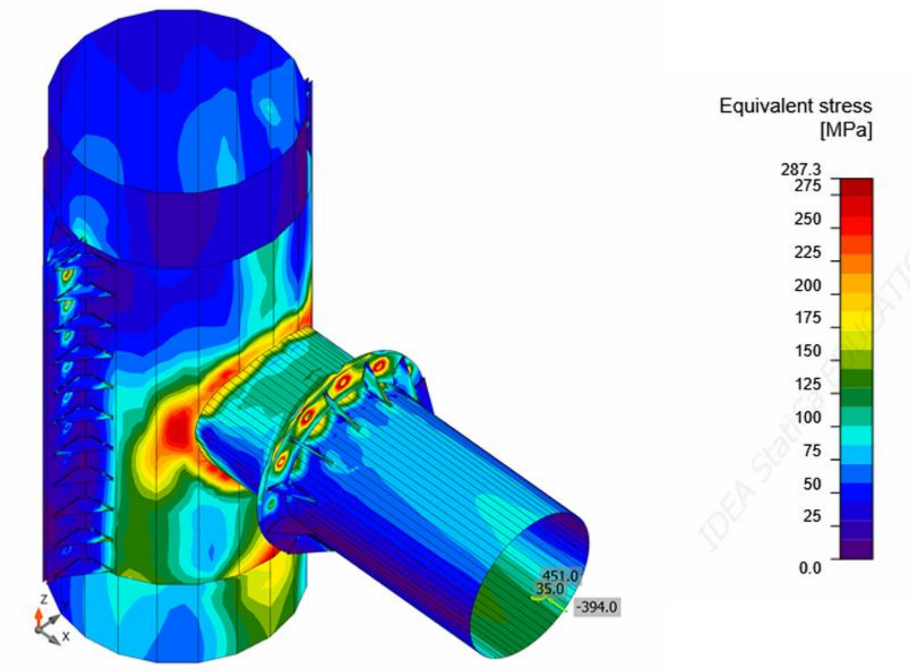
The IDEA StatiCa check summary confirms that the proposed mechanical friction clamp connection satisfies all governing checks for load case LC STM4, as tabulated in the Table 4.6.

Table 4.6. Component Wise Check Summary

Check Components	Result	Status	Remark
Analysis	100.00%	OK	Analysis completed successfully
Plates	0.5% < 5.0%	OK	Plate plastic strain is within limit
Local deformation	0.4% < 3.0%	OK	Local deformation is within allowable limit
Bolts	87.2% < 100%	OK	Governing check among all components
Preloaded bolts	50.5% < 100%	OK	Slip-resistant bolt check is satisfactory
Welds	76.8% < 100%	OK	Weld utilization is within allowable limit
Buckling factor	43.85	OK	Buckling safety margin is adequate
GMNA	Calculated	OK	Geometrical nonlinear analysis completed

4.4.7 EQUIVALENT / VON MISES STRESS

The plate check results show that all plates and tubular components are safe for load case LC STM4. The equivalent stress $\boldsymbol{\sigma_{Ed}}$ as shown in Figure 4.9, plastic strain $\boldsymbol{\varepsilon_{Pl}}$, and contact stress $\boldsymbol{\sigma_{c,Ed}}$are within the allowable limit as shown in the Table 4.7.



Equivalent stress, LC STM4

Fig. 4.9. Equivalent Stress Distribution in Mechanical Friction Clamp under LC STM4

Table 4.7. Plate Stress and Strain Check Summary under LC STM4

Component	**Material**	**t p [mm]**	**Loads**	**σ Ed [MPa]**	**ε Pl [%]**	**σ c,Ed [MPa]**	**Status**
M1-Chord	A36	13	STM4	206.9	0	3.1	OK
M2-Brace	A36	16	STM4	206.9	0	0	OK
SM 1-Clamp	A572 Gr.50	20	STM4	287.4	0.1	0.3	OK
STUB1	A36	16	STM4	207.8	0.5	0	OK
SP 1	A572 Gr.50	19.1	STM4	167.2	0	29.2	OK
SP 2	A572 Gr.50	19.1	STM4	164.3	0	29.2	OK
SP 3	A572 Gr.50	19.1	STM4	214.3	0	38.5	OK
SP 4	A572 Gr.50	19.1	STM4	213.7	0	38.5	OK
STUB1-EPa	A572 Gr.50	24	STM4	287.5	0.1	92.7	OK
STUB1-EPb	A572 Gr.50	24	STM4	287.4	0.1	92.7	OK

4.4.8 LOCAL DEFORMATION

The local deformation check confirms that all main components of the clamp connection remain within the allowable deformation limit under load case LC STM4. Refer the Figure 4.10 for the deformed shape and Table 4.8 for check summary.

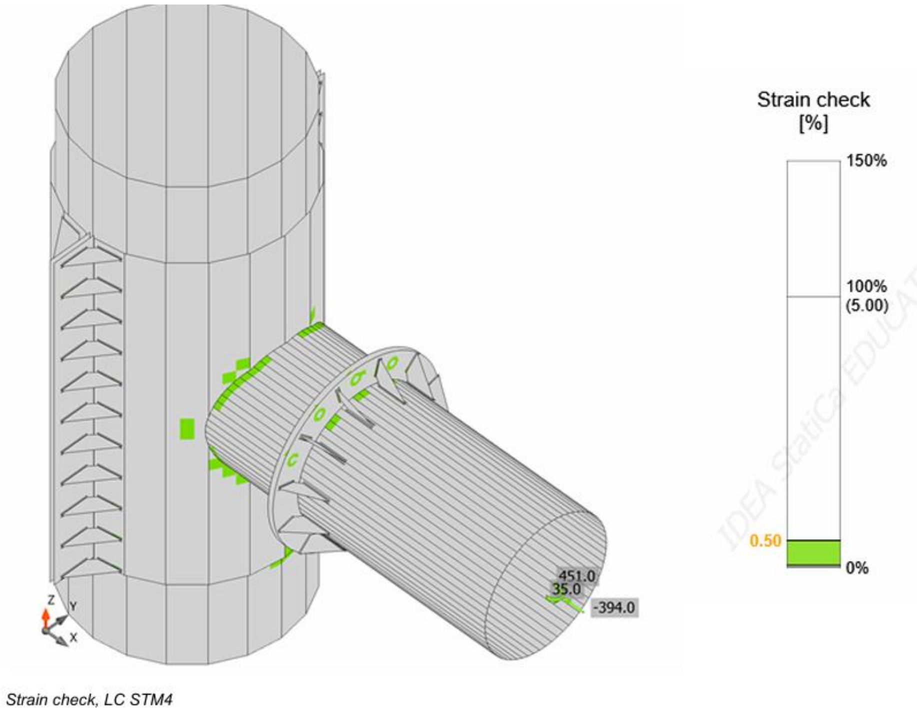


Fig. 4.10. Local Deformation in Mechanical Friction Clamp under LC STM4.

Table 4.8. Local Deformation Check Summary under LC STM4

Component	**d_0 [mm]**	**Loads**	**δ [mm]**	**δ lim [mm]**	**δ/d_0[%]**	**Check status**
M1-Chord	920	STM4	4	28	0.4	OK
M2-Brace	600	STM4	0	18	0	OK
SM 1-Clamp	960	STM4	4	29	0.4	OK
STUB1	600	STM4	0	18	0.1	OK

4.4.9 BUCKLING ANALYSIS

The buckling analysis confirms the mechanical friction clamp connection has adequate stability and is not prone to buckling under the applied extreme load condition STM4. It is observed that localized deformation mainly near the lower portion of the clamp and stiffened region as shown in the Figure 4.11. Buckling factor against the mode shape are plated in the Table 4.9.

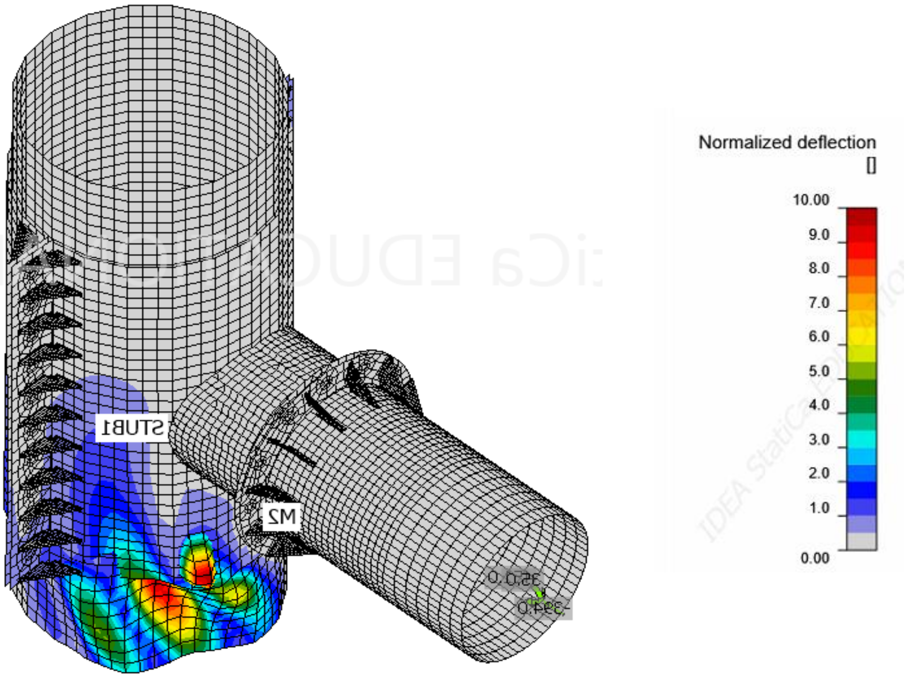


Fig. 4.11. Buckling Analysis of Mechanical Friction Clamp under LC STM4

Table 4.9. Buckling Analysis Results under LC STM4

LC	Mode Shape	Buckling Factor
LC STM4	1	43.85
LC STM4	2	48.84
LC STM4	3	48.99
LC STM4	4	49.26
LC STM4	5	49.38
LC STM4	6	49.72

4.4.10 PRELOADED BOLT CHECK

The preloaded bolt check was carried out to verify the slip-resistant behavior of the mechanical friction clamp under the governing load case LC STM4. Since the clamp transfers load mainly through friction developed by bolt pretension, the tension force, shear force and slip utilization of the bolts are reviewed in tension (blue), shear (orange) and combined tension shear (green). The detailed preloaded bolt results are tabulated in Table 4.10, and the corresponding bolt utilization graph is shown in the Figure 4.12.

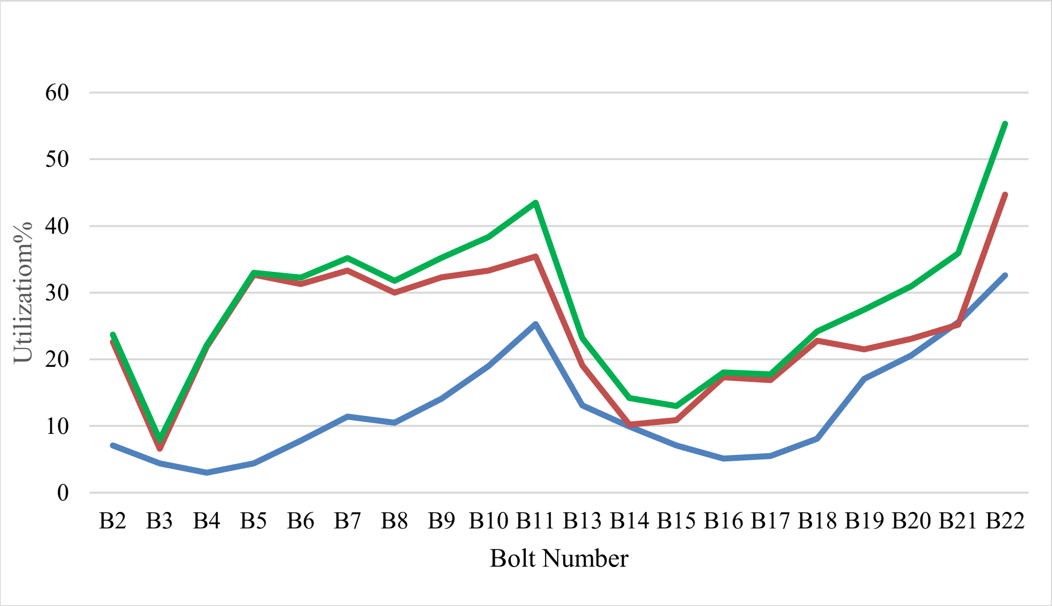


Fig. 4.12. Preloaded Bolt Force Distribution in Clamp under LC STM4

Table 4.10. Preloaded Bolt Check Summary for Clamp under LC STM4

Item	**Grade**	**Loads**	**F t [kN]**	**V [kN]**	**R /Ω n,slip [kN]**	**Ut t [%]**	**Ut s [%]**	**Ut ts [%]**	**Status**
B2	1 A490	STM4	18.8	14.5	64.1	7.1	22.6	23.7	OK
B3	1 A490	STM4	11.5	4.4	66.6	4.4	6.6	7.9	OK
B4	1 A490	STM4	7.8	14.8	67.8	3	21.9	22.1	OK
B5	1 A490	STM4	11.6	21.8	66.5	4.4	32.7	33.0	OK
B6	1 A490	STM4	20.4	19.9	63.6	7.8	31.3	32.3	OK
B7	1 A490	STM4	30.1	20.1	60.4	11.4	33.3	35.2	OK
B8	1 A490	STM4	27.7	18.4	61.2	10.5	30	31.8	OK
B9	1 A490	STM4	37.1	18.8	58.1	14.1	32.3	35.2	OK
B10	1 A490	STM4	50.1	17.9	53.8	19	33.3	38.3	OK
B11	1 A490	STM4	66.7	17.1	48.3	25.3	35.4	43.5	OK
B13	1 A490	STM4	34.4	11.3	59	13.1	19.1	23.2	OK
B14	1 A490	STM4	26.2	6.3	61.7	9.9	10.2	14.2	OK
B15	1 A490	STM4	18.7	7	64.2	7.1	10.9	13.0	OK
B16	1 A490	STM4	13.4	11.4	65.9	5.1	17.3	18.0	OK
B17	1 A490	STM4	14.5	11.1	65.6	5.5	16.9	17.8	OK
B18	1 A490	STM4	21.4	14.4	63.3	8.1	22.8	24.2	OK
B19	1 A490	STM4	45.2	11.9	55.5	17.1	21.5	27.5	OK
B20	1 A490	STM4	54.3	12.1	52.5	20.6	23.1	31.0	OK
B21	1 A490	STM4	67.5	12.1	48.1	25.6	25.2	35.9	OK
B22	1 A490	STM4	85.9	18.8	42	32.6	44.7	55.3	OK

4.4.11 RING STIFFENER CONNECTION

After evaluating the mechanical friction clamp arrangement, a separate connection model was prepared for the ring stiffener strengthened chord–brace joint as shown in Figure 4.13. This model represents the connection between the main chord member and the incoming brace member. The purpose of providing ring stiffeners is to improve the local stiffness of the chord wall and reduce local deformation and stress concentration at the brace–chord intersection.

4.4.12 MATERIAL PROPERTIES

Material Properties are used for FEM analysis are tabulated below in the Table 4.11.

Table 4.11: Material Properties of Structural Components

Member / Component	Cross-section / Thickness	Material	Property
303L	CHS 1250 × 45	A36	Yield strength = 248.2 MPa
303X	CHS 450 × 20	A36	Yield strength = 248.2 MPa
4103L	CHS 600 × 16	A36	Yield strength = 248.2 MPa
302X	CHS 450 × 20	A36	Yield strength = 248.2 MPa
4100L	CHS 600 × 16	A36	Yield strength = 248.2 MPa
STIFF PLATE	Ring stf plt, 20	A36	Yield strength = 248.2 MPa
WELDING	Weld Electrode	E70xx	Tensile strength = 482.6 MPa

4.4.13 LOAD EFFECT

Under extreme load condition STM4 for tie and STM8 for brace member, forces extracted for connection design are tabulated below in Table 4.12.

Table 4.12. Load Effect

Load Case	Member	(N) (kN)	(My) (kNm)	(Mz) (kNm)
STM8	303X / End	3192	146	254
STM4	4103L / End	-1210	136	486
STM8	302X / End	2642	288	153
STM4	4100 / End	-496	276	113

4.4.14 EQUIVALENT / VON MISES STRESS

The Figure 4.14 compares the equivalent stress distribution of the tubular joint without and with ring stiffener strengthening. In the unstiffened joint, higher stress concentration is observed around the chord–brace intersection, especially near the tie-brace and inclined brace connections. After providing the ring stiffener, the stress spread becomes more uniform and the intensity around the joint region reduces. A comparison of equivalent stress for the joint model with and without ring stiffeners is presented in Table 4.13. The table also includes the stress values developed in the stiffener plates.

Table 4.13. Equivalent Stress Comparison with and without Ring Stiffener

Member	**Without Ring Stiffener, σ_{Ed} MPA**	**With Ring Stiffener, σ_{Ed} MPa**	**Reduction**
303L	335.2	240.6	28.20%
303X	320.3	242.3	24.40%
4103L	355.3	286.9	19.30%
302X	343.9	246.0	28.50%
4100	336.4	163.0	51.50%
STIFF1a	-	285.0	-
STIFF1b	-	266.3	-
STIFF1c	-	137.0	-
STIFF1d	-	145.3	-
STIFF1e	-	164.4	-

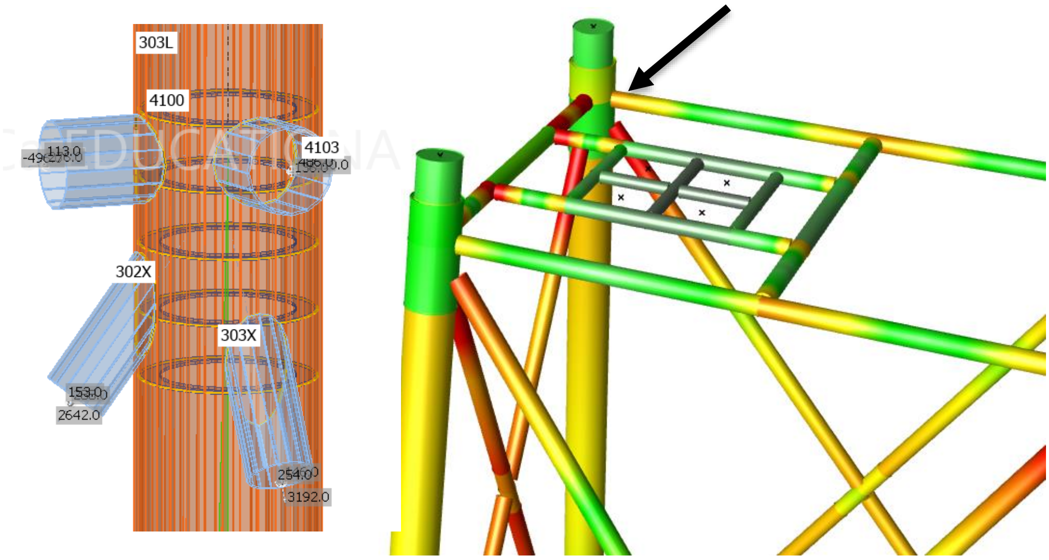


Fig. 4.13. Render view of Ring Stiffened Chord- Brace joint

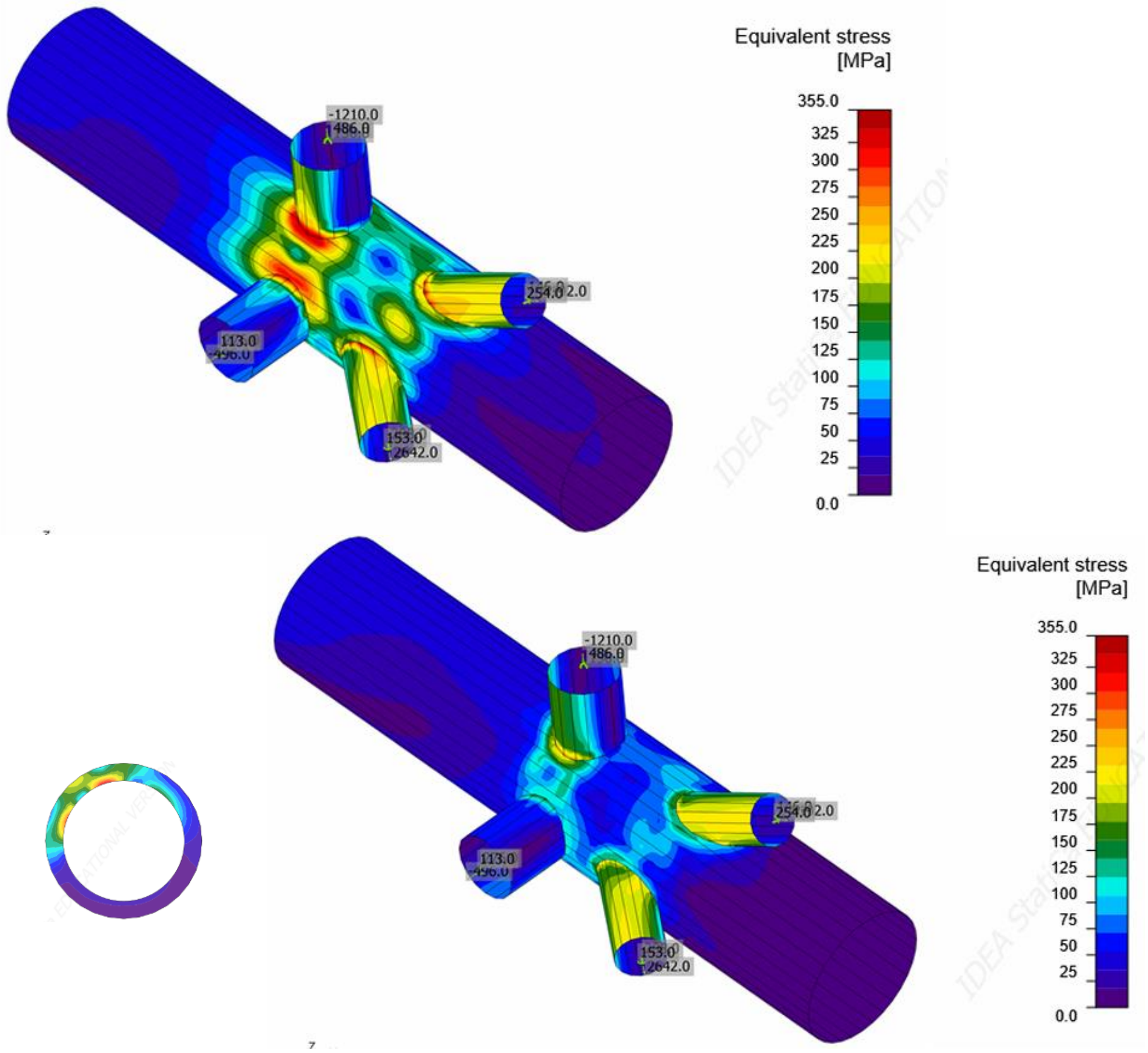


Fig. 4.14. Equivalent Stress Distribution of Tubular Joint Without and With Ring Stiffener

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 GENERAL

This chapter summarizes the major findings obtained from the structural reassessment, pushover analysis, and local strengthening evaluation of the fixed jacket-type offshore platform. The conclusions are drawn from the SACS in-place and pushover results, along with the connection-level checks performed for the mechanical friction-grip clamp and ring stiffener arrangements. The future scope highlights additional studies that may further improve the life-extension assessment of aging offshore jacket platforms.

5.2 CONCLUSION

The present study was carried out for the assessment of structural adequacy, reserve strength, and retrofitting requirement of an existing fixed jacket-type offshore platform. The platform was modelled and analysed in SACS under operating and extreme environmental loading conditions. The analysis included gravity loads, deck loads, equipment loads, and direction-wise metocean/environmental loads due to wave, current, and wind. The results obtained from the global analysis were further used to identify critical members and tubular joints requiring strengthening. On the basis of the analysis following conclusion are drawn:

- The in-place analysis indicates that the platform remains generally satisfactory under operating load conditions. However, under extreme storm loading, higher unity check values are observed in selected tubular joints, with some joints exceeding the permissible limit. This shows that the extreme environmental load condition governs the reassessment of jacket joint capacity.
- The strengthening check using grout filling showed significant improvement in the capacity of several overstressed joints. For example, the unity check of joint 303X reduced from 1.63 to 0.945 after grout filling, indicating that grout filling can be effective for moderately overstressed joints. However, joints 4103 and 4102 remained critical even after grout filling.
- The pushover analysis showed that the jacket platform possesses adequate reserve

strength against global collapse. The minimum obtained Reserve Strength Ratio was 1.80 for the 135° storm direction, which is higher than the required value of 1.60 for high exposure category platforms. These results show that although some joints are locally overstressed, the platform as a global structural system has sufficient redundancy and reserve capacity to sustain the extreme load conditions.

- For the most critical joint 4103, a mechanical friction-grip clamp with splice connection was studied as a retrofit solution in IDEA StatiCa. The connection satisfied all component checks. The maximum utilization was observed in bolts, with a value of 87.2% and weld utilization of 76.8%. The plate stress checks showed that the maximum equivalent stress was about 287.5 MPa, while the local deformation remained within the allowable limit. The buckling analysis also showed a high first buckling factor of 43.85, indicating adequate stability of the clamp arrangement.
- A separate ring stiffener model was also studied for the chord–brace joint. The comparison between unstiffened and ring-stiffened models showed clear improvement in local stress distribution. The equivalent stress in member 4103L reduced from 355.3 MPa to 286.9 MPa, giving a reduction of about 19.3% and which meet the permissible stress limit of 287.5 Mpa. The stiffener plates remained within acceptable stress limits, showing that the ring stiffeners effectively participate in load transfer and reduce stress concentration near the chord–brace intersection.
- The study also demonstrates that targeted strengthening measures such as grout filling, ring stiffeners, and mechanical friction-grip clamps can improve the adequacy of deficient joints without full-scale replacement of the jacket structure. This approach supports sustainable infrastructure management and aligns with UN Sustainable Development Goals, particularly SDG 9, SDG 12, and SDG 13, by promoting resilient infrastructure, efficient use of existing assets, reduced material consumption, and lower environmental impact.

5.3 FUTURE SCOPE

- Detailed fatigue reassessment of critical tubular joints may be carried out using spectral fatigue analysis or fracture mechanics-based crack growth assessment to estimate the remaining fatigue life more accurately.
- Corrosion effects may be included in future studies by considering wall thickness reduction, corrosion mapping, splash-zone deterioration, and time-dependent degradation of structural members.
- The pushover analysis may be improved by considering nonlinear soil–pile interaction, lateral soil degradation, and pile capacity checks for a more actualistic collapse and reserve strength evaluation.
- The proposed mechanical friction-grip clamp may be further studied for offshore installation aspects such as bolt pretension loss, surface preparation, friction coefficient variation, marine growth removal, corrosion protection, inspection access, and installation tolerance.
- Experimental validation or advanced finite element modelling may be carried out for the friction-grip clamp and ring stiffener arrangements to verify contact behaviour, load transfer mechanism, local stress concentration, and possible failure modes.
- The study may be extended into a complete Structural Integrity Management framework by linking reassessment results with inspection planning, repair priority, monitoring strategy, and future re-certification intervals.

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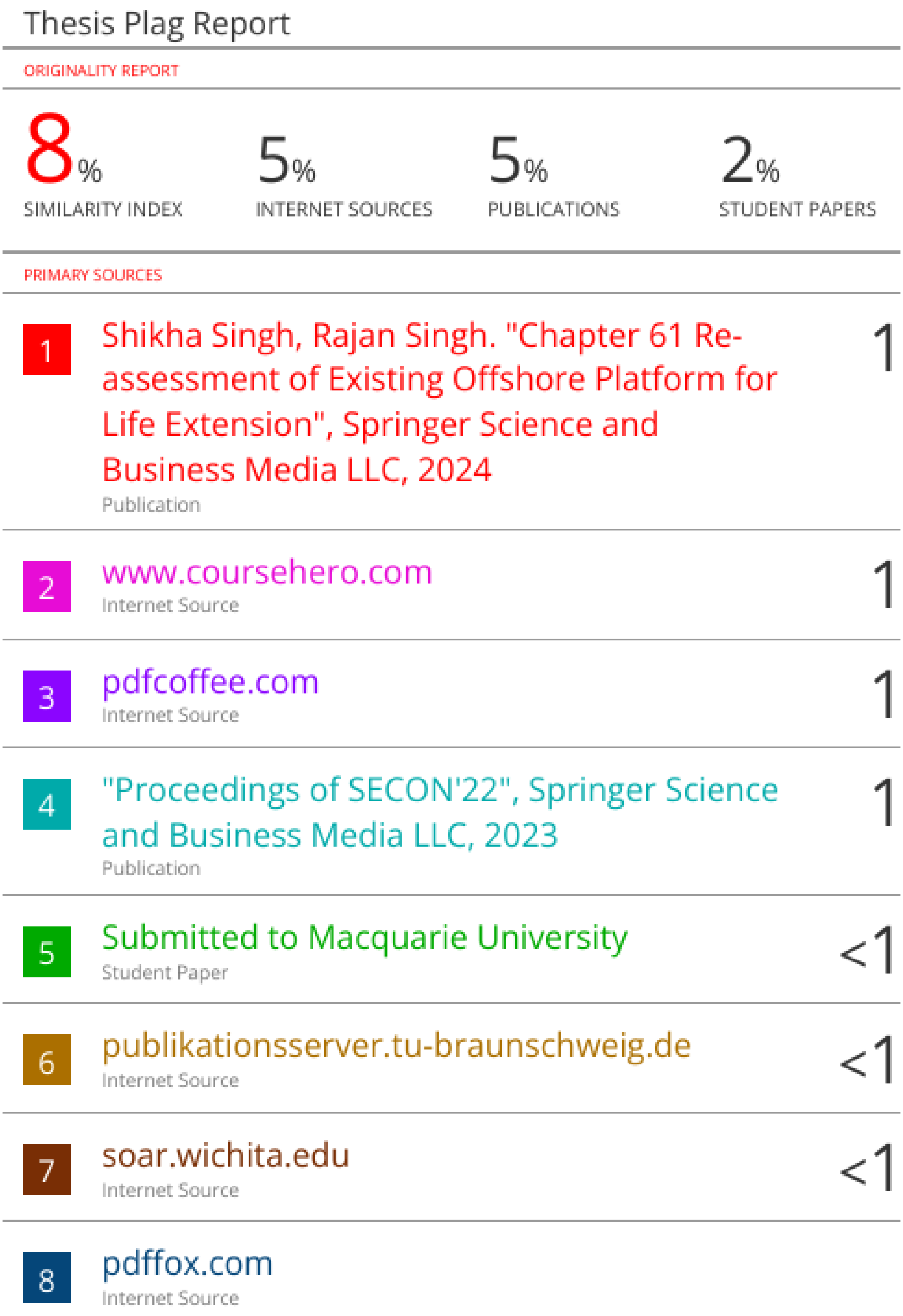
PLAGIARISM REPORT



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