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MASTER'S THESIS

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Abstract

Offshore structures subject to severe environmental loading may exhibit fatigue damage over time. In particular, fatigue cracks are a significant concern in welded components. Previous work has been published regarding the mitigation measures for many types of damage in steel structures. In addition, codes and standards, as for example, ISO, NORSOK, API, DNV, suggest suitable methods for mitigation and fatigue life improvement of welded components. Repair methods such as dry welding, structural clamps, remedial grinding, stop-hole drilling, and member removal can permanently or temporarily resolve the joint's fatigue damage. Mitigation methods like weld improvement techniques and grout filling can enhance the fatigue life of joints. The selection of repair methods is challenging as many parameters can influence the mitigation performance, such as crack size, location, and local detail geometry. Particularly, the repair method is different if the repair is to be performed in the atmospheric zone, splash zone, or in the submerged zone.

The thesis aims to study different repair methods for fatigue damage in welded components and compare in terms of applicability, time of work, cost, fatigue life gain, and work deployment process. Analytic hierarchy process and Multi-criteria dimensional analysis are used to study the influence of selection criteria while choosing the suitable mitigation method. Case studies are performed based on the assumption of the crack size and location to select suitable mitigation measures. The conclusions are drawn regarding the selection criteria and work execution process.

Acknowledgment

This thesis is part of the study in order to complete my Master's degree in Structural Engineering with a specialization in Civil Engineering Structures at the University of Stavanger. The thesis was done in the spring semester of 2021.

I would like to express my gratitude to my supervisor, Professor Gerhard Ersdal, for all the support, useful comments, and remarks throughout the learning process of the thesis and for giving me the opportunity to work on this topic.

I would like to thank my co-supervisor, Mostafa Ahmed Atteya, for his assistance. His advice throughout the thesis, sharing his knowledge with many valuable comments was tremendously helpful.

During this period, I had to gain knowledge about offshore structure damage, review of literature and code on damage assessment, mitigation measures and their selection criteria, and work deployment process. All the guidance was excessively helpful to complete my task.

Finally, I would like to thank my family and friend for their support and motivation.

Devendra Subedi

Stavanger, June 2021

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List of abbreviations

AHP	Analytic Hierarchy Process
API	American Petroleum Industry
C.I	Consistency Index
C.R	Consistency Ratio
DNV GL	Det Norske Veritas Germanischer Lloyd
FCAW	Flux Cored Arc Welding
FRP	Fiber Reinforced Composites
GMAW	Gas Metal Arc Welding
GTAW	Gas tungsten Arc Welding
HSE	Health and Safety Executive
MCA	Multicriteria Analysis
MMS	Mineral Management Service
MPI	Magnetic Particle Inspection
NDT	Non-Destructive Test
ROV	Remotely Operated Vehicle
SCF	Stress Concentration Factor
SIM	Structure Integrity Management
SMAW	Shielded Metal Arc Welding
SMR	Strengthening Modification and Repair

Chapter 1: Introduction

1.1 General

Offshore structures are constructed below or above the continental shelves or slope. These structures are of various shapes and sizes and with various purposes as well. Mostly, the structure is constructed for extracting oil and gas products. Those structures for oil and gas purposes are situated either in shallow depth or in the deep ocean. The condition for constructing these structures depends on the water depth and environmental factors *(Dehghani and Aslani 2019)*. These offshore structures are continuously exposed to:

- The corrosive environment of the sea which can cause corrosion and erosion.
- Active environment waves and wind load may cause fatigue cracking and buckling.
- Accidents and incidents cause physical damages *(Sharp and Ersdal 2021)*.

When we review the history of offshore structure construction, the earliest structure for oil drilling was constructed in 1887 on the coast of southern California near Santa Barbara. The structure was simply a wooden dock fitted with a vertical rig for drilling the seabed. Several platforms made of wood were constructed in Caddo lake, Louisiana, during 1911 and in Maracaibo, Venezuela, in 1927. Later, the realization of the effect of marine growth in timber and its effect on lifetime leads to the replacement of timber in late 1940 *(Wilson 2002)*. Various types of offshore platforms were introduced over many years. Among them, the prosperous fixed type offshore platform was a wooden one and used pure oil and superior oil. It was constructed in 1937 with a distance of 1 mile from the coast, and the depth of water was 4.3m, respectively. In mid of 1940, two different platforms were introduced in the Gulf of Mexico. One was constructed at the Louisiana coast, which was 18 miles away from the coast and 5.5m deep in 1946; another one was also 18 miles away from the coast and 6.1m deep in the Louisiana coast in 1947. In 1969 Norway discover the Ekofisk field by Philips petroleum. Now, the Ekofisk field is one of the important oil-producing sectors in Norway *(Ersdal, sharp et al. 2019)*.

There is a high necessity of life extension and repair in offshore structures for different regions such as the Gulf of Mexico, North Sea, Australian Water, etc. It is believed that some of the structures have passed their design life and are still needed for continued production. Offshore structures, various types of marine and underwater structures need repair and re-strength *(Dehghani and Aslani 2019)*. Materials that are exposed to under water environment mostly get damage either by corrosion or due to fatigue. Various loads are involved in the water, such as Environmental load, cyclic load, ice load, etc. These loads reduce both the static and fatigue life of the structure. Life extension and repair solutions must be employed to overcome these difficulties. It is important to mitigate the problem in an offshore jacket structure to extend the lifetime without failure or risk to structural integrity *(Hemashrif 2018)*.

Fatigue and corrosion are the main causes of damage in fixed steel platforms. In 1965, an offshore platform, Sea Gem was collapse due to fatigue and brittle failure of the suspension system. In the Gulf of Mexico, most of the failures has occurred during the hurricane. In 1992, Andrew hurricane passed across the platform, causing damage to twenty platforms *(Ersdal, sharp et al. 2019)*. Besides several reasons are there for offshore failure that needs to be repaired. The main intention of repair is to increase the structure's static and fatigue life, minimize the damage, reduce the life cycle cost, and ensure the safe operation of the structure.

Fatigue cracking generally occurs at the weld toe of tubular joints. Fatigue crack needs to be repaired to maintain the structural integrity of the structure. Removal of those fatigue cracks can be done either by cutting out the crack or by the mechanical method of strengthening. The selection of the method depends upon the characteristics of the crack.

This paper reviews the different literature and studies regarding repair methods for fatigue damage and fatigue life enhancement of the tubular joints. Furthermore, the selection of repair methods is made as per their applicability, fatigue life gain, cost and time of work, work deployment process, and the use of Analytic Hierarchy Process for Multicriteria Dimensional Analysis of those criteria followed by case study work.

1.2 Objective

Many of the offshore structures have exceeded their design life. For example, more than 50% of offshore operating structures have passed their original design life in GOM, Norwegian continental shelf, and UK continental shelf. Hence life extension is a necessary issue for controlling the structural integrity of the structure for extending the design life *(Dehghani and Aslani 2019)*.

The objectives of the thesis are:

- To review the literature on different damage scenarios for steel structures and tubular joints.
- To perform the literature review on repair assessment of fixed offshore platforms and evaluate the different repair methods for fatigue damage in tubular joints.
- Selecting the repair method for different scenarios and situations and perform the AHP method of project management for hierarchy system and multicriteria analysis along with the case study work.
- To review about work execution process, deployment method, and use of ROV.
- To compare mitigation methods for fatigue cracks according to the applicability, fatigue life gain, work deployment, time and cost of repair work, and so on.

1.3 Scope of work

This thesis is limited work for the fixed offshore platform made of steel jacket especially related to tubular welded connections and joints. The study of damage type is related to fatigue damage that can possibly occur at tubular welded joints. All the mitigations measures, their comparison, selection of the suitable methods are related to repair the fatigue crack and fatigue life enhancement of the joints. The highlighted mitigation methods are Dry welding, Structural clamp, Grinding technique, Grout filling work, Hole drilling technique, and weld improvement method. The selection criteria of mitigation methods are limited to the applicability, fatigue life gain, time of repair, cost of work, and work deployment process.

1.4 Structure of the thesis

Table 1.1 shows the main outline structure of the thesis.

Chapter 1: Introduction • Introduction to thesis • Scope and objectives of work
Chapter 2: Background and Theory • Damage assessment in steel structure and tubular joints. • Fatigue damage and assessment method
Chapter 3: Literature Review • Repair of the fixed platform • Fatigue crack repair of tubular joints • Codes and guidelines for crack repair method.
Chapter 4: Methodology • Repair method for fatigue crack at tubular joints • Fatigue life enhancement method
Chapter 5: Selection of the technique • Analytical Hierarchy Process method and Multicriteria Dimensional analysis for selecting the repair method • Case study for fatigue crack repair
Chapter 6: work execution • Work execution process by divers and ROV for different repair method • Literature review on work execution
Chapter 7: Comparison and conclusion • Comparison of fatigue damage mitigation method according to the applicability, strength, time cost, etc.
Chapter 8: Conclusion and summary • Conclusion and summary of work.

Table 1.1: Structure of the thesis

Chapter 2: Background and theory

2.1 Fixed steel offshore structure

The offshore structure consists of primary and secondary structures. The primary structure is defined as the structure which supports the platform and the deck. In comparison, secondary structures are the part besides primary structures such as caisson, conductors frame.

Fixed steel structures design depends on the subsystem such as deck and foundation. The jacket top part dimension depends on the deck area governed by the number of wells and rigs as well as production capacity *(Clauss, Lehmann et al. June 1991)*. Besides, various load factors affect the design of structures such as gravity loads, dead load, live load, drilling load, and environmental load such as wind loads, wave loads, ice load, seismic load, and so on *(Rajju Wankhede 2019)*.

Tubular member and Tubular joints in the steel structure

The different members of steel jackets are mainly connected by welding. These tubular connections are highly sensitive to fatigue crack and damages mostly at the weld toes. Tubular members are the main load-bearing member in the steel jacket platform. Various types of members such as Circular hollow sections, square hollow sections are welded to form the tubular joints. The connection and fabrication work for the square section is easier for the submerged part but, circular sections are preferred more over the square section due to their low drag coefficient and regular symmetrical cross-section, which has no sensitivity towards lateral loads*(Rodriguez-Sânchez march 1999)*. A typical example of fixed steel platform is shown in figure 2.1, and an example of K joints is shown below in fig 2.2 where two typical brace members are connected to a chord member at a distance gap of "g." crown toe and crown heel is the place of the joints in the member.

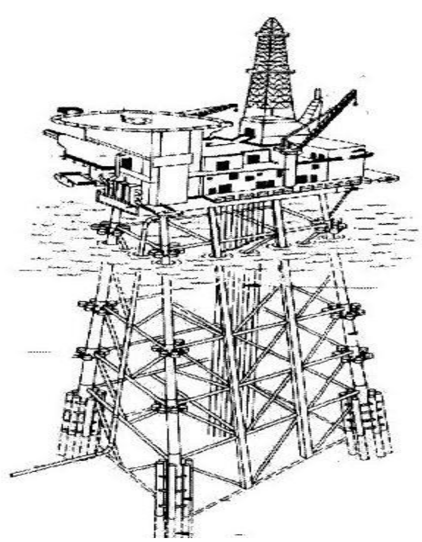

Fig 2.1: Fixed steel jacket platform *(zribi, lautairi et al. November 2003)*

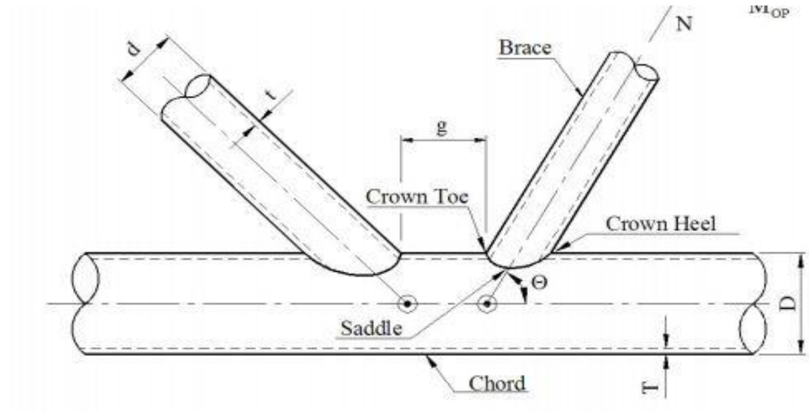

Fig 2.2: K joints in offshore jacket *(Dong, Moan et al. 2011)*.

Stresses in tubular joints:

The stress present in the joints is nominal stress, deformation stress, and notch stress. Nominal stress is originated from an external load applied, which produces stress on the jacket. Deformation stress occurred around the intersection of the chord with the brace member, and the notch stresses are the result of welding and its geometry *(Rodriguez-Sânchez march 1999)*. Figure 2.3 shows the stress in joints.

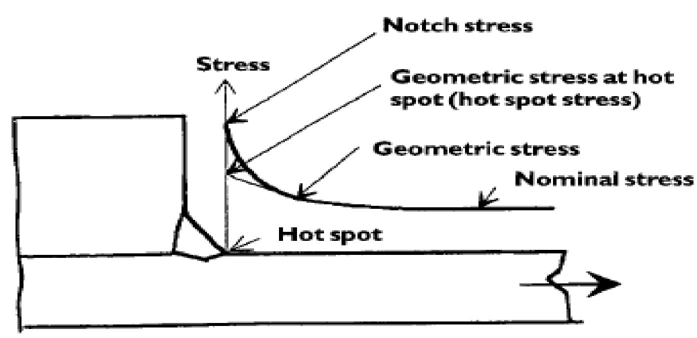

Fig 2.3: stress distribution in a welded connection *(Haagensen 1997)*.

2.2 Literature on Damage assessment of steel structures

"Repair to North-sea" by UEG 1983

"Repairs to North-sea offshore structure- a review" is a report prepared by UEG (1983) inspect 61 different cases of damages in North-sea. The various damages were recorded, such as Fatigue failure, dropped object, vessel collision, installation damage, design upgrading, and so on. Forty-one damages were involved in the primary structure, and 18 damages were present in the secondary structure, and two damage cases were on both structures. As per the report, most of the damage scenario was due to fatigue failure and collision. The overall data is shown in table 2.1.

Causes of damage	number of cases
Dropped object during installation	4
Dropped object during other time	5
Collision	17
Installation damage	4
Fatigue failure	17
Design upgrading	7
Welding fault	1
Concrete construction	1
others	5

Table2.1: damage causes and number of cases *(UEG 1983)*

"Review of repair to offshore structure and pipelines" by MTD 1994
The Marine Technology Directorate (MTD) present a report on "Review of repair to offshore structure and pipelines" in 1994 about several damage cases. The report includes both steel and concrete offshore structure. In steel, 158 different damage cases were detected and 14 different damages in the concrete structure. As per the report, out of 158 different damage cases in steel structures, 39 damages were recorded as fatigue damage. Besides, vessel impact was the second major cause of impact in the report, which was 36 cases in number. Table 2.2 shows the various damage case and their number of incidents as per the MTD report

Cause of damage	Number of incidents
Fatigue	39
Vessel impact	36
Dropped object	14
Fabrication fault	12
Installation fault	12
Corrosion	10
Design fault	9
Operating fault	4
Design upgrade	11
Others	8
unknown	3

Table 2.2: causes of damage in steel structure (*MTD 1994*).

A review paper on "Reassessment issue in life cycle structural integrity management of fixed steel installation" on 21st international conference of Offshore Mechanics and Arctic Engineering on June 2002 shows the causes of damages of 174 platform where 180 incidents were recorded in period 1972-1991.

Out of 180 incidents, 71 incidents were due to boat impact, and 46 impact were due to fatigue. Table 2.3 shows the overall incident recorded by the report.

CAUSE	DAMAGE (JACKETS)							
	Severance	Through crack	Dent (>50mm)	Bow (>100mm)	Tear	Hole	Crease	Total
Boat impact	10	13	22	23	1	2	-	71
Dropped objects	3	2	6	-	1	-	-	12
Fatigue	5	41	-	-	-	-	-	46
Fatigue from fabrication defect	1	11	-	-	-	-	-	12
Installation		10	2	2	-	2	1	17
Other / unknown	1	2	13	1	1	4	-	22
Total	20	79	43	26	3	8	1	180
No. of repairs								105

Table 2.3: damage incidents occur in the period 1972-1991 *(A. Stacey 2002)*.

P.J. Haagensen (NTNU) in 1997 on paper "fatigue of tubular joints and fatigue improvement methods" shows the various damage causes like fatigue, vessel impact, dropped objects, installation faults, fabrication faults, design upgrade, corrosion, and so on during period 1974 to 1992. The contribution of fatigue damage was 24.7%, which was the most serious recorded damage in between those periods. Figure 2.4 is the percentage bar diagram of the recorded damage between 1974 to 1992.

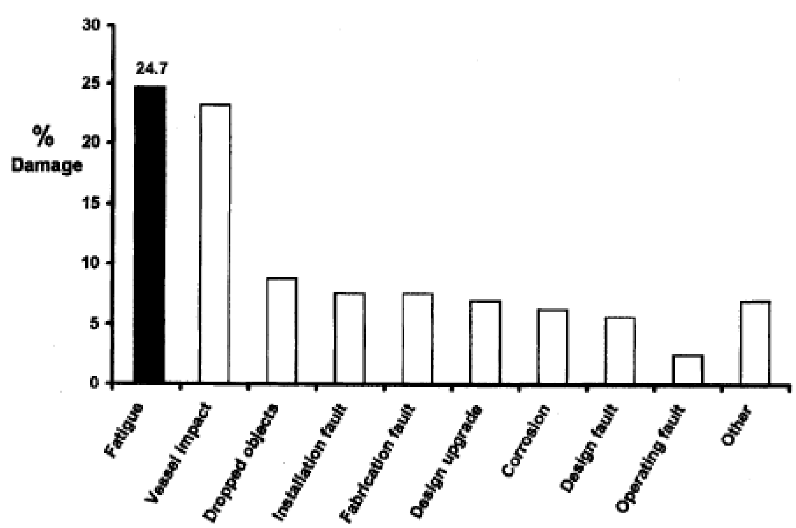

Fig2.4: damage to north sea structure during 1974-1992*(Haagensen 1997)*.

A book by M.M.K lee on " Fatigue, fracture mechanics and defect assessment of tubular structures" from the University of Wales, Swansea U.K. shows the data of damage scenario in the north sea between the period 1974-1992 which states that the cases of fatigue damage are 24.9% followed by second highest damage scenario of vessel impact by 23.2%. Figure 2.5 shows the rest of the data:

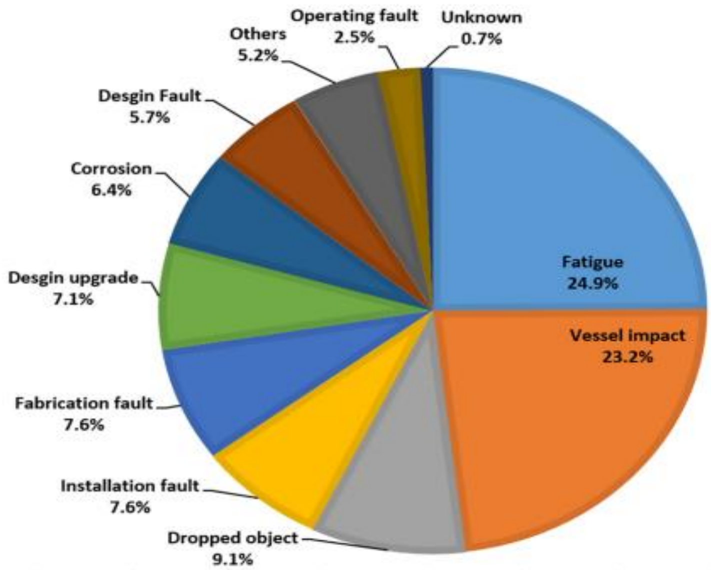

Fig2.5: damage assessment in the north sea between 1974-1992 *(Lee 1998)*

2.3 Damage in tubular joints

In the previous section, various types of damage cases were reported on the basis of literature. So, damage can be classified as mechanical damage, defect in weld or joints, corrosion damage, or non-structural components damage. Mechanical damages include dents, gauge, deflection from the original axis, full separation of the member due to cracking. Dent is the change in the shape of the structure without change in the wall thickness of the tubular member. Similarly, the gauge is the change in structure along with the change in the change in wall thickness. The reason behind these damages is due to fatigue loading, collision, vessel impact, or dropped object or from installation fault. Fatigue crack starts from the joining point of chord and brace member, and the reason is due to the undercut and defect in the weld geometry. The various damage scenario for fixed platform steel jacket structure are listed below:

- Fatigue load
- Vessel impact
- Dropped objects
- Installation and fabrication fault
- Corrosion
- Marine growth
- Design and operating fault
- Welding fault etc. (Sharp and Ersdal 2021).

Among all the damages, fatigue loading exerted by wave and wind action is the main loading experienced in the structure. So, fatigue failure and fatigue crack is the major concern for offshore structure these days. The repeating force from the wind and the waves decreases the service life of the joints *(Dehghani and Aslani 2019)*. Fatigue cracks are mostly seen close to the splash zone. Other locations of fatigue cracks are such as weld that join top submerged horizontal framing that provides lateral support to well conductor pipes to the jacket in drilling platform *(RodrÍGuez-SÁNchez, RodrÍGuez-Castellanos et al. 2011).* The figure 2.6 and 2.7 shows the damage of joint by hurricane Katrina and Rita.

Fig 2.6: fatigue damage of horizontal member of East Cameron Area platform (ENERGO May 2007).

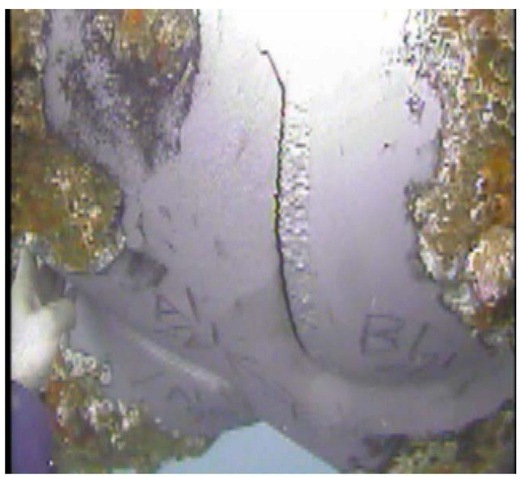

Fig 2.7: damage of X brace member of Grand Isle Area platform *(ENERGO May 2007)*

2.4 Fatigue damage of joints

Various loads are involved in the offshore structures, such as gravity load and environmental load. Continuous cyclic loading is one of the major reasons for fatigue damage. The fatigue loads may affect the member, especially the joints and the connection. Fatigue cracks are mostly seen in the joint and welded connections. There are three phases of fatigue crack, i.e., Initiation phase, crack growth phase, and fracture *phase (Besten 2018).* The figure 2.8 and 2.9 shows the phase of the crack from initiation to fracture phase.

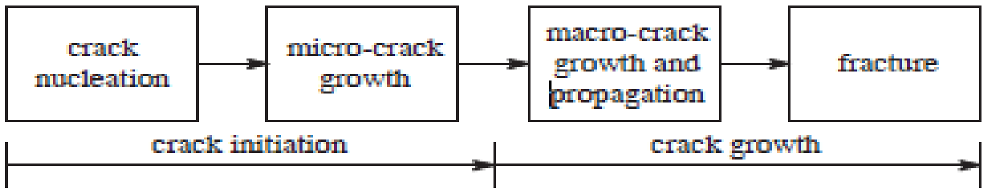

Fig2.8: fatigue damage process *(Besten 2018)*.

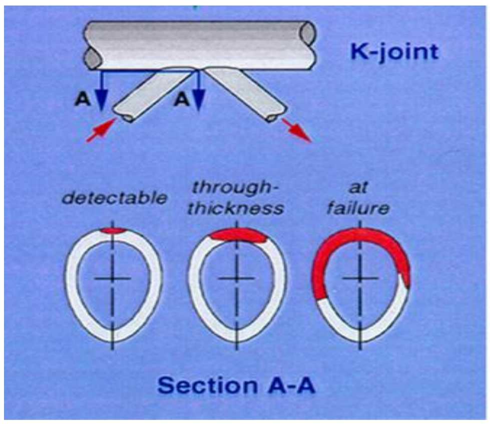

Fig2.9: crack growth at K joint *(Dong, Moan et al. 2012)*.

The result of fatigue failure starts with through-thickness cracking at the welded joint. Later the crack can cause a loss of stiffness in the part of the structure. This result can lead to the structure being loaded more heavily that can cause more rapid fatigue crack, also called multiple cracking in the joints. Historical data shows a high probability of fatigue crack underwater with an annual probability rate of 2 x 10^{-5} *(A. Stacey 2002*). The main reason for low fatigue strength in the joints is high local stress at the weld, which generates due to the shape of the component and weld toe geometry. Besides, the defect in the weld toe in the critical region also results in high stress *(Haagensen 1997).*

Factor affecting the fatigue life of the joints

As the stress in the joint includes nominal stress produced by an external load, deformation stress, and notch stress due to weld geometry. Notch stress is more concentrated on the weld surface, due to which crack starts propagating from the surface. The various factor affecting the fatigue life of welded connection depends upon,

- Applied stress
- Residual stress
- Environment
- Defect, shape, and size
- Notch severity *(Rodriguez-Sânchez march 1999)*.

2.5 Methods for fatigue assessment

Fatigue assessment can be done in two way:

i. S-N approach
ii. Fracture mechanics approach

The S-N approach includes the Hot Spot Stress method, Nominal Stress method, and Notch Stress method.

Hot spot stress method: This method has been widely used in the analysis of results from the test of tubular joints. The three main stress involved in the joints is Notch stress, Geometric stress, and nominal stress. The sum of nominal stress and geometric stress is equal to the notch stress, which is maximum stress in the joint. The main causes of stress in tubular joints are:

- Basic stress response of joint due to global action of remote applied load (nominal stress)
- The bending of the tube wall to maintain compatibility between the member generates geometric stress.
- High local stress near the intersection lines between number where the stresses are influenced by weld shape *(Haagensen 1997)*.

The relationship between nominal stress, stress concentration factor and hot spot stress is given as:

$$\sigma_{\text{hotspot}} = S.\text{C.F} * \sigma_{\text{nominal}} \text{.............................(2.1)}$$

Where $\sigma_{\text{hotspot}}=$ Hotspot stress, $\sigma_{\text{nominal}}=$ Nominal stress, and S.C.F= stress concentration factor *(Milana, Banisoleiman et al. June 2016).* The S.C.F factor is measured by using strain gauge measurement or by finite element analysis. Thus, obtained Hot spot stress is validated by the S-N graph for different types of joint and loading cases.

Notch stress method: The notch stress method is also referred to as the local stress or strain method. The stress used in this method is the notch stress that can be defined as peak stress at the root of weld or notch *(Giulia, Kian et al. 2016*). The relation is shown in the equation below:

$$\sigma_{hotspot} = K.\,\text{SCF}.\,\sigma_{nominal} \text{..........................(2.2)}$$

Where, SCF is the stress concentration factor, K is the weld stress concentration factor, and $\sigma_{nominal}$ is the nominal stress.

Nominal stress method: Nominal stress method is another way of S-N approach to estimate fatigue life and damage. The method is based on the number of cycles N for different stress ranges *(Keprate and Ratnayake 2015).* The equation is given as:

$$S_m \cdot N = C \text{................................(2.3)}$$

Where N and C are the constant, which depend on material type, geometric configuration, and environmental settings.

Fracture mechanics approach: This method assures the crack that exists in the structure and employing the deterministic crack growth model to predict the remaining life of the structure *(Giulia, Kian et al. 2016)*. The three important variables for this approach are flaw size, fracture toughness, and applied stress. This method is based on fracture mechanics that cover crack growth independently from the S-N approach and use when the S-N approach gives inappropriate results (Keprate and Ratnayake 2015). The Paris Law model equation is shown below:

$$da/dn = c\,(\Delta k)^m \quad \text{..............................} (2.4)$$

where da/dn= crack growth rate

Δk= The range of stress intensity factor

C and m are two parameters that can be fitted once two points are known *(Giulia, Kian et al. 2016)*.

Miner's rule: Miner's rule is the most popular one due to ease of implementation but difficulty in calibrating more sophisticated models *(Giulia, Kian et al. 2016)*. The yearly fatigue damage calculation by Miner's rule is given in the equation below:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \quad \text{..............................} (2.5)$$

Where D is cumulative of yearly fatigue damage,

n_i= Number of stress cycle in stress block I,

N_i= The number of cycles that lead to failure at a constant stress range $\Delta\sigma i$

K= Number of stress blocks.

Chapter 3: Literature review

3.1. Repair methods of fixed Platform steel offshore structure

A large amount of literature on the repair of damage structure are published for different types of platform. Some of the literature related to repair method of all types of damage in steel structures are reviewed below:

“Assessment of repair technique for ageing or damaged structures.” by A.F. Dier *(MSL and Dier 2004)*

MSL service corporation proposed a report in November for repair techniques on behalf of Mineral Management Service (MMS). The main objective of the project is to review data and information on the basis of interviews and discussion with operators, designing houses, authorities and will be made available for study and repair implementation work. The report consists the information regarding different repair techniques in the offshore structures, including all possible literature, and will be available as new data or source of information. Thus, obtain a report will be used as a review of work to make the conclusion on the present state of the art of work. This report also contains the diver less technology for work execution in offshore repair work.

The document consists of two parts:

Part 1: This part includes the executive summary, objective, initiation of work, assessment of SMR scheme selection technique, designing, and implementation work.

Part 2: Part explains the work process of every repairing technique, such as Description of repair technique, Limitation of work, Design approach, Installation and fabrication, Previous offshore application of the techniques.

The repair method discussed in the report are:

- Member removal
- Dry and wet welding
- Structural clamp
- Grout filling of member and joints
- Weld improvement techniques
- Remedial grinding
- Bolting
- FRP composites
- Other miscellaneous techniques

The overall report is about:

- Initiating event
- Assessment
- SMR technique
- Design

- Implementation

A comparison of various SMR techniques by the report is shown below in table 3.1.

Technique	Used offshore	Data available for		Equipment needs	Offshore installation timescales	Onshore fabrication costs	Load penalties		Relative post installation inspection requirements	Design guidance available
		Static strength	Fatigue strength				Weight	Wave load		
Dry welding	yes	yes	yes	heavy	very slow	high for habitat	none	none	low	yes
Wet welding	yes	yes	no	moderate	quick	none	none	none	low	yes
Toe grinding	yes	N/A	yes	low	moderate	none	none	none	moderate	yes
Remedial grinding	yes	yes	yes	low	moderate	none	none	none	moderate	yes
Hammer peening	yes	N/A	yes	low	quick	none	none	none	moderate	yes
Stressed mechanical clamps	yes	yes	yes	moderate	moderate	high	moderate	high	high	yes
Unstressed grouted connections	yes	yes	yes	moderate	moderate	low	low	low	low	yes
Unstressed grouted clamps without shear keys	yes	yes	yes	moderate	moderate	moderate	moderate	moderate	moderate	yes
Unstressed grouted clamps with shear keys	yes	yes	yes	heavy	slow	moderate	moderate	moderate	moderate	yes
Stressed grouted clamps	yes	yes	yes	moderate	slow	high	moderate	high	high	yes
Elastomer-lined clamps	yes	yes	yes	moderate	moderate	high	moderate	high	high	yes
Pressurized connections	no	yes	no	light	slow	moderate	low	low	low	no
Grout filling members	yes	yes	no	light	quick	low	high	none	low	no
Grout filling joints	yes	Yes	No	Light	Quick	Low	High	None	Low	no
Bolting	yes	yes	yes	light	moderate	low	low	low	moderate	yes
Member removal	yes	N/A	N/A	moderate	quick	none	none	none	none	N/A
Adhesives	yes	yes	yes	light	quick	low	low	low	low	no
Composites	Yes	Yes	yes	Light	quick	moderate	low	low	low	yes
Swaging	yes	yes	yes	moderate	quick	moderate	low	none	low	yes

Note: N/A=not applicable

Table 3.1: Comparison of different SMR techniques *(MSL and Dier 2004)*.

A report on strengthening Modification and repair of offshore installation by MSL *(MSL 1995*)

MSL report of Strengthening, modification, and repair of offshore installation was published in November 1995. The scope of the report is based on:

- Design and recommendation for SMR schemes
- The requirement of SMR technology
- Recommendation for design practice
- Data basis for selection of suitable SMR technique
- Diver less work execution of SMR work

The report consists of 7 parts explained as below:

- Part1: First part provides the executive summary, scope of work, and summaries of findings.

- Part2: second part includes the recognition of proper SMR schemes for related scenarios.
- Part3: This part includes the design and recommendation for offshore repair through which it can be used in the selection process or in design calculation.
- Part4: This part covers the background data and assessment for that topic discuss in part 3.
- Part5: This is the part related to clamp stud bolt load variation for clamp design work, laboratory test, and numerical analysis.
- Part6: this part explains the diver less implementation and work execution of SMR work.
- Part7: Bibliography

The repair method included in this report are as follow:

- Welding
- Weld improvement method
- Clamp technology
- Grouting of member and joints
- Bolting
- Member removal
- Adhesive and epoxy grouts
- Cold forming

"Repair to north-sea offshore structure" by UEG (UEG 1983)

UEG proposed a report in 1983 for the repair work in the northern sea. The report collects the data of sixty-one damages, out of which 41 damages were recorded in primary structure, 18 damages were recorded in secondary structure, and two damages were recorded in both structures. The report explains the causes of the defect, the repair method, difficulties, and recommendations for design and installation work.

The following repair method was included in the report:

- Welding- Habitat, cofferdam construction
- Wet welding
- Clamp technique- Friction clamp, grouted clamp, stressed grouted clamp
- Grout filling
- Bolting

"Review of repairs to offshore structures and pipeline" (MTD 1994)

The report was prepared by the Marine technology Directorate limited. After the UEG report in 1983 covers the various repair schemes and damage assessments on various structures, MTD prepared a report in 1994 with various damage assessment and repair methods. The report covers the assessment for steel structure as well as concrete platform and compliant structure. For steel structure, 158 different damages were detected and mostly affected due to fatigue, and vessel impact was found. Table 3.2 shows the execution of different repair methods along with the depth of the water presented by the MTD report.

The repair method included in the report are:

- Clamp technology
- Air weld
- Wet weld
- Grouted member
- Bolted and others repair

		Percentage of total for each band of water depth:							
Water depth, m	Number of incidents	Mechanical clamps	Grouted clamps	Air weld	Cofferdam weld	Hyperbaric weld	Wet weld	Grouted members	Bolts plates
0 & above	48	13	17	60	6	0	0	0	4
0 - 10	32	31	19	6	16	19	0	9	0
10 - 25	30 (2)	40 (7)	23	0	0	23	7	7	0
25 - 50	21 (3)	24 (5)	24 (5)	0	0	33 (5)	0	19	0
50 - 100	7 (1)	0	29	0	0	14 (14)	14	14	29
100 & below	6 (1)	33	0	0	0	33 (17)	0	17	17
Total	144								

Table 3.2: repair work along with water depth *(MTD 1994)*.

"Grouted and mechanical strengthening and repair of tubular steel offshore structures"(Shuttleworth 1988)

OTH 88 283 is the final report of the joint industry Repair Research Project finalized by Wimpey offshore Engineers and constructor limited funding with other organizations. The author R.G. Harwood and E.P. Shuttleworth prepared the report in five parts of the original report.

- Designers manual
- Engineering assessment of test data
- Test reports for are 1 to 5
- Test report of area 6 to 11
- Crack data

The mitigation method included in this report are:

- Grouted connection
- Grouted repairs
- Mechanical and stressed grouted repairs
- Grout filled tubular member

Each of these methods is explained in different categories such as application, factor affecting strength, fatigue, applied stress, and safety factors.

“ Underwater inspection and repair for offshore structures”(Sharp and Ersdal 2021)
The book is prepared by the author John V. Sharp (Cranefield University) and Gerhard Ersdal (University of Stavanger) in 2021. In this book, an assessment of damage and mitigation methods for both steel structures and concrete structures are included. The major structure damages are Fatigue cracking, Corrosion, Accidental damage. The inspection of these damages, monitoring and appropriate repair of these structures are explained in the literature. The mitigation method for fixed steel structures are:

- Grinding
- Remelting method
- Weld residual stress improvement method
- Stop holes and crack deflecting holes
- Welding
- Structural modification
- Doubler plates
- Clamp and sleeves
- Grout filling of tubular member and joints
- Bonded type repairs

A review on defects in steel offshore structures and developed strengthening techniques (Dehghani and Aslani 2019)
A review paper on defects in steel offshore structures is prepared by Ayoub Deghani and Farhad Aslani in 2019. According to the author, there is high demand for life extension of offshore structures in the different regions such as the Gulf of Mexico (GOM), Northern sea, Malaysian and Australian waters, and most of them have exceeded their design life. So, the author suggested the SMR technique such as Welding repairs, weld improvement technique, Clamp system, Grout filling, Member removal or load reductions, and fiber-reinforced polymers (FRP). The future challenge and conclusion made in the paper is fatigue loading by the wind and action are one of the main loading experienced on offshore structures. So, fatigue failure is a major concern for steel structures.

3.2 Fatigue crack and fatigue life enhancement Tubular joints

The following literature is related to the repair methodology of tubular joints especially related to fatigue damage:

“Repair to offshore installation, Background to section 60 of the guidance notes by HSE”(HSE May 1997)OTO 96 057 is the background document to section 60 of the Health and Safety Executive guidance note, originally referred to as OTH (89)308. The report was prepared by Techword Services in May 1997. The report consists of the repair for steel and concrete structures. The repair method for steel structures are:

- Welded repair for underwater work in different types of weld habitat and several welding processes.

- An alternative method for weldings such as Clamp, Grouted repair, Grout filling of members and joints.

Chapter five of this report explains the repair of the crack method as:

- Repair of surface crack by grinding.
- Repair of through-thickness crack by hole drilling.

"Fatigue performance of repaired tubular joints by Department of Energy"(Tubby 1989)
OTH 89 307 is an offshore technology report prepared by the Department of Energy by author P.J. Tubby in 1989. The report describes the test on welded tubular T joints in steel where fatigue cracks were repaired by the following methods:

- Repair welding after grinding
- Welding and followed by grinding
- Hole drilling and cold expansion
- Grinding alone

The objective of the report is to establish the ranking of repair methods in terms of residual fatigue performance *(Tubby 1989)*.

"Offshore fatigue crack repair by grinding and wet welding" ***(RodrÍGuez-SÁNchez, RodrÍGuez-Castellanos et al. 2011)*** is a paper published in Oct 2010 on technology to repair the fatigue crack at offshore joints by grinding and wet welding. First, the crack is repaired by grinding, and the groove of the grinded surface is filled with the wet welding procedure so that further crack does not propagate from the tip of the grind surface. Additionally, weld toe can be profiled for further fatigue life enhancement. The procedure of repair is:

- Crack removal by grinding
- Groove filling with the wet weld
- Extend fatigue life either by toe grinding or inducing compressive stress

In conclusion, the author state that the proposed procedure can reinstate the original fatigue life of a cracked repaired joint regardless of crack depth before repair *(RodrÍGuez-SÁNchez, RodrÍGuez-Castellanos et al. 2011).*

"Fatigue of tubular joints and Fatigue improvement method" (Haagensen 1997) is a review paper published in 1997 about the fatigue life enhancement method of the tubular joints. At the starting of the paper, the author shows the data as fatigue damage is one of the most prolonged problems in the northern sea in the period between 1974 to 1992. Besides, the paper reviewed the important parameters and conditions that determine the life of welded joints and explain the research development in fatigue design of the welded structure. The implementation of techniques like fatigue life improvement and life extension of fatigue damage structure were included in the paper. The repair methods are:

1. weld geometry technique:
    - weld profiling
    - weld toe burr grinding
    - weld toe remelting
2. residual stress technique: peening method.

"Underwater repair of fatigue cracks by gas tungsten arc welding process"(Rodriguez-Sanchez, Perez-Guerrero et al. 2014) is a paper published in January 2014 regarding the repair of fatigue crack with Gas Tungsten Arc Welding process. This technique is applicable for short depth crack of 5mm and can be done immediately after detection of the crack. For the implementation of work, a hyperbaric chamber is constructed as small as possible. This method can reinstall the original fatigue life of the welded joints *(Rodriguez-Sanchez, Perez-Guerrero et al. 2014)*.

3.3 Codes and guidelines mitigation method

NORSOK standards: The Norwegian petroleum industry develops NORSOK standards to ensure adequate safety, cost-effectiveness for petroleum industry development and operations.

NORSOK N-005: Condition monitoring of load-bearing structures

NORSOK N-006: NORSOK N-006 specifies the guidelines for the assessment of structural integrity of the existing offshore structure and should be used with standard N-003, N-004, and N-005. This is applicable for all types of offshore structures and contains ten sections on it. Figure 3.1 shows the assessment process flow chart for mitigation in a broad way. Chapter 7.6 include the improved method for fatigue life i.e.

- Grinding of crack up to 60% of plate thickness as long as grinding is performed in the limited area and completely remove the crack
- Hammer peening may also be used once at any specific location to reset the fatigue life to zero provided there is no evidence of cracking (N-006 2015).

The mitigation measures for fatigue crack according to NORSOK n-006 are:

- Reduce loading
- Reduce stress level by strengthening
- Reduce stress concentration by grouting
- improve fatigue capacity by fatigue improvement method
- perform controlled in-service inspection such that cracks are detected before they are through the wall thickness, and they can be removed by grinding *(N-006 2015).*

If through-thickness cracks are detected during inspection, other mitigations should be considered, such as installation of bolted or bolted and grouted clamps.

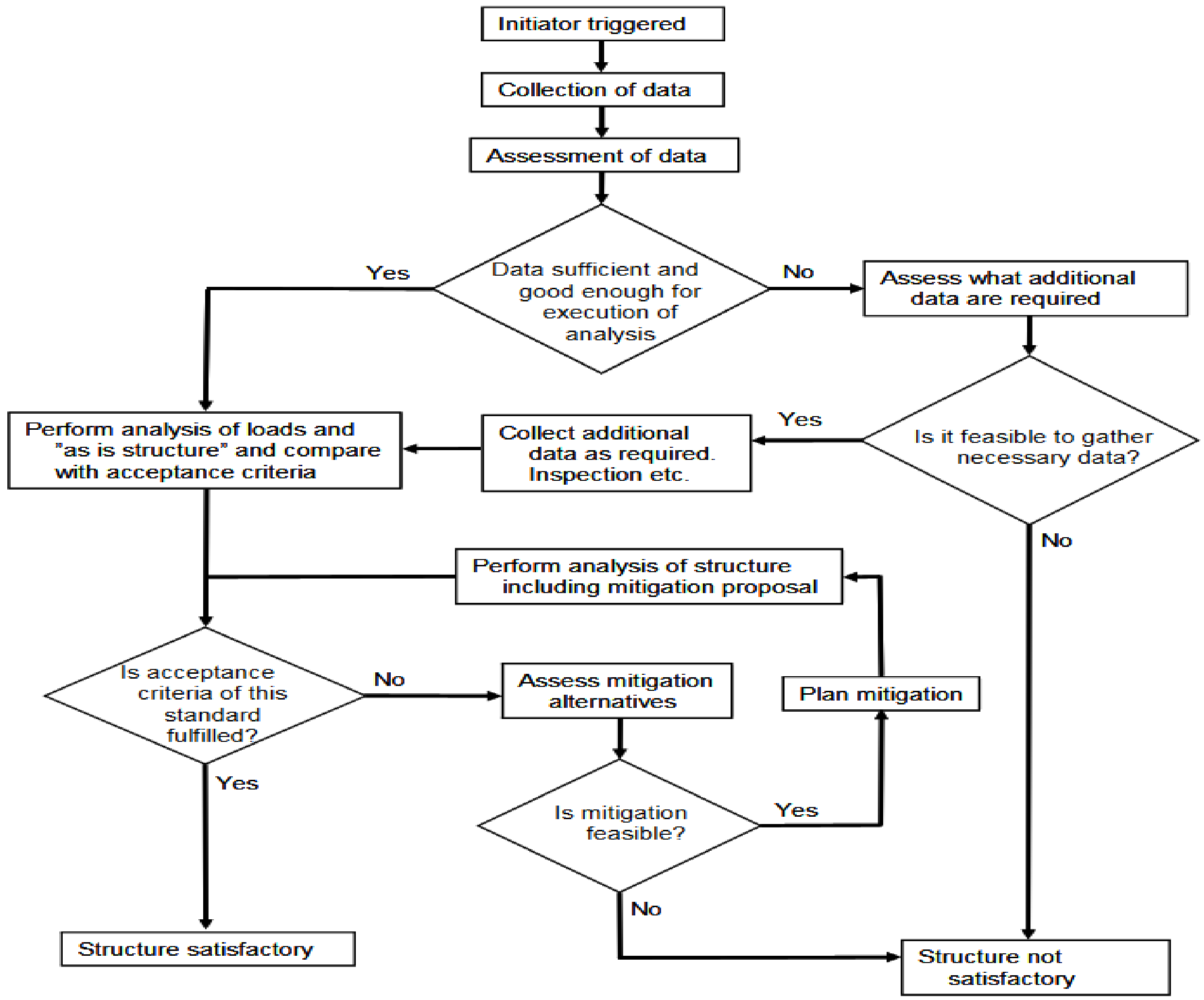

Fig3.1: Flow sheet of assessment process by NORSOK *(N-006 2015)*.

API standard: American Petroleum Institute (API) is working for more than 90 years and maintains nearly 700 standards and practices.

Strengthening modification and repair by API RP-2SIM "Structural integrity management of fixed offshore structures": There are various techniques mentioned in the standard. According to the standard, the SMR selection is made as:

- Damage removal: Component removal, Crack removal
- Load reduction: Gravity load, Hydrodynamic loading
- Local SMR: Grouting of the member, Grouting of joints, Structural clamps, Welding, Bolting, Adhesive and Epoxy grouts, Cold forming

- Global SMR: Leg pile annulus grouting, external bracing

Figure 3.2 shows the selection of SMR processes according to API standards.

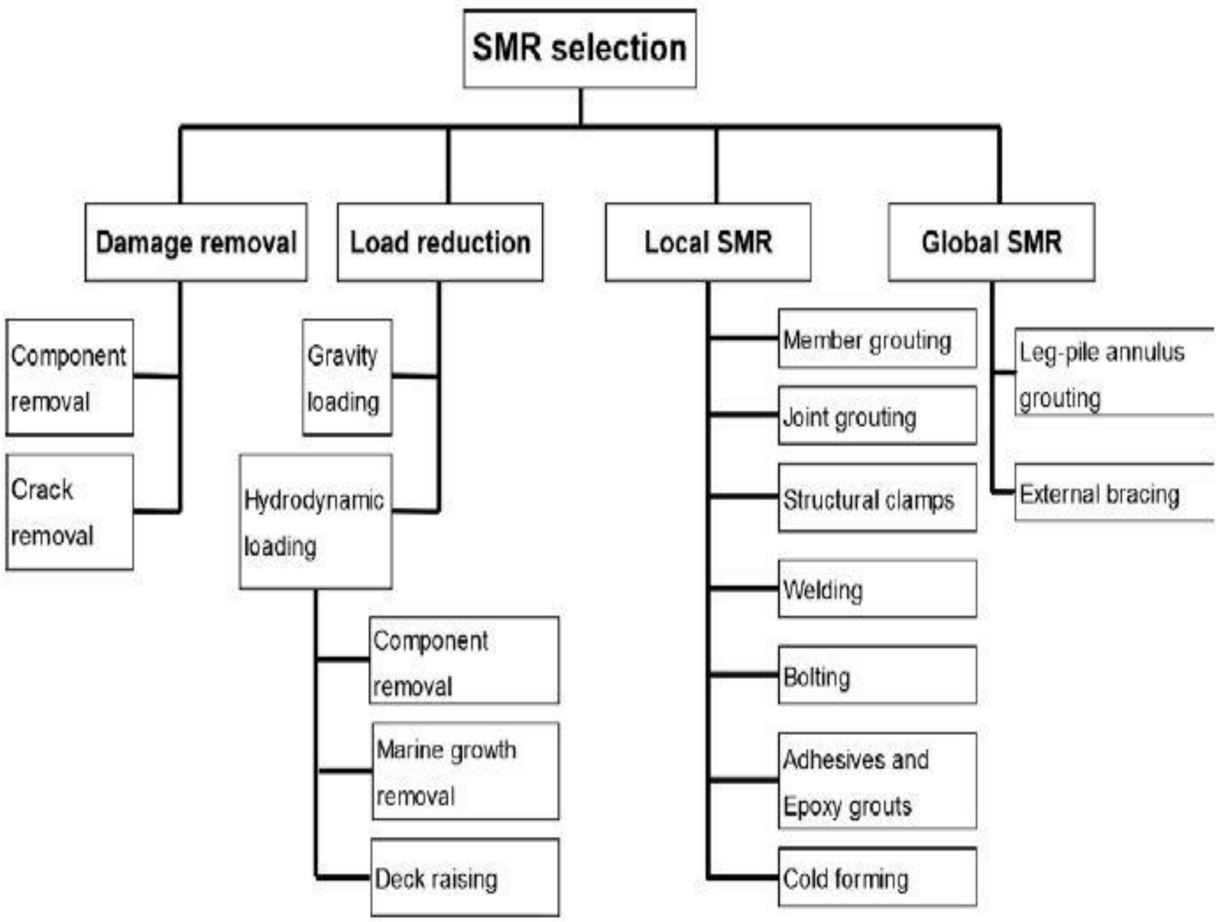

Fig 3.2: SMR technique selection process (API 2014)

DNV GL guidelines: DNV GL is two company Det Norske Veritas (Norway), and Germanischer Lloyd (Germany), merged together in 2013 to form DNV GL for quality assurance and risk management.

DNV GL-RP-C2303: This practice is related to the fatigue design of offshore steel structures. The practice recommends fatigue analysis based on fatigue test, S-N approach, and fracture mechanics. The aim of the fatigue design is to ensure the structure with adequate fatigue life. Section three describes the tubular joints and members, especially the stress concentration factor for tubular joints(*DNV-GL 2014)*. Section 7 includes the fatigue life improvement method of the joint such as:

- Weld profiling by machining and grinding
- Weld toe grinding
- TIG dressing
- Hammer peening method.

Section 8 of the guidelines describe the extended fatigue life of the structure where the evaluation is based on:

- Crack growth characteristics
- Reliability of inspection method used

Chapter 4: Repair methodology

4.1 Fatigue damage mitigation methods

Dry welding

Welding is an effective strengthening, modification and repair (SMR) technique that can be executed both in dry and wet surroundings. The main challenge is underwater welding. Figure 4.1 shows different ways of welding underwater *(Dehghani and Aslani 2019)*.

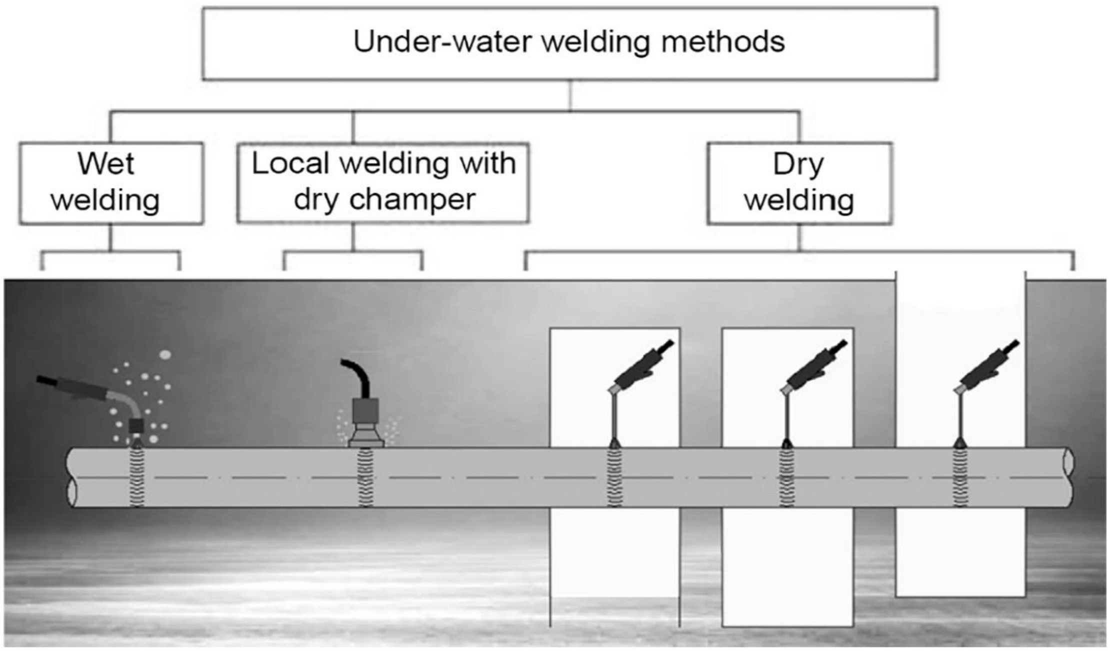

Fig 4.1: Underwater welding process *(Dehghani and Aslani 2019)*

The dry welding process is executed in a dry environment, either in one atmosphere or using hyperbaric chambers, as described below:

1. Dry welding at one atmosphere:

   In this method, a duplicate surface is constructed to provide a one-atmosphere environment to the structure that needs to be repaired. Further, this method can be executed in two ways:

i. Cofferdam construction: Cofferdam is a water-tight structure that covers the location in one atmosphere. Figure 4.2 shows the open-topped cofferdam structure for welding repairs. This method is preferred for repair welding in the splash zone *(Nichols and Khan 2017).* Cofferdam, especially open-top ones, are expensive in construction for greater depth than 15m (HSE May 1997). The reason behind this is the requirement for the cofferdam to resist different pressure across the wall, and at the bottom sealing. Signinificant wave forces are produced by shallow water cofferdams *(HSE May 1997)*.
ii. Pressure resistant chamber: In this process, the structure is surrounded by a chamber constructed as a pressure vessel. It can resist water pressure at a depth of repair location. At

first, the chamber is constructed, sealed well, and it is then dewatered and creates internal pressure to one atmosphere *(MSL and Dier 2004).*

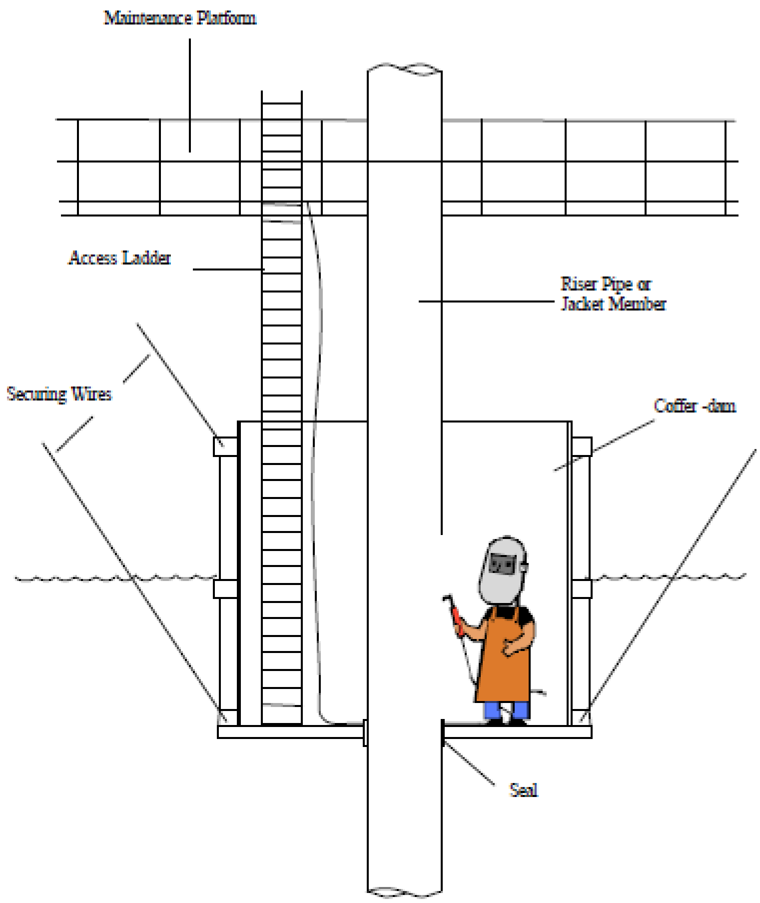

Fig 4.2: open top cofferdam *(MSL and Dier 2004)*

2. Dry hyperbaric welding:

This technique is a widely used repair technique for primary structure repair work. The work is performed in a closed working habitat which is dewatered by filling the habitat with a compressed gas at ambient pressure *(MSL 1995)*. The chamber is open to the sea at its base, allowing diver access. The gas composition inside the chamber should be controlled to limit the pressure of oxygen, nitrogen, and hydrogen *(Nichols and Khan 2017)*.

Welding process:

- For dry welding either at one atmosphere or using the cofferdam, all the normal welding processes can be used but mostly Gas tungsten Arc Weld (GTAW), Shielded Metal Arc welding (SMAW), and lesser extent, Flux Cored Arc welding is used (FCAW) (MSL and Dier 2004).
- For dry hyperbaric welding, mostly used methods are GTAW and SMAW, and sometimes FCAW and Gas Metal Arc welding (GMAW) is used.

Limitation and precautions of dry welding work:

- Use of cofferdam for welding repair, especially open-top greater than 15m deep, can be uneconomic *(HSE May 1997)*.
- It is very difficult to work and install habitat as well as cofferdam at splash zone due to wave current *(MSL and Dier 2004).*
- Hyperbaric welding may not be feasible to use around the complex joint due to the complexity of fitting and sealing the habitat *(MSL 1995)*.

Advantages and disadvantages of Dry welding:

Dry welding is a universally accepted technique. This method is important in repair work such as fatigue crack, non-fatigue crack, corrosion and dent. However, it is expensive and time-consuming to plan, design and construct.

Structural clamp

Structural clamps are used to transfer the load from an existing member through the clamp system to another member or across a discontinuity in the original member. The clamp can be made in a complex shape that covers nodal joints in two or three or more planes and is heavy in size. A repair clamp of 22 tones has been installed. The assessment or inspection after using structural clamp should be done so that crack will remain stable inside the clamp system *(MTD 1994).* The clamp is one of the versatile SMR techniques that can be used for various forms of damage, repair and retrofitting work. The clamp is also the workable method for connecting new components to an existing member. However, they need heavy equipment, precise design and inspection work, and are costly and requires significant onshore and offshore work hours *(Dehghani and Aslani 2019).*

A clamp is made in two or more segments that can be connected together by stud bolts. The main types of the clamp are:

1. Stressed mechanical clamp:

   The stressed mechanical clamp is also known as a friction clamp consisting of two or more segments that closely fit together with the help of long, high-stressed stud bolts. The friction is generated in the steel to steel connection due to the stress of stud-bolts. Thus, generated friction provides strength in the mechanical clamp. Hence, the strength of the mechanical clamp is dependent on the effective friction coefficient of the two steel contact surfaces. Figure 4.3 shows an example of typical stressed mechanical clamp use in offshore structures *(MSL 1995)*.

2. Unstressed grouted clamp:

   Unstressed grouted claps is a type of clamps in which the annulus between the grouted connection and the structure is filled with the grout. Load is transferred by the bond between the cementitious grout and the steel surface. The grouted clamp, also called sleeve connection, is suitable to repair complex nodes, as it allows for lager tolerances. Figure 4.4 shows an example of a typical unstressed grouted clamp.

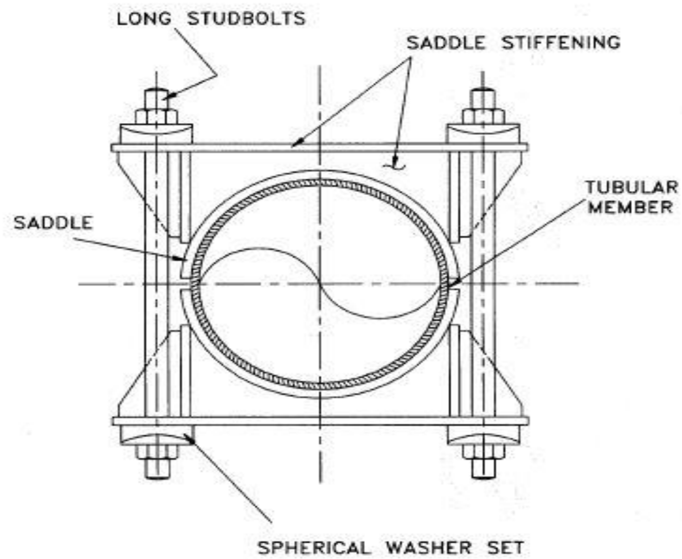

Fig4.3: stressed mechanical clamp *(MSL and Dier 2004).*

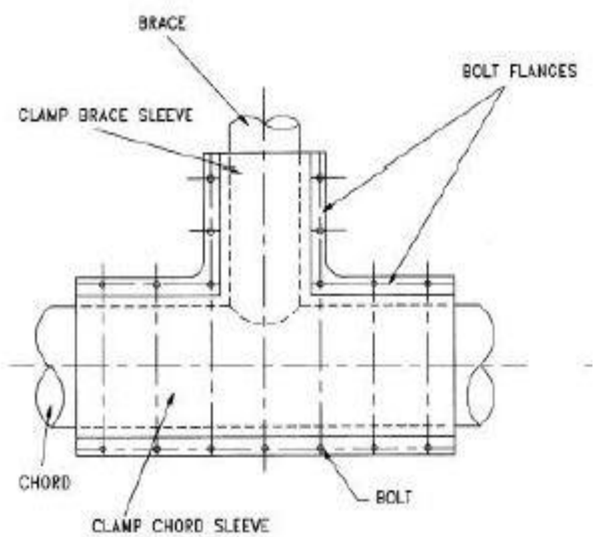

Fig 4.4: unstressed grouted clamp *(MSL and Dier 2004).*

3. Stressed grouted clamp:

The stressed grouted clamp is a hybrid of the mechanical and unstressed grouted clamp. A stressed grouted clamp is made by connecting two or more segments together through long stud bolts after the grout has been injected in the annulus between the clamp and the tubular member. Hence, both the grout and friction are significant for these clamps *(MSL and Dier 2004)*. So, the factor affecting the strength of a grouted stressed clamp are:

- Stressed grouted connection

- Grout strength
- Stud-bolt load design *(Harwood and Shuttleworth 1988)*

4. Stressed elastomer-lined clamp:

The stressed elastomer-lined clamp is similar to a stressed mechanical clamp, but the elastomer lining is used inside the clamp, as shown in figure 4.5. A thin neoprene sheet is used as a elastomer lining. The strength of this clamp is also due to the external stud-bolt load, which generates friction between the liner and steel interface. The liner used is flexible, so an elastomer-lined clamp has not to date been used to repair primary structures *(MSL and Dier 2004)*.

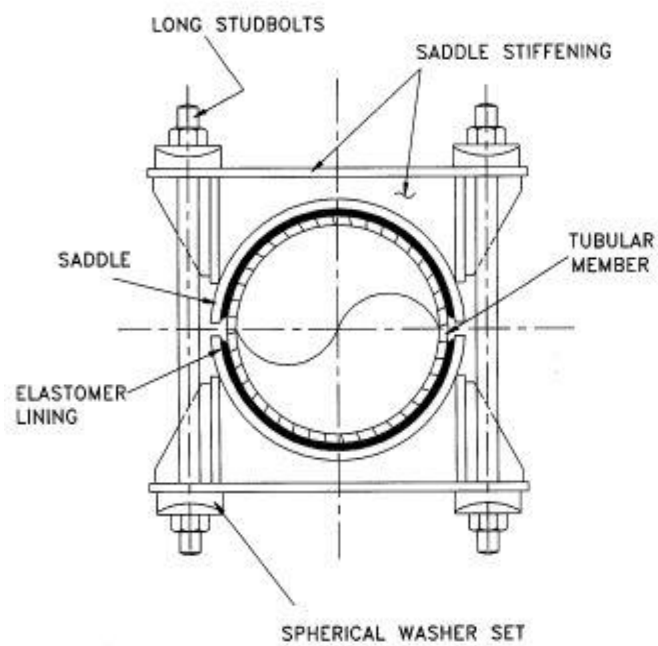

Fig 4.5: stressed elastomer line clamp *(MSL and Dier 2004)*

Limitation and precautions:

- A stressed mechanical clamp requires low tolerances and, hence, an accurate survey of the structure that need to be repaired. The clamp relies on steel-to-steel contact between the tubular member and clamp. As a result, they are not preferred for the repair of joints (MSL 1995).
- In stressed grouted clamp and unstressed grouted clamp, during the grouting period, grouted clamp or sleeve should not be subjected to undue loading or relative movement of the clamp member until the grout gains sufficient strength.

- All the clamped members should have sufficient strength to avoid crushing loads.
- Elastomer lined clamp cannot be used for fatigue damage repair of joints *(MSL and Dier 2004)*.

Advantages and disadvantages:

The comparative strength gain by the clamp system is higher and has high tolerance acceptability. Clamps are a versatile method for repairing any kind of damage in a offshore structure. The clamp an important techniques to resolve fatigue damage problems. However, the work is costly, heavy and time and cost of design are high *(Dehghani and Aslani 2019)*.

Remedial Grinding

Remedial grinding is a proven technique in which grinding equipment is used to excavate the crack from the weld joints. A smooth surface trench is excavated, as shown in figure 4.6. In addition, the use of burr grinding tool to remove vicinity of weld toe is a well-established technique to improve the fatigue strength. When the task is performed correctly, the process can remove the sharp slag intrusion that is intrinsic at weld toes. However, the grinding work changes the local geometry at the weld toe *(Tubby and Wylde 1990).* The grind-out surface need to be checked using a Non-destructive test (NDT), even if the traces of cracks have been removed or not. For deep cracks, grinding should not be carried out for more than 90% of the plate thickness *(MSL and Dier 2004)*.

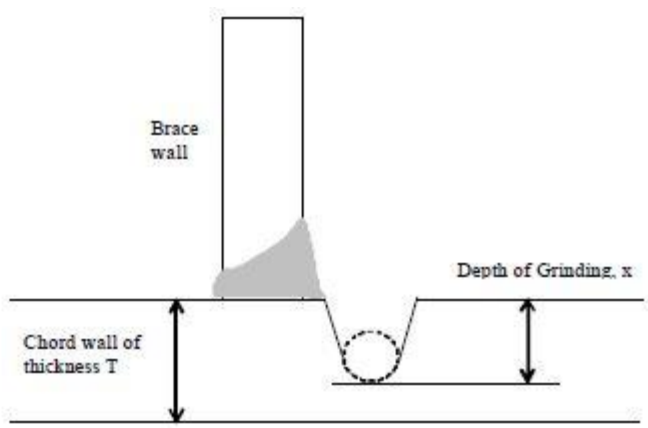

Fig 4.6: Remedial grinding of crack *(MSL and Dier 2004).*

Limitation and precaution: The work should be executed by a skilled worker as grinding operation needs high precision to perform deep long crack in brace member where the tensile load is high. This method is favorable for a shallow crack at weld joints *(MSL 1995).*

Advantages and disadvantages: The remedial grinding technique is a useful technique for fatigue crack removal. As per MSL 1995 report, fatigue life gain by the remedial grinding can be 2.2 times the basic fatigue life, but the strength depends upon the experiment and size of the crack.

Stop hole drilling

The hole drilling technique is the easiest, most accessible technique to arrest a crack tip. This technique is used to diminish the stress on the crack tip to improve the fatigue life of the structure *(Ayatollahi, Razavi* *et al. 2014).* The improved fatigue life in the drilled specimen depends upon several variables, such as the properties of test materials and the near hole stress states *(Song 2004)*. The main principle of hole drilling is to transfer the sharp crack tip to the blunt notch. This process reduces the stress concentration of the crack. The crack tip should be tested using a NDT method. The stress concentration factor of the hole is given as:

$$SCF= 1+ 2\sqrt{(a/r)} \quad \text{..................(1)}$$

Where a is the length of the crack and r is the radius of the stop hole *(Sharp and Ersdal 2021)*. The size of the hole, as a result, should be determined by the length of the crack. As a result, stop holes are primarily favorable for short-length crack. Figure 4.7 shows a stop hole at the crack tip. Crack deflecting holes are drilled away from the crack to alter the stress field and deflect the crack into lower stressed areas (Sharp and Ersdal 2021).

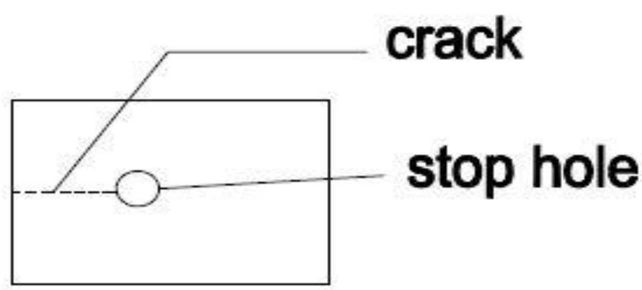

Fig 4.7: stop hole drilling at the crack tip.

Advantages and disadvantages:

A very simple method that is capable of delaying cracks. However, this technique is more effective for short-length crack and the hole placement is very critical and needs a good understanding of the existing stress field.

Member removal or load reduction

Member removal is a valid repair technique that sometimes avoids further crack propagation and damage of a member. In some cases, member removal is done to execute other SMR techniques as well, such as member replacement *(Nichols and Khan 2017).* The removal of a non-load carrying element or redundant member is also reducing the load to the structure. In some cases, removal of a structural member in a jacket structure may result in improving the overall reliability of the structure *(Dehghani and Aslani 2019).* This method can also mitigate fatigue cracks in the location where calculated fatigue life is estimated to be short *(Samarakoon and Ratnayake 2015)*. As per the MTD report 1994, removing unnecessary horizontal members by 10 to 15% loading can increase the fatigue life factor by 1.5.

The cutting technique used for underwater structural elements are:

i. Mechanical method
ii. Thermal method
iii. Explosives
iv. Electrochemical method *(MSL and Dier 2004).*

Figure 4.8 is an example of a mechanical method diamond wire cutting system. The main advantage of using this technique is the relatively quick method. Safety precautions should be followed while using the explosive cutting technique *(MSL and Dier 2004)*.

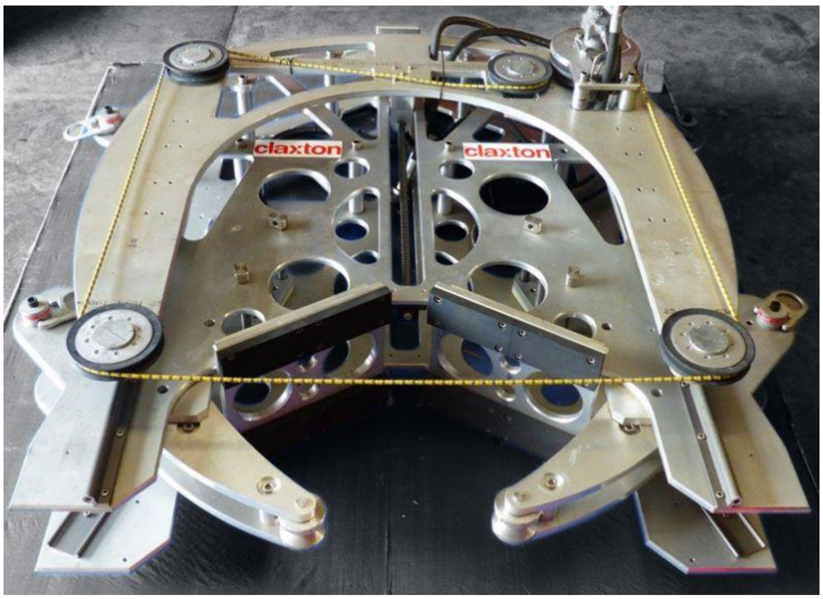

Fig 4.8: Diamond wire cutter *(claxtonengineering)*

4.2 Fatigue life enhancement methods

Weld improvement methods

Weld improvement method can be also used to enhance the fatigue performance of welded joints either by improving the weld geometry or by increasing compressive residual stress of the weld. Weld geometry improvement method includes:

- Toe grinding,
- Remelting process, and
- water jet eroding.

The toe grinding process is wildly used, but remelting process and water jet eroding process are less common in the offshore industry *(Dehghani and Aslani 2019).*

Compressive stress increasing method can also be used to improve welds and their fatigue. These methods includes such as shot, needle, hammer and ultrasonic peening method.

Toe grinding

Burr grinding equipment at a high-speed pneumatic, hydraulic or electric grinder at a rotational speed of 15,000 rpm to 40,000 rpm is used to shape the weld geometry of the structure. Thus, the ground surface gives the weld a favorable shape which reduces the stress concentration at the joint. The grinding work is performed at the rate of 1 man per hour by a skilled operator *(K.J. Kirkhope!, Caron et al. 1999).* The previous data shows that improved fatigue strength is obtained if the grinding is extended to a depth below the surface of at least 0.5mm and the grinding task must remove all the weld defects located at the weld toe *(Haagensen 1997)*. Thus, profiled surface postponed the initiation of fatigue crack at the weld toe. The grinding work is preferred to be performed by burr grinding machine. However, disc grinding machine is less time-consuming and less expensive, but does not give a smooth finish on the surface. The groove depth limit of 5% of plate thickness is placed on the depth of cut. The cut is usually less for the brace member than for the chord member *(MSL and Dier 2004).*

Advantages and disadvantages:

The fatigue life gain by the toe grinding work is believed to be 2.2 times the basic fatigue life of the joint. It is relatively quick and economic work in offshore. This method is only concerned with the fatigue life enhancement but not the static strength of the structure.

Peening methods

Peening method is done with the tool like hammer, shot, needle or ultrasonic peening tool. The effect is obtained by the cold working in which the weld layer of the joint is plastically deformed by a peening tool. Each impact or shot creates a plastic zone on the surface. This zone is elastically deformed in compression *(MSL and Dier 2004)*. In the progress of the process, compressive residual stresses are generated in the surface layer. To compensate these compressive stresses, tensile stresses are induced within underlying layers. Thus, generated compressive stress improves the fatigue life of the weld joint *(Dehghani and Aslani 2019)*.

Shot peening is done with the small cast iron or steel shot. The shot is propelled on the surface at high velocity. The advantage of using shot peening is that it covers a large area at a low cost, but one should take care that shot size must be small enough to reach the bottom of all undercut *(K.J. Kirkhope!, Caron et al. 1999).*

Hammer peening is carried out manually using a pneumatic hammer at approximately 5000 blows per minute. This method can produce higher fatigue strength improvement as compared to shot and needle peening due to the large amount of cold working process *(K.J. Kirkhope!, Caron et al. 1999)*.

Needle peening is similar to hammer peening, except the solid tool is replaced by steel wire bundles. The overall improvement is less than hammer peening (*K.J. Kirkhope!, Caron et al. 1999)*.

Advantages and disadvantages: Hammer peening is the method that is providing the most fatigue strength gain. However, shot peening is preferred method in offshore structures. The shot peening method is not suitable for underwater application, but can be used in a hyperbaric chamber. The peening method is a quick method of increasing the fatigue strength of weld joints.

Grout filling

This technique refers to partial or complete filling of the cementitious or epoxy grout materials to the damaged or intact structure. The grout-filled structure formes a composite section that carries the load without any increase in environmental load *(Dehghani and Aslani 2019)*. Grout filling can be done for members and joints.

When tubular member or joints is completely filled with grout materials, the local and global buckling resistance of the structure increases. Grout filling can also be effective as a repair method for dents and damaged member, and can enhance the static and fatigue performance of the structure and joints *(Dehghani and Aslani 2019)*.

Grout filling of member: The whole tubular member is completely filled with epoxy grout materials such that end compressive load is transferred in the bearing grout. Complete grout filling of members can be useful for intact structure and damaged members as well. One should be careful with the void formation while grout filling work *(MSL and Dier 2004)*.

Grout filling of joints: When the tubular joints chord member is completely filled with epoxy grout materials. In the case of the pile leg, the annulus between the tubular section is filled with grout. It increases the static and fatigue strength of joints *(MSL and Dier 2004).*

The consideration should be given for larger diameter structures while placing. The technique is quite an economical and fast working process. The grouting work can be done in 2 to 3 working days in general. One of the examples of grouting is; Baltic beta jack-up platform life extended by ten years by grout filling on its leg with high strength grout *(Samarakoon and Ratnayake 2015)*.

Chapter 5: Selection Criteria

5.1 General

Selection of the technique is the part of decision making. When selecting the mitigation method, it is advisable to review as many options as possible even one option seems to be a possible choice. We are going to make a final decision of selecting the mitigation method for fatigue problem in offshore structure:

1. Applicability: According to the suitability of the method, the selection process is done. Factor like size, length, phase of damage, locations is considered in this selection criteria.
2. Fatigue/static life gain by the structure: This is an important criterion for selecting the method. Our main intention of doing the repair is to extend the life of the structure.
3. Cost of installation: Cost varies according to different repair methods. It is important to minimize the cost along with the work execution
4. Time of work, design, installation, and fabrication: It is better to complete the task as soon as possible. Especially, when working with divers, the work should be executed fast. Besides, to prevent further expansion of damage and minimize possible risk, time should be considered.
5. Work deployment: Work can be deployed either by divers or by ROV. All the work cannot be executed by ROV, and every environment condition is not favorable for divers.
6. Environmental condition: It is also an important criterion for selection. Every situation is supportive of work execution. Besides, various environmental loads are associated with the structure as well.

As per the MSL report 2004, the several selecting criteria of SMR techniques are:

- Technical performance
- Reliability
- Cost
- Time
- Environmental and legislative factor
- Tolerance acceptability
- The remaining life of the structure
- Depth limitation
- Potential problem areas
- Operators' preferences *(MSL and Dier 2004)*.

5.2 Repair methods based on different scenarios

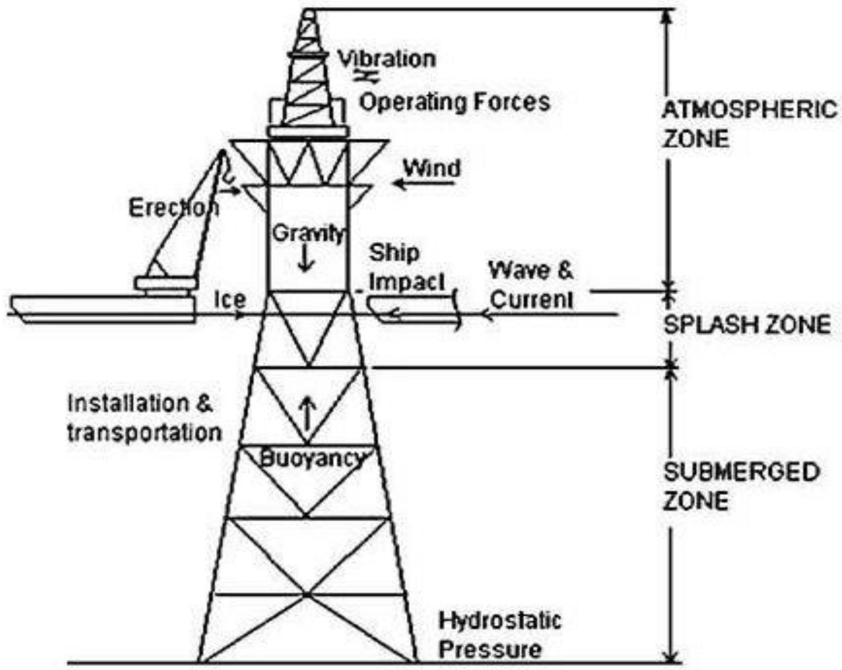

Fig5.1: jacketed offshore structure*(Ishwarya, Arockiasamy et al. 2016)*

Figure 5.1 shows a simple model of an offshore structure. The three main zones of the structure are the atmospheric zone, splash zone, and submerged zone. Dependent on the zone and damage, different repair methods can be used. The major influencing factors on the selection of the repair methods are shape, size, and length of the crack, location of the crack, crack stage, cost, and time repair installation and fabrication work. So, here we assume the three different situations, i.e., Situation I (crack initiation), Situation II (crack growth), and Situation III (unstable fracture), as shown in figure 5.2 – 5.4. Each situation shows a different scenario and location of damage for which we are trying to solve by using the flow chart in figure 5.5. The figure 5.6, 5.7, 5.8 and 5.9 shows the flow chart process of repairing situation I, Situation II, situation III and overall process respectively.

Situation I: When we have a shallow fatigue crack at different locations:

i. Atmospheric zone
ii. Splash zone
iii. Submerged zone

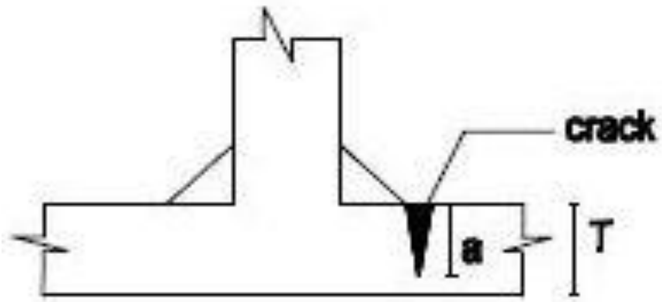

Fig 5.2: shallow crack at weld toe

Situation II: when we have deep through thickness crack at different locations:

i. Atmospheric zone
ii. Splash zone
iii. Submerged zone

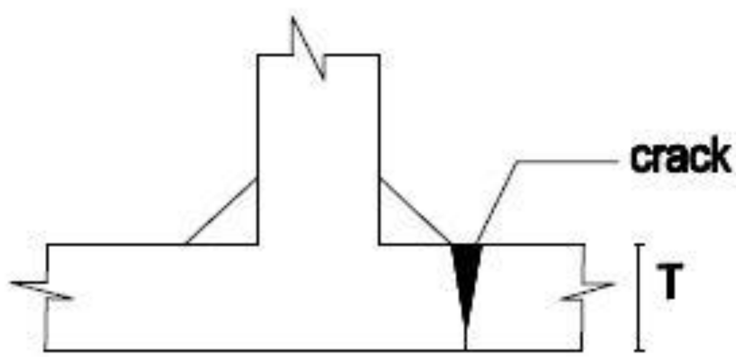

Fig 5.3: Through thickness crack in a weld toe

Situation III: when we have severance or fracture conditions crack at different locations:

i. Atmospheric zone
ii. Splash zone
iii. Submerged zone

Fig 5.4: severance or fracture *(Dehghani and Aslani 2019)*

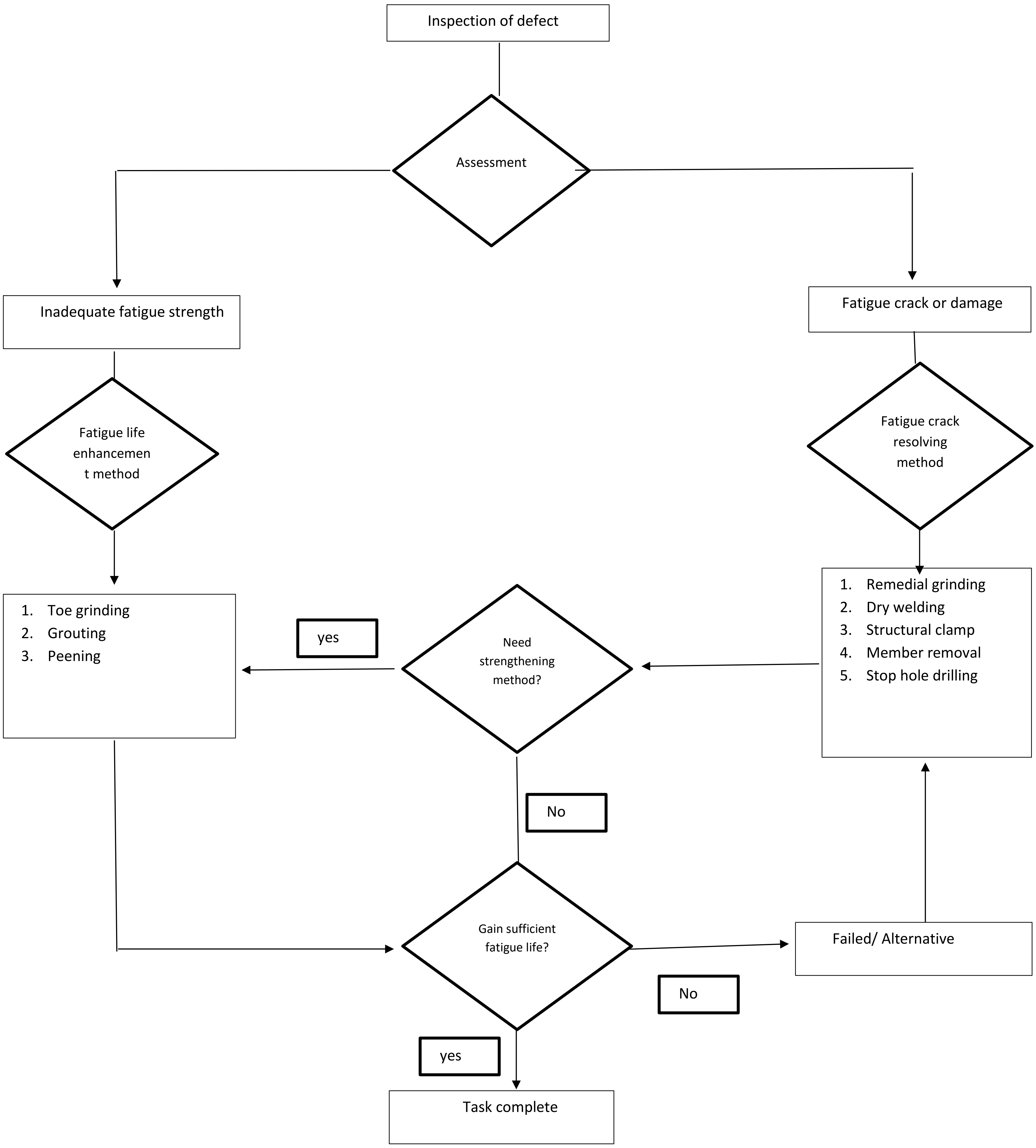

Fig 5.5: Procedure of doing a repair for fatigue damage.

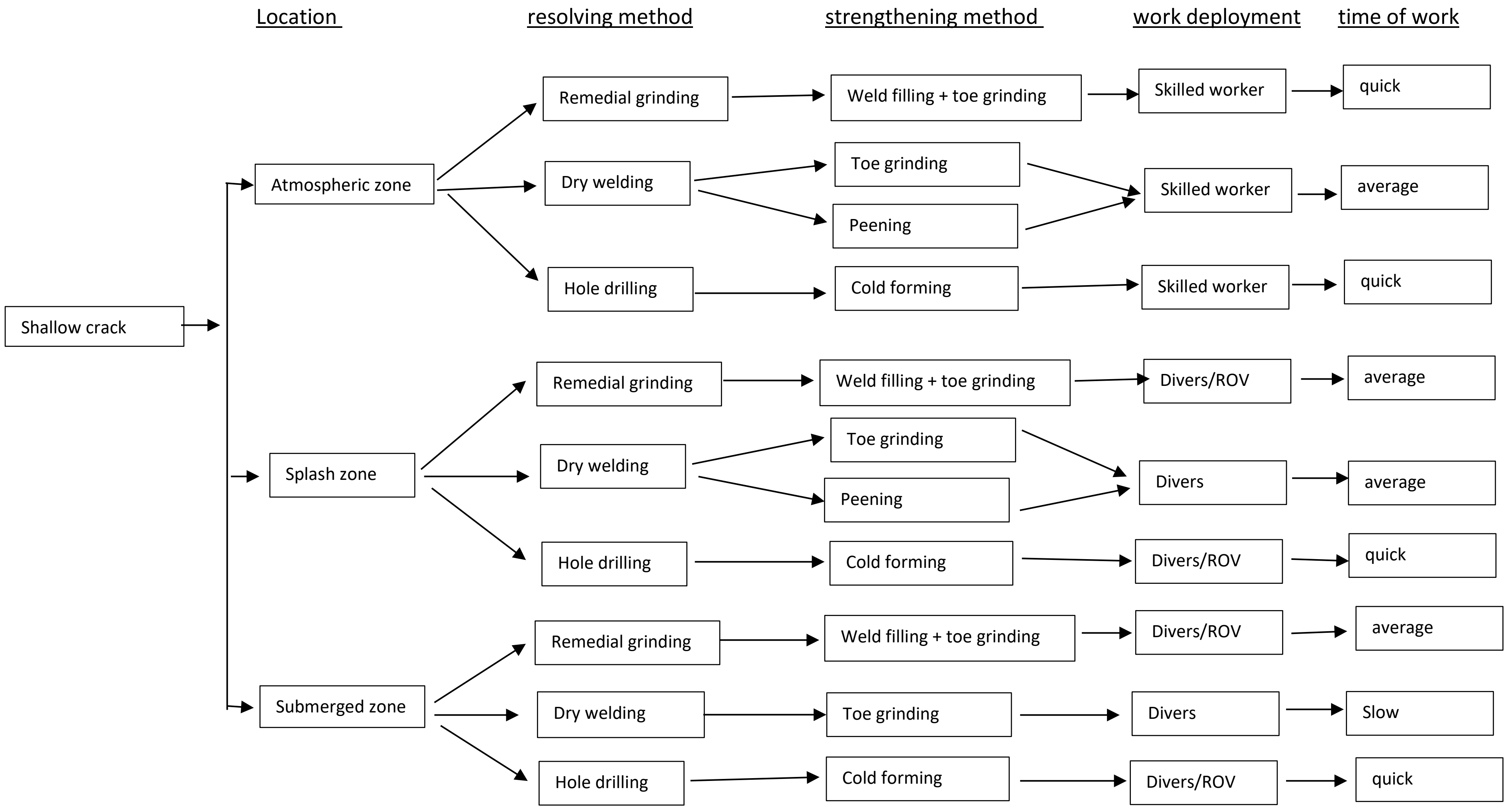

Fig 5.6: Flow chart for situation I

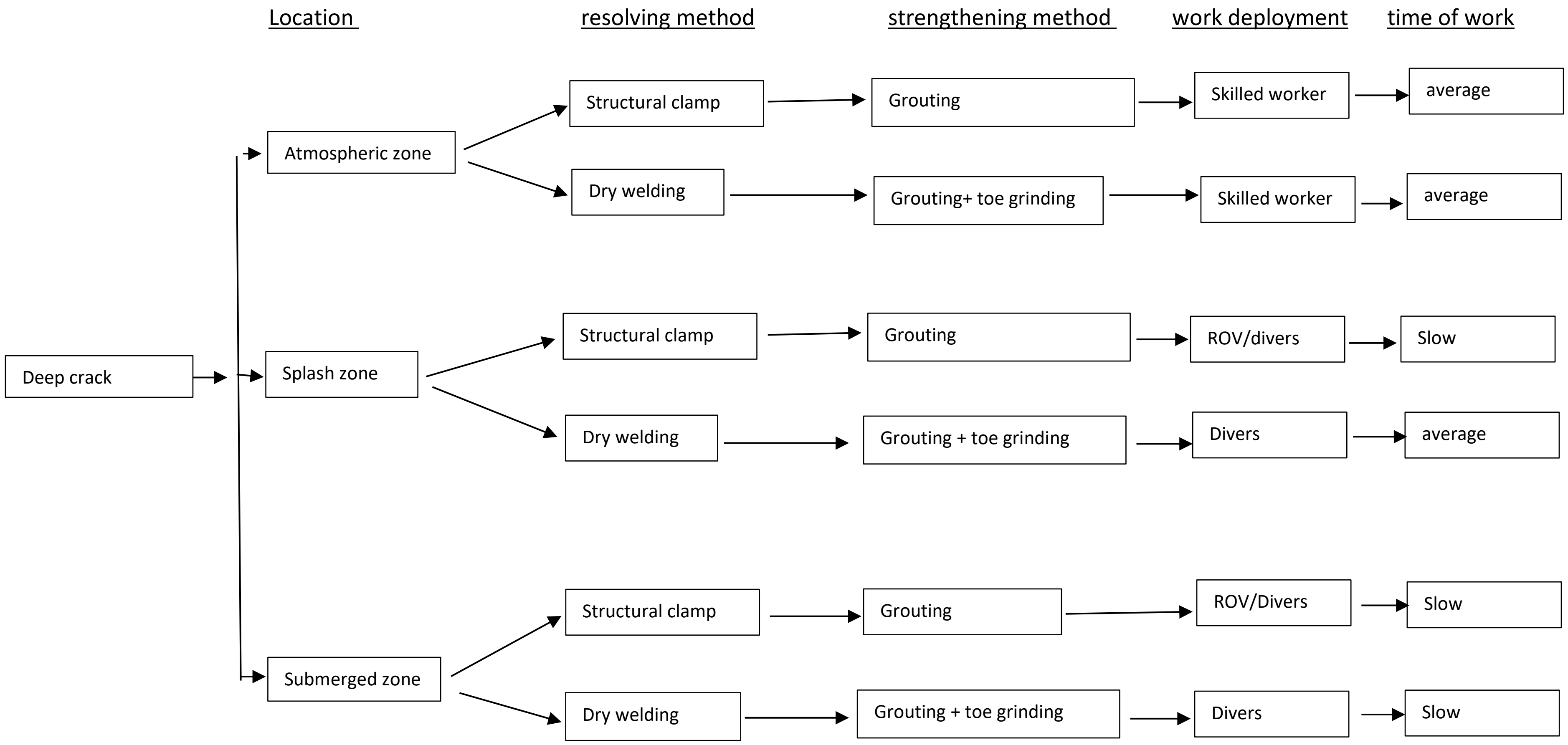

Fig 5.7: Flow chart for Situation II

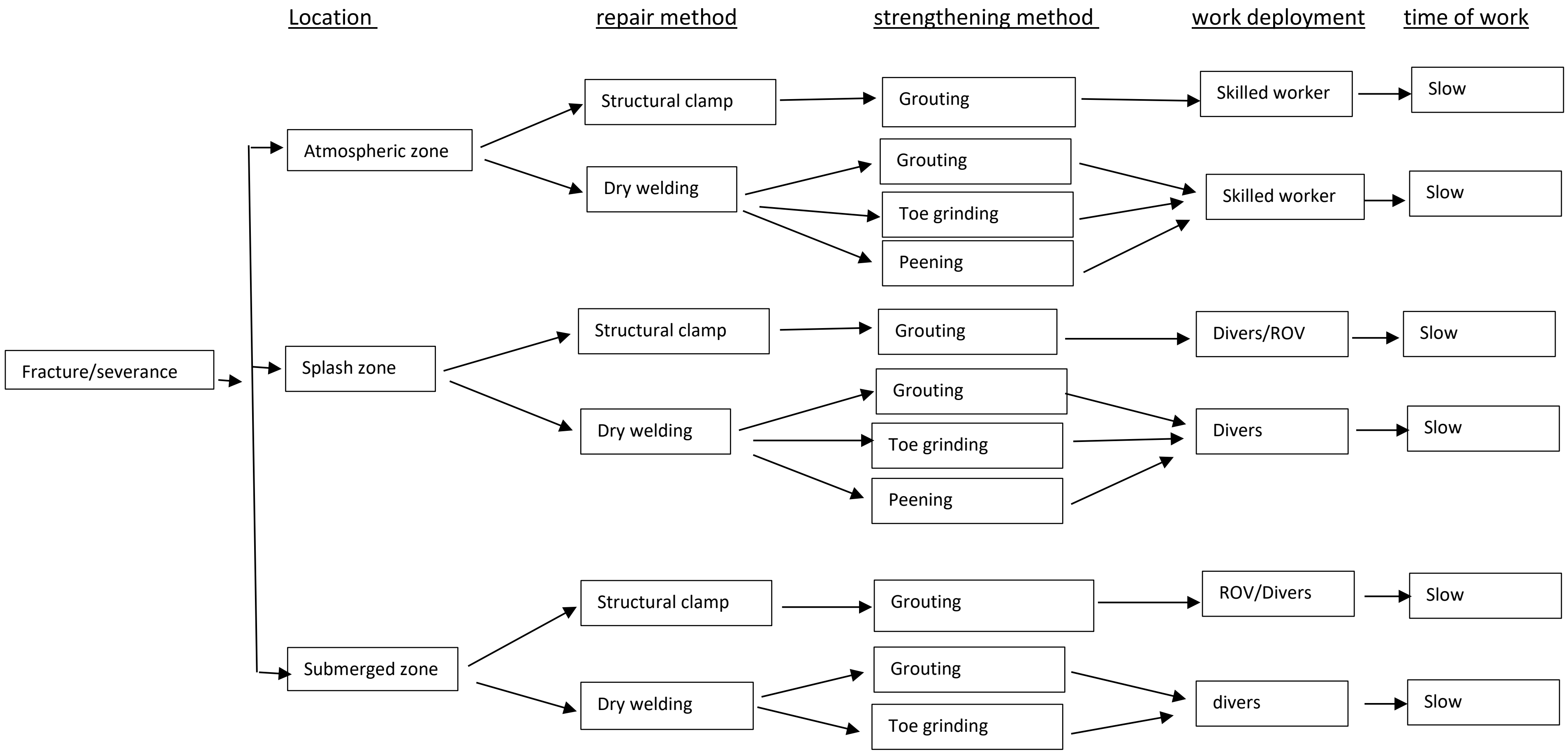

Fig 5.8: Flow chart for situation III

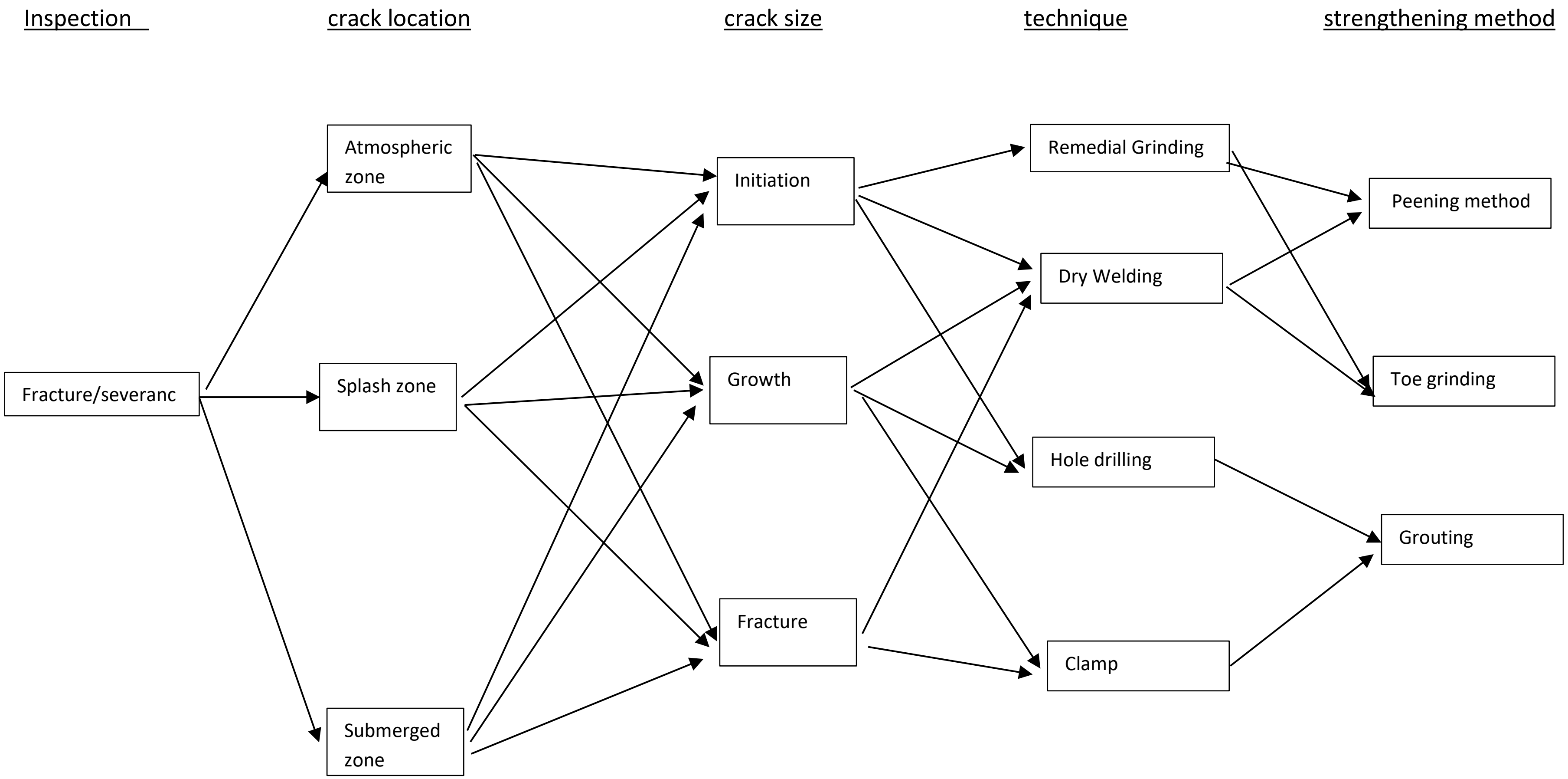

Fig 5.9: Overall process for selection of technique on the basis of size and location of the crack

5.3 Analytic Hierarchy Process method and multicriteria dimensional analysis:

Analytic Hierarchy Process is a method for analyzing the decision-making process in project management. When we try to compare the different criteria or options, we find out the dominance of one criterion over another. The main way of ranking in the AHP process is on the basis of the number between 1 to 9. So, the AHP procedure ranks the different criteria dominance on the number. Table 5.1 explains the intensity of dominance *(Saaty 2008)*.

Intensity	Description
1	Equally importance
2	Weak or slightly importance
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus importance
7	Very strong importance
8	Very-very strong importance
9	Extremely strong importance

Table 5.1: Scale of the importance of criteria *(Saaty 2008)*

Multicriteria dimensional analysis:

MCA is the method where several criteria are measured to find out the preferences. For example, we have the main goal of the project as G, which can be achieved by several criteria C1, C2, C3………. Cn. Each criterion can give an alternative solution for achieving the goal of the project. So, MCA gives comparing and ranking way of those criteria C1, C2……..Cn *(Samarakoon and Ratnayake 2015)*.

We can consider MCA as an easy way in the decision-making of the project. The main theme of using this process is to study the different situations and problems in the project and make an easy decision-making way *(Habibi May 1999).*

Hierarchy structure:

On the basis of MCA, a hierarchy structure is made where the goal will be the first step followed by the criteria and the alternatives, as shown in figure 5.10.

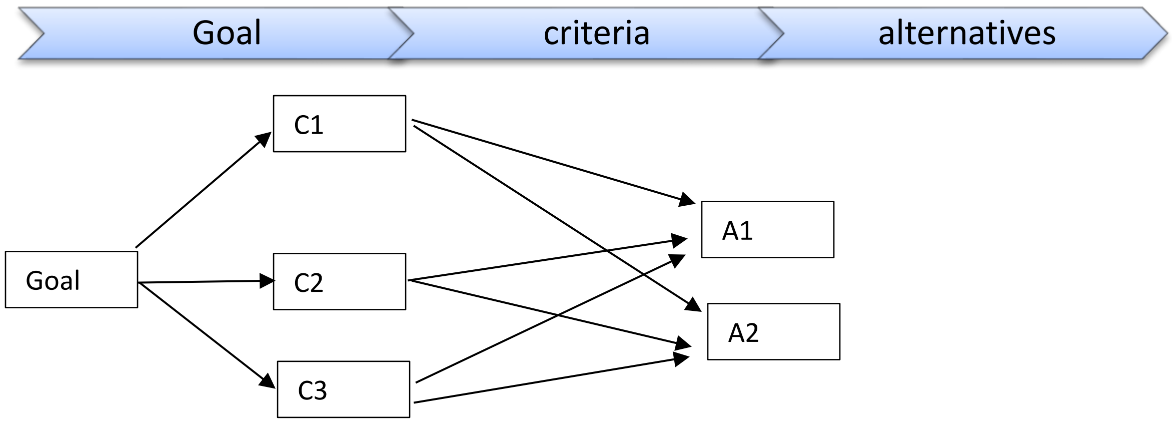

Fig 5.10: hierarchy structure

Previous use of AHP method for decision making in Offshore repair:

On November 13, 2014, Samindi M.K. Samarkoon and R.M. Chandima Ratnayake published a paper on "strengthening, modification, and repair technique prioritization for structural integrity control ageing offshore structures" from the department of mechanical and structural engineering and material science of University of Stavanger. In this paper, they introduce the MCA and AHP method for selecting the SMR technique forming a pairwise matrix. The criteria involved in the project of SMR was:

a. Applicability
b. Cost of design/fabrication and installation
c. The time scale for the design
d. Technical performance
e. Reliability
f. Legislative requirements

The alternative method involve was Grout filling, member removal, clamping, and welding. As per the report, the performance-based comparison of the criteria weight value was:

Cost of project: 10.8%

Fabrication/installation: 14.7%

Technical performance: 15.6%

Applicability: 19.7%

Legislative requirements: 19.3%

AHP method for selecting repair method for fatigue crack:

In selecting the repair method and constructing the hierarchy structure model, we will use the study and literature for ranking. As the selection criteria always depend on the situation. When we see the situation and selection method of repair for offshore structures, we have various selection methods as mention in section 4.1. But, here, we are mainly focusing on fatigue crack repair and few criteria for their selection *(Samarakoon and Ratnayake 2015*). Figure 5.11 shows the hierarchy structure of the method. The main criteria we are going to discuss are:

a. Applicability
b. Fatigue/static life of the structure
c. Cost of repair and installation work
d. Time of repair, installation, and fabrication work
e. Work deployment by

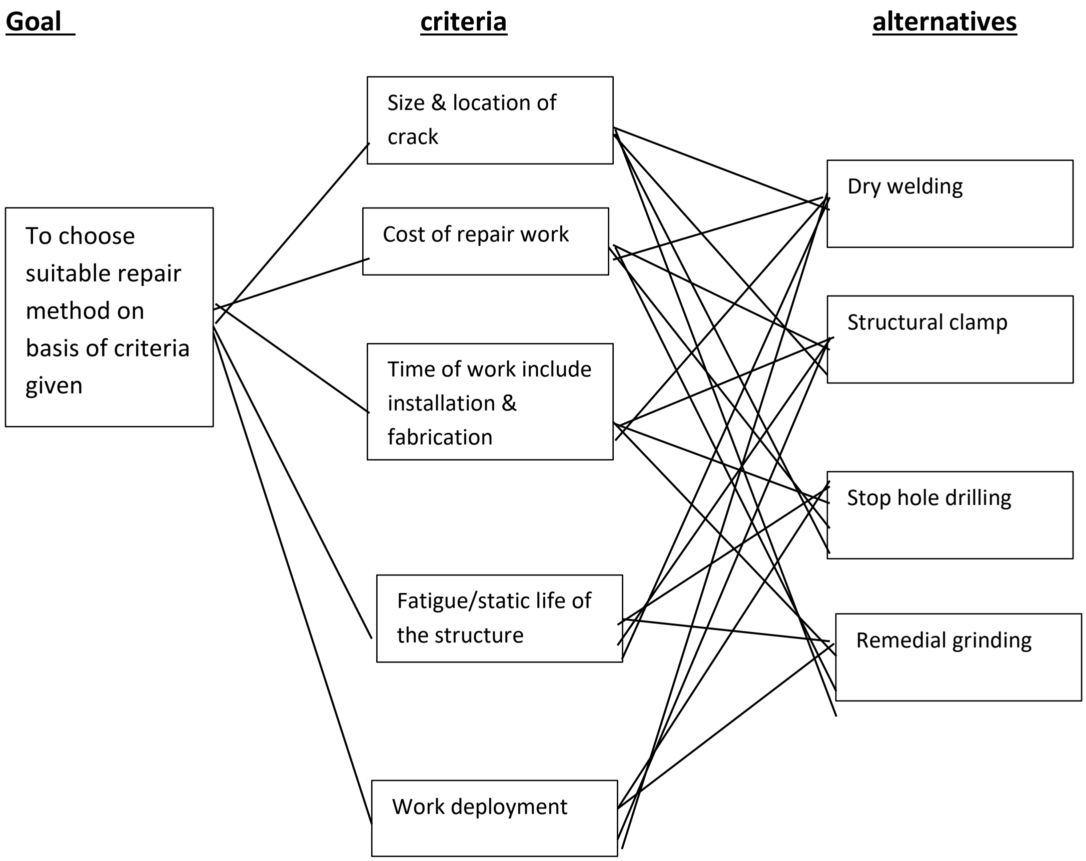

Fig 5.11: Hierarchy structure of repair method on the basis of different criteria.

Pair wise matrix formation:

For the model structure given above, we can compare it with the table of importance given above so that we can form the matrix. Here, we have chosen five different criteria so, the matrix will be 5*5 matrix.

Let us consider a matrix model A, with five different criteria, i.e., A1, A2, A3, A4, A5 and W1, W2, W3, W4, W5 be the important factor of each other taken from table 5.1 so that our matrix form would be:

$$\begin{array}{cc} & \begin{array}{ccccc} A1 & A2 & A3 & A4 & A5 \end{array} \\ \begin{array}{c} A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} & \begin{pmatrix} w1/w1 & w1/w2 & w1/w3 & w1/w4 & w1/w5 \\ w2/w1 & w2/w2 & w2/w3 & w2/w4 & w2/w5 \\ w3/w1 & w3/w2 & w3/w3 & w3/w4 & w3/w5 \\ w4/w1 & w4/w2 & w4/w3 & w4/w4 & w4/w5 \\ w5/w1 & w5/w2 & w5/w3 & w5/w4 & w5/w5 \end{pmatrix} \end{array} \begin{pmatrix} w1 \\ w2 \\ w3 \\ w4 \\ w5 \end{pmatrix} = 5 \begin{pmatrix} w1 \\ w2 \\ w3 \\ w4 \\ w5 \end{pmatrix} \quad ....(1)$$

So, for n number of criteria, our equation will be:

$A*W= n* W$..............................(2)

All the matrix row is the multiple values of the first row. When the value of W is unknown and can occur little inconsistency in matrix formation, and the eigen value of n will be λ_{max}, where $\lambda_{max} > n$.

So equation will be $A*W= \lambda_{max}W$...............(3)

The value of λ_{max} cannot be less than n to make the matrix consistence. Then the normalized matrix is formed by adding all the columns and dividing each column element with that sum. Criteria weight is the average value is calculated by adding the row elements. For an example:

Let (b1 b2 b3 b4 b5) be the value of the first-row element of the normalized matrix; then, the average or criteria weight will be: (b1+b2+b3+b4+b5)/5, here n=5.

Consistency index: consistency index represents the average value of the remaining eigenvalue

i.e. $C.I=(\lambda_{max} -n)/(n-1)$........................(4)

consistency ratio: consistency ratio is the ratio of C.I to RCI index, C.R.= C.I/RCI..........(5)*(Saaty 1990)*

where RCI table for different values of the matrix is shown in table 5.2.

Size of matrix	1	2	3	4	5	6	7	8	9	10
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 5.2: RCI index of the matrix *(Samarakoon and Ratnayake 2015)*

Pairwise matrix formation for Fatigue crack repair method:

Here, w1, w2, w3, w4, w5 are the importance from 1 to 9 in comparison with others. For example, while selecting a repair method, crack size and location criteria are of strong importance over the cost of repair and installation work. Hence the matrix is formed on the basis of the importance of one to another.

- Here we have five criteria as, applicability, cost of work, time of design work installation and fabrication, fatigue life gain, and work deployment.
- Our goal is to repair or resolve the fatigue crack.
- The method is Structural clamp, Dry welding, Stop hole drilling, and Remedial grinding.
- Applicability is a moderately important factor over time and the cost of repair. As the selection of repair methods is done on the basis of the types of crack and its location. However, time is considered slightly important over cost according to the situation of crack.
- Cost over time and time over cost can be taken as an equally important factor. Both criteria have almost equal effect in choosing repair work.
- Fatigue/static life gain by the structure should be noted as important as applicability to achieve the desired goal. Our main goal in doing the repair is to extend the life of the structure.
- Work deployment is the least important in overall factor while choosing the repair method. According to the physical factor and environmental situation, sometimes work should be done either with ROV or only with Divers. In this kind of situation, work deployment has little effect in choosing the method. The formation of a pairwise matrix is shown in table 5.3.

	Applicability	cost	time	Fatigue/static life gain	Work deployment	Criteria weight
Applicability	1	4	3	1	7	0.35
cost of repair	¼	1	1	¼	5	0.12
time of repair	1/3	1	1	1/3	5	0.13
fatigue/static life gain	1	4	3	1	7	0.35
work deployment	1/7	¼	¼	1/5	1	0.05
sum	2.73	10.25	8.25	2.78	25.00	1

Table 5.3: Pairwise matrix formation for fatigue crack resolving method.

Calculating the consistency:

Here we have the five different criteria by which we can calculate the λ_{max} = 5.329

Calculation of consistency index: $\frac{\lambda max-n}{n-1}$Where n is the number of criteria *(Saaty 2008).*

So we have consistency index C.I= 0.082

Calculation of consistency ratio:

For calculating consistency ratio, we have RCI index for different size of the matrix shown below:

For our matrix 5*5, the RCI index is 1.12. Now we can calculate the consistency ratio as:

C.R.= C.I/RCI=0.0735

If the C.R. is less than 10%, then the judgment is considered to be consistent. Hence, our consideration is supposed to be consistent.

Our criteria weight values are:

$$\begin{pmatrix} \text{Applicability} \\ \text{Cost of repair:} \\ \text{Time of repair work} \\ \text{Fatigue/static life gain:} \\ \text{Work deployment:} \end{pmatrix} = \begin{pmatrix} 0.3519 \\ 0.1200 \\ 0.1321 \\ 0.35199 \\ 0.0437 \end{pmatrix}$$

Since the contribution of these criteria while selecting the repair method on the basis of percentage is shown below in diagram 5.12 below.

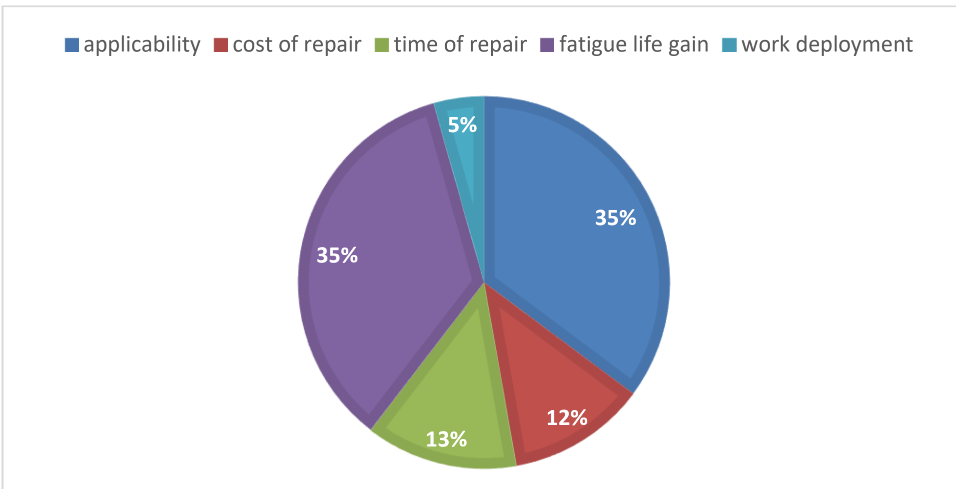

Fig 5.12: pie chart showing the percentage contribution of different criteria of repair method

Conclusion:

We made the following conclusion by this process:

- The pairwise matrix we made is consistent. As consistency ratio is less than 10 percent.
- Applicability and fatigue/static life gain by the structure is the strongest factor to decide the repair method. They almost contribute 35% each while selecting.
- Cost of work and time of design, installation, and fabrication has 12% and 13% contribution in choosing the repair method. But this factor is dependable according to the size, location, and types of cracks we have.
- The work deployment process has an effect of 6% in choosing the repair method.

AHP method for selecting strengthening method for fatigue life extension:

The method for fatigue life enhancement of the welded structure is Grout filling, Peening method, and Toe grinding work.

Using the similar hierarchy structure, we have the following criteria for restrengthening the fatigue life of the structure:

a. Fatigue life gain
b. Applicability
c. Cost and time of work
d. Work deployment

Here, our main goal will be to achieve the desire fatigue life in relevant to other factors. So, the flow chart is shown in figure 5.13.

Goal **criteria** **alternatives**

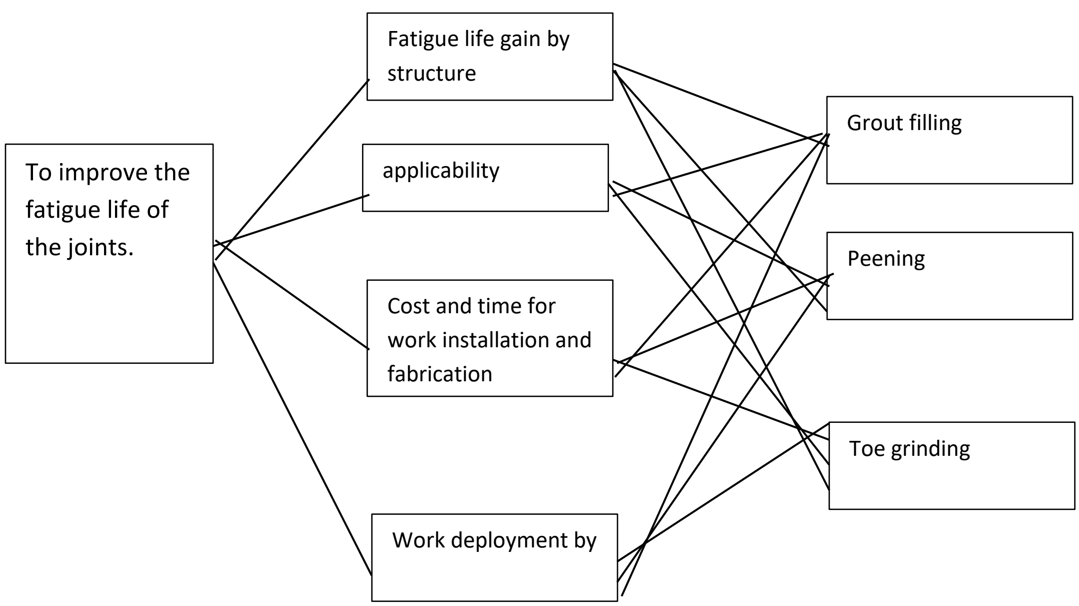

Fig 5.13: Hierarchy structure of fatigue life improvement method on the basis of different criteria.

Formation of the pairwise matrix:

- Our goal is to improve the fatigue life of the joints.
- The criteria for selecting the method are Fatigue life gain, Applicability, Cost & time, and Work deployment.

- Fatigue life gain by the structure is of moderate importance over time and cost because our main goal is to gain the desire fatigue life.
- Applicability is considered as equal importance over fatigue life gain by the structure.
- For fatigue life improvement work, factor like time and cost is less important because work can be executed in a short time and low cost as well.
- Besides grout filling work, all the other strengthening work is done by divers. So, work deployment has little contribution in selecting the method in accordance with physical and environmental considerations. Table 5.4 shows the matrix formation.

	fatigue life gain	applicability	cost & time	work deployment	Criteria weight
fatigue life gain	1	1	3	7	0.40
applicability	1	1	3	7	0.40
cost & time	1/3	1/3	1	3	0.14
work deployment	1/7	1/7	1/3	1	0.06
sum	2.48	2.48	7.33	18.00	1

Table 5.4: pairwise matrix formation for fatigue life enhancement method

Calculating the consistency of the matrix:

λ_{max}= 4.0079

and C.I. = $\frac{\lambda max - n}{n-1}$ Where n is the number of criteria

C.I.= 0.026

And from table 4.2 of RCI, we have RCI for 4*4 matrix as 0.90

So, C.R.= 0.026/0.90= 0.0029 <0.10, so the matrix is consistence and our average value can be considered as weightage for selecting criteria. The criteria weight and their percentage contribution is shown below in figure 5.14.

$$\text{Criteria weight}= \begin{pmatrix} \text{fatigue life gain} \\ \text{Applicability} \\ \text{Cost and time} \\ \text{Work deployment} \end{pmatrix} = \begin{pmatrix} 0.4014 \\ 0.4014 \\ 0.143 \\ 0.054 \end{pmatrix}$$

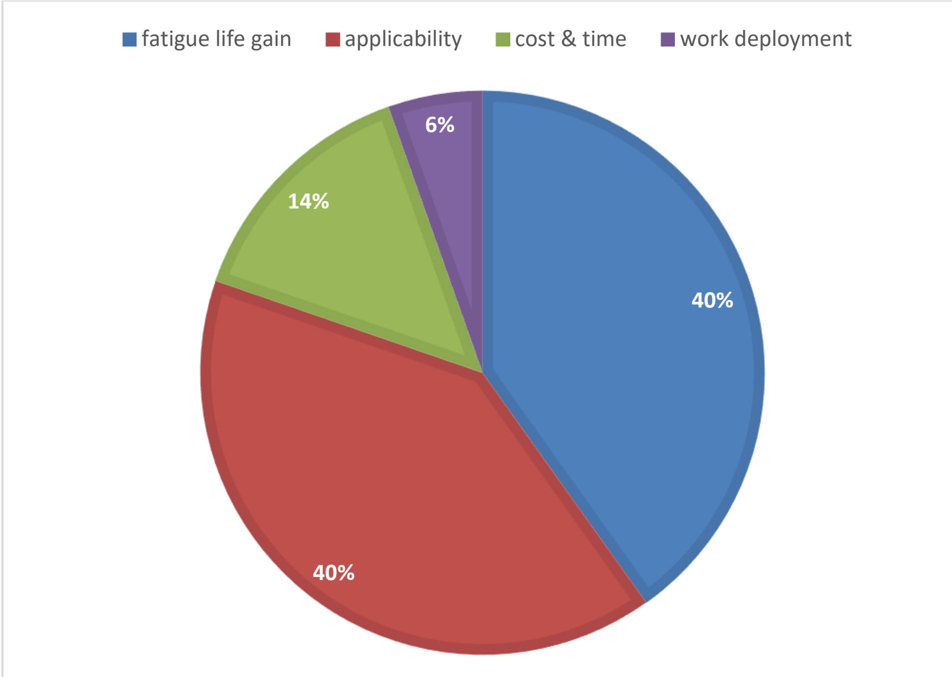

Fig 5.14: pie chart showing the percentage contribution of different criteria

Conclusion:

The following conclusion is made:

- While choosing the fatigue life improvement method, fatigue life gain is the most important thing to consider, i.e., 40% contribution. The reason is to have a long-lasting life of the joints and structure.
- The applicability refers to the location of joints either in the submerged zone or in the splash zone or atmospheric zone, types of joints, or in scenario of repair method followed by strengthening method. While considering all these factors, the consideration is up to 40% in choosing the technique.
- Time and cost are economic work for fatigue improvement techniques. It has less contribution in overall i.e., 14% in overall contribution.
- Work deployment is less among all. It has the only 6%effect on choosing the technique.

AHP method of hierarchy for three situations we assumed in section 5.2

As we have three different situations and three different flow charts for the fatigue crack resolution method. Each situation includes a different repair method. In this section, we are going to make the hierarchy structure for the decision-making of those situations. The main goal will be to choose the repair method for different crack sizes.

Situation I

As mention in flow chart I, the condition was assumed to be a shallow crack for a different location

The mitigation measures mention for shallow fatigue crack are:

1. Dry welding
2. Remedial Grinding
3. Stop hole drilling.

And the criteria of the selection method were based on:

1. Fatigue/static life gain by the structure
2. Applicability/location of the crack
3. Work cost and time, along with fabrication and installation work.

The hierarchy structure is shown below in figure 5.15.

Hierarchy structure

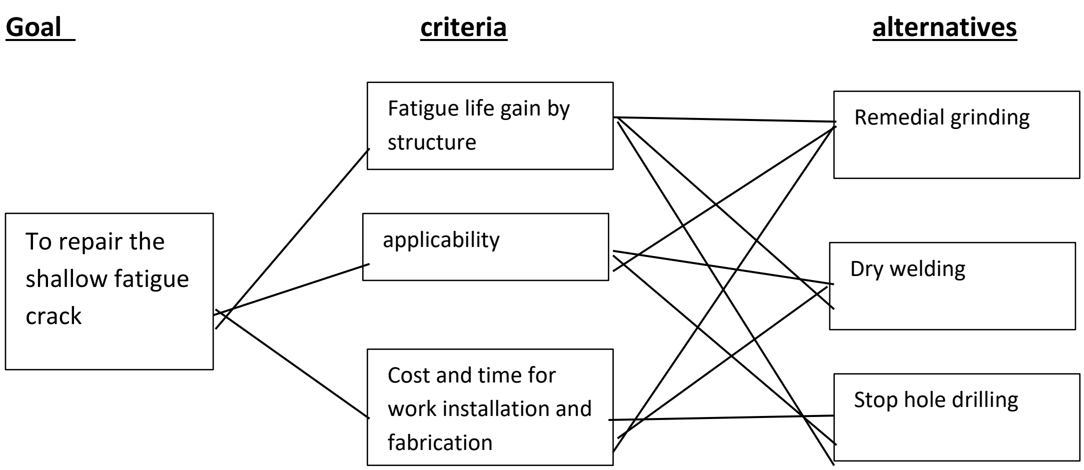

Fig 5.15: hierarchy structure of repairing shallow fatigue crack

Pairwise matrix formation:

Taking those criteria to choose the alternatives, we can answer the following questions:

“how much does alternative A1 contribute to dominate A2 in case of fatigue life extension?”

“how much does alternative A1 contribute to dominate A2 in case of applicability?”

“how much does alternative A1 contribute to dominate A2 in case of time and cost of repair?”

Taking these questions and rating the importance from 1 to 9 from the rating importance table we can form a pairwise matrix as:

1. **Criteria 1: For fatigue life gain:**

Pairwise matrix formation:

- While considering fatigue life gain by the structure, Dry welding can be the most effective one as compared to Remedial grinding and Hole drilling work. As we know, Hole drilling is just a temporary measure of repair work. Remedial grinding work strength depends upon the depth and size of the crack. Dry weld work can return the damaged structure to the previous life span. Table 5.5 shows the pairwise matrix formation for fatigue life gain by different repair methods.

	dry weld	remedial grinding	hole drilling	Criteria weight
dry weld	1	2	3	0.54
remedial grinding	1/2	1	2	0.30
hole drilling	1/3	1/2	1	0.16
sum	1.83	3.50	6	1

Table 5.5: pairwise matrix formation for criteria fatigue life gain.

Now calculating the $\lambda_{max=}$ (3.008945+3.014726 + 3.004405)/3= 3.009

Consistency index C.I. = (λ_{max}-3)/(3-2) =0.0046

Consistency ratio= C.I/ RCI, where RCI is 0.58 for 3*3 matrix from RCI table above

C.R. = 0.0046/0.58= 0.0079< 0.10 (okay)

Hence the consistency ratio is okay, which is below 10%.

2. **Criteria 2: applicability of the method**

Pairwise matrix formation:

- As per the situation, the size of the crack is predefined as initiation phase crack. Dry weld work is the mostly applicable technique as compared to remedial grinding and hole drilling. Several situations affect applicability such as length of the crack, type of joints, location of the joints that need to be repaired. While considering all these factors, we have some limitations over Hole drilling and Remedial grinding work. The table 5.6 shows the pairwise matrix formation of the method as per their applicability.

	Dry weld	remedial grinding	hole drilling	Criteria weight
dry weld	1	3	2	0.54
remedial grinding	1/3	1	½	0.30
hole drilling	½	2	1	0.16
sum	1.83	6	3.5	1

Table 5.6: Pairwise matrix formation for criteria applicability of repair method

Calculating the λ_{max} = 3.009
Calculating C.I. = 0.0460
Calculating C.R. = 0.00793 < 0.10 (okay)
So, the consistency ratio is less than 10%

3. **Criteria 3: time and cost for working, including installation and fabrication work.**

Pairwise matrix formation

- The installation, fabrication time, and cost for dry weld are too expensive as compared to remedial Grinding and Hole drilling work.
- Remedial grinding work is almost equal or can be slightly costly over Hole drilling work. Sometimes, we need to grind until the crack is fully grind out. Table 5.7 shows the pairwise matrix formation of criteria time and cost of repair work.

	Dry weld	remedial grinding	hole drilling	Criteria weight
dry weld	1	1/5	1/6	0.08
remedial grinding	5	1	½	0.34
hole drilling	6	2	1	0.58
sum	12	3.2	1.67	

Table 5.7: pairwise matrix formation for criteria time and cost of repair work.

Calculating the λ_{max}= 3.0291

Calculating the C.I.= 0.0145

Calculating C.R.= 0.025 < 0.10 hence okay.

The consistency ratio is less than 10%, which is acceptable.

The criteria weight table is shown in table 5.8. Figure 5.16 is the percentage bar diagram plot of criteria weight of repair method along with the criteria in percentage.

	fatigue/static life gain	applicability	cost and time
Dry welding	0.54	0.54	0.08
Remedial grinding	0.30	0.16	0.34
Hole drilling	0.16	0.30	0.58
C.F	1	1	1

Table 5.8: Criteria weight table

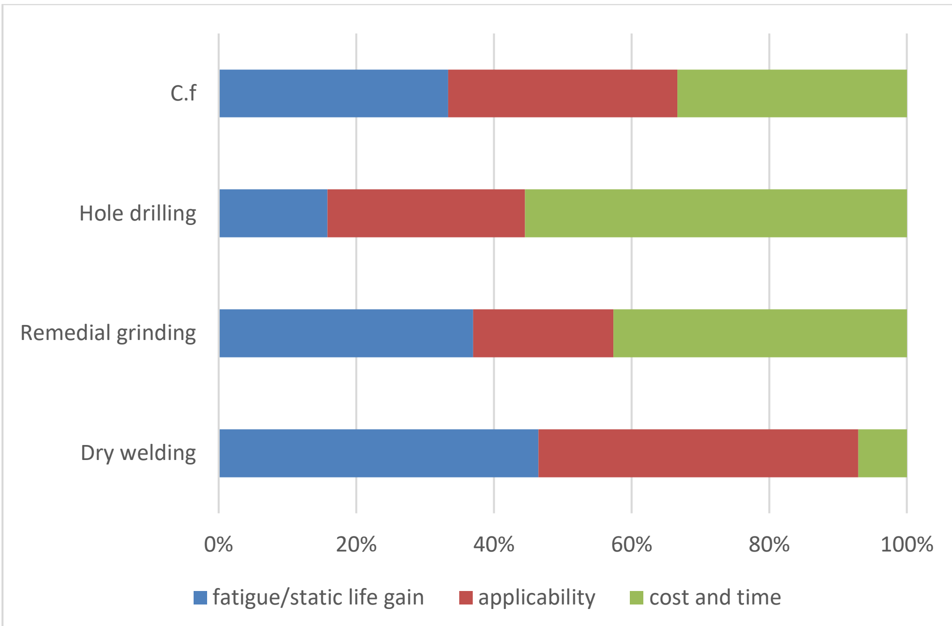

Fig 5.16: comparison of the hierarchy of different repair methods as per cost &time, applicability, and fatigue/static life gain.

Conclusion:

The following conclusion can be made from the above work:

- In terms of fatigue life gain, we should mostly prioritize the Dry welding work as compared to Hole drilling and Remedial grinding work.
- Similarly, Dry welding work is mostly applicable as compared to Hole drilling and Remedial grinding work.
- In terms of time and cost of repair, Dry weld is the most expensive than the other two works. Hole drilling is more effective if the work must be done in a short time and low budget

Situation II and III: As mention above, the second situation involves a growth phase long length and through-thickness fatigue crack. The mitigation measures involve are:

1. Structural clamp.
2. Dry welding.

The criteria of selection of techniques are:

1. Fatigue/static life gain by the structures
2. Applicability and location of the crack
3. Cost and time of repair, design, fabrication, and installation
4. Work deployment

Hierarchy structure: The hierarchy structure is shown below in figure 5.17.

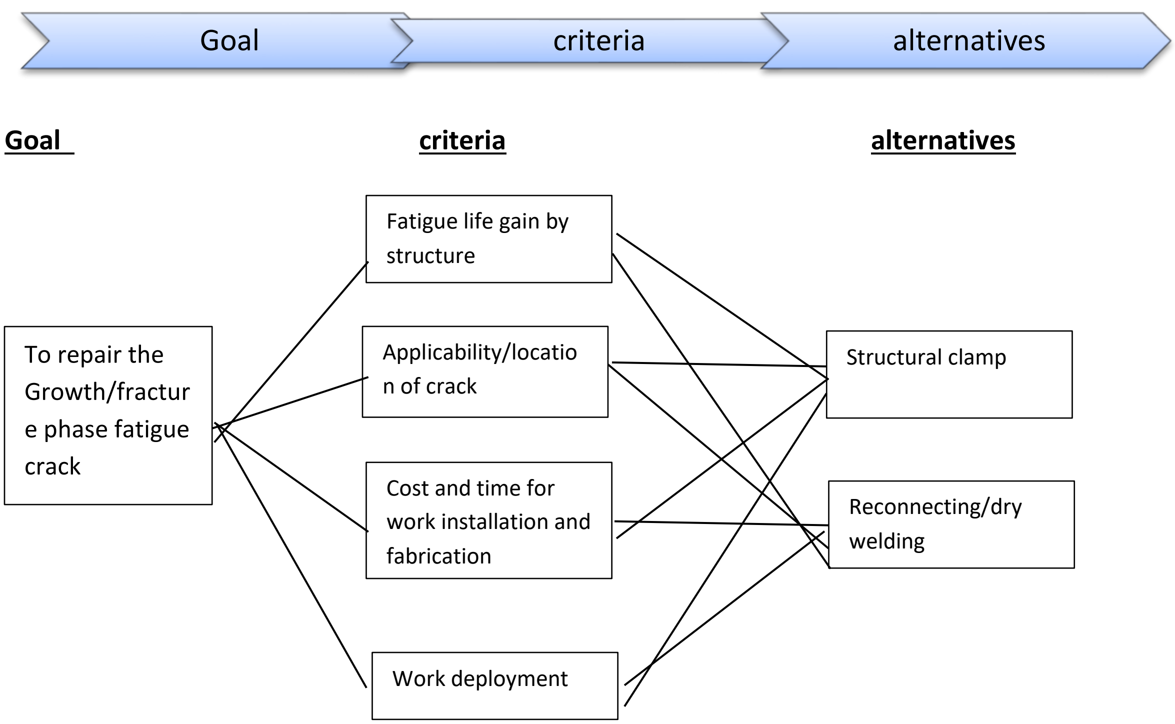

Fig 5.17: hierarchy structure of repairing fracture phase fatigue crack

Pairwise matrix formation:

- Our goal is to repair the fatigue crack either in the growth phase or fracture phase.
- Repair method included as Alternatives are either structural clamp or Dry welding/reconnecting with weld.
- Since the size of the crack is known, our focus will be on getting desire fatigue and static life of the structure so that the life span of the joint increase. So, the influence of fatigue and static life

gain is more than the applicability of the method and moderate important than time and cost of repair.

- Applicability over time and cost is slightly important over cost and time of repair work.
- Work deployment is less considered over other criteria. The deployment is done as per the need, and sometimes it changes along with the environmental situation. Table 5.9 is the pairwise matrix formation of repair method for growth phase or fracture phase crack.

	Fatigue/static life gain	applicability/location	Cost &time	work deployment	criteria weight
fatigue/static life gain	1	2	4	7	0.51
applicability/location	½	1	2	5	0.28
Cost &time	¼	½	1	3	0.15
work deployment	1/7	1/5	1/3	1	0.06
sum	1.89	3.7	7.33	16	1

Table 5.9: pairwise matrix formation for the growth phase and fracture phase crack.

Calculation of $\lambda_{max} = 4.0282$

Calculation of C.I. = 0.0094

Calculation of consistency ratio C.R. = 0.010< 0.10 (okay)

Since C.R. is less than 10%, the consistency of matrix is fine.

The criteria weight of the repair method is shown in figure 5.18 with their percentage cntribution.

$$\begin{pmatrix} \text{Fatigue/static life gain} \\ \text{Applicability and location of crack} \\ \text{Cost \& time of repair} \\ \text{Work deployment} \end{pmatrix} = \begin{pmatrix} 0.51 \\ 0.28 \\ 0.135 \\ 0.06 \end{pmatrix}$$

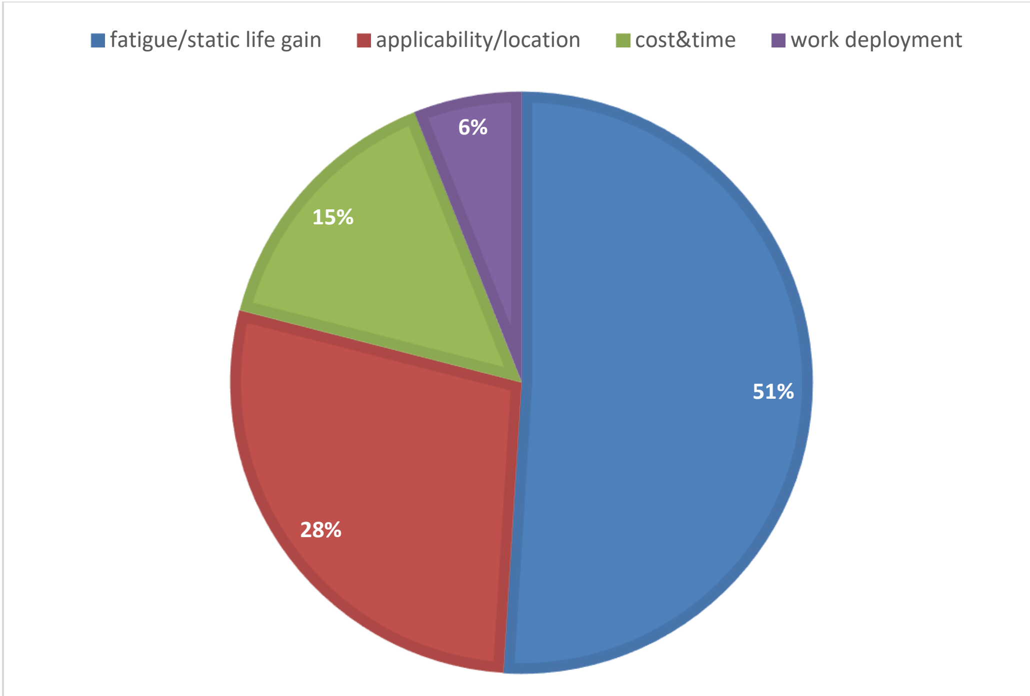

Fig 5.18: pie chart showing the criteria weight on choosing the repair method

Conclusion:

The following conclusion was made from the above process:

- When we have a completely fractured structure or growth phase fatigue crack at joint, our main target will be to repair the structure and maximize the life cycle of the structure. So, choosing a repair method in accordance with fatigue and static life gain is the most. The contribution is 51% to choose the method.
- For the given crack size, the repair methods are fixed, which means that the applicability of the repair method is slightly less considered over fatigue/static life gain. The contribution of applicability is 28% in deciding the alternatives.
- Cost and time are the physical factors that can decide the technique by 13% contribution. In some cases, time can be considered a little more to prevent further accidents and damage or crack propagation.
- Work deployment is done as per the need for the repair. It is the least consideration criteria of 6%. In the worst weather condition or in severe water situations, work deployment either by ROV or by Divers is considered.

5.4 Case study

Case I

Fig 5.19: damage of joints from MMS project *(ENERGO May 2007)*

"Figure 5.19 and 5.20 show the case of damage of joints. Several members are involved in the same joint. There are five members connected to the main member, out of which one is completely disconnected, and little dent on the end point, and one member has an adverse effect on the shape at the end point. The condition is the severance of joint and dent damage along with marine growth on the structure. Let us consider this part as a case study. Assumption of the depth of the given picture be at submerged zone, below splash zone".

Solution measures:

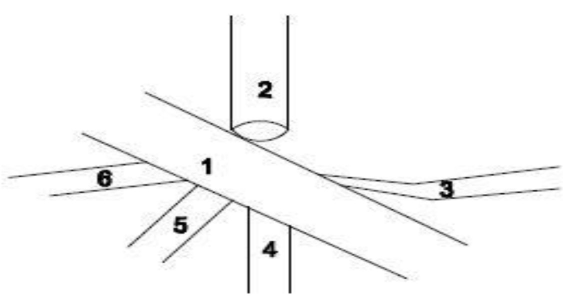

Fig 5.20: diagram of broken joints.

As seen in figure 4.19, member two is totally disconnected from the main member, and member three is a completely dented structure at the joint. Besides, member 4,5 and 6 seems okay with little marine growth. The joint is located below the splash zone. The possible repair mitigation can be:

1. Structural clamp
2. Joint replacement
3. Reconnecting with dry welding and grouting.

The structural clamp is not feasible for this member. As the joint is complex and the member has dents on it. For clamp, it can be complex work. Replacement of a complete joint can be an option, but an uneconomic task as the other brace member seems fine. Re-welding the structure along with grouting for member two can work better in this case. When we see member 3, it is in the worst condition. So, we can replace member 3 with a new brace member and can reconnect with the joint. Hence, welding and grouting can be the best mitigation for this task.

The task procedure and equipment required are:

1. Construction of Habitat chamber for welding along with all the welding equipment's.
2. Grout filling materials for the fatigue life enhancement of the joints.
3. Divers for working
4. ROV for support and grout filling task
5. Replacement member for member 3.
6. NDT test equipment and inspection equipment after task completion.

Case II

> *"Figure 5.21 shows the crack in an X joint in a brace member. Let us consider the crack as a through-thickness crack and more than half of the length of the perimeter of joints. The condition is near about fracture. The location of the joint is supposed to be near around splash zone. The weather condition was worse and cold temperature."*

Figure 6: GI-40 I photograph of damage to X-brace on Row 2

Fig 5.21: Damage of X-joints MMS project *(ENERGO May 2007)*

Solution measures:

As we can see the crack at X joint exactly at the weld toe. The condition is near about fracture and through-thickness crack. The length of the crack is almost 50% of the circumference. In this situation, we should choose the method which can extend the fatigue life and static life by numbers. The possible mitigation can be:

1. Structural clamp.
2. Welding followed by grouting.
3. Replacement of joints.

Mitigation measures two cannot be much effective because of the complexity of welding the crack whereas, replacing the joint can be more complex. The structural clamp can be the perfect one in this scenario, as ROV use can be done in case of worse climatic and water conditions. Using clamps changes the load path of the structure and increases the fatigue life by several times. As the following type of clamp is available:

1. Mechanical clamp
2. Stress elastomer lined clamp
3. Stress grouted clamp
4. Unstressed grouted clamp

A mechanical clamp cannot be used for nodal joints, and a stress elastomer lined clamp will be too flexible for use at this joint. We can use a stressed grouted clamp or unstressed grouted clamp as per the needs. The procedure and equipment of working are:

1. Detail inspection of the structural member and surface
2. Detail designing of structural clamp
3. Cleaning the surface of the structural member
4. Fitting of the clamp with the help of ROV and divers if necessary. Multiple cameras and ROV for support can be required
5. Inspection of the joints after work completion.

Case III

Fig 5.22: severance *(Dehghani and Aslani 2019)*.

Figure 5.22 shows the condition of severance where a K joint is completely disconnected due to fatigue. Let us assume the member was located below the splash zone, and the joint was in one of the chord members. Two brace members are connected to a chord member.

Solution measures:

The condition of severance is shown above in the picture. The situation is near around the splash zone, which can be done by both divers and ROV. In the above scenario, possible mitigation can be:

1. Re-connecting with dry welding addition with grout filling and toe grinding.
2. Clamp with wet welding

When we do dry welding to reconnect the member, we can get the original fatigue life of the structure. Further, the fatigue life can be extended with the grout filling and toe grinding of the weld toe so that we can reduce the hot spot stress at the weld toe or by changing the load path by grouting. Figure 5.23 shows the connection of joint with dry weld and grout filling work.

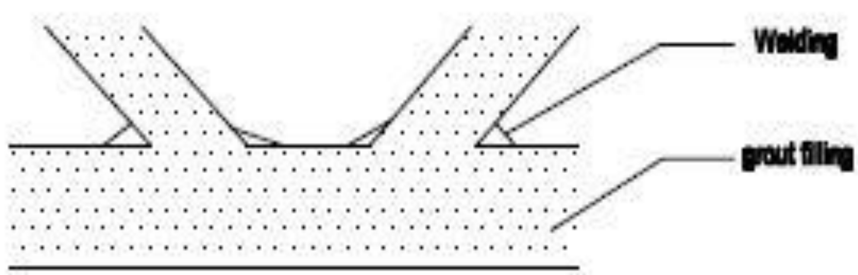

Fig 5.23: Connecting K joint with dry weld and grout filling

Procedure and equipment of working:

1. Habitat chamber for the dry environment working.
2. Divers for work execution.
3. Welding equipment and rods such as GTAW or SMAW are required.
4. Grout filling materials with ROV if necessary.
5. NDT test equipment to test after completion of work.

As per the second method, the connection can be made with the structural clamp. Either by using a stressed grouted connection or unstressed grouted connection. At first, the connection is done with the wet welding equipment and then followed by the clamp. The procedure and equipment are as follows:

1. Reconnecting the joints with wet welding can be done by divers.
2. Detail inspection of the structure surface for the design of clamp.
3. Design of clamp work.
4. ROV or divers for installation work.
5. NDT test after work completion.

Case IV

Fig 5.24: shallow crack at the weld toe.

Figure 5.24 shows the minor fatigue crack in a weld joint where the length of the crack is assumed to be one-fourth of the perimeter. Let us suppose the crack was penetrated 50% of the thickness. The location of the crack was around the splash zone.

Solution measures:

The situation above is assumed to be minor, or initiation phase fatigue crack supposed to be the depth of a and length l shown below in figure 5.25

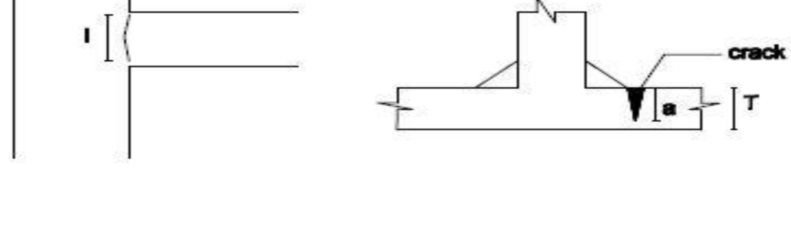

Fig 5.25: Picture of a shallow crack

For the above situation following measures can be applied:

1. Remedial grinding.
2. Stop hole drilling.
3. Dry welding.

Remedial grinding can be an effective measure for solving shallow cracks like these. In this situation, we can use heavy grinding disc equipment to extract out the crack. The work is done with a skilled expert, and the groove left should be filled with weld. Figure 5.26 shows the way of grinding and weld filling of the groove.

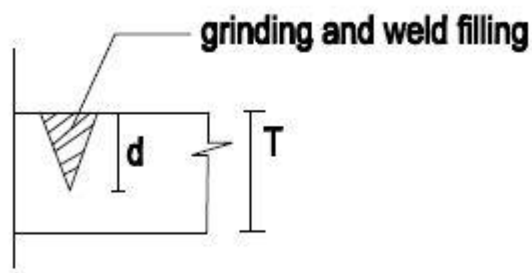

Fig 5.26: Grinding out the crack along with weld filling.

Equipment and procedure for grinding work:

1. Skilled diver for work execution
2. Heavy grinding disc machine for grinding work.
3. Divers support if necessary.
4. Inspection and NDT work after work completion to test the desired strength.
5. Those prepared grooves of grinding should be filled with wet welding so that to prevent the further crack from that groove.

Case v

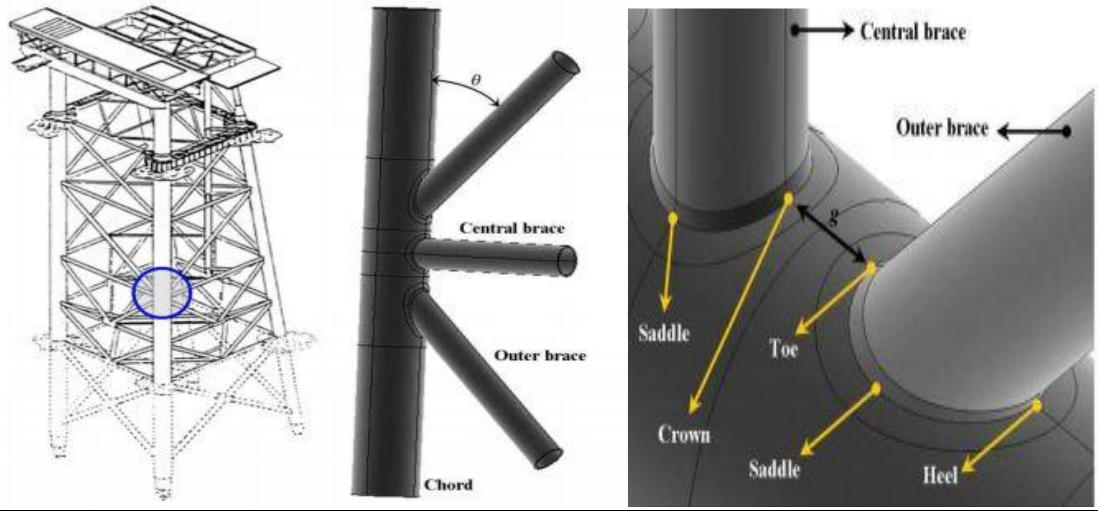

Fig 5.27: offshore steel platform with KT joints *(Ahmadi, Mayeli et al. 2019)*

Let us consider a minor fatigue crack at the weld toe of the outer brace member in between the central brace and outer brace member. The distance between them is considered as g, which is a small distance. The crack is located in almost the middle of the structure, as shown in figure 4.27. More detail of crack is assumed in figure 5.28 below

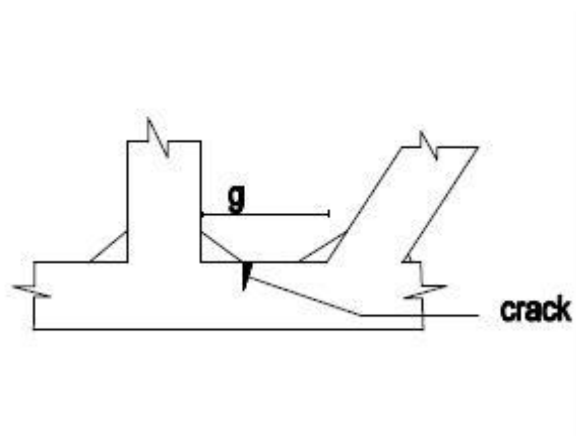

Fig 5.28: shallow crack at weld toe in between two chord members

Solution measures:

We can resolve these shallow fatigue cracks by choosing an easy way with less time spending on it. As it will be too expensive to work with a clamp or hyperbaric chamber for small crack. The best mitigation can be with grinding equipment followed by wet welding. Other measures like stop hole drilling can also be used but for temporary propose. So, in this case, we choose a remedial grinding task for crack extraction.

Procedure and equipment used:

1. Skill divers for work execution.
2. The rotary burr grinding disc machine for grinding work.
3. Inspection of the grind surface after remedial grinding work.
4. Weld equipment

Figure 5.29 shows the grinding procedure of crack in between the joints.

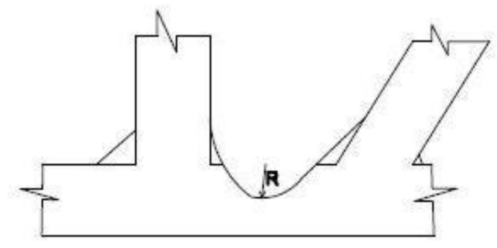

Fig 5.29: Grinding out the crack in between the brace member

Chapter 6: Work Execution

6.1 General

Work execution refers to the whole project starting from initiation to work completion. The project starts with the initiation phase by doing the inspection of the structure. After we find out the problem, either it is due to inadequate fatigue strength or a fatigue crack, then we go for mitigation measures. The most challenging part is the selection of the technique and design of the work process, where we choose the special mitigation approach to solve the problem. At last, we deploy the work either by Divers or by ROV to complete the task and followed by an NDT test and inspection if the structure gains the desired strength. Hence the work execution phase is completed *(MSL and Dier 2004)*. Figure 6.1 shows the structure of work execution.

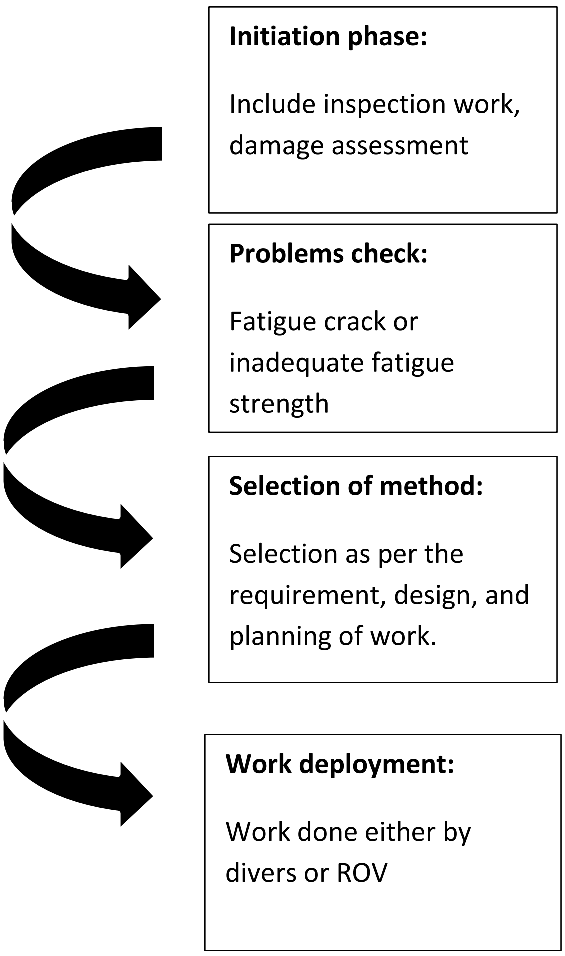

Fig 6.1: work execution cycle

6.2 Work deployment process

In offshore, repair work is done either with the diver or with diver less technology. In several situations, we can use both processes at a time to complete the work. As the work start from the initiation phase with inspection of the damage, where directly divers can perform the task, or we can use ROV for inspection. Divers used to work almost for every work in offshore industry before. When to execute work at a deeper level, saturation diving was needed along with diver support which can be expensive to execute. Besides, when divers used to work for a longer period in water is a high-risk task in terms of health and safety. That can further lead to accidents and life loss. So, for better work execution, diver less work implementation process was started. In 1950 U.S developed ROV for the purpose of removing mines but later developed it as offshore equipment work by the military *(Sharp and Ersdal 2021)*.

The major things for implementation of driver-less techniques are:

- For deep-water work, beyond saturation level work is very hard by divers
- A health issue for divers, even chances of life loss
- For safety issue when working at caisson points
- Cost-benefit, easy operations, efficient to perform *(MSL and Dier 2004)*

6.3 ROVs in offshore structure

ROV refers to Remotely Operated Vehicles. They help to make our work easier and more convenient. Since the starting of ROV has completely changed in operational style in oil production as well. They are the human-controlled equipment which can work up to water unreachable zone for inspection and repair work *(Shukla and Karki 2016).* On using ROV for inspection and repair work, we should maintain a stable position, and heading is important for operation. Nowadays, the latest ROV equipped with station-keeping can easily process to observe stationary targets for a long time *(Tena August 2011)*.

Various sizes of ROV with their classification and uses are available. The application of ROV depends upon its size, power, weight, and classifications. The classification of ROV is described below:

1. Observation class: These are vehicles that weigh around 100 kilograms. And use for observation purposes. Mostly, they are used for backup to divers. Their work depth limit ranges to less than 300m.
2. Mid-size ROV: The vehicles weigh from 100 kg to 1000kg with sufficient AC power supply and can work up to deeper depth.
3. Work class ROV: They are heavy electromechanical vehicles running on high voltage. They are vehicles with tooling functions.
4. Special use vehicles: they are the special vehicles without swimming capacity, such as crawling underwater vehicles, towed vehicles *(Christ and Robert L. Wernli 2014)*.

Fig 6.2: Powerful Magnus plus ROV *(oceaneering)*

Fig 6.3: mid-size ROV *(Christ and Robert L. Wernli 2014)*

6.4 Work deployment of different repair method

As mention in chapter 4, we have several mitigation measures for fatigue crack and inadequate fatigue strength. Each method has a different work deployment process. On the basis of different literature studies, we tried to find out the different work and their work deployment process in table 6.1.

Mitigation method	Work deployment by	Description
Dry welding	Divers	It can only be executed with divers with the construction of cofferdam or in a hyperbaric chamber *(MSL and Dier 2004)*.
Structural clamp	Divers/ROV	They are heavy work, mostly preferred by ROV.
Remedial grinding	Divers/ROV	It can be executed by both Divers and ROV
Hole drilling	Divers/ROV	Work can be executed by both divers and ROV (Sharp and Ersdal 2021).
Member removal	Divers/ROV	It can be executed in both ways.
Peening	Divers	Work cannot be executed underwater, so always executed with divers (MSL and Dier 2004).
Toe grinding	Divers/ROV	It can be executed by both Divers and ROV

Grout filling	Divers/ROV	It can be executed in both ways i.e., using two ROV at a time or by divers *(Welham and Gilfrin 1993)*.
Wet welding	Divers/ROV	It can be deployed in both ways.

Table 6.1: work deployment process of different repair method

6.5 Literature on ROV and Driverless technology

"Beryl Bravo: Diver less structural repair" 1994

Beryl Bravo is a platform installed in the northern sea in 1983, which, ten years later, faces severe corrosion due to seawater at the caisson. The repair task was carried out completely by remote operating without any involvement of divers. According to the report, the use of ROV in this task was due to cost-effectiveness. On detailed surveying, the platform was found corroded in a lift caisson, where MSL Engineering was appointed as a consultancy engineer for the repair of the platform. Various repair method was considered but rejected due to physical factors like cost and technical problem and later Stress elastomer lined clamp was chosen for repair work.

Installation: Installation work was performed by ROV, cameras were installed together with a monitor placed in the ROV cabin for clear vision and control. The diameter of the caisson was 674mm, and the diameter of the clamp was 508mm. At first, the inspection was done before the installation of the clamp by ROV for finding the position of the clamp relative to its surroundings. A hydraulic lift was used to raise the installation frame. The major challenge was to control ROV for observation work.

Time: The installation work was started on 1 September and worked end on 26 September. The weather condition was a little worst at that time.

"Strengthening modification and repair of offshore installations: Driverless implementation studies" by MSL 1995

The report by MSL consists of a topic on Diver less work implementation on section VI. The topic contains about:

- The deployment of heavy steelwork using ROV and buoyancy
- Scenario and selection
- Feasibility investigation for the selected scenario.

During 1994, on Beryl Bravo platform repair, MSL engineering was appointed as Consultancy engineer for the repair of lift caisson. So, the report also explains the repairing of the Beryl Bravo platform in 1994.

"Scope, Feasibility of Autonomous robotic subsea intervention systems for offshore inspection, maintenance, and repair" November 2018 by L. Fahrni, P.R. Tries, L. Johanning, J. Cowles.

The paper explains the scope and operation work of ROV and AUV for inspection and repair work over the diving system in marine work. According to the paper, there are six different classes of ROV for operating marine work, as shown below in table 6.2.

Class	Description
I	Pure observation ROVs
IIA	Observation class vehicles with a payload option.
IIB	Observation class vehicles with light in-tervention/survey and construction capability
IIIA	Standard work class vehicles with a pay-load of <200kg and through frame lift of approx. 1000kg
IIIB	Advanced work class vehicles with a pay-load of >200kg and through frame lift of up to 3000kg
IVA	Towed vehicles, typically ploughs used in subsea cable burial operations.
IVB	Tracked vehicles utilising water jetting and specialised rock cutting tools, again used in the burial of subsea cables and pipelines.
V	Prototype or development vehicles
VIA	Autonomous Underwater Vehicles (AUVs) weighing <100kg
VIB	Autonomous Underwater Vehicles weighing > 100kg

Table 6.2: ROV class *(Fahrni, Thies et al. 2018)*.

And the potential field for the use of ROV inspection work are:

- Offshore oil and gas
- Offshore wind
- Cathodic protection monitoring
- Weld inspection
- Grout inspection
- Cable survey*(Fahrni, Thies et al. 2018)* .

"Subsea robotic friction welding repair system" by A. Meyer, A roos, J.F. Dos Santos, D. Gibson, G. Blakemore, National hyperbaric center, offshore technology conference 2001

The paper is about ROBHAZ robotics, an affordable robotic for underwater welding repair system where an advanced friction welding process is involved FHPP (friction hydro pillar processing). In this robotics, Friction head welding is known as HMS 3000, which is attached with the TRICEPS robot. TRICEPS robot is a six axes electric robot for subsea application. So, the major part of this robot is

- Subsea robot (TRICEPS)
- Friction welding head

The major application of this robot is

- Subsea pipelines
- In-situ underwater repairs *(Meyer, Roos et al. 2001)*.

OTC 7195 "Installation of grouted pile-sleeve connection" a state-of-the-art review by T. R. Welham and J.A. Gilfrin, 1993

The paper is about grout filling for pile sleeve connection in offshore structures. A short section in this article describes how robotics can be used for grout filling. According to the author, two ROVs can be used at a time during operation for Grout. This is considered heavy ROV operation work. One of the ROVs is employed with hoses and operating valves, whereas others carry the grout materials *(Welham and Gilfrin 1993).*

Chapter 7: Comparison and discussion

The selection of the technique is made as per the necessity of the repair. However, the selection criteria are based on various aspects such as cost, working time, the location of the crack, size of the crack, etc. The main thing is that the selected technique should be able to cope with the damage and be able to extend the static and fatigue life of the structure. When we discussed the fatigue problem in the structure, the techniques to solve the problems, that are mention below:

Fatigue crack resolving method

1. Remedial Grinding
2. Structural clamps
3. Dry welding

Damage delaying and fatigue life improvement method

1. Stop hole drilling
2. Member removal

When we want to strengthen up the fatigue strength or to upgrade the fatigue life of the joint and structures, the following measures can be used:

1. Toe grinding
2. Weld residual stress improvement method (peening)
3. Grout filling of the member and joints

Besides these techniques, the wet welding method can also involve fatigue crack removal while connecting with the weld beads before stress-grouted connections. The physical aspects affecting the repair are the time of working, strength gain after repair, size, and shape of the crack, location of the crack either inside or outside the water and so on. The different technique needs a different way of execution, inspection, equipment types, and planning. Some are simple and easy to execute, and some are difficult for work deployment. However, we are trying to distinguish the feature of those mentioned technique

Cost

Cost is one of the prioritized things while comparing different mitigation methods. For example, the work cost for repair underwater and above the water surface is different. So, the cost is also a factor-dependent with other physical aspects. It shows that every cost-efficient work will not be feasible for every type of repair work. Some of the tasks should be beyond the cost feasibility criteria. Following is the description of the cost and expenses of different repair method:

1. Dry welding: Dry welding technique is an expensive technique in terms of cost. Mainly, the cost of fabrication and installation work can be expensive in dry welding. The work like construction of cofferdam or habitat and their sealing work may also take time. The cost of installation for cofferdam work increases with the increase in depth needed to be repaired. Cofferdam's work is not feasible with the increase in depth of water from the splash zone for more than 15m. the sealing work for habitat and divers employed for welding is also heavy work compared to other mitigation measures. But, the equipment used for welding is low-cost work.

2. Remedial grinding: Grinding is done with a burr grinding machine. Those equipment are heavy and require skilled manpower for work along with the skill divers to execute the work. The comparative cost of equipment, installation work, and deployment cannot be considered as expensive one while comparing with other methods. The inspection work after the task is also low-cost work as compared to other tasks.
3. Clamp technology: There are four different clamps mentioned in chapter 4, but only three different clamps can work for fatigue crack repair and fatigue life extension. They are:
   i. Mechanical clamp
   ii. Stressed grouted clamp
   iii. Unstressed grouted clamp
   ~~iv. Stress elastomer-lined clamp~~

   Stress elastomer lined clamp cannot be used for primary structure repair. A thin neoprene sheet is used in between the connection of clamp and structure, which is made of solid polychloroprene. Thus, the flexibility of those liners can reduce the total efficiency of the clamp on the structure. But this type of clamp can be used at caisson and guide frame repairs.

   Clamp technology is tedious and costly work for repair. The inspection cost is higher than others because it requires the complete inspection of the structure surface that needed to be repaired. The deployment work is also costly as compared to other repairs. In comparison, the mechanical clamp is a bit low-cost work than the others clamp. And the cost of planning and designing the work of clamps is more than other crack repair methods.

4. Toe grinding: Toe grinding work is executed with a normal burr grinding tool or with disc grinding. But mostly preferred with the rotary burr grinding machine. This task is only for weld improvement at joints for fatigue life improvement. The equipment cost is low for this work execution. Besides, inspection work, planning, and grinding task need skilled manpower and divers to execute work. The comparative cost of repair is lower than other methods.
5. Peening method: Peening method can be done by the tool like hammer peening, shot peening, needle peening, ultrasonic peening to increase the compressive residual stress method at joints. As per their previous application, the peening method is used for the structure above the splash zone or in a dry environment like cofferdam. This can be an economical technique because less equipment is needed to improve the weld stress at the joints.
6. Grout filling: Grout filling include both the member and joint filling work with cementitious grout. Grout filling work can also be used along with the clamp. The material cost for grout is low-budget work, and work deployment is also an easy task as compared to other methods.
7. Member removal: Member removal for fatigue life restrengthening is done when the member is redundant. It requires the cutting equipment of moderate cost and less time for working, which means that the onshore cost for member removal is low. While removing and replacing a severance damaged member, additional cost involves in it with the further requirement for connection.
8. Stop hole drilling: Stop hole drilling technique can be the most efficient technique for retarding the fatigue crack temporarily. As the technique can be performed by cost-efficient tools and skilled divers. In terms of cost, stop-hole drilling requires low offshore costs as well.

Working time

Time of working for repair is a physical factor that depends on other criteria as well. For example, in Beryl Bravo offshore repair, the working time starts from September 1 to September 26. The cause of delay was due to adverse weather conditions *(Gallbrith, Ltd. et al. May 1994)*. The work time is also a proportional factor to the cost of repair as well. When we see the different repair methods, the difference in work time is due to the different way of work execution, such as working by divers and ROV. The variations of time for different repair methods are explained below:

1. Dry welding: Dry welding is an easy task to deploy for working. But the construction of cofferdam and habitat chamber is a major difficult task. When we construct the chamber, we should be very careful in sealing work so that water doesn't leak inside. Overall, dry welding is a time taking task due to the installation and fabrication work of the chamber. But the welding task is a very short period of work followed by the inspection of work through MPI or APCM.
2. Remedial Grinding: Grinding out the crack from the weld joints takes a little more time than normal grinding work. When we do the remedial grinding, we should follow the crack until the grinding machine completely evacuates the crack. Those grind surfaces should have a smooth and perfect finish. One should take care of thickness as well while performing. Besides, this task needs a skilled diver to perform the work. So, considering all these works, remedial grinding can be taken as the average time taking work for fatigue crack repair. And work time is dependent on the length and depth of the crack as well.
3. Clamp technology: As already mentioned, only three different clamps can be used for fatigue crack repair. In which the mechanical clamp is the easiest and fastest work of repair. The others two clamps require a little more time for work. This is because, in an unstressed grouted clamp, the tolerance capacity of the grout material over the structure surface should be checked. Similarly, in the stressed grouted clamp, the stress produced by both stud bolts and grout material tolerance capacity over the damaged structure surface should be capable. Besides, it includes design work of clamp, fabrication work, installation time, and proper inspection of the surface so that clamp can be perfectly fit on the surface. Hence, all these tasks cover a lot of time for work. We can conclude clamp as time taking task.
4. Toe grinding: Toe grinding work is one of the quick works of weld improvement. The task is done in weld surface with the rotary burr grinding machine and skilled divers. The time of work can be said as 1 man hr/m *(MSL and Dier 2004).*
5. Peening method: Peening work is also considered as a quick method of working required skilled manpower. In a lab test of hammer peening, the time of working was noted as 0.25 hours per meter for a skilled worker *(MSL and Dier 2004)*.
6. Grout filling work: Nowadays, grout filling work can be done easily with the help of ROV, so the installation of grout either in the member or in the joints is also a quick work of repair and strengthening method.
7. Member removal: Member removal, especially redundant member removal, is a quick task performed by a special cutting machine.
8. Stop hole drilling: Hole drilling work is also a short period of work of repair. Inspection of the crack size and calculation of hole size according to the need is done. With the help of drilling equipment, the task is done in a quick time.

Fatigue life gain
After the successive repair work, the structure enhances its fatigue life by a certain percentage. Different repair method improves the fatigue life by different way either locally or globally. The description of fatigue life gain is discussed below:

1. Dry welding together: The dry welding process can return back the structure to basic fatigue and static life.
2. Remedial grinding: The strength gain by the remedial grinding is dependent upon the length and size of the crack. Generally, grinding is done up to 60% of the thickness of the structure. So, the strength varies with the depth of the crack. As per MSL report 1995, the remedial grinding work can gain the fatigue life by 2.2 times the basic fatigue life of the joints.
3. Clamp technology: In clamp technology, the fatigue life gain is comparatively higher than any others method. The reason is solving the method globally by changing the load path of the structure. The different clamp has a different strength to withstand against the fatigue load. As per the MTD report 1993, the fatigue life can be 750 times the basic fatigue life.
4. Toe grinding: In toe grinding, we resurface the parent weld materials by reducing the stress at the weld joints. Toe grinding reduces the stress involved at the joints. Various experimental work has been done for this method. In most of the experiments, the fatigue life gain is more than two times the basic fatigue life. In the experiment of J.E. Rodriguez shows that the minimum fatigue life gain of one sample was 1.6, and the others were ranging in between 2 to 4 times the basic fatigue life. As per MSL report 1995, the fatigue strength gain by toe grinding work is 2.2 times the basic fatigue life.
5. Peening method: The peening method strengthen up the fatigue life more than the basic fatigue life. This method also reduces the tensile stress at the notch and increases compressive strength. Due to which the fatigue life is improved at the joints. The fatigue life gain by peening work depends upon the experiments.
6. Grout filling: As per the MTD report 1993, the strength gain after grout filling is 60 times the basic fatigue life. This method works globally by changing the load path of the structure. Grouting is a very effective way to reduce stress concentration.
7. Member removal: Unnecessary member removal from the structure by 10-15% can re-strength the fatigue life by 1.5% *(MTD 1994).*
8. Stop hole drilling: The fatigue life gain by the hole drilling technique depend upon the experiment work, length, and size of the crack.

Work deployment
Normally work deployment is done either by divers or by ROV. Early repair work used to be done with the help of divers. But concerning the health and safety of divers, diver less work implementation has been started. Still, every task cannot be done with ROV because of some limitations. The way of deployment is explained below:

1. Dry welding: Dry welding is done in the chamber or in habitat with personnel involvement and divers. So, ROV is not used for dry welding.
2. Remedial grinding work: In the case of remedial grinding, Burr grinding machine is used for work. Rotary burr grinding tools have a rotational speed of range 15,000 to 40,000 rpm. The work is mostly preferred by the divers but can be executed by both divers and ROV *(Rodriguez-Sanchez 2004).*

3. Clamp technology: Clamp technology is heavy and tedious work for divers. As the size of the clamp is also heavy. The mechanical clamp is little light but, the unstressed grouted clamp and stressed grouted clamp require heavy support for the work. So, clamp technology is better to execute with ROV. It can be done by both divers and ROV.
4. Toe grinding: Toe grinding is also done with a burr grinding machine. This method also requires a precise grind on the surface. This method is better to perform with divers but can be executed with ROV as well.
5. Peening method: Peening work need skilled worker to perform. As mention before, peening is preferred for air work only. So, the task is done with a skilled worker.
6. Grout filling: Grout material is a heavy Cementous liquid that is hard to carry. Basically, grout can be done with the help of two ROVs and can also be done with divers.
7. Member removal: The cutting tools should be handled carefully, and further precautions after cutting are required to prevent the fall and accident. This can also be done either by divers or by ROV.
8. Stop hole drilling: The drilling work also need precise work. But the task of drilling is short time taking work which can be done by divers. Further implementation of ROV for drilling work will surely be done *(Sharp and Ersdal 2021)*.

comparison table

Table 7.1 shows the comparison of a different technique in terms of applicability, fatigue life gain, equipment used, work deployment, work time, cost, and advantages.

	Fatigue crack resolving method					damage delaying and fatigue life enhancement method				
Description/repair method	Remedial Grinding	Dry welding	clamp			Stop hole drilling	Member removal	Grouting	Toe grinding	Weld stress residual method (peening)
			Mechanical clamp	Stress grouted clamp	Unstressed grouted clamp					
Applicability	Good for crack depth up to 60% thickness of the steel structure.	Applicable for all type of crack type and size. Cofferdam only applicable for splash zone repair.	Applicable for any types of crack except in joints and connection due to complexity	Good for shallow to severance type of crack but choice as per the economic needs	Good for shallow to severance type of crack but choice as per the economic needs	Effective for short length crack.	Applicable for any depth just to strengthen up the fatigue life by removing redundant member	Fatigue strength improvement method is done at weld repair joint to increase the strength of joints	Applicable for removing the parent materials and weld stress removal of joints. It can also be used for minor crack removal work	Mostly applicable for weld joints above the splash zone
Fatigue life gain	Depend upon the experiment and size of the crack.	Can gain the normal fatigue strength.	Depend on the design and complexity of the clamp.	Depend on the design and complexity of the clamp.	Depend on the design and complexity of the clamp.	Depend on the work and size of the crack.	Fatigue strength gain as per the weight removal from the structure	Fatigue life gain is high.	2.2 times the basic fatigue life	It depends as per the work and higher than any other method
Equipment use	Burr grinding machine	Welding equipment, fabrication, and sealing equipment for chamber and habitat construction	Mechanical clamp, stud bolts	Clamp, grout materials	Clamp, stud bolts, grout materials	Drilling equipment	Cutting equipment like a diamond wire cutter	Grout materials	Burr grinding machine	Peening tool
Work deployment	Divers/ROV	Divers	ROV/Divers	ROV/Divers	ROV/Divers	Divers/ROV	Divers/ROV	Divers/ROV	Divers/ROV	Divers
Work time	Quick task in compared to crack resolving method.	Quick repair time but take a long time in construction and installation work of chamber and habitat	A quick task, comparison to other clamp but take time in inspection, fabrication, and installation.	Long time taking task including installation, inspection, and fabrication work	Long time taking task	Quick work	Quick work	Quick work	Easy and quick task	Quick work
Cost	Economic work	Can be costly for construction of habitat and cofferdam	Average cost work	Expensive work	Expensive work	Economic work	Economic work	Economic work	Economic work	Economic work
Advantages	A quick method of fatigue crack removal	Universally accepted technique	Strengthen up the fatigue life by several times	High tolerance capacity	High tolerance capacity	Quick and temporary method for retarding fatigue crack	A relatively quick method of repair	A quick method for improving fatigue life	A quick method for weld improvement	Good for reducing tensile stress at joints

Table 7.1: comparison of the different method in different aspects

Chapter 8: Summary and conclusion

There is a necessity for repairs and fatigue life extension for ageing steel offshore structures. Based on the statistics of experienced damages to offshore steel structures, fatigue and corrosion damage are the dominant problems in steel structures. In addition, damage due to vessel impact, installation and fabrication faults are also relevant.

Fatigue crack mainly occurs at welded connections due to the inherent weld defects under continuous cycling loading. Fatigue crack has different phases according to their size, length, and situation, e.g., initiation, growth, and fracture phases.

A literature review of different reports and articles is performed on the topic of repair methodology. There are several methods for the repair of steel structures, but only a few techniques can be used to repair fatigue crack, e.g., techniques such as dry welding, structural clamp, and remedial grinding. Stop hole drilling and member removal techniques can be used as damage delaying techniques for the crack. In addition, the fatigue life of the joint can be increased by weld improvement techniques and grout filling. Grout filling can also be used as a repair method.

Codes and standards like ISO, NORSOK, API, DNV suggest the needed remediation measures and strategies for different kinds of damage. In addition, they provide assessment methods for fatigue life calculation.

The choice of repair method is based on several factors such as applicability, fatigue cost, time of installation and fabrication, reliability, work deployment process, and many more. Analytic hierarchy process and multicriteria dimensional analysis are used to determine the repair method's hierarchy as per the selection criteria. The influencing factor for selecting a repair method, like applicability and fatigue by the structure, affect most in selecting the repair method. However, time and costs are also important factors in choosing a repair method according to the size and location of the crack. Different repair methods can be executed for different locations of crack, e.g., in the atmospheric zone, splash zone, or the submerged zone.

Dry welding and clamp technology are the best techniques to repair fatigue cracks or member severance, but they are also the most expensive and time-consuming techniques. The time needed for design, installation, and fabrication for these repair methods is relatively high. For shallow fatigue cracks, quick and low-cost repair techniques such as remedial grinding and stop hole drilling can be used. The fatigue strength of these techniques depends on the crack size and location.

Weld improvement technique reduces the stress concentration at the weld toes and increases the fatigue strength of the joints. Weld improvement methods such as toe grinding, hammer peening, shot peening are used offshore. The peening work is preferred in a dry environment whereas, grinding work can be done in deep water as well. Grout filling work can be used for both fatigues life enhancement methods and repair methods. The fatigue life gain by grout filling is generally high, and the work is quick and economical.

The work deployment can be done either by ROVs or by divers. Concerning the environmental situation and diver health, ROVs are preferred over divers if possible. The limitation is, every work cannot be executed by ROVs like dry welding.

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Appendix

The normalize matrix formation of different method from excel sheet is shown below

Table 1: Normalize matrix form of fatigue crack repair method

Table 1	size/location	cost	time	fatigue life gain	work deployment	sum	avg
size/location	0.37	0.39	0.36	0.36	0.28	1.76	0.35
cost of repair	0.09	0.10	0.12	0.09	0.20	0.60	0.12
time of repair	0.12	0.10	0.12	0.12	0.20	0.66	0.13
fatigue life gain	0.37	0.39	0.36	0.36	0.28	1.76	0.35
work deployment	0.05	0.02	0.03	0.07	0.04	0.22	0.04

Table 2: Check for the normalize matrix to calculate C.I and C.R.

Table 2	size/location	cost	time	fatigue life gain	Work deployment	sum	sum/avg
size/location	0.35	0.48	0.40	0.35	0.31	1.89	5.36
cost of repair	0.09	0.12	0.13	0.09	0.22	0.65	5.39
time of repair	0.12	0.12	0.13	0.12	0.22	0.71	5.34
fatigue/static life gain	0.35	0.48	0.40	0.35	0.31	1.89	5.36
work deployment	0.05	0.03	0.03	0.07	0.04	0.23	5.20

Table 3 and table 4: Normalize matrix form for fatigue life enhancement method and check for the normalized matrix to calculate C.I. and C.R.

Table 3	fatigue life gain	applicabilit y	cost & time	work deployment	sum	avg
fatigue life gain	0.40	0.40	0.41	0.39	1.61	0.40
applicability	0.40	0.40	0.41	0.39	1.61	0.40
cost & time	0.13	0.13	0.14	0.17	0.57	0.14
work deployment	0.06	0.06	0.05	0.06	0.22	0.05

Table 4	fatigue life gain	applicabilit y	cost & time	work deployment	sum	sum/avg
fatigue life gain	0.40	0.40	0.43	0.38	1.61	4.01
applicability	0.40	0.40	0.43	0.38	1.61	4.01
cost & time	0.13	0.13	0.14	0.16	0.57	4.00
work deployment	0.06	0.06	0.05	0.05	0.22	4.00

Table 5 and table 6: Normalize matrix formation of repair method in terms of fatigue life gain by the structure and check for normalized matrix C.I. and C.R.

Table 5	dry weld	remedial grinding	hole drilling	sum	avg
dry weld	0.55	0.57	0.50	1.62	0.54
remedial grinding	0.27	0.29	0.33	0.89	0.30
hole drilling	0.18	0.14	0.17	0.49	0.16

Table 6	dry weld	remedial grinding	hole drilling	sum	sum/avg
dry weld	0.54	0.59	0.49	1.62	3.01
remedial grinding	0.27	0.30	0.33	0.89	3.01
hole drilling	0.18	0.15	0.16	0.49	3.00

Table 7 and table 8: normalize matrix formation of shallow crack repair method in terms of applicability and check for C.I. and C.R. of the matrix.

Table 7	dry weld	remedial grinding	hole drilling	sum	avg
dry weld	0.55	0.50	0.57	1.62	0.54
remedial grinding	0.18	0.17	0.14	0.49	0.16
hole drilling	0.27	0.33	0.29	0.89	0.30

Table 8	dry weld	remedial grinding	hole drilling	sum	avg	sum/avg
dry weld	0.54	0.49	0.59	1.62	0.54	3.01
remedial grinding	0.18	0.16	0.15	0.49	0.16	3.00
hole drilling	0.27	0.33	0.30	0.89	0.30	3.01

Table 9 and table 10: Normalize matrix formation of shallow crack repair method in terms of cost and time of work, installation and fabrication along with the check of C.I. and C.R.

Table 9	dry weld	remedial grinding	hole drilling	sum	avg
dry weld	0.08	0.06	0.10	0.25	0.08
remedial grinding	0.42	0.31	0.30	1.03	0.34
hole drilling	0.50	0.63	0.60	1.73	0.58

Table 10	dry weld	remedial grinding	hole drilling	sum	sum/avg
dry weld	0.08	0.07	0.10	0.25	3.01
remedial grinding	0.41	0.34	0.29	1.04	3.03
hole drilling	0.49	0.69	0.58	1.75	3.05

Table 11 and table 12: Normalize matrix formation for growth phase and fracture phase crack repair method and check for C.I. and C.R. of the matrix.

Table 11	fatigue/static life gain	applicability/location	Cost &time	work deployment	sum	avg
fatigue/static life gain	0.53	0.54	0.55	0.44	2.05	0.51
applicability/location	0.26	0.27	0.27	0.31	1.12	0.28
Cost &time	0.13	0.14	0.14	0.19	0.59	0.15
work deployment	0.08	0.05	0.05	0.06	0.24	0.06

Table 12	fatigue/static life gain	applicability/location	Cost &time	work deployment	sum	avg	sum/avg
fatigue/static life gain	0.51	0.56	0.59	0.42	2.08	0.51	4.05
applicability/location	0.26	0.28	0.30	0.30	1.13	0.28	4.03
Cost &time	0.13	0.14	0.15	0.18	0.59	0.15	4.02
work deployment	0.07	0.06	0.05	0.06	0.24	0.06	4.01