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ASSESSMENT OF REPAIR TECHNIQUES FOR AGEING OR DAMAGED STRUCTURES

Project #502

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Assessment of Repair Techniques for Ageing or Damaged Structures

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Final Project Report:

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MMS Project Number 502

November 2004

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UNITED STATES DEPARTMENT OF THE INTERIOR

MINERALS MANAGEMENT SERVICES

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Table of Contents

EXECUTIVE SUMMARY

General

This document has been prepared by MSL, on behalf of the Mineral Management Services, for all those concerned with the Strengthening, Modification and Repair (SMR) of offshore steel installations.

SMR is an important aspect of offshore engineering to ensure continued safe operation of offshore installations. However, it requires rather different skills and knowledge to normal jacket/topsides design and is considered by many to be specialist work. SMR operations tend to be highly engineered, certainly for moderate and major works, in order to minimize the high costs associated with offshore works. All too often, however, either inappropriate, unnecessary or expensive SMR schemes have been deployed, primarily as a result of the lack of skills/knowledge. This document has been written with the intent that such inappropriate schemes can be avoided, by guiding the engineer through the main ideas involved in selecting optimal SMR scheme and individual SMR techniques.

It is noted that with the exception of the rise of composite materials in SMR schemes, there has been no fundamental change over the last decade in the available techniques to effect SMR. However, there have been some developments in welding consumables and in grout materials.

A ‘road map’ of how to use this document, and which summarizes the relationship of the various sections within this report, may be found in Section 1.3.

Initiators

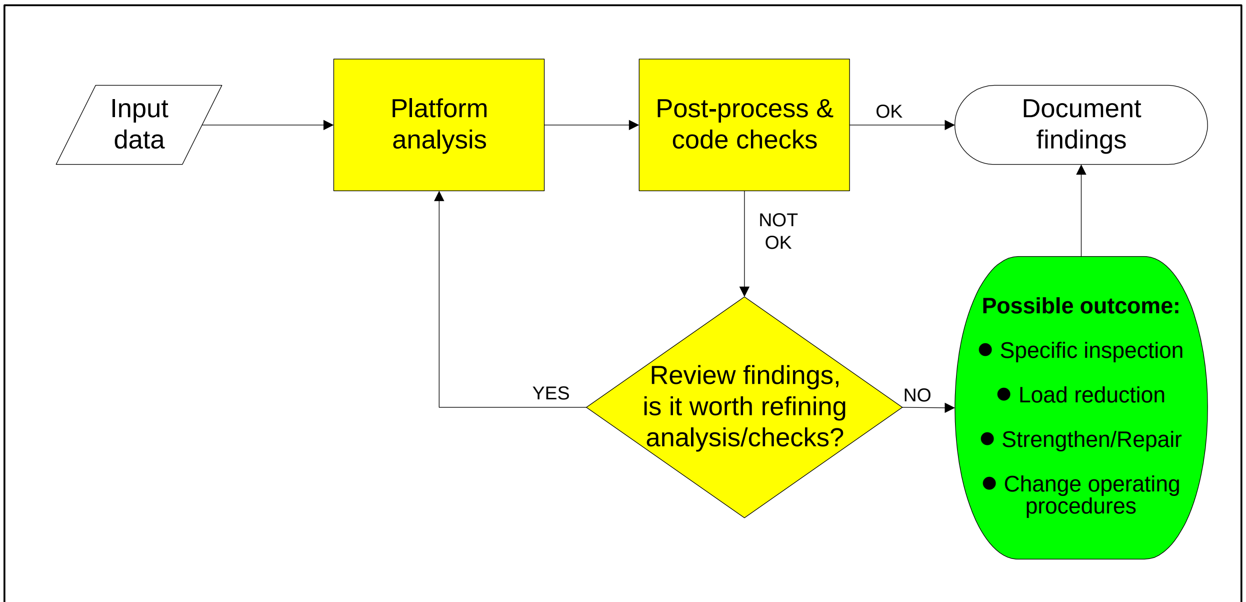
The SMR scheme and individual SMR technique selection process begins by gaining an appreciation of the causative agents that may, but not necessarily, lead to a requirement for SMR. These initiators can be summarized as falling into one of four categories:

1. Change in platform operation
2. Life extension
3. Damage (or potential damage) caused by:
    - Vessel collision
    - Dropped object
    - Fatigue
    - Corrosion
    - Mishandling during the installation process
    - Fabrication / design fault
    - Occurrence of design event

4. Code updates or operator-led safety measures.

Structural Assessment

A structural assessment will normally be required at the outset to ascertain whether or not some level of SMR is required, and if so to indicate the extent of the required SMR scheme. The structural assessment comprises both platform analysis (to establish member loads or the resistance of the whole platform to design events) and code or other checks on the (intact or damaged) component capacity. Whereas it is normal engineering design practice to conduct simple linear analysis and code checks (e.g. to API RP2A) for demonstrating the structural adequacy of new build structures, it will often prove beneficial in potential SMR situations to use refined or advanced analysis techniques and/or component checks falling outside the scope of standard codes. In many cases such refined/advanced analysis or component checks will demonstrate that the structure is fit-for-purpose and that no SMR is required. A staged approach to the assessment is recommended, where the results of each stage are reviewed to decide on the merits of further refining the analysis and/or component checks. This process is summarized in the figure below.



Overall assessment approach

The quality of the input data has a significant bearing on the success of above assessment process. The as-built structural geometry, together with any subsequent modifications, should form the basis of the model. It will usually prove advantageous to have knowledge of the actual yield strength (e.g. from traceable mill certificates) of the materials used in the fabrication as these can be 15% or more, higher than the specified minimum yield strength (SMYS).

The possibilities for refining the analysis, and the possibilities for improved component checking are summarized in the tables below. It should be noted that these refinements and improvements are independent of each other, e.g. refined code checking can be, and often is, used in conjunction with the results from a basic analysis.

ANALYSIS	POST-PROCESSING / CODE-CHECKING
BASIC ANALYSIS • As-built + modifications • Node-to-node stick model • Remove damaged member?	**STANDARD CODE CHECK (API RP2A)** • Yield based on SMYS
SIMPLE REFINED ANALYSIS • Member eccentricities/offsets • Remove double counting of wave load • Residual stiffness of damaged member	**REFINED P-P / C-C** • Yield based on Mill Certificates. • Review member effective lengths • Review SCFs • Appraise capacity of damaged elements - Assessment of existing test data - Conduct Fracture Mechanics study • Reliability analysis
COMPLEX REFINED ANALYSIS • Local Joint Flexibilities (LJFs) • Hindcast site data • Probabilistic loading combinations	
ADVANCED ANALYSIS (PUSHOVER) • Non-linear member behaviour • Non-linear joint behaviour	**ADVANCED P-P / C-C** • Conduct FEA component study • Commission tests

Assessment Outcome and SMR Scheme selection

At the end of the assessment phase, it will be known that either no SMR is called for or that one of four outcomes should be pursued:

1. Specific inspection requirements are drawn up, for instance to monitor a defect.

2. A load reduction program is instigated. This may encompass removal of redundant topsides equipment, redundant members (as demonstrated in the assessment phase) or simply the removal of excess marine growth to reduce drag loading.

3. Some level of SMR is warranted.

4. Operating procedures are changed, e.g. manning/de-manning philosophy or direction of approach of service vessels.

In the case of item 3, when some level of SMR is proposed, four levels of remedial works of increasing complexity can be identified:

1. Remove damage (e.g. grinding out of cracks or removal of bent/bowed member).

2. Local SMR (defined as when no change of system load path occurs as a result of the SMR scheme – e.g. the introduction of a clamp around a member or joint is considered to be a local SMR).

3. Global SMR (defined as when a change of system load path does occur – typically when an additional member is introduced). Note that a global SMR scheme may include some local SMR elements.

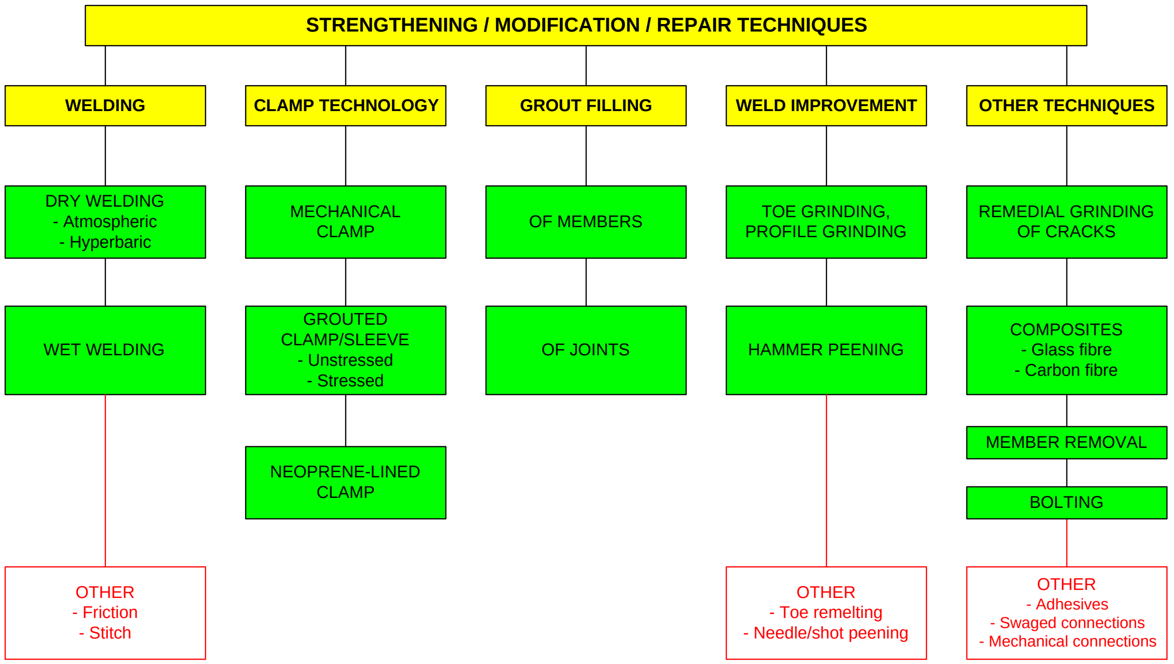
4. Total SMR (this entails major works such as tying in to a new adjacent structure). Note that a total SMR scheme will necessarily include some global SMR elements.

It should be apparent that for the global and total SMR schemes, the structure needs to be re-analyzed and checked to demonstrate that the proposed SMR scheme will achieve the required level of structural integrity.

SMR Techniques

Having selected the level of SMR, the individual SMR technique (or techniques) has to be chosen to realize the SMR scheme. In most cases there are alternatives that would achieve this objective; although in many instances, particularly for local SMR schemes, the choice may be fairly obvious. The selection of SMR technique(s) requires: knowledge of the available range of techniques, including variants; their strengths and weaknesses; and an appreciation of other factors such as ease of design, buildability, offshore support and equipment requirements, local supply infrastructure, etc.

A summary of the main SMR techniques that are available is presented in the figure below. (A more complete chart is given in the main text of this document.) The techniques at the bottom of the chart that are highlighted in red are considered to have limited application at the present time. Further detailed information on each technique is presented in Part 2 of this document.



Main SMR techniques that are available

The various techniques lend themselves to address one or more commonly occurring scenarios as indicated in the table below.

Technique	Defect							
	Fatigue crack	Non-fatigue crack	Dent	Corrosion	Inadequate static strength		Inadequate fatigue strength	
					member	joint	high loads	fabr. fault
Dry welding	yes(1)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes
Wet welding	no(2)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes
Toe grinding	no	no	no	no	no	no	yes	no
Remedial grinding	yes	yes(1)	no	no	no	no	no	no
Hammer peening	no	no	no	no	no	no	yes	no
Stressed mechanical clamp	yes	yes	no	yes	yes	no	yes	yes
Unstressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes
Stressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes
Neoprene-lined clamp	no	yes	no	yes	no	no	no	no
Grout-filling of members	no	no	yes	yes	yes	yes(4)	yes(4)	no
Grout filling of joints	no	no	yes	no	yes	yes(4)	yes(4)	no
Bolting	no	yes	no	no	no	no	no	no
Member removal	yes(5)	yes(5)	yes(5)	yes(5)	no	no	yes(5)	yes(5)
Composites	yes	yes	yes	yes	yes	yes	yes	yes

Notes: (1) Usually in conjunction with additional strengthening measures
(2) Except to apply weld beads in unstressed grouted connection/clamp repairs
(3) To apply patch plates
(4) Applicability depends on type and sense of loading
(5) If member is redundant (otherwise replace it)

Color coding	
Applicable	Not applicable

Applicability of SMR techniques

However, for a given scenario, some techniques offer better advantages than others in terms of offshore equipment requirements, timescales, costs and loading penalties, as indicated below.

Technique	Design Background		Equipment Needs	Offshore Installation Timescales	Onshore Fabrication Costs	Load Penalties	
	Static Strength	Fatigue Strength				Weight	Wave Load
Dry welding	yes	yes	heavy	very slow	high (for habitat)	none	none
Wet welding	yes	yes	moderate	quick	none	none	none
Toe grinding	N/A	yes	low	moderate	none	none	none
Remedial grinding	yes	yes	low	moderate	none	none	none
Hammer peening	N/A	yes	low	quick	none	none	none
Stressed mechanical clamps	yes*	yes*	moderate	quick	high	moderate	high
Unstressed grouted clamps	yes*	yes*	moderate	moderate	moderate	moderate	moderate
Stressed grouted clamps	yes*	yes*	moderate	slow	high	moderate	high
Neoprene-lined clamps	yes*	yes*	moderate	moderate	high	moderate	high
Grout filling	yes*	yes*	low	quick	low	high	none
Bolting	yes	yes	low	moderate	low	low	low
Member removal	N/A	N/A	moderate	quick	none	none	none
Composites	yes*	yes*	low	quick	moderate	low	low

Notes: * MSL has proprietary information

Bad	Poor	Color coding applies vertically not horizontally
OK	Good	

Comparison of SMR techniques

In the above table, it can be seen that dry welding carries severe cost and timescale penalties – mainly in respect of the need to construct either a cofferdam (for shallow repairs) or a hyperbaric habitat. Where wet welding is not considered feasible, then clamp technology must be employed to introduce new members into the structure or to reinforce nodal joints. A summary of the advantages and disadvantages of the individual techniques is presented in the table below.

Technique	**Advantages**	**Disadvantages**
Dry welding	Universally accepted from a technical standpoint.	Hot work permit required. Below the waterline, requires the construction of either cofferdam or hyperbaric habitat - both being time consuming and expensive. The cofferdam, in particular, will attract high wave loading.
Wet welding	Proven technique. Relatively quick method.	Not accepted in all parts of the world. Weld properties not as good as dry welds, although this can be accounted for in the design.
Toe Grinding	Doubles fatigue life.	Only applicable for fatigue life extension.
Remedial Grinding	Proven technique. Relatively quick method for arresting fatigue cracks.	Static strength needs to be assessed.
Hammer Peening	Very effective method for increasing fatigue life.	Only applicable for fatigue life extension.
Stressed Mechanical Clamp	Proven technique. Immediate capacity realized on tensioning studbolts. Can be used as an end connection to introduce new members into the structure.	Poor tolerance acceptability precludes use around nodal joints or over girth joints between tubular cans. Welds and other protuberances have to be ground flush or otherwise accommodated in depressions machined in saddle plate.
Unstressed Grouted Clamp	Proven technique. High tolerance acceptability. Can be used as an end connection to introduce new members into the structure.	Clamps are relatively long unless they, and the clamped member, are provided with weld beads.
Stressed Grouted Clamp	Proven technique. High tolerance acceptability. Clamps are relatively short. Can be used as an end connection to introduce new members into the structure.	There is a requirement to allow the grout to cure sufficiently before returning to tension the studbolts.

Technique	Advantages	Disadvantages
Neoprene-lined Clamp	Some tolerance acceptability. Can be used as an end connection to introduce new members into the structure.	Friction coefficient is lower than generally realized. Neoprene introduces flexibility, thereby compromising its ability to take up load if alternate load paths exist.
Grout-filling of Member	Proven technique. Relatively quick method.	Weight penalty, especially poor in seismic regions. Complete grout filling may be difficult to achieve.
Grout-filling of Joints	Proven technique. Relatively quick method. Good for improving both static and fatigue strengths.	Weight penalty, especially poor in seismic regions. Joints with expanded cans, or internal ring stiffening, are more difficult to grout fill.
Bolting	Good for topsides SMR.	Limited use below water.
Member Removal	Proven technique. Relatively quick method	Safety issue if member springs when final ligament severed.
Composites	Lightweight strengthening and repairs are possible. No hot work.	Longevity for underwater use is not yet proven.

Design

Details are given in the main text of the main drivers to consider in the design of the techniques. It is considered that the main driver for SMR schemes and SMR techniques is to reduce the offshore effort in implementing the scheme. One day saved in having an offshore diving support vessel stationed near the platform will more than offset the design effort.

Diverless Implementation

Whereas the great majority of SMR schemes are installed by divers, diverless SMR intervention has already achieved successes in the industry. It is expected that diverless implementation solutions for SMR will be used more often in the future primarily because of concerns over health of divers, but also because of economics and technical necessity for SMR in water depths beyond the reach of saturation diving. Three alternative approaches are considered herein: use of deployment frames, use of remotely operated vehicles (ROVs) and use of manned submersibles. A key element in diverless solutions is the interface between the chosen deployment system and the SMR technique. It is cost effective and economic to modify the design of the SMR technique to make it more amenable for remote activation rather than demanding additional tasks from the deployment system.

PART I – OVERVIEW AND SELECTION OF SMR SCHEMES/TECHNIQUES

1. INTRODUCTION

1.1 Background

This report has been prepared by MSL Engineering Limited (MSL) for The United States Department of the Interior, Minerals Management Service (MMS). It is concerned with the strengthening, modification and repair (SMR) of steel offshore installations, and covers aspects from the identification of the need for SMR, through selection of suitable SMR schemes and techniques, to design and execution. It builds on earlier work (1, 2), bringing it up to date with recent developments in this field of technology.

The document has been prepared for the guidance of the asset owner, the practicing engineer charged with the installation's integrity management, approval/certifying agencies and regulatory authorities.

The continuing requirement for conducting strengthening, modification and repair of existing installations is an important and integral part of offshore engineering practice. The reappraisal of existing installations, or the presence of damage, may lead to a requirement for strengthening and/or repair, either at a local component level or at a global system level. The need for SMR is expected to increase with time as platforms age or as a result of platform refurbishment or field development. The Mineral Management Services, in August 2003, issued a NTL (Notice to Lessees) (3) requiring owners of all Gulf of Mexico OCS region offshore platforms that have been in service for more than 5 years to carry out an API RP2A Section 17 assessment. This, too, will inevitably lead to many platforms to require some level of SMR for their continued safe operation.

SMR makes commercial sense as it will most often be more economical than building a completely new structure. The activity in SMR research has reflected this.

SMR operations tend to be highly engineered, certainly for moderate and major works, in order to minimize the high costs associated with offshore works. Often, however, either inappropriate, unnecessary or expensive SMR schemes have been deployed, primarily as a result of:

- the lack of readily available guidance,
- a lack of understanding on the part of the designer of the advantages/disadvantages of the various SMR techniques that are available, or
- insufficient effort during the assessment/analysis phases to 'work' the perceived problem.

MSL has played a vital role in many SMR projects. MSL's contribution to SMR technology involves research and technology development, preparing SMR guidelines, and hands on experience in numerous SMR projects. It is against this background that MMS commissioned MSL to undertake the present study, with the objective and scope of work presented in Section 1.2. The rest of this document is structured along the following lines:

- For the convenience of the reader, Section 1.3 explains how to use the document effectively.
- Section 1.4 is a glossary of terms and abbreviations used in the document.
- As part of the work, a comprehensive literature review was undertaken. The overall findings of the review are presented in Section 2. (Detailed findings are presented in the various sections on individual SMR techniques.) This section also includes aspects dealing with diverless SMR.
- Section 3 discusses what may constitute a trigger for carrying out an assessment, leading to a possible SMR requirement.
- The assessment process is outlined in Section 4, and this may show that no SMR is needed or, if it is required, how extensive the SMR scheme has to be.
- Section 5 guides the designer to the possibilities that exist for various SMR schemes. This section also gives a summary of the various SMR techniques including their strengths and weaknesses, and their applicability to address common SMR scenarios.
- The references for Part 1 (i.e. Sections 1 to 5) may be found after section 5. The references for Part 2 sections are included under the individual sections.
- Sections 6 to 16, contained in Part 2 of the document, provide detailed information on each of the various SMR techniques that can be presently considered. Each section in Part 2 has been prepared as a stand-alone chapter.
- A bibliography of recent documents not referenced elsewhere in this report may be found after Section 16.

1.2 Objective and Scope of Work

The objective of this study is to undertake an assessment of new and/or improved repair techniques for ageing or damaged structures, including the use of ROVs in repair operations.

The scope of work was as follows:

1. Capture all new data and information on the use of different repair techniques for offshore components and systems. Data capture will include an exhaustive literature search using established MSL search engines linked to worldwide databases.

2. Undertake interviews and discussions with operators, design houses, research establishments and regulatory authorities. The North Sea experience has recently been captured by MSL staff based in the United Kingdom, and this will be made available to the study.

3. Arrange for the release of MSL JIP findings to this study.

4. Undertake a review of the data and information captured from the above, with specific focus in the following areas:

    - Research efforts and extent of available guidelines.
    - Available technology for each repair technique.
    - Available experience for each repair technique.
    - Offshore application including health, safety and environmental (HS&E) considerations.
    - Catalogue case histories and experience for different applications, including problems and difficulties encountered.

5. On the basis of the MSL JIP on diverless intervention, undertake a review of present-day practices and their applicability to implementation without the use of divers.

6. Use the results of the above reviews and assessments to draw conclusions on the present state-of-the-art and state-of-practice for repair methods.

7. Develop guidelines in this field, including the implementation of repair solutions using ROVs.

8. Present findings of study to MMS and others as requested.

9. Prepare detailed final report on findings and recommendations.

1.3 How to Use This Document

This section gives guidance on the effective use of this document, particularly for those who are relatively inexperienced in SMR technology. It provides a ‘road map’ to the various sections of this document, allowing access to the relevant information and ideas in a rational and rapid manner.

The document comprises two parts:

- Part 1 (Sections 1 to 5) contains those aspects and process descriptions that lead to the selection of a SMR scheme and associated SMR technique(s). It includes a summary discussion of the very important stage of assessment, by which the need for and extent of SMR is determined.
- Part 2 (Sections 6 to 16) gives details of the individual SMR techniques. Each section is devoted to a single technique and presents a description of the technique; its typical applications; advantages and disadvantages; general design guidance; and case histories.

A summary flowchart of the main steps leading from an initiating event to the implementation of a SMR scheme is presented in Figure 1.1. Where appropriate, the relevant document section is identified in the flowchart. It can be seen that there are five phases involved in the overall process:

1. Initiating event

Section 3 describes events, including review of inspection data, which may trigger further assessment. Note that an event itself may prompt a special inspection, e.g. as may be the case when an object is dropped.

2. Assessment

Section 4 summarizes what may be done in the assessment stage, firstly to try to negate the need for any SMR, but if this is not possible to establish the minimum extent of any SMR.

3. SMR scheme and technique selection

Following assessment, an appropriate SMR scheme, e.g. the introduction of a new bracing member, is selected as discussed in Section 5.1. Note, that a structural analysis may be required to verify the scheme. SMR techniques compatible with the scheme are then assessed. For example, if the scheme consists of introducing a new member, either welding or the use of clamps can be considered to affix the member to the new structure. If clamps are selected, it will be necessary to choose the most appropriate type of clamp. These kinds of issues are summarized in Section 5.2, but it is very helpful to have knowledge of all techniques to a sufficient depth to make the optimal selection. The various techniques are discussed in Sections 6 to 16.

4. Design

Guidance is given in Sections 6 to 16. It is important during the design phase to consider carefully how the SMR scheme is to be implemented, particularly with regard to the provision of installation aids for certain techniques.

5. Implementation

SMR scheme implementation is not specifically addressed herein because each tends to be unique and the Installation Contractor may have particular preferences on how to accomplish the operation. However, some discussion of underwater implementation without the use of divers may be found in Section 2.3.

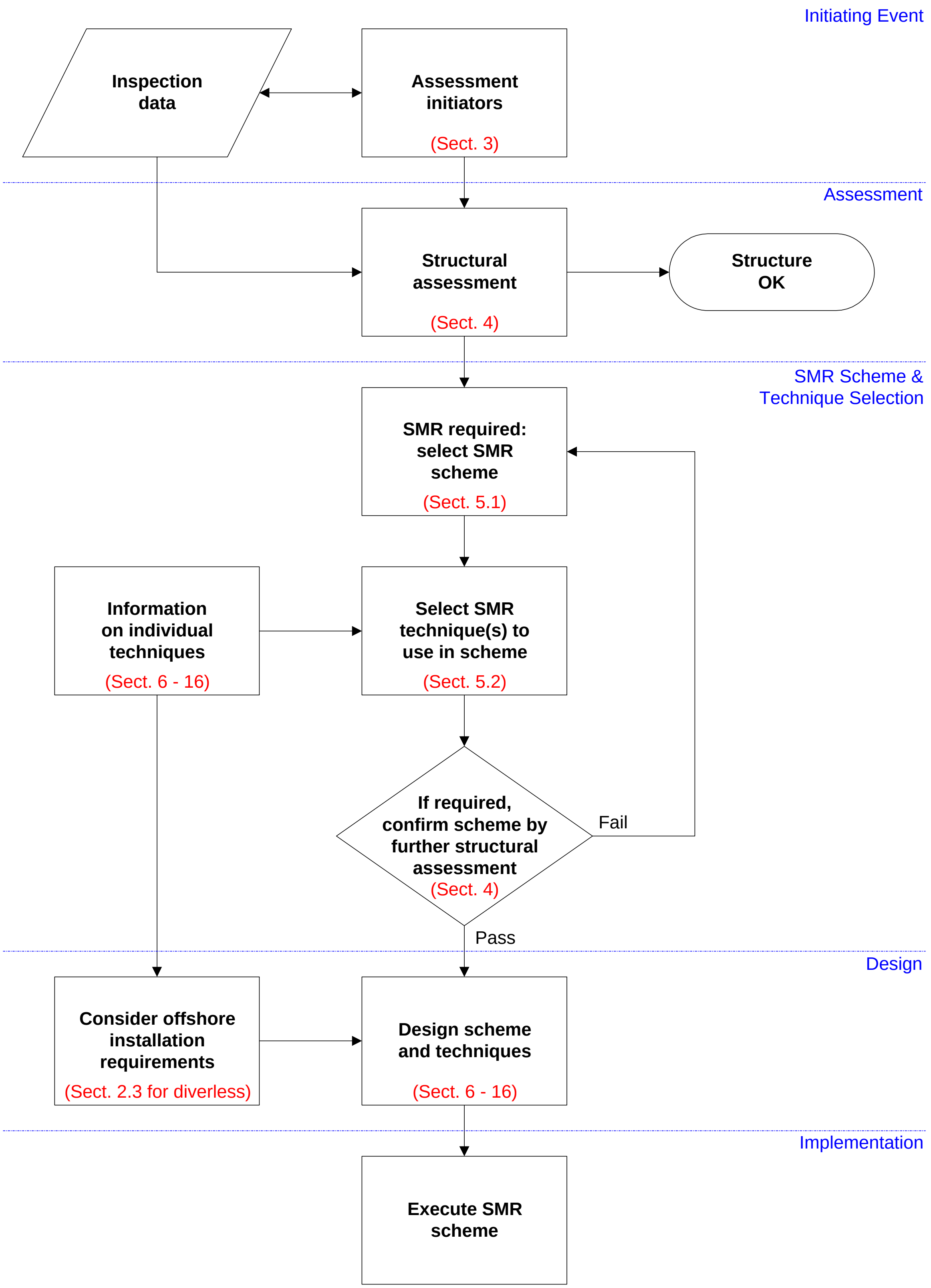


Figure 1.1: **Overall SMR procedure**

1.4 List of Terms and Abbreviations

The following words and phrases as used in this report have the meanings assigned below.

ACFM:
Acronym for Alternating Current Frequency Modulated (type of inspection)

ACPD:
Acronym for Alternating Current Potential Drop (type of inspection)

CFRP:
Acronym for Carbon Fiber Reinforced Polymer

Clamp:
A fabricated steel construction encompassing an existing tubular member or a nodal joint. A clamp consists of two or more parts that are bolted together. There are a number of clamp variants depending on whether or not the clamp parts are compressed against the existing member/joint and on whether there is a medium (grout or neoprene) placed between the clamp steelwork and the member/joint. A clamp should not be confused with a *guide*, which can appear to be superficially similar.

CP:
Acronym for Cathodic Protection

FCAW:
Acronym for Fluxed Cored Arc Welding

FRP:
Acronym for Fiber Reinforced Polymer

Galling:
A destructive process that occurs when two metal surfaces slide over each when the interface is subject to pressure, such as may occur in the threads of a bolt/nut assembly. Surface degradation or even seizure is the result.

GMAW:
Acronym for Gas Metal Arc Welding

GTAW:
Acronym for Gas Tungsten Arc Welding

Guide:
A guide consists of a steel barrel that surrounds and provides lateral support to a riser, conductor or caisson. The inner surface of the barrel is normally provided with a neoprene liner (plain or ribbed) and there is a nominal gap between the guide and enclosed tubular. In the case of a retrofitted guide, the guide will necessarily be split longitudinally and the two halves joined during installation using bolts. A guide may

therefore appear to be similar to a *clamp*, but there is no structural connection at the guide/member interface.

HAZ:
Acronym for Heat Affected Zone

HICC:
Acronym for Hydrogen Induced Cold Cracking

HSE:
Acronym for Health & Safety Executive (UK regulatory authority)

JIP:
Acronym for Joint Industry Project

MAG:
Acronym for Metal Active Gas

MIG:
Acronym for Metal Inert Gas

MMA:
Acronym for Manual Metal Arc

MPI:
Acronym for Magnetic Particle Inspection

NDE:
Acronym for Non Destructive Examination

OPB:
Acronym for Out-of-Plane Bending

PWHT:
Acronym for Post Weld Heat Treatment

ROV:
Acronym for Remotely Operated Vehicle

SCF:
Acronym for Stress Concentration Factor

Sleeve:
A sleeve is a concentric tubular surrounding a leg or brace member that is several diameters long. The annular gap between the sleeve and member is normally grouted. In the case of an existing member, the sleeve is necessarily split longitudinally and the two halves joined during installation using short bolts.

SMAW:
Acronym for Shielded Metal Arc Welding

SMR:
Acronym for Strengthening, Modification and Repair.

SMR scheme:
A SMR scheme is a solution to reinstate adequate structural integrity. It will comprise one or more SMR techniques and will usually require definition of solution geometry and materials used.

SMR technique:
An individual process or technique (e.g. wet welding, grinding, clamp, grout-filling, etc.) that may be used within a SMR scheme. The available techniques are summarized in Section 5.2.

SMYS:
Acronym for Specified Minimum Yield Stress

Studbolt:
A threaded rod, generally used in stressed clamps

TIG:
Acronym for Tunsten Inert Gas

2. PAST, PRESENT AND FUTURE PERSPECTIVES

In the last decade, industry's attitude and approach to SMR has evolved. This has encompassed all phases of SMR from initial assessment, through SMR technique selection, to implementation of SMR schemes. It is the purpose of this section to identify these changes, and to indicate the direction that the industry is heading with respect to SMR technology. The information presented has been gleaned from recent literature, discussions with industry and MSL's experience in this field of technology.

As further field developments continue, new facilities can be designed with SMR in mind so that future expansion, modification and repairs to the platform can be carried out more efficiently, or even avoided all together (e.g. ensuing that the fatigue life of non-inspectable components is at least an order greater than the intended service life).

2.1 Assessment Technology

There has been more emphasis in the assessment stages for the structure before deciding which, if any, SMR techniques are to be used. Without proper assessment, and knowledge of SMR techniques, remedial work can be more costly, unnecessary or even disastrous. Changes have been observed in analysis techniques, knowledge of residual strength of damaged components, and in standards and codes of practice.

Analysis techniques

The growth in computing power has led to a commensurate increase in the sophistication of software packages and structural modeling techniques. As one example, structural models used to be simple stick models but now more often than not the model will include offsets and eccentricities at nodal joints. Another example is that non-linear analyses including both geometric and material non-linearity are increasingly being used, even at the design stage, to determine structural integrity. The increased accuracy of structural response that ensues is clearly beneficial in SMR decision-making processes.

System strength, as obtained by a 'pushover' analysis, rather than component strength is now being increasingly used as an indicator as to whether or not SMR is required. Such analyses allow for member yielding and buckling, and the formation of plastic hinges. Recently, MSL developed the technology to simulate realistic non-linear joint behavior (coupled $P\delta/M\theta$ response) over the whole of the elastic, peak and post-peak range, in an efficient manner thus allowing greater accuracy to be achieved (4).

Residual strength of damaged components

It is often required to assess the strength of damaged members and joints as even when in the damaged state, they may have sufficient residual capacity to preclude the necessity of SMR works. Research on the residual strength of bowed and dented members begun over 30 years ago, and formulations have been included in the relatively recent ISO (5) and NORSOK (6) standards. Research on the capacity of cracked joints has been carried out in the last decade, but again has been translated to code provisions within ISO and NORSOK standards.

Fracture Mechanics is increasingly used to assess the effect of cracks and other defects on the structural integrity of members and joints. Much of the more recent research has been encapsulated within BS 7910 (7).

Standards and codes of practice

Reference to provisions for the residual strength of damaged components has been made above. The inclusion of such provisions results from a general recognition that assessment is an important part of offshore engineering. However, API RP2A (8) took the lead in devoting a whole section (Section 17) to the reassessment of platforms, and details what structures require assessment and what types of analyses are relevant for particular structures. This is currently being reinforced by a proposed new Recommended Practice (9) entitled 'Structural Integrity Management of Existing Offshore Structures'.

It is expected that the future trend of drafting bodies will be to place more emphasis on the behavior of structures beyond first yield, and to give more guidance on the residual strength of damaged components (and strength of repaired components), as the results of research are assimilated.

2.2 **SMR Techniques**

A review of the literature written in the last decade has not identified any fundamentally new SMR technique with the possible exception of the use of carbon or glass fiber reinforced composites. Nevertheless, there have been a number of improvements made, or suggested, to existing techniques. There has also been research into the effectiveness of certain techniques.

Fiber reinforced composites

The most notable new SMR technique involves fiber reinforced plastic (FRP) composites. During the last ten years the development of FRP as a material in the offshore industry has gained momentum. FRP has already established itself as an alternative material in fluid transportation piping secondary items such as floor gratings in the offshore industry. Research and development has been carried out for it to be used as a SMR technique (10, 11). Indeed, the number of structural strengthening publications using composites tripled between 1992 and 1995 (12) and has continued to rise.

The MMS has made significant contributions to the advancement of FRP in the offshore industry through international workshops (13, 14). A project (15) sponsored by MMS and carried out by Det Norske Veritas (DNV) resulted in a published standard (16). A HSE (17) study discusses FRP as a load-bearing component in structural applications. A separate HSE report (18) provides guidelines on temporary/permanent pipe repair techniques. MSL have conducted research under the auspices of JIPs (19, 20) into the use of FRP for strengthening and repair applications through large-scale laboratory and near shore tests; and formulated guidance for the repair of existing metallic structures. The JIPs and other work (21, 22) eventually led to a publication (23) by the Institution of Civil Engineering on a design and practice guide to life extension and strengthening of metallic structures using FRP. A CIRIA report (24) provides guidance on a similar theme. MSL experience of structural strengthening using FRP includes work in the Gulf of Mexico (25). A publication from the American Concrete Institute (26) provides guidance in strengthening concrete structures using composites.

It should be recognized that the success FRP has had so far is mainly confined to above water applications. The development of advanced adhesive and resins resistant to water (10, 11, 27) will only further the popularity of FRP. Although the initial cost, strength performance and fire performance and the requirement for more research and design specifications has been highlighted (28), the inherent versatility of this technique still makes FRP an attractive option, particularly for topsides SMR.

Improvements to existing SMR techniques

In the last decade there has been little development of current SMR techniques apart from the use of ultrasonic (29, 30) in peening. Further developments are being made to make the equipment available for underwater use (31).

There has also been development in improving consumables. Wet welding is known for poorer quality welds than those made in the dry, partly contributed by the skill of the diver/welder and partly by the weld process. Whilst there have been discussions (32) for the former, there have been developments in electrode consumables (33 to 36) that improve the weld properties by reducing the hydrogen content within the welds.

Improvements to underwater wet welds have been attempted by creating an air cavity (37, 38) by dispersing pressured gas in a shroud with different weld methods.

SMR techniques using grout (grout filling of members/joints and grouted clamps) are well established. High strength grout can contribute to the effectiveness of these SMR techniques. Improvements through increasing the strength of the grout have been documented (39). There have been reports (40, 41) of epoxy-based grouts and cementitious grouts constituting fly ash or river sand achieving superior strength than that of normal cement. Grout strengths up to 175 N/mm^2 are available in commercial quantities.

Information on the effectiveness of SMR techniques

Information on the capacity, or structural behavior, of various SMR techniques has increased in the last decade. The increased knowledge is conducive to designing efficient SMR schemes that use these techniques. MSL research (1) into the behavior of stressed grouted, mechanical, and unstressed grouted clamps, clarified how studbolt loads vary in response to applied loadings, enabling more efficient clamp designs. In a MSL JIP sponsored by MMS, HSE and operators (42), a series of tests to determine the slip capacity of neoprene-lined clamps was carried out. Another MSL JIP (43, 44) examined the benefits of grout filling of joints through large-scale tests on SCFs and ultimate capacity. MSL (1) have also examined the axial load carrying capacity of damaged and undamaged structural tubular and members which are fully and partially filled with grout. Similar studies (45 to 48) have also been conducted.

Some of the information generated has been included in recent standards and codes. The ISO (5) provides provisions for the design of clamps. Design provisions for grouted connections are also provided by ISO. Eurocode 4 (49) provides guidelines to check the capacity of grout filled reinforced members.

2.3 Diverless SMR

It is to be expected that implementing SMR schemes without using divers will increase in the years to come. This expectation is driven by:

- necessity, as installations are already in waters too deep for saturation divers to operate and the trend is for oil/gas extraction in even deeper waters,
- health concerns for divers due to long term exposure to hyperbaric conditions,
- general concerns about safety of diving operations on live platforms, particularly near caisson intake points, and
- economics – the cost benefits arise from the ability of ever more reliable remote systems to utilize less costly support vessels and smaller operating crews.

There are essentially three approaches to effecting diverless repairs: (1) remotely controlled deployment frame launched from the surface, (2) use of ROVs or robotic systems, and (3) use of manned submersible units.

Remotely controlled deployment frame

A deployment frame was used in the repair of six corroded caissons on Mobil's Beryl Bravo structure in the North Sea (50). The repair scheme, designed by MSL, is accredited as the first known structural repair conducted without the use of divers (51). The SMR repair technique was elastomer-lined clamps, and was complicated by the close proximity of chemical injection lines piggy-backed on the caissons. The clamps were provided with sacrificial hydraulic actuators to close the clamps and to tension the studbolts. The deployment frame was launched onto each caisson in turn from a working platform below the spider deck, and was designed to maneuver the clamp into position with long stroke jacks. An eyeball ROV was used together with cameras mounted on the deployment frame to monitor operations. A number of full-scale trials were conducted before going offshore. The repairs were entirely successful. Further details may be found in Reference 50.

A similar exercise is currently being designed to install additional riser guides, supported of friction clamps affixed to jacket brace members, in Norwegian waters. MSL are assisting with this project, for which the driver for diverless implementation is one of economics.

Use of ROVs and robotic systems

Only limited experience has been gained with the use of ROVs in conducting structural repairs on offshore installations. This is mainly due to the limited versatility of the machines compared to divers, poorer visualization at the work site and control. However, the advancement of computer technology has assisted development in diverless techniques using ROVs (52, 53), and therefore ROVs may become more adept for such work in the future.

Feasible SMR techniques that can be considered for ROV deployment include grinding, welding, grout filling and the use of clamps. The techniques have to be optimized or modified for ROV deployment because of the relatively limited versatility of ROVs. The use of ROVs may introduce complications (54); therefore procedures must be carefully thought out. Methods requiring complex tools may be less favored if ROV must be deployed. Underwater tool changing capability is required if the vehicle is not to re-surface. Indeed, it would be extremely time consuming if this was the case.

Visual impairment is a potential problem, particularly at lower depths; even though more than one engineer can assess the repairs through visual facilities. Other visual problems occur with certain SMR techniques. Most notably this is for wet welds where significant bubbles are produced, giving almost zero visibility. Grout dispersion in the water will also impair visibility.

The use of remotely operated vehicles for conducting repairs has been developed pipeline repairs, but not structural repairs. It may be possible that ROV pipe repair technology can be adapted and modified for offshore structural repairs. However, ROVs are generally bulky and rather clumsy machines, which is less of a problem in pipeline repair as the currents are weaker at the sea bed and where there are few obstructions. Structural repairs tend to be much closer to the water surface and therefore will involve stronger currents and wave action, and where access may be reduced due to the presence of bracing members.

Demonstration trials of diverless strengthening techniques for offshore installations were executed by MSL Engineering (55). This JIP was established to conduct large-scale in-water demonstration trials using a work-class remotely operated vehicle (fitted with 5-function and 7-function manipulator arms) and atmospheric diving suit (ADS). Activities comprised design, fabrication, component trials, dry ‘fit-up’ trials, in-water demonstration trials and experimental assessment of the repair and strengthening work for the following scenarios:

- Repair T-joint with a stressed grouted clamp using ADS and ROV intervention.
- Placement of an additional brace member into a structure, utilizing an elastomer-lined clamp and a tube-to-tube stressed grouted clamp and using ROV intervention. This scenario represented, in practice, both the repair of an existing damaged member and introduction of a new braced member.

The study provided hands on experience in deploying such techniques. Much was learnt and implemented into a set of recommended installation procedures. It was found that a single manifold provided on each SMR scheme for the ROV to interface with, and provide power to, the clamp hydraulic systems and grouting system was an appropriate approach. An eyeball (observation) ROV should be considered to assist the pilot of the work-class ROV with a second visual perspective of both the work site and the work-class ROV itself. Visual indicators are recommended for all tasks requiring ROV observation; the indicators should be appropriately graduated or colored to permit accurate logging of the progression of the task. The work-class ROV should carry a dedicated work sled containing all tools and fittings required for the completion of the intervention tasks being performed. The SMR scenarios were successfully implemented with the ROV.

A recent development is the marriage of friction stitch welding (a relatively recent SMR technique in itself) and the use of ROVs. Blakemore (56) used a ROV in the North Sea to experiment with friction welds. A reloading system was required to increase efficiency as the ROV was required to re-surface each time a repair was done. Meyer *et al* (57, 58) developed a subsea robotic friction welding repair system. The system can be used with a work-class ROV or as a remote tool. The robot is capable of six degrees of freedom, giving it a high degree of control and accuracy. Data recording systems and sensors help monitor the welding process. The robot was tested and was successful in carrying out simulated repairs.

Welham and Gilfrin (54) review the use of ROVs for grouting operations. They recognize problems such as entanglement of umbilicals when two ROVs are used (one to operate stabbing hoses and valves whilst the other carries the probe). Grout spillage can occur, which temporarily obscures vision and therefore reconnection is required in poor visual conditions. Any significant delay can lead to blockages. The weight of the grout hose may be too heavy for the ROV to maneuver. It is therefore essential that ROV companies are fully involved in the design process and in planning of procedures. Grout filling was also performed by ROV on a number of platforms in the North Sea (52, 53). A sea bed flange connection in the Foinaven field was successfully sealed using a ROV to install a clamp and inject the sealing compound (59).

Use of manned submersible units

Some of the versatility and visualization impediments noted above with respect to ROVs can be circumvented by manned submersible units.

During the demonstration trials referred to above (55), an atmospheric diving suit was used in an attempt to install a stressed grouted clamp around a T-joint. Following advice from the ADS contractor, minimal changes were made to the clamp design such that it was a fairly traditional design suitable for a diver-installation. In the event, it was found that the claw-like manipulator was not entirely successful in performing some of the required implementation tasks which would have been routine for divers. The clamp was modified to include the ROV-friendly systems and the ADS then performed well, installing the clamp with considerable timesavings over the ROV. The timesavings resulted from better 3D visualization, direct control of the limbs and manipulator, and the speed with which the ADS could move about the worksite.

It should be noted, however, that some operating companies have concerns about, or operational restrictions on, the use of ADSs, relating principally to a requirement to have a back-up or rescue system available whenever an ADS is in the water. This requirement precludes their deployment from many offshore installations.

3. ASSESSMENT INITIATORS

Introduction

This section describes some of the possible scenarios, which may give rise to a need for SMR, including a qualitative description of the types of damage that may occur. It is important to identify the root cause leading to a requirement for SMR as this may affect the selection of the SMR scheme and SMR techniques to be utilized.

The requirement for SMR may be due to a structure suffering some kind of damage or an intact structure subject to a change of use. It will be seen that a useful distinction can be drawn between damaged and intact structures.

In the case of a damaged structure, an inspection survey will normally be required to map the extent of the damage (as well as the local geometry around the damage site) to enable a rational appraisal of SMR requirements to be made.

Scenarios for Damaged Structures

Several causes and resulting types of damaged are described below. It is not the purpose here to reflect on the extent and occurrence of these but rather to identify the resulting types of damage sustained and their impact on the relevance of the SMR techniques that may be adopted. The causes and resulting types of damage include:-

- Fatigue loads

These, of course, may cause fatigue cracks and are a design consideration. However, an ignorance of both environmental loads and aspects of structural behavior has led to an occurrence of fatigue cracks. They may be severe, even leading to member severance. The growth of the crack may affect other members at a joint; cracking originally in a secondary brace member may eventually grow into and affect the primary member.

- Dropped objects

Examples of dropped objects cited in the literature comprise tubular components (e.g. drill strings and piles), a link bridge, a lifting crane and miscellaneous items such as wire ropes. A further cited example of a dropped object is a complete horizontal frame, which having failed at the connection to the leg members (due to fatigue under panting loads), dropped onto the next lower frame and caused extensive further damage.

Dropped objects may cause damage varying from denting, bowing and holing of members, to member severance and joint tearing and deformation. In the case of wire ropes which become entangled onto horizontal members, wave action can make the wire rock to and fro, thereby causing the wire to chafe the member. In at least one incidence wire chafing has led to the member being cut through.

- Vessel collision

Supply boat collisions, and at least one case of submarine impact, have caused denting and bowing of members. Dragging of anchor lines across the structure has also occurred.

The relative magnitude of denting and bowing depends on the D/t ratio, the overall slenderness of the member and the degree of restraint (rotational and axial) afforded to the ends of the member by the rest of the structure. In addition to bowing and denting, deep scratches and gouges are often formed.

- Corrosion

Excessive corrosion may be relatively general, as in the case of an under-designed, or failed, cathodic protection system, or rather localized, as in galvanic (bimetallic) corrosion of caissons housing stainless steel pump/strainer components. In either case, thinning and/or perforation of the carbon steel occurs.

- Damage during installation

Most of the incidents of damage relate to pile driving operations. Piles falling through the guides damaging the guides and skirt structures can be classified as dropped objects as above. However there have been reports of extensive cracking at joints attributable to excessive vibration, resulting from the hammer blows. The fouling of a member on the installation barge during platform launch caused it to bow in one case.

- Welding and/or fabrication fault

Under this category can be included general errors such as use of inferior materials, incorrect member sizes, or incorrect member positions (and even omissions). More commonly, however, errors are of a detailed nature such as lack of penetration or excessive undercutting, and the failure to provide vent holes for intended flooded members. The latter has caused implosion of such members on installation. The former can lead to unexpected fatigue cracks.

- Explosions

In more than one case, local enterprising fishermen have adopted an extreme method to catch the fish, which tend to congregate around platforms. This consisted of detonating dynamite in close proximity to the platforms, stunning the fish, which then rose to the surface. The resulting damage consisted of severe denting deformation to members (enough to give a crescent shaped cross-section).

- Ice

In arctic waters, pack ice can impart substantial forces onto a platform. In one reported incidence, build-up of ice within the structure caused one end of a major diagonal bracing member to sever.

- Build-up of drill cuttings

Under certain conditions, drill cuttings can accumulate and bear onto lower frames or members, thereby damaging them.

- Under-design

Under-design can cause member buckling, or joint failure either statically with commensurate permanent deformation and possible tearing, or from fatigue with associated cracking.

To summarize, damage, depending on its cause, may manifest itself as dents, bows, permanent deformations, loss of thickness, gouges, cracks, tears, holes and severance of members. These forms of damage can occur singly or in combination.

The damage may or may not be important to the integrity of the platform. This depends on the severity of the damage, the loads carried by the damaged component and the degree of structural redundancy. Each situation has to be assessed individually to enable a rational decision to be made on whether repair and/or strengthening is required. (See Section 5.)

Scenarios for Intact Structures

The scenarios that may give rise to the need for SMR of intact structures fall into one of three broad categories:-

- Change in Platform Operation

In the refurbishment of topside structures, the placement of additional equipment or the upgrading of existing equipment may lead to the imposition of increased superstructure and substructure loadings.

The development of marginal or satellite fields using sub-sea systems is finding increasing favor. This often places an additional burden on receiving `parent' platforms through, for example, the placement of additional risers, other appurtenances or additional topside equipment.

In either case, the integrity of the platform requires re-evaluating and this reassessment may indicate a need for modification or strengthening of the supporting structure.

- Availability of New Information

During the lifetime of a structure and as the industry experience and knowledge grows, new information (through code updating, for example) on environmental loadings and/or structural response can indicate that the platform is under-designed. Again, a structural appraisal would confirm whether SMR is required.

This is particularly important for older installations, which may be required to remain in service beyond their originally perceived service life. Within the context of this requirement, corrosion and fatigue life could be dominant considerations as these are time-dependent phenomena.

iii. Measures for Increased Safety

In recent times, a number of measures have been proposed to increase the operational safety of existing installations. For instance, the Cullun Report on the Piper Alpha disaster (60) includes a number of safety-related recommendations, and this may lead to a requirement to strengthen or modify the superstructure and substructure.

Certification and/or regulatory requirements may stipulate the necessity for structural integrity evaluations at regular periods. For example, the Mineral Management Service issued a Notice to Lessees (3) requiring all platforms on the OCS in the Gulf of Mexico to be subject to an API RP2A Section 17 assessment.

There are instances where a requirement for SMR is operator led. For example, should a reanalysis of a structure indicate that a member or joint is overstressed (statically or from a fatigue standpoint) before any damage has actually occurred, or where similar platforms have already suffered some form of damage to which the subject platform is also likely to sustain, the operator may decide on SMR measures. Even in those cases where it can be shown that the member concerned is redundant, it will sometimes be required to take steps (for example, placing additional ties or removal of the member) to avoid the consequences of the member potentially separating from the structure and causing further damage on its way down to the seabed.

4. ASSESSMENT PROCESS

There are two main purposes of conducting assessments:

- to explore the need for, and extent of, SMR in the first place, and
- to demonstrate the adequacy of the selected SMR scheme.

A structural assessment will normally be required at the outset to ascertain whether or not some level of SMR is required, and if so to indicate the extent of the required SMR scheme. The structural assessment comprises both platform analysis (to establish member loads or the resistance of the whole platform to design events) and code or other checks on the (intact or damaged) component capacity. Whereas it is normal engineering design practice to conduct simple linear analysis and code checks (e.g. to API RP2A) for demonstrating the structural adequacy of new build structures, it will often prove beneficial in potential SMR situations to use refined or advanced analysis techniques and/or component checks falling outside the scope of standard codes. In many cases such refined/advanced analysis or component checks will demonstrate that the structure is fit-for-purpose and that no SMR is required. A staged approach to the assessment is recommended, where the results of each stage are reviewed to decide on the merits of further refining the analysis and/or component checks. This process is summarized in the figure below.

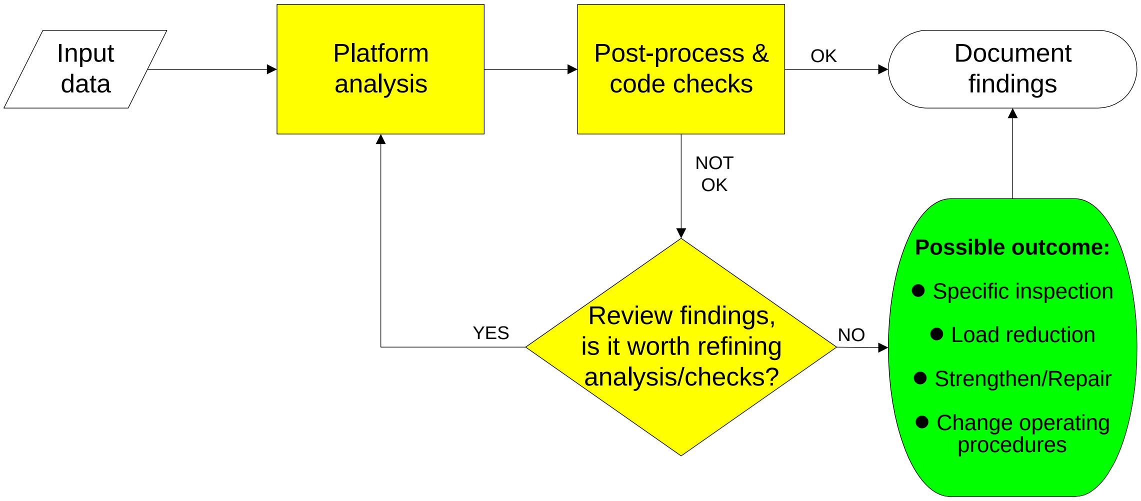


Figure 4.1: Overall assessment approach

The quality of the input data has a significant bearing on the success of above assessment process. The as-built structural geometry, together with any subsequent modifications, should form the basis of the model. It will usually prove advantageous to have knowledge of the actual yield strength (e.g. from traceable mill certificates) of the materials used in the fabrication as these can be 15% or more higher than the specified minimum yield strength (SMYS).

Where the analysis is to be based on an existing structural model, it is important to review the model to make sure that it reflects the present condition of the platform. For example, the following items may allow the gravity and/or environmental loadings to be reduced:

- a platform may no longer have a prospect of filling all the conductor slots. Therefore, modeling the existing number of platform conductors, risers, caissons and not counting on futures can be a major environmental load reduction from the original design loading
- including the conductor pile-like lateral support
- making sure conductor and riser shielding assumptions are correct
- making sure boat landing wave and current loading assumptions are correct
- making sure rig gravity and wind loading assumptions are correct
- making that the possible restriction of rig loading to non-cyclonic times of the year has been considered
- making sure of the rig size that will possibly return. Many times the original big horsepower rigs will never return to a drilling platform
- often the original deck gravity loading was very conservative and no longer realistic
- often the original rig loading may never be never be experienced again by the platform and can be removed along with its associated wind loading
- often the original analysis considered some future equipment areas and future equipment loads that never were installed on the platform and therefore can be eliminated
- sometimes deck loadings exceed what the platform was originally designed for and those need to be updated correctly.
- making sure that docking piles are modeled if they exist to reduce pile loading.
- consider effect of mudmats, if pile overloading is indicated as a primary failure mechanism. Often the ultimate strength analysis shows that the piles are the first mode of failure. Subsequent underwater inspection of these structures usually shows that pile pullout or pile plunging have not occurred even though the actual platform loading and platform analysis showed this should have been a problem.

The possibilities for refining the analysis, and the possibilities for improved component checking are tabulated below. It should be noted that these refinements and improvements are independent of each other, e.g. refined code checking can be, and often is, used in conjunction with the results from a basic analysis.

ANALYSIS	**POST-PROCESSING / COMPONENT-CHECK**
BASIC ANALYSIS • As-built plus subsequent modifications • Node-to-node stick model • Remove damaged member?	STANDARD CODE CHECK (e.g. to API RP2A) • Yield based on specified minimum yield stress (SMYS)
SIMPLE REFINED ANALYSIS • Member eccentricities/offsets • Remove double counting of wave load • Residual stiffness of damaged member	REFINED CHECKING • Yield based on mill certificates • Review member effective lengths • Review SCFs • Appraise capacity of damaged elements: o Assess existing test data o Fracture Mechanics study • Reliability analysis
COMPLEX REFINED ANALYSIS • Local Joint Flexibilities (LJFs) • Hind cast site data • Probabilistic loading combinations	
ADVANCED ANALYSIS (PUSHOVER) • Non-linear member behavior • Non-linear joint behavior	ADVANCED CHECKING • Do FEA component study • Commission tests

Table 4.1: Summary of refinements in analysis and component checks

Where API RP2A (8) is the applicable standard, reference should be made to Section 17 for further guidance on assessment practice. One phrase that has cause difficulty is the definition of significant damage: i.e. that which causes 10% lowering of system strength. The problem lies in how to estimate the percentage reduction for various types and levels of component damage. MSL has executed a JIP (61) to resolve this issue. It is expected that key findings of the JIP will appear in the proposed API Recommended Practice on Structural Integrity Management of Existing Offshore Structures (9).

5. SELECTION OF SMR SCHEME & TECHNIQUES

5.1 Selection of SMR Scheme

The seriousness, and hence an indication of the extent of SMR required, will be determined during the assessment phase of the study work. The first action in the consideration of SMR schemes is to identify whether a 'local' SMR will suffice, or whether a more elaborate 'global' solution is required. Clearly, a local SMR is likely to offer the cheaper solution, provided it meets the technical requirements.

There are essentially five basic approaches to SMR:

- Remove damage
- Reduce loadings
- Local strengthening/modification/repair
- Global strengthening/modification/repair by provision of new members
- Total strengthening/modification/repair by tying into a new adjacent structure.

These approaches can, and often are, used in combination. They are further discussed, and defined, in the following subsections.

5.1.1 Remove Damage

This approach, of course, is only applicable where the problem relates to damage, howsoever caused. Damage removal can be achieved in one of two ways:

i. Removal (and possible replacement) of member

The damage is clearly removed if the affected member is cut out. However, unless it is a member no longer required for the in-place condition, perhaps as proven during the assessment phase or because its function has expired, it will need replacing. In that case only that part of the member containing the damage has to be cut out and replaced. The primary issue then becomes the method of attachment of the replacement member. Viable SMR techniques are welding, clamps and bolted connections. Temporary bracing may be required until the replacement member or part member is installed. Restraining relative movements may have to be addressed for welding and some types of clamping techniques.

ii. Crack removal

The removal of cracks can be achieved by properly executed remedial grinding. The resulting groove can be left as is or filled in with weld metal. In the case of cracks caused solely by fatigue loads (i.e. not in combination with a fabrication defect), other SMR techniques will be required in addition to the grinding, unless the remaining planned life of the installation is sufficiently short.

5.1.2 Reduce Loadings

This approach is closely related to the first in that it involves removing parts of the structure. However, it is applicable to both damaged and undamaged structures. Two examples can be given:

Reduced loading can sometimes be effected with respect to a fatigue crack in a secondary member, which connects with a primary member. Removal of the secondary member, leaving a stub with the crack still in place, will eliminate the fatigue loading on the crack and thus arrest its potential growth into the primary member.

Anticipated problems in undamaged conductor guide frames may be circumvented by removing conductor plating and thereby reducing the ‘sail’ area. The reduced panting loads may extend sufficiently the fatigue lives of the joints to negate the need for future, more extensive, repairs.

Removing marine growth will also reduce loadings.

5.1.3 Localized Strengthening /Modification/Repair

In this approach, the member or joint is strengthened directly (leaving any damage in place) without altering load paths within the structure. Additional load may be attracted to the member or joint, however, either by virtue of its increased stiffness following the SMR or due to increased drag forces acting on, say, clamps. Three broad categories of techniques may be recognized as being applicable to localized SMR:

i. Internal SMR

Grout filling is the main suitable technique although a bolted connection has been used inside a member on one occasion. Internal grout filling can be used:

- To act compositely with the steel to increase member stiffness and overall buckling capacity, or
- To act as a packer to restrain local shell distortions (i.e. to decrease SCFs, to increase collapse strength of joints, to increase local buckling capacity (possibly at a dent) and to prevent radial collapse of a member against external loads arising from stressed clamps).

ii. External SMR

External SMR can be achieved by clamping technology or by employing welding to install doubler plates or sleeves. These techniques can be used for either members or joints.

SMR schemes, which deploy external clamps or sleeve concepts, may be designed to carry only part of the subsequent applied load. In other words, the existing component is assumed to share the environmental or seismic load with the SMR scheme. This may be applicable, for example, at a tubular joint, which is shown to be under-strength for a particular predicted design event, but there has been no damage to date. (If damage has occurred, it is usual to assume conservatively that the existing component has no residual strength and design the SMR scheme to carry the full-applied load, including the gravity loading.) In load sharing schemes, it is necessary to determine the amount of load carried by each component. For member SMR, it is usually sufficient to apportion the load according to the relative stiffnesses of the components. For tubular joint SMR, the situation is more complicated due to the local flexibility of the joint and the clamp or sleeve. A finite element analysis may be carried out in this case to determine the state of stress, particularly in the joint. Where load-sharing schemes are employed, careful consideration should be given as to the confidence, which may be placed on the estimate of the load apportioning and the consequences of not actually realizing the estimate in practice.

iii. Fatigue life improvement

The fatigue life of welded components can be improved by modification techniques such as toe grinding. However, this technique cannot be applied to existing cracked joints unless the damage is first removed.

5.1.4 Global Strengthening/Modification/Repair

Global SMR implies that new load paths are created. Load is diverted away from the damaged or understrength component by:-

- Providing a S/R scheme which is sufficiently stiff to attract a suitable proportion of the load which would otherwise have been applied to the defective part of the structure
- Jacking load into the S/R components during the installation of the scheme so that they carry both the full or partial dead load and a proportion, depending on relative stiffness, of the live load.

There are, potentially, numerous schemes that could be proposed, e.g. in terms of overall structural solution or where to locate new members. Again, each SMR scenario is different and it is not possible to be dogmatic about how to select the optimal scheme. Initially and most importantly, however, experience and engineering judgment will be brought to bear to reduce the number of candidate schemes to a few. The candidate schemes can then be appraised for:

- Technical sufficiency (this may require platform analyses incorporating the schemes)
- Costs
- Installation effort (including a consideration of water depth, craneage capacity, availability and experience of contractors, etc)
- Operator preferences.

Careful consideration must be given to tolerances (length and angles) for problem-free installation. The use of grouted connections and clamps, with their forgiving annuli, and sliding or telescopic joints, which can be fixed on installation by welding, grouting or bolting, are useful devices in this respect.

5.1.5 Total Strengthening/Modification/Repair

Total strengthening/repair is intended to encompass those schemes where a new structure is built alongside the existing one, and is used to support the existing structure.

The design, fabrication and installation of the new structure, together with the tying in to the existing structure is, of course, a major undertaking. Nevertheless, where the problems of the existing structure are so severe that technically viable global SMR becomes too extensive, or the problems are foundation related, a total SMR scheme may provide the best overall solution.

5.2 Selection of SMR Techniques

This section summarizes the SMR techniques and gives the relevant summary guidance for their application. Having arrived at the type of SMR scheme required (as discussed in Section 5.1), it is necessary to chose the technique(s) that will realize the scheme. It is prudent to consider a number of SMR techniques to ensure that the chosen solution is the best from a technical, operational and economic standpoint, even though a particular technique may appear an obvious choice. There are a number of techniques available. These are summarized in Figure 5.1.

Table 5.1 draws together salient information on each technique from the sections presented in Part 2 of this document. Reference should be made to these sections for further detailed information and possible limitations for application to the scenario under study.

Table 5.2 indicates the potential applicability of SMR techniques for selected defect scenarios. Again, reference should be made to Part 2 and a decision reached based on pertinent criteria such as:

- Technical performance
- Reliability
- Costs
- Depth limitations
- Offshore support requirements
- Existing applications
- Extent of background knowledge
- Timescales for design/fabrication/installation
- Tolerance acceptability

- Post-installation inspection requirements
- Potential problem areas
- Remaining life of installation
- Environmental and other legislative requirements
- Operator preferences.

Figure 5.3 presents the interrelationship between commonly occurring scenarios, appropriate SMR schemes and SMR techniques, both for intact and damaged structures/components. It should be noted that at the component level, it is possible that a SMR scheme can comprise elements from both diagrams in the figure. For instance, a possible repair scheme following a vessel collision incident might comprise removal of the bowed member and the addition of a nodal clamp to an under-strength but otherwise intact joint so that it can resist redistributed loading.

It can be seen that for global SMR schemes, either welding or clamps (or indeed both) are the techniques of choice. Where welding is not suitable, then clamps must necessarily be used to affix the new member(s) to the existing structure. Clamps are also an option in many of the local SMR schemes. Thus clamps assume an important role and constitute one of, if not being the most, important single SMR technique.

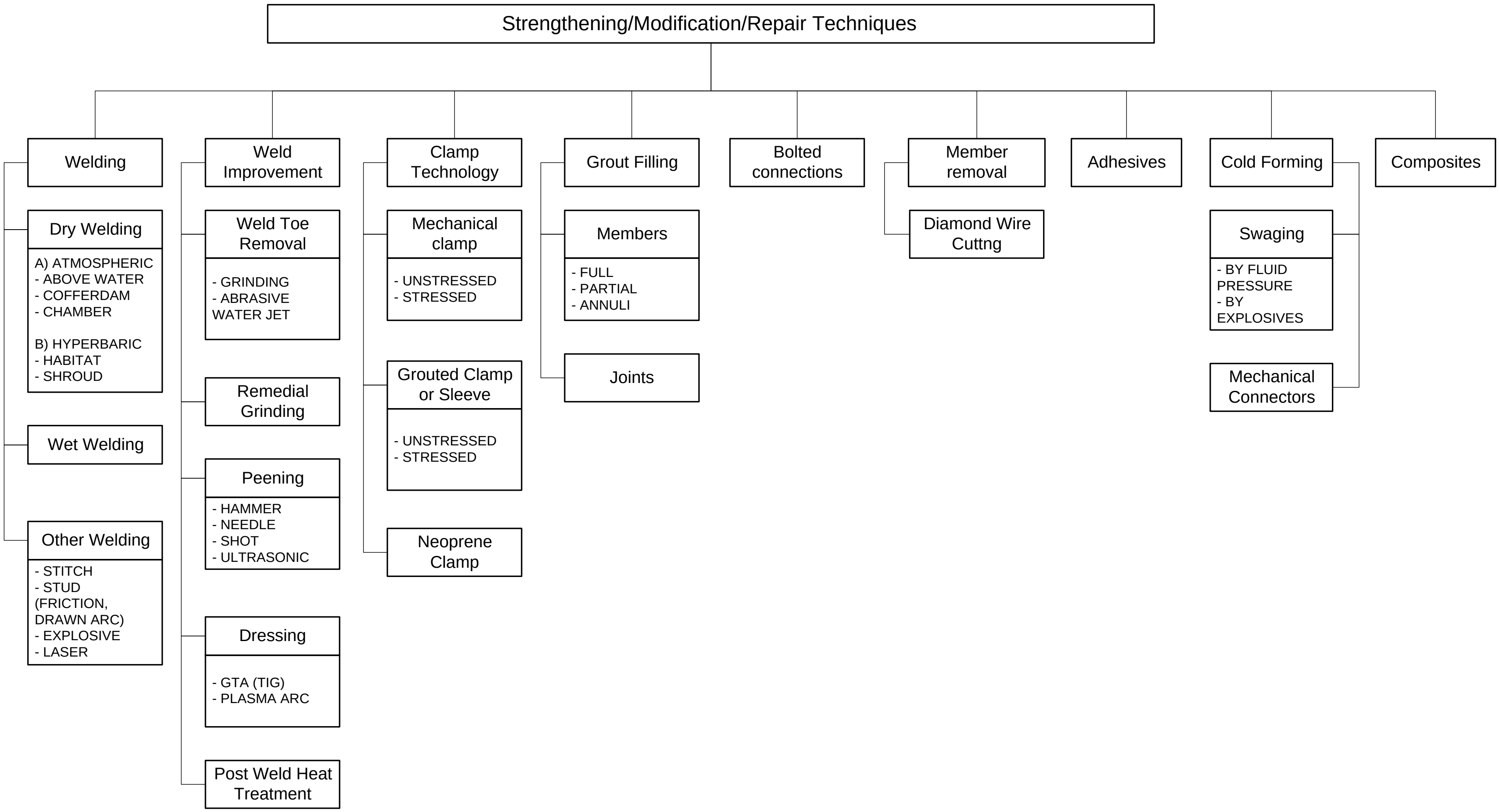


Figure 5.1: Overview of Techniques used in Strengthening, Modification and Repair

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 5.1: Comparison of SMR Techniques

Technique	Defect								
	Fatigue crack	Non-fatigue crack	Dent	Corrosion	Inadequate static strength		Inadequate fatigue strength		Understrength topsides plating
					member	joint	high loads	fabr. fault	
Dry welding	yes(1)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes	yes
Wet welding	no(2)	yes	yes(3)	yes(3)	yes(1)	yes(1)	no	yes	no
Toe grinding	no	no	no	no	no	no	yes	no	yes
Remedial grinding	yes	yes(1)	no	no	no	no	no	no	no
Hammer peening	no	no	no	no	no	no	yes	no	yes
Stressed mechanical clamp	yes	yes	no	yes	yes	no	yes	yes	no
Unstressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes	no
Stressed grouted clamp	yes	yes	yes	yes	yes	yes	yes	yes	no
Stressed elastomer-lined clamp	no	yes	no	yes	no	no	no	no	no
Grout-filling members	no	no	yes	no	yes	yes(4)	yes(4)	no	no
Grout filling of joints	no	no	yes	no	yes	yes(4)	yes(4)	no	no
Bolting	no	yes	no	no	no	no	No	no	yes
Member removal	yes(5)	yes(5)	yes(5)	yes(5)	no	no	yes(5)	yes(5)	no
Adhesives	yes(6)	yes(6)	yes(3 or 6)	yes(3 or 6)	yes(3 or 6)	yes(6)	yes(3 or 6)	yes(3 or 6)	yes(3)
Composites	yes	yes	no	yes	yes	yes	yes	yes	yes

Notes: (1) Usually in conjunction with additional strengthening measures
(2) Except to apply weld beads in unstressed grouted connection/clamp repairs
(3) To apply patch plates
(4) Applicability depends on type and sense of loading
(5) If member is redundant
(6) Used as epoxy grout in clamps
(7) If damage can be by-passed

Table 5.2: SMR Techniques directly applied to various scenarios

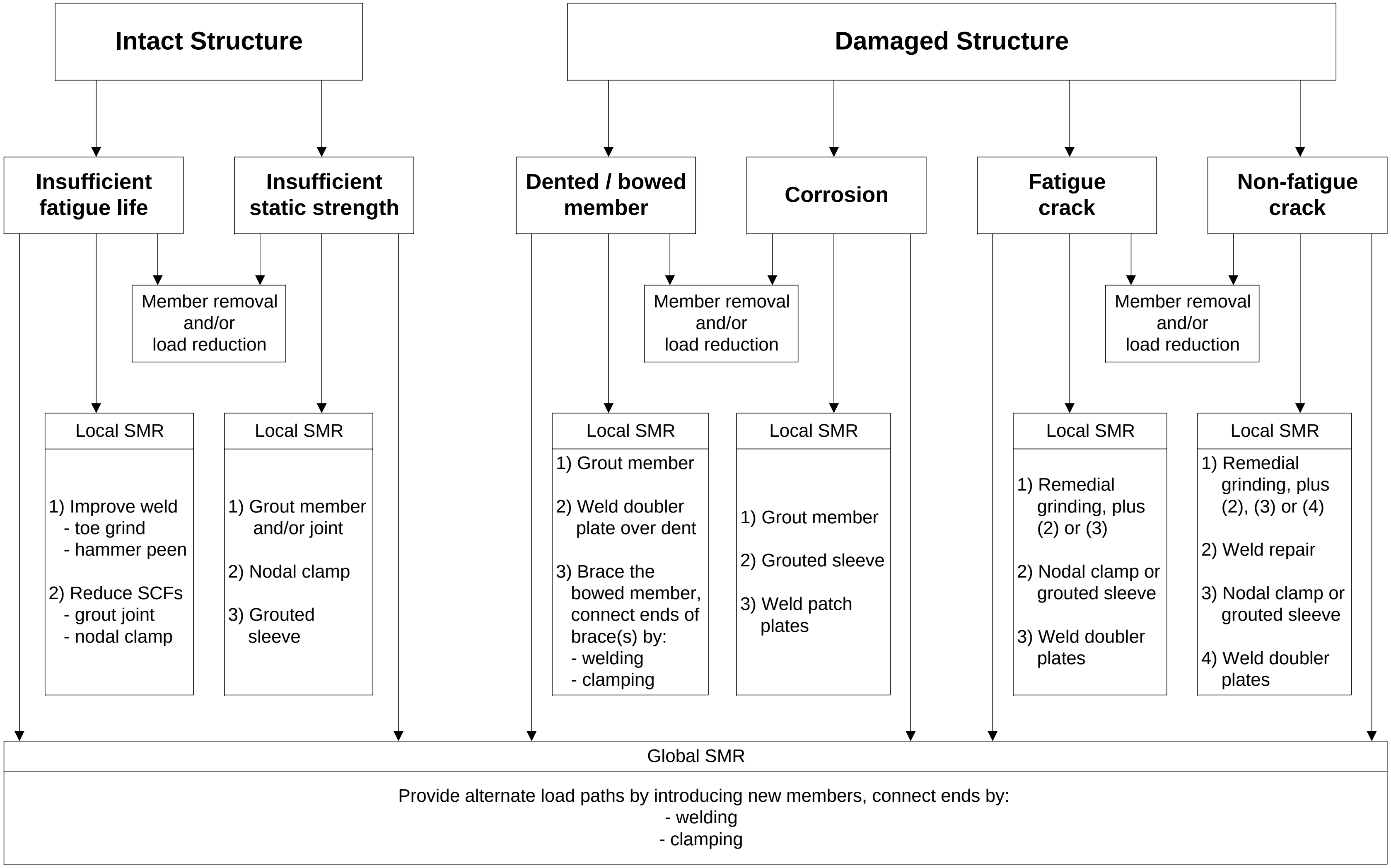


Figure 5.2: Interrelationship between scenarios, SMR schemes and SMR techniques

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PART II – DETAILS OF SMR TECHNIQUES

SECTION 6 – MEMBER REMOVAL

6. MEMBER REMOVAL

6.1 Description

6.1.1 General

The purposeful removal of a structural element is a valid structural repair technique in its own right (6.1) and is a relatively commonplace activity. Element removal may also be a temporary measure, as in the first phase of a repair scheme (6.2), or so as to prevent escalation of damage especially if there is danger of a partially severed element failing and impacting other members on its way down to the seabed.

The removal of redundant appurtenances (or other non-load carrying elements) is particularly attractive if the superfluous members are found in the wave action zone. Several structural elements, both above and below the waterline may be removed as part of a load-shedding exercise.

In some instances the installation of an underwater repair demands the removal of structural and non-structural elements in order to provide access to the repair site. On completion of the repair, the larger elements may be reinstated. In the case of bolted clamp repairs, the design of a repair clamp often means that minor connections into the repaired node have to be severed and the cut elements are then permanently removed. In such cases the removal of the element does not constitute a repair by itself, but is a requirement of the installation procedure for the clamp.

Removing the conductor guides frame has been proposed by a number of authors (6.1, 6.3, 6.4). It may be of value as a repair technique for older structures (designed before about 1981) because the understanding of how conductors behave under internally applied string loads has changed as a result of work undertaken in the early 1980's and reported by Imm and Stahl (6.5). The earlier platform designs did not separate out the effects of internally and externally applied loads in conductors, producing a heavier design than would be now required. Consequently there will be an inherent capacity for the earlier type of conductors to span greater distances. This inherent strength may mean that there can be circumstances in which the removal of a damaged conductor-bracing frame could be justified, as was found to be the case by Lang *et al* (6.3) in approximately 25% of the Gulf of Mexico platforms that he examined. The removal of conductor guide frames and braces as a repair technique, in the Gulf of Mexico, was reported by Daniel *et al* (6.6) and Souza (6.7).

In an ageing platform, there may be economies to be had by revisiting the structure and removing structural elements in order to reduce hydrodynamic loads and cathodic protection demand. Submerged pile guides are often removed at such a stage because they are fabricated from plate steel and consequently place a greater strain on the structural resources than a tubular element of equivalent weight. Other items, which have been removed from platforms, include the following list:

- Redundant caissons, conductors and risers
- Conductor guide frames
- Launch rails
- Boat landings
- Miscellaneous installation aids (bumpers, padeyes, and pile guides)
- Pile sleeve grout lines.

6.1.2 Cutting Techniques

The cutting techniques which may be used to remove structural elements underwater are generally similar to those used in air. The UEG publication UR18 (6.8) has a section, which details several tools and suppliers of underwater cutting equipment. The HSE (6.9) published a comprehensive document for evaluating and selecting cutting techniques. Although the focus of the document is removing redundant offshore structures, parts of the document can be referred to for removal of a single member, as sometimes required in SMR. The document includes a description and the associated advantages and disadvantages of each cutting technique including techniques, which are found to be unsuitable for offshore use. Health and safety issues are also discussed.

A summary of the general limitations to the use of underwater cutting techniques is given in Table 6.1 below. Simple guillotines and rotating discs can be used for thicknesses of steel up to 25mm. For greater thicknesses, Oxy-acetylene and oxy-arc methods are used. However, the acetylene-fuelled method is depth limited. The oxy-arc technique, where the heat is supplied by as electric arc, may be employed for a greater range of water depths. However, caution is advised when electric currents are controlled by free-swimming divers, because of the amplified effect of electric shocks when sustained underwater. Thermic lances may be used to cut steel and also grout filled steel elements underwater. In particularly awkward situations it may be necessary to use explosives, preferably shaped charges. The use of demolition charges is probably unsuitable for most SMR applications. In several offshore oil production zones there are strict controls governing the use of explosives with legislation covering prevention of theft, safety of personnel, other craft in the water and environmental impact.

Brandon *et al* (6.10) stated that abrasive water-jet and diamond wire-cutting systems will continue to be the preferred choice of cutting techniques for removing marine structures. Schematic diagrams and photographs of typical water jet systems and diamond wire-cutting machines are shown in Figures 6.1 and 6.2 respectively.

Method Type	Cutting Technique	Steel Thickness Range (mm)	Water Depth Limit	Comment
Mechanical	Cutter	2-60		Used for weld preparation
	Wire saw			Closing of crack due to platform movement can be troublesome
	Abrasive water jet	2-230		Safety hazard
	Diamond wire			
Thermal	Oxy-acetylene	10-40	6m	Decomposes under pressure
	Oxy-hydrogen	10-40	1500m	
	Oxy-arc	10-40		Electric shock hazard
	Thermic and ultra-thermic lance			Used to cut grout-filled members
	Plasma arc			
	Pyronol			Custom made `firework' operating on thermic reaction
Explosives	Primer cord	2-6		May be wrapped around thin tubular sections and used as a cutter without main charge
	Shaped charges	20-120	> 7	Tailor-made charges in a soft metal casing with `V' notch
Eletro-chemical	Spark corrosion			
	Assisted grinding			

Table 6.1: Summary of methods for making underwater cuts

Figure 6.1: Abrasive water-jet systems

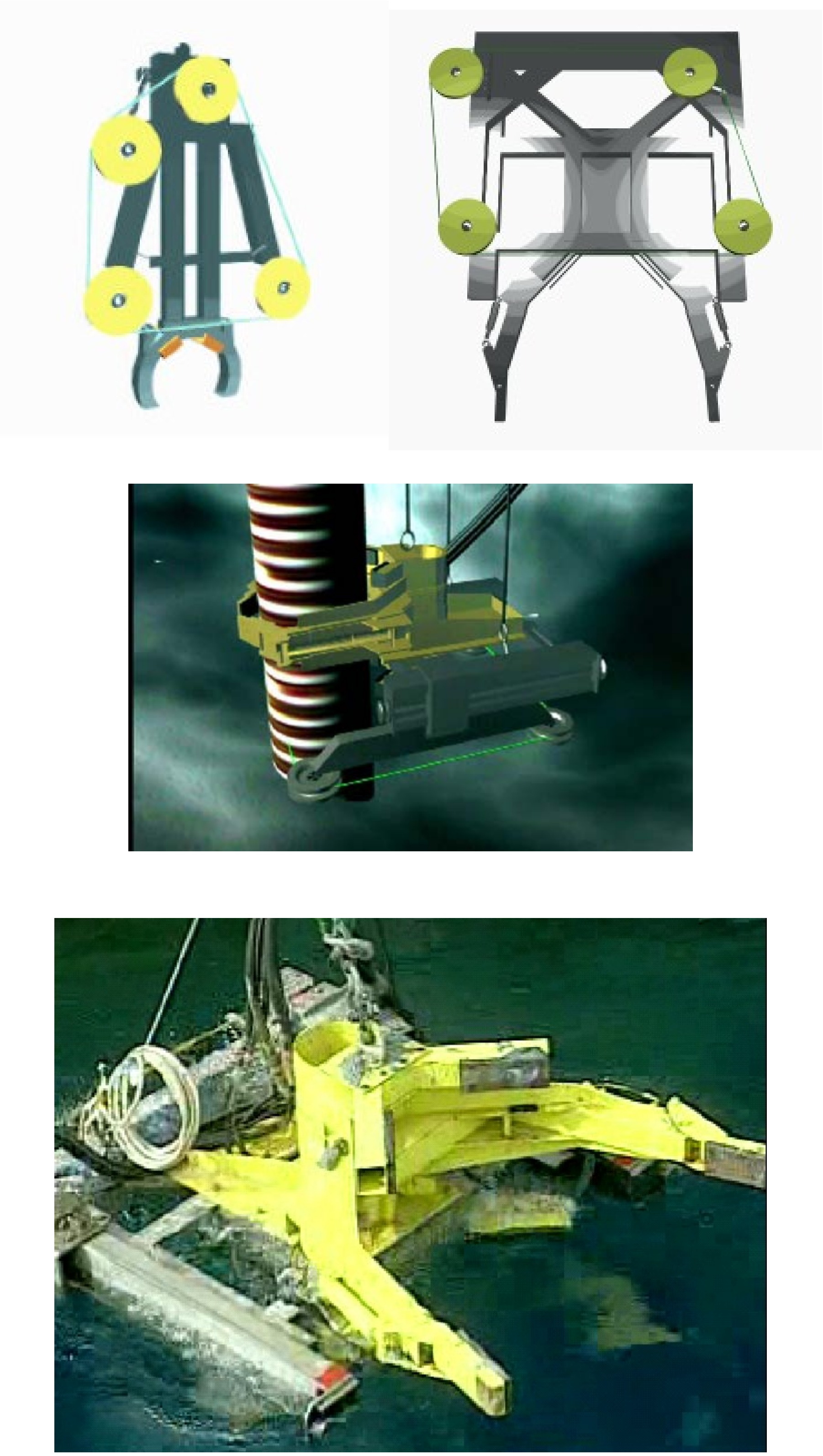

Figure 6.2: Diamond wire cutting systems

6.2 Limitations

No specific limitation has been identified for member removal as a technique in principle. Some cutting techniques, however, are not suited to cut thick sections, as noted in the above table. There will almost certainly be restrictions on the use of explosives as a cutting technique, as also noted above.

6.3 Design Approach

When an element is to be removed from an offshore structure, a systematic analysis of the effects of the element removal should be made. The analysis of the repair scheme is essentially concerned with checking the structural integrity with the chosen element removed, and with verifying the change in fatigue life of the remnant structure. The following notes give explicit advice for element removal schemes.

- An in-situ stiffness analysis of the modified structure should be undertaken. The analysis should take account of the change in the loading regime due to the removal of the member as well as the change in the stiffness and connectivity of the structural arrangement. Both calm and storm loadings should be computed. Element code-checks should be re-computed where the loadings have changed or where the effective brace lengths have been modified as a result of the element removal.
- The fatigue analysis of the modified structure should be assessed if significant changes are made to the loading or support conditions of all or part of the structure. In many cases a qualitative analysis will suffice. However, if primary structural elements are to be removed then a re-computation of the fatigue life of the remaining structure may be warranted.
- The element pre-stresses immediately prior to cutting should be computed and the spring-back of the cut element should be assessed. Account may need to be made of any tie-back arrangements necessary to achieve the safe removal of the element.

The above list is provided only as an indicative guide. There will be significant variation between projects.

When individual instances of repair are investigated it may be important to concentrate the analysis on a specific aspect of the removal. For example, Lang et al (6.3) reports that where the conductor guides were removed from structures it was necessary to re-evaluate the structural stability of the conductors themselves.

6.4 Fabrication/Installation Issues

The offshore operations associated with an element removal scheme may involve multi-discipline engineering work both in planning and executing the works. Typical problems associated with making underwater cuts are detailed by Stevenson and Sleveland (6.1) who chose to rough-cut the (removed) brace using oxy-arc cutting whilst the final weld preparation for the replacement was made using a hydraulic cutter running on a guide ring.

The brace needs to be fully rigged before any cuts are made so that it does not drop through the water on completion of the cut. A lifting appliance and a lay-down area need to be provided. Account should be taken of any possible hydrodynamic or shock loads arising during element severance and removal. If a sub-assembly is to be removed, then temporary bracing may be required to stabilize the lifted item.

Cutting structural steelwork underwater can be a hazardous operation and needs to be planned with care. Special arrangements may be required in respect of environmental impact if underwater cutting is to be performed using explosives.

When tubular elements are severed care should be exercised to prevent the tubular filling with potentially explosive fumes. In many cases the preliminary work includes the drilling of relief holes in the tubular brace.

If a brace is to be cut then the possibility of the partially severed element rotating and injuring any persons in the water should be considered. Also, when a cut is completed the member may spring due to the release of the previously locked in stress. Schemes should also examine the possible disruption of pressurized lines (risers, umbilicals, and conductors) due to the inadvertent movement of a cut bracing section.

The cutting of a brace from a structure leaves a remnant stub, often with a rough cut edge. It is conventional to grind back the stub. The re-working of the stub may take one of three likely forms:

- Grinding the cut back so that a short, smooth stub profile remains.
- Using a combination of cutting and grinding so as to produce a flush finish to the node. This finish is unusual and may be called for in cases where the remaining node barrel may be susceptible to further fatigue damage.
- Machining the cut brace stub so as to produce a welding profile on the stub, which then forms the connection for a "pup" piece to be installed at a later date.

There are very few circumstances in which it would be admissible to leave a rough-cut stub on an existing structure.

6.5 Previous Offshore Applications

Member removal is often done, either as a prelude to member replacement (as shown in the case study for wet welding, see Section 8.5), or to gain access, or as a SMR technique in its own right.

The removal of conductor guide frames and braces as a repair technique, in the Gulf of Mexico, was reported by Daniel *et al* (6.6) and Souza (6.7).

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SECTION 7 - DRY WELDING

7. DRY WELDING

7.1 Description of Techniques

Welding is often regarded as the best strengthening, modification and repair (SMR) technique and no doubt would be used even more often if it were not for certain operational challenges in its execution. These challenges mainly relate to the provision of a suitable environment underwater in which to conduct the welding.

There are several SMR welding techniques and a number of welding processes that can be considered:

- Dry welding at one atmosphere using cofferdam or pressure-resisting chambers. All normal welding processes can be used but Gas Tungsten Arc Welding (GTAW), Shielded Metal Arc Welding (SMAW) and, to a lesser extent, Flux Cored Arc Welding (FCAW) are the main methods used in practice.
- Dry hyperbaric welding using pressurized habitats. Main processes used are GTAW and SMAW although FCAW and Gas Metal Arc Welding (GMAW) are sometimes employed.
- Wet welding. Practically, only the SMAW process is used. Wet welding is the subject of Section 8.

Welding processes are discussed further in Section 7.1.3

7.1.1 Dry Welding at One Atmosphere

Because a large body of welding technology exists relating to normal atmospheric pressure, a logical approach to underwater welding repair is to duplicate surface welding conditions by providing a one-atmosphere environment at the repair site. Two methods are available which can achieve this:

i. Cofferdam

This essentially is a watertight structure, which surrounds the repair location and is open to the atmosphere. The structure can be open topped, as illustrated in Figure 7.1, or have a closed top with an access shaft to the surface (see Case Study in Section 7.5). Whether the cofferdam is open topped or has an access shaft, a dry environment is provided such that dry welding repair techniques can be performed.

ii. Pressure-resistant chamber

The worksite is surrounded by a chamber constructed as a pressure vessel, capable of withstanding the water pressure at the depth of the repair location. Once the chamber is in place and sealed to the structure, it is dewatered and the internal pressure is then reduced to one-atmosphere. The repair crew can transfer to the welding chamber in a one-atmosphere environment, within a diving bell, to carry out the repair.

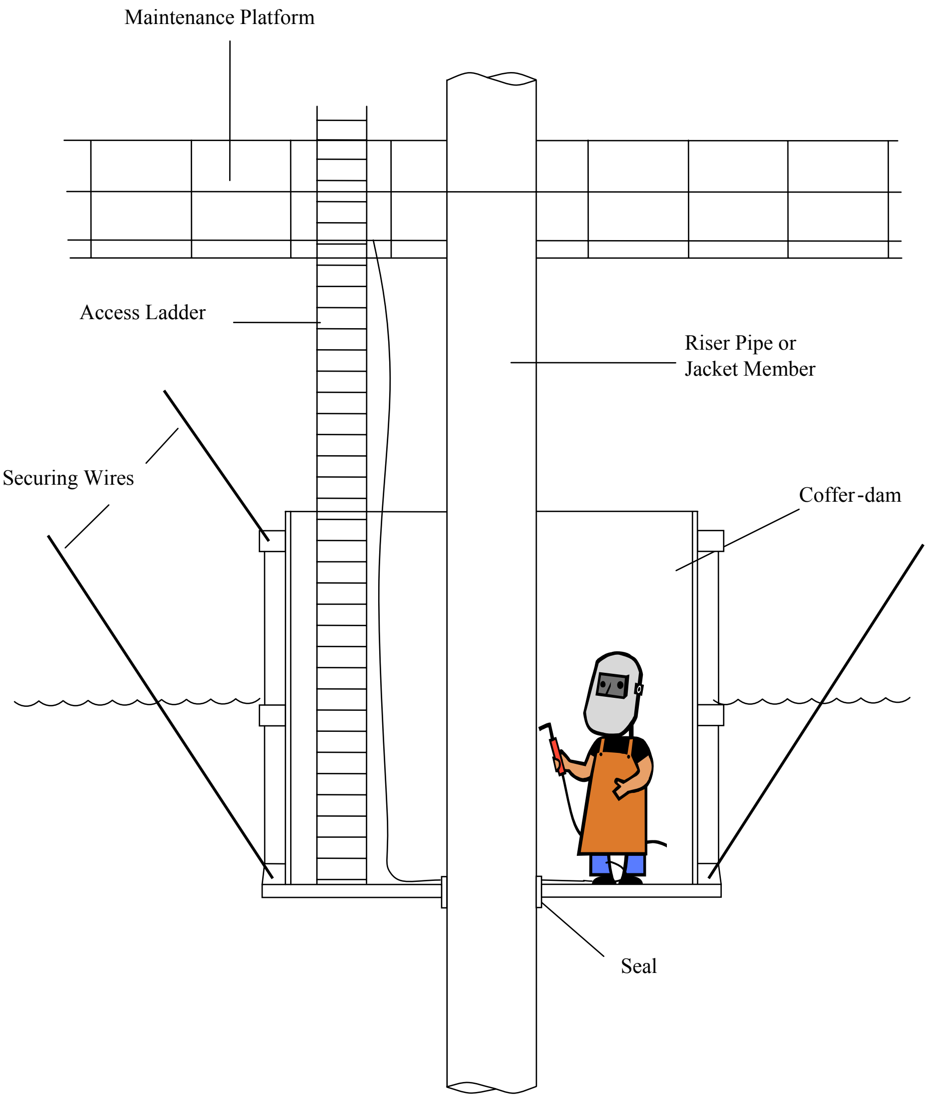

Figure 7.1: Open-topped cofferdam repair

7.1.2 Dry Hyperbaric Welding

Hyperbaric welding is the most widely used repair technique for primary structures and pipelines. The repair site is again enclosed within a working habitat, which is dewatered by filling the habitat with gas. Since the gas and water will be at equal pressure at a point close to the bottom of the chamber, the maximum differential pressure will be at the top of the chamber, and obviously depends on the height of the chamber. This differential pressure (normally a few tenths of a bar) is easily resisted by lightweight habitats and simple flexible seals, making deployment and sealing of the work chamber operationally feasible.

A variety of habitats have been used, dependent on such factors as the extent of welding required, the complexity of the repair site geometry, depth of repair, welding process and ancillary equipment, and environmental conditions. Generally, designs of dry hyperbaric habitat fall into one of the following four groups:

i. Lightweight steel habitats

These are of stiffened plate construction and are fabricated in two or more sections to allow their placement around jacket members. They may have an open grate floor with an access hole, see Figure 7.2, or be fitted with a closed floor and access shaft. The latter is used in shallow depths where the shaft acts as a surge tube, thereby reducing the volume and pressure changes in the habitat which otherwise could affect diver physiology.

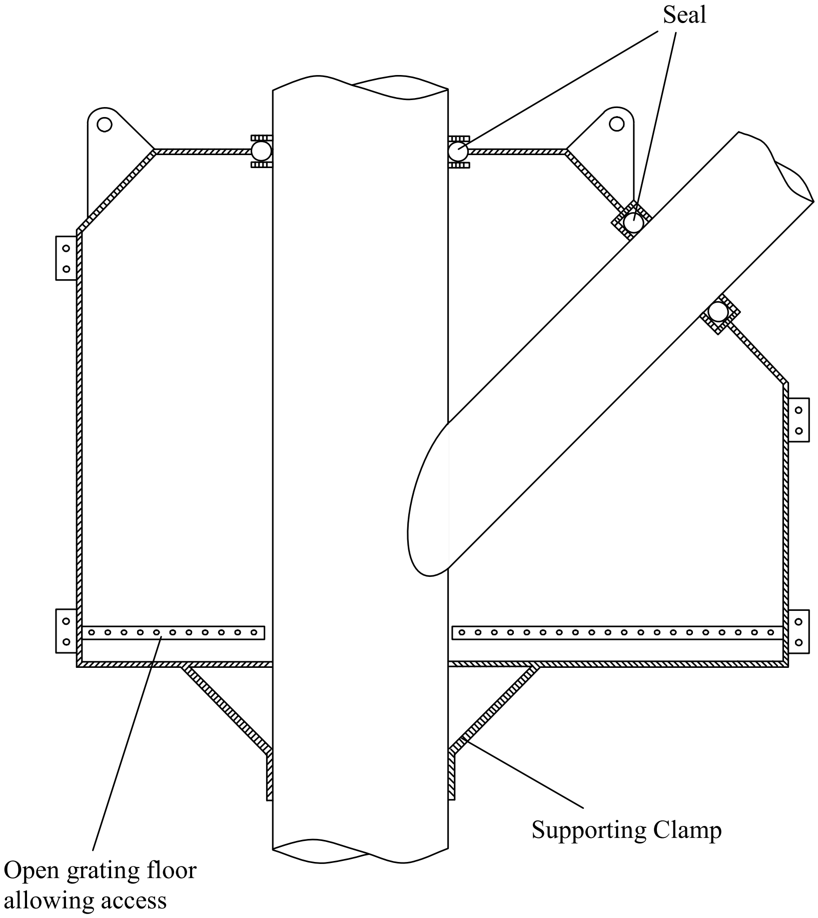

Figure 7.2: Hyperbaric welding habitat

ii. Inflatable flexible habitats

Because differential pressures are low, flexible habitats of sufficient strength are practicable and have been used, see Figure 7.3. The skin of the habitat takes up a shape dictated by the skin membrane stresses and the depth-dependent differential pressure, and is the same shape that would be obtained onshore by turning the habitat upside down and filling it with water.

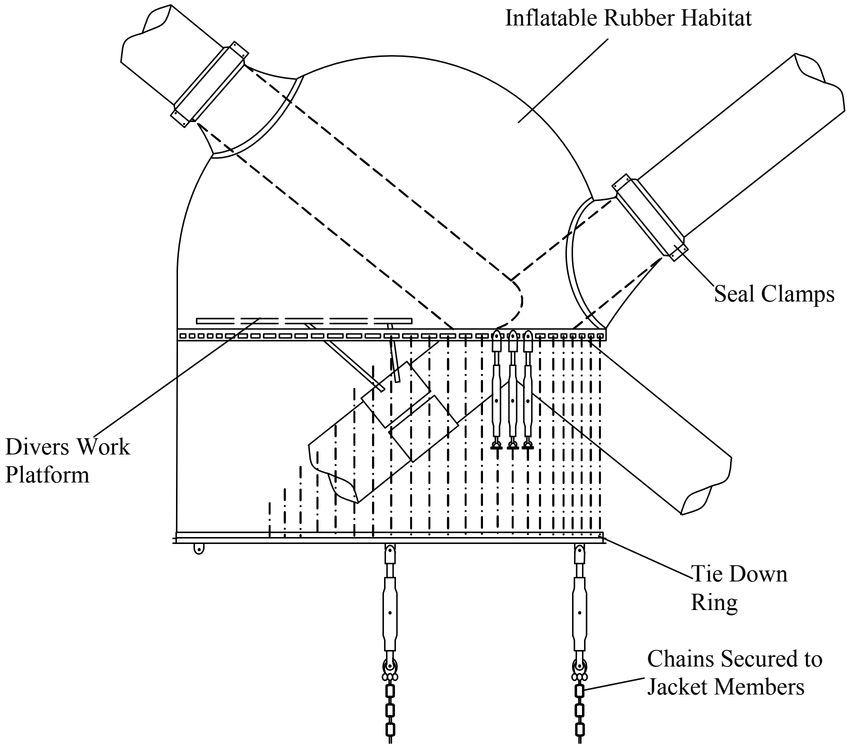

Figure 7.3: Inflatable habitat

iii. Mini habitats

As the name suggests, these are small constructions with just enough room for the arms and sometimes the head of the welder/diver.

iv. Portable dry spot habitats

These, in essence, only protect the welding head and a small area around the weld. The clear plastic box, fitted with sponge or flexible rubber seals, moves with the head. These devices have not undergone as much development as either large habitat welding or wet welding

7.1.3 Hyperbaric Welding Processes

The problem with hyperbaric techniques is that the environmental pressure at which the weld is carried out is essentially that of the worksite. These elevated pressures affect the gas/slag/metal reactions for all welding processes, and the high-density gas enhances the rate of heat loss from the weld. Hyperbaric welding research is mainly concerned with ensuring that for any specific environmental pressure and composition, welding parameters can be specified which will ensure the production of welded joints with properties acceptable to the certification authorities responsible for the structure on which the weld is being made. Because the welding process has to be specially optimized for hyperbaric conditions, the number of techniques used has been limited. The great majority of welding is carried out using GTAW and SMAW, with small amounts of FCAW and GMAW.

Shielded Metal Arc Welding (SMAW)

Also known as Manual Metal Arc (MMA) welding, hyperbaric Shielded Metal Arc Welding (SMAW) is carried out using flux covered welding electrodes, electrode holders and welding techniques very similar to those used for SMA welding on the surface. Because of the simplicity of the technique and equipment, and the availability of a relatively large number of diver/welders trained in SMAW, it is the most widely used operational repair technique. Due to excessive electrode burn-off, the process has heat input limitations, and careful procedure control is necessary to avoid problems relating to hydrogen-induced cold cracking (HICC).

Gas Tungsten Arc Welding (GTAW)

Also known as Tungsten Inert Gas (TIG) welding, Gas Tungsten Arc (GTA) Welding is the most controllable technique available to hyperbaric welding engineers. Similar techniques are used for both hyperbaric and surface welding.

Because of its simplicity, it has been widely studied by process physicists, and is better understood than other hyperbaric welding techniques. An arc is struck between a non-consumable tungsten electrode and the work piece. Filler material can be added by the welder in rod form. Automated variants on the process are also used underwater.

The high level of control available to a skilled diver / welder has led to its use for critical welding situations such as root and hot pass welds, and for capping passes and temper beads where the shape and hardness of the material at the toe of a weld must be controlled, normally for fatigue resistance (TIG dressing).

Gas Metal Arc Welding (GMAW) & Flux Cored Arc Welding (FCAW)

Also known as Metal Inert Gas (MIG) or Metal Active Gas (MAG) Welding, this technique, GMAW, is a consumable electrode process. A hand torch is used, and a continuous wire electrode, between 1/40th and 1/12th inches in diameter, is fed through it.

This wire, and the work piece, is connected to the output poles of the welding power supply, so that when the wire touches the work piece, an arc is struck which melts the wire and the work piece to form a molten weld pool. To protect the pool, a shielding gas is fed through the torch concentric with the wire in a similar manner to that employed for the GTA process.

GMAW was proposed for underwater use in the 1970's, but the welding equipment available at the time could not respond to the unusual demands of the hyperbaric environment, and the process lacked stability and adequate fusion characteristics. When these limitations were recognized, the use of tubular consumables (FCAW) was suggested as a way of overcoming the deficiencies. FCAW is a variant using tubular consumables covered with flux. Unfortunately, the relatively high cost of these consumables, and the relative complexity of GMAW welding equipment, with its associated consumable feeding systems, made the process unattractive to the offshore industry compared with hyperbaric SMAW, and little use has been made of the technique.

Plasma Hyperbaric Welding

Plasma welding is a development of GTAW in that the plasma arc is constricted by means of a copper or carbon constriction about ¼ inch in front of the electrode tip. The process has enhanced arc stability compared to GTAW, and has greater resistance to external influences such as magnetic fields. However, considerable development work is required to bring it to operational status.

Laser Beam Welding

Habenicht *et al* (7.1) conducted under water weld tests using a laser beam. The weld zone was kept water-free by surrounding a flexible rubber seal round the nozzle (portable dry spot habitat). Pressured gas is dispersed through the nozzle creating a water-free laser welding zone. The experiments were carried out in a glass tank. Much more development is required for this to be an under water weld option. One of the advantages of laser weld over conventional arc welding process is that the former produces deep penetration welds by low heat input. Thus, the heat-affected zone is reduced. Due to the relatively lower welding temperatures, there will also be less concern with cooling rates, a problem inherent in conventional welding, which can lead to locked stresses in weldments.

7.2 **Limitations**

Cofferdams, especially the open top variety, are uneconomic for depths greater than about 50 feet due to the substantial amount of steelwork required to resist the differential pressure. Sealing the cofferdam can also be a problem for these depths. Even for smaller depths, cofferdams are heavy items and this, together with the large environmental forces they attract, has limited their usage to members having appropriate strength and rigidity, such as leg members. Nevertheless, cofferdams should be considered for all splash zone repairs because of the significant advantages that are gained: protection from environment (shallow depth hyperbaric chambers suffer from wave depth effects), non-diver welders and inspectors have access, normal one-atmosphere welding processes are all applicable, and simplification of life support services.

Pressure-resistant chambers have been little used, despite having the great advantage that the technique can utilize the consumables and welding procedures developed for the original construction of the structure under repair. Their major drawback centers on the problem of sealing the working chamber to a structure with a joint capable of ensuring the pressure integrity of the chamber. Operational systems have been developed in the past for use in the Amazon basin, but these were used for pipeline tie-ins where the end of the pipeline could be fitted with a special coupling for the pressure joint, and where the work chambers were repositioned on the platform structure. This technique will undoubtedly be considered very carefully as a potential system for use in very deep water in a few years' time, but the engineering problems are formidable, and become worse as water depth increases.

A significant design constraint for hyperbaric welding concerns the habitat. It may not be feasible to use a habitat around a complex joint due to the complexity of fitting and sealing the habitat around each of several brace members. It is also difficult to install a habitat in shallow water due to wave and current forces.

Habitats having flexible chambers can accommodate the significant departures from design geometry frequently encountered on offshore structures much more easily than rigid chambers. However, such chambers cannot be utilized as mountings for the ancillary equipment required for the repair procedure, and a support structure must be constructed within the chamber to provide secure standing room for the divers working within. This, together with the problem of reacting the buoyancy forces generated by the flexible chamber, complicate the installation procedure. The Magnus repair carried out in 1991 by Comex utilized a compromise solution in the form of an ingenious combination of flexible and rigid chamber to overcome access problems at the repair site.

The effect of depth on hyperbaric welding processes also requires most careful consideration.

7.3 Design Approach

Reference should be made to specification AWS D3.6M (7.2) that specifically addresses underwater welding in both dry and wet environments, and applies equally to new construction and to modification and repair of existing structures. The specification does not address design considerations such as arrangements of parts or stress calculations.

7.4 Fabrication/Installation Issues

Equipment and Offshore Support

- A typical dry welding operation will require the following items of equipment:
- Purpose-built habitat or cofferdam
- Saturation diving support (habitat only)
- Environmental control equipment (habitat only)
- Pre- and post-weld heating equipment
- Welding equipment (often GTAW and one other)
- Weld inspection equipment
- Equipment to remove marine growth and grit blast to Sa 2½
- Temporary holding clamps to take weight of additional members and maintain root gaps
- Craneage.

Most underwater welding equipment is transported offshore in a standard transport container. It is common practice, upon reaching the worksite, to remove the service umbilicals and welding equipment, and utilize the container as the welding control station. Often, it will also be used as the diver communication centre. Space is therefore required, as close to the repair site as reasonably possible, for a container of this type, adequate supplies of gas for dewatering the chamber and supplying shielding gas if required, and to lay out service umbilicals. Adequate craneage is required to deploy welding chambers if required, and procedures developed to ensure that access to the repair site, for both cranes and diving personnel, is optimized.

For all forms of arc welding, a power supply of appropriate output characteristics is required. Normally, these operate from a three phase 380 or 440 V AC electrical supply, although units powered by other prime movers are also available. In practice, several or more kilowatts of electrical power will be required for welding operations, which will create a rapidly changing load for the power system. It is necessary to ensure that this can be supplied without disruption to other systems on the offshore platform or vessel from which the welding operation is being undertaken.

Timescales

The time expended on cofferdam or habitat design, fabrication and deployment can take up a considerable portion of the schedule, depending on the complexity of the enclosure. The time for weld procedure trials, and for welder/diver training and qualification must also be included in the schedule, although often this can be concurrent with habitat constructions.

Most of the time required for an underwater welding repair is not taken up by welding operations, but by the necessary preparatory work, and this must be planned with considerable care. Assembling and sealing the welding chamber can take a time comparable to the welding operation, especially around the more complex node geometries. A compromise must be struck between deploying the chamber in as few pieces as possible, so minimizing the amount of underwater assembly work, and the increase in risk for divers working with large chamber components, especially where such work is to be carried out in tidal or splash zone conditions. It should not be assumed that the actual geometry of the structure is precisely as designed, and it is normal practice to undertake a survey of the location before building the welding chamber. It will be necessary to clean portions of the structure to ensure that an effective seal can be achieved, allowing the chamber to be dewatered. The welding chamber must be made sufficiently large to enable the welders to have effective access to the weld site.

Inspection/Maintenance

Monitoring during welding is as important as post-weld inspection. It is essential that all organizations concerned with an underwater welding operation agree the parameters, which will be monitored, and the techniques used to record them. All certification authorities have codes of practice relating to process monitoring, as do many offshore operators. Care should be taken to ensure that the process monitoring and quality assurance procedures selected conform to the requirements of all relevant organizations.

At various stages during a welding repair procedure, it will be necessary to carry out some form of inspection to ensure that the weld meets the required standards. The techniques used are similar to those employed for surface based inspection of welds. Visual, magnetic particle, eddy current, ACPD, ultrasonic and radiographic techniques are all available for underwater use, and suitably trained diver-inspectors are available. As with process monitoring, care must be taken to ensure that the procedures selected conform to the standards of the certification and operating authorities.

Subsequent inspection would normally be of the same type and frequency as applied to other, similar, parts of the installation.

7.5 Previous Offshore Applications

Repairs by both cofferdam and hyperbaric habitat welding techniques have proven track records. Hyperbaric welding has been used as an underwater SMR technique since about 1970 and is the normal method for effecting subsea weld repairs in the North Sea. References 7.3 to 7.11 give details of some case histories.

CASE STUDY 1: Hyperbaric Habitat – Repair to Jacket Brace/Leg Weld

Magnus (Figure 7.4) is a 4-leg drilling/production platform operating in 610ft of water in the most northerly UK field of the North Sea. The platform was installed in 1982. During routine inspection a brace member was found to be flooded. A through thickness crack approximately 1½ ft long was found at the brace to leg connection at a depth of 600ft. Fabrication records revealed the weld had been repaired several times during fabrication due to root flaws.

A hyperbaric habitat/dry weld SMR solution was chosen due to the criticality of the weld.

The following project phases were encompassed during the repair:

- Detailed measurements of the location
- Hyperbaric habitat designed for geometry and water depth
- Cleaning of marine growth from repair area
- Deployment and sealing of hyperbaric habitat (Figure 7.5) followed by dewatering
- Based on structural and fracture mechanics assessment, 20% of the joint circumference was repair using TIG and manual arc welding.
- Abrasive water jetting was used to cut out the defect leaving beveled openings for welding
- Welding followed by NDT of finished weld.

Figure 7.4: Magnus Platform

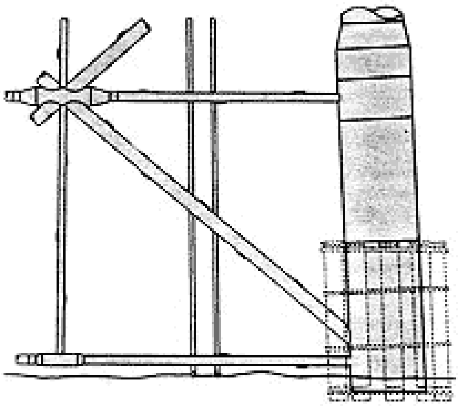

Figure 7.5: Location of Hyperbaric Habitat

<u>CASE STUDY 2: Cofferdam Repair to Jacket Bracing</u>

A brace of a shallow water jacket, located on the Dutch continental shelf of the North Sea, was damaged approximately 6ft below the water surface by boat impact in 2002. The extent of damage required replacement of the brace member. A cofferdam solution was chosen primarily due to the repair being in the splash zone.

GB Diving carried out the repair using the DSV Deurloo. The cofferdam was fabricated at Genius-Vos.

Detailed emergency escape procedures were developed and the cofferdam was designed with an emergency escape. The welders were trained for diving and underwater escape.

The repair project encompassed the following phases:

- Detailed measurements of the damaged brace and surrounding structure
- Cofferdam designed for geometry, water depth and internal lifting of removed damaged brace and new brace sections
- Onshore trial fit-up (Figure 7.6)
- Cleaning of marine growth from braces
- Deployment and sealing of cofferdam (Figure 7.7)
- Removal of damaged brace using jet cutting
- Welding of replacement brace (Figure 7.8).

The duration of the offshore repair was 8 days, including cofferdam deployment, weld repair and cofferdam retrieval.

Figure 7.6: Trial fit-up of cofferdam

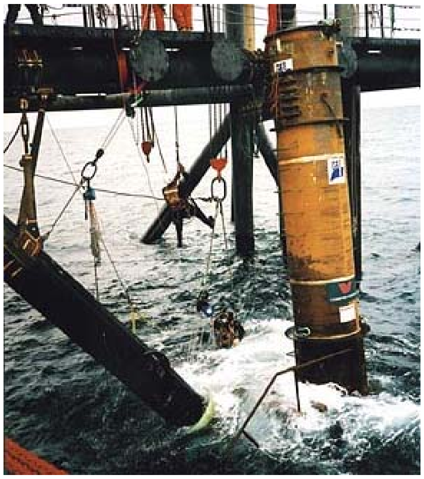

Figure 7.7: Cofferdam in position

Figure 7.8: Welder at work in cofferdam

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SECTION 8 - WET WELDING TECHNIQUES

8. WET WELDING TECHNIQUES

8.1 Description of Technique

8.1.1 General

Wet welding is underwater welding when the arc is operated in direct contact with the water. Examples of wet welds being made are shown in Figure 8.1. It is the oldest underwater welding technique, and has as its major advantage the lack of a requirement for a welding habitat or chamber. The advantage of avoiding the assembly of a welding chamber around the repair site is particularly relevant for platform repairs, where the geometry of the steelwork adjacent to the repair site may be complex, requiring any chamber to be assembled from several sections, a task which may be comparable in duration with the welding time. This advantage is offset against the poorer weld metal properties, the low deposition rate possible with wet welding, and the high levels of skill required by the welders. Although widely used in America, it has found little favor in Europe.

Figure 8.1: Examples of wet welding

8.1.2 Welding Processes

Virtually all wet welding is carried out using Shielded Metal Arc Welding (SMAW), although some research has been carried out into wet Flux Cored Arc Welding (FCAW). Using waterproofed electrode holders and welding consumables, it is possible to maintain an arc underwater. However, the welder's view of the weld pool can be disrupted by gases evolved from the breakdown of the electrode flux material, see the left hand photograph in Figure 8.1.

During wet welding, because of the proximity of cold seawater to the weld pool, high cooling rates are experienced by the weldments. In addition, dissociation of water within the welding arc ensures the presence of hydrogen in the weld pool. Both of these phenomena adversely affect the final weld. The high cooling rates generated in the Heat Affected Zone (HAZ) and weld metal, for the types of steel used in offshore construction, generate brittle metallurgical structures of low toughness.

FCAW has been proposed as an alternative to SMAW, and offers higher heat inputs and greater productivity, at the cost of more complex equipment.

Shielded Metal Arc Welding (SMAW)

Also known as Manual Metal Arc (MMA) welding, hyperbaric Shielded Metal Arc Welding (SMAW) is carried out using flux covered welding electrodes, electrode holders and welding techniques very similar to those used for SMA welding on the surface. Because of the simplicity of the technique and equipment, and the availability of a relatively large number of diver/welders trained in SMAW, it is the most widely used operational repair technique. Due to excessive electrode burn-off, the process has heat input limitations, and careful procedure control is necessary to avoid problems relating to hydrogen-induced cold cracking (HICC).

Friction stud welding

Underwater friction stud welding is not a flexible joining system, but it is reasonably well developed. It is debatable whether it should be seen as a wet welding technique as defined above, but is included here as no habitat needs to be constructed.

In essence, a circular stud is pressed against the object to which it is to be welded with a controlled level of force, and then rotated at a defined speed for a set time. The friction between the stud and the work piece generates heat, which raises the temperature of the material close to melting point adjacent to the interface, as indicated in Figure 8.2. Once sufficient heat is generated, the rotation is stopped, and the stud pressed harder against the work piece, and held until the material has cooled sufficiently to weld together. The joint area is protected from the cooling effects of the surrounding water by a polymeric shroud mounted over the stud prior to welding.

This system has been tested at pressures equivalent to 600 meters of water, and seems unaffected by depth. Current development programs are seeking to make it deployable by current generation ROVs, and successful operations have recently been undertaken utilizing ROV deployment.

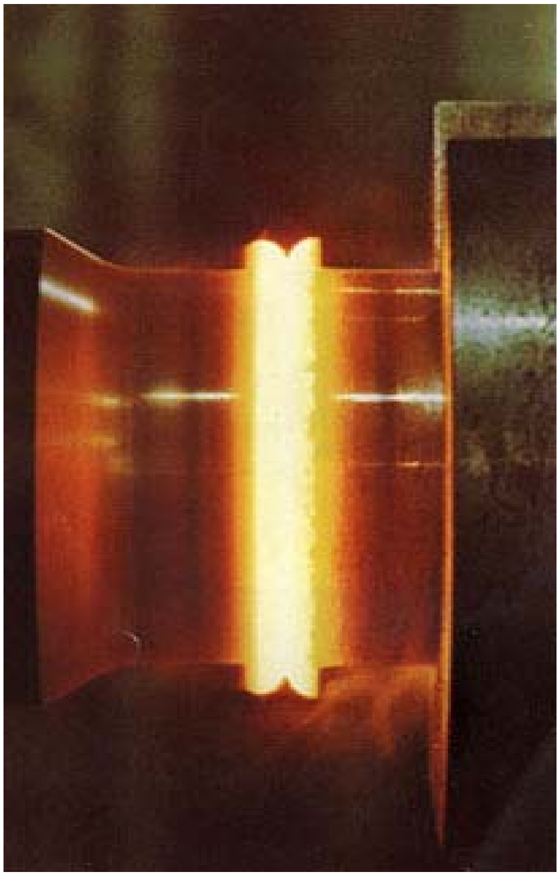

Figure 8.2: Friction stud welding

Although limited to circular or near circular studs of up to 30mm diameter, the system has found a wide range of applications in the fixing of protective anodes and their connections, and the mounting of shear pins. Most repair work has been used to attach sacrificial anodes to structures, weld beads for clamp repairs and other similar tasks.

Stitch welding

A variant of the friction weld process has been tried for the repair of cracks. A tapered hole is formed at the crack tip, and then a tapered pin is inserted and friction welded in place. A series of contiguous pins are thus formed, giving rise to the name of the technique - stitch welding. The hole and stud can also by cylindrical. However, the process is still largely experimental and has only been subjected to limited trials offshore.

Facilitated by the repetitive nature of stitch welding and the necessity to carry out repairs at greater depths, ROV-deployed applications for this technique have also been developed (8.1, 8.2). Meyer *et al* (8.3) experiments with a portable friction weld tool, which is therefore also suitable for diver repairs at shallow depths. ROVs are probably more difficult to handle at shallow depths due to wave and current forces. Nevertheless, the tool had been adapted to be compatible with ROVs. Generally, trials of the method have proven to be successful.

8.2 Limitations

It is generally accepted that the weld quality of welds formed by wet welding is not as good as those formed by dry welding techniques. Some of this is due to operational difficulties such as lack of visibility because of the gases liberated, but most of the difficulties are metallurgical in nature:

- Dissociated water vapor leading to hydrogen entrapment and the possibility of hydrogen induced cold cracking (HICC)
- Hard, crack-susceptible (HAZs) caused by the rapid quenching effect of the water.
- The fatigue strength of wet welds is lower than dry welds and thus wet welding is not recommended for locations subject to significant fatigue loading.

The above comments do not apply to friction welding. This can be used on members of any thickness and the fatigue life can be predicted using standard approaches.

Technical considerations aside, recognition should also be given to the fact that some operators and some regulatory authorities do not favor wet welding, at least for repairs on primary structural elements. Thus, wet welding is not commonly used in Europe.

Research to improve the inferior properties of wet welds, compared to dry welds, is cited in the literature. The existence of hydrogen in underwater welds and methods to reduce it are reported in Liu *et al* (8.4). Szelagowski *et al* (8.5) reported of comparable wet weld mechanical properties to that of hyperbaric welding after developing new electrodes and improving the wet welding process. Thandavamoorthy (8.6) points out that apart from the inherent weld quality of wet welds, the weakest link lies in the divers/welders ability to transfer tried and proved land-based technology to offshore environment. Irie *et al* (8.7) developed a method of producing full penetration welds underwater using the combination of a ceramic backing and super-water-repellent material.

Significant development in underwater welding is demonstrated by the MMS (Mineral Management Services). The MMS organized workshop (8.4, 8.8), which involved a gathering of representatives from commercial companies, to certification bodies, and government. With respect to wet welding, the aim of the workshop was to improve the quality of underwater welds. As a result, developed underwater weld consumables leading to quality underwater welds was achieved. Weld inspection methods were reviewed to assure the quality of the welds. Furthermore, the use of Remotely Operated Vehicles (ROVs) is also being developed for deep-water applications. Although great strides towards underwater welding were made, there is still ample room for improvement. Several recommendations were made to continue the research. This work was followed up by an underwater welding program (8.9).

8.3 Design Approach

Reference should be made to specification AWS D3.6M (8.10) that specifically addresses underwater welding in both dry and wet environments, and applies equally to new construction and to modification and repair of existing structures. The specification does not address design considerations such as arrangements of parts or stress calculations.

Joints should be designed to assist wet welding, see examples in Section 8.5.

8.4 Fabrication/Installation Issues

Equipment and Offshore Support

A typical wet welding operation will require the followings items of equipment:

- Diving team support
- Welding equipment (power supply, gas supply, consumable handling units, welding torches and umbilicals)
- Equipment to clean work area
- Temporary holding clamps to take weight of additional members and maintain root gaps
- Craneage.

The arrangements for wet welding are generally similar to those in dry welding operation.

For all forms of arc welding, a power supply of appropriate output characteristics is required. Normally, these operate from a three phase 380 or 440 V AC electrical supply, although units powered by other prime movers are also available. In practice, several or more kilowatts of electrical power will be required for welding operations, which will create a rapidly changing load for the power system. It is necessary to ensure that this can be supplied without disruption to other systems on the offshore platform or vessel from which the welding operation is being undertaken.

Timescales

Wet welding is faster overall than dry welding, as fabrication and installation of a habitat is not required.

There are little factual data in the literature. Hughes *et al* (8.11) reports that over 12,000lbs (5440kg) of welding electrodes was used in 10,000 man-hours of underwater work concerning wet welding of patch plates to correct corrosion faults in the Gulf of Mexico. Green (8.12) states that it took 35 days for a wet welding team to conduct repairs to two platforms, taking 55 hours of arc time to lay 63 feet of 0.4" (9.5mm) fillet weld. The repairs involved 7 sites at various depths from 12 to 120 feet (3.7 to 36.5m).

Inspection/Maintenance

Monitoring during welding is as important as post-weld inspection. It is essential that all organizations concerned with an underwater welding operation agree the parameters, which will be monitored, and the techniques used to record them. All certification authorities have codes of practice relating to process monitoring, as do many offshore operators. Care should be taken to ensure that the process monitoring and quality assurance procedures selected conform to the requirements of all relevant organizations.

At various stages during a welding repair procedure, it will be necessary to carry out some form of inspection to ensure that the weld meets the required standards. The techniques used are similar to those employed for surface based inspection of welds. Visual, magnetic particle, eddy current, ACPD, ultrasonic and radiographic techniques are all available for underwater use, and suitably trained diver-inspectors are available. As with process monitoring, care must be taken to ensure that the procedures selected conform to the standards of the certification and operating authorities.

Subsequent inspection would normally be of the same type and frequency as applied to other, similar, parts of the installation.

8.5 Previous Offshore Applications

Wet welding is a popular method of repair in the Gulf of Mexico where a combination of shallow water, low fatigue environment, and operator philosophy has promoted its usage over a number of years.

Although it has been used in the North Sea for the repair and attachment of secondary items, it has not been used for major structural repairs with one notable exception (8.13), see Case Study 2 below.

CASE STUDY 1: Gulf of Mexico T-23 Platform

The T-23 platform, located in South Timbalier Block 52 in the Gulf of Mexico, is a four-leg jacket platform operating in 68 feet of water. The jacket structure is horizontally braced at four levels with K diagonal braces, see Figure 8.3.

The platform was inspected immediately after the passage of Hurricane Andrew. The inspection discovered that two midpoint joints, which are located at EL (-) 39' level between A1 and B1 and A2 and B2 (as indicated in red in Figure 8.3), were damaged. The repair scheme involved removing the joints, together with member stubs, as a single unit and replacing the unit with a new construction that was wet welded in place.

Global Divers and Contractors performed the wet welding repair work of replacing the two damaged joints. Divers worked from the diving support vessel M/V "GD 122".

The project phases encompassed the following aspects:

- Designed new joints.
- Determined proper welding technique by collection specimens from jacket structure and measuring the carbon equivalent – the wet multiple temper bead was chosen.
- Wet welding specimens were tested.
- Removed the two damaged joints (see Figure 8.4).
- Grit blasting the remaining structural members in preparation for welding.
- Final dimensions were measured to insure the new joints fit.
- Install new joints (see Figure 8.5).
- All welds were magnetic particle inspected.

The repair was undertaken over the period May 20, 1993 - June 26, 1993.

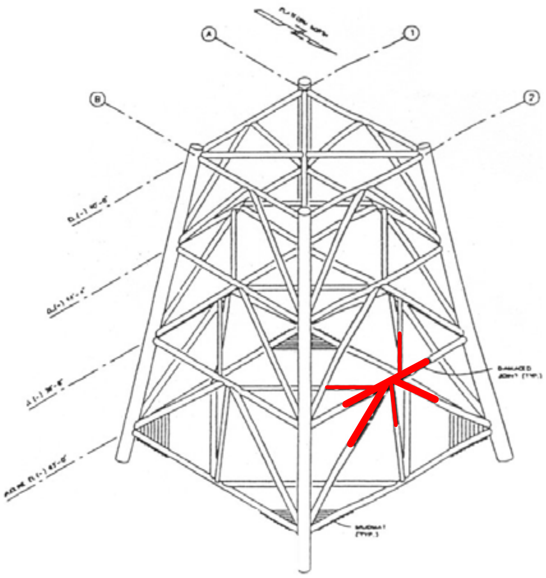

Figure 8.3: Jacket isometric view of T-23 structure and damage location

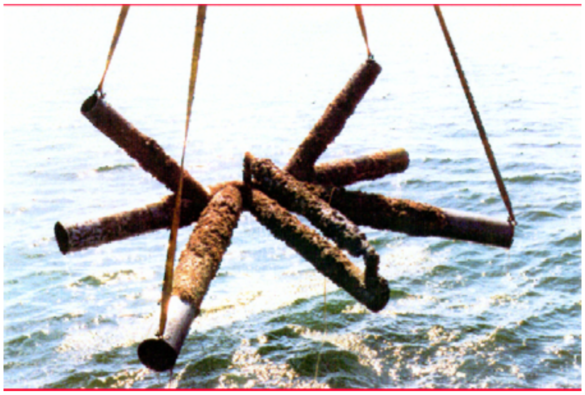

Figure 8.4: Removal of the damaged joint

Figure 8.5: Installation of new joint

CASE STUDY 2: North Sea Platform

An Amoco platform, located in the North Sea, is an eight-leg jacket platform operating in 300 feet of water. The jacket structure is horizontally braced at six levels with inverse K and diagonal braces, see Figure 8.6.

The underwater inspection in 1987 revealed that a diagonal brace connecting Leg B3, at EL (+)26' to Leg E3, at EL (-) 36' (as indicated in red in Figure 8.6) had a severed weld which has connected the brace to the E3 leg joint. The failure was the result of ship impact on the brace. The damaged brace was removed in July 1987 to prevent further degradation. Dry hyperbaric welding was considered as a repair option, but the cost and possible damage to the platform member due to the habitat's size prevented its use for this repair. The member was eventually replaced in 1990 using wet welding techniques.

Comex of Aberdeen and Marseille was selected to undertake the repair work. Global Divers and Contractors was involved to provide technology transfer on wet welding techniques to Comex.

The project phases encompassed the following aspects:

- Determined proper welding technique based on the carbon equivalent – the temper bead technique was chosen.
- Global Diver proprietary welding electrodes were selected based on satisfactory tests.
- Detailed measurement of the underwater repair site and trial fit-up (see Figure 8.7)
- Wet welding (see Figure 8.8).
- All welds were magnetic particle inspected.

The repair was undertaken over the period July 26, 1990- August 4, 1990

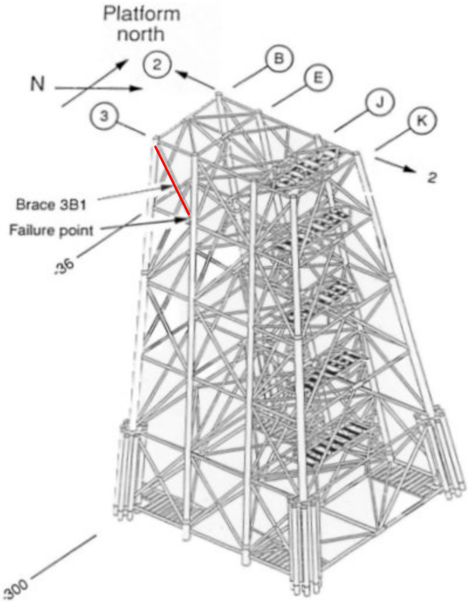

Figure 8.6: Jacket isometric view of jacket structure and damage location

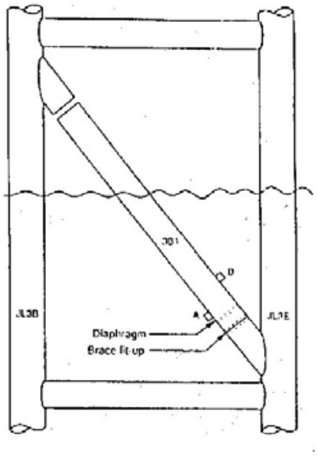

Figure 8.7: Sketch of proposed brace replacement

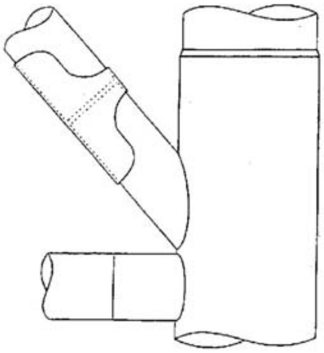

Figure 8.8: Wet welded scalloped sleeve to reduce overhead welding

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SECTION 9 – STRUCTURAL CLAMPS

9. STRUCTURAL CLAMPS

9.1 Description

9.1.1 Introduction

This chapter presents the background to and the description of a number of strengthening and repair techniques, which deploy clamping technology. The main clamping techniques covered are as follows:

- Stressed mechanical (friction) clamps
- Unstressed grouted clamps/sleeve connections
- Stressed grouted clamps
- Stressed elastomer-lined clamps

The common features among these clamps are that they are deployed in two or more pieces, are fastened by bolts (or studbolts), and typically surround a structural component such as a joint or member. However, a key distinction can be made on the basis of what function and effect the bolts have, resulting in two generic types of clamps: unstressed (grouted) clamps and stressed clamps.

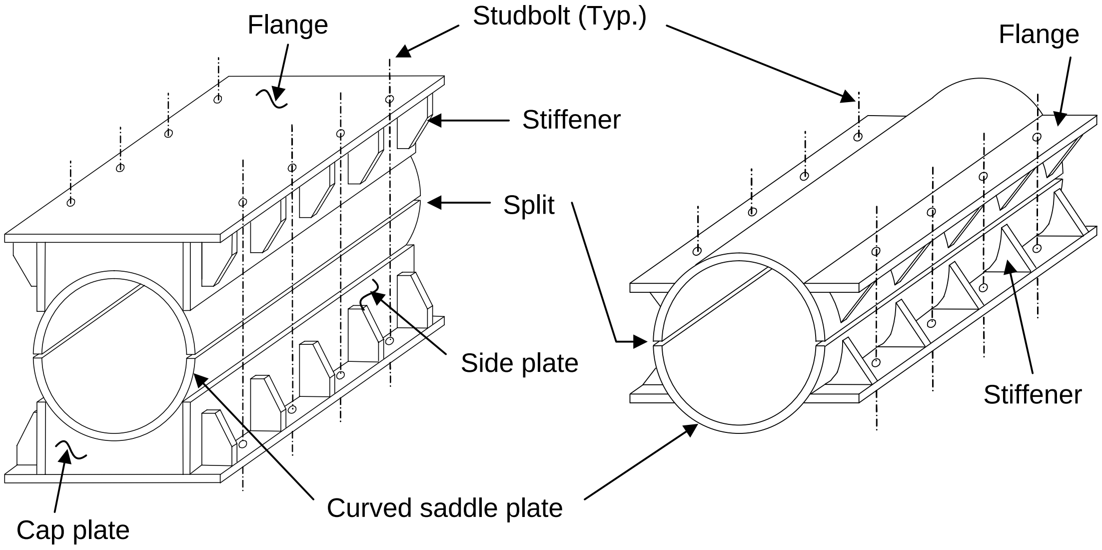
Although inter-related to some extent, the clamp types differ mainly with respect to load transfer capability and their tolerance to small and often unknown variations in the geometry of the existing structure. Load transfer capability is a function of the interface materials (existing steel with clamp steel, grout, or neoprene) and whether or not the interface is pre-stressed by the clamp bolts. Tolerance to geometry variations is increased when neoprene or grout is used. Each clamping technique exhibits advantages, disadvantages and limitations. These are discussed in detail in the following sub-sections.

Clamping technology has been used in SMR schemes for numerous projects over two decades, and this level of maturity is reflected in the many clamp variants that now exist in the field. Some of these variants are discussed herein, but the focus of this document is in explaining the principles behind any successful clamp application.

Clamps constitute a very versatile SMR technique and there are five main ways in which they can be used:

- Member clamp, for repairing/strengthening a damaged/under-strength member
- Nodal clamp, for repairing/strengthening a damaged/under-strength joint
- Means to connect a new member to the existing structure
- Means to provide a length adjustment for a new or replacement member
- Means to support a new guide.

Before discussing individual clamp types, it is helpful to begin with some general definitions. Figure 9.1 illustrates two simple generic clamps of the stressed variety, such as may be used to connect two similar tubulars together. One clamp is fabricated with a continuous flange plate and the other with a discontinuous flange. (The discontinuous flange type is often used over large diameter tubulars, such as jacket legs or primary bracing, to reduce the clamp weight and drag loadings.) All clamps are split longitudinally, most commonly into two halves, but sometimes into more pieces to allow assembly around complex nodal joints. All clamps have a curved saddle plate that bears onto the existing member either directly or indirectly through grout or neoprene. The remaining parts of the clamp (flanges, stiffeners, side plates and cap plates) essentially provide a platform for studbolt nuts and a means of transferring the studbolt loads to the saddle plates and thence to the interface between the clamp and original structure.



a) Continuous flange **b) Discontinuous flange**

Figure 9.1: Clamp terminology

9.1.2 Stressed-Mechanical (Friction) Clamps

A stressed mechanical clamp comprises two or more segments of closely fitting stiffened saddle plates, stressed directly onto a tubular section by means of long studbolts. The strength of a mechanical connection is obtained from the steel-to-steel friction, which is developed by means of the external studbolt loads, which lead to compressive forces normal to the tubular/clamp saddle interface. Therefore the strength is dependent on the magnitude of the normal force and the effective coefficient of friction between the two steel contact surfaces. The clamp saddles are stiffened to ensure that studbolt loads can be carried without distress to the saddle itself or the tubular member. Figure 9.2

illustrates a cross-section showing the various components of a mechanical clamp. The spherical washers prevent substantial bending loads being induced in the studbolts.

Stressed mechanical clamps are used for connecting new members, or for the strengthening of intact members. Examples of such uses are shown in Figure 9.3. Due to their low tolerance to geometric variations, mechanical clamps should not be used around existing nodal joints.

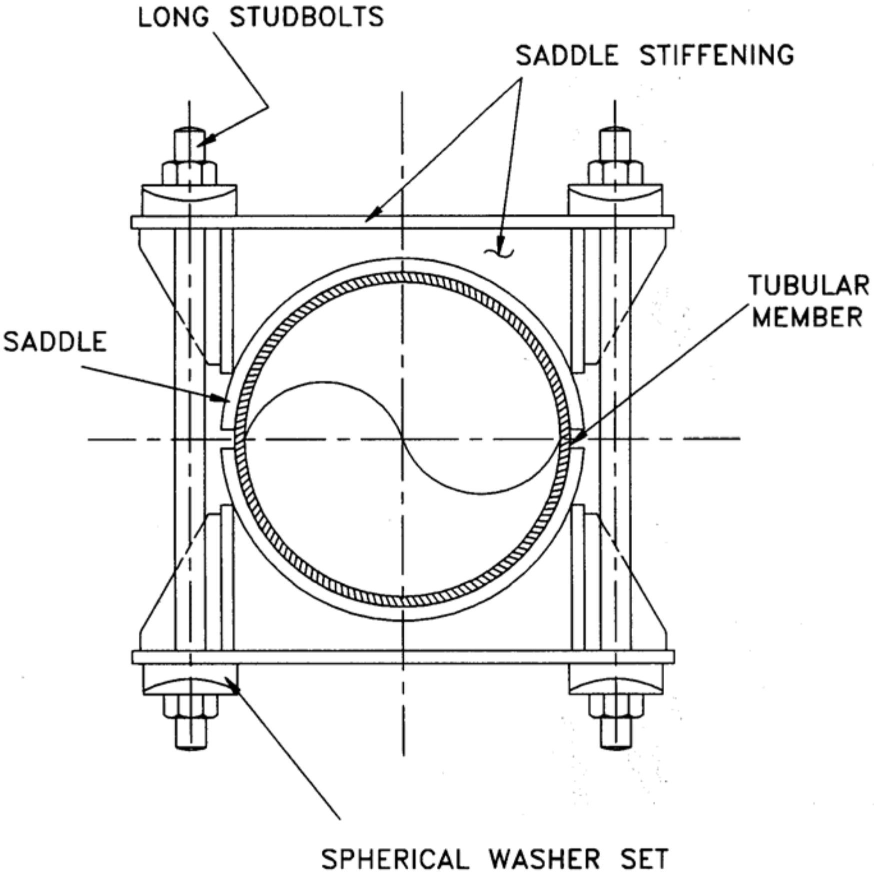
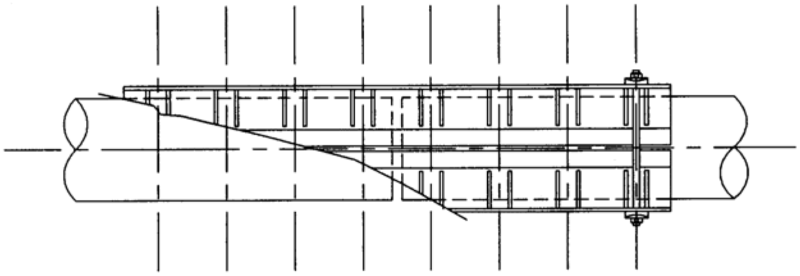
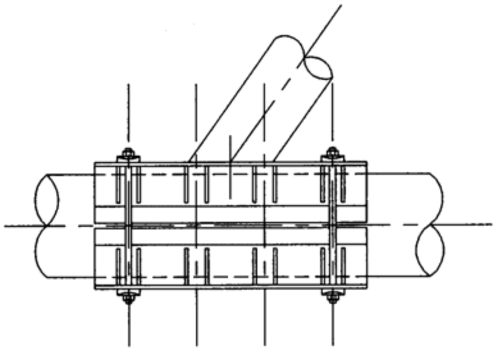


Figure 9.2: Typical stressed mechanical clamp



a) Connection of two members.



b) Attachment of a new brace.

Figure 9.3: Some applications of stressed mechanical clamps

9.1.3 Unstressed Grouted Clamps/Sleeve Connection

An unstressed grouted clamp or sleeve connection comprises sleeves, which are placed around a tubular member or joint with the annular space so created filled with grout. The sleeves may be split, as in an unstressed grouted clamp, or continuous as in a pile/sleeve connection. For split sleeves, short bolts are generally specified and these bolts are tightened prior to injection of grout into the annular space between the clamp and the existing tubular member. The grout/steel interface is not therefore pre-stressed. Figures 9.4 and 9.5 respectively show typical details of an unstressed grouted clamp and sleeve connections.

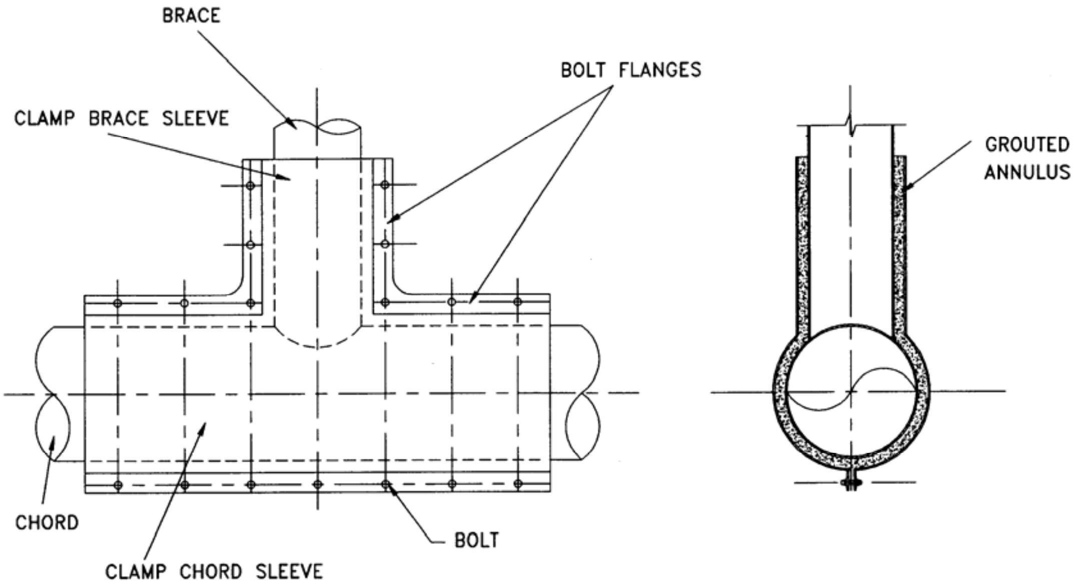
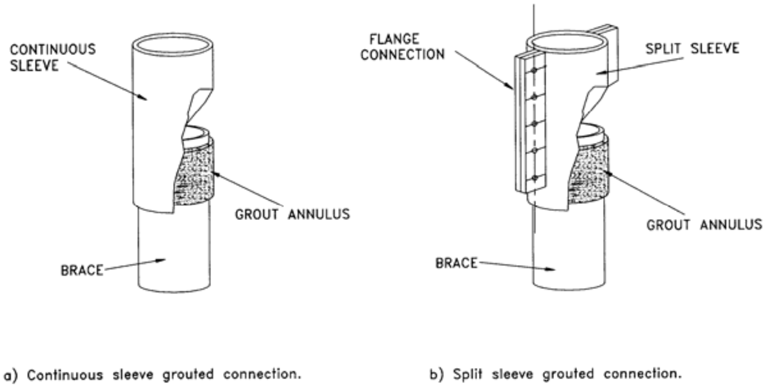


Figure 9.4: Typical unstressed grouted clamp



a) Continuous sleeve grouted connection.

b) Split sleeve grouted connection.

Figure 9.5: Examples of typical unstressed grouted sleeve connections

The bond and interlock between the grout/steel interface provides the means of load transfer between the tubular member and the clamp. Although bond and interlock may be sufficient in certain conditions, it is often necessary to substantially increase the length of the clamp to generate sufficient load transfer capacity. The provision of shear keys (usually in the form of weld beads) can increase the clamp capacity, but the need for underwater welding on existing underwater members may render this option prohibitively expensive and impractical. On the other hand, if the member is a new member, then it is a relatively simple matter to apply the weld beads to it (and the clamp) before it is sent offshore.

Unstressed grouted clamps and connections offer a versatile means for strengthening or repair of tubular joints and members since they require less accurate offshore surveys than do the mechanical clamps described earlier. Both angular and translational tolerances can be readily accommodated.

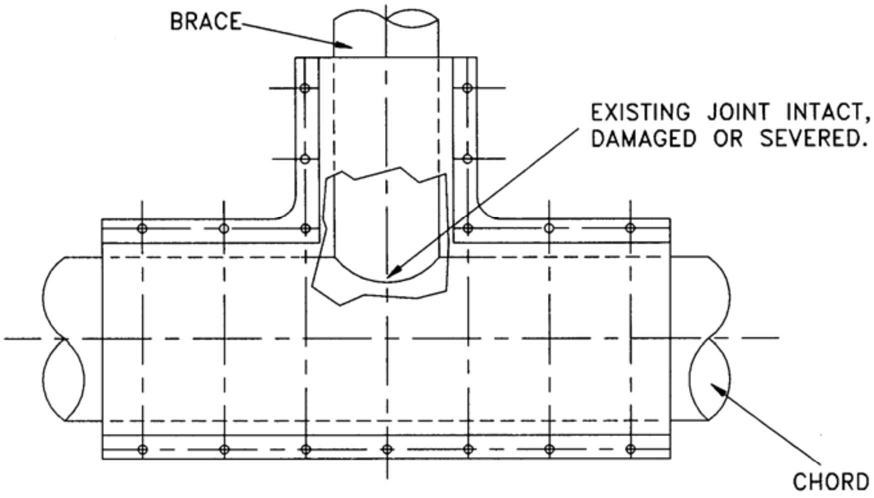
As shown in Figure 9.6, unstressed grouted clamps may be used as follows:

- To strengthen or repair an existing tubular joint subjected to static and/or fatigue loads,
- To facilitate the attachment of a new member to the structure.

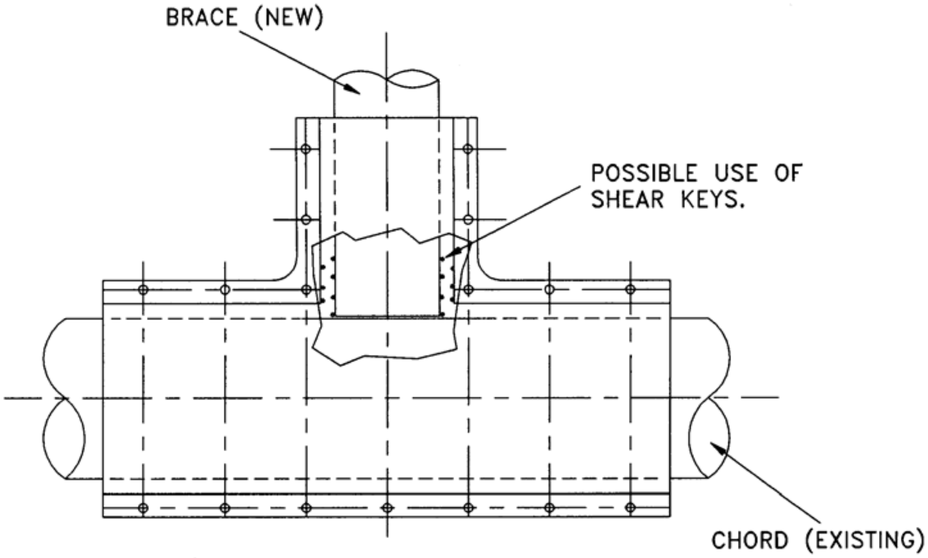
Some applications of sleeve connections are shown in Figure 9.7, and can be described as follows:

- To facilitate the attachment of a new member to the structure by providing length and fit-up adjustment. This can be accomplished by either a retractable sleeve which is slid over from one segment to the other segment of the new member, see Figure 9.7(a), or by a telescopic sleeve whereby the member is installed into location as a single piece, see Figure 9.7(b). Both member and sleeve are new fabrications, and the efficiency of the connection can be greatly enhanced by the provision of shear keys.
- To strengthen members by the use of a steel ‘bandage’ in order to enhance stability against local or overall buckling, see Figure 9.7(c).
- To strengthen or repair members, which have sustained dents, punctures, corrosion or other damage, see Figure 9.7(d).
- To facilitate the attachment of a new member to the structure by creating a new joint, see Figure 9.7(e).

The first noted application above will normally be formed using a continuous sleeve. The remaining applications will be formed using split sleeves, to enable installation around existing tubulars.

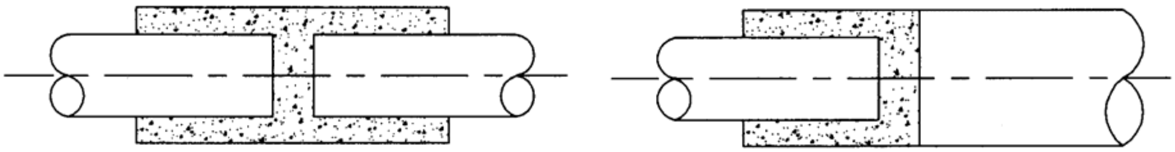


a) Repair of an existing tubular joint.



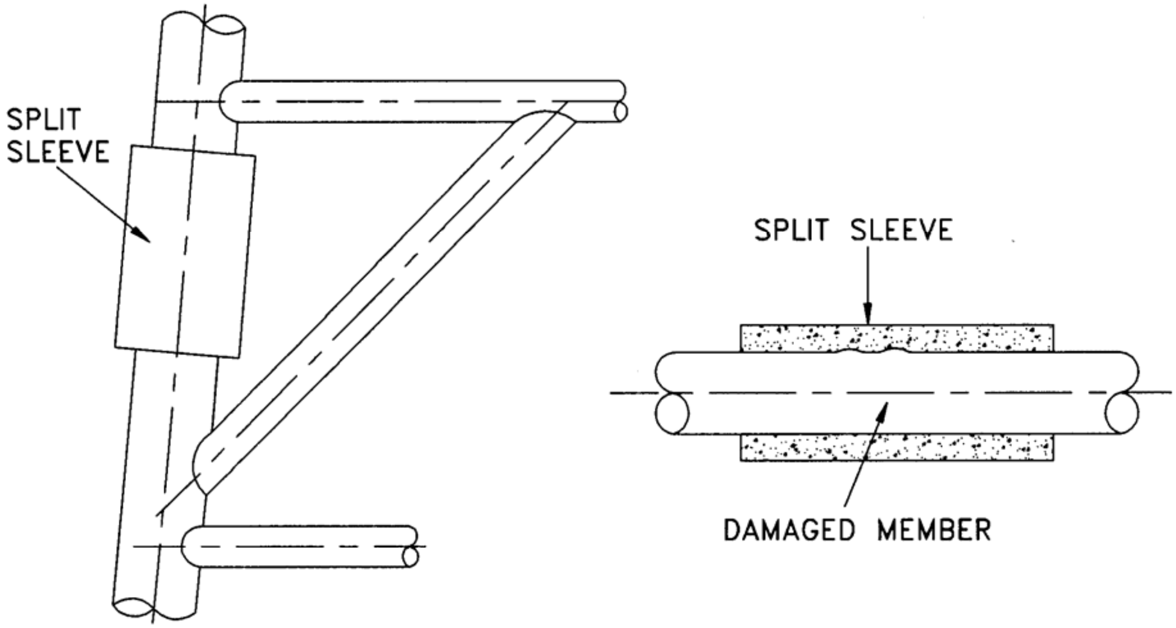
b) Attachment of a new member.

Figure 9.6: Some applications of unstressed grouted clamps



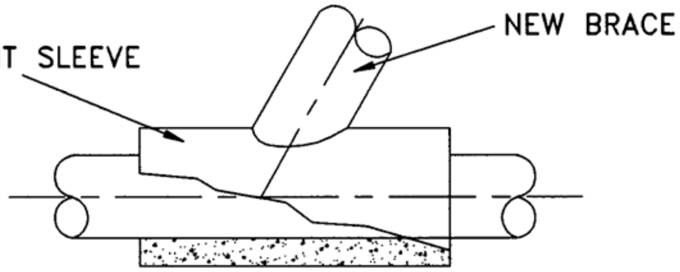
a) Retractable

b) Telescopic



c) Member strengthening

d) Damaged member repair



e) Attachment of new member

Figure 9.7: Some applications of unstressed grouted sleeve connections

9.1.4 Stressed Grouted Clamps

A stressed grouted clamp is formed when two or more segments of oversized, strengthened saddle plates are stressed by means of long studbolts onto a tubular member after grout has been injected and allowed to cure in the annular space between the clamp and the tubular member, see Figure 9.8. This form of clamp is a hybrid between a stressed mechanical clamp and an unstressed grouted clamp. The strength of a stressed grouted clamp is obtained from a combination of 'plain-pipe' bond and grout/steel friction developed as a result of compressive radial stresses at the grout/tubular member interface.

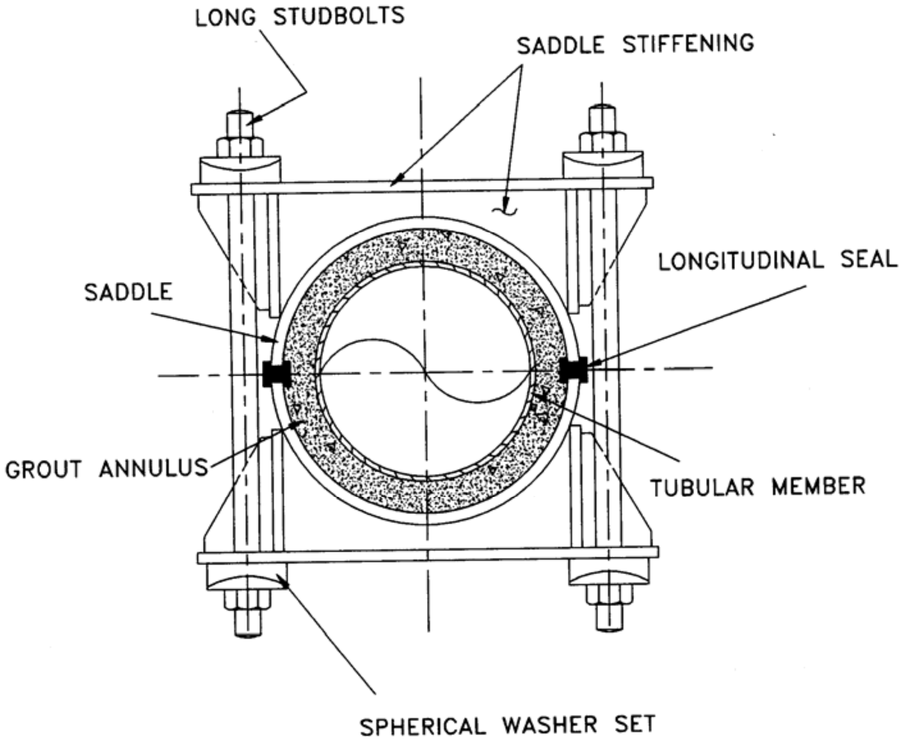


Figure 9.8: Typical stressed grouted clamp

Stressed grouted clamps offer the benefits of stressed mechanical clamps of high strength-to-length ratio, and the benefits of unstressed grouted clamps of the ability to absorb significant tolerances. This form of clamp is therefore very popular. Stressed grouted clamps can be used for similar applications to those defined for stressed mechanical clamps and unstressed grouted clamps.

9.1.5 Stressed Elastomer-Lined Clamps

Stressed elastomer-lined clamps are very similar to stressed mechanical clamps, except that an elastomer lining is bonded to the inside faces of the clamp saddle plates, see Figure 9.9. In general, the liner is made up of solid polychloroprene (neoprene) sheet. The strength of an elastomer-lined clamp is derived from external bolt loads, which lead to compressive radial stresses at the interface of the elastomer-lined saddle and the tubular member. The strength is therefore dependent on the magnitude of the radial stresses and the effective coefficient of friction between the liner/steel interfaces. The use of an elastomer offers a degree of translational and angular tolerance, thus removing the need for very accurate offshore surveys as required for stressed mechanical clamps.

Elastomer-lined clamps have not been used for primary structural repairs, because of concerns that the flexibility of the liner may reduce the efficiency of the repair system. The use of this type of repair scheme has been limited therefore to secondary components where stiffness is not critical to its effectiveness. Typical examples of the use of an elastomer-lined clamp are to seal holed caissons and for stub connections to appurtenance guides.

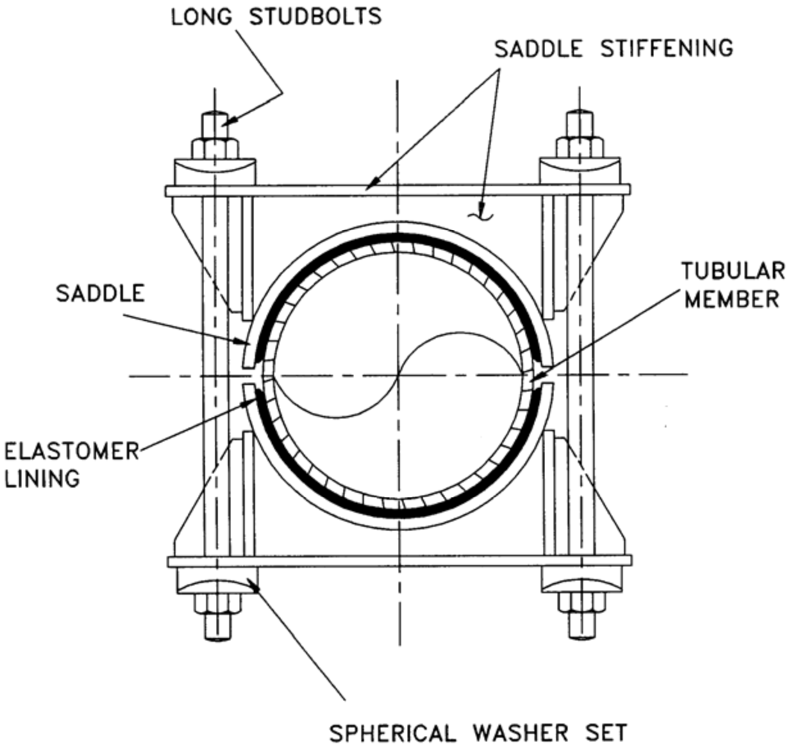


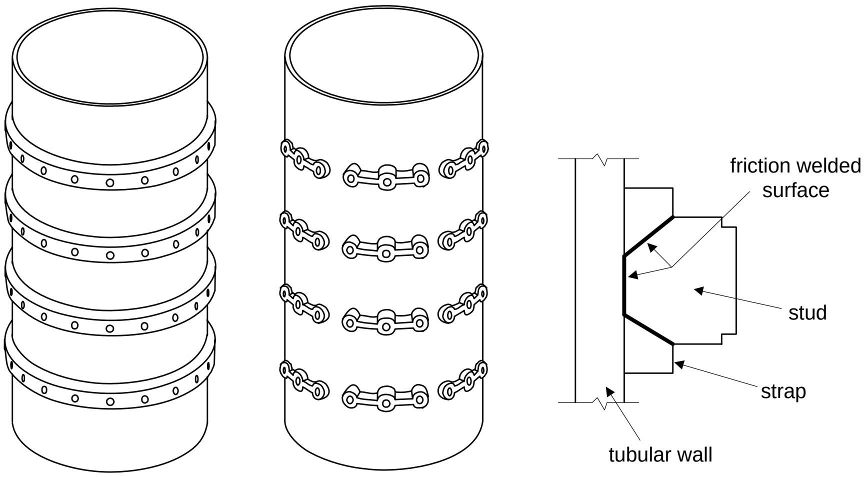
Figure 9.9: Typical stressed elastomer lined clamp

9.1.6 Other Types of Clamps

Over the last three decades, over clamp types have been experimented with and these are discussed below. It is believed that none have found a practical application. They are included here, however, for completeness.

Grouted stud/strap connection

It was noted in Section 9.1.2 that unstressed clamps might have to be long to be able to sustain the applied loads. Although the clamps would be shortened if shear keys could be used, the expense and practical difficulties in applying weld beads to the original structure will almost certainly rule this option out. The grouted stud/strap (9.1, 9.2) connection was developed to overcome this problem, see Figure 9.10. It is a combination of the grouted pile sleeve connection and stud friction welds. Friction welding is versatile under water and therefore the stud strap becomes a viable solution to welding studs underwater. (See Section 8 for more details on friction welding.) It is understood that patents may apply for the stud/strap connection.



a) Continuous straps **b) Segmental straps** **c) Detail**

Figure 9.10: Stud/strap connection

Expansive grout connections

The use of expansive grout, which swells on hardening/curing, has been tried (9.3, 9.4). The basic principle is that as the grout swells, it would induce a radial stress at the grout/steel interface and therefore the connection performs similarly to a stressed grouted connection. A perception that expansive grouts are more difficult to handle than normal grouts, and doubts over the long term integrity of these grout materials, has prevented the offshore adoption of this technique.

Pressurized grouted connections

Another means to induce radial stresses is to pressurize the grout and hold the pressure until it has hardened. In the pile/sleeve arrangement discussed by Elnashai *et al* (9.4, 9.5), a secondary annulus was introduced by means of a thin steel membrane, see Figure 9.11. Grouting of the primary annulus was carried out first and the grout allowed to harden. The secondary annulus was then grouted under pressure. It was found that the thickness of the secondary annulus had to be made very small (of the order of 1/8’’ or less) to avoid significant loss, due to chemical shrinkage under pressure, of the initial prestress. This led to constructional problems, and therefore this technique was never adopted.

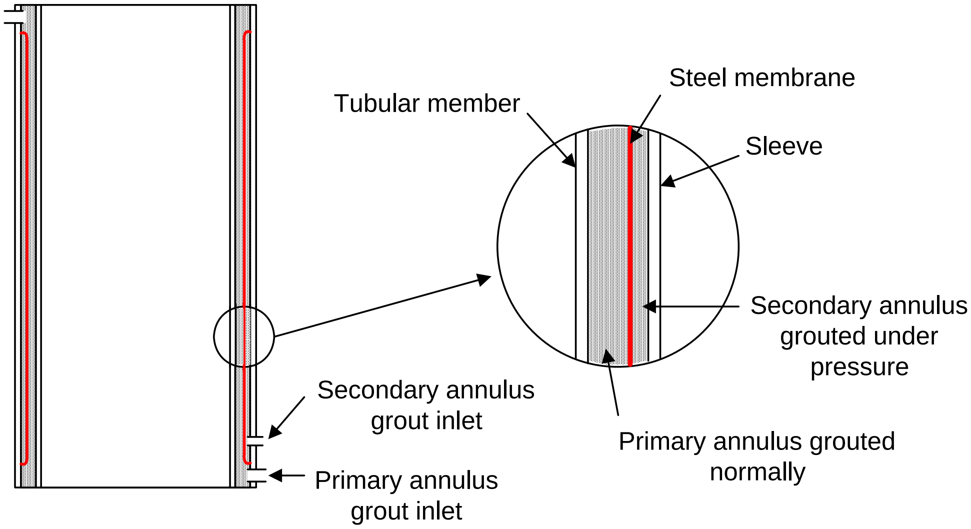


Figure 9.11: Pressurized grouted connection

Epoxy/sand coatings

Again with unstressed grouted pile/sleeve applications in mind, a shear key variant was proposed by Buitrago (9.6). The traditional weld beads were replaced with an epoxy coating containing crushed flint. Four axial load tests were conducted, and the results showed that failure was associated within the grout, not the coating. Although the technique appears promising for pile/sleeve connection geometry, its use in SMR scenarios is limited because of the difficulty in applying the coating underwater.

Ferrocement jackets

Thandavamoorthy *et al* (9.7, 9.8) adapted the unstressed grouted clamp concept by constructing the clamp body from mesh-reinforced cement (calling it a ferrocement jacket), and using a high strength epoxy/fly ash/sand grout. Tests were conducted on repaired fatigue damaged tubular joints. The authors state that ferrocement jackets provide better corrosion resistant properties than metallic sleeves; and the specifically developed grout is superior to standard cement grout in grouted sleeve connections giving a better bond strength.

9.2 **Limitations**

Stressed mechanical (friction) clamps

Stressed mechanical clamps rely on close tolerance steel-to-steel contact between the tubular member and the clamp saddles and therefore offer minimal translational or angular tolerances. Local yielding of a tubular member to make it conform to the saddle shape is not normally detrimental; nevertheless, stressed mechanical clamps require extremely accurate offshore surveys of the contact zone. Furthermore, very tight tolerances are required for the fabrication of the clamp. For these reasons, stressed mechanical clamps are not recommended for the strengthening and repair of tubular joints. Neither should they be used at locations that cover two can segments of a member, as the cans will neither be perfectly collinear nor of identical diameter. Seam weld reinforcements require grinding to make the weld flush or otherwise accommodated by providing a groove in the saddle plate or aligning the split to coincide with the weld. Anode stubs also require similar considerations.

The capacity of the clamped member has to be sufficient to avoid crushing loads from the studbolts.

Unstressed grouted clamps/sleeve connections

Loading regime and the availability of space are dominant in deciding the suitability of unstressed grouted clamps/sleeve connections. Without the use of shear keys, the required connection lengths may be unacceptably large to resist axial forces (i.e. causing slip along the member) and torques that tend to cause the clamp/sleeve to rotate about the member. Reduction in connection lengths may be achieved by the use of weld beads, friction welded studs, or other forms of shear key. However, the costs associated with the provision of such shear keys on existing underwater parts of the structure may be prohibitively high. Furthermore, weld beads do not significantly increase the resistance to torsion loads causing rotation of the clamp about the clamped member.

During the grout-curing period, grouted clamp/sleeve connections should not be subjected to undue loading or relative movement of the clamp and member before the grout has attained sufficient strength. In certain instances, temporary clamps may be necessary.

Stressed grouted clamps

The capacity of the clamped member has to be sufficient to avoid crushing loads from the studbolts. There is a requirement to allow time for the grout to harden sufficiently (e.g. 36 hours) before tensioning the studbolts. Where more than one clamp is to be installed at a given depth, some of the ‘waiting time’ can be reduced by concurrent activity.

During the grout-curing period, grouted clamp/sleeve connections should not be subjected to undue loading or relative movement of the clamp and member before the grout has attained sufficient strength. In certain instances, temporary clamps may be necessary.

The capacity of the clamped member has to be sufficient to avoid crushing loads from the studbolts.

Stressed elastomer-lined clamps

The slip capacity of elastomer-lined clamps is lower than traditionally thought (see Section 9.3.3). The in-plane flexibility of the liner has to be considered in the analysis/design, particularly in respect of the reduced ability of the clamp to attract load.

The capacity of the clamped member has to be sufficient to avoid crushing loads from the studbolts.

9.3 **Design Approach**

9.3.1 General

Design philosophy for local SMR of components

It is possible to design a clamp on the basis that load sharing exists between the clamp and the original structural component. However, it is recommended that this philosophy should not be adopted in the case of damaged components, particularly if it has suffered fatigue cracking. The growth of cracks would eventually invalidate the assumption that the original component is capable of sustaining load. It should also be recognized that a clamp will render any covered weld non-inspectable, for which a longer life is required than if it were inspectable. Given these observations, the preferred philosophy in most cases will be to design clamps to be able to sustain the full set of loads, without benefit from load sharing.

Design drivers for sizing clamp

There are three main requirements that dictate the minimum clamp size:

1. The requirement to provide sufficient slip capacity. For stressed clamps, the slip capacity is largely related to the total studbolt load.

2. The requirement to provide sufficient bolt load to prevent the clamp being pried open by member loads.

3. The requirement that the studbolt loads must not cause distress to the clamped member.

For unstressed grouted clamps, the function of the bolts is to hold the two halves of the clamp together, not to apply prestress at the grout/steel interface. Therefore, item 3 above is not applicable for such clamps. The sizing of unstressed grouted clamps is practically always controlled by item 1 only. Indeed, the design length of such clamps is simply a matter of referring to pile/sleeve connection formulae.

The sizing of stressed clamps may be determined by any one of the above items, and requires iteration of the clamp length to optimize the geometry. The iterative process is addressed below in Section 9.3.2.

Acting slip stresses

In establishing the acting slip stresses at the clamp/structure interface, it is necessary to consider the various connections within the clamp as separate entities. For example, in the case of a clamp connecting the ends of two collinear tubulars together, there are two such connections corresponding to the two tubular ends. In the case of a new member being introduced into the structure and one end is joined with a clamp, there are again two connections, one corresponding to that part of the clamp surrounding the new member, and the other to the part surrounding the existing member. The acting interface slip stress is calculated for each connection, and compared to the corresponding slip capacity.

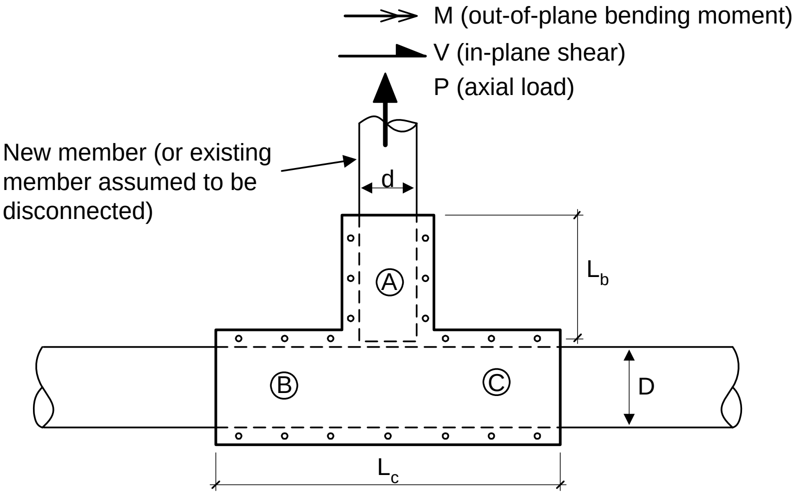
It is axial forces along the connection axis and torque about the axis that tend to produce relative slippage between the connection and the enclosed member. The design engineer needs to consider how member loads are transferred through the clamp to establish the axial force and torque for each connection. Although not difficult, it does require a little thought. By way of example, consider the clamps depicted in Figure 9.12, the clamps being used to introduce a new member (or reinstate an existing member that has severed or is assumed to have done so).

In the upper diagram, the slip stress for the connection to the new member (Connection ‘A’) is related to the axial force in the new member. (This assumes that the torque in the new member is negligible.) For an existing member that is continuous and undamaged, the clamp ends denoted ‘B’ and ‘C’ can be considered as a single connection for which the force along the axis is the shear in the new member (and axial force both resolved along the existing member if necessary - e.g. for a Y-joint) and the torque is the (resolved) out-of-plane bending moment in the new member. The axial and torque components are transformed into longitudinal and circumferential stresses respectively, and a vector sum taken. (Special considerations apply to unstressed grouted clamp connections that have been provided with weld beads. In this case, as well as taking the vector sum and checking it against the slip resistance of the weld bead connection, the acting slip stress due to torque acting alone should be checked against the slip resistance of the plain pipe, ignoring the presence of the weld beads.)

In the lower diagram of Figure 9.12, the clamp is shown in an alternative configuration; it has been rotated through 90 degrees with respect to the upper diagram, and the new member is welded directly to it. The long studbolts give a very flexible shear connection between the two halves of the clamps, to the extent that axial slip of the upper half will occur before the lower half is eventually dragged along the member. Out-of-plane bending of the new member will mobilize the circumferential resistance of the upper half of the clamp, but not the lower half until the upper half has slipped. This is because there is no torsion transmitted to the lower clamp half until there is differential straining in the studbolts and this cannot occur unless the two clamp halves move relative to each other.

(Note, this may happen in the case of elastomer-lined clamps due to flexibility of the liner.) In short, this clamp arrangement gives twice the applied slip stress compared to the preferred arrangement shown in the upper diagram. The situation is exacerbated by the presence of tensile loads P in the new member, as these will tend to lift the upper clamp half off the existing member and reduce the interface preload and slip resistance.

The loads P, M and V in Figure 9.12 may be conservatively taken from the structural model node at the intersection of the members. In determining member loads, the effects of both the modified stiffness and the increased environmental loads should be assessed.

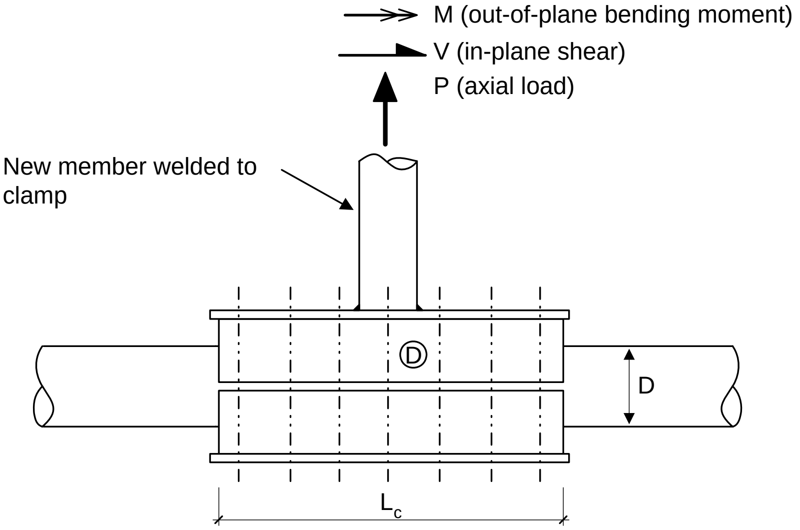


Connection A interface slip stress, $f_s = \dfrac{P}{\pi\, d\, L_b}$

Connections B and C considered together :

interface slip stress, $f_s = \dfrac{1}{\pi\, D\, L_c}\ [V^{2} + (2\ M / D)^{2}]^{0.5}$

a) Preferred configuration



Connection D interface slip stress, $f_s = \dfrac{2}{\pi\, D\, L_c}\ [V^{2} + (2\ M / D)^{2}]^{0.5}$

Note:
Only one half of the clamp is effective in resisting slip, and the slip capacity is reduced by the effect of P in reducing the preload at the interface.

b) Alternative configuration

Figure 9.12: Establishing interface slip stresses

Clamp prying loads

Shear forces and bending loads in the clamped member tend to separate the clamp halves. It is important that sufficient bolt load is used to maintain positive contact pressure at the interfaces at all times during the design life of the clamp. The traditional approach for estimating the prying force in the end pair of bolts shown in Figure 9.13. The bolt preload should exceed the calculated prying force (per bolt) by a factor of safety (minimum F.o.S = 1.2). This approach is known to be very conservative (from MSL proprietary tests on clamps).

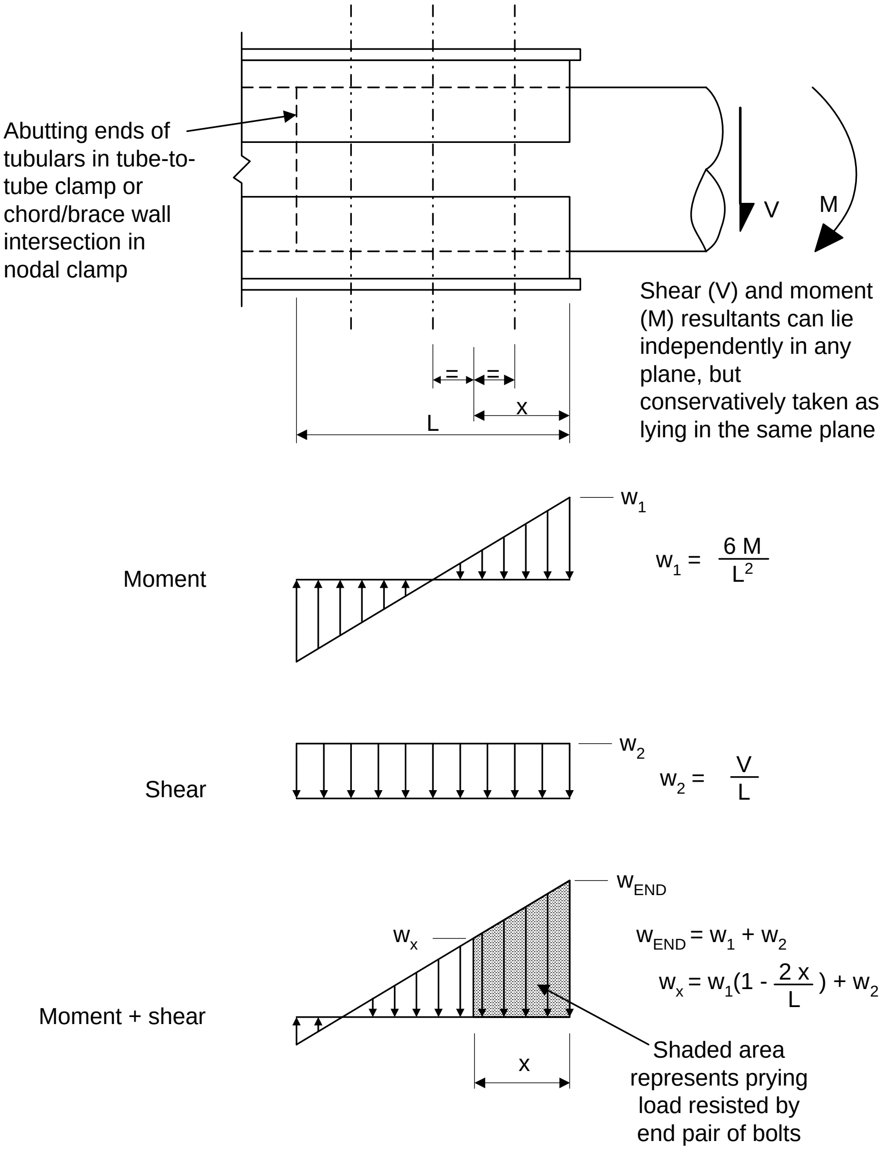


Figure 9.13: Traditional approach for estimating prying forces

9.3.2 Design Procedure for Stressed Clamps

As mentioned above, optimization of a stressed clamp is an iterative process. This is recognized in ISO 19902 (9.9) but the flowchart presented therein is not efficient in terms of the entry point into the process. Figure 9.14 presents a more appropriate flowchart.

The suggested starting point is a consideration of the capacity of the clamped member to resist the crushing loads due to the bolts. The bolt loads induce hoop compressive stress in the member, and this should be combined with the hoop stress due to the hydrostatic head and longitudinal stresses due to member axial and bending loads in a von Mises check. In addition, for mechanical and elastomer-lined clamps, local buckling of that part of the member wall not covered by the clamp should also be checked. The calculations will determine the maximum bolt load per unit length of the connection. The total bolt load may be estimated from the target slip resistance required and an assumed coefficient of friction. For a first estimate of the coefficient of friction, values of 0.25 and 0.33 may be assumed for stressed mechanical and grouted clamps respectively (note these coefficients are global values – see Section 9.3.3 and Figure 9.14). From the maximum bolt load per unit length and the total bolt load required, an estimate of the connection length is thus obtained. If the clamp is too long to fit into the space available in the structure, grout filling of the member can be considered. For elastomer-lined clamps, the effective friction depends on the bolt load, and eventually a limiting slip stress of about 40 psi (0.29 N/mm^2) is attained that is independent of bolt load.

The clamp length so determined, together with trial bolt size and number of bolts, should then be used in more careful checks of slip capacity and member strength. Slip capacity formulations are addressed in the next subsection. It should be noted that for stressed grouted clamps with a continuous grout ring, the grout will itself resist some of the bolt load by hoop compression, thereby effectively reducing the prestress at the grout/member interface. This effect should be accounted for in the calculation when determining the slip capacity.

The next stage is to check that the bolt preload is sufficient to withstand the prying loads that tend to open the clamp, as discussed in the previous subsection. If the bolt preload has to be increased to prevent prying, member crushing should be considered again.

Assuming all is well, the design of the main clamp steelwork can proceed. For continuous flange clamps (see Figure 9.1) hydrostatic pressure could be a governing factor in the design of steelwork because of the watertight compartments. In particular, hydrostatic pressure may govern the flange plate design unless the pressure is relieved through provision of holes in the otherwise enclosed chambers. The holes can be capped off by divers following clamp installation, to prevent internal corrosion. If the fatigue-loading environment is not negligible, appropriate checks should be conducted on both the steelwork and the bolts.

Thereafter, installation aids (padeyes, hinges, centralizing bolts, locating pins, etc), CP systems, and where relevant grout seals and grout inlets/outlets need designing. It is very beneficial to involve the Installation Contractor during this phase of the design.

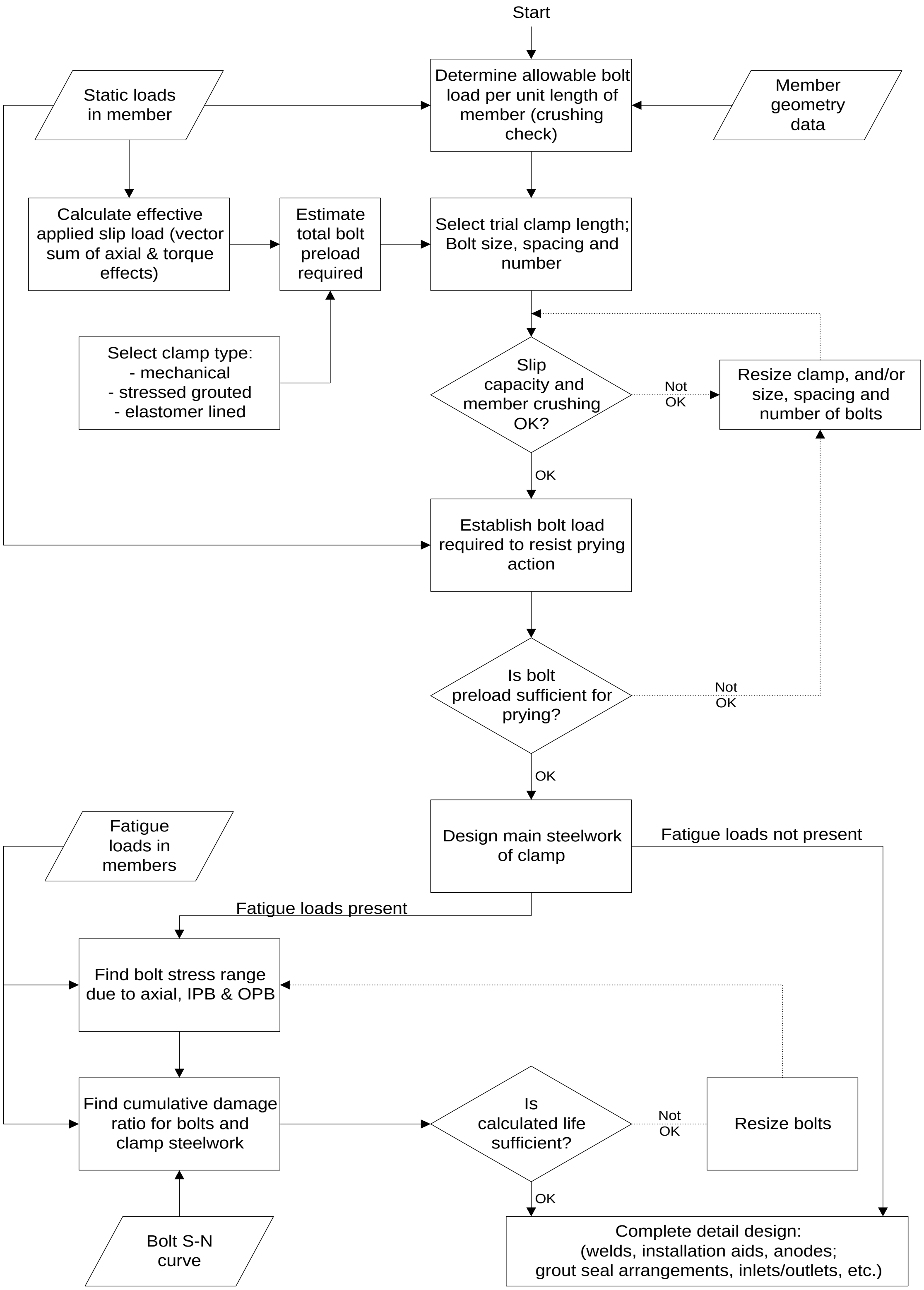


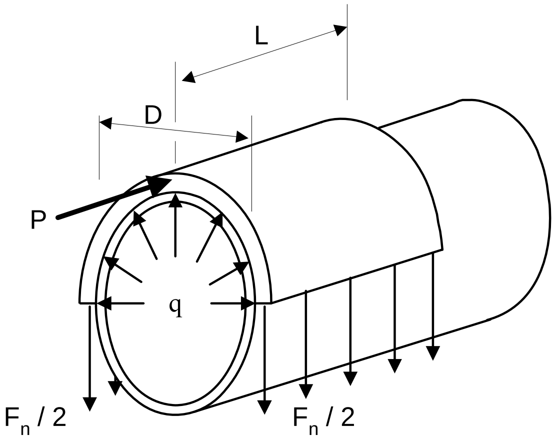
Figure 9.13: Design process for stressed clamps

9.3.3 Slip strength formulations

The slip strength of clamps can only be determined by reference to experimental data. Much of the existing test database and development of clamp repairs was carried out in the early1980's in the UK (9.10). The emphasis was on grouted and mechanical clamps. Since then, little additional testing has been performed with the exception of the MSL JIP on neoprene-lined clamps (9.11).

Despite the popularity of clamps the database is rather limited, as detailed below. Nevertheless, the data has been used to generate slip strength formulations in a number of studies (9.10, 9.11, 9.12, 9.13). Recently, a new set of slip formulations for grouted and mechanical clamps have appeared (9.14) and these may be found in ISO 19902 (9.9). The slip formulations quoted below are mainly those derived in MSL JIPs (9.11, 9.12), but reference can be made to the other formulations.

No matter which formulation is selected, it is important to understand the basis of it with respect to whether a local or global definition of resistance is being used. Global resistance is based on a factor times the total studbolt load whereas local resistance is more related to the interface shear stress resistance due to radial contact pressure. As indicated in Figure 9.14, for a given studbolt load and clamp capacity, the numerical value of the global (friction) coefficient μ_g is $\pi/2$ times greater than that of the local coefficient μ_L. It would therefore be inadmissible to use a global coefficient in a design procedure ostensibly based on a local approach.



F_n = Total bolt load
q = Radial contact pressure
P = Slip load

a) Global definition

$$P = \mu_g F_n$$

b) Local definition

$$P = A\ \tau = \pi D L \mu_L q$$

but $q = F_n / D L$, therefore:

$$P = \mu_L \frac{\pi F_n}{2}$$

Figure 9.14: Definitions of coefficients of friction

Stressed mechanical (friction) clamps

The slip resistance of mechanical clamps is based on the data of ten mechanical clamp specimen configurations (the test variables were clamp length, studbolt diameter, studbolt preload, D/T of clamped member, and member surface condition). Each specimen configuration was tested nine times, with the studbolt force changed after every set of three tests. It was found that the effective friction coefficient for consecutive sets always decreased, regardless of whether the studbolt force was increased or decreased at the beginning of each set. It was concluded that this was likely due to the degradation of the steel/grout interface. As a result, only test results for the first set of tests for each specimen are considered valid. A non-linear regression analysis to determine the variables was use to fit the curve to the test data. The following allowable slip strength formulation (f_{sa} – in stress units) is recommended for the design of mechanical clamps:

$$f_{sa} = \frac{0.12C_s'}{SF}\left[1 + 20\left[\frac{T}{D}\right]\right](1 + 66K_b)F_n$$

The surface condition factor (C_s') can be taken as:

Surface Condition	**Surface condition Factor** C_s'
Shot blasted	1.00
Mill scale	0.85
Underwater grit blast	0.85

T	Chord thickness
D	Chord diameter
F_n	Total studbolt load

K_b is the studbolt stiffness parameter given by:

$K_b = (n\ A_b\ E_b) / (2\ L\ L_b\ E_s)$

in which n is the number of studbolts in the connection; A_b is the effective area of one studbolt; E_b is Young's modulus for the studbolt material; L is the length of the clamp connection; L_b is the stressed length of the studbolt; and E_s is Young's modulus for the clamped member.

The safety factor, SF may be taken as 1.7 and 2.25 for extreme and operational loading conditions, respectively.

The above formulation is based on experimental data falling within the following ranges:

$$0.5 \le L/D \le 2.0$$

$$20.0 \le D/T \le 50.0$$

$$0.002 \le K_b \le 0.01$$

Unstressed grouted clamps/sleeve connections

The slip strength of an unstressed grouted clamp/sleeve connection is obtained from a combination of chemical bond, friction and mechanical interlock. Mechanical interlock may arise from micro and macro geometric imperfections, or from the addition of shear keys, e.g. weld beads.

The basic geometrical arrangement of an unstressed grouted clamp/sleeve connection is similar to that of a traditional grouted pile/sleeve connection. However, the presence of the split in the clamp reduces the hoop stiffness (practical bolt sizes and spacings do not necessarily restore this lost stiffness) and member D/T ratios tend to be somewhat higher than those of piles.

Numerous tests have been conducted over the past three decades on continuous sleeve (pile/sleeve) connections and this has led to a large present-day database. Several codified guidance formulations exist and these are widely used by the offshore industry. The most recent formulation was developed for ISO 19902 (9.9, 9.15). Some of the available test data (9.10) were generated specifically for repair geometries. This has allowed the extrapolation of plain pipe (no weld beads) formulations developed for pile/sleeve connections for application to geometries more akin to repair scenarios. For clamp connections with weld beads, the loss of hoop stiffness at the split has a significant detrimental effect on slip capacity compared to continuous sleeve arrangements. For example, the use of API RP2A pile/sleeve provisions will over-predict the capacity of an unstressed grouted clamp with weld beads by a factor of about 1.5 (9.12). Unfortunately there are too few split sleeve weld bead results to derive robust guidance. However, given the relatively uncommon usage of this connection in predominantly axial load situations, the lack of data is not considered a serious handicap as other types of clamps can be selected.

Stressed grouted clamps

The slip strength of a stressed grouted clamp is derived from a combination of chemical bond, mechanical interlock and friction at the grout/steel interface.

In terms of ultimate slip tests, there are surprisingly few data given the popularity of this form of clamp. Not only is the tested number of such clamps small, but also rather limited geometric ranges have been studied. Further work is required in this important area. A review of the test data was performed in the MSL JIP [9.12] and the following allowable slip strength formulation (f_{sa} – in stress units) is recommended for the design of stressed grouted clamps:

$$f_{sa} = \left(\frac{0.95C_s}{SF_b} + \frac{0.35C_s{}'(F_n / DL)}{SF_f} \right) \left[1 - 0.13 \left[\frac{L}{D} \right] \right] \left[1 + 12 \left[\frac{T}{D} \right] \right]$$

where:

F_n Total studbolt load

C_s and C_s' Surface condition factor for the bond component and frictional component respectively. The surface condition factors can be taken as $C_s = 0.6$ and $C_s' = 1.0$ for grit blasted steel surface conditions.

T	Chord thickness
D	Chord diameter
L	Length of connection
SF_b	Bond safety factor 4.5 and 6.0 for extreme and operational loading conditions
SF_f	Friction Safety factor 1.7 and 2.25 for extreme and operational loading conditions

The above formulation is based on experimental data falling within the following ranges:

$$0.9 \le L/D \le 2.2$$
$$17.7 \le D/T \le 50.0$$
$$21.2 \le D_s/T_s \le 36.0$$
$$7.4 \le D_g/T_g \le 18.2$$
$$50.0\,N/mm^2 \le \sigma_{cu} \le 78.0\,N/mm^2$$
$$1.3\,N/mm^2 \le F_n/DL \le 12.0\,N/mm^2$$

Stressed elastomer-lined clamps

As a result of an unexpected low coefficient of friction obtained during an ad-hoc test, MSL conducted a joint industry project [9.11] to specifically investigate the slip capacity of neoprene-lined clamps. It was found that the coefficient of friction of neoprene-lined clamps is related to the interface contact pressure and exhibited time dependent (creep) effects. There appeared to be a limiting interface shear resistance. The results of the tests were used to formulate design guidance and this may be found in Reference 9.11.

The coefficient of friction between elastomer and steel are often quoted by manufacturers. However, these friction coefficients only apply to relatively low contact pressures and therefore should not be used.

9.3.4 Details to Avoid

Figure 9.15 illustrates some often-used details for clamps, which should be avoided.

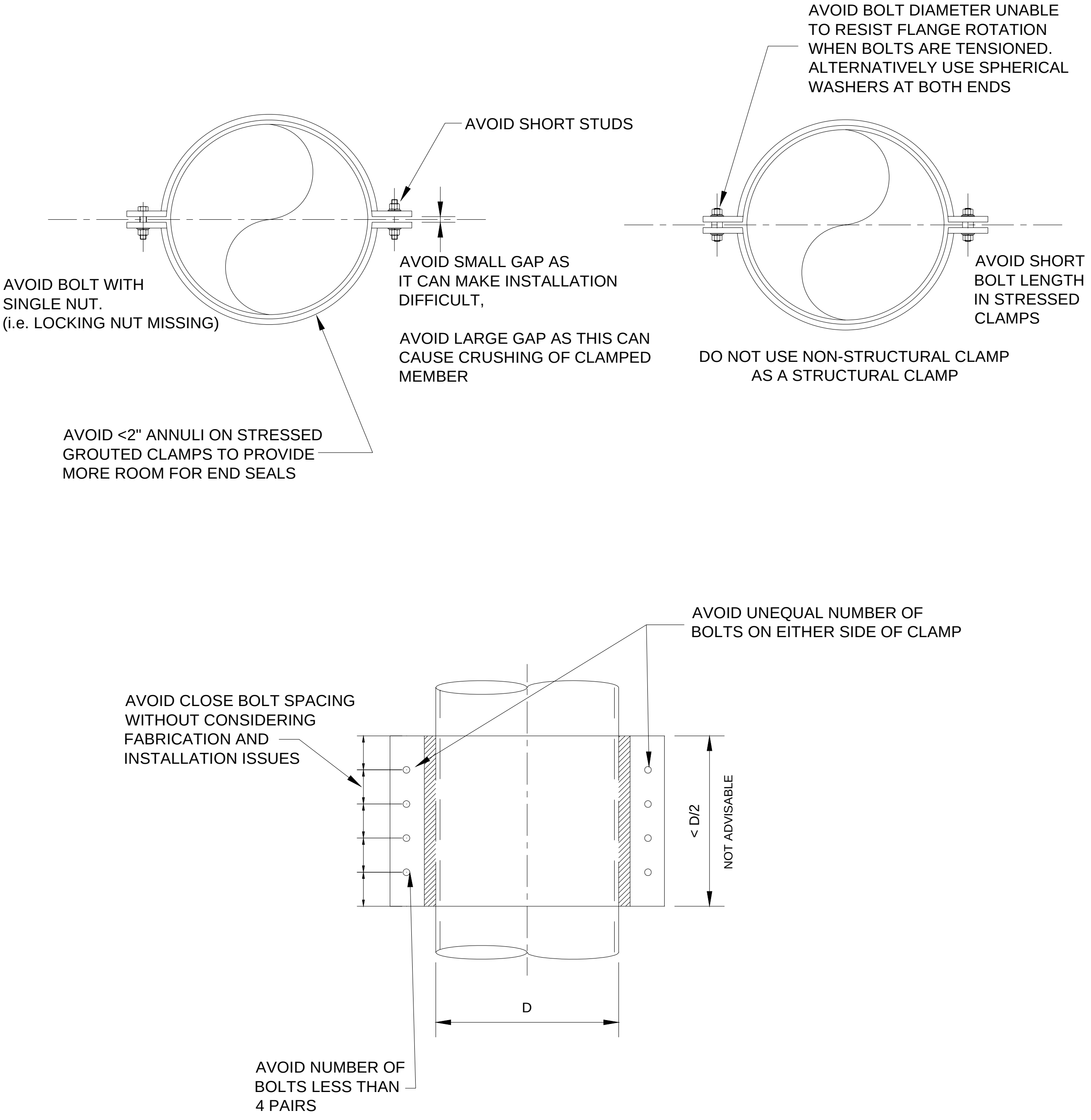


Figure 9.15: Clamp Details to Avoid

9.4 Fabrication/Installation Issues

Equipment and Offshore Support

For a diver-installed clamp, the following equipment and personnel are required offshore:

- Crane for lift purposes
- Rigging for installation purposes
- Underwater cutting and grinding equipment, if obstructions have to be removed
- Underwater cleaning equipment
- Studbolt tensioning equipment
- Grouting spread where relevant
- Diving spread and divers

It is highly recommended that for stressed clamps, all bolts are tensioned simultaneously, preferably by hydraulic tensioning jacks connected to a common pressure line. Slightly higher bolt loads than the long term loads need to be applied during the tensioning operation to account for effects such as transfer losses and creep of grout.

Inspection/Maintenance

Checks on clamp dimensional tolerances (especially for stressed mechanical clamps) and MPI weld inspections should be performed during the fabrication stage to ensure the clamp will perform as intended.

For grouted clamps, grout quality is assured by checking the density of the grout immediately prior to pumping. Further, the density of grout samples taken from the outlet points on the clamp is monitored during the grouting operation, which should continue until the outlet grout density is within specified limits.

Clamps should be inspected periodically to ensure continued satisfactory performance. In the absence of platform-specific requirements, it is usual to recommend a regular general visual inspection of all clamp steelwork and studbolts. A more detailed inspection should be performed within the two years following installation, and thereafter at regular intervals in accordance with the inspection philosophy for the platform. These inspections should check for:

- No slippage of the connection is evident
- All studbolts are in place
- CP potential levels are retained and that CP continuity straps (if any) are intact
- Sacrificial anodes (if any) are sufficient
- Bolt tension checks are sometimes called for and these can be achieved by re-stressing or through checks of load indicating devices (if installed)

- Tension and corrosion of studbolts

Timescales

Installation timescales for clamps vary depending on the type, size and complexity of the clamp (for instance, number of clamp segments and number of bolts), space limitations and water depth of the repair site. Much of the time is spent preparing the site, e.g. in constructing work platforms, removing obstructions, and grit blasting the existing member. Timescales are also very dependent on the environmental conditions as these may severely limit dive time and greatly influence weather downtime.

As an example, eight stressed grouted clamps were fully installed on a platform in the Gulf of Mexico over a total of 18 days. About one-third of this time was used in removal of obstructions while cleaning, clamp installation, grouting and studbolt tensioning took about equal time.

9.5 Previous Offshore Applications

Over the past twenty years there have been numerous applications of all types of SMR clamps and sleeves worldwide. Given their universal ability to address all SMR requirements (see Figure 5.2), it is not surprising that clamps and sleeves have become so popular in practice. It is estimated that about a thousand clamp SMR systems have been implemented.

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SECTION 10 - GROUT-FILLING OF MEMBERS

10. GROUT-FILLING OF MEMBERS

10.1 Description

Grout filling a tubular member inhibits the development of local buckling of undamaged tubulars and the growth of dents in damaged tubulars, and enables the full strength of the cross-section (net cross-section at a dent) to be realized. Where the tubular is completely filled with grout, such that end compressive loads are transferred in bearing to the grout, the overall column buckling strength is also enhanced. If a compression member is only partially grouted along its length, tests have shown that a progressive mode of shear failure occurs at the grout/steel interface with the net result that the grout carries negligible axial load.

Complete grout filling therefore offers benefits for both intact and especially damaged members, without any increase in the environmental load acting on the member. Grout filling of dented tubulars can not only reinstate the original strength but even increase it. However the presence of the grout in a member increases the weight of member and inertial loads under dynamic loadings, e.g. earthquake loadings. The extra stiffness of the tubular joints along the member's length should also be considered, although this will not usually cause any difficulties.

Member grout filling is also sometimes carried out as part of the preparatory works for installing a stressed structural clamp. In this instance, partial grout filling is acceptable as the aim is to prevent member crushing under the clamp studbolt loads.

10.2 Limitations

It is important that grouting procedures are developed which completely fill the tubular, as small voids close to the tubular joints at each end of the member will limit the benefits of grouting. This is because the only way that load can be transferred to the grout is by direct bearing on the grout column; sufficient load cannot be relied upon to be transferred in bond between the tube inner wall and grout (tests show that a progressive mode of failure acts). Void formation is also a potential problem at internally ring-stiffened joints or at joints with expanded can diameters.

This technique applies to loads, which act on the brace after the grout has cured. Any gravity, or other loads, in the brace at the time of grouting will remain in the steel skin.

There are no test data on the performance of grout filled members under tension, although benefits in this respect would be expected to be restricted.

The placement of grout in large diameter (24" or more) may generate excessive heat whilst setting and lead to grout degradation. The mix design should pay attention to this and ensure that the rate of heat production is not excessive.

The added mass of the grout needs consideration in seismically active regions.

Some of the possible instances where voids may be formed are indicated in Figure 10.1.

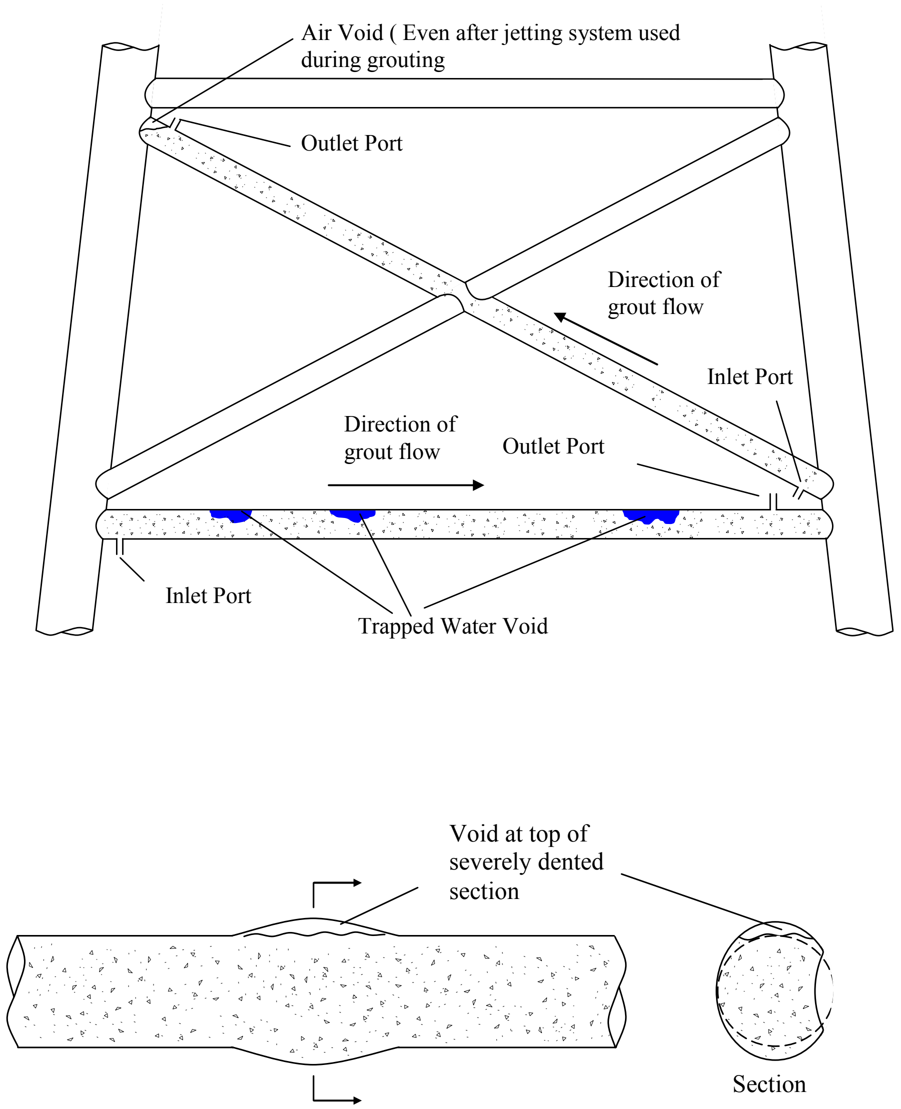

Figure 10.1: Void formation

10.3 Design Approach

Background Research

A significant amount of research in this field has been conducted (10.1 to 10.12). Much of the experimental data relates to small-scale test specimens. In a JIP, MSL (10.13) examined the applicability of design methods to predict the ultimate axial load carrying capacity of undamaged or damaged structural tubular members, which are partially or fully grouted. The study concluded that Parsanejad's method (10.1, 10.2), as developed by Loh (10.8), reasonably predicts the ultimate strength capacity of grout filled damaged and undamaged tubular members. The approach has formed the basis of the codified guidance given in ISO 19902 (10.14), to which reference should be made.

10.4 Fabrication/Installation Issues

Inspection

It is important to ensure:

- That grouting procedures are developed and tested which ensure complete grouting
- That the grout mix is sampled before filling starts to ensure that significant grout bleed does not occur
- That offshore inspection techniques are capable of ensuring that complete filling has occurred (e.g. ultrasonic or probes).

No long-term maintenance is required.

Equipment and Offshore Support

The following equipment/personnel are required for offshore grout filling:

- Rigging
- Cutting/drilling equipment
- Divers to place grout inlets/outlets and assist in grouting operations (unless ROV intervention is used)
- Grouting spread
- Inspection/monitoring equipment.

Timescales

Based on an assessment of typical offshore timescales, a grouting operation should be achievable with 2-3 days offshore work.

10.5 Previous Offshore Applications

Grout filling has been adopted in a number of cases. The life of Baltic Beta jack-up platform was extended by 10 years through filling its legs with high-strength grout (10.15). High strength grout (10.16, 10.17) was used to strengthen members in a number of platforms in the North Sea. This was carried out by ROVs.

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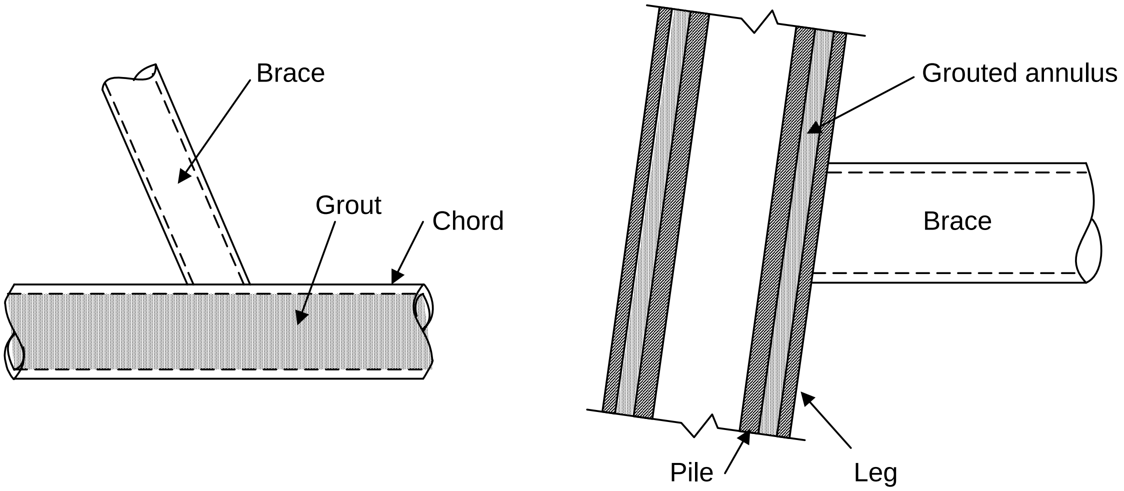
SECTION 11 - GROUT-FILLING OF JOINTS

11. GROUT-FILLING OF JOINTS

11.1 Description

A grout-filled tubular joint is one in which the chord member is filled with a cementitious grout material. The chord may be completely filled (grouted joint) or, in the case of a piled leg, the annulus between the tubulars is filled (double-skin joint), see Figure 11.1. The strength of a tubular joint is enhanced by grout filling, as it reinforces the chord wall and restricts local bending and section ovalization. Both static and fatigue endurance may be increased due to the composite action of the chord steel shell and the confined cementitious grout.



a) Grout-filled joint **b) Double-skin joint**

Figure 11.1: Grout-filled and double-skin joints

A number of technical benefits can be demonstrated through grout filling of tubular joint chords:

- The presence of the grout increases the radial stiffness of the chord member. The grout restricts local chord wall deformations, which leads to a reduction of deformation-induced bending stresses and associated SCFs.
- Any reduction in SCF implies an enhancement in fatigue life.
- The chord member bending stiffness is increased, resulting a reduction of stress at crown locations which are driven by the α ratio. The increased chord bending stiffness also implies that the capacity of large β ratio, grouted T/Y joints, subjected to axial loads, may not be limited by chord failure in the beam-bending sense.
- The grout severely restricts ovalization of the chord cross-section, which indicates a substantial increase in the static capacity of grouted joints when compared with the ungrouted cases.

Grouting filling of joints is a relatively simple SMR technique. It is arguably the most cost-effective and technically efficient technique available and, although specialist input to design is required, it is expected that this technique will find increasing application in the future.

11.2 **Limitations**

There is a paucity of data in grouted joints, and therefore specialist input is required to ensure safe compliance of the procedures.

In many instances, the strength of a grouted joint may be limited by the strength of the incoming brace member. This places an absolute limit on the increase in strength available by this technique. Joints with low γ ratios and high β ratios may have restricted benefit from composite action.

Consideration should be given to the global response of a structure before grouting the entire length of a leg or other member. Grouting will stiffen the member, and may lead to additional load being attracted to the member which may overstress unstrengthened joints in its vicinity. Local grouting does not significantly change the stiffness of a member.

The placement of grout in large diameter (24” or more) may generate excessive heat whilst setting and lead to grout degradation. The mix design should pay attention to this and ensure that the rate of heat production is not excessive.

The added mass of the grout needs consideration in seismically active regions.

Some of the possible instances where voids may be formed at joints are indicated in Figure 11.2. These instances may be avoided by using appropriate grouting procedures (use of grout bleed points).

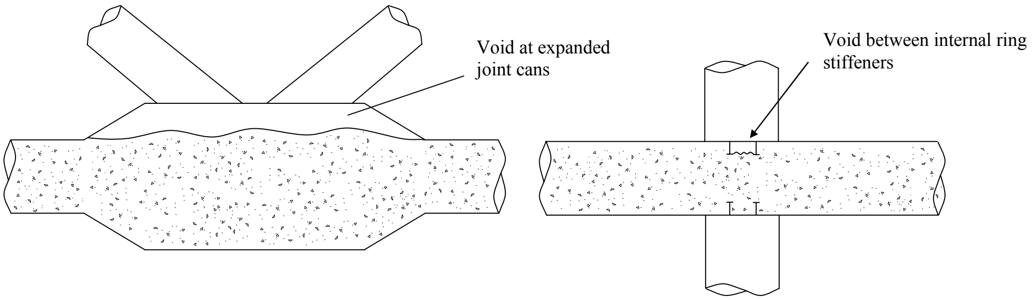


Figure 11.2: Void formation at joints

11.3 Design Approach

A decade ago, and despite the cost effectiveness of joint grout filling even then, there were surprisingly few test data from which robust design guidance could be formulated. Many of the tests were conducted in response to specific problems and therefore no systematic variation of the pertinent variables had been undertaken. More recently under the auspices of a JIP (11.1), MSL conducted a systematic test program encompassing SCF measurements and ultimate load tests in bending, and developed a detailed design practice.

Static strength

The static strength of grout filled tubular joints can be assessed by using appropriate Q_u factors in standard joint equations such as may be found in most offshore codes of practice. A set of Q_u factors has been included in the ISO 19902 standard (11.2), and will also appear in the forthcoming 22nd edition of API RP2A.

Fatigue strength

The fatigue strength of grout filled tubular joints can be assessed by using an effective chord thickness when calculating SCFs from parametric equations. This approach has been adopted in the ISO 19902 standard (11.2). The MSL JIP (11.1) has generated expressions giving factors to apply to the SCFs derived for the ungrouted joint, and is a more accurate method than the effective thickness approach.

11.4 Fabrication/Installation Issues

Equipment and Offshore Support

The following equipment/personnel are required offshore:

- Rigging
- Cutting/drilling equipment
- Divers to install grout bag seals (if used) and perform grouting operations
- Grouting spread.

Grouting technology is well proven and offshore grouting works can be executed with confidence. The grout can be placed through 1-inch diameter inlets and outlets, which may be drilled and tapped into the tubular wall. It is relatively easy to fill a chord member over its full length where the member is other than a jacket leg, as this avoids the necessity of cutting windows in the member to insert seals to localize the grout plug. Jacket legs need only be filled up to the level that is required in view of the quantity of grout otherwise used.

Timescales

Based on experience of other operations and given good conditions, a grouting operation of the complete chord length should be achievable in 2-3 days. When only a partial length of chord is to be filled, then additional activities involved with setting two grout plug seals will add a further 1-2 days to the timescale.

Inspection

Following injection and setting of the grout, no further inspection is considered necessary as the grout is confined in a sealed environment.

11.5 Previous Offshore Applications

Grout filling of joints has been conducted. However, the previous lack of robust design guidance has meant that other SMR techniques have sometimes been adopted in the past. It is expected that joint grout filling will become more popular.

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SECTION 12 - WELD IMPROVEMENT TECHNIQUES

12. WELD IMPROVEMENT THECHNIQUES

12.1 General

Weld improvement techniques are solely concerned with the enhancement of fatigue life, and are not applicable to increasing static strength. Weld improvement techniques are not associated with weld failures; the objective of a weld improvement operation is to reduce the potential for weld failure, i.e. increase the endurance of the welded connection.

Weld improvement techniques improve fatigue life by eliminating one or more deleterious aspects, which occur at weldments, through one of the following mechanisms:

- Removal of inherent welding imperfections and other defects thus greatly extending the fatigue crack initiation period,
- Local improvement of weld profile which reduces stress concentration factors and thereby the stress range acting at the weld,
- By introducing compressive residual stresses in the surface layer, replacing the tensile residual welding stresses,
- Changing the orientation and shape of welding imperfections and other defects.

The main weld improvement techniques that may be considered are:

- Toe grinding
- Hammer, shot, needle and ultrasonic peening

Other techniques exist (e.g. TIG and plasma arc dressing; prestraining; and post-weld heat treatment) but these have limited, if any, application for SMR situations.

The overall benefits of local improvement can be limited by the fatigue conditions elsewhere. With potential improvements as large as 10 or more on life, root defects and inter weld bead cracking may become the limiting condition. Weld improvement techniques may be ineffective where, for example, inaccessible root defects remain which then allow crack initiation and premature failure.

12.2 Toe Grinding

12.2.1 Description

Toe grinding is the purposeful removal of weld and parent metal from the toes of the welded joint. Inherent weld defects that act as crack initiators at the toes are thus removed. The operation is normally undertaken with a grinding tool though milling is also used. Two major techniques have evolved:

- Disc grinding, using an angled tool technique to cut a groove in the weld toe. (Note: the use of a disc grinder is not the preferred method.)

- Rotary burr grinding. A special portable machine tool is used to cut a neat groove in the weld toe. It is slower, more expensive and more specialized than disc grinding.

The aim of the operation is to excavate a regular groove, a circular curve, into the toe of the weld, thereby removing toe weld defects and providing a smooth transition from the weld profile to the parent plate. The toe is ground on both the chord and the brace side of the weld, as shown in Figure 12.1. **The grooves must remove some of the parent metal** in order to be effective, and yet a physical limit must be placed on the cut dimensions x and y in Figure 12.1, as discussed below.

If inter-run failure is a possibility, full grinding will be necessary. Full burr grinding involves grinding the whole of the visible weld profile, using a rotary burring tool. The benefit of full as opposed to toe grinding is not clearly established.

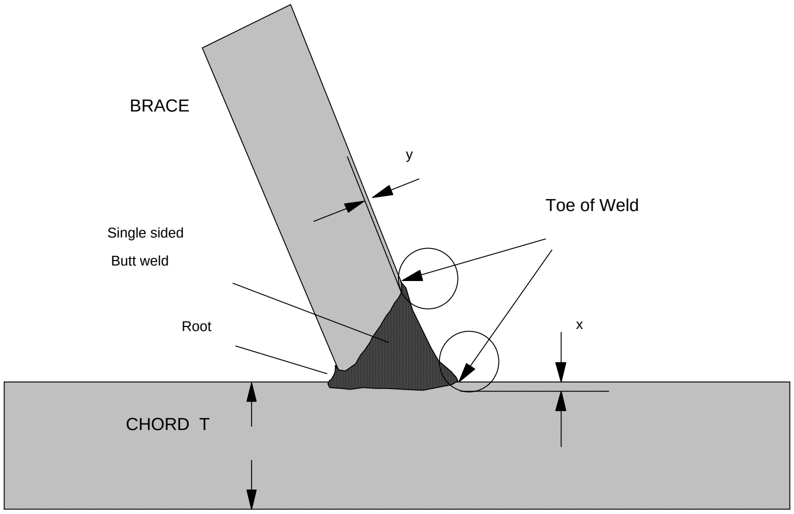

Figure 12.1: A typical application of toe grinding

12.2.2 Limitations

In certain cases, the benefits of toe grinding may not be realized in increased fatigue performance. Two major problems must be identified:

- Defects will remain in the root of a single-sided butt weld, the root defects then becoming the more prone fatigue initiation site.
- If the joint is in a corrosive environment, the ground area may quickly become subject to corrosive attack and the corrosive cracks will take the place of the (removed) weld toe imperfections.

Weld improvement, if required, is likely to be confined to areas of a jacket structure where fatigue damage is likely to occur. In broad terms, the conductor guides, conductor guide framing nodes, caisson and riser supports between elevations LAT -50' (-15.0m) and LAT +40' (+12.00m) are often the affected areas. Offshore work will therefore generally be in the domain of air divers. Environmental conditions will probably restrict the operations to periods of low wave height (7' (2m) significant sea state). In certain coastal sea areas, shallow diving is restricted by sea currents and may only be possible in a time slot one hour each side of slack water.

Booth (12.1) states that the advantages of weld toe grinding in extending fatigue life should only be admissible for underwater welds, which have adequate cathodic protection.

12.2.3 Design Approach

Most relevant codes and standards recognize the benefit of properly executed grinding operations in extending fatigue life. Codes and standards allow the original fatigue life to be at least doubled (sometimes a factor of 2.2 is quoted). Furthermore, the clock is reset at the time the grinding operation is carried out.

The depth of the cut relative to the thickness of the base metal is the key controlling parameter in ensuring that the operation is properly executed. The depth of the cut should be sufficient to remove some of the plate material. The depth of cut into the local plate (x or y in Figure 12.1) is given by:

1/50" (0.5mm) ≤ groove depth ≤ 1/12" (2mm)

A limit of 5% of the plate thickness is normally placed on the depth of the cut. The depth of cut will usually be less on the brace than on the chord side, as shown on Figure 12.2.

There may be justification for restricting the toe grinding to only certain areas of the node under consideration. The regions of the joint, which have the highest pseudo-elastic stress in the fatigue climate, should be selected if timing places a limit on the areas to be ground.

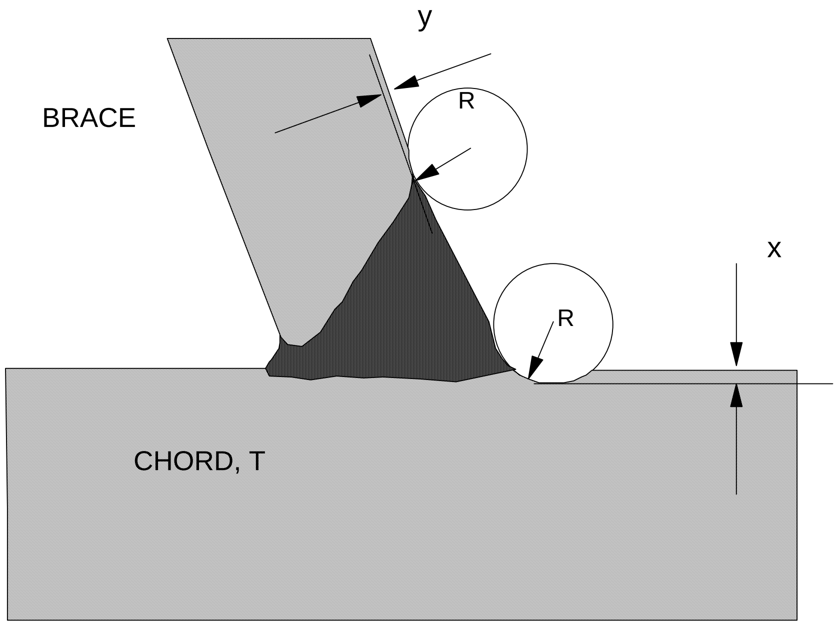

Figure 12.2: Weld toe grinding detail

12.2.4 Fabrication/Installation Issues

Equipment and Offshore Support

Toe grinding (or milling) is undertaken by specialist diving and subsea contractors. It is normal for the contractor to supply men, light equipment and small tools.

Grinding of weld toes is undertaken using one of two tools:

- Tungsten tipped rotary (or "burr") grinder
- Disc grinder (gritstone in epoxy matrix type)

Both types of tools can be employed for toe grinding in air (i.e. at the fabrication stage or for elements of the structure that are out of the water or inside a dry welding habitat). For wet repairs underwater, specialized grinding tools are required, which are readily available. Standard units are powered by hydraulic pressure; other power sources are rarely used for reasons relating to operator safety. The rotary head (or burr) grinder should be operated at a speed in the range 18,000 to 48,000 rpm in order to achieve the desired effects (12.2). Surface trials should be undertaken to check the finish produced by an individual power tool/cutting head arrangement. The speed of operation of a revolving power tool will generally be lower in water than in air for a particular power input.

Burr grinding is the preferred method for weld improvement. The use of a disc grinder results in scratch marks, which run along the length of the weld seam. A tungsten burr grinder produces much smaller scratches, which are aligned across the weld. Scratches produced by a rotary burr are less likely to lead to fatigue cracks because the principal stress in the weld is not aligned across the defect produced by the cutting operation. If a disc grinder is used, however, not only are the scratch marks deeper, but they are also aligned across the direction of principal stress and therefore more likely to become crack initiation sites.

Tubby (12.2) emphasizes the problem of residual defects and suggests that weld polishing with emery bands may help bring a uniformity of finish to ground welds. However, Tubby and Wylde (12.3) conducted burr grinding on experimentally induced fatigue cracks on a T-joint. The joint was subsequently tested again. They concluded that providing a good quality burr grind is achieved, further treatment such as polishing (or peening) would not extend weld fatigue life.

It is standard practice to specify the radius of the tool, R, to be achieved in the grinding operation. Typically R is 3/8" (10 mm), which is consistent with the manual arc welding of conventionally sized tubular joints. Smaller tool sizes may be justified with plate thicknesses less than ¾" (20mm), or where other welding techniques have been employed.

The process of abrasive water jetting has been described by King (12.4) as a possible alternative to toe grinding. The technique is not recommended, for reasons relating to safety and tool control.

Grinding a joint in air demands little preparatory work, save to ensure that the work is adequately supported. Grinding the weld provides an unprotected surface that will rust if the grinding was performed in air. Booth (12.5, 12.6) advises that the ground weld be treated with grease so that it is unable to rust under atmospheric conditions before it is immersed in seawater and hence protected by the jacket CP system.

For underwater repairs the position is completely changed. If a diver is to provide a reaction to a high-powered grinding tool then a demountable cradle or strap must be provided. Marine growth must be removed from the target area to be repaired.

Inspection and Maintenance

When toe grinding is performed using a disc grinder, the groove radius is not directly specified but a standard weld inspection tool is employed to check the finished weld.

If a weld is to be improved by grinding then detailed inspection is advised on completion of the toe grinding operation. It is important that NDE of the finished weld should target surface defects in the toe grooves and root defects in single sided weld preparations. Dye penetration and MPI techniques or eddy current methods should form the basis of testing for surface cracks for operations undertaken in air.

Inspection of the toe groove can turn up defects which require further remedial action, see Section 13.

Timescales

Toe grinding is time consuming work. Woodley (127) quotes typical rates for grinding as follows:

Technique	Rate
Disc grinding	0.5 man hr /m
Toe burr grinding	1.0 man hr /m
Full burr grinding	3.0 man hr /m

The time taken to perform operations underwater may be significantly longer than those recorded for work in the dry. Account should be taken of the time required for reaching and identifying the work place, setting up the supports, lowering equipment, taking photographs and the exchange of divers. Knowledge of diving tables and associated practices may be required to estimate the duration of a particular piece of work. It is often found that the actual work (i.e. grinding the joint) is a minor element of the total time required for the job to be completed. However, the time to grind the work may be estimated from tool cutting times, and an estimate can be made based on crack length and depth of excavation.

12.2.5 Previous Offshore Applications

Toe grinding is very commonly used has been accepted as a technique for dealing with "problem joints" in offshore platforms since 1980 (12.8, 12.9). It has been used on numerous, undocumented, occasions.

12.3 Shot, Needle, Hammer and ultrasonic Peening

12.3.1 Description

Peening is a cold working process in which the surface layer of the component (or weld) is plastically deformed either by high velocity shot (shot peening) or by a tool (needle or hammer or ultrasonic peening).

Under each impact of shot or tool, a plastic zone is created; the material outside this zone being elastically deformed in compression. After the shot has recoiled, or the tool has passed by, the elastic stresses in the adjacent underlying material will impose permanent compressive stresses within the plastically deformed zone. Gradually, as the treatment progresses, the whole surface layer will contain compressive residual stresses. Deeper in the material tensile stresses are induced which compensate for the compressive surface stresses.

It is the introduction of the compressive surface stresses, which allows improved fatigue lives to be realized. The majority of all fatigue cracks initiate at weld toes where welding defects exist and where, normally, the residual stresses are tensile and approaching or are at yield values. In a peened part, however, the residual stresses are compressive and the service stresses will superimpose to give a lower net tensile stress. The net result is that the initiation and propagation of fatigue cracks will be delayed or even prevented.

During peening, work hardening occurs in the plastically deformed zone. The work hardening increases the yield strength and this also contributes to increased fatigue strength.

In the case of hammer peening, and to a lesser extent needle peening, the weld toe profile may be improved, thus reducing the severity of the stress concentration leading again to an apparent increased fatigue life. Since the hammer tends to jump and miss small regions, a single pass along the weld toe is not usually sufficient to ensure that no area remains in the as-welded condition after peening. Consequently 2 to 4 passes are normally specified. Even better is to use a gauge to confirm the depth of the groove formed by hammer peening is as specified.

12.3.2 Limitations

As in all weld improvement techniques, the benefit of extended fatigue life may only be realized if premature failure does not occur at defects at the root or within the weld. Any defects likely to cause crack initiation must be eliminated.

Peening techniques have to be subject to careful control during their implementation. The degree of fatigue life improvement obtained is dependent on the care taken when applying the treatment. The work should only be performed by properly trained and qualified personnel.

Peening relies to a large extent on the introduction of compressive residual stresses in the surface layer. The magnitude of these residual stresses depends on the intensity of the treatment and process controls such as the tool tip radius, hammer angle and velocity in the case of hammer peening.

Shot peening is unsuitable for application underwater (except possibly in a hyperbaric chamber) as the water slows the shot down and renders the technique ineffective.

There are no data for hammer and needle peened tubular joints. The degree of fatigue life enhancement therefore has to be estimated from data obtained on plate cruciform specimens or from specially commissioned tests.

12.3.3 Design Approach

AWS (12.10), Health and safety guidelines (12.11), NORSOK (12.12), and ISO (12.13) all recognize the benefits of peening. The ISO standard (12.13) allows the original fatigue life to be at multiplied by a factor of 4. Furthermore, the clock is reset at the time the grinding operation is carried out.

It should be noted that tests on flat plate specimens (12.1, 12.5, 12.14 to 12.18) have shown even greater levels of improvement (i.e. fatigue life extended by a factor of 10 and more), particularly at the high stress / low cycle end of the spectrum. However, concerns over possible overload conditions that may cause local yielding of the tubular wall and 'wash out' some of surface compression have restricted the useful factor to 4.

The improvement in fatigue life by shot peening has been explored by reference to data mainly generated from flat plate specimens (12.14, 12.19 to 12.23) although some tubular joint data exist (12.24). The tubular joint data confirm the great improvement in life observed in the flat plate specimens. Furthermore, the improvements observed in air would appear to follow through to joints with adequate cathodic protection. Most data are concerned with constant amplitude tests but the few variable amplitude tests have shown that shakedown (i.e. partial loss of the compressive residual stresses caused by overstressing) should not be a significant factor.

12.3.4 Fabrication/Installation Issues

Equipment and Onshore Support

Development of equipment and procedures for under water hammer peening has been reported in Buitrago and Zettlemoyer (12.25). They demonstrate that there are no inherent disadvantages of peening underwater. Fatigue results of specimens peened in water were comparable with the mean of collected results where specimens were treated in air.

In hammer peening, a steel round-nosed tool bit is impacted onto the weld using pneumatic, electric or hydraulic power. The bit is round-nosed, typically of diameter 3 to 13mm. The tool forms a depression or groove, the depth of which is a function of material type, power input, and the shape of the bit. As well as introducing compressive residual stresses, hammer peening will also deform defects, such as undercuts and surface slag intrusions, to the benefit of improved fatigue life.

Needle peening has some operational similarity to hammer peening in that similar tooling is used. However, rather than just a single tool bit, the impacting is achieved with a bundle of rods (needles), each rod being about 1/8" (3mm) in diameter. Since the impact energy is spread amongst the rods, no groove is formed.

During shot peening the surface of the steel is bombarded with small balls having a diameter from 0.2 to 2.0mm. The balls are made from steel, stainless steel, glass or ceramics, and are accelerated by a spinning wheel or by compressed air. Shot peening is not suitable for in water operations.

An ultrasonic tool has been developed (12.26) and is faster and more easily controllable than conventional pneumatic tools. Currently, work is underway to further develop it for underwater use. Its power output is such that it is similar in effect to needle peening. This method is now accepted and implemented by the E.O Paton Welding Institute, Ukraine (12.27).

Inspection and Maintenance

In all peening techniques, the magnitude of the compressive surface stresses, the depth of the surface layer and the uniformity of the operation should be reproducible. The inspection methods used to ensure that this is achieved differ between shot and hammer peening as discussed below. There does not appear to be a standard method for needle or ultrasonic peening.

In the case of shot peening, an ALMEN strip is used (12.28). The ALMEN strip is a standard metal strip attached to the work-piece and which is treated similarly (e.g. rate of coverage) as for the weld toe. On removal, the strip will curl due to the residual stresses imparted by the treatment, and the amount of curling may be compared to the standard scale defining the ALMEN intensity. The ALMEN intensity is, to a first approximation, proportional to the cold working depth. To ensure uniformity a second control is generally used and this relates to coverage. Preliminary trials are carried out to establish the time for shot peening to completely remove a fluorescent dye applied before peening. This time is normally doubled, to obtain a coverage of 200%, in the actual operation to ensure uniformity (12.19).

The effectiveness of hammer peening depends on the number of passes and the duration of the operation. If the operation is carried out too rapidly, the depth of the deformed area may be insufficient to surround all defects with the required level of residual compressive stress. The easiest parameter to inspect, to ensure that the operation has been carried out to a satisfactory standard, is the depth of the groove. This will depends on the strength of the steel and trials may be called for. As a guide, 4-pass hammer peening forms grooves of approximately 0.6mm and 0.45mm in steels having yield strength of around 275N/mm^2 and 350N/mm^2 respectively. Further passes should not appreciably alter the depth.

For both shot and hammer peening, the treated area may be inspected for any remaining defects using, for instance, MPI. Note that unless toe grinding has been carried out first, hammer peened welds may still give crack-like indications.

Timescales

Data on timescales are restricted to in-air applications performed in testing laboratories. Knight (12.14) quotes a time of 0.25 hours per meter length of weld for 4-pass hammer peening. However, operator skill and experience, together with the differences entailed in underwater working, could alter the above rate considerably.

As in the case of grinding, the actual operation of peening may only form a minor element of the total time spent underwater.

12.3.5 Previous Offshore Applications

Peening is a technique which has been applied in air but not, to any great extent, underwater. Although operators are actively contemplating using peening, no offshore use has been reported in the literature. However, peening has been used onshore to good effect in such applications as bridges, earth-moving equipment and other structures subject to dynamic excitation.

12.4 Other Weld Improvement Techniques

There are a number of other weld improvement techniques covered in the literature (12.19, 12.29). These include:

- Remelting techniques (dressing)
  Here the weld toe is remelted using autogenous GTA (TIG) welding (12.23, 12.30) or plasma arc welding. These processes remove the defects and generally improve the toe shape.
- Prestraining
  The effect or large tensile preloads is to reduce residual tensile welding stresses. Although apparently effective (12.16), it is not feasible for assembled structures.
- Post weld heat treatment (PWHT)
  Post weld heat treatment is used to improve the metallurgical structure of the weld after welding. If used, it will be part of the weld procedure. Whilst PWHT is not new, post heat treating under water is. Szelagowski (12.32) reports of successful tests where weldments made by wet welding techniques have been heat treated underwater to assist in diffusing hydrogen. Favorable metallurgical structures and a reduction in hydrogen levels have been noted. However, more research is required for this method for it to be practically and economically viable. PWHT underwater is difficult, even when a habitat is employed. It is recommended that other techniques, such as improving welding consumables, and grinding should be favored to avoid the use of PWHT.

In strengthening and repair scenarios, the above techniques will find either no or very little application. A possible exception may be in dry welding, in which remelting techniques and/or PWHT may be applied to the repair weld.

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SECTION 13 - REMEDIAL GRINDING

13. REMEDIAL GRINDING

13.1 Description

Remedial grinding involves the excavation and removal of a crack, sited at or near a welded joint, by cutting a smooth shaped trench in the cracked metal, sees Figure 13.1.

The bulk of the removed material would normally be removed with a heavy grinding disc and the profile and surface finish of the trench would be improved by machining with a burring tool. In thin plate sections (T < 15 mm) only the burr grinding tool would be employed.

On completion of the first pass of grinding, the finished profile is checked using NDT. The ground area is extended until all traces of cracks have been removed. The remedial grinding is advanced until all the observed crack has been chased out. It is good practice to extend the grinding a distance T (T= plate thickness) past the end of the crack so that sub-surface defects are removed. In the case of deep cracks, grinding is not normally carried out to more than 90% of the plate thickness.

It is possible that remedial grinding by itself forms the permanent repair. However, the ground repair may subsequently form the weld preparation for a weld performed in a dry habitat or it may be encapsulated by a bolted clamp.

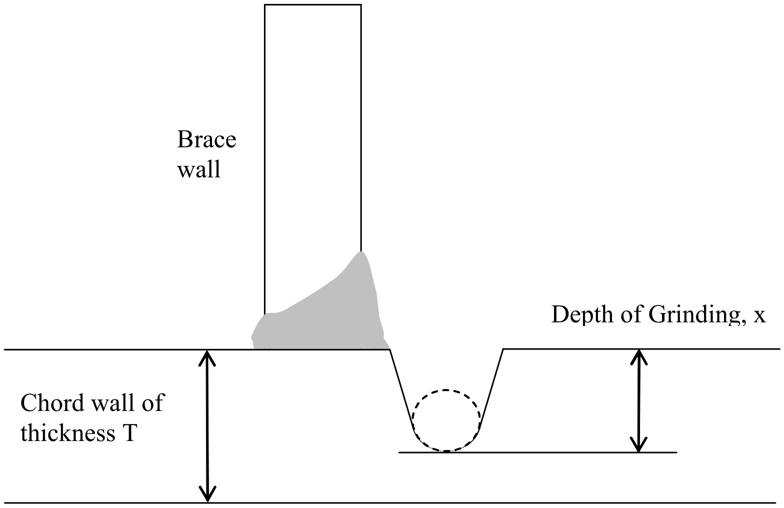

Figure 13.1: A deep remedial grind repair to a cracked joint

13.2 Limitations

Apart from restrictions on the environmental conditions in which grinding operations can be performed, the only other limitation relates to safety when grinding deep long cracks in brace members having high tensile loads.

13.3 Design Approach

Only two studies (13.1, 13.2) have been performed on the repair of underwater joints by remedial grinding, but the quality of research undertaken reflects the importance of this type of repair. In both projects, large scale T-joints were tested.

The publication OTH 89 307 'Fatigue Performance of Repaired Tubular Joints' (13.1) records the details of a joint industry project undertaken by the Welding Institute on behalf of a number of sponsor companies. The project, completed in 1987, concerned a series of fatigue tests on welded tubular T-joints in steel in which fatigue cracks were repaired by a number of alternative methods. A number of principal findings were made, including that the "*Removal of part-wall flaws by grinding is an effective repair method giving endurances after repair equal to or up to four times greater than the mean for unrepaired joints"*.

Veritec performed a project of similar proportions in their work of 1987 (13.2). The project entitled 'Grind Repairs of Welded Structures' encompassed two phases: flat plate and tubular joints. The static strength of grind-repaired joints was investigated. A stress analysis method was also outlined and verified (13.3). The Veritec report confirms that the improved profile resulting from grind repair has a higher strength and reliability that a similar, cracked joint.

MSL examined the fatigue data generated by the above studies and concluded that the improvement in fatigue life due to remedial grinding is very similar to that afforded by toe grinding, no matter what the groove depth may be (13.4).

In addition to checking the fatigue performance, an appraisal of the static strength of the joint is required.

13.4 Fabrication/Installation Issues

The excavated groove should go deep enough to remove the cracked material (a process known as 'chasing'), without creating a free flooding situation in the joint. On the brace side, partial element severance needs to be fully considered, along with the need to provide alternative support for any tensile loads.

The depth of the remedial grinding should not normally exceed 90% of the plate thickness. It is normal to place a limit whereby the depth of grinding does not exceed 66% of the plate thickness.

In the case of the crack occurring on the chord side of a tubular joint, the depth of excavation may be increased in order to chase out the crack, with the excavation normally stopped off when a nominal metal thickness (one third of chord wall thickness) remains. The limiting groove depth is influenced by the attempt to keep the tubular element internally dry. If the crack has already gone through thickness, and the element is flooded, there is little point in limiting the depth of the groove until the crack has been chased out.

The circumstances surrounding a cracked weld on the brace side of the joint are somewhat different. The brace stub thickness is usually thinner than that of the chord and may often represent a highly stressed cross section. Care should be taken when grinding a brace stub, which is loaded in tension. A check calculation should be performed so that a simple limit can be set on the depth of excavation to be made at the joint. The engineer should have access to the results of in-place and fatigue computer analyses, along with the appropriate frame, node and detail drawings of the structure.

Inspection

Remedial grinding must be allied with a surface crack inspection scheme. Dye penetrant, eddy current or magnetic particle inspection (MPI) methods are used. The crack grinding proceeds until no further defects can be observed in the parent material. Dye penetrant tests are particularly useful as a skilled operator can chase out the visible dyeline under good lighting conditions. Such criteria may not apply to many underwater locations.

Electro-potential measurement techniques (ACPD and ACFM) are particularly accurate methods for determining crack location and size and are recommended for underwater work.

Inclined cracks can pose a problem as the underlying defect may extend well past the originally discovered surface cracks. Ultrasonic or ACPD probing may be advised for mapping the possible extent of the cracked region before any grinding is attempted.

Timescales

Remedial grinding is more time consuming than toe grinding due to the greater excavation depths involved. The defect needs to be chased out, smooth ground, inspected and then the whole process repeated if any remaining crack is found.

13.5 Previous Offshore Applications

Remedial grinding is probably the most common type of underwater repair work as it is standard practice to undertake remedial grinding of any joint found to be cracked.

Williams and Callan (13.5) give a detailed account of the grind repair of a very large defect on a tubular brace (caused by a dropped object) forming part of a steel offshore structure. The approach taken, which was to minimize the local SCF effect whilst removing a large section of the damaged element, is totally consistent with the design philosophy used for the grind repair of smaller weld defects. A novel approach was to model the defect in acrylic in order to establish the SCF associated with the repair.

Remedial grinding is an operation, which is commonly undertaken in the course of underwater examination and repair. There have been numerous examples of this type of repair, with the result that few individual cases are recorded in the literature.

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SECTION 14 - BOLTING

14. BOLTING

14.1 <u>Description</u>

In the following sections, the term ‘bolt’ will refer to a threaded fastener, either with an integral head of some manufactured geometry, or without (as in the case of a studbolt). The threaded fastener may screw into a threaded hole or into a nut.

A bolted joint is assumed to consist of three main elements:

- Bolt, complete with nuts and washers
- Fixing plate or structure, normally drilled with a clearance hole to accept the bolt
- Parent plate or structure.

Bolts are used extensively offshore on topsides structural applications, but their subsea application is more restricted and is mainly for pipelines, as connections, flanges, and collars. Bolts are often incorporated into other repair methods, such as clamps, and may be used to introduce compressive stresses around defects (14.1).

The advantages of bolted repairs include:

- Speed of application
- No delay in obtaining full strength
- Ease of fabrication
- Ready availability of components and bolts
- Proven technology
- Design using existing codes
- Flexibility of use, including removal.

Bolted repairs are thus eminently suitable as temporary measures, to allow time for a more permanent job. They may also be attractive if access is difficult for other techniques such as hyperbaric or one-atmosphere dry welding. In principle, they are capable of being largely or completely deployed by ROV or other diverless methods, thereby minimizing diver risk.

The properties of a bolted joint depend on numerous factors, many of them interacting:

- Role of the bolt (acting essentially as a shear pin or as the stressing component to induce frictional resistance)
- Relative stiffness of bolt and components to be joined
- Location and numbers of bolts
- Nature of plate surfaces (planarity, friction coefficient etc)

- Thread design and lubrication of thread
- Preload
- Properties of materials (galling, relaxation, corrosion resistance etc).

The design of the joint itself will be similar to normal onshore practice, with due allowance for the fatigue loading of offshore installations. Most of the differences from conventional design arise from the practical effects of the marine environment as discussed below.

Effective designs using bolts offshore must consider:

- Fatigue
    - Innate susceptibility of the bolting materials
    - Effect of preload
    - Effect of environment (corrosion fatigue?)
- Effect of the design on bolt behavior
    - Bolt stress distributions (e.g. locations and numbers of bolts)
    - Effect of the elasticity of other components (e.g. elastomers)
- Bolt relaxation with time
- Corrosion and hydrogen embrittlement.

Three main factors affecting the response of the bolts to the above variables are: materials, preload, and thread manufacture.

- Materials
    - Static rupture behavior
    - Creep/relaxation behavior
    - Corrosion resistance
    - Susceptibility to CP levels when used subsea.
- Bolt preload
    - Affects static joint behavior (separation/loading)
    - Affects fatigue behavior

The value of the preload is itself affected by:

- Method of application of preload
- Friction (lubrication and galling)
- Thread design and manufacture
    - Cut or rolled threads

- Heat treatment
- Variability of bolts

Some of these factors will be detailed further below, but as it is not possible to give a comprehensive account of all these factors in this document, the reader is referred to standard texts such as Bickford (14.2). In the following sections, attention focuses on factors differing substantially from conventional practice.

14.2 Limitations

There are limitations with respect to the use of some materials in the splash zone and subsea.

There must, of course, be adequate access to the work site for the equipment and divers.

14.3 Design Approach

Offshore design codes do not cover bolting practice, but such repairs to topsides structures may be designed using onshore codes. However, these codes are not completely satisfactory for splash zone and underwater uses, and much more emphasis must be given to corrosion.

Most bolts used offshore conform to the usual onshore standards, and are usually made from low-alloy steels. Although these perform satisfactorily for many applications, in certain circumstances corrosion considerations may force selection of other materials.

Corrosion takes many forms, but for bolts used underwater on a cathodically protected structure, the most serious aspect is likely to be hydrogen embrittlement (HE). HE is sometimes also discussed under the terms 'environmentally-assisted cracking' (EAC), or 'stress corrosion cracking' (SCC) in the literature. For steels, susceptibility to HE increases with strength, and for some of the high-strength steels used in bolts, otherwise acceptable levels of cathodic protection (say 1100mV Ag/AgCl) can cause failure.

The critical level of cathodic protection for a bolt depends on the alloy, its manufacture, including heat treatment, and the loading environment, including CP level, applied stress, and preload. It is not possible to give general guidance, other than to recommend that specialist advice should be sought. It may be wise to design for low bolt stresses and to use relatively low-strength bolts.

It should be noted that cathodic (over)-protection is not the only way of introducing hydrogen into the material. Electroplated coatings, such as cadmium plating, supposedly used to protect the bolt, can in fact embrittle it because of hydrogen evolution during plating, unless the plating has been done properly or steps taken to remove absorbed hydrogen by a low-temperature heat treatment.

A number of materials possess increased resistance to HE, and are suitable for bolt manufacture. There are only limited sources of independent data available (14.3 to 14.6), and since many of these alloys are proprietary, it is recommended that the alloy manufacturers and specialist bolt suppliers be consulted prior to specification. Suitable materials may include some of the stainless steels, especially the higher-alloyed duplex grades and precipitation-hardening grades. Austenitic stainless steels are not recommended for marine bolts because of the risk of chloride stress corrosion cracking. Among the non-ferrous alloys, attention has been paid to many systems, particularly the nickel- and copper-based compositions such as the various Inconels, Incolloys, and Marinel. Some titanium grades have also been studied.

Correct heat treatment is essential for these sophisticated alloys at the appropriate stage during manufacture of the bolts. A number of bolt failures have occurred from errors in these steps, because of the formation of deleterious phases or otherwise unsuitable microstructures.

Corrosion may also take the form of general attack and waste the exposed parts of the bolt, or the first few threads (this is especially serious as these take most of the load). Crevice corrosion can be a problem, and galvanic effects caused by using the wrong combination of materials should be avoided - it is better to make the bolt noble with respect to the structure, though slight differences should not be unduly serious. It is wise to consult the manufacturer for advice on corrosion effects, especially for some of the more exotic alloys.

Protective coatings such as PTFE not only avoid the hydrogen problem, but should also improve the resistance to galling and corrosion and minimize thread friction (14.7).

Fatigue failures may be minimized by attention to a number of factors, of which preload is probably the most important. Note that the influence of preload is not simple, and the precise effect depends on the load excursions seen by the bolt (14.2). For bolts seeing only little load excursion, an increased preload has a moderately detrimental effect on fatigue life by increasing the mean load on the bolt. However, for high levels of bolt load excursion, increased preload markedly improves fatigue life by raising the critical load required for joint separation above the maximum external load to be seen by the joint, and by reducing the prying forces at the joint. There is also an intermediate loading regime where the effect of preload is indeterminate.

14.4 Fabrication/Installation Issues

Since bolts are made by a large number of manufacturers and may be obtained from many stockholders and suppliers, it can be difficult to establish the ultimate source of some bolts. The fact that manufacturing standards may be identified on the bolt heading may not be significant, as it has been known for inferior and sub-standard bolts to carry such markings, and the only sure method of obtaining good quality bolts is to deal with reputable suppliers with good QA. In any event, it is highly advisable for the end-user to have good QC/QA systems, and the testing of batches of bolts is sound practice. In these ways, failures can then be minimized or, if they occur, traced to source. Should bolts be made to order then QC is even more important, especially if unusual alloys are being used.

Quality of manufacture is extremely important: sharp changes of section should be avoided, especially at the junction between the shank and the head of the bolt, and the thread profile should be smoothly finished. Incorrect heat treatment may result in micro-cracking of bolts at thread roots, or even the formation of embrittling phases in some alloys, with deleterious effects on fatigue and fracture performance. Poor quality electroplating can cause bolt failures.

There is relatively little difference in the performance of rolled threads and cut threads of high quality. In general, rolled threads are preferred for fatigue resistance, but may not be feasible for small production runs of odd sizes or for some alloys, especially if heat treatments are involved. Cut threads should be chased after cutting to improve surface finish.

The measurement of preload can be a problem (14.2). Initial preload may be estimated by several methods. If both ends of the bolts are accessible, then a direct measurement of stretch can be made, and hence the preload estimated. Should this not be feasible, then indirect methods will have to be used, of varying efficacy and reliability. The use of torque to gauge preload is fraught with inaccuracy. Turn-of-nut techniques seem to offer some improvement, but the best results seem to be obtained by the use of bolt tensioners, which grip the bolt and stretch it before the nut is run down. There are several proprietary bolt tensioners available and the manufacturers should be consulted before installation of the bolts. Note that tensioning equipment may not be suitable for short bolts as the reduction in preload from transfer losses is proportional to the reciprocal of bolt length. Equipment using ultrasonic probes to measure bolt stretch has also been developed and offers the opportunity to assess bolting in blind holes.

Lubrication is crucial to prevent galling and to assist the development of preload in bolts tensioned by torque or turn-of-nut methods. It may be noted that for consistent results to be obtained, not only the type of lubricant to be used, but also the method of application and the quantity used, should be specified. As noted above, some protective coatings also improve lubrication.

It is important that the surfaces to be bolted are prepared properly so that little or no bending stresses are present in the bolt. Measures must be taken to minimize misalignment - if plane surfaces cannot be attained, even by spot-facing, then spherical washers may be used. This is particularly important for short bolts, and mounting tensioner jacks on spherical washers is recommended in that case.

Equipment and offshore support

The following equipment and support may be required:

- Divers and associated support
- Survey equipment if required
- Cleaning equipment
- Hole-drilling equipment and preparation of surfaces

- Bolt tensioners and hydraulic power
- Gear to install any temporary support structure
- Monitoring equipment to gauge preload or bolt stretch
- Craneage.

Timescales

The actual accomplishment of repairs and strengthening by bolting is quick, and the procurement and fabrication stages usually present no undue difficulty. The planning and design stages are likely to be the most time-consuming parts of the exercise.

Inspection/Monitoring during Service

Although in principle there are a variety of methods for fulfilling the various demands of inspection of bolts in service, the practical reality is quite difficult.

There are two problems: to determine the actual preload attained by the bolt on installation and during service; and secondly, to assess the integrity of the bolt, including the state of any corrosion around the threads.

Ways of assessing the preload attained during bolting have been discussed above, and the methods for checking preload after a period of service are generally similar. In effect these require the tension to be re-applied to the bolt. In some cases, the simple check of applying a torque to ascertain that the bolt is still under load, or has not fractured, is all that is required, but it should be noted that corrosion may fix broken bolts quite effectively. It is recommended that the complete exercise of bolt-tightening be used.

The assessment of bolt integrity is less easy. Although attempts have been made to develop ultrasonic methods, these have really not progressed beyond the laboratory, and in practice, the only solution is to remove the bolt for examination.

14.5 Previous Offshore applications

Bolts are used extensively in clamp SMR schemes. The most popular materials for subsea work are L7 and B7 (1¼% chromium-molybdenum steels) and have proved themselves with a substantial track record. Macalloy bar used to be specified in clamp applications but has fallen out of favor following a number of hydrogen embrittlement failures.

Bolting, as a SMR technique in its own right, has only rarely been used subsea and thus is mainly confined to topsides applications. Bolted patch plates were used to repair a damaged bottle section of rather complex geometry on the Heather platform (14.8). Bolting was also used to repair a large severed brace on a platform in the Cook inlet, Alaska, where tidal conditions meant only a very short working window was available each day (14.9). Both of these applications had unusual circumstances that led to the decision to use a bolted repair.

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SECTION 15 - FIBER REINFORCED POLYMER (FRP) COMPOSITES

15. FIBER REINFORCED POLYMER (FRP) COMPOSITES

15.1 Description

Fiber reinforced polymer (FRP) composite materials comprises two distinct constituents: a resin matrix and one or more types of embedded fiber reinforcement. In their simplest form (unidirectional laminates) they comprise one type of fiber and one type of resin. The main aim is to exploit the properties of the constituents to produce a material whose properties are markedly different from those of the constituents. The performance of the composite depends on the binding matrix, the reinforcing fiber and how they are bonded together. Composite materials for use in structural engineering applications are most likely to be based on glass, Aramid or carbon fiber reinforcements embedded in either polyester, vinyl ester or epoxy resin.

The primary purpose of the matrix is to provide a medium by which loads can be transmitted into the relatively high strength/stiffness fibers. In addition, the matrix protects the surface of the fibers and inhibits the brittle fracture generally associated with such reinforcements. The matrix defines the chemical and environmental resistance, and maximum service temperature. When the load is not aligned with the reinforcing fibers, the matrix properties also define the compressive, shear and tensile strengths of the composite in the direction of the load.

The reinforcement largely dictates the mechanical properties of the material in the direction of the fibers. Tensile strength, stiffness, and elastic modulus in the direction in which fibers are aligned are a function of the properties of the reinforcing fibers. Fiber reinforcements are available with elastic moduli in the range of 70 GPa to 800 GPa, and tensile strengths in the range of 1000 MPa to 7000 MPa. These properties become 'diluted' when mixed with the resin and when the fibers are placed in more than one direction.

It is worth noting here some of the reasons for the growing offshore interest in carbon fiber reinforced polymer (CFRP) technology and the advantages that this class of materia1s can confer in strengthening/repair applications. On a technical level, these materials can be designed to be immensely strong and stiff. Coupled with their low weight, compared to steel and other metallic alloys, this leads to high strength/weight and modulus/weight ratios, both of which are important in strengthening and repair situations. The materials are durable, and this in turn leads to low life cycle costs. Laminates can be formed in-situ, and the raw materials (fibers and resin) can be easily manhandled into confined spaces. There is minimal disruption of platform activities: no hot work, low labor requirements, no requirement for cranage, minimal amount of process equipment required and fast implementation.

Composites have been used in SMR situations in one of three ways:

- As the material of choice for replacement components such as gratings, handrails, stairwells, louvers, etc. Their main advantage in these applications is their resistance to corrosion, coupled with low weight compared to the steel alternatives. There are a number of suppliers from which these products may be obtained.

- To create a containment formwork and to contribute to the strength of reinforced concrete. Repairs to corroded conductors have been performed using this approach.
- As a reinforcing plate bonded to the existing steelwork, the composite/steel hybrid then work together in composite action. Typical applications under this category include the strengthening of beam and column flanges; reinforcement of webs and deck plating; and repairs to pipe work, vessels, caissons and tanks.

15.2 Limitations

Composites have so far proven to be a practical and economical solution in many instances. However, in the book 'Composites in Offshore Oil' (15.1), Lo states that the concerns of composite use in offshore construction are: the initial cost, composite-to-composite and composite-to-steel connections performance, and fire performance. It is believed, however, that these concerns are mainly prompted by the relative lack of industry experience in using these materials. Intelligent design and implementation based on sound procedures will lead to good SMR solutions based on composites.

Where the composite is to be attached to existing structure, there is a need to prepare the steel surface to ensure that good bond strength develops. It will normally be required to have a dry, physically clean, and chemically free surface. This creates a difficulty under water, and applications to date have been on topsides structure and process equipment. There would also appear to be concerns about the longevity of using composites underwater due to possible degradation of the matrix and/or bond with the reinforcing fibers or substrate.

Composites may be prone to impact damage if used in exposed situations. Impact damage detection in thick laminates or laminates bonded to a supporting structure is less of a problem as, with the laminate unable to deflect, front surface damage occurs.

Any stress present in the steel when a composite is bonded to it will remain in the steel. Such pre-existing stresses have to be accounted for in the design. If the pre-existing stresses are high, and although additional loads will be partly resisted by the composite, there may be only a small enhancement of strength before the steel fails.

15.3 Design Approach

General

In the design of steel structural elements, the designer is normally only concerned with establishing the form (size and shape) of the steelwork. In designing composite elements however, the designer has to consider the material to a much greater extent as mechanical properties of the composites can be selected (or designed) from a wide range of possible values. Composites are often anisotropic (different properties in different directions) and their properties are affected by the chosen manufacturing route. For this reason, it is recommended that the advice of specialists should be sought at an early stage in the design process. Such specialists may be found in consulting engineering companies or in composite supplier organizations.

Design procedures are more likely to involve analysis of the micro- and macrostructure of the laminates, often using computer-based codes.

The designer should be aware of the various ways in which composites can fail including rupture, delamination, inter-laminar shear failure, loss of bond to substrate, etc. It should be noted that bonded composites do not perform well under peel conditions, and peel loading should therefore be avoided.

Published Guidelines on the use of FRP Composites

A US Army Corps of Engineers technical report gives guidance in the use of FRP composites (15.2). Other FRP publications are cited therein, and although not of direct relevance for SMR they do indicate the wider application of FRP composites. MSL was the major contributor to an Institution of Civil Engineers publication (15.3) that provides a design and practice guide for life extension and strengthening of metallic structures using composites. A report prepared for the HSE (15.4) provides guidelines on temporary/permanent pipe repair techniques for carbon steel pipe work on topsides, and includes a review of pipe repairs using glass or carbon fiber reinforcement in a polyester, vinyl ester or epoxy matrix. The Concrete Society (15.5) published guidance on strengthening concrete structures using composites. A report by CIRIA (15.6) provides comprehensive design guidance on external FRP structural strengthening systems for metallic structures. The report for the MMS project for the repair of corroded steel tubular columns using FRP composites (15.7) is anticipated. It appears that the only codified provisions for the use of composites are those given by DNV (15.8).

Lay-up and properties of Composite

Usually, laminates will be made from many plies of fibers stacked on top of each other, with the plies often being placed at different orientations and sometimes comprising different fibers. Plies appear as woven cloth-like sheets in which the reinforcing fibers are typically either unidirectional (with about 5% of the fibers running transversely to hold the sheet together), biaxial (about equal quantities of fiber running longitudinally and transversely) or quadraxial (fibers in 0, +/-45 and 90 degree directions). Other fabric biases are also available. To estimate the properties of such laminates, it is necessary to use classical laminate theory and an appropriate failure criterion. The details of such analysis are beyond the scope of this document, but there are many excellent works detailing these techniques such as Reference (15.9). It should be apparent, however, that composites can exhibit different mechanical properties in different directions, a fact that may be used advantageously in design. Composite properties are tabulated in Reference (15.1).

To a first approximation, a simple rule of mixtures approach can be used to estimate the elastic properties of a composite material in the fiber direction as follows:

$$E_1 = K\left[\left(V_f E_f\right) + \left(\left(1 - V_f\right)E_m\right)\right]$$

where: E_l is the Young's modulus of the composite ply in the direction of the fibers
K is an empirical factor to take account of imperfections in the ply
V_f is the fiber volume fraction
E_f is the Young's modulus of the fiber
E_m is the Young's modulus of the resin.

Estimating the strength of the composite material is more difficult. However, for carbon fiber based laminates a reasonable estimate can be made by assuming that the composite laminate fails at the same tensile strain as the fibers from which it is made.

Whilst properties estimated by calculation are sufficient for initial stages of design development, the final stages of design should always be carried out using laminate properties determined by testing. In this way, the effects of raw material variability, processing conditions and process variability, which all affect the laminate properties, can be accounted for. Also, whilst composite materials do not corrode, their properties do degrade with time due to the effects of moisture, fatigue, creep and chemical exposure. Consequently, the properties used in design should reflect the amount of degradation that is expected to occur, during the life of a component.

Material Selection

As in any design process, the objective and design life of the component must be explicitly stated. The design should take into account the function the composite is expected to perform, the geometry of the structure, loading type, the effects of the environment and the consequences of accidental damage. The functional requirement will often determine the choice of the proportions and type of the components (fibers and resin) to achieve the desired material specification. For example, in the strengthening, modification or repair of an existing structure, limit state conditions may favor the choice of either high modulus or high strength laminate. For serviceability requirements such as limiting bending deflections, it may be sufficient to use a high modulus composite, while for ultimate limit state conditions, high strength composites may be desirable.

The following parameters should be considered during the selection of the constituents for the composite material:

- Environmental effects such as operating temperature, maximum and minimum temperature and expected temperature cycling, maximum relative humidity, ultra violet (UV) exposure and chemical exposure
- Long/short term fatigue/static loads
- Consideration should be given for fire and blast where applicable

- Geometry of composite
- Manufacturing process and costs
- Interfacing with other components and materials.

In areas exposed to high temperature or where particularly good fire response is required, phenolic resins are considered suitable, and for structural applications in chemical environments, epoxy resins are to be preferred.

In order to prevent the possibility of galvanic corrosion between carbon fibers and steel substrates, it is common to lay down a layer of glass fibers first.

Design of composites bonded to existing structure

It is necessary, of course, to ensure that no premature failure can occur in any component part. This entails a consideration of the original structure (the substrate), the FRP laminate and the adhesive bond between them. The stresses in each component are dependent on the structural interaction between the substrate and the laminate and therefore, in turn, on the mechanical properties of the component materials. Furthermore, recognition has to be given to the different stress distributions arising from loads already existing in the structure before implementing the scheme and those (additional) loads applied afterwards. Note that sometimes it may be possible to reduce the existing loads before scheme implementation by jacking, propping or removal of dead load. Following the scheme implementation, the laminate will resist a proportion of the reinstated load (plus any new additional loads) with attendant benefits.

Figure 15.1 illustrates, in flow chart form, the logical steps involved (15.10). Generally the existing and additional loads will be known, as will be the existing structural form and mechanical properties of the substrate material. The only variable is the design of the laminate itself (fiber type, resin, fiber architecture/orientations and thickness). The designer is free to select and orientate the fibers to optimize the laminate properties in any direction (i.e. the properties can be anisotropic) and hence the performance of the strengthening/repair scheme. In many cases, such as beam flanges, the direction of the principal stress will be fairly obvious and clearly the optimum laminate will have very nearly all the fibers so orientated. (There will be a small percentage of fibers laying in the orthogonal direction; these hold the fiber sheets together.) However, in other instances, the principal stress direction will not be known beforehand and numerical analysis (i.e. Finite Element Analysis) may be required. Unfortunately, the computed stresses in the laminate are themselves a function of the laminate properties and it may be necessary to consider a number of alternative laminate designs to establish the optimum one. This design loop is indicated by the broken lines in Figure 15.1. The laminate selection process is usually facilitated by the use of computer programs tailored for laminate analysis.

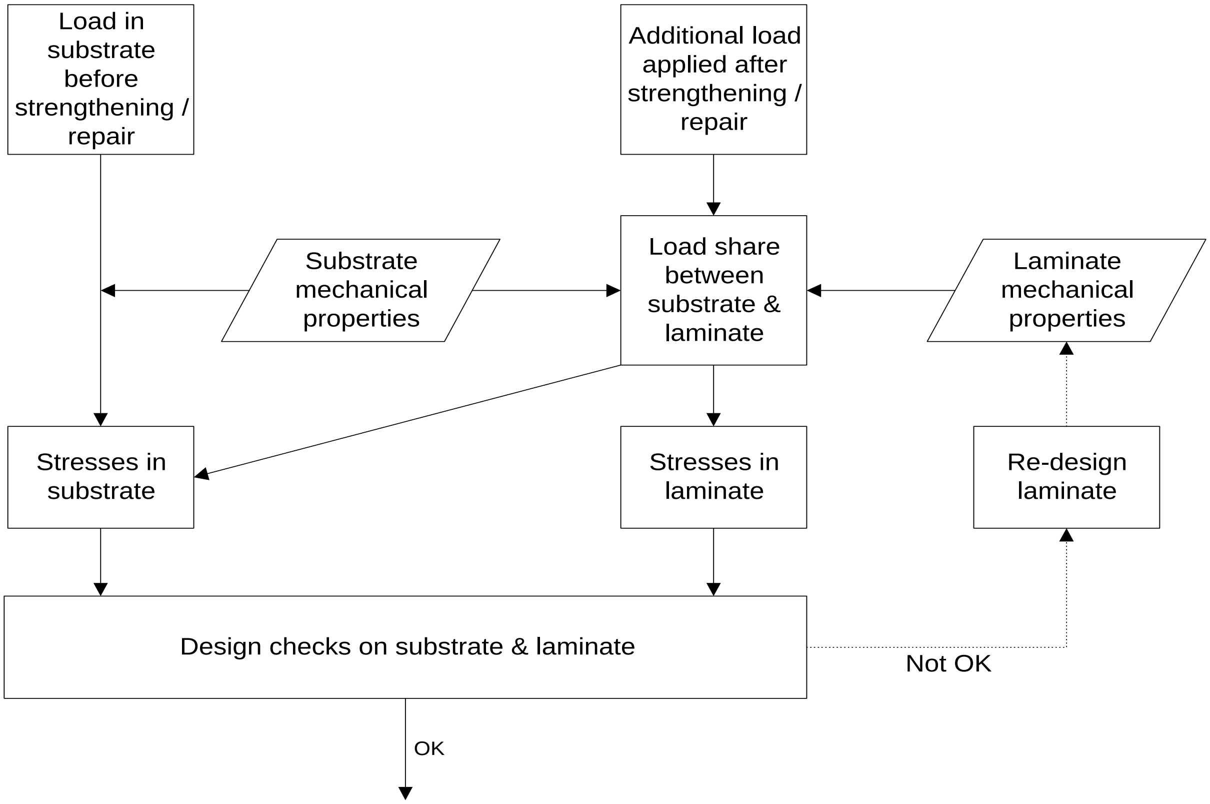

Figure 15.1: Overview of design process for laminates bonded to steel

In the case of composites applied to undamaged simple structural elements, such as rolled beams and columns, recourse to first principles can be made. For example, in the case of an axially loaded column, it should be realized that before failure, lateral deflections of the column will be small and thus the stresses due to preload can be simply assumed to be due to nominal values (e.g. the average preload stress in a column, no bending stress from Pδ effects). After the column is reinforced, further loading will be resisted by the composite member (transformed section) until first fiber yield occurs at failure. A detailed analysis (15.11) of the stress patterns along the lines indicated in Figure 15.1 shows that failure is dependent on the ratios of the section properties before and after reinforcement is applied, at least for slender sections. However, the relevant equations become simpler for stocky members and it can be shown that the following semi-intuitive linear interaction applies:

$$\frac{P_O}{R_O} + \frac{P - P_O}{R_t} \leq 1.0$$

where: P_0 is the preload
P is the total load after the member is reinforced
R_0 is the capacity of the unreinforced member
R_t is the capacity of the reinforced member.

The above interaction equation is a lower bound for slender members.

A most important part of the design concerns the transfer of load from the substrate into the laminate. An appreciation of structural behavior is essential here as stress concentrations could cause premature failure of the adhesive bond. There are techniques, given in standard texts, on how stress concentrations can be mitigated, e.g. specifying a taper on the ends of a laminate used to reinforce the flange of a beam. In any case, the shear strength of the adhesive bond, and the interlaminar shear strength, has to be assessed to ensure it is sufficient.

In summary, therefore, the following main steps are required to analyze the behavior of intact members reinforced with FRP:

- Consider which material (substrate or FRP) will govern the design according to the lesser of the yield strain of the substrate or the limiting strain of the FRP. Use a reduced design value of the substrate yield stress if necessary to ensure the FRP always remains elastic.
- Ensure local buckling is prevented (thicken the FRP if necessary).
- Check overall buckling modes (flexural and lateral torsional modes), accounting for the presence of any preload.
- Check ability of adhesive bond to transfer shear from substrate to FRP.
- Conduct deflection and other serviceability checks.

Research

The first international workshop (15.12) on FRP composites was held in 1993 by the MMS to unite, and to share experience and knowledge from, representatives from different parts of the industry. From 35 presentations, recommendations were made for further research and development in FRP composite for offshore applications. In 2002, the MMS and DNV published design guidelines (15.13). The project was subsequently transformed into a DNV standard (15.8). The MMS held another workshop (15.7) in 1999 to further FRP composite progress in offshore platforms. MSL contributed to composite repair research through two JIPs (15.11, 15.14), which involved preparation of design guidelines and designing repairs for tubular T-joints that were then tested. The results of the FE models of the T-joints under out-of-plane bending loads correlated well with the test data. A recent study by the HSE (15.15) discusses FRP composites as load bearing components in structural applications. The study indicated that the use of composites would lead to significant weight savings

15.4 Fabrication/Installation Issues

Manufacture of Composite

There are many fabrication routes for composites, but those most applicable for strengthening, modification and repair are contact molding, vacuum bag molding and resin transfer molding processes. In many cases, it will be highly desirable to form the laminate in-situ by vacuum bag or resin transfer processes. This will facilitate bringing the materials to site as the reinforcement can be rolled up, and the resins carried in containers, as opposed to maneuvering laminate planks into position. In-situ molding also allows the laminate to conform to the substrate geometry.

Timescales

In view of the potentially wide application of composites and the countless combinations of fiber orientations and the different resins available, it is difficult to estimate the timescale. However, in terms of installation one would expect a longer installation period for complex geometries. The time spent in preparing the substrate surface, will depend on the location, i.e. topside, splash zone, or under water. Methods for attaching composites to wet surfaces have, until recently (15.16, 15.17), involved extensive preparation in order to achieve good adhesion between the substrate and composite. The geometry will play a part in installation time. As mentioned in an HSE document (15.15), there are essentially two methods of application, the bandaged and engineered method. As the name suggests the bandage involves wrapping the composite around the affected area. This operation can be executed by maintenance personnel. The engineered method requires specific design and specialists to execute the repair: the engineered method is probably more time consuming and expensive.

15.5 Previous Offshore Applications

The earliest significant usage of CFRP for structural repairs in a marine environment concerns the reinstatement of integrity of cracked ships' deck plating back in the early 1980s. Following the success of these first repairs, which were carried out on UK ships, the Australian Navy adopted the technique for repair of similar damage. More recently, carbon fiber reinforced laminates have been used to upgrade firewalls in Mobil's Beryl Bravo platform to enable them to withstand blast loading (15.10, 15.18). This project is the subject of the Case Study presented below.

Composite materials are being increasingly used for the strengthening and repair of offshore structures. MSL has designed repairs of corroded conductors using composites on several Gulf of Mexico platforms. MSL have also carried out structural analysis and designed repairs for corroded caissons on North Sea platforms.

The number of publications on strengthening of structures using composites tripled between 1992 and 1995 (15.19).

CASE STUDY 1: Beryl B wall strengthening

Mobil North Sea Limited required to upgrade some firewalls on the Beryl B platform to enable the walls to resist blast loadings. In 1993, DML carried out a 'proof of concept' study in which the use of carbon fiber composites to strengthen steel structural elements was demonstrated. As a result of the study, Mobil North Sea Limited initiated a further study to determine whether or not the technique could be used to provide the blast strengthening on the Beryl B platform. This showed that the technique would be the cost effective way of providing the necessary levels of blast strengthening. The reasons for this were:

- The low weight of the materials and process equipment removed the need for mechanical handling equipment.
- The compact material packages could be taken into areas where access was tight without dismantling existing equipment or temporarily removing parts of the existing structure.
- The high mechanical properties of the materials meant that they could be applied in small amounts to strengthen only critical parts of the structure, allowing a structural efficient solution to be developed.
- There was no need to shut down platform operations, as the installation process did not require hot work.

Consequently, it was decided to use the CFRP composite solution to strengthen the Beryl B firewalls. However, recognizing that this would be the first commercial application of the technique, a detailed design and validation program was initiated that would allow approval of the scheme by the Certifying and Regulatory authorities. The program comprised five phases:

- Development of a robust application process for the offshore environment
- Characterization of materials properties
- Structural design and analysis
- Manufacture and testing of prototypes
- Design review.

Issues that had to be addressed with respect to taking the process offshore were:

- Hot working would not be allowed. Therefore, suitable substitutes for any electrically driven equipment had to be found.
- It would not be possible to heat the working areas. Therefore resins had to be found that could be used at temperatures as low as 5 deg C and the detailed set up

of the process had to be modified to ensure that a good quality composite material and adhesive bond were formed at this temperature.

The results of the preliminary engineering study and the process trials indicated that the best solution would be based on three types of carbon fiber with Young's moduli between 230 GPa and 550 GPa with laminate thicknesses being between 12mm and 30mm. The high modulus fibers were used to provide a composite material with a Young's modulus very close to that of steel, whilst the standard modulus fibers were used to provide strength in secondary directions at reasonable cost. Test laminates were manufactured and a wide range of tests carried out.

The final design and analysis was carried out, using a combination of static and non linear dynamic analyses using finite element codes, on those parts subjected to blast loading. The final design required 13 columns to be strengthened to achieve an almost three times increase in blast capacity on two walls of size 40m x 8m.

To validate the design, half scale models of the strengthened blast wall were built and blast tested. In all, 14 blast tests were carried out. Good correlation between blast test results and the predictions of the finite element analysis model was seen and the mode of failure was as expected.

The system was installed by a small team in three, two-week visits offshore, compared with the four visits that had been allowed for in the schedule. Amongst the issues that had to be dealt with during implementation include the minimum gap between the flange faces of the columns to be strengthened and adjacent structure was only 25mm, and severe access restrictions in some areas where planned platform modifications had not been carried out. The benefits of using the lightweight, compact and flexible materials quickly became apparent in these conditions.

It was considered a major achievement that every stage of the design, validation and implementation work was achieved within budget and to schedule, particularly as this was a development project. This was in no small part due to the way in which Mobil pulled together a team of specialists at the beginning of the job that then worked together to ensure that the project objectives were met.

CASE STUDY 2: WD 90 A Platform Conductor Composite Repair

WD 90 A is an eight-leg jacket drilling platform operating in 184 feet of water offshore Gulf of Mexico. The platform was installed in 1964. The original conductors were heavily corroded, as shown in Figure 15.2. A cost analysis verified that composite repair system to be the most cost effective repair method.

MADCON Corporation carried out inspection and performed the structural composite repair work.

The following project phases were encompassed during the repair:

- Underwater and above water repair site inspection.
- Plan staging area for equipment and material.
- Surface preparation including removal of excess scale; removal of internal grout where not structurally sound; and grit blasting to near white metal (see Figure 15.3).
- Install shear lug, re-bar cage (see Figure 15.4), and translucent FRP jacket outside re-bar cage.
- Pump epoxy grout into FRP jacket from bottom up.
- Install wear pads and conductor centralizers at guide bell.

Figure 15.2: Photo of heavily corroded conductor

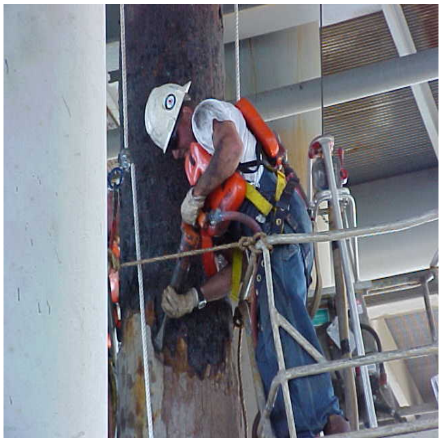

Figure 15.3: Conductor surface preparation

Figure 15.4: Photo of re-bar cage

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SECTION 16 - MISCELLANEOUS SMR TECHNIQUES

16. MISCELLANEOUS SMR TECHNIQUES

16.1 General

This section describes certain techniques that have been developed for joining steel components but as of yet have not been applied in offshore structural SMR schemes. Given the right circumstances, however, they may find an application. The techniques considered here include:

- Uses of adhesives to bond patch plates.
- Mechanical connectors - using grab, twist and/or gripping devices to achieve the mechanical locking of two tubulars.
- Swaging - forming a localized plastic region in a metal tube which creates an interference lock joint with another concentric tube.

The latter two techniques rely, to various degrees, on cold forming the tubulars. Each may offer advantages in particular repair/strengthening situations as discussed below.

16.2 Adhesives and Patch Plates

16.2.1 Description

For structural steelwork, resin adhesives may be employed to stick on patch plates. Adhesives potentially offer a number of advantages:

- Stresses are distributed more evenly over the entire joint
- Dissimilar materials may be joined
- Properties are largely independent of depth
- Jointing by adhesives avoids heating of adjacent structure
- May be used for patch plates and other applications on topsides structures, without hot work
- May be applied in geometries to which access is relatively restricted
- Normally perform well in fatigue if the joint is well-designed.

Epoxy grouts allow bond strengths an order greater than those of cementitious grouts to be obtained.

The following parameters may affect the selection of resins:

- Preparation requirements for the substrates
- Design arrangements for injecting the resin or otherwise making the joint, including allowances for volume changes during curing
- Curing period

- Short pot life once mixed
- Arrangements for supporting the joint against relative movement during curing
- QA needed to ensure the desired bond has been attained
- Availability of information on long-term stability of the adhesive, including degradation and creep
- Inspectability of joint during service
- Ability to remove the joint should it prove defective or inadequate.

Whilst there are a range of structural resins, including acrylic, cyanoacrylic, and urethane products, the epoxy resins are the most commonly used and are available as one-component and two-component systems. They may have fillers added to increase the thixotropy or to improve the strength of the final joint. Various catalysts or inhibitors might be added to modify the curing behavior. Doles and Love developed an acrylic resin for temporary underwater structural applications (16.1). The Resin is mixed underwater and cured using an illuminating visible blue light source. Viscosity of the resin is adjustable with the addition of viscosity modifiers. Good bonding strength was achieved in various conditions, including fouled steel. Reference (16.2) was unobtainable at the time of this report, however, it promises to provide further useful information on the use of adhesives in underwater environments.

16.2.2 Limitations

By comparison with their long-standing successful use in the aerospace industry, the use of resins offshore is not well-established, and there is a considerable degree of justified suspicion by engineers concerning their reliability, especially as adhesives. Their successful use depends on a variety of factors, many of which are poorly understood and further dependent on ill-defined variables such as the cleanliness of the surface. Even under controlled conditions, adhesives can give unpredictable results. It is this uncertainty of the behavior of the joints made, rather than any limitations of adhesives themselves, that have restricted their use.

Furthermore, for topsides applications, consideration may have to be given to their heat- and fire-resistance.

16.2.3 Design Approach

In view of the specialist technical nature of resins and because of the lack of applicable standards and codes, it is recommended that detailed liaison should be set up between designers, adhesive manufacturers, and installation contractors at an early stage in design.

General guidance for the use of adhesives can be found in a HSE publication (16.3). In a discussion on the performance of structural adhesives it is stated that the initial static strength of an adhesively bonded connection using a thick adhesive layer is adequate for a number of offshore applications. Stress distributions, even in simple standard tests, are far from uniform and stress concentrations occur around the joint periphery. A factor of safety of 10 on the average stress has been adopted to account for such concentrations, but this is considered to be usually unacceptable. Rather, finite element analysis may be used to quantify the stress concentrations to allow for a more rational factor of safety to be specified. Further testing is required in real conditions. However, a number of uncertainties such as impact resistance, durability (wet/humid environments) and fatigue have yet to be understood.

The properties developed by a glued joint depend on a number of factors:

- Properties of the adhesive, which will be influenced by the age and condition of the adhesive, its preparation, and the curing time and conditions
- Degree of surface bonding to the substrate, itself dependent on the nature of the substrate and its surface, including roughness and cleanliness
- Thickness of the adhesive layer
- Design of the joint itself.

In general, only modest bond strengths are achievable by gluing, but these can be compensated for by good design, which can now be done using CAD and other design tools (16.4). The strength of lap joints generally increases with the area of overlap, but decreases with the thickness of the glue layer. The mechanical properties of the adhesive may differ substantially from those of steel: the modulus of elasticity is typically one or two orders of magnitude reduced.

The resin itself may exhibit visco-elastic and visco-plastic behavior (16.5), which will be extensively modified by the design of joints.

Volume changes during the setting of epoxy resins can be quite considerable, and complicated, changing from expansion caused by heat evolution during the early stages of curing, to subsequent shrinkage. In general, all adhesives shrink as they set, whether from loss of solvent, cooling from a fluid state, or from polymerization during curing. Such volume changes should be allowed for in the design of the joint in order to avoid either de-cohesion of bonds.

Owing to the shrinkage, the adhesive in a completed joint is in a state of tensile residual stress, which is exacerbated by thicker glue layers, thereby reducing the strength of the joint. When the stress concentration at the ends of a lap joint are also included, the average (effective) shear strength of the joint can be reduced to only 30% of the shear strength of the bulk adhesive.

The performance of joints depends very much on the nature of the substrate, and it is advisable to test samples in the laboratory and to hold a full-scale trial onshore before the employment of an adhesive offshore. Performance may be heavily influenced by the joint configuration, so laboratory data should be used with caution.

Only limited data are available on the long-term behavior and fatigue resistance under offshore conditions of joints made using adhesives (16.6 to 16.8). Although trials have shown that the stability of some forms of adhesive underwater can be very good over a number of years (16.9), attention should nevertheless be given to the possible long-term effects of the underwater environment on the degradation of resins. In particular, water may penetrate the joint at the interface.

Some resins may 'creep' under load, though the mechanism is not the same as for metals, since it involves internal changes in the structure of the resin at the level of the molecular chains.

16.2.4 Fabrication/Installation Issues

General

Surfaces must be free of loose debris, rust, and scale, and should be cleaned to Sa 2½. It is also necessary for the surface to be chemically clean if a good bond is to be achieved. In underwater applications, it is possible to use a hydrophobic agent to coat the steel before the adhesive proper is applied. The hydrophobic agent is then incorporated into the adhesive (16.9).

The equipment to be used to handle and inject the adhesive must obviously be capable of functioning reliably at the depths and temperatures under consideration. Injection is the most effective way of incorporating adhesives into closed spaces, but a variety of methods may be used for applying adhesives to joints before assembly. Note that the design of the injection equipment will affect the useable life of the mixed resin, and it may be necessary to compromise on life to ensure thorough mixing. It is possible to mix the components of epoxy resins at the injection head. Manufacturers should be consulted for the best method for a particular adhesive.

Curing can be a protracted process, requiring longer times at colder temperatures. In general, the slower the setting time, the stronger the eventual bond, but it should be noted that some adhesives will not set effectively below certain temperatures. The lower limit seems to be around 3°C, but the manufacturer of the resin should be consulted. The rates of setting can be controlled not only by altering the temperature (for example, by the use of heating pads), but also by the use of catalysts.

Obviously, during curing, the joint is weak and must be supported temporarily, yet the setting time should not be so rapid as to restrict the useful life of the mixed resin in the injection equipment. Any such support structure must not overload the main installation structure, and if not readily removable after the repair, may be designed to be incorporated into the final repair.

It may be necessary to add continuity straps to a glued joint, if part of the steelwork is electrically insulated by the adhesive, or electrically-conductive fillers may be considered.

Thought should be given to the flushing arrangements available should something appear amiss during injection.

Equipment and Offshore Support

The following equipment and support may be required:

- Divers and associated support
- Cleaning equipment
- Resin transport (from the surface) and mixing equipment
- Gear to install any temporary support structure
- Resin injection equipment, including pumps.

Timescales

In view of the lack of experience with the method, and its likely dependence on the precise requirements of the repair, it is not possible to give estimates of the time required. However, the preparation for the repair is likely to form the overwhelming bulk of the effort and time, with the injection itself being relatively straightforward. Curing time might be protracted, especially at low temperatures, unless arrangements are made for the external application of heat.

Inspection/Monitoring During Service

The non-destructive inspection of glued joints is difficult, although some ultrasonic methods have been developed for in-air use. It is not known whether this equipment has been marinised.

In view of the unreliability of the non-destructive examination of bonded joints, destructive testing of replicate samples prepared from the same batch of adhesive used in the joint is normally used to assess the success of joints, but it is recommended that the joint should be designed for a service life not requiring the reassurance of inspection.

16.2.5 Previous Offshore Applications

Resin, in the form of a grout, has been used on a novel repair in West Africa, but otherwise no major use of these materials seems to have been reported. Resins and adhesives are more popularly used for fiber reinforced plastic composites. Composites are discussed in Section 15.

16.3 **Mechanical Connectors**

16.3.1 Description

A variety of mechanical connectors have been developed for connecting and repairing pipelines. They are generally proprietary products and recourse to the manufacturer will be necessary to determine the suitability of any particular connector in an application.

The great majority of pipeline connectors are activated by torquing bolts or studbolts. The simplest connectors comprise two halves with the axis of the pipe lying in the plane of the split. Bolt tightening in these types of connectors induces a simple clamping action. Some types of connectors are multi-component devices incorporating a variety of metal-to-metal and/or elastomer seals. Loads are often transferred from the pipe to the connector by serrated, segmented, metal rings. These may rely on a wedging action to be produced between sliding angled faces within the connector when bolts are tightened.

Some of the attributes of mechanical connectors that may lead to their consideration in SMR applications are:

- No welding is required
- The connection can be made quickly
- Full strength is obtained immediately on installation
- Permanent or temporary SMR can be effected (some connectors can be reused)
- Such connectors may be amenable to installation by ROV.

It may be possible to replace a structural member by using two connectors and a spool-piece. Some connectors may have the facility to accommodate misalignment and even certain errors made in measurement of the replacement spool section.

16.3.2 Limitations

As the range of tubular geometries for structural elements differ to that for pipelines, some mechanical connectors may be unsuitable due to:

- Overall size (member diameter and length of connector)
- Small tubular thickness in members may lead to crushing on connector activation
- The presence of girth or longitudinal weld reinforcement in members may preclude connector installation.

Pipeline connectors are necessarily designed to resist the pressure and axial tension found in pipelines. For structural SMR application, the loads will be somewhat different with axial and bending loads predominating, pressure being absent. The different arrangements used in mechanical connectors give rise to a range of axial and bending load capacities; recourse to manufacturers' data would be necessary to determine safe capacities. Not all connectors will have been tested under fatigue situations appropriate to structural SMR applications.

16.3.3 Design Approach

Limited guidance may be found in the ISO standard (16.10). Generally, recourse to test data or finite element analyses has to be made. Many connectors have undergone substantial development programs. Recourse to the manufacturer is required.

16.3.4 Fabrication/Installation Issues

Equipment and Offshore Support

The following equipment and personnel would be required for a diver-installed connector:

- Crane
- Rigging for installation purposes
- Underwater cutting and grinding equipment, if obstructions have to be removed
- Underwater cleaning equipment
- Studbolt tensioning/torquing equipment
- Diving spread and divers.

Inspection

The integrity of the connection is dependent on following the make-up procedure for the connector. It may be possible to get a positive indication of the connector's effectiveness by internally pressurizing the member and testing for leakage. Naturally, if the test were to be used, the strength of the member and its lengthening would need to be considered.

At regular intervals, in accordance with the platform's inspection philosophy, the condition of the connector would be checked with respect to corrosion and studbolt tension.

Timescales

Requiring essentially mechanical operations, the installation of such connectors can be expected to be completed within one or two days.

16.3.5 Previous Offshore Application

No experience of structural SMR using these connectors has yet been gained though individual manufacturers may have relevant information relating to pipeline repairs.

16.4 **Swaged Connections**

16.4.1 Description

Swaged connections were originally developed, in the context of the offshore industry, for well operations before being applied to pile-sleeve connections. In principle, the pile is expanded into a groove, or grooves, machined into the sleeve, thereby locking the two concentric tubulars together.

The established method for carrying out the pile expansion is by use of a special tool, shown in Figure 16.1, which is inserted down inside the pile to where the grooves on the sleeve are situated. Two seals are then activated and pressurized seawater between the seals is used to force the pile to expand plastically into the grooves of the sleeve. Use of explosive charges have been proposed, but a means of dewatering the annulus between the pile and sleeve is necessary for this to work (16.11). This limitation, plus obvious concerns about the use of explosives, has prevented the explosive expansion technique being used offshore.

Figure 16.1: An 84-inch Oil State Hydra-Lok tool being deployed to the skirt piles of a jacket in 693 feet (211 m) of water

Details of a proprietary pile-sleeve swaged connection have been described by Clarke *et al* (16.12). This and other commercial systems may be covered by patent protection.

The particular advantages of such systems, which may make them a favorable SMR technique in certain applications, are:

- The connection can be made quickly
- Remote operation, often several hundred feet from power source
- Full strength is obtained immediately once the inner member has been expanded
- Such connections may be amenable to ROV operation
- A significant amount of developmental work has already been carried out and there is an established track record of usage, albeit for pile-sleeve connections.

16.4.2 Limitations

There has to be sufficient access and length of inner member to allow the tool to be inserted. After making a connection, it might not be possible to retrieve the tool.

The capacity of the connection is a function of tubular geometry and groove details (number, depth and width). The tool manufacturer can give guidance on these aspects.

Tests (16.12) indicate that the load/extension behavior of connections under axial tension exhibit a soft response. This response needs to be considered during the analysis stage in determining the loads in the connected member and in other nearby members.

16.4.3 Design Approach

Recourse to the manufacturer is required.

Design guidance of the aforementioned connection can be found in Reference (16.13). A number of static and fatigue tests have been conducted on members up to 72 inches in diameter (16.12, 16.14). Clarke *et al* (16.15) proposed improvements to the design of the swage connection in view of reducing the weight of the pile sleeve by modifying the geometry of the connection. Weight savings of 30% to 40% is reported.

16.4.4 Fabrication/Installation Issues

Equipment and Offshore Support

The following equipment would be required:

- Crane
- Rigging for installation of member
- Underwater cutting and grinding equipment, if obstructions have to be removed
- Diving spread and divers if obstructions need removing, or if a stub needs end preparing.

In some situations, the end of a replacement member may be above the water granting easy access for tool insertion from the surface.

Inspection

The expansion process can be effectively monitored, by observing the volume/pressure curve of the pressurizing seawater, as it is pumped. However, the proper formation of swaged connections is better confirmed by examining the profile of the expanded tube; this can be obtained by instrumentation affixed to the tool and operated as the tool is withdrawn (16.12).

Timescales

A typical operation involving the connection of four piles can be completed in 6 to 8 hours, with joint formation itself taking about one hour per pile (16.12). For SMR applications, although joint formation times can be expected to be similar, rather more time and effort may be required in inserting the tool, particularly in horizontal members where the assistance of gravity can not be called on.

16.4.5 Previous Offshore Applications

Swaged connections have not yet been applied to SMR schemes. However over 550 subsea pile-sleeve connections have been made using the system.

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CONVERSION TABLE

Quantity	Multiply	by	to obtain	
Length	Inch	25.40	Millimeter	mm
	Foot	0.304 800	Meter	m
	Millimeter	39.370 079 X 10^{-3}	Inch	in
	Meter	3.280 840	Foot	ft
Area	Square inch	0.645 160 X 10^{3}	Square millimeter	mm^{2}
	Square foot	0.092 903	Square meter	m^{2}
	Square millimeter	1.550 003 X 10^{-3}	Square inch	in^{2}
	Square meter	10.763 910	Square foot	ft^{2}
Volume	Cubic inch	16.387 06 X 10^{3}	Cubic millimeter	mm^{3}
	Cubic foot	28.316 85 X 10^{-3}	Cubic meter	m^{3}
	Gallon (U.S. Liquid)	3.785 412	Liter	l
	Cubic millimeter	61.023 759 X 10^{-6}	Cubic inch	in^{3}
	Cubic meter	35.314 662	Cubic foot	ft^{3}
	Liter	0.264 172	Gallon (U.S. Liquid)	gal
Mass	Pound	0.453 592	Kilogram	kg
	Kilogram	2.204 622	Pound	lb
Force	Pound-force	4.448 222	Newton	N
	Newton	0.224 809	Pound-force	lbf
Pressure	Pound-force per in^{2}	6.894 757	Kilopascal	kPa
	Kilopascal	0.145 038	Pound-force per in^{2}	lbf / in^{2}
Temperature	Degree Fahrenheit	°C = (°F-32) / 1.8	Degree Celsius	°C
	Degree Celsius	°F = 1.8 X °C +32	Degree Fahrenheit	°F
Power	British thermal unit per hour	0.293 071	Watt	W
	Watt	3.412 141	British Thermal Unit	Btu/h
Energy Work Heat	British thermal unit	1.055 056 X 10^{3}	Joule	J
	Joule	0.947 817 X 10^{-3}	British thermal unit	Btu
	Kilowatt hour	3.600 000 X 10^{6}	Joule	J
	Joule	0.277 778 X 10^{-6}	Kilowatt hour	kW-h

For conversion of other units check out http://gordonengland.co.uk/conversion/