GROUTED AND MECHANICAL STRENGTHENING AND REPAIR OF TUBULAR STEEL OFFSHORE STRUCTURES

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FOREWORD

This report is the final outcome of the Joint Industry Repairs Research Project, carried out by Wimpey Offshore Engineers and Constructors Limited with funding from the following organisations:

- Amoco (UK) Exploration Company
- BP International Limited
- Chevron Petroleum (UK) Limited
- Conoco (UK) Limited
- Hydrocarbons Great Britain Limited
- Occidental Petroleum (Caledonia) Limited
- Phillips Petroleum Company
- Shell UK Exploration and Production
- Societe Nationale Elf Aquitaine (Production)
- UK Department of Energy.

The report is in five parts, corresponding to the five volumes of the original report:

- Designers' Manual – Part I of this printed report
- Engineering Assessment of Test Data – Part II of this printed report except for the following, which are included as microfiches in the back cover of this report:
  - Tables and Figures of Section 114
  - Appendix II.7A
  - Appendix II.10A
  - Appendix II.6
- Test Reports for Areas 1 to 5 – included as microfiches in the back cover of this report
- Test Reports for Areas 6 to 11 – included as microfiches in the back cover of this report
- Crack Data – included as microfiches in the back cover of this report.

The original five reports were prepared with the guidance of a Technical Steering Committee comprising:

- Dr J V Sharp (Chairman) Marine Technology Support Unit
- Mr N E Johnson (Secretary) Wimpey Offshore Engineers & Constructors Limited
- Mr P E G O'Connor Amoco (UK) Exploration Company
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- Mr R G Harwood (Principal authors) Wimpey Offshore Engineers & Constructors Limited.

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SUMMARY

This document is the outcome of the Joint Industry Repairs Research Project (JIRRP), funded by the UK Department of Energy and nine oil companies. The research carried out investigated the static strength and fatigue performance of grouted and mechanical connections and clamps of the types used to strengthen or repair underwater tubular steel members. The repairs may be needed as a result of fatigue damage, increased code requirements, damage from ship impacts, etc.

Data from the research and from other sources has been assimilated and used in the compilation of Part I of the document, the 'Designers' manual'. In general the factors addressed for each type of underwater repair include:

- its applications
- factors affecting its strength
- general recommendations
- static strength
- ranges of application
- permissible working loads
- safety factors
- applied loads
- fatigue.

The concluding chapters of the manual describe grouting materials and procedures and other relevant considerations in the design of repairs, such as bolting and sealing systems, CP, inspection and wet welding.

An experienced and competent engineer should find the manual of considerable benefit in designing a specific repair and justifying the design to the regulatory authorities. However, each repair is unique and the manual does not give standard solutions to standard problems.

Part II of the document is a more detailed 'Engineering assessment of test data' in which the factors affecting the strength and behaviour of each type of clamp or connection are discussed in more detail.

The microfiches at the back of the document contain the remaining three parts of the original JIRRP report:

- Part II - Test reports from Areas 1–5
- Part IV - Test reports from Areas 6–11
- Part V - Crack data.
NOMENCLATURE

A = bond area of grout slip surface (mm²)
A_b = area of studbolt (mm²)
A_c = composite brace section area (mm²)
A_g = cross-sectional area of grout in a composite section (mm²)
A_j = joint brace section area (mm²)
A_k = cross-sectional area of steel (mm²)

C_c = shear connector circumference ratio
C_x = surface condition factor (bond)
C_s = surface condition factor (friction)
C_l = grouted connection length to diameter ratio coefficient

d = outside diameter of brace (tubular joints) (mm)
D = outside diameter of chord (tubular joints) (mm)
D_{b, p, g, s} = outside diameter of brace, pile, grout, sleeve respectively (mm)

E_s = Young’s modulus of studbolt material (N/mm²)
E_g = Young’s modulus of grout (N/mm²)
E_s = Young’s modulus of steel (N/mm²)

f_a = allowable grout bond stress (N/mm²)
f_{ax} = nominal axial stress in brace member (N/mm²)
f_{ba} = applied bond stress (axial) (N/mm²)
f_{b} = nominal in-plane bending stress in brace member (N/mm²)
f_{bo} = nominal out-of-plane bending stress in brace member (N/mm²)
f_{bu} = ultimate bond strength (test result) (N/mm²)
f_{bcu} = characteristic bond strength (N/mm²)
f_{bme} = mean expected (predicted) bond strength (N/mm²)
f_{cu} = characteristic grout compressive strength (N/mm²)
f_{HS} = ‘hot spot’ stress (N/mm²)
F = gross studbolt load (kN)
F_b = bond stress factor
F_{cu} = bond strength parameter
F_n = net normal contact force (kN)
F_{p} = permissible working load (kN)
F_y = yield strength (N/mm²)
F_{ys} = yield strength of stud steel (N/mm²)

h = minimum shear connector outstand (hoop) (mm)
h_s = minimum shear connector outstand (discrete) (mm)

I = second moment of area (mm⁴)
I_c = composite brace second moment of area (mm⁴)
I_j = joint brace second moment of area (mm⁴)
\( K \) = stiffness factor
\( K_b \) = studbolt stiffness factor
\( K' \) = stress concentration factor relevant to the clamp flange radius detail
\( K^* \) = stress concentration factor based on standard solutions for radii

\( l_c \) = length of hoop shear connection at a circumference (mm)
\( L \) = connection length (mm)
\( L_s \) = stressed length of studbolt (mm)

\( m \) = modular ratio
\( m_c \) = median value of test population
\( M \) = moment (kNm)
\( M_{bi} \) = design out-of-plane bending strength (kNm)
\( M_{bl} \) = design out-of-plane bending load (kNm)
\( M_{ci} \) = design in-plane bending strength (kNm)
\( M_{cl} \) = design in-plane bending load (kNm)
\( M_u \) = ultimate moment of resistance (kNm)

\( n \) = number of studbolts in a connection
\( n_t \) = test population
\( N_b \) = number of cycles to first discernible surface crack
\( N_c \) = number of cycles to first through-thickness crack
\( N_e \) = number of cycles to end of test, eg extensive cracking, deflections or fracture
\( N_s \) = number of discrete shear connectors in a connection

\( p \) = load in an individual studbolt (kN)
\( P \) = slip strength (kN)
\( P_{ca} \) = characteristic slip strength per effective slip surface (kN)
\( P_{ca} \) = design axial load (kN)
\( P_{crit} \) = critical buckling load of a member (kN)
\( P_{ca} \) = design axial strength (kN)
\( P_s \) = load carried by grout in a composite member (kN)
\( P_{m} \) = mean slip strength (kN)
\( P_p \) = permissible slip load per effective slip surface (kN)
\( P_{R} \) = squash load of a member (kN)
\( P_{s,sc} \) = characteristic shear load capacity of a stud (kN)
\( P_{T} \) = total axial load in a member (kN)

\( R \) = fatigue stress ratio

\( s \) = shear connector spacing (hoop) (mm)
\( s_{nh} \) = discrete shear connector circumferential spacing (mm)
\( s_s \) = discrete shear connector longitudinal spacing (mm)
\( S \) = population standard deviation
\( SCF_{c} \) = SCF at crown point
\( SCF_{m} \) = stress concentration factor calculated from parametric formulae
SCF<sub>R</sub> = SCF in repaired joint
SCF<sub>s</sub> = SCF at saddle point

:t<sub>b,p,g,s</sub> = wall thickness of brace, pile, grout, sleeve, respectively (mm)
:t<sub>i</sub> = parameter used in the t-distribution
:T = chord wall thickness

:V = shear force (kN)
:V<sub>u</sub> = ultimate shear resistance (kN)
:w = width of hoop shear connector (mm)
:Z = section modulus (mm<sup>3</sup>)

:β = d/D for tubular joints
:γ = D/2T for tubular joints
:γ<sub>f</sub> = factor of safety on friction component in a stressed grouted
:γ<sub>b</sub> = factor of safety on bond component in a stressed grouted clamp
:γ<sub>f,b,3</sub> = partial factors

:Γ = partial factor on stress concentration factors
:Γ<sub>b</sub> = safety factor on grout bond capacity
:Γ<sub>c</sub> = partial factor on joints
:Γ<sub>t</sub> = safety factor on tubular wall local buckling failure
:Γ<sub>μ</sub> = safety factor on friction capacity
:Γ<sub>i</sub> = partial factor on loads
:Γ<sub>m</sub> = partial factor on materials
:Γ<sub>σ</sub> = safety factor on steel yield (stud shear connectors)

:θ = angle between chord and brace (≤90°)
:μ<sub>c</sub> = characteristic coefficient of friction
:μ<sub>μ</sub> = median value of an infinite population
:σ<sub>a</sub> = axial stress (N/mm<sup>2</sup>)
:σ<sub>b</sub> = bending stress (N/mm<sup>2</sup>)
:σ<sub>θ</sub> = shear stress (N/mm<sup>2</sup>)
:τ = t/T
:Φ = discrete shear connector diameter (mm)
:ψ = angle from point under consideration on a tubular joint to the saddle point, in degrees
1.1 INTRODUCTION

1.1.1 General

This manual is intended to provide designers with some basic information obtained from specific laboratory tests concerning grouted and mechanical repair systems. The design formulae and other information provided here and in the microfiches is the product of a comprehensive research project on grouted and mechanical strengthening and repair systems carried out between 1982 and 1984 at Wimpey Laboratories with funding from nine oil companies and the UK Department of Energy. The design methods and formulae presented also draw on test work carried out prior to 1982 on an ad hoc basis for oil companies and the UK Department of Energy.

The use of grouted and mechanical repair systems in both underwater and splash-zone applications has increased dramatically in recent years. This has been due to the increased number of repairs being effected as designers and operators recognise the cost effectiveness of grouted and mechanical repairs and the availability of test data describing their performance. This document represents a major step forward in the assimilation of test data into a format which can readily be used in both the design of a repair and in the justification of the design to regulatory authorities.

It should be noted that all repairs are unique. This is because of the wide range of reasons for repair and strengthening, the many different structural configurations, member sizes and joint details, and the physical constraints of access to different water depths and different parts of the structure. For this reason this designers’ manual cannot give a standard solution for a particular problem. It is recommended that the designer of a repair or strengthening systems should be familiarised with recent projects and techniques before making judgements on the efficacy of particular systems.

Although there is no standard repair scheme, it is possible to recognise the following components within the various grouted and mechanical repair schemes that have already been employed and are defined below:

- **GROUTED CONNECTION**
  A connection between two concentric tubulars formed by the injection of a cementitious material into the annular space between the tubulars. Unless specifically stated the outer tubular is taken to be continuous in the circumferential direction.

- **GROUTED CLAMP**
  A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. The splits are closed by pre-tightened bolts prior to the injection of a cementitious material into the annular space between the clamp and the existing tubular joints.

- **MECHANICAL CONNECTION**
  A connection formed between two concentric tubulars relying for load transfer on the friction capacity of the interface between the two tubulars. The outer tubular will be formed from two or more segments which are stressed together to generate a force normal to the friction surface.

- **MECHANICAL CLAMP**
  A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. The clamp body will be formed from two or more segments which are stressed together to provide the load path in the clamp.

- **STRESSED GROUTED CONNECTION**
  A connection formed between two concentric tubulars. The outer tubular is formed in two or more segments. Cementitious material is placed into the annular space between the tubulars and allowed to reach a predefined strength prior to the application of an external stressing force normal to the steel-grout interface.

- **STRESSED GROUTED CLAMP**
  A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. Cementitious material is placed into the annular space between the
clamp and the existing tubular joint and allowed to reach a predefined strength prior to the application of an external stressing force normal to the steel-grout interface.

- **GROUT FILLED TUBULAR**
  A tubular which has been filled with a cementitious material.

A clamp is distinct from a connection in that it is used to repair or strengthen a tubular joint within an existing structure by providing an alternative parallel load path, whilst a connection is a device for joining concentric tubular members together.

The design of a clamp will involve the following:
1. design of the connections which transmit a proportion of the load in the incoming brace members into the clamp
2. design of the joints to transmit the loads between the brace and chord members of the clamp and existing joint
3. design of the connections which retransmit the clamp loading back into the chord member of the existing joint.

For an illustration of these distinctions see Figure I1.1.

All the above design components have been studied within the Joint Industry Repairs Research Project and are addressed within individual sections of this manual.

This part is one of five volumes which represent the final report of the Joint Industry Repairs Research Project. The full list of volumes is:
- **Volume I** – Designers’ manual (printed here as Part I)
- **Volume II** – Engineering assessment of test data (printed here as Part II)
- **Volume III** – Test reports for Areas 1 to 5 (see microfiches)
- **Volume IV** – Test reports for Areas 6 to 11 (see microfiches)
- **Volume V** – Crack depth measurement and propagation data (Areas 7 to 9) (see microfiches).

### 1.1.2 The need for repair and strengthening

This section identifies the major causes leading to a requirement for repair and strengthening of tubular steel offshore structures and draws on experience gained in the North Sea and other similarly harsh environments on a world-wide basis.

**Fatigue**

The design of the early jackets in the North Sea was heavily dependent on experience in the Gulf of Mexico and elsewhere. In general these designs have been found unable to withstand the incessant wave loadings of the North Sea and most structures, or some component of them, have required fatigue damage to be repaired, or have needed to be strengthened to prevent anticipated damage. Fatigue damage typically takes the form of cracks at the end of horizontal members where they frame into the main structure.

**Increased code requirements**

Since the 1960s, following the assimilation of fresh environmental data, the wave loads which regulations require offshore installations to withstand have increased – dramatically in some respects. On occasion it has been found necessary to upgrade the structural performance of jackets to meet the new requirements, or to meet other requirements subsequently introduced by the owners of the jacket.
Ship impacts

Damage is also caused by shipping. Personnel transfer in the North Sea is now almost exclusively by helicopter. Regular transfer by boat has proved impossible because of the sea states in the North Sea and much damage was caused by ship impact before platform operators started to use helicopters. Ship impacts still occur as vessels are used to transport equipment and supplies, but the vessels can stand further off the platforms whilst the goods are taken aboard by cranes. Damage caused by ship impacts typically takes the form of bent or buckled members, although on occasion entire members have been ripped out.

Impact by debris

Objects are sometimes dropped overboard causing damage to the jacket on their way to the seabed. The most serious damage has been caused during the installation of jackets or during other erection work. An entire bridge intended to link two platforms has been dropped, and heavy offshore piles have been lost on more than one occasion.

The reader is referred to Reference 1.1 for a more detailed review of repairs that have been carried out on North Sea structures.

1.1.3 Use of the designers' manual

The design methods and formulae given here and later in this report provide the designer with the means to design the individual components of some repair schemes such as clamps or connections. It is not intended that this document should provide the designer with guidance on the form of specific repair schemes since each repair problem is unique. The choice of whether to clamp an understrength joint locally or to introduce extra members into the structure, thereby changing the load path around the understrength joint, is one that should be made with full knowledge of the platform geometry and loading regime and should be such as to give maximum benefit to the structure as a whole. It is at this early stage that proper consideration should be given to the extra loads that will be attracted by the repair scheme; these loads would be used at a later stage in the design of the individual components.

Extra loads which should be considered would typically include:

1. environmental loads due to increased projected area and weight of components for wave impingement and higher drag coefficients due to non tubular fabrication
2. framing loads due to changes in load paths and increased local stiffness due to clamps.

Within the individual sections of this manual giving the design methods and formulae, ranges of application are given which reflect the geometries tested and the designer should not exceed these limits except where guidance is given in the text on how this may be achieved without loss of conservatism.
Figure 1.1.1  Distinction between clamps and connections
12 BACKGROUND TO THE DESIGNERS’ MANUAL

1.2.1 General

This designers’ manual has been made possible by:

- the recognition that grouted and mechanical repairs can offer major advantages in cost and timescale
- the existence of rationally based design formulae for axially loaded grouted connections supported by test data
- the generation of a basic database under UK Department of Energy funding on grouted repairs
- the availability of the results of some ad hoc testing programmes carried out to justify the design of some repairs installed before the existence of this manual
- the data collected under the Joint Industry Repairs Research Project
- experience gained by the authors in the design and execution of actual repairs, many of which have been undertaken in parallel with all the development work leading to this manual.

1.2.2 Grouted connections

The majority of steel offshore structures are founded on tubular piles, which are generally driven through tubular sleeves attached to the lower part of the main legs of the structure or through the main legs. The annulus between pile and sleeve is then filled with cement grout to form the permanent connection between the structure and its foundation. The strength of this connection depends upon many parameters and is generally defined in terms of an equivalent bond strength (obtained by dividing the load transmitted by the nominal surface area of the grout-pile interface).

The current design method is based primarily on static strength considerations and uses formulae derived from test data. Data are now available on the fatigue performance of grouted connections and it is therefore now possible to address fatigue design.

The first design guidance provided for grouted connections was given by early editions of API RP2A. A single figure of permissible bond stress was given for plain pipe grouted connections which was based on rest data from relatively small diameter specimens. The development of a capability to install larger piles to meet the demand of larger structures in the North Sea led in the early 1970’s to an investigation of the static strength of large diameter grouted connections. This showed that plain pipe connections of the type and length envisaged could not provide sufficient load transfer capacity; shear connectors in the form of circumferential or spiral weld beads were placed on the steel surfaces in contact with the grout to provide additional capacity and tests were carried out to validate the design.

Further ad hoc tests were carried out between 1975 and 1978 for oil companies wishing to solve particular design problems. Whilst these tests were useful in establishing the parameters which affect static strength, the accumulated data did not cover all aspects of the problem and the results could not be used to formulate rationally based design recommendations giving consistent levels of safety. A detailed programme of research was therefore formulated and undertaken with funding from the UK Department of Energy.

The UK Department of Energy project consisted of five phases:

- Phase I Static strength tests
- Phase II Early age cyclic loading tests
- Phase III Long term fatigue tests
- Phase IV Measurement of grout compressive strengths
- Phase V Tests on connections recovered from West Sole.

Much of the information used to generate the design formulae given in this manual has been derived from this important project and the results and findings of the work are taken into account in Part 2.
Phase I of the project led to the derivation of a design formula for grouted pile/sleeve connections. A Working Party was subsequently set up by the UK Department of Energy to prepare revisions to the Guidance Notes covering grouted pile/sleeve connections. This culminated in the issue in April 1982 of the amendment to the Guidance Notes(2,1). This amendment and the associated formulae are now in general use on a world-wide basis.

A parametric study of tubular sizes used in pile/sleeves and grouted repairs showed that the pile/sleeve Guidance Notes did not cover an adequate range of geometries. Further testing relating specifically to the repair situation has been carried out, including some work under the Joint Industry Repairs Research Project and the resulting design recommendations are an integral part of this manual.

I.2.3 Grouted repairs

The potential advantages of grouted repair techniques have been recognised for some years. In summary these are:

1. normal fabrication imperfections are easily accommodated by the grout
2. geometrical damage is easily accommodated
3. full strength of damaged sections can be restored
4. where increased strength is required this can readily be provided
5. uses known and proven technology
6. repairs can be carried out at any depth within the range of current structures.

However, the use of grouted strengthening systems was limited by the lack of readily available design information. The design of schemes so far carried out has in most cases been based on the results of individual test programmes formulated to solve the specific design problem. For general application this situation implies an extended design period to include the necessary tests and a possible duplication of tests by operators having similar problems. It also resulted in abbreviated testing programmes to meet time-scale and certification requirements with the result that the long term fatigue behaviour of such strengthening schemes had only received cursory attention. This situation has now been overcome by the Joint Industry Repairs Research Project and earlier work funded by the UK Department of Energy. Following the commissioning of the work on grouted pile/sleeve connections it was recognised that similar grouted connections would have application in strengthening and repair and indeed such a system was used in the strengthening of platforms in BP’s West Sole Field(2,1). A research programme was formulated and the first phase of this programme, which included tests on grouted connections and preliminary tests on tubular joint strengthening systems, was funded by the Department of Energy. Details of the scope of this programme are given in Part II here. This programme also included the definition of a second phase programme to cover the following areas:

1. Further static tests on pipe-to-pipe connections to cover fully the practical range of tubular geometries
2. The effect of various alternative shear connector arrangements
3. Static strength of tubular joint strengthening systems
4. Study of fatigue performance to include:
   • the effect of adding shear connectors to existing tubulars
   • behaviour of pipe-to-pipe connections
   • behaviour of tubular joint repair systems
5. Study of the effect of cyclic movements during grouting on strength
6. Effect of corrosion products arising from underwater cleaning on bond strength
7. Investigation of wet welding procedures for placing shear connectors on existing tubulars.
Items 1 to 7 were incorporated in the Joint Industry Repairs Research Project.

During 1980 another relevant programme of work was undertaken at Wimpey Laboratories on behalf of Conoco which involved the design, testing and installation of a grouted tubular joint strengthening system to increase the punching shear strength of X joints on a structure in the Viking Field[8,9]. This strengthening work involved several novel aspects:

- split sleeves were bolted around the joint and then filled with grout. This involved the development of special grout seals
- hoop weld bead shear connectors were applied underwater using a mini habitat thereby reducing the sleeve length over which loads are transferred from the brace members to the sleeve
- the divers who installed the sleeves had been trained in the laboratory in a large seawater tank on a test piece which was used to test both the installation and grouting procedures and provide information on stress concentration factors and punching shear strength.

This project indicated two areas requiring further study in addition to those identified during the Department of Energy programme:

9. The application of complete hoop weld beads to existing tubulars underwater can be time consuming; there would be very significant advantages in some cases if the bead on the underside of the tubular could be omitted
10. Analytical procedures are required to determine stress concentration factors in the composite strengthened assembly.

1.2.4 Mechanical and stressed grouted repairs

A number of mechanical repairs have been used for offshore installations, notably those described in References 2.2 and 2.4. The repairs designed for Occidental were subjected to tests at Wimpey Laboratories. Various unstrengthened and strengthened joints were tested and relevant results have been made available by Occidental to the Joint Industry Repairs Research Project. These include tests on mechanical clamps and stressed grouted clamps used to strengthen T and DT joints and mechanical and stressed grout connections which were tested to establish load transfer capacities in terms of friction coefficients.

The following areas of further study were identified:

1. the relationship between friction coefficient and dimensions of clamp and tubular member for mechanical clamps
2. the long term performance of high strength bolts in the marine environment
3. the advantages of externally applied clamping forces in improving the strength of grouted split sleeves.

Items 1 and 3 have been included within the Joint Industry Repairs Research Project.

1.2.5 Grout-filled tubulars

The filling with grout of a tubular member may be carried out for one or more of the following reasons:

1. to increase axial compressive (squash) strength of the member
2. to improve overall member strength (stability)
3. to improve strength or reduce the SCF at a tubular joint in which the member is the chord.

In cases 1 and 2, if sufficient strength can be demonstrated, grouting a member offers the advantage of not increasing member diameter (as an outer sleeve would) or wave loading. For tubular joint
strengthening, although only local strengthening is required, the absence of diaphragms will in most cases dictate grouting the full member length.

A method of calculating the load-deflection behaviour and ultimate load for an eccentrically loaded concrete-filled tube has been developed at Imperial College\textsuperscript{28,29} and compared with the results of tests on columns of circular cross-section. Generally good agreement was obtained although the method is conservative in estimating the strength of stocky columns (L/D \leq 15). However, the grout generally used for offshore structural purposes differs from the concrete used in the Imperial College tests in a number of ways:

- grout contains no aggregate
- grout is higher strength (50 to 80 N/mm\textsuperscript{2} compared to 30 to 50 N/mm\textsuperscript{2} for concrete)
- Poisson’s ratio is slightly higher.

Therefore the validity of the computer program for grout-filled tubulars has been tested as part of the Joint Industry Repairs Research Project.

The use of chord grouting to improve the strength of tubular joints has been recognised to be of significant advantage and is being investigated separately\textsuperscript{28,29}. Although some data and some tests have been published, many data are currently unavailable for confidentiality reasons.

\subsection*{1.2.6 Description of the Joint Industry Repairs Research Project}

Having carried out the various programmes referred to in the previous sections it became apparent that a coordinated programme of research could be formulated from which design methods would evolve for grouted clamps and connections, mechanical clamps and connections and the combination of the two in the form of externally stressed grouted clamps and connections. This research programme (subsequently entitled the ‘Joint Industry Repairs Research Project’) was successfully launched in 1982 and completed in 1984 with the issue of this manual.

A number of possible applications of grouting and mechanical strengthening methods have been identified in previous sections, together with areas requiring research. These were combined into the following research study areas of the Joint Industry Repairs Research Project:

Area 1 Static strength of grouted connections (including a study of the effects of underwater cleaning on bond strength, the effectiveness of various forms of shear connectors including discontinuous weld beads and studs, a study of the effects of axial movement between members and sleeve during the grouting operation and a study of the effects of pressure on bond strength)

Area 2 Static strength of grouted clamps (including measurement of stress concentration factors in the joint and in the sleeve)

Area 3 Static strength of mechanical connections

Area 4 Static strength of externally stressed grouted connections including the effect of time

Area 5 Strength of grout-filled tubulars subjected to combined axial compression and bending

Area 6 Fatigue performance of grouted connections

Area 7 Fatigue performance of grouted clamps

Area 8 Fatigue performance of mechanical clamps

Area 9 Fatigue performance of externally stressed grouted clamps

Area 10 Static and fatigue performance of alternative fasteners

Area 11 Investigation of wet welding techniques for application of weld bead shear connectors underwater.

A more detailed description of the scope of work is given in Part II here and full details are available in the Area test reports contained in Volumes III and IV (see the microfiches).
I.3 DESCRIPTION OF GROUTED AND MECHANICAL REPAIR SYSTEMS

I.3.1 General

The repairs that have been carried out to date using grouted and mechanical systems can be divided into two broad categories:

1. local repair by, for example, strengthening of an existing tubular joint by a clamp constructed in segments which fits around the existing joint and is subsequently bolted together

2. global strengthening achieved by the introduction of additional members into the structure. In this case connection is necessary to the existing tubulars.

Although there is no standard repair scheme and each repair should be regarded as unique, the following components can be recognised in grouted and mechanical repair schemes:

- grouted connections
- grouted clamps
- mechanical connections
- mechanical clamps
- stressed grouted connections
- stressed grouted clamps
- grout-filled tubulars.

I.3.2 Terminology

This section contains a single paragraph definition of the standard terminology used throughout this designers’ manual and supporting volumes.

**TUBULAR**
A structural member or other component of the structure which is of hollow circular cross-section.

**TUBULAR JOINT**
The area encompassing the intersection of tubulars which are welded together.

**CHORD**
The through TUBULAR at a TUBULAR JOINT.

**BRACE**
A TUBULAR which intersects and is connected to the CHORD at a TUBULAR JOINT.

**GROUTED CONNECTION**
A connection between two concentric tubulars formed by the injection of a cementitious material into the annular space between the tubulars. Unless specifically stated the outer tubular is taken to be continuous in the circumferential direction.

**SPLIT SLEEVE GROUTED CONNECTION**
A grouted connection in which the outer tubular has one or more longitudinal splits which are closed by pre-tightened bolts prior to the injection of the cementitious material.

**GROUTED CLAMP**
A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. The splits are closed by pre-tightened bolts prior to the injection of a cementitious material into the annular space between the clamp and the existing tubular joints.

**SHEAR CONNECTOR**
A keying device, usually in the form of weld beads, welded studs or welded bars, placed on
surfaces in contact with a cementitious material of a grouted connection or grouted clamp in order to enhance the load transfer capacity of the steel-grout interface.

MECHANICAL CONNECTION
A connection formed between two concentric tubulars relying for load transfer on the friction capacity of the interface between the two tubulars. The outer tubular will be formed from two or more segments which are stressed together to generate a force normal to the friction surface.

MECHANICAL CLAMP
A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. The clamp body will be formed from two or more segments which are stressed together to provide the load path in the clamp.

COMPOSITE CLAMP
A clamp, which may be a GROUTED CLAMP, a MECHANICAL CLAMP or a STRESSED GROUTED CLAMP which is used to strengthen an existing tubular which can be considered as contributing to the load capacity of the system.

STRESSED GROUTED CONNECTION
A connection formed between two concentric tubulars. The outer tubular is formed in two or more segments. Cementitious material is placed into the annular space between the tubulars and allowed to reach a predefined strength prior to the application of an external stressing force normal to the steel-grout interface.

STRESSED GROUTED CLAMP
A clamp in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. Cementitious material is placed into the annular space between the clamp and the existing tubular joint and allowed to reach a predefined strength prior to the application of an external stressing force normal to the steel-grout interface.

ADDMEMBER CLAMP
A clamp, which may be a GROUTED CLAMP, a MECHANICAL CLAMP or a STRESSED GROUTED CLAMP, which is used either to connect a new tubular at an inclined angle to an existing tubular or to strengthen an existing tubular joint in which the original joint is considered to have failed.

GROUT FILLED TUBULAR
A TUBULAR which has been filled with a cementitious material.

BOLT
Hexagonal or other headed bolt usually installed between closely fitting flanges and usually post-tensioned by the application of torque.

STUDBOLT (STUD)
Fully or partially threaded bar with nut/washer assemblies at each end usually post-tensioned by application of axial force by hollow ram hydraulic jacks. These may be installed as 'short studs' between closely fitting flanges or as 'long studs' between widely spaced flanges.
1.4 GROUDED CONNECTIONS

1.4.1 Introduction and definitions

A grouted connection is a connection formed between two concentric, or near-concentric, tubular members when a cementitious material is injected into, and allowed to set and cure in, an annular space provided between them.

The outer tubular (sleeve) of the connection may be formed from either a continuous section or, where end access is not available, it may be installed in two or more sectors of cylinders placed around the inner tubular. To differentiate between the two forms of grouted connections the former are referred to as 'continuous sleeve' and the latter as 'split sleeve' grouted connections (see Figure 1.4.1).

The strength of a grouted connection is obtained from a combination of chemical bond and friction plus any mechanical interlock that may result from geometric imperfections in the tubulars. It is possible to substantially enhance the strength of a grouted connection by providing mechanical shear connectors (eg weld beads, studs, welded flats, etc) on both grout/steel interfaces.

A substantial amount of research was performed during the 1970's to investigate the strength of grouted connections used for the pile foundation to structure connection for steel tubular offshore structures. In this research, performed with continuous sleeves, the inner tubular was referred to as the pile; for repair work the inner tubular is referred to as the brace. Therefore these two names are interchangeable with reference to grouted connections and both are used in the literature on this subject.

The design guidance given in this section on grouted connections is based on the engineering assessment of the available data, contained in Part II, Section II.4 of this document. The guidance is presented in, and uses formulae of, similar format to the UK Department of Energy Notes on 'Grouted Pile/ Sleeve Connections' on which it has been modelled. However, the guidance given herein is not wholly interchangeable with the UK Department of Energy Guidance and therefore the respective guidance should be used for its intended application.

1.4.2 Applications

Grouted connections can be used in a number ways in repair schemes, and because of their inherent simplicity offer a cost effective means of repair. The major uses of grouted connections are:

1. as an installation aid to facilitate the connection of two parts of a member together to form a continuous structural element, see Figures 1.4.2.a and b
2. to strengthen, by sleeving, understrength members, such as legs, to increase their squash and stability characteristics, see Figures 1.4.2.c
3. to strengthen damaged members by offering a parallel load path across defective areas. (defects such as dents, punctures, corrosion holes, etc may be repaired in this manner, see Figure 1.4.2.d)
4. to offer a means of connecting a new member into a structure; the new member being welded onto the sleeve (this can be an effective way of reducing the effective length of a member which has been bent, see Figure 1.4.2.e).

The major advantage of using grouted connections is that the grouted annulus offers a large tolerance and therefore reduces fit-up problems. For this reason they are most suited to the repair of damaged areas of structures where deformations from the as-built geometry have occurred (eg dents caused by impact).

This freedom from requiring close tolerances can also be used to advantage when fitting a new member into a structure. Small angular deviations can cause large linear translations over large
distances, which may lead to fit-up problems. Using a grouted connection of the type shown in Figures I.4.2.a or b at one end of the member allows rotation of the new member, thus allowing the other end of the member to be positioned where intended. It should also be noted that by including this level of tolerance in a system at one point means tolerances can be reduced elsewhere. This will in turn influence the types of clamp used to attach the new member into the structure.

I.4.3 Factors affecting the strength of grouted connections

The following factors which may affect the strength and behaviour of grouted connections have been investigated and design guidance is offered on these:

1. grout compressive strength and elastic modulus
2. tubular geometry (radial stiffness)
3. geometry of continuous hoop (eg weld bead) shear connectors
4. discontinuous hoop shear connectors
5. discrete (stud) shear connectors
6. grouted length to brace diameter ratio
7. loading régimes
8. surface condition of the tubulars
9. underwater cleaning
10. long term grout shrinkage
11. pressurisation of the grout annulus
12. early age cyclic movements.

I.4.4 General recommendations

It is recommended that where possible and where it can be shown to be economically viable mechanical shear connectors should be used. The presence of shear connectors not only offers structural economy by reducing the length of connection required but it also increases reliability as the effects of long term grout shrinkage are eliminated.

Shear connection can be provided in the form of weld beads, welded flats or studs. In all cases the shear connectors must be provided on both grout/steel interfaces if the additional strength they provide is to be accounted for. When using studs on a structure it may be advantageous to use weld beads of an equivalent h/s on the sleeve to reduce the size of the annulus.

The majority of data on which this guidance has been drafted is for plain pipe and weld bead (hoop) shear connector grouted connections. The guidance given on grouted connections employing stud (discrete) shear connectors is based on a pilot study of four tests and therefore should be used with caution and with reference to the engineering assessment contained in Part II here, Section II.4.3.6.

I.4.5 Static strength of a grouted connection

1. The characteristic bond strength of a grouted connection with or without mechanical shear connectors, satisfying the requirements of Section I.4.6, may be taken as:

\[ f_{bcu} = KC_t (9C_s + 1100C_h h/s)(f_{cu})^{1/2} \]  

(I.4.1)

where 
- \( f_{bcu} \) is the characteristic bond strength (N/mm²)
- \( f_{cu} \) is the characteristic grout compressive strength (N/mm²) (see Section I.11)
- \( K \) is the stiffness factor (see below)
- \( C_t \) is the coefficient for grout length to pile diameter ratio (see below)
- \( C_s \) is the surface condition factor bond (see below)
- \( C_h \) is the shear connector circumference ratio (see below)
h  is the minimum shear connector outstand (mm)
s  is the nominal shear connector spacing (mm).

2. For stud (discrete) shear connections an equivalent h/s may be used in Equation I.4.1 such that:

\[
\frac{h}{s_{\text{equivalent}}} = \frac{\Phi h_s}{s_n s_t}
\]  \hspace{1cm} (I.4.2)

where \( \Phi \) is the stud diameter (projected plan width)
\( h_s \) is the stud height (projected plan height)
\( s_n \) is the circumferential stud spacing
\( s_t \) is the longitudinal stud spacing.

For definitions also see Figure I.4.3.

In addition the requirement of Section I.4.6 should be satisfied.

3. The stiffness factor K is defined by:

\[
K = \frac{1}{m} \left[ \frac{1}{(D/t)_g} \right]^{-1} + \left[ \frac{1}{(D/t)_b} + \left( \frac{D}{t} \right)_s \right]^{-1}
\]  \hspace{1cm} (I.4.3)

where \( m \) is the modular ratio of steel to grout
\( D \) is the outside diameter
\( t \) is the wall thickness
suffixes g, b and s refer to grout, brace and sleeve respectively.

In the case of a grouted connection employing a split sleeve the diameter and wall thickness of the sleeve should be considered as if it were a continuous sleeve, but the recommendation given in Section I.4.5.4 should be satisfied.

4. In the absence of other data the modular ratio m may conservatively be taken as 18 for long term (ie 28 days or more).

5. The available data on the parameter \( C_L \) are limited, therefore in the absence of data relating to the specific tubular and shear connector geometry, the following values of \( C_L \) should be assumed:

\[
\begin{array}{cc}
\text{L/D}_b & C_L \\
2 & 1.0 \\
4 & 0.9 \\
8 & 0.8 \\
\leq 12 & 0.7 \\
\end{array}
\]

where \( L \) is the nominal grouted connection length.

Intermediate values for \( L/D_b \leq 12 \) should be calculated by linear interpolation.

6. The surface condition factor, \( C_s \), in the absence of other data, should be taken according to one of the following conditions:

1. Where the member has been cleaned underwater to remove deposits back to bare steel and it can be ensured that a corrosion product film will either not form or will be removed immediately prior to grouting then the following should be used:
   - if shear connectors are present and satisfy the requirement \( h/s \geq 0.005 \), then \( C_s \) may be taken as 1.0
   - for plain pipe connections and for connections with shear connectors but with \( h/s < 0.005 \), then \( C_s \) should be taken as 0.6.

2. Where it is not possible to ensure that a corrosion product film, that may build up on the steel surface after cleaning underwater, will be removed prior to grouting the following should be used:
• if shear connectors are present and satisfy the requirements $h/s \geq 0.005$, then $C_c$ should be taken as 0. (ie no surface bond allowed)
• for plain pipe connections and for connections with shear connectors with $h/s \leq 0.005$, then $C_c$ should be taken as 0.5.

3. Where it is proposed not to remove surface coatings, investigations will be required to determine the value of $C_c$ to be used.

7. The shear connector circumference ratio $C_c$ has been introduced to account for the situation where it is not practical to install a full hoop shear connector (not applicable to studs). The value of $C_c$ is defined as:

$$C_c = \frac{l_c}{\pi D_o} \quad \text{(1.4.4)}$$

where $l_c$ is the total length of shear connector at a circumference.

### I.4.6 Ranges of application and other requirements

#### I.4.6.1 General requirements

The relationship given in Equation I.4.1 may only be applied to connections which satisfy the geometric limits given below. In addition connections using mechanical shear connectors, stud shear connectors and split sleeves should also satisfy the requirements given in Sections I.4.6.2, I.4.6.3 and I.4.6.4 respectively. The notation is illustrated in Figure I.4.3 and Figure I.4.4.

- Tubular geometry
  - Either $20 \leq (D/t)_b < 32 \quad 40 < (D/t)_b \leq 140 \quad 10 \leq (D/t)_b \leq 45$
  - Or $32 \leq (D/t)_b < 72 \quad 24 < (D/t)_b \leq 140 \quad 10 \leq (D/t)_b \leq 45$

- Whilst $D/t$ ratios are given for sleeve and brace geometries the design of these components should be in accordance with relevant steel design methods.

- Grouted connection length to brace diameter ratio $L/D_b \geq 2$
- Shear connector height ratio $0^* \leq h/D_b \leq 0.012$
- Shear connector spacing ratio $0^* \leq D_c/s \leq 8$
- Shear connector ratio $0^* \leq h/s \leq 0.06$
- Shear connector shape factor $1.5 \leq w/h \leq 3$
* Refers to plain pipe connections.

The above limits are imposed because of the range of geometries for which test data are available. The restriction on shear connector shape factor (width/outstand) is consistent with connectors formed either by welded square bar or approximately semi-circular section weld beads and generally covers current practice.

These limitations should not be taken to exclude the use of connections outside the stated ranges providing that it is demonstrated that the strength of such connections can be reliably estimated. Connections with pile and sleeve $D/t$ ratios below the lower limits (ie more radially stiff) can be conservatively designed by assuming the limiting $D/t$ ratios in calculations. Alternatively test data may be used as the basis for design. However, care must be taken in using the results of limited test programmes to provide a characteristic bond strength equivalent to that given in Equation I.4.1. Guidance is given in Part II, Section 11 on the use of additional data to support a design.
I.4.6.2 Special requirements for mechanical shear connectors

Shear connectors must be placed on both the brace and sleeve surfaces which are in contact with the grout.

The shear connector spacing should be uniform along the length of the connection.

The outstanding and spacing of the shear connectors should be the same on the brace and sleeve, except where studs are used on the brace and hoop shear connection on the sleeve. In this case the hoop shear connection has should be made the same as the equivalent stud h/s given in Equation I.4.2.

The shear connector cross-section and welds should be designed to transmit the total load applied to the connection.

If partial hoop shear connection is used (i.e. \( C_c \leq 1 \)) it should be placed symmetrically around the circumference (see Figure I.4.4).

I.4.6.3 Special requirements for stud shear connectors

The guidance provided here on the use of stud shear connectors is based on a limited test database and designers wishing to use it should refer to the engineering assessment, Part II, Section II.4.3.6, prior to using the following.

Three failure mechanisms have been identified:

1. bond slip (typical of weld bead grouted connection failure)
2. stud failure
3. local buckling failure of the tubular wall on which studs are attached.

Failure mechanism 1 is undesirable as the primary failure mode as this will cause distortion of the tubular wall, thus reducing the overall buckling capacity of the member. Limiting the stud diameter to the following will ensure this failure mode does not control the design:

\[
\phi \leq \frac{2.3t}{F_y} \left( \frac{F_y}{F_{st}} \right)^{0.5} \tag{I.4.5}
\]

where:
- \( t \) is the thickness of the tube
- \( F_y \) is the yield strength of steel (N/mm\(^2\))
- \( F_{st} \) is the yield strength of the stud (N/mm\(^2\))
- \( \Gamma_f \) is the factor of safety on the tubular failure mode (taken as 1.4).

The strength of the connection can therefore be based on the sum of the plain pipe strength and the stud strength (i.e. failure 2); this strength shall, however, not be greater than the strength based on Equation I.4.1 using an equivalent h/s given in Equation I.4.2 (i.e. failure 1). The following conditions should also be satisfied to comply with the available data:

- stud connector height ratio \( 0 \leq h_c/D_b \leq 0.07 \)
- stud hoop spacing ratio \( 0 \leq \pi D_b/S_b \leq 16 \)
- stud longitudinal spacing ratio \( 0 \leq D_b/S_a \leq 3 \)
- stud connector ratio \( 0.33 \leq h_c/\phi \leq 2 \)

The stud shear connectors should be placed symmetrically around the circumference of the member, and care should be taken to avoid positioning studs opposite the split in a sleeve.

Shear tests on studs that have been welded using the same method and in the same environment to their proposed use should be performed to obtain shear strength values prior to any design.
I.4.6.4 Special requirements for split sleeve grouted connections

The split sleeve of a grouted connection must have prestressed sleeve contact surfaces such that at the factored design load this prestress is maintained.

To maintain the prestress it is recommended that a load of 1.8 times the design axial load divided by the number of splits should be provided on each sleeve contact surface. (For further information see Part II, Section 11.4.3.3). In addition forces due to bending, torsion and tension that will tend to cause changes in the interfacial stresses on the splits should also be designed for.

* 1.8 is based on the extra load which is attracted by the first bead within a connection and a safety factor of 1.2.

The bolts should be evenly spaced along the sleeve, preferably at the same centres and location as the shear connectors, if provided.

The bolts should also all be loaded to the same level to provide a uniform prestress along the connection length.

I.4.7 Permissible working stress

In determining the permissible working bond stress for a plain pipe connection or a connection employing hoop shear connectors the safety factors, recommended in Section 11.4.8 should be applied to Equation 11.4.2 such that:

$$f_a = \frac{f_{bc}}{\Gamma_b}$$  \hspace{1cm} (I.4.6)

where $f_a$ is the allowable bond stress (N/mm²)

$\Gamma_b$ is the safety factor on grout bond capacity.

In determining the allowable working bond stress for a grouted connection employing stud shear connectors the following two equations have been proposed from the limited data available:

$$f_a = \frac{\pi \delta F_{ph}}{16 \Gamma_b h_s s_s s_i} + \frac{9KC_s C_t f_{cu}}{\Gamma_b}$$  \hspace{1cm} (I.4.7)

which must not be greater than

$$f_a = \frac{KC_s (9C_s + 1100 \delta h_s / s_s s_i) f_{cu}}{\Gamma_b}$$  \hspace{1cm} (I.4.8)

where $\Gamma_b$ is the factor of safety on stud steel yield

and all other parameters are as previously defined.

It is assumed in Equation 11.4.7 that yield of the stud in bending will occur before the stud weld is failed in shear. If the shear strength of the studs is known by tests to be lower than the bending strength then Equation 11.4.7 becomes:

$$f_a = \frac{P_{scu}}{\Gamma_s s_s s_i} + \frac{9KC_s f_{cu}}{\Gamma_b}$$  \hspace{1cm} (I.4.9)

where $P_{scu}$ is the characteristic shear load of a stud, based on tests.

I.4.8 Safety factors

In determining the permissible working bond stresses from Equations 11.4.6, 11.4.7, 11.4.8 and 11.4.9 the safety factors given below may be applied in the absence of any other guidance:
- Safety factor on bond strength $\Gamma_b$
  (These factors are consistent with the UK Department of Energy Guidance for grouted pile/sleeve connections)
  
  \[
  \begin{array}{|c|c|}
  \hline
  \text{Condition} & \text{Safety factor} \\
  \text{Extreme} & 4.5 \\
  \text{Operating} & 6.0 \\
  \hline
  \end{array}
  \]

- Safety factor on stud strength $\Gamma_s$
  
  \[
  \begin{array}{|c|c|}
  \hline
  \text{Condition} & \text{Safety factor} \\
  \text{Extreme} & 1.70 \\
  \text{Operating} & 2.25 \\
  \hline
  \end{array}
  \]

### I.4.9 Applied stresses

In calculating the applied bond stress in comparison with the permissible working bond stress the maximum applied axial load divided by the brace to grout nominal contact area shall be used; bending loads may be conservatively ignored.

The overall deflection of a grouted connection at the working load may need consideration in the design of the structure.

### I.4.10 Fatigue

The bond stress to cause fatigue failure of a grouted connection has been shown to be greater than the current permissible working bond stress, as defined by Equation I.4.6 used in conjunction with the safety factors given in Section I.4.8. Therefore fatigue of the connection itself may be ignored in the design. However, consideration must be given to fatigue of the component parts of the connection.

### I.4.11 Movements during grouting

Relative axial movements between the brace and the sleeve should be restrained. Failure to do this may result in loss of connection stiffness and/or impair the fatigue performance.

Lateral movements between the brace and sleeve have not been investigated and it is recommended that these should be restrained.

---

**Figure I.4.1** Forms of grouted connections
CONNECTIONS OF TWO MEMBERS USING GROUTED CONNECTIONS

c) MEMBER STRENGTHENING
d) DAMAGE REPAIR OF A LOCALLY DENTED MEMBER

PARALLEL LOAD PATH REPAIRS

e) REPAIR OF A BENT MEMBER

Figure 1.4.2 Uses of grouted connections
Figure I.4.3  Notation used in shear connector calculations – longitudinal sections

Figure I.4.4  Notation used in shear connector calculations – cross-sections
1.5 GROUTED CLAMPS

1.5.1 Introduction and definitions

A grouted clamp is one in which the outer sleeve is formed in two or more segments which are placed around an existing tubular joint. The splits are closed by pre-tightened bolts prior to the injection of a cementitious material into the annular space between the clamp and the existing tubular joint.

Alternatively, a grouted clamp may be of the ‘addmember type’ where it is used either to connect a new tubular at an inclined angle to an existing tubular joint or chord member or to strengthen an existing tubular joint in which the original joint is considered to have failed.

The various components of a grouted clamp are illustrated in Figure 1.5.1.

The design guidance given in this section on grouted clamps is based on the engineering assessment of the available data contained in Part II, Section II.5 of this document.

Designers wishing to use grouted clamps should also refer back to Section 1.4 ‘Grouted Connections’.

1.5.2 Applications

The applications of grouted clamps fall into two main categories:

1. Strengthening of one or more brace members at a tubular joint against static or fatigue loading. The brace members may be considered to be severed from the original joint or the original joint may be assumed to be intact.
   
   For an illustration see Figure II.5.2.
   
   In this case weld beads may have to be applied to the tubular joint underwater as a means of obtaining the required load transfer from the brace to the clamp.

2. Connecting a new brace member into the structure, in which case the brace member is connected to the structure by means of the grouted clamp only.
   
   For an illustration see Figure II.5.3.
   
   In this case, if weld beads are required, they may be applied to the brace and repair clamp in the fabrication shop prior to installation.

1.5.3 Factors affecting strength

The following factors which may affect the strength and behaviour of grouted clamps have been investigated and design guidance is offered:

1. tubular geometry
2. bolting flanges/bolt loads
3. weld beads
4. grout strength.

1.5.3.1 Tubular geometry

The repair sleeve may be considered as a tubular joint provided the bolting flanges are adequately stressed (see Section 1.5.3.2). The usual parametric formulae may be used to estimate the design static strength of the tubular joint\(^{(5.1, 2, 3)}\).

The design of the repair sleeve will be governed by the usual nondimensional parameters, i.e. \(\gamma\), \(\beta\) and \(\tau\). These may be selected to give the appropriate repair sleeve static strength, but \(\beta\) will be controlled...
mainly by the geometry of the original joint and should not exceed 1.0 as this leads to problems in the application of the SCF parametric equations.

Within the design process it must be decided if the static strength of the original joint may be considered as contributory to the static strength of the entire repair scheme. Where the repair is of the 'addmember type' or is to repair a cracked original joint, then the static strength of the original joint will be ignored. Where the original joint is undamaged, a degree of composite action may be incorporated in the design.

The equations which may be utilised to determine the characteristic static strengths of the original joint and the sleeve are given in References 5.1, 2 and 3. The design of the sleeve is carried out on the following assumptions:

1. the sleeve is proportioned on the assumption that it forms a tubular joint without any additional strengthening from the original joint or any other members within the sleeve
2. the existence of the sleeve flanges is ignored in the calculation of the strength of the tubular joint
3. the brace/sleeve grouted connection and the chord sleeve grouted connections are proportioned in accordance with Section 1.4. assuming that the full design load is transferred through the grouted connection to the sleeve.

The static strength of the 'composite' repair scheme is given by:

\[
\text{static strength} = 1.2 \times \Sigma \text{characteristic static strengths of original joint and sleeve}
\]  \hspace{1cm} (1.5.1)

where the characteristic strength of the original joint alone is calculated using References 5.1, 2 and 3 and the characteristic strength of the sleeve alone is calculated using References 5.1, 2 and 3 and the above stated assumptions.

The static strength obtained in this way is a 95% characteristic lower bound value.

Where the repair is of the 'addmember type' then Equation 1.5.1 reduces to:

\[
\text{static strength} = 1.2 \times \text{characteristic static strength of sleeve}
\]  \hspace{1cm} (1.5.2)

where the characteristic strength of the sleeve alone is calculated using References 5.1, 2 and 3 and the above stated assumptions.

The static strength obtained in this way is a 95% characteristic lower bound value.

1.5.3.2 Bolting flanges/bolt loads

The purposes of the bolting flanges are two-fold:

1. to permit the clamp to be installed in two or more sections around an existing tubular joint within a structure
2. to transfer the bolt tension to the mating faces of the tubular sleeve, thereby maintaining continuity of the repair sleeve section.

The assessment of the required bolt torque/tension relies upon knowledge of the applied stresses and geometry of the grouted connection. The various loads which have to be considered in the design are given in Section 1.5.5, and design guidance is given in Section 1.4.6.4.

1.5.3.3 Weld beads

The weld beads form an integral part of the grouted connection which transfers load from the brace member of the original joint or addmember to the brace member of the repair sleeve.

It is recognised that weld beads may be undesirable in the repair of an original joint due to the cost of underwater welding, however they may be used to economic advantage by reducing the length of an addmember repair scheme since weld beads may be applied at the fabrication stage.
The established design formulae and extensions to them given in Section 1.4 may be applied to the design of the grouted connection.

The application of weld beads with an h/s value of 0.04, for example, increases grout bond stress to a value equivalent to ten times the plain pipe bond stress. A corresponding reduction in the required grouted length results from the increased allowable grout bond stress. A small grouted length may be desirable to avoid a clash with adjacent members or to minimise the clamp weight.

1.5.3.4 Grout strength

The effect of grout compressive strength on the strength of the grouted connection can be conveniently expressed by a parabolic relationship with bond stress \(f_{\text{she}}\) proportional to the square root of grout compressive strength \(f_{c\text{u}}\).

1.5.4 Fatigue

1.5.4.1 Steelwork

The repair sleeve may be treated as a tubular joint, ignoring the flanges, for all load cases except in-plane bending, for the purposes of fatigue design. Recognised standard parametric formulae may be used to estimate the design SCFs, see Tables 1.5.1 to 1.5.3, however under in-plane bending the effect of the flanges must be considered because of their inherent bending stiffness.

The predicted SCFs obtained for axial load and out-of-plane bending can be reduced due to composite action between the repair sleeve and original joint according to the table below.

<table>
<thead>
<tr>
<th>Loading</th>
<th>Actual SCF/predicted SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Replaced joint</td>
</tr>
<tr>
<td></td>
<td>95% confidence</td>
</tr>
<tr>
<td>Axial</td>
<td>0.55</td>
</tr>
<tr>
<td>OPB</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Within the repair sleeve the actual SCF is defined as the ratio between the maximum measured ‘hot spot’ stress in the sleeve and the maximum nominal stress in the brace of the original joint.

The JJRRP programme tested sleeves which were proportioned on the assumption that the sleeve would transmit the full load in the original joint, hence the repair sleeve members are of similar thicknesses to the original joint members. The range of geometries tested is given below:

\[
1.164 \leq \frac{d_{\text{sleeve}}}{d_{\text{joint}}} \leq 1.247 \quad 0.790 \leq \frac{t_{\text{sleeve}}}{t_{\text{joint}}} \leq 1.080
\]

\[
1.098 \leq \frac{D_{\text{sleeve}}}{D_{\text{joint}}} \leq 1.184 \quad 1.000 \leq \frac{T_{\text{sleeve}}}{T_{\text{joint}}} \leq 1.270
\]

Repairs having sleeves with stiffnesses outside these ranges cannot be designed using all of the above SCF multipliers.

A sleeve which is flexible in comparison to an original joint will have minimal composite effect in reducing the SCFs of the joint, however the sleeve SCFs will be greatly reduced by the presence of the comparatively stiff original joint. Similarly, a sleeve which is stiff in comparison to an original joint will have a large composite effect in reducing the SCFs of the joint, however the sleeve SCFs will undergo minimal reduction due to the presence of a comparatively flexible original joint.
A summary of the application of the SCF reductions for repairs outside the validity ranges is given below.

<table>
<thead>
<tr>
<th>Repair scheme</th>
<th>SCFs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original joint</td>
<td>Sleeve</td>
</tr>
<tr>
<td>Stiff sleeve</td>
<td>Composite effect</td>
<td>No composite</td>
</tr>
<tr>
<td>on original</td>
<td>applicable</td>
<td>effect</td>
</tr>
<tr>
<td>joint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeve on</td>
<td>No composite</td>
<td>Composite</td>
</tr>
<tr>
<td>stiff original</td>
<td>effect applicable</td>
<td>effect</td>
</tr>
<tr>
<td>joint</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The values for repair sleeves are independent of whether the original joint is intact or is considered to be of the 'addmember' type.

For in-plane bending the SCFs in the bolting flanges and the tubular joint must be considered separately. The maximum SCF in the flanges occurs at the outside face of the radiused section, while the maximum SCF in the tubular joint occurs close to the crown position, (the maximum SCF does not occur at the crown because the flanges carry the load at that location).

The SCF for the repair sleeve under in-plane bending is reduced by a greater degree compared to the predicted value than for either axial load or out-of-plane bending.

The predicted SCF obtained for the tubular joint portion of the sleeve under in-plane bending can be multiplied by a factor of 0.4, which is an upper bound value, to account for the effect of the bolt flanges.

The SCF in the radiused section of the bolt flanges for in-plane bending is calculated based upon the following equation:

\[ K' = 1.3K^* \sin \theta \text{ (flange property factor)} \]  

\[ (1.5.3) \]

where \( K^* \) = the flange detail SCF based on standard solutions presented by Hartman and Levin\(^{[5]}\) which are reproduced in Figures 1.5.4 and 1.5.5

\( \theta \) = the angle of intersection between the brace and the chord

flange property factor = nominal flange cross-sectional area/reduced flange cross-sectional area at bolt holes.

The information required to calculate \( K^* \) is illustrated in Figure 1.5.6.

The maximum stress in the radiused section of the sleeve bolt flanges can be expressed as:

\[ \text{maximum stress} = K' \sigma_{\text{SFB, nom}} \]  

\[ (1.5.4) \]

where \( \sigma_{\text{SFB, nom}} \) = the maximum nominal stress in the sleeve flanges based on the full composite section and using simple bending theory.

The maximum hot spot stress range is calculated in the usual manner by multiplying the nominal brace stress at the tubular joint (axial, IPB or OPB) by the appropriate reduced SCF for the position on the tubular joint under consideration and summing those components which are coincident at that location, see section 1.5.5.

The tests undertaken in this programme have shown that the family of S-N curves provided by design codes adequately represent a lower bound estimate of fatigue life using the hot spot stress range extrapolated to the toe of the tubular joint weld. Examples of such curves are the Department of Energy T curve\(^{[6]}\) or the API X curve\(^{[7]}\).

The fatigue life of the radiused section of the flange can be estimated using the appropriate parent metal S-N curve. It is recommended that S-N curve type C, as defined in Table 6.6 of BS 6235\(^{[8]}\), be adopted since this allows for fatigue induced by surface corrosion; the equivalent S-N curve given in the AWS Code\(^{[9]}\) is type C.
The bolt holes should be checked by determining the stress range at the bolt hole (taking account of the SCF appropriate to the hole geometry) and comparing this with the type C S-N curve.

Initial cracking does not cause significant increases in local joint flexibility since there are a number of alternative load paths available. Indeed, there are significant post-cracking reserves of stiffness which can be relied upon until cracks have propagated at a number of locations. This effect can be seen in the load-deflection plots obtained during the fatigue tests, which are presented in Volume IV of this document (see microfiches).

1.5.5 Applied stresses

1.5.5.1 Grouted connections

There are two grouted connections to be designed in a T joint grouted clamp; they are the brace grouted connection and the chord grouted connection. Figure 1.5.7 illustrates the brace loads which are to be given consideration in the design of the various connections. The brace bolts maintain the continuity of the brace sleeve under the applied brace loading and the chord bolts maintain the chord sleeve continuity under the components of brace load appropriate to the chord connection.

In the case where damage has been so extreme that the chord wall strength has been impaired, for example due to cracking on the chord side of the weld, the chord clamp may have to re-instate the full load-carrying capacity of the chord; in this case Figure 1.5.8 illustrates which chord loads are to be treated. Within the design of the clamp it should be remembered that the portion of the clamp on each side of the damaged area should be proportioned to carry the full chord load.

1.5.5.2 Steelwork fatigue

The stress distributions under axial and bending modes around the periphery of the brace/chord intersections may be estimated using the following approach:

1. compute SCFs at the crown and saddle for each loading mode for the original joint and sleeve using the recommendations of Section 1.5.4
2. assume a simplified stress distribution in the absence of finite element analysis or model tests
3. obtain SCFs at equi-angular points between the saddle and crown for the original joint and sleeve, hence defining eight points on the periphery with known SCFs
4. compute stresses at each of the eight points by using the principle of superposition.

The recommended stress distribution in Step 2 is defined below. For a point around the periphery of the intersection at an angle of $\phi^\circ$ away from the saddle point the ‘hot spot’ stress under combined loading is given by:

$$f_{hs} = \left[ SCF_s - \left( SCF_s - SCF_c \right) \frac{\psi}{90} \right] f_{ax} + SCF_s \sin \psi f_{sx} + SCF_s \cos \psi f_{so}$$  \hspace{1cm} (1.5.5)

where

- $f_{hs}$ = ‘hot spot’ stress
- $SCF_s$ = SCF at saddle
- $SCF_c$ = SCF at crown
- $\psi$ = angle from point under consideration to the saddle point, in degree
- $f_{ax}, f_{sx}, f_{so}$ = stresses in brace member of original joint or addmember.

The ‘hot-spot’ stress ranges can then be determined for each position around the joint. The ‘hot-spot’ stress ranges for each wave height and direction are then computed and the damage that occurs from each load application is summed using the Miner Cumulative Damage hypothesis to give the cumulative damage due to the entire loading spectrum.
I.5.6. Safety factors

This section presents the factors of safety appropriate in the use of design recommendations presented for static strength and fatigue considerations.

I.5.6.1 Static strength of tubular joints

A partial safety factor approach is outlined in Section II.5.6.1. The combination of the partial safety factors produces global safety factors which are summarised below:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Global safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>1.38</td>
</tr>
<tr>
<td>Operating</td>
<td>1.78</td>
</tr>
</tbody>
</table>

These are consistent with current safety margins quoted in the background publications to API RP2A, ie a safety factor of 1.8 for normal loads and 1.38 for extreme loads when these safety factors are based on lower bound strengths of test results.

I.5.6.2 Static strength of grouted connections within grouted clamps

The recommendations given for static strength are based upon the Department of Energy Guidance Notes\(^6\) for grouted connections.

The permissible working bond stress is determined by dividing the characteristic bond strength of the grouted connection calculated from the recommendations of Section I.4 by the appropriate safety factor given below (these are consistent with those given in the UK Department of Energy Guidance on ‘Grouted pile/sleeve connections’):

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>4.5</td>
</tr>
<tr>
<td>Operating</td>
<td>6.0</td>
</tr>
</tbody>
</table>

I.5.6.3 Fatigue life of steelwork and tubular joints

Calculations of fatigue lives are made based on calculated stress ranges using design SCFs and design S-N curves. This approach has an implicit factor of safety since design SCFs are typically 95% characteristic upper bounds and design S-N curves are typically minus two standard deviations from the mean or 97.7% probability of survival.

The usual approach is to calculate the cumulative fatigue damage and limit it to a value of 1.0 for the design life of the structure. The limiting value for cumulative damage depends on the degree of conservatism in the calculation, reliability of corrosion protection, degree of structural redundancy and ease of inspection or repair. Should uncertainties exist with respect to these or other matters then the limiting value for cumulative fatigue damage should be reduced.

I.5.6.4 Fatigue endurance of grouted connections within grouted clamps

A grouted connection which is designed in accordance with Section I.5.6.2 will not experience a fatigue failure, since at no time will the acting bond stress exceed the fatigue endurance limit.
<table>
<thead>
<tr>
<th>NO</th>
<th>joint type and load case</th>
<th>chord single scf</th>
<th>chord crown scf</th>
<th>validity range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3</td>
<td>( \frac{0.25 \gamma}{\beta} - \sin^2 \gamma )</td>
<td>[ \frac{\sin \gamma}{\sin^2 \beta} ]</td>
<td>( 2.5 &lt; \alpha &lt; 40 )</td>
<td>22.0 &lt; ( \gamma &lt; 37.4 )</td>
</tr>
<tr>
<td>2:2</td>
<td>( \frac{0.25 \gamma}{\beta} - \sin^2 \gamma )</td>
<td>( \frac{0.25 \gamma}{\beta} - \sin^2 \gamma )</td>
<td>( 0.13 &lt; \beta &lt; 1.00 )</td>
<td>0.25 &lt; ( \gamma &lt; 37.4 )</td>
</tr>
<tr>
<td>3:3</td>
<td>( \frac{0.25 \gamma}{\beta} - \sin^2 \gamma )</td>
<td>( \frac{0.25 \gamma}{\beta} - \sin^2 \gamma )</td>
<td>( 0.13 &lt; \beta &lt; 1.00 )</td>
<td>0.25 &lt; ( \gamma &lt; 37.4 )</td>
</tr>
</tbody>
</table>

**Notes:**
1. \( \phi \beta = 1 \) for \( \beta < 0.6 \) and \( \phi \beta = 0.7 \) for \( \beta > 0.6 \); \( \phi \gamma = 1 \) for \( \gamma < 10.0 \) and \( \phi \gamma = 4.00 \) for \( 20 < \gamma < 37.4 \) \( \gamma > 60.0 \).
2. For 1/3 joints where \( \phi \beta > 0.25 \) formulae for SCFs refer to brace 1 and are based on nominal stress in brace 1.
3. For brace SCF use \( SCF = 1 - 0.63 SCF \).
4. The SCFs are limited to a minimum of 2.5.
5. The chord length can be taken as the distance between points of contraflexure on the chord.
6. Formulae based on Tebwe and Lalani (10).
### Table I.5.2  Characteristic SCF formulae for in-plane moment loaded simple joints

<table>
<thead>
<tr>
<th>JOINT TYPE AND LOAD CASE</th>
<th>CHORD CROWN SCF</th>
<th>VALIDITY RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Joint Diagram" /></td>
<td><img src="image" alt="Equation" /></td>
<td><img src="image" alt="Validity" /></td>
</tr>
</tbody>
</table>

**NOTES:** (1) Notes (1), (3), (4) and (6) of Table I.5.1 are applicable

(2) For DT joints, γ range can be increased to 0.0 ≤ γ < 37.4

### Table I.5.3  Characteristic SCF formulae for out-of-plane moment loaded simple joints

<table>
<thead>
<tr>
<th>JOINT TYPE AND LOAD CASE</th>
<th>CHORD SADDLE SCF</th>
<th>VALIDITY RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Joint Diagram" /></td>
<td><img src="image" alt="Equation" /></td>
<td><img src="image" alt="Validity" /></td>
</tr>
</tbody>
</table>

**NOTES:** (1) \( q_1, q_2 \), as defined in Table I.5.1

(2) Notes (1), (3), (4) and (6) of Table I.5.1 are applicable
Figure I.5.1  Typical grouted clamp for T joints
Figure I.5.2  Composite/adjacent T joint clamps

Figure I.5.3  Clamp connecting new brace member into a structure
Figure 1.5.4  *Factors of stress concentration K plotted against L/D (D/d = 2)*
Figure 1.5.5  Factors of stress concentration $K$ plotted against $L/D$ ($D/d = 3$)
Figure I.5.6  Clamp idealisation for calculation of K factor in assessment of bolt flange SCF

Figure I.5.7  Brace member loads to be considered in the design of grouted clamp
FOR CHORD CLAMP DESIGN THE BRACE LOADS ARE NOT REQUIRED SINCE THEY ARE INCLUDED IN THE CHORD LOADS PRODUCED BY THE STRUCTURAL ANALYSIS.

Figure I.5.8  Chord member loads to be considered in the design of a grouted clamp which reinstates the strength of a damaged chord.
1.6 MECHANICAL CONNECTIONS

1.6.1 Introduction and definitions

A mechanical connection is a connection formed between two concentric tubular members (the inner chord member being a complete circular section and the outer being formed from two or more saddles) which are stressed, by means of 'long' studbolts, onto the inner member.

The saddles forming the less-than-180° segments of the outer tubular are stiffened to allow the stud forces to be carried without distress to the saddle itself or the inner chord member. The design guidance given in this section only considers connections which have 'continuous top plates' as shown in Figure I.6.1.a. Special consideration should be given to connections such as shown in Figure I.6.1.b which have 'discontinuous top plates' as they are not covered by existing test data.

The strength of a mechanical connection is obtained from the steel-to-steel friction which is developed by means of the stressed studs applying a normal compressive force on the chord/saddle interface. Therefore, the strength obtained is dependent on the magnitude of the normal force and the coefficient of friction between the two contact surfaces.

Long studbolts are used for tensioning mechanical connections instead of the short, high strength, friction type bolts used on split sleeve grouted connections. The reason for this is that in a split sleeve grouted connection it is the flange faces which are being stressed together and therefore sufficient prestress can be applied to the flanges to reduce fluctuating stresses to negligible magnitudes. However, in a mechanical connection the segments of the clamp are not stressed directly together but are connected by a relatively flexible member (ie the chord) compared to a rigid steel-to-steel flange contact. Therefore, Poisson strains in the chord or external forces on the connection, which reduce the saddle/chord contact pressure, will cause fluctuating strains in the studbolts. Increasing the studbolt length reduces the magnitude of the strain for a given change in diameter of the chord and hence reduces the possibility of the nuts loosening and studbolt fatigue damage.

The research into the strength of mechanical connections performed in the JIRR project complemented a small series of tests commissioned by Occidental of Britain Inc in 1980. In addition two separate testing programmes commissioned by George Wimpey PLC and Shell, BP, Todd (SBPT) on the friction between steel-to-steel plates with various surface conditions have been valuable in producing design guidance for underwater repairs.

The design guidance given in this section on mechanical connections is based on the engineering assessment of the available data contained in Part II, Section I.6 of this document.

1.6.2 Applications

The major uses for mechanical connections are for transferring loads between structural elements as described below:

1. For connecting two parts of a member together to form a continuous structural element, see Figure I.6.2.a.

2. For connecting a new member into a structure, the new member being welded onto the saddle of the connection. This is the most common use of a mechanical connection and is shown in Figure I.6.2.b.

The major advantage of a mechanical connection is that large forces can be transferred through friction, over a short contact length. Therefore they are very useful when space is limited. However, because mechanical connections rely on close tolerance steel-to-steel contact surfaces their uses are limited to the situation where this can be achieved.

If, for example, a new member was to be placed into a structure between two fixed points it would not be advisable to use mechanical connections at both ends of the member without providing a method
for increasing or reducing its length and/or changing the angle. Thought should be given to tolerances such as pipe ovality when assessing the results of underwater surveys.

1.6.3 Factors affecting the strength of mechanical connections

The following factors which may affect the strength and behaviour of mechanical connections have been investigated and design guidance is offered on these:
1. surface condition
2. connection length
3. chord geometry
4. stud geometry.

1.6.4 General recommendations

The design guidance given in the following sections is for mechanical connections with ‘continuous top plates’ and employing ‘long’ studbolts.

The use of short studbolts is not recommended as this is likely to lead to fatigue failures and/or loss of prestress due to the untightening of the nuts.

If it is considered advantageous to use a ‘discontinuous top plate’ connection for reasons of economy then care should be taken to ensure that the bolt force will not collapse both the saddle and chord. In the absence of any other data the coefficient of friction may be taken as 0.25. This value has been generally accepted and used in previous designs.

1.6.5 Static coefficient of friction for mechanical connections

a. The characteristic static coefficient of friction for a mechanical connection satisfying 1.6.6 may be taken as:

\[ \mu_c = 0.18 \left[ 1 + 20 \left( \frac{D}{T} \right)^{-1} \right] (1 + 66K_b)C_s^* \]  \hspace{1cm} (1.6.1)

where \( \mu_c \) is the characteristic coefficient of friction
\( D \) is the chord diameter (mm)
\( T \) is the chord thickness (mm)
\( K_b \) is the studbolt stiffness factor, see b below
\( C_s^* \) is the surface condition factor, see c.

A design chart is given in Figure 1.6.3 for \( C_s^* = 1.0 \).

b. The studbolt stiffness factor \( K_b \) is defined by:

\[ K_b = \frac{nA_sE_s}{2L_bL_s} \]  \hspace{1cm} (1.6.2)

where \( n \) is the number of studbolts in the connection
\( A_s \) is the area of a studbolt (shaft area)
\( E_s \) is the Young’s modulus of the studbolt material
\( L \) is the length of the connection
\( L_b \) is the stressed length of the studbolt (nut to nut face)
\( E_s \) is the Young’s modulus of the chord steel.
c. The surface condition factor, in the absence of other data, should be taken according to the following:

1. For mechanical connections installed above water with the saddle contact surface grit blasted to BS 4232: surface profile 50–60 microns (average):
   
<table>
<thead>
<tr>
<th>Chord surface condition</th>
<th>$C_i^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grit blasted</td>
<td>1</td>
</tr>
<tr>
<td>Mill scale</td>
<td>0.85</td>
</tr>
<tr>
<td>Coal tar epoxy</td>
<td>0.60</td>
</tr>
</tbody>
</table>

2. For mechanical connections installed below water cleaned in accordance with Section 1.6.6.2.(4):
   
<table>
<thead>
<tr>
<th>Chord surface condition</th>
<th>$C_i^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both contact surfaces grit blasted to BS 4232</td>
<td>0.85</td>
</tr>
<tr>
<td>Surface profile 50–60 micron (average) with a maximum of 72 hours exposure after grit blasting.</td>
<td></td>
</tr>
</tbody>
</table>

### I.6.6 Ranges of applicability and other requirements

#### I.6.6.1 Geometric requirements

The relationship given in Equation I.6.1 may only be applied to connections which satisfy the geometric limits given below. In addition the requirements of Section I.6.6.2 shall also be satisfied. The notation is illustrated in Figure I.6.4.

- chord geometry: $20 \leq D/T \leq 50$
- connection length to diameter ratio: $0.5 \leq L/D \leq 2.0$
- studbolt* stiffness factor: $0.002 \leq K_6 \leq 0.010$

* Whilst limits on the structural components of the connection are given these components should also be in accordance with the relevant design method.

These limitations should not be taken to exclude the use of connections outside the stated ranges providing that it is demonstrated that the strength of such connections can be reliably estimated. Connections with chord D/T ratios below the lower limits (i.e. more radially stiff) can be conservatively designed by assuming the limiting D/T ratio in calculations. Alternatively test data may be used as the basis for design. However, care must be taken in using the results of limited test programmes to provide a characteristic coefficient of friction equivalent to that given in Equation I.6.1. Guidance is given in Part II, Section II on the use of additional data to support a design.

#### I.6.6.2 Further requirements

1. The characteristic coefficient of friction should not exceed the maximum allowable coefficient of friction defined as:

$$\mu_{\text{max}} = 0.45C_i^*$$

$$\mu \leq 0.45C_i^*$$  \hspace{1cm} (I.6.3)

2. The saddle should be formed from a stiff fabrication having a continuous top plate.

3. Long stud bolts should be used.

4. The maximum exposure period after grit blasting to bare steel should be limited to 72 hours prior to installation of the connection. All 'gel-like' corrosion products which develop in the period between grit blasting and installation should be cleaned off immediately prior to installation.

5. All studbolts in a connection should be of similar dimensions and should be stressed to the same load, therefore the gross studbolt load may be expressed as:
\( F = n \times p \)  

where \( F \) is the gross studbolt load  
\( p \) is an individual studbolt load.

6. The studbolt load (p) should be designed not only to prevent static friction failure of the connection by satisfying the recommendations of Section 1.6.7, but also to ensure that a positive contact pressure is maintained over the full length of the connection during all combinations of loading. This will ensure that the studbolts are not overstressed statically. To achieve this it is recommended that the potentially highest studbolt load is identified and a load at least 1.2 times greater be applied to all studbolts. (NB. This factor of 1.2 is independent of the safety factor on friction capacity and, depending on the moment loading applied to the saddle, this condition may determine the studbolt force and not the friction capacity.)

7. A check should be made on the hoop stresses that develop in the inner (chord/brace) member of a connection at the position between the longitudinal gap in the connection segments, this stress being induced by tensioning of the studbolts.

### 1.6.7 Permissible working loads

In determining the permissible working load per effective friction surface for a mechanical connection the following recommendations should be applied.

1. The permissible load per effective friction surface perpendicular to the normal interfacial contact force should be limited to:

\[
p_x = \frac{F_n \mu_c}{\Gamma_p} \tag{1.6.5}
\]

where \( p_x \) is the permissible load perpendicular to the normal interfacial contact force  
\( F_n \) is the net contact force  
\( \mu_c \) is the characteristic coefficient of friction  
\( \Gamma_p \) is the safety factor on frictional capacity, see Section 1.6.8.

2. The permissible prestress in the studbolts should be limited to 0.6\( F_y \) for service conditions.

### 1.6.8 Safety factors

In determining the permissible working load from Equation 1.6.5 the following safety factors on the frictional capacity \( \Gamma_p \) may be applied in the absence of any other guidance:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>1.70</td>
</tr>
<tr>
<td>Operating</td>
<td>2.25</td>
</tr>
</tbody>
</table>

### 1.6.9 Applied loads

When comparing the applied load perpendicular to the normal interfacial contact force with the permissible load the net normal contact force \( (F_n) \) shall be considered.

The net normal contact force \( (F_n) \) is defined as the contact force provided by the prestressed studbolts minus any external forces which tend to reduce it.

Consideration should be given to all six components of load acting on a mechanical connection with respect to their effect on the strength of the connection, the studbolt loads and the steelwork.
I.6.10 Fatigue

See Section I.7.4

I.6.11 Studbolt load attenuation

No data is available on load attenuation of studbolts used in mechanical connections. Results from tests on stressed grouted connections (see Part II, Section II.8.2.5) suggest that observed losses were due entirely to grout shrinkage and therefore it is expected that losses in mechanical connections will be minimal. A small excess preload may be applied if desired to compensate for these losses.

Figure I.6.1 Mechanical connection

Figure I.6.2 Uses of mechanical connections
Figure 1.6.3  Design chart giving the characteristic coefficient of friction at $C_s^* = 1.0$
Figure I.6.4  Top plate mechanical connection
1.7 MECHANICAL CLAMPS

1.7.1 Introduction and definitions

A mechanical clamp is a clamp in which the outer sleeve is formed in two or more segments which are placed around a tubular joint. The clamp body is formed from two or more segments which are stressed together to provide the load path between the clamp and the joint.

The stressing together of the clamp body is achieved by long studs between widely spaced flanges.

Mechanical clamps may be of the ‘addmember’ type which connects a new member at an inclined angle to an existing tubular; or they may be used to strengthen an existing tubular joint in which the original joint is considered to have failed.

Designers wishing to use mechanical clamps should also refer to Section 1.6 ‘Mechanical connections’.

The various components of a mechanical clamp are illustrated in Figure 1.7.1.

1.7.2 Applications

The applications of mechanical clamps fall into two main categories:

1. Strengthening of one or more brace members at a tubular joint against static or fatigue loading. The brace members may be considered to be severed from the original joint or the original joint may be assumed to be intact.

2. Connecting one or more new members at an inclined angle into an existing structure or tubular joint. Additional members may also be connected into a structure using a stressed grouted clamp (see Section 1.9).

For an illustration of these applications see Figure 1.7.2.

A mechanical clamp requires no grout and therefore the fabrication and installation is quicker than for an equivalent stressed grouted clamp. A disadvantage of this type of clamp is that an accurate survey of the existing joint is required before fabrication; and the fabrication must be very carefully controlled to avoid possible fit up problems due to pipe ovality etc during installation. Typical dimensions which would have to be verified in a survey are given in Figure 1.7.3.

1.7.3 Factors affecting the strength of mechanical clamps

The following factors which may affect the strength and behaviour of mechanical clamps have been investigated and design guidance is offered:

1. mechanical connections
2. steelwork design
3. stud-bolt load losses
4. stressing sequence.

1.7.3.1 Mechanical connections

Each portion of the clamp may be considered to be an individual mechanical connection for the purpose of estimating the coefficient of friction between the existing brace or chord and the clamp body.

Reference should be made to Section 1.6 for recommendations on the design of mechanical connections.
The calculation of studbolt load can be made once the brace forces have been resolved into those terms which require friction for their transfer and those which do not, see Section 1.7.5. For example, a T joint clamp, whether constructed in two or more parts, normally has two friction surfaces in contact with an incoming brace member. Benefit may be taken from this fact in determining the required studbolt load, by assuming that the resolved brace forces may be taken equally by the two friction surfaces, as both will be equally effective.

Continuous top plate clamps must be used if the benefits from improved coefficients of friction given in Section 1.6 are to be allowed. If the use of discontinuous top plate clamp is considered beneficial then a coefficient of friction of 0.25 may be used in the absence of any other data. This value has been generally accepted and used in previous designs.

I.7.3.2 Steelwork design

Once the studbolt load has been determined, the steelwork in the mechanical clamp can be designed.

The clamp steelwork may be designed to resist the stud bolt loads using normal structural analysis and the design stresses given in the AISC Manual17.3.

The clamp should be designed to be stiff in comparison to the tubular joint for the following reasons:

1. the stiffer the clamp the more brace load it attracts with all the corresponding benefits to the existing joint
2. a stiff clamp reduces the stud bolt load fluctuations which minimises the possibility of fatigue therein
3. a stiff clamp reinstates a damaged joint to the original rigid state assumed in the structural analyses.

There are a number of potential disadvantages with stiff clamps which should be given proper consideration:

1. a stiff clamp will attract extra wave loading and impose a greater dead load on the structure than, say, a flexible type clamp
2. a stiff clamp will attract greater framing loads than did the original joint which, although it was assumed to be rigid in the analysis, in reality has more local joint flexibility than a stiff clamp.

Load distribution through the brace portion of the clamp may be estimated using the composite section since the friction interface has a very high stiffness up to near the slip load. A direct path for the brace top plate stress into the chord saddle should be provided by ensuring that the brace top plates coincide with either the chord top plates for a two part clamp or the chord side plates for a three part clamp (see Figure 1.7.1). In this way the secondary plate bending stresses are minimised.

If discontinuous top plate clamps are used care must be taken to avoid collapse of the saddle and chord by transverse bending due to the studbolt load.

I.7.3.3 Studbolt load losses

Losses in studbolt loads can be divided into two categories based upon the time at which they occur:

1. short term (immediate) losses (eg bedding down of threads at transfer and top plate bending).
2. long term losses (eg relaxation).

Short term losses due to bedding down can be reduced by adopting a stressing procedure which involves repeated bolt stressing operations. Short term losses due to top plate bending can be minimised by using stiff top plates or thick washers, see Part II, Section II.7.3.3.

Long term losses were found to be small in this programme. However, an excess preload may be appropriate in actual applications.
I.7.3.4 Stressing sequence

It has already been stated that this type of clamp is sensitive to fabrication errors and tolerances. The sequence of stressing has some bearing upon the effective friction developed between the brace and the clamp. The primary purpose of this type of clamp is to provide an alternative load path to the tubular weld in the existing joint. It is, therefore, essential that a proper connection is made between the brace and the clamp; to this end it is recommended that the brace clamp studbolts be stressed up to their full load before any load is placed in the chord stud bolts. This ensures that the clamp firmly grips the brace member, and any effects of chord ovality are removed. The chord clamp studbolts can then be stressed, before giving the brace studbolts a final recheck.

The chord clamp is less critical since the major component of brace load in a T-joint is usually axial load, for which friction is not required in the chord clamp. If, however, the chord clamp is additionally required to strengthen the chord then it is important that an accurate survey is performed to ensure that all mating surfaces are in full contact.

I.7.4 Fatigue

I.7.4.1 Fatigue of the original joint

A linear relationship appears to exist between the values of SCF_{repaired joint} / SCF_{predicted for unrepaired joint} and joint brace section properties/composite brace section properties for axial load and bending.

Expressions have been developed which give 95% confidence upper bounds to the values of SCF_{repaired joint} / SCF_{predicted for unrepaired joint} for axial load and bending loads. The derivation of the expressions is given in Part 2, Section 7.

For axial loads:

\[
\frac{SCF_R}{SCF_U} = 0.73 \frac{A_J}{A_C}
\]  

For bending loads:

\[
\frac{SCF_R}{SCF_U} = 2.17 \frac{l_J}{l_C} \quad \text{but with a maximum value of 1.0}
\]  

where

- SCF_{R} = SCF in repaired joint
- SCF_{U} = SCF predicted for unrepaired joint based on parametric equations
- A_{J} = joint brace section area
- A_{C} = composite brace section area
- I_{J} = joint brace second moment of area
- I_{C} = composite brace second moment of area.

The composite brace section properties are defined here as the sum of the appropriate joint brace section property and the clamp brace section property.

The difference in the coefficients in Equations I.7.1 and I.7.2 reflects the efficiency of this type of clamp in restraining global chord wall deformation caused by brace axial loads, in comparison to the less efficient, but still substantial, way in which this type of clamp restrains local chord wall deformations caused by brace bending loads.

The value of SCF_{repaired joint} / SCF_{predicted for unrepaired joint} should not exceed 1.0 for any load case, since that would imply that a clamp is having a negative composite effect on the original joint.

The SCFs determined for a repaired joint may be treated in the same way as SCFs for an unrepaired joint in the determination of stress ranges and fatigue lives. The commonly used tubular joint weld S-N curves eg API X curve and DEn T curve are applicable to repaired joints.
1.7.4.2 Fatigue of the clamp

Details of the clamps tested are given in Figure 1.7.3. Elastic tests indicated that within this type of clamp the maximum stresses occurred at the corner of the intersection of the brace top plate with the chord top plate. The maximum measured stress in the clamp steelwork can be expressed as a ratio of the nominal clamp stress; this ratio will be called the Stress Multiplier. For mechanical clamps of the type shown in Figure 1.7.4 typical Stress Multipliers are:

<table>
<thead>
<tr>
<th>Load type</th>
<th>Stress Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial load</td>
<td>3.8</td>
</tr>
<tr>
<td>OPB</td>
<td>3.2</td>
</tr>
</tbody>
</table>

For clamps of other geometries than those tested a finite element analysis would be an appropriate method of calculating the Stress Multipliers. Alternatively, standard solutions for shoulders, fillets, radii, etc. may be applied to the calculated nominal stress, to arrive at the maximum local stress.

The cracks which formed during fatigue tests propagated along the weld between the brace top plate and chord top plates. Through thickness cracking in the chord top plate did not occur, therefore a crack depth of 0.5 mm was taken as being indicative of significant cracking.

Prediction of the life at which a crack reaches a depth of 0.5 mm can be carried out conservatively using an appropriate weldment mean S-N curve, type F in this case. Consequently a design for a ‘no-cracking’ situation can be achieved using a mean minus two standard deviation design S-N curve.

1.7.4.3 Fatigue of studbolts

The stress range in the studbolts should be determined taking account of the appropriate elasticity of the tubular members and local joint flexibility of the tubular joints. The use of long bolts is essential to minimise stress variations. The maximum nominal stress range obtained in the JIRRP tests was 17.5 N/mm² which is below the endurance limit of all commonly used bolting materials, at typical allowable studbolt tensions, for fatigue tests carried out in air.

1.7.4.4 Fatigue of the friction surfaces

The friction surface is very stiff for loads up to approximately 90% of the static failure load at which point slip commences. Therefore, see the section on mechanical connections in Volume III (in the microchips). Hence, for loads of less than 90% of the static failure load there is no surface damage due to the repeated loading (e.g. fretting). The allowable storm design load represents 59% of the static failure load, hence for repeated loading of amplitude less than 59% of the static failure load there will be no fatigue failure of the friction surfaces.

1.7.5 Applied stresses

1.7.5.1 Mechanical connections

There are two mechanical connections to be designed in a T joint mechanical clamp; they are the brace mechanical connection and the chord mechanical connection. Figure 1.7.5 illustrates the brace loads which are to be given consideration in the design of the various connections.

The brace bolts maintain the normal force between the brace and brace clamp which is required to transfer the brace loading into the brace clamp. The chord bolts maintain the normal force between the chord and chord clamp required to transfer the components of brace load appropriate to the design of the chord clamp.
I.7.5.2 Fatigue of original joint

The stress distributions under axial and bending loads around the periphery of the brace/chord intersection of the original joint may be estimated using the following approach:

1. Compute SCFs at the crown and saddle for each loading type using the recommendations of Section I.7.4.
2. Assume a simplified stress distribution in the absence of a finite element analysis or model tests.
3. Obtain SCFs at equiangular points between the saddle and crown, hence defining eight points on the periphery with known SCFs.
4. Compute stresses at each of the eight points by using the principle of superposition.

The stress distribution outlined in Section I.5.5 should be used in the absence of a finite element analysis or model tests.

I.7.6 Safety factors

This section presents the safety factors appropriate for use with the design recommendations presented for static strength and fatigue.

I.7.6.1 Static strength of steelwork

No data are available to evaluate the static strength of an original joint repaired by a mechanical clamp. Therefore the clamp must be conservatively designed to withstand the full brace member loads without load sharing with the original joint or composite action.

The clamp steelwork is to be designed using normal structural theory and allowable stress methods to resist the applied brace and studbolt loads using the permissible stresses given in the AISC Manual[7,11] with the inbuilt factors of safety (1.67 for axial stresses and 1.52 for bending stresses for operating conditions and a one third increase for storm conditions).

The portion of the mechanical clamp where the tubular saddles intersect should be designed as a tubular joint using the safety factors given in Section I.5.6.1.

I.7.6.2 Static strength of mechanical clamps

In determining the net contact force required to develop the friction force the safety factors given below may be used in the absence of any other guidance:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremes</td>
<td>1.70</td>
</tr>
<tr>
<td>Operating</td>
<td>2.25</td>
</tr>
</tbody>
</table>

I.7.6.3 Fatigue

The fatigue design of the steelwork should be carried out in accordance with the relevant steel design methods.
Figure I.7.1  Typical mechanical clamp for T joints
Figure I.7.2  Applications of a mechanical clamp

Figure I.7.3  Typical dimensions to be verified in a survey prior to fabrication of a mechanical clamp
Figure 1.7.4  Three-part mechanical clamp
DETAIL 1  TYPICAL GUSSET PL DETAIL

IMPORTANT NOTE
SADDLE 16.5 MUST BE VERY ACCURATELY FORMED TO MATE WITH THE TUBULARS PROBABLY INVOLVING FIT-UP TESTS

Figure I.7.4  (continued)
**Figure I.7.5** 
**Brace member loads to be considered in the design of a mechanical or stressed grouted clamp**
I.8 STRESSED GROUTED CONNECTIONS

I.8.1 Introduction and definitions

A stressed grouted connection is a connection formed between two concentric, or near concentric, tubular members (the inner chord member being a complete circular section and the outer being formed of two or more saddles) when a cementitious material is injected into and allowed to cure in an annular space provided between them before an inward radial prestress is applied to the connection by means of 'long' studbolts.

The saddles forming the less-than-180° segments of the outer tubular are stiffened to allow the studbolt forces to be carried without distress to the saddle itself or the inner chord member. The design guidance given in this section only considers connections which have 'continuous top plates' as shown in Figure I.8.1.a. Special consideration should be given to connections such as shown in Figure I.8.1.b which have 'discontinuous top plates' as they are not covered by existing test data.

The strength of a stressed grouted connection is obtained from a combination of 'bond' (apparent adhesion) as for grouted connections and the grout-to-steel friction developed by means of the stressed studs applying a normal compressive force on the grout/chord interface. Therefore, the strength is dependent on both the contact area and the normal force applied to the contact surfaces.

Long studbolts are used for tensioning stressed grouted connections instead of the short, high strength, friction type bolts used on split sleeve grouted connections. The reason for this is that in a split sleeve grouted connection it is the flange faces which are being stressed together and therefore sufficient prestress can be applied to the flanges to reduce fluctuating stresses to negligible magnitudes. However, in stressed grouted connections the segments of the clamp are not stressed directly together but are connected by a relatively flexible member, compared to a rigid steel-to-steel flange contact. Therefore, Poisson strains in the chord or external forces on the connection which reduce the saddle/chord contact pressure will cause fluctuating strains in the studbolts. Increasing the studbolt length reduces the magnitude of the strain for a given change in diameter and hence reduces the possibility of nuts loosening and stud fatigue damage.

The research into the strength of stressed grouted connections performed in the JIRRP project complemented a small series of tests commissioned by Occidental of Britain Inc in 1980.

The design guidance given in this section on stressed grouted connections is based on the engineering assessment of the available data contained in Part II, Section II.8 of this document.

I.8.2 Applications

The major uses for stressed grouted connections are for transferring loads between structural elements as described below:

1. For connecting two parts of a member together to form a continuous structural element, see Figure I.8.2.a.

2. For connecting a new member into a structure; the new member being welded onto the saddle of the connection, see Figure I.8.2.b.

The major advantage of stressed grouted connections is that they are the most efficient of the mechanical repair methods available, offering load transfer in short contact lengths. They also overcome the tolerance problems associated with mechanical connections as the grout annulus can accommodate small surface irregularities, such as for example an anode connection doubler plate.
1.8.3 Factors affecting the strength of stressed grouted connections

The following factors that may affect the strength and behaviour of a stressed grouted connection have been investigated and design guidance is offered on these:

1. surface condition
2. connection length
3. chord geometry
4. stud geometry
5. grout strength.

1.8.4 General recommendations

The design guidance given in the following sections is for stressed grouted connections with 'continuous top plate' and employing 'long' studbolts.

The use of short studbolts is not recommended as this is likely to lead to fatigue failures and/or loss of prestress due to the unlightening of the nuts.

If it is considered advantageous to use a 'discontinuous top plate' connection for reasons of economy then care should be taken to ensure that the bolt force will not collapse both the saddle and chord.

1.8.5 Static strength of a stressed grouted connection

a. The characteristic slip strength per effective slip surface of a stressed grouted connection satisfying Section 1.8.6 may be taken as:

\[
P_s = 0.22 \left[ F_n C_s + 1.75 \times 10^{-3} AC_s \right] 1 + 33 \left( \frac{D - 1}{T} \right)
\]

where:
- \( P_s \) is the characteristic slip strength per effective slip surface (kN)
- \( D \) is the chord diameter (mm)
- \( T \) is the chord thickness (mm)
- \( F_n \) is the net normal contact force (kN)
- \( A \) is the bond area of the slip surface being mobilised (mm²)
- \( C_s \) is the surface condition factor for the bond component, see b. below
- \( C_s^f \) is the surface condition factor for the friction component, see b. below.

b. The surface condition factors, in the absence of other data, should be taken according to the following:

1. Stressed grouted connections installed above water with the saddle contact surface grit blasted to BS 4232 surface profile 50–60 microns (average):
   - Chord surface condition (bond) \( C_s \)
   - Grit blasted \( 1.00 \)

   Where it is proposed not to remove surface coatings, investigations will be required to determine the value of \( C_s \) to be used:
   - Chord surface condition (friction) \( C_s^f \)
   - Grit blasted \( 1.00 \)
   - Mill scale \( 0.85 \)
   - Coal tar epoxy \( 0.60 \)

2. Where the member has been cleaned underwater to remove deposits back to bare steel and it can be ensured that a corrosion product film will either not form or will be removed immediately prior to grouting then the following should be used:
\[ C_s = 0.6 \]
\[ C_x = 0.85 \]

3. Where it is not possible to ensure that a corrosion product film, that may build up on the steel surface after cleaning underwater, will be removed prior to grouting the following should be used (assuming the saddle is grit blasted to a surface profile of 50–60 microns):
\[ C_s = 0.5 \]
\[ C_x = 0.85 \]

4. Where it is not proposed to remove underwater surface coatings, investigations will be required to determine the values of \( C_s \) and \( C_x \) to be used.

### 1.8.6 Ranges of application and other requirements

#### 1.8.6.1 Geometric requirements

The relationship given in Equation 1.8.1 may only be applied to the connections which satisfy the geometric limits given below. In addition the requirements of Section 1.8.6.2 shall also be satisfied. The notation is illustrated in Figure 1.8.3.

- chord geometry: \( 20 \leq D/T \leq 50 \)
- connection length to diameter ratio: \( 0.5 \leq L/D \leq 2.0 \)
- studbolts: \( \geq 20 \) mm nominal diameter
- grout strength: \( \geq 40 \) N/mm² @ 28 days

* Whilst limits on the structural components of the connection are given these components should also be in accordance with the relevant design method.

These limitations should not be taken to exclude the use of connections outside the stated ranges providing that it is demonstrated that the strength of such connections can be reliably estimated. Connections with chord \( D/T \) ratios below the lower limits (i.e., more radially stiff) can be conservatively designed by assuming the limiting \( D/T \) ratios in calculations. Alternatively test data may be used as the basis for design. However, care must be taken in using the results of limited test programmes to provide a characteristic strength equivalent to that given in Equation 1.8.1. Guidance is given in Part II, Section 2 on the use of additional data to support a design.

#### 1.8.6.2 Further requirements

1. The saddle should be formed from a stiff fabrication having a continuous top plate.

2. Long studbolts should be used.

3. All studbolts should be stressed to the same load, therefore the total connection load will be:

\[
F = np
\]

where \( F \) is the gross studbolt load

\( p \) is an individual studbolt load.

4. The studbolt load \( (p) \) should be designed not only to prevent static failure of the connection by satisfying the recommendations of Section 1.8.1, but also to ensure that a positive contact pressure is maintained over the full length of the connection during all combinations of loading. This will ensure that the studbolts are not overstressed statically. To achieve this it is recommended that the potentially highest loaded studbolt should be identified and a preload of at least 1.2 times this load be applied to all studbolts. (NB This factor of 1.2 is independent of the safety factors for bond and friction capacity and, depending on the moment loading applied to the saddle, this condition may determine the studbolt force and not the static capacity requirements.)

5. A check should be made on the hoop stresses that develop in the inner (chord/brace) member of a connection at the position between the longitudinal gap in the connection segments, this stress
being induced by tensioning of the studbolts.

6. The maximum exposure period after grit blasting should be limited to 72 hours prior to installation of the connection. All gel-like corrosion products which develop in the period between grit blasting and installation should be cleaned off immediately prior to installation.

7. The connection shall only be stressed after the grout has reached sufficient strength to withstand the imposed studbolt load.

**I.8.7 Permissible working loads**

In determining the permissible working load for a stressed grouted connection the following recommendations should be applied.

1. The permissible load per effective slip surface perpendicular to the normal interfacial contact force should be limited to:

   $$P_s = 0.22 \left[ \frac{F_n C_p}{\Gamma_p} + \frac{1.75 \times 10^{-3} A C_p}{\Gamma_p} \right] \left[ 1 + 33 \left( \frac{D}{T} \right)^{-1} \right]$$  \hspace{1cm} (I.8.3)

   where $P_s$ is the permissible load per effective slip surface perpendicular to the normal interfacial contact force (kN)
   $F_n$ is the net contact force (kN)
   $\Gamma_p$ is the safety factor on frictional capacity, see Section I.8.8
   $\Gamma_\sigma$ is the safety factor on grout bond capacity, see Section I.8.8
   $A$ is the area of the grout slip surface (mm$^2$).

2. The permissible prestress in the studbolts should be limited to $0.6F_n$.

**I.8.8 Safety factors**

In determining the permissible working load from Equation I.8.3 the safety factors given below may be applied in the absence of any other guidance:

1. Safety factor on the frictional capacity $\Gamma_p$

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>1.70</td>
</tr>
<tr>
<td>Operating</td>
<td>2.25</td>
</tr>
</tbody>
</table>

2. Safety factor on grout bond capacity $\Gamma_\sigma$ (the values given below are consistent with those given in the UK Department of Energy Guidance for 'Grouted pile/sleeve connections')

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>4.5</td>
</tr>
<tr>
<td>Operating</td>
<td>6.0</td>
</tr>
</tbody>
</table>

**I.8.9 Applied loads**

When comparing the applied load perpendicular to the normal interfacial contact force with the permissible load the net normal contact force ($F_n$) shall be considered.

The net normal contact force ($F_n$) is defined as the contact force provided by the prestressed studbolts minus any external forces which tend to reduce it.

Consideration should be given to all six components of load acting on a mechanical connection with respect to their effect on the strength of the connection, the studbolt loads and the steelwork.
I.8.10 Fatigue

See Section I.9.4.

I.8.11 Studbolt load attenuation

The loads in the studbolts are known to reduce with time due mainly, it is thought, to the slight shrinkage of the grout annulus. To overcome this it is recommended that either the studbolts are retensioned after a one year period or a preload in excess of that structurally required be used to ensure the long term efficacy of the connections.

The data on load attenuation is limited and it is recommended designers refer to Part II, Section II.8.2.5 for further information on this subject.

Figure I.8.1  *Stressed grouted connection*
(a) Connection of two members using a stressed grouted connection

(b) Connection of a new brace into a structure

Figure I.8.2 Uses of stressed grouted connections

Figure I.8.3 Top plate stressed grouted connection
I.9 STRESSED GROUTED CLAMPS

I.9.1 Introduction and definitions

A stressed grouted clamp is a clamp in which the outer sleeve is formed in two or more segments which are placed around a tubular joint. Cementitious material is placed into the annular space between the clamp and the existing tubular joint and allowed to reach a predefined strength prior to the application of an external stressing force normal to the steel-grout interface.

The stressing together of the clamp body is achieved by 'long' studbolts between widely spaced flanges.

Stressed grouted clamps may be of the 'addmember' type which connects a new member at an inclined angle into an existing tubular joint; or they may be used to strengthen an existing tubular joint in which the original joint is considered to have failed.

The various components of a stressed grouted clamp are illustrated in Figure I.9.1.

Designers wishing to use stressed grouted clamps should also refer to Section I.8 ‘Stressed grouted connections’.

I.9.2 Applications

The applications of stressed grouted clamps fall into two categories:

1. Strengthening of one or more brace members at a tubular joint against static or fatigue loading. The brace members may be considered to be severed from the original joint or the original joint may be assumed to be intact.

2. Connecting one or more new members at an inclined angle into an existing structure or tubular joint.

Additional members may also be connected into a structure using a stressed grouted connection (see Section I.8).

For an illustration of these applications see Figure I.9.2.

The fabrication and installation of a stressed grouted clamp is more complex than a comparable mechanical clamp because of the inclusion of grout. However, a stressed grouted clamp has the considerable advantage over its ungrouted equivalent of being able to accommodate fabrication tolerances, fit up problems and surface irregularities (eg doubler plates or member stubs).

I.9.3 Factors affecting strength

The following factors which may affect the strength and behaviour of stressed grouted clamps have been investigated and design guidance is offered.

1. stressed grouted connections
2. steelwork design
3. studbolt load losses
4. stressing sequence
5. grout strength.

I.9.3.1 Stressed grouted connections

Each portion of the clamp may be considered to be an individual stressed grouted connection for the purpose of estimating the frictional force required between the existing brace or chord and the clamp body. The static strength of the connection to be taken in design is given in Section I.8.
The calculation of bolt load can be done once the brace forces have been resolved into those terms which require friction for their transfer and those which do not, see Section I.9.5. A T joint clamp, whether constructed in two or more parts, normally has two friction surfaces at its contact with an incoming brace member. Benefit may be taken from this fact in determining the bolt load, by assuming that the resolved brace forces may be taken equally on each effective frictional surface. The required net studbolt load \( F_r \) is therefore given by applying the appropriate safety factors, see Section I.9.6, to the bond and friction components.

### I.9.3.2 Steelwork design

When the total bolt load has been determined the steelwork in the stressed grouted clamp can be designed.

Discontinuous top plate stressed grouted clamps are not covered by the test data and should be given special consideration due to the problem of secondary bending moments induced by the studbolt stressing loads, as with a mechanical clamp.

The clamp steelwork may be designed to resist the studbolt loads using normal structural analysis and the design stresses given in the AISC Manual\(^9\).\(^1\).

The clamp should be designed to be stiff in comparison to the tubular joint for the following reasons:

1. the stiffer the clamp the more brace load it attracts with all the corresponding benefits to the tubular joint
2. a stiff clamp reduces the studbolt load fluctuations which minimises the possibility of fatigue therein
3. a stiff clamp reinstates a damaged joint to the original rigid state assumed in the structural analysis.

There are a number of potential disadvantages with stiff clamps which should be given proper consideration:

1. a stiff clamp will attract extra wave loading and impose a greater dead load on the structure than, say, a flexible type clamp
2. a stiff clamp will attract greater framing loads than the original joint which, although it was assumed to be rigid in the analysis, in reality has more local joint flexibility than a stiff clamp.

Load distribution through the brace portion of the clamp may be estimated using the composite section since the friction interface is very stiff. A direct path for the brace top plate stress into the chord saddle should be provided by ensuring that the brace top plates coincide with the chord top plates for a two part clamp or, the chord side plates for a three part clamp (see Figure I.9.1). In this way the secondary plate bending stresses are minimised.

### I.9.3.3 Studbolt load losses

Losses in studbolt loads can be divided into two categories based upon the time at which they occur as follows:

1. short term (immediate) losses, eg bedding down of threads at transfer and top plate bending
2. long term losses, eg relaxation, grout shrinkage.

Short term losses due to bedding down can be reduced by adopting a stressing procedure which uses repeated bolt stressing to overcome the initial bedding down. Short term losses due to top plate bending can be minimised by using stiff top plates or thick washers, see Section II.7.3.3 dealing with mechanical clamps.

Long term losses due to relaxation and grout shrinkage should be dealt with in the manner described in Section I.8.11.
I.9.3.4 Stressing sequence

As has been stated already, a grouted clamp is not sensitive to fabrication tolerances or fit up problems because the grout acts as a filler medium between the clamp and joint. It is not, therefore, necessary to have a special stressing sequence which ensures grip on critical parts of the structure. In fact it may be undesirable to only partially stress a grouted clamp as this may lead to local slippage causing degradation of the steel/grout bond.

In summary, it is recommended that all studbolts on a stressed grouted clamp be stressed simultaneously.

I.9.3.5 Grout strength

Grout strengths greater than 40 N/mm² are recommended for stressed grouted connections. Rate of gain of grout strength forms an important part of the installation procedure as the clamp may only be stressed to its final condition once the grout has achieved sufficient strength to withstand the crushing stresses induced by the stressing process.

I.9.4 Fatigue

I.9.4.1 Fatigue of the original joint

A linear relationship appears to exist between the values of $\frac{SCF\text{\_repaired\_joint}}{SCF\text{\_predicted\_for\_unrepaired\_joint}}$ and joint brace section properties/composite brace section properties for axial load and bending.

Expressions have been developed which give 95% confidence upper bounds to the values of $\frac{SCF\text{\_repaired\_joint}}{SCF\text{\_predicted\_for\_unrepaired\_joint}}$ for axial load and bending loads. The derivation of the expressions is given in Part II, Section II.7.

For axial loads:

$$\frac{SCF_R}{SCF_U} = 0.73 \frac{A_j}{A_c}$$  \hspace{1cm} (I.9.1)

For bending loads:

$$\frac{SCF_R}{SCF_U} = 2.17 \frac{l_j}{l_c} \text{ but with a maximum value of 1.0 for bending loads}$$  \hspace{1cm} (I.9.2)

where $SCF_R = SCF\text{\_repaired\_joint}$

$SCF_U = SCF\text{\_predicted\_for\_unrepaired\_joint}$

based on parametric equations, eg Reference 9.2

$A_j = \text{joint brace section area}$

$A_c = \text{composite brace section area}$

$l_j = \text{joint brace second moment of area}$

$l_c = \text{composite brace second moment of area}$

The composite brace section properties are defined here as the sum of the appropriate joint brace section property and the clamp brace section property.

The difference in the coefficients in Equations I.9.1 and I.9.2 reflects the efficiency of this type of clamp in restraining global chord wall deformation caused by brace axial loads, in comparison to the less efficient, but still substantial, way in which this type of clamp restrains local chord wall deformations caused by brace bending loads.

The value of $\frac{SCF\text{\_repaired\_joint}}{SCF\text{\_predicted\_for\_unrepaired\_joint}}$ should not exceed 1.0 for any load case, since that would imply that a clamp is having a negative composite effect on the original joint.
The SCFs determined for a repaired joint may be treated in the same way as SCFs for an unrepaired joint in the determination of stress ranges and fatigue lives. The commonly used tubular joint weld S-N curves eg API X curve\(^6\) and DE|NT curve\(^5,4\) are applicable to repaired joints.

1.9.4.2 Fatigue of the clamp

Details of the clamps tested are given in Figure 1.9.3. Elastic tests indicated that within this type of clamp the maximum stresses occurred at the corner of the intersection of the brace top plate with the chord top plate. The maximum measured stress in the clamp steelwork can be expressed as a ratio of the nominal clamp stress; this ratio will be called the Stress Multiplier. For stressed grouted clamps of the type shown in Figure 1.9.3 the Stress Multipliers are:

<table>
<thead>
<tr>
<th>Load type</th>
<th>Stress Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial load</td>
<td>3.6</td>
</tr>
<tr>
<td>OPB</td>
<td>3.9</td>
</tr>
</tbody>
</table>

For clamps of other geometries than those tested, a finite element analysis would be an appropriate method of calculating the Stress Multipliers. Alternatively, standard solutions for shoulders, fillets, radii, etc may be applied to the calculated nominal stress, to arrive at the maximum local stress.

The cracks which formed during fatigue tests propagated along the weld between the brace top plate and chord top plates. Through thickness cracking in the chord top plate did not occur, therefore a crack depth of 0.5 mm was taken as indicative of significant cracking.

Prediction of the life at which a crack reaches a depth of 0.5 mm can be carried out conservatively using an appropriate weldment mean S-N curve, type F in this case\(^4,5\). Consequently a design for a ‘no-cracking’ situation can be achieved using a mean minus two standard deviation design S-N curve.

1.9.4.3 Fatigue of studbolts

The stress range in the studbolts should be determined taking account of the appropriate elasticity of the tubular members and local joint flexibility of the tubular joints. The use of long bolts is essential to minimise stress variations. The maximum nominal stress range obtained in the JIRRP tests was 45.6 N/mm\(^2\) which is below the endurance limit of all commonly used bolting materials, at typical allowable studbolt tensions, for fatigue tests carried out in air.

1.9.4.4 Fatigue of the friction surfaces

The friction surface is very stiff for loads up to approximately 90% of the static failure load at which point slip commences, prior to failure of the connection, see the section on stressed grouted connections in Volume III (in the microfiches). Hence for loads of less than 90% of the static failure load there is no surface damage due to the repeated loading (eg fretting). The allowable storm design load represents a maximum of 59% of the static failure load, hence for repeated loading of amplitude less than 59% of the static failure load there will be no fatigue failure of the friction surfaces.

1.9.5 Applied stresses

1.9.5.1 Stressed grouted connections

There are two stressed grouted connections to be designed in a T joint stressed grouted clamp; they are the brace stressed grouted connection and the chord stressed grouted connection. Figure 1.9.4 illustrates the brace loads which are to be given consideration in the design of the various connections.

The brace bolts maintain the normal force between the brace and the brace clamp which is required to transfer the brace loading into the brace clamp. The chord bolts maintain the normal force between the chord and chord clamp required to transfer the components of brace load appropriate to the design of the chord clamp.
I.9.5.2 Fatigue of original joint

The stress distributions under axial and bending modes around the periphery of the brace/chord intersection of the original joint may be estimated using the following approach:

1. Compute SCFs at the crown and saddle for each loading type using the recommendations of Section I.7.4.
2. Assume a simplified stress distribution in the absence of finite element analysis or model tests.
3. Obtain SCFs at equiangular points between the saddle and crown, hence defining eight points on the periphery with known SCFs.
4. Compute stresses at each of the eight points by using the principle of superposition.

The stress distribution outlined in Section I.5.5 should be used in the absence of finite element analysis or model tests.

I.9.6 Safety factors

This section presents the safety factors appropriate for use with the design recommendations presented for static strength and fatigue considerations.

I.9.6.1 Static strength of steelwork

No data are available to evaluate the static strength of an original joint repaired by a stressed grouted clamp. Therefore the clamp must be conservatively designed to withstand the full brace member loads without load sharing with the original joint or composite action.

The clamp steelwork is to be designed using normal structural theory and allowable stress methods to resist the applied brace loads and studbolts using the allowable stresses given in the AISC Manual[14] with the inbuilt factors of safety (1.67 for axial stresses and 1.52 for bending stresses for normal conditions and a one third increase for storm conditions).

The portion of the stressed grouted clamp where the tubular saddles intersect should be designed as a tubular joint using the safety factors given in Section I.5.6.1.

I.9.6.2 Static strength of stressed grouted connections

In determining the permissible working load from Equation I.9.1 the safety factors given below may be applied in the absence of any other guidance:

1. Safety factor on the frictional capacity $\Gamma_f$

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>1.70</td>
</tr>
<tr>
<td>Operating</td>
<td>2.25</td>
</tr>
</tbody>
</table>

2. Safety factor on grout bond capacity $\Gamma_g$ (the values given below are consistent with those given in the UK Department of Energy Guidance for 'Grouted pile/sleeve connections')

<table>
<thead>
<tr>
<th>Condition</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>4.5</td>
</tr>
<tr>
<td>Operating</td>
<td>6.0</td>
</tr>
</tbody>
</table>

I.9.6.3 Fatigue

The fatigue design of the steelwork should be carried out in accordance with the relevant steel design methods.
Figure I.9.1  Typical stressed grouted clamp for T joints

Figure I.9.2  Applications of a stressed grouted clamp
Figure I.9.3  Three-part stressed grouted clamp
Figure 1.9.3 (Continued)
Figure I.9.4  Brace member loads to be considered in the design of a mechanical or stressed grouted clamp

BRACE CLAMP DESIGN

BRACE LOADS TO BE RESISTED:

\[ F_{y}, F_{z}, F_{ax}, M_{cpb}, M_{ipb}, M_{tor} \]

CHORD CLAMP DESIGN

CHORD CLAMP MUST RESIST ALL THE COMPONENTS OF BRACE LOAD, TAKING INTO CONSIDERATION ECCENTRICITIES FROM CHORD CENTRE.
I.10 GROUT FILLED TUBULAR MEMBERS

I.10.1 Introduction and definition

A grout filled tubular member is a tubular member filled with an unreinforced cementitious grout material, forming a composite load carrying section.

The increase in load carrying capacity of the member is predominately in compression and bending. Tensile strength is not increased as the grout is only confined by the tubular and not attached directly to the end supports. In addition as the grout is unreinforced its tensile strength is small relative to its compressive strength.

A method of calculating the load-deflection behaviour and ultimate load for an eccentrically loaded concrete filled tubular member was developed at Imperial College and compared with the results of tests on columns of circular cross-section. Generally good agreement was obtained although the method is conservative in estimating the strength of stocky columns (L/D ≤ 15).

A limited test programme was carried out as Area 5 of JIRRIP on grout filled tubulars to generate test data at the extreme of practical ranges. These data were then used to check the validity of the analytical method developed for composite concrete members. The method was then used to develop design curves for the full range of practical geometries.

The design guidance given in this section is based on the engineering assessment of the available data contained in Part II, Section II.10 of this document.

I.10.2 Applications

Grout filled tubulars can be used either as a repair method or as a strengthening method for new members.

The major uses of grout filled tubulars are:

1. to increase the capacity of existing members in a structure by either full or partial filling of their unsupported length
2. to increase the capacity of members in vulnerable areas (eg adjacent to boat landings) to resist local damage
3. to increase the capacity of damaged members that are either locally buckled, dented or bent.

I.10.3 Factors affecting the strength of grout filled tubular members

The following factors have been demonstrated to affect the strength of grout filled tubular members and design guidance is offered on these:

1. tubular geometry: length (L), diameter (D), wall thickness (T)
2. material properties of both steel tubulars and grout
3. initial imperfections and other imperfections (eg dents).

Factor 3 was beyond the scope of this project, but has been the subject of previous investigation for members used in structures.

I.10.4 General recommendations

I.10.4.1 General

The guidance given in this section is limited to newly installed members which are fully filled with grout (ie unstressed when grouted). The guidance can also be used to give an indication of the
additional strength obtainable when existing members are grout filled. This will enable repair
designers to assess whether grout filling of the members is a viable strengthening or repair option.

The design curves given in this section can be used to determine the load capacity of a grout filled
tubular member of known geometry and with known material properties. Further information is
contained in the engineering assessment, Part II, Section II.10, and repair designers are
recommended to read this prior to using this design guidance.

### I.10.4.2 Partial filling along a member length

If a member is to be partially filled along its length it must be ensured that a sufficient grouted length
is provided to transfer the load from the steel section to the composite grout-steel section. A simple
method of determining the required length is given below.

1. Determine the axial load to be carried by the grout using linear elastic theory:

\[
P_g = \frac{P_T A_g E_g}{A_g E_g + A_s E_s}
\]

where
- \(P_g\) = axial load carried by grout
- \(P_T\) = axial load in member
- \(A_g\) = cross-section area of grout
- \(E_g\) = Young's modulus of grout
- \(A_s\) = cross-section area of steel
- \(E_s\) = Young's modulus of steel.

2. Assuming an average plain pipe bond stress of 1 N/mm\(^2\), a safety factor of 6 and a surface
condition factor of 0.6 gives:

\(f_{es} = 0.10\) N/mm\(^2\)

3. Therefore, the required grouted transfer length is:

\[
L = \frac{P_g}{f_{es} \pi (D - 2T)}
\]

where
- \(L\) = connection length
- \(D\) = outside diameter
- \(T\) = wall thickness.

The method of calculating the bond length is inherently conservative as it ignores the 'jamming' effect
which will occur when bending loads are applied to the column.

### I.10.5 Range of application

The design guidance covers the following range:

- connection length to diameter ratio \(10 \leq L/D \leq 30\)
- chord geometry \(15 \leq D/T \leq 75\)
- characteristic grout compressive strength \(20\) N/mm\(^2\) \(\leq f_{es} \leq 80\) N/mm\(^2\)
- yield strength \(F_y = 255\) and \(345\) N/mm\(^2\)

These limitations should not be taken to exclude the use of grout filled tubulars outside the stated
ranges providing that it is demonstrated that their strength can be reliably estimated.
10.6 Determination of ultimate capacity of a grout filled tubular

The ultimate capacity of a grout filled tubular can either be determined analytically or by using the non-dimensional curves, Figures 1.10.1 to 1.10.4. The following describes a method that can be applied to determine the capacity of a grout filled tubular member. An example calculation is given in Appendix II.10.A, in Part II of this document (see microfiches).

1. Determine applied loading (ie ratio of bending stress to axial stress).
2. Determine the member axial load $P$ and bending moment $M$ for the given applied stress.
3. Calculate the member squash load. Assuming it to be grout filled, the squash load is defined as:

\[ P_{sq} = A_s f_y + S_p f_u \]  \hspace{1cm} (I.10.3)

where $P_{sq}$ is the squash load
\[ A_s \] is the area of steel
\[ S_p \] is the area of grout.

Calculate the ultimate moment of resistance of the member. Using BS 5400 Part 5\(^{10.2}\) Appendix C.4.3, the ultimate moment of resistance ($M_u$) is defined as:

\[ M_u = 0.91 S_f (1 + 0.01 m) \]  \hspace{1cm} (I.10.4)

where $S_f$ the plastic section modulus of the steel section, is given by:

\[ S = T^3 \left( \frac{D}{T} - 1 \right) \]

$m$ is determined from Figure I.10.5, in which

\[ \rho \] is defined as $0.4 f_u / 0.91 f_y$

4. Non-dimensionalise the member axial load $P$ and bending moment $M$ by dividing by $P_{sq}$ and $M_u$ respectively.
5. Plot the values obtained from 4. on each Figure I.10.1 to I.10.4 and extrapolate through the origin and to the given values of L/D, D/T, $f_u$, and $f_y$.
6. Determine extrapolated values of $P/P_{sq}$ and $M/M_u$ from L/D graph, Figure I.10.1.
7. Apply partial factors $\gamma_1$, $\gamma_2$ and $\gamma_3$ to values $P/P_{sq}$ and $M/M_u$. The partial factors are obtained as shown in Figures II.10.A.2 to II.10.A.5 (see microfiches).
8. Re-dimensionalise $P/P_{sq}$ and $M/M_u$ by multiplying by $P_{sq}$ and $M_u$ respectively to obtain values of $P$ and $M$.

10.7 Permissible working loads and safety factors

In determining the permissible working load for a grout filled tubular it is recommended that the safety factors, as determined from the AISC\(^{10.3}\) specification should be applied to the ultimate load as determined either by the analytical method or graphical method described in Section I.10.6.

10.8 Applied loads

The applied loads on a grout filled tubular member should be determined using a recognised analytical technique which takes account of the increased stiffness due to the presence of the grout.
I.10.9 Heat generation

The heat generated in the grout mass by the hydration process should be considered especially when filling large diameter tubes. No data are available on this subject and it is likely that on-shore trials will be required before filling large members. To reduce the problems of large temperature gradients being set up in the grout, which may induce thermal cracking, consideration should be given to grouts other than cement-water grouts, i.e. grouts containing inert fillers.

Figure I.10.1 Effect of variation in L/D

Figure I.10.2 Effect of variation in D/T
Figure I.10.3  *Effect of variation in $f_{cu}$*

Figure I.10.4  *Effect of variation in $F_y$*
Figure I.10.5  Chart for evaluating $M_e$ of concrete filled circular hollow sections
I.11 GROUT MATERIALS AND GROUTING PROCEDURES FOR GROUTED REPAIRS

I.11.1 Materials

The types of materials which may be used for grouted repairs include:

1. Portland cement grouts with or without inert fillers mixed preferably with fresh water, although seawater may be used. There may be special circumstances, such as repairs in the splash zone, where the use of seawater is undesirable and therefore not recommended because of corrosion and other durability effects.

2. Fresh water/high alumina cement grouts providing that, to take account of the conversion process, the design is based on the minimum strength appropriate to the curing temperature, service temperature and water:cement ratio. In this respect the water cement ratio should not be greater than 0.4. However, high alumina cement grouts shall not be used in the splash or emergent zones of a structure.

Admixtures may be used to improve properties of the slurry or the hardened grout provided that it is satisfactorily established that they have no harmful effect on the performance of the connection. The use of calcium chloride or admixtures containing significant levels of chloride ions are not permitted. Guidance on the strength-time characteristics of typical grout mixes can be obtained from Reference 11.1.

I.11.2 Assessment of compliance of grout strength

I.11.2.1 Grout specimens

Equation I.4.1 for bond strength is based on the characteristic grout compressive strength as determined by tests on 75 mm cubes at the design age (usually 28 days), as recommended by the UK Department of Energy Guidance Notes. Other cube sizes and cylinders may be used to determine and check grout providing a conversion factor is applied as determined by appropriate tests. It should be noted that for any given mix the conversion factor will depend on the age of the grout.

Testing of grout specimens to determine grout compressive strength should be in accordance with BS 1881.

I.11.2.2 Mix specification

Evidence that the proposed mix will meet the specified strength at a given age should be obtained from previous production data or trial mixes. The mean strength calculated from these data should exceed the specified characteristic grout compressive strength by either:

\[ 1.64 \sigma \left(0.86 + \sqrt{2/n}\right) \text{ for } 10 \leq n < 100, \quad \text{or} \]
\[ 1.64 \sigma \quad \text{for } n \geq 100, \]

where \( \sigma \) is the standard deviation calculated from \( n \) results
\( n \) is the number of test results (not less than 10).

Previous production data for use in the above criteria should be test results from separate grout batches selected over an immediately prior period not exceeding two years, using the materials and plant which are proposed for the work.

Where laboratory trial mixes are used to provide data at least three separate batches of grout should be prepared and at least six cubes should be made from each batch for each age at which compliance is to be determined.
I.11.2.3 Offshore quality control

During the grouting of each connection, samples of grout should be taken from randomly selected batches. The rate of sampling should take account of the nature of the work.

At least four samples, each of three cubes, should be taken for each connection. One cube for each sample should be tested to assess compliance (usually at 28 days). The remaining cubes may be tested at earlier ages to indicate the grout quality.

The specimens should be subjected, until test, to a curing regime representative of the curing conditions of the grouted connection, ie underwater and at the appropriate seawater temperature.

Strength compliance should be assumed if no test result in each set of four is below the specified characteristic grout compressive strength. In the event of non-compliance, the action taken should have due regard for the kind of degree of non-compliance and the implication safety.

I.11.3 Offshore practices

The grouting procedure used offshore should recognise the practical difficulties associated with the different conditions that may prevail at the repair site. These conditions may be summarised as:

1. Location
   - above water
   - under water

2. Orientation
   - vertical
   - horizontal
   - raked

3. Application
   - annulus grouting (eg grouted clamps)
   - member grouting

4. Displaced fluid
   - air
   - water

The procedure should address all four parameters recognising the various problems and complexities associated with each. For example when grouting a horizontal member care must be taken not to leave an air void at the soffit of the tube and in addition a low shrinkage grout should also be used.

This list is intended to highlight to the repair designer parameters he should be aware of. However, a repair designer is advised to call for specialist advice in this area as quality control and NDE methods are severely lacking in the field of detecting if a volume is completely filled with grout and the only quality control available is the adherence to a proven grouting procedure. If a proven procedure does not exist serious consideration should be given to on-shore grouting trials which include destructive testing, sectioning and any other inspection necessary to prove the integrity and completeness of filling.

The grouting procedure should incorporate provision for sampling of the grout emitting from the grout return lines. This may be provided by piping back to surface, by diver sampling or by the provision of proven remote monitoring devices at the top of the grout volume.

Deliberate pressurisation of the grout annulus has been shown to be an unreliable method of increasing the grout bond strength and is therefore not recommended. However, accidental pressurisation of the grout annulus must be considered when the grouting procedure is being drafted. High hydrostatic pressures when grouting at depth may result in collapse of a member. The risk of collapse is increased if the member under repair is already damaged as the pressure can cause high chord wall bending.

The risk of hydrostatic collapse should also be considered when comparing the merits of diver grout sample, remote sensing or returns to surface for grout quality control.
I.12 BASIC INFORMATION ON TUBULAR JOINTS

I.12.1 Static strength

I.12.1.1 Introduction

The following sections are concerned with the static design of tubular joints formed by the full penetration welding of two or more tubular members, fabricated from steel plate satisfying BS 4360\textsuperscript{12.1} or equivalent specifications.

The parametric equations presented for the static strength of tubular joints were developed from a database produced within extensive research work undertaken for the UEC\textsuperscript{12.2}.

The Department of Energy are currently proposing to introduce static strength formulae of this type into the ‘Guidance Notes’\textsuperscript{12.3} and any design should be based on the current edition of this document.

Equations of this form have been used throughout this document to determine predicted loads and other design factors in the engineering assessment and designer’s manual.

I.12.1.2 Classification of joints for static strength design

The simplifying assumptions given in Section I.5.3.1 permit a repair sleeve of a grouted clamp to be designed as a tubular joint in the first instance, with the subsequent application of a factor to account for composite action.

Each joint should be considered as a number of independent chord/brace intersections and each intersection should be designed using the formulae in the ‘Guidance Notes’. Each chord/brace intersection should be classified according to the classification given in the ‘Guidance Notes’.

I.12.1.3 Factors affecting the strength of a tubular joint

The following principal factors have been shown to affect the strength of a tubular joint:

1. chord outside diameter (D)
2. brace outside diameter (d)
3. chord wall thickness (T)
4. the included angle between chord and brace (θ)
5. gap or overlap (for K joints only) (g)
6. chord material yield stress (F\textsubscript{y})

Within the design of a repair sleeve the parameter which is most conveniently varied is chord wall thickness (T) since D, d, θ and g are all governed by the geometry of the original tubular joint.

I.12.1.4 General format of formulae for characteristic strength of tubular joints

The characteristic static strength of a welded tubular joint subjected to undirectional loading can be derived from formulae having the following general formats:

\[ P_c = \frac{F_y \cdot T^2}{\sin \theta} (3 + 15\beta)Q_g \]

Axial compression

Axial tension

- 77 -
In-plane bending \[ M_{ki} = F_{y} T^{2} d (4.6 \beta) Y^{0.5} Q_{d} \]

Out-of plane bending \[ M_{kd} = \frac{F_{y} T^{2} d}{\sin \theta} (1 + 7.5 \beta) Q_{d} \]

The values of the coefficient \( Q_{d} \) for each load type and joint classification are given in the current edition of the proposed recommendations of the 'Guidance Notes' review pane\textsuperscript{[13,3]}.

I.12.2 Stress concentration factors

I.12.2.1 Introduction

The following sections are concerned with the method by which the stress concentration factors (SCFs) within a given tubular joint may be safely predicted using parametric formulae. The formulae are applicable to tubular joints formed by full penetration welding of two or more tubular members fabricated from steel plate satisfying BS 4360\textsuperscript{[12,1]} or equivalent specifications.

The parametric equations presented for the SCFs within tubular joints were developed from a database produced within extensive research work undertaken for the UEG\textsuperscript{[12,4]} which was summarised by Tebbett and Lalani\textsuperscript{[12,5]}.

The parametric equations in Reference 12.5 have been used throughout this document to determine predicted SCFs and other design factors in the engineering assessment and designers' manual.

I.12.2.2 Classification of joints for stress concentration factors

Tubular joints should be classified according to whether they are of T, Y, DT, X or K configuration and according to the sense and magnitude of applied loading, for the calculation of SCF. The simplifying assumptions given in Section I.5.4 permit a repair sleeve of a grouted clamp to be designed as a simple tubular joint in the first instance, with the subsequent application of factors to account for composite action.

I.12.2.3 Factors affecting the SCFs of a tubular joint

The following principal non-dimensional parameters have been shown to affect the SCFs of a tubular joint:

\[
\frac{D}{2T} \quad (\gamma) \\
\frac{t}{T} \quad (\tau) \\
\frac{d}{D} \quad (\beta)
\]

included angle between chord and brace \( (\theta) \).

Within the design of a repair sleeve the parameters which are most conveniently varied are \( \gamma \) and \( \tau \) since \( \beta \) and \( \theta \) are governed by the geometry of the original tubular joint.

I.12.2.4 General formulae for characteristic SCFs of tubular joints

Tables I.12.1, I.12.2 and I.12.3 present formulae for characteristic stress concentration factors for tubular joints. Reference 12.5 presents a reliability approach to the use of SCFs which reflects factors such as:

1. confidence in the overall assessment of the fatigue performance of the structure
2. consequence of fatigue failure
3. redundancy.

These factors are dealt with by introducing a partial factor \( \Gamma \) which is applied to the SCF calculated from the formulae and is selected to give the appropriate level of confidence.
<table>
<thead>
<tr>
<th>JOINT TYPE AND LOAD CASE</th>
<th>CHORD SADDLE SCF</th>
<th>CHORD CHORD SCF</th>
<th>VALIDITY RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\gamma T (6.78 = 6.43 \text{ kN}) \sin (1.7 + 0.7\beta) \gamma \sqrt{\frac{y}{\beta}} \frac{Q'}{Q'}$</td>
<td>$\left(\sqrt{x_0 + x_0^*} \frac{Q'}{Q'} \right)$</td>
<td>$2.5 \leq x \leq 49$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.13 \leq \beta \leq 1.00$</td>
<td>$12.0 \leq \gamma \leq 37.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.25 \leq \gamma \leq 1.00$</td>
<td>$30^\circ \leq \phi \leq 90^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$1.7\gamma 3(2.42 - 2.30\beta^2) \sin 2^2 (15 - 14.0\beta) \gamma \sqrt{\frac{y}{\beta}} \frac{Q'}{Q'}$</td>
<td>$\gamma \sqrt{\frac{y + \phi}{\beta}} \frac{Q'}{Q'}$</td>
<td>$0.13 \leq \beta \leq 1.00$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.025 \leq \gamma \leq 1.00$</td>
<td>$30^\circ \leq \beta \leq 90^\circ$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.13 \leq \beta \leq 1.00$</td>
<td>$12.0 \leq \gamma \leq 37.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.25 \leq \gamma \leq 1.00$</td>
<td>$30^\circ \leq \beta \leq 90^\circ$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\beta (1/0.53 \gamma) \frac{Q'}{Q'}$</td>
<td>$0.13 \leq \beta \leq 1.00$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.025 \leq \gamma \leq 1.00$</td>
<td>$30^\circ \leq \beta \leq 90^\circ$</td>
</tr>
</tbody>
</table>

**Notes:**
1. $Q'_y = 1$ for $\beta < 0.6$ and $\frac{12y}{1-0.63\gamma}$ for $\beta > 0.6$; $Q'_y = 1$ for $\gamma < 20.0$ and $\frac{0.998}{(1-0.63y)\gamma}$ for $20 \leq \gamma < 37.4$
2. For $K$ joints where $\theta_1 \neq \theta_2$, formulae for $\alpha$ refers to brace 1 and is based on nominal stress in brace 1.
3. For brace SCF use $\gamma_{br} = 1 + 0.03 SCF$.
4. The SCFs are limited to a minimum of 3.5.
5. For $T/Y$ joints, the chord length can be taken as the distance between points of contraflexure on the chord.
### Table I.12.2  Characteristic SCF formulae for in-plane moment loaded simple joints

<table>
<thead>
<tr>
<th>Joint Type and Load Case</th>
<th>Chord Moment SCF</th>
<th>Validity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Joint Diagram]</td>
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<td>![Joint Diagram]</td>
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<td>![Joint Diagram]</td>
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</tr>
</tbody>
</table>

**NOTES:**
1. Notes (3), (4) and (6) of Table I.5.1 are applicable
2. For MC joints, $\gamma$ range can be increased to $0.7 \leq \gamma \leq 37.4$

### Table I.12.3  Characteristic SCF formulae for out-of-plane moment loaded simple joints

<table>
<thead>
<tr>
<th>Joint Type and Load Case</th>
<th>Chord Moment SCF</th>
<th>Validity Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Joint Diagram]</td>
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<tr>
<td>![Joint Diagram]</td>
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<tr>
<td>![Joint Diagram]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTES:**
1. $S_1$, $S_2$, as defined in Table I.5.1
2. Notes (1), (3), (4) and (6) of Table I.5.1 are applicable

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I.13 ADDITIONAL DESIGN CONSIDERATIONS

I.13.1 Introduction

The main aim of the JIRRP project was to establish design data for both the static and fatigue performance of connections and clamps. The project did not specifically set out to investigate the peripheral design considerations such as:

- bolting systems
- sealing systems
- cathodic protection
- inspection
- additional loading.

The aim of this section is therefore to draw the designers attention to these areas of the design without giving specific recommendations.

I.13.2 Bolting systems

Two types of bolting systems are used in repair systems; these are the high strength friction type and the long bolt type.

1. High strength friction type

   The high strength friction type are used on grouted connections and clamps and work on the same principle as the high strength friction connections used in steel frame buildings. However, torque values used in air are not applicable in water due to the lubricating effect of the water. Therefore if torquing is to be used offshore it is prudent to perform some laboratory trials on strain-gauged bolts to determine the correct torque value to induce the desired load.

   Alternatively short studbolts may be used in conjunction with a stud puller which hydraulically tensions the stud to the correct load. This is the favoured method as it allows a number of studs to be tensioned simultaneously and does not induce high torsional shears in the shaft of the bolt. The order of bolt stressing should also be considered.

2. Long bolt type

   Long bolt type systems are used on all the stressed connections and clamps. These systems are used to reduce the effect of the fluctuating studbolt stresses caused by fluctuating hoop displacements of the chord. The term 'long bolt' is a relative term and consideration should be given to the chord diameter and the expected hoop displacements. Typically 600 mm is considered a long bolt for clamps up to about 1000 mm diameter.

   Torquing of long stud bolts is not recommended and tensioning by means of hydraulic jacks is the preferred method. When considering which system of jack to use the extension of the studbolt versus the maximum extension of the jack should be compared. It is desirable for economy of underwater effort that the extension of the studbolts should be achieved in a single pull without resetting the reaction nuts.

   The order in which the studs are tensioned should be considered carefully especially on mechanical clamps and connections where the variation of stiffness of the underlying members can cause redistribution of the stud loads.

   It is also recommended that spherical seatings should be used in conjunction with long studbolts as misalignment and angular tolerances of the stressed flanges can result in large bending stresses. However, it should be noted that the spherical seat only takes out initial tolerances prior to loading. Once the studbolt is loaded friction prevents the seating from rotating.

   Transfer losses should also be considered. These occur when the tension load is transferred from the jack to the nut via the washer to the flange. Losses can be caused by a number of reasons which are listed below:
1. bedding-in of the nut/washer/flange interfaces
2. bending of the flange plate as the load is transferred from the larger diameter of the jack to the smaller diameter of the nut
3. slack in the thread of the nut and stud.

Typical bolting materials which are used offshore are B7 studbolts, Macalloy bars, nickel alloys and high strength friction type short bolts. In the past the bolting materials used on repairs have varied considerably with the location of the repair and the operator of the platform.

Long term service records are not available for many of these materials and data is limited to results of tests performed by the manufacturers. However, some failures have occurred, notably in Macalloy studbolts, the cause of which appears to be stress corrosion cracking. Conventional high strength austenitic stainless steel studbolts are also susceptible to stress corrosion cracking, although, it is claimed that recently introduced ferritic austenitic stainless steels provide good resistance to stress corrosion cracking.

B7 studbolts and high strength friction type bolts require protection from corrosion fatigue. They are not particularly susceptible to stress corrosion cracking as a consequence of their lower ultimate strength compared to Macalloy bars. Coatings on bolts in the form of platings (eg cadmium) and fluoro-polymer coatings (eg PTFE or Xylan) have been used. Again there is a paucity of in-field service records to allow recommendations to be offered on this subject.

The remaining bolt type is the nickel alloy type material, eg Monel K-500. Manufacturer’s test data indicate that these bolts are not susceptible to either corrosion fatigue or stress corrosion cracking.

The requirements for high strength materials to reduce the studbolt size for diver handling and increase the load per studbolt cause problems in the marine environment especially with cathodic protection systems in operation. Hydrogen charging due to overprotection by the CP system can promote hydrogen embrittlement in some of the high strength alloys. The reaction between the elements of the repairs and the cathodic protection system should be considered carefully when using high strength steels and dissimilar materials.

### I.13.3 Sealing systems

The sealing systems employed in grouted repairs are required to seal the longitudinal split and the annulus at the ends, to confine the grout prior to its initial set.

The longitudinal seal does not normally have to absorb large tolerances as the mating edges of the clamp are machined during fabrication to effect fitup. The requirements of the seal are therefore to resist the imposed hydrostatic pressure of the grout and to effectively create a continuous seal with the end seal. Elastomeric materials such as a low hardness Neoprene are often used for this type of seal.

The end seals are generally harder to engineer as the tolerances which they have to absorb are greater. Two types of tolerance normally have to be accommodated, namely out of roundness and variation in annulus size.

The first of these can be accommodated by a low stiffness elastomer such as the BTR registered product ‘Sorbothane CD’. However, the second of these is usually too great to overcome simply by the compression of the elastomer. The problem is to make the sealing flange concentric with the chord so that the elastomer only has to accommodate out-of-roundness tolerances. This is traditionally achieved by using a ‘floating’ end sealing ring which can be positioned to become concentric with the chord.

An alternative to an elastomeric end seal is a purpose-made grout bag. The bags can be made from either a porous or non-porous woven fabric or a combination of the two.
The bags are either zipped or lapped to obtain a full 360-degree seal at the end of the annulus. Once in place the bag is inflated with grout and allowed to set. After a cure period the main annulus can be filled with grout.

The relative merits in terms of cost, time and efficacy of the two sealing systems – elastomeric seals and grout bags – will have to be considered for each repair situation on an individual basis.

Other important points to consider when designing a sealing arrangement are:
1. the maximum pressure the seal will encounter
2. the load imposed on the seal due to 1.
3. the shape factor of an elastomer under confinement
4. the Young’s modulus of an elastomer.

I.13.4 Cathodic protection

In order that corrosion of a clamp and a repaired structure is minimised following a repair, the method of corrosion protection (CP) must be given proper consideration.

A connection or clamp will increase the surface area of steelwork exposed in comparison to the surface area of the unrepaired joint. This means that the existing CP system may be inadequate and will have to be enlarged.

Many structures use sacrificial anode CP systems underwater, in which case the most appropriate method of protection is to supply the repair with sacrificial anodes attached. The repairs are usually painted on all exposed surfaces with an appropriate underwater protective coating, which reduces the surface area available for corrosion and therefore increases the life of the sacrificial anodes. However, consideration should be given in the design of the clamp CP system to the quality and expected bonding life of the paint. Repairs can be electrically connected to the remainder of the structure by either connectors screwed through the saddle plate or by electrical continuity straps which are welded or strapped to the structure.

It is not advisable to attempt to isolate a clamp from a structure since while the two are isolated a potential difference may develop which, in the event of accidental short circuiting, would lead to more rapid anode consumption and a reduced platform protection life.

Those structures utilising an impressed current system may be treated in a similar manner from the standpoint of corrosion protection. Sacrificial anodes may be omitted from the clamp if the operator is confident that the impressed current system will not be inactive for any length of time.

I.13.5 Inspection

Periodic inspection should be carried out to ensure that the repair is performing in a satisfactory manner. Various levels of inspection will be involved, from general visual inspection to MPI and ultrasonic thickness measurements. At each stage a properly qualified inspection diver should be employed.

A typical inspection programme would be performed on a four yearly cycle from installation for the remaining life of the structure.

A general visual inspection of all clamps, connections, tubulars and bolts would be performed each year. A more detailed visual inspection of the bolts (for corrosion) elastomeric seals, sacrificial anodes, and CP straps would be performed every second year.

More detailed measurements to obtain bolt loads, ultrasonic thickness measurement, MPI on critical welds and CP potentials would be performed every second year.

MPI measurements should be carried out with care every second year because of the low warning of impending through thickness cracking which is given on the sleeve of a grouted clamp (see Volume
V of this document – in the microfiches). This requirement may be relaxed for mechanical and stressed grouted clamps because of the slower rate of crack development which they exhibit.

I.13.6 Additional Loading

The addition of a clamp or a connection into a structure will change the magnitude of loading within the structure. This is due to:

1. the change in projected area of the structure, for wave loading, compared to its original area in conjunction with the change in drag and inertia coefficients
2. the change in dead weight which the structure must sustain – particularly if clamping near the centre of a long chord member without vertical support
3. the stiffness of a clamped joint is greater than in the unclamped state, therefore extra framing loads will be attracted.

These factors should be considered in the assessment of design forces for the clamp before the detailed design is finalised.

I.13.7 Wet welding

A study has been carried out into techniques for wet welding, see Part II of this document, which recommended that where top quality code-graded welding is required at depth then hyperbaric welding using a habitat provides the best solution, whilst for welding near the water surface a cofferdam provides the most cost effective environment.

Consideration should be given to the type of consumable being used within certain environments and with certain steels as this affects the weld quality.

Information is also available on the properties of studs attached by the drawn arc and friction processes. Such studs would be used as shear connectors in a grouted connection and provide an alternative to laying weld beads either by wet welding or within a habitat.
REFERENCES – PART I

References used in each of the sections in Part I are given below.


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9.5 British Standards Institution. 'Code of Practice for fixed offshore structures'. BS 6235: 1982.


