SSC-328

FRACTURE CONTROL FOR FIXED OFFSHORE STRUCTURES

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SR-1288

The authors of this report reviewed numerous documents and discussed the fracture control practices which were in use at the time of their interviews with engineers involved in designing fixed offshore platforms.

Based on the aggregate of the information then available to them, the authors summarized the state-of-the-art in material selection, design, construction and operation. Using their own engineering judgement, they then recommended research in those same general categories. Thus, this report represents the authors' opinions based on the information gathered at a specific "point in time."

As our knowledge of the fracture problem continues to increase, we will continue to advance the state-of-the-art in preventing detrimental fractures. To those entering the fixed offshore platform fracture control discipline, this report will serve as a sound basis from which to begin.

CLYDE T. LUSK, Jr.
Rear Admiral, U.S. Coast Guard
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16. Abstract

Literature and telephone surveys were conducted to determine the current status of fracture control as practiced by U.S. designers, builders, and operators. From this, recommendations are made for strengthening industry practices: promising areas for research are identified and prioritized, as are areas where cost-effective improvements could be made within existing technology. A fracture control checklist is also provided as an example of an unstructured, yet responsive, fracture control plan.

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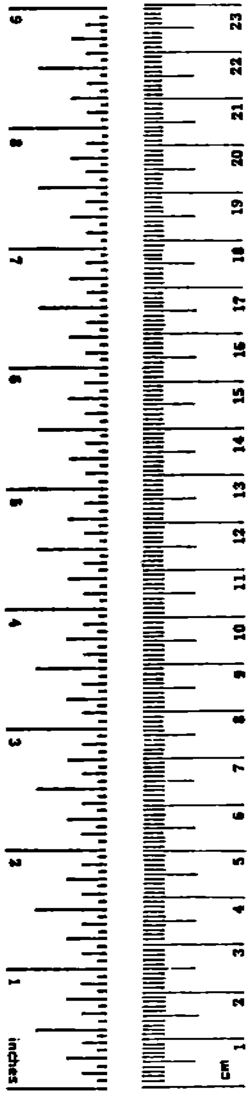
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

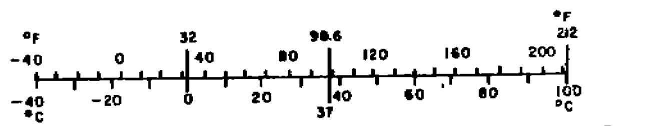
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Listing of Acronyms and Symbols

ABS	American Bureau of Shipping
API	American Petroleum Institute
API X, X', D', and K curves	Stress vs. Number of Cycles (S-N) curves for fatigue design contained in API RP-2A (see below)
API RP-2A	Publication of the American Petroleum Institute which is the primary design guide for American fixed offshore structures (see reference listings)
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
BIGIF	A general purpose computer program for fracture mechanics analysis relying heavily upon quantities called Boundary Integral equation Generated Influence Functions
BOSS	Behavior of Offshore Structures (conference)
BSI	British Standards Institute
CEGB	Central Electricity Generating Board, United Kingdom
COD, CTOD	Crack-Tip Opening Displacement (test)
CVA	Certified Verification Agent (USGS program)
CVE, CVNE	CVN energy (see CVN)
CVN	Charpy V-Notch (test)
da/dN	Crack propagation rate (most often due to fatigue), in units of crack length per load cycle
da/dt	Crack propagation rate (most often due to stress corrosion cracking) in units of length per unit time
DAF	Dynamic Amplification Factor
d/D	Ratio of brace-to-can diameter in welded tubular joints
DFM	Deterministic Fracture Mechanics
DIRT	Design-Inspection-Redundancy Triangle (after Peter Marshall)
DNV	Det norske Veritas
DT	Dynamic Tear (test)
D/T	Diameter-to-thickness ratio of can or chord member
DWT	Drop-Weight Test
FAD	Fracture Analysis Diagram
FASD	Failure Assessment Diagram
FCAW	Flux Cored Arc Welding (semiautomatic welding)

GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone (adjacent to weld)
IIW	International Institute of Welding
J	Applied J-Integral, a measure of near crack-tip stress under elastic-plastic conditions
J_C,J_{IC}	Critical J-Integral required to initiate crack extension under static loads that cause significant elastic-plastic deformation. A property of the material, environment, and plastic constraint condition
K	Stress intensity factor, a measure of near-crack tip stress under primarily elastic conditions
$K_{applied}$	Applied stress intensity factor
ΔK	Applied stress intensity factor range
K_C,K_{IC}	Critical stress intensity factor
K_Q	Critical stress intensity factor computed from the applied loads at failure without regard to plastic deformation or failure mode
K_r	K/K_Q
LEFM	Linear Elastic Fracture Mechanics
MMS	Minerals Management Service
NAVSEA	Naval Sea Systems
NDE	Non-Destructive Examination or Inspection
NDT	Nil-Ductility Transition
n/N	Ratio of applied-to-critical number of constant amplitude fatigue cycles of specified stress
NRL	Naval Research Lab
OCS	Outer Continental Shelf
OTC	Offshore Technology Conference
P-Δ effect	The change of applied bending moment upon a column due to its large deformation
PFM	Probabilistic Fracture Mechanics
PWHT	Post-Weld Heat Treatment
R, R-ratios	Ratio of minimum and maximum stress (or stress intensity factor) in a fatigue cycle
RMS	Root-Mean-Square
s	Standard deviation, as in 2s
SCF	Stress Concentration Factor
SF	Safety Factor
σ	Stress

$\bar{\sigma}$	Plastic-Collapse Stress (often taken as average of yield and ultimate stresses)
SMAW	Shielding Metal Arc Welding
S-N	Stress vs. Number of cycles (curve used for fatigue design)
SPE	Society of Petroleum Engineers
S_r	$\sigma/\bar{\sigma}$
Θ	Brace-to-Chord intersection angle
TIG	Tungsten-Inert-Gas (underwater welding technique)
t/T	Ratio of brace-to-can thickness
UK DOE	United Kingdom, Department of Energy
USGS	United States Geological Survey
WI	Welding Institute
WRC	Welding Research Council
z-direction	Direction normal to plate rolling plane

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I. INTRODUCTION

The Ship Structure Committee sponsored this examination of the technology and practices that constitute the fracture control plans used by designers, builders, and operators of fixed steel offshore structures. This report presents the findings of that study as responsive to four identified tasks:

Task 1: Determine the current status of fracture control practices through review of pertinent U. S. and foreign literature and interaction with designers, builders, operators, and classification societies in order to identify the extent of and contributors to the fracture problem for fixed offshore structures.

Task 2: Identify the essential elements and rationale of a fracture control plan to provide a framework which could eventually evolve to a fracture control plan for fixed offshore structures.

Task 3: Identify areas where existing technology would suggest cost-effective improvements in current practices.

Task 4: Identify promising areas of technical research which would provide a sounder basis for fracture control of fixed offshore structures.

Performance of Task 1 was approached in two ways: through discussion (and formal interviews) with experts in the field and through a review of standards, specifications, and fracture control studies and surveys available in the open literature. The authors contacted members of the Ship Structure Subcommittee, Coast Guard, Naval Sea Systems Command (NAVSEA), and other members of the offshore community and requested direction to key publications and noted industry experts as a beginning point for both the literature survey and the interview phases of the project. From this point on, the two approaches became complementary as the literature brought forth names of people to contact, and the new people suggested (and sometimes supplied) literature for review.

Extensive telephone interviews were conducted with eighteen experts in the offshore oil industry, most of whom are design engineers or fracture control "generalists." The interviews covered five key areas: (1) scope of the fracture problem, (2) current practices, (3) identification of immediate cost-effective improvements, (4) identification of areas for further research, and (5) additional opinions/references. Thus, while the most direct outcome of the Task 1 survey was the definition of current practices (Section II of this report), the material gathered during completion of this task formed the basis for defining future needs as well (Tasks 2, 3, and 4).

Since the interviews averaged over two hours in length, and since they were not taped, the authors were concerned about possible misunderstandings and misquotation. The phone notes from these interviews were sent to the participants for correction. Not only did this ensure that the information gathered was an accurate representation of each man's opinion, but it often resulted in the interviewee including additional material and references.

The report necessarily reflects a U. S. focus, since U. S. participants are the major concern of the Committee, and since only U. S. design, construction, and operating companies were contacted during the telephone survey phase of this contract. Although several of these companies (and interviewees) have experience with European operating environments and regulations, this experience has not been researched as extensively or reported with the same degree of confidence as the information on U. S. practices. Also please note that the report emphasises the occurrence and prevention of structural failures. Detailed discussion of the reduction of their consequences, such as through better evacuation plans or designs to withstand collision damage, is outside the scope of this report.

Once completed in draft form, the "Summary" report (Section II) was sent out for review. It was reviewed by the Project Advisory Group (composed of members of the Committee on Marine Structures and the Ship Structure Subcommittee) in October of 1982 (Sections 1 through 4) and in January of 1983 (Sections 1 through 7), then as a complete draft report in late 1983. It was also sent to various overseas experts to verify references to European practices. This final report has been modified to reflect the questions, comments, and corrections received from these various sources.

In reviewing how the procedures currently used constitute an informal fracture control plan, holes and weaknesses in the practices were identified and indications of new directions in research, particularly in materials and design for frontier areas came to light. Many of the current and future trends identified in the "Recommendations" (Section III) stem from the enthusiastic recommendations (or equally enthusiastic condemnations) voiced by participants in the telephone survey. Others were gathered from the literature and from the authors' own experienbce in fracture control. The "Recommendations" section references the "Summary" heavily, so that there is a clear correlation made between the recommended practices and the historical and operating environments from which these have emerged.

II. A SUMMARY OF CURRENT PRACTICES AND TRENDS FOR FRACTURE CONTROL OF FIXED STEEL OFFSHORE STRUCTURES

1.0 INTRODUCTION

1.1 Scope

This is a summary of the current practices and trends that constitute the fracture control plans for fixed steel offshore structures used by their designers, builders, and operators. The practices used for structures located in the U.S. Gulf of Mexico are emphasized; however, American practices outside of the Gulf of Mexico, as well as abroad, are mentioned when appropriate. A brief comparison with current practices used in the North Sea (Norwegian and British sectors) and a discussion of the scope of the fracture problem are included for completeness.

Information for this summary was gathered from the "API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms," API RP-2A, Thirteenth Edition, published by the American Petroleum Institute, Washington, D.C. This document will, hereinafter, be referred to as the API RP-2A. Other important references are listed at the end of each section, although no effort has been made to list all the references used. Knowledge gained through the authors' personal communications with members of the offshore industry, especially in telephone interviews conducted as part of this survey, has been incorporated. Attempts were made to contact offshore operators for detailed service experience; however, what little information was offered to the authors was only provided confidentially and off-the-record. Finally, the authors' own experience with fracture control and offshore structures is included.

1.2 Fracture Control Background

Fracture control is the rigorous application of those branches of engineering, management, manufacturing, and operations technology dealing with the understanding and prevention of crack initiation and propagation leading to catastrophic failure. Fracture control plans as such did not exist until about 1940. Until then fracture was controlled implicitly by low working stress levels and evolving design procedures based on trial-and-error experience. When fracture did occur it often was not catastrophic due to the high degree of redundancy built into the structures. If a failure were catastrophic (often in prototype or early production structures), subsequent designs would often use large factors of safety and thus lower working stresses.

Fracture control has recently become an important design consideration. Modern high strength materials allow the designer to use higher working stresses, but often at the expense of lower ductility and less "forgiveness" in the material due to decreases in resistance to aggressive environments and/or crack-like defects. At the same time, better analytic techniques and understanding of structural behavior (e.g., dynamics) have led to reduced redundancy and smaller factors of safety. Thus some of the controls implicit in past design methods have been removed.

In the 1940s, attention was drawn to the fracture problem by the cracking of a large number of World War II ships, in particular by the brittle fracture and sinking of Liberty ships. Study of this problem led to design rules which minimized stress concentrations. These rules, along with further research in the 1950s, led to the use of improved notch- and crack-toughness materials by some designers.

Thus the engineering application of fracture mechanics was born largely to prevent brittle fracture in ships. Today fracture mechanics is used to predict initiation and arrest of brittle (and several types of ductile) fracture, fatigue and other subcritical crack propagation rates, and critical crack sizes leading to final fracture in many kinds of structures. For example, fracture control plans based on the principles of fracture mechanics are used or proposed for pressure vessels and piping in nuclear power plants, turbines in power plants and jet engines, steel bridges and ships, military and commercial aircraft, and the space shuttle.

While it is still rare to find formal documentation and procedures which emphasize integration of the subspecialties of fracture control, attention to each subspecialty has been increasing and some integration is guaranteed by the negotiations and trade-offs needed to satisfy the subspecialists. Thus, fracture control plans, whether explicit or implicit, govern design stress levels, stress concentrations, welding procedures, welding defects and inspections, and material properties such as fracture toughness and crack growth resistance. They also provide for redundance or "fail-safety" to maintain the safety of a structure in the event of the fracture of a part. The philosophy behind these plans may be simply described as to:

1. Prevent cracks when possible;
2. Contain or tolerate growth of those cracks not prevented;
3. Contain a fracture within a part or tolerate the loss of the part if a crack should grow critically.

When implemented, a fracture control plan uses both seen and unseen elements. Some visible elements are, for example, the specification of material properties and inspection procedures. Some unseen elements are among those, such as the use of prequalified joint configurations, which control stress concentrations. Thus while fracture control is often based on fracture mechanics, a fracture mechanics expert is not always necessary to perform it.

The adoption of a fracture control plan has many benefits. Obviously costly inspections of and repairs to cracked parts can be avoided by preventing the cracks from forming, or by critically assessing the severity of the cracking a priori and designing tolerance into the structure. Increased attention to cracking in the design and fabrication of a structure will lead to a higher quality structure. The ultimate result is a safer, more cost-efficient structure and a better use of resources.

1.3 Fracture Control of Fixed Offshore Structures

Fracture control practices consider the risk of fracture as a part of the entire risk of an offshore project. For ease of discussion, this report has determined four major activities related to the fracture control of fixed steel offshore platforms. First, **material selection** and **quality control** are aimed at the prevention of brittle, and types of ductile, fracture and fatigue due to substandard material properties. Second, **design** provides the structure with resistance to crack growth and tolerance of damage. Third, **construction phases** are conducted and inspected in such a way as to minimize substandard fabricated details (especially welds), initial defect sizes, and detrimental residual stresses. And fourth, **operation** and **inspection*** are carried out to maintain the integrity of the structure. In examining the current practices used in the fracture control of these structures, it is necessary to consider all practices used in the four major activities and see how they may relate to fracture control.

The current practices related to fixed steel offshore structures constitute a fracture control plan, whether or not explicitly or formally stated as such. Much of the documentation of this plan can be found in industry publications (e.g., API RP-2A and the American Bureau of Shipping's "Rules for Building and Classing Offshore Installations" (referred to hereinafter as the ABS Rules**), professional journals (e.g., American Society of Civil Engineers, or ASCE, journals), and the proceedings of technical conferences (e.g., Offshore Technical Conference, or OTC). Also many of the practices summarized in this report are discussed in more quantitative detail by P.J. Fisher in the proceedings of the 1981 Conference on Fatigue and Offshore Structural Steels.

The most basic American fracture control document is the API RP-2A, "API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms," which is not a code or regulation, but a compilation of recommendations describing currently acceptable practices. It was first issued in October 1969, and is now in its thirteenth edition. Because

*Inspection may be treated as a separate activity (see Section III:4.4) but, because most inspection occurs before and during the operation phase, is considered here as a part of that activity.

**As noted in the references, the 1982 draft version of this document was used in preparing this report, and that version has not been checked against the nonavailable 1983 ABS Rules.

American experience has been mainly in the Gulf of Mexico, the API RP-2A generally represents that experience. Two types of structure covered by this document are discussed next.

> **Template Platform:** A template-type platform consists of three parts. The jacket is a welded tubular space frame which is designed as a template for pile driving and as lateral bracing for the piles. The piles anchor the platform permanently to the sea floor and carry both vertical and lateral loads. The superstructure is mounted on top of the jacket and consists of the deck and supporting trusses necessary to support operational and other loads. Generally, template-type platforms are carried from the fabrication yard to the site on a barge and are either lifted or launched off the barge into the water. After positioning the jacket, the main piles are driven through the jackets' legs (usually four or eight), one through each leg. Other piles, "skirt piles," may be driven around the perimeter of the jacket as needed.
>
> **Tower Platform:** A tower platform is a tubular space frame which has a few, generally four, large diameter legs (e.g., 15 feet). The tower may be floated to the site on its large legs without a barge; such a tower is also known as a "self-floater." Piles, when used, are usually driven in groups or clusters through sleeves located either inside or outside the large legs. When piles are not used, spread footings may support the tower.

The ABS Rules apply to "fixed structures" defined as pile-supported platforms, gravity structures, guyed towers, and (with other requirements) to articulated buoyant towers and tension leg platforms. All of these are discussed, individually or collectively, in this summary report. Figure 1 illustrates several types of platforms.

In addition to oil and gas drilling and production platforms, fixed steel structures have also been used for light stations, oceanographic research, supertanker terminals, and other applications. However, the main interest of this report is in drilling and production platforms, which are steel tubular space frames.

Offshore technology is growing rapidly. The first shallow water steel template was installed in twenty feet of water in 1947. Today there are over 2000 platforms installed in the Gulf of Mexico, in water depths of up to 1050

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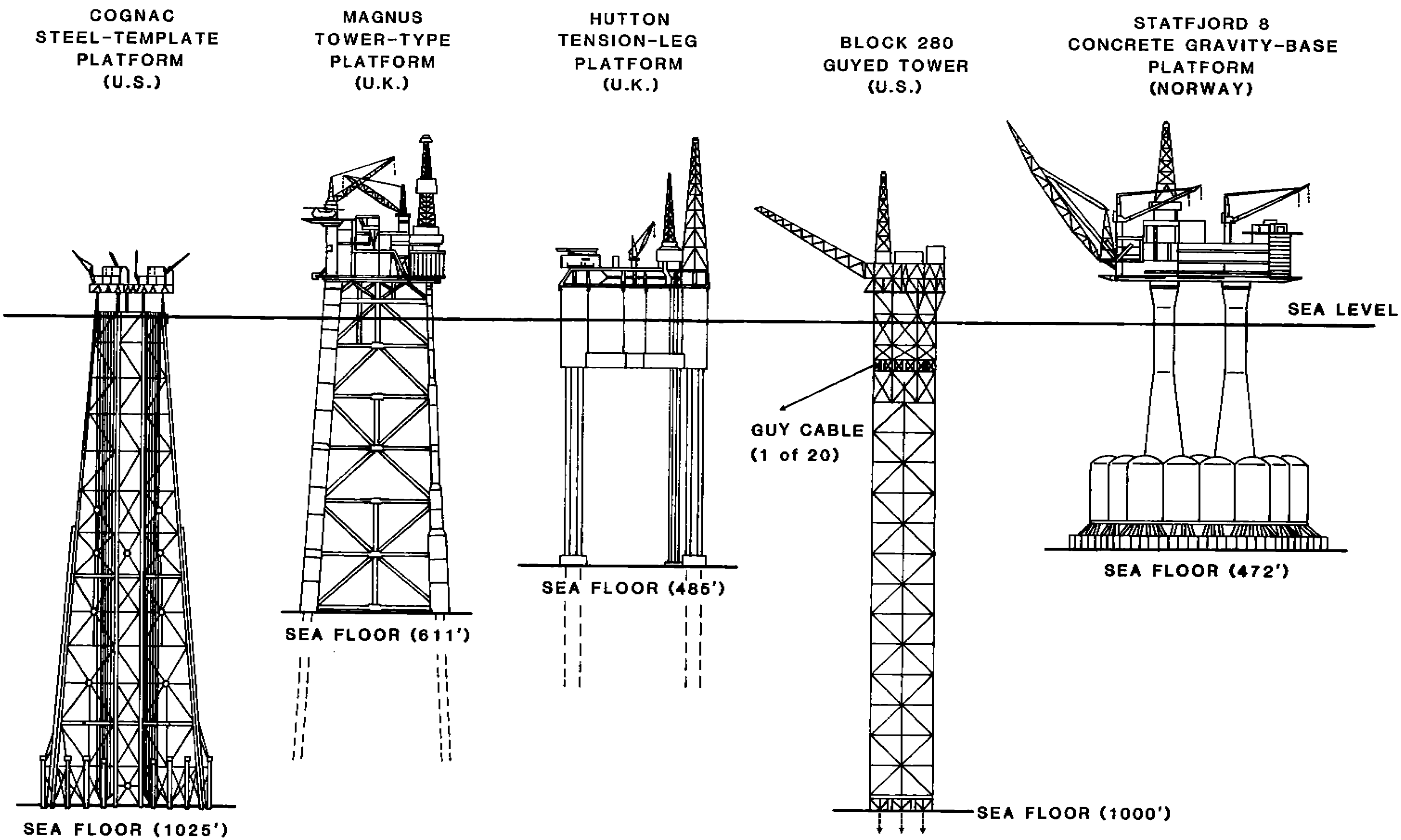

Figure 1. Examples of different types of platforms.

1/2" Head

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feet. Along with this growth in technology, fracture control related practices have also changed. The API RP-2A is now in its thirteenth edition in as many years.

The primary motivation for all this development has been the extension of the technology to deeper and rougher waters. The ABS Rules/1982 Draft, in its foreword, states that the document is specifically aimed at "unique structural types or structures located in frontier areas, which are those characterized by relatively great water depth or areas where little or no operating experience has been obtained." New frontiers have opened in the North Sea, Southern California, Alaska, Canada, the East Coast of the United States, and all around the world. Aiding this development has been the concurrent growth in computer-aided structural analysis and design. Today's large complex structures are designed with computer programs which characterize wave loads and analyze dynamic response, stress, and fatigue life.

The prevailing types of designs have also been changing. For example, early tubular joints were designed to transfer loads through gusset plates. Modern tubular joints transfer loads through shell action, without the use of gussets. Large joints in deep water platforms are often stiffened internally with rings, as in aircraft frames. Future trends in the design of offshore structures will, undoubtedly, involve more complex analyses and more thorough understanding of tubular joints.

Thus, the fracture control practices of this industry are clearly a fast moving target. A summary of current practices must, therefore, not only define the average, or typical, practice and the variation about the average, it must define the trend, or direction, of those practices. This is a goal of this project.

1.4 A Summary of Current Practices and Trends

After a short discussion of the scope of the fracture problem (Section 2), the current practices of the four major activities related to fracture control will be summarized (Sections 3, 4, 5, and 6). Emphasis is placed on Gulf of Mexico practices because most American offshore structures are located there. The concluding section (Section 7) will compare Gulf of Mexico practices with North Sea practices.

The four current practices sections will discuss material selection, design, construction (including fabrication, transportation, and installation), and operation and inspection. In each section, the philosophy of the current practices with respect to fracture control will be indicated, including fracture control goals and trade-offs between goals made when using particular practices. The current practices will be summarized. Quality control measures such as testing or inspection will also be summarized. And a brief discussion will highlight current trends, points of controversy, etc. A short list of principal references for the subject will conclude each section.

Offshore technology has spread around the world. In spite of the number of different areas being developed, international practices tend to fall into two types. One type follows American Gulf of Mexico practices. The other follows North Sea practices.

The practices used in the North Sea have grown out of a different physical environment and a different regulatory structure than those in the Gulf of Mexico. In a sense, they represent the opposite philosophical pole. These practices are documented by the Det norske Veritas "Rules for the Design, Construction and Inspection of Fixed Offshore Structures," 1974 (the DNV Rules), and by the United Kingdom Department of Energy "Offshore Installations: Guidance on Design and Construction," 1977 (the UK DOE Guidance).

The final section of this report compares the main differences between Gulf of Mexico practices and North Sea practices. The practices found elsewhere in the world, or the United States, will probably resemble one or the other, or will be somewhere between the two.

1.5 Principal References*

1. American Petroleum Institute, "API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms," API RP-2A, Thirteenth Edition, Dallas, Texas, January 1982.

2. Det norske Veritas, "Rules for the Design, Construction and Inspection of Fixed Offshore Structures," Oslo, Norway, 1974.

3. United Kingdom Department of Energy, Petroleum Engineering Division, "Offshore Installations: Guidance on Design and Construction," Her Majesty's Stationery Office, London, 1977.

4. Marshall, P.W., "Fixed-Bottom, Pile-Supported, Steel Offshore Platforms," ASCE Convention, Atlanta, Georgia, October 1979.

5. McClelland, B. (ed.), The Design of Fixed Offshore Structures, to be published by Van Nostrand Reinhold, New York, 1982.

6. American Bureau of Shipping, Rules for Building and Classing Offshore Installations, ABS Special Committee on Offshore Installations, New York, (Draft) 1982.

7. Fisher, P.J., "Summary of Current Design and Fatigue Correlation," in "Fatigue in Offshore Structural Steels," Conference Proceedings, London, February 24-25, 1981.

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*All references cited in this document were current or the most recent available to the authors at the time this study was undertaken. The ABS rules were finalized in 1983.

2.0 THE SCOPE OF THE FRACTURE PROBLEM

2.1 Introduction

While it is well known that welds often crack during fabrication of fixed steel offshore structures, and that divers' inspections sometimes reveal cracked or parted joints, or even missing braces, there is a reluctance of some members of the offshore industry to admit that cracks exist in these structures. This apparently is due to a desire to maintain the public's confidence in offshore operations. In truth, cracks or crack-like defects always exist in all of the welds and heat-affected zones of steel structures, whether they be offshore platforms, bridges, buildings, or nuclear reactors. The question is not, do they exist, but rather, how significant and serious are they?

This section will briefly examine the common sources of crack initiation in fixed steel offshore structures and some typical examples. The significance of these types of cracking will also be considered.

2.2 Sources of Crack Initiation

Cracks or crack-like defects may initiate during the construction of an offshore structure, during its transport and installation, or after installation, during its operation. The first source of crack initiation encountered in the life of any structure is a defect in the original material. In steel plate such a defect might be a porous region, or a non-metal inclusion or lamination. In good practice the largest and most significant of these defects are detected and rejected before the plate is used.

There are several opportunities for cracks to initiate from the welding process. Poor weldability of the materials or poor welding technique can leave large crack-like defects in the weld. Certain joint configurations lead to heavy restraint of the welds, which results in high residual stresses and, sometimes, cracking as the welds cool and shrink. The worst examples of this type of cracking are normally caught in inspections during fabrication, and can be prevented by using the proper preheat and other welding procedures.

Improved and special welding procedures can also alleviate problems with material embrittled by welding. Such material is susceptible to brittle fracture when loaded. Also, the use of material with special through-thickness ductility in critical locations can reduce the chance of fracture by lamellar tearing, and of brittle crack extension in the rolling-plane of leg and brace walls subjected to significant out-of-plane loads.

Finally, during construction, there are many opportunities to overload a joint. For instance, assembly of the frames may require the coordinated effort of several cranes. Mispositioning a crane, not balancing the loads correctly between cranes, or sudden impact loading could lead to joint overload, and hence crack initiation. Cracks may initiate in several ways during the load out, transport, launch, and operation of the structure. Impact damage is probably the most common cause. A boat collision or a dropped object from the deck are examples of this. In these cases, the operator usually knows when (and perhaps where) to check for crack initiation.

More subtle sources of crack initiation are corrosion and fatigue. Since these processes occur slowly and their cracks evolve over a period of time, continued or periodic surveillance is required to find these cracks.

Cracks due to overloads may be suspected after a severe environmental loading such as a storm or an earthquake. However, cracks may initiate, but not be anticipated, if the ordinary loading is not properly considered in design, i.e., if the structure is underdesigned. In the first case, overload, the operator usually knows where cracks may initiate and should find them easily. In the second case, underdesign, the operator probably doesn't expect cracks to initiate, so they might not be discovered until they become rather large, or make themselves known by causing problems.

2.3 Typical Examples

With good welding practice and proper controls, cracks and crack-like defects large enough to degrade the structure are usually prevented or caught and rejected during the welding process. However, there are classes of defects that are known to exist in a welded joint but are allowed to remain.

A small defect in the weld root is one example. When found, the defect and the joint are considered for their "fitness-for-purpose,"* that is, they are evaluated to see if, even with the defect, the joint will still accomplish its intended purpose (i.e., strength and useful fatigue life). Thus, these cracks are not considered to be problems.

Lamellar tearing was a serious problem about ten years ago. The extra-thick plate used in North Sea platforms was particularly sensitive to this problem. Today, when conditions of heavy weld restraint and through-thickness loading occur, a special plate material is used, with high through-thickness (or z-direction) ductility, which resists lamellar tearing and in-plane brittle crack extension.

Crack indications are sometimes picked up with underwater ultrasonic testing only a few years after the platform has been installed. In the cases where the indications correspond to real cracks, many questions are asked. The first always is, when did the crack occur? Sometimes the cracks initiated during fabrication, but were not found; possibly those welds were not inspected thoroughly at that time. In other cases, it is suspected that they initiated from an overload during installation or from fatigue during transport. If either of these is the case, the operator's concerns are clearly different than in the case where no significant crack existed at the time of installation, and the crack has suddenly appeared in a few years. For this serious situation of structural degradation with time, the operator must determine whether the structure is underdesigned, or whether the crack is due to another problem, and then must estimate how much time is available before remedial measures (inspection, repair, or replacement) are needed.

An apparently common problem is to have heavy objects drop off the deck and strike one or several braces on their way down. For example, pile followers, used as an (above water) extension to the hammer when the top of the pile is under water, have been dropped. Obviously, depending on the

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*"Fitness-for-purpose" will be defined and discussed in more detail in the sections on Construction and Operations and Inspection.

object dropped, the resulting damage could be negligible, a dent in a brace, a crack, a gouge, a tear, or complete separation of a joint.

Corrosion, as mentioned, can be a subtle problem; however, it isn't always. An improper or inadequate ground for an offshore welding operation can turn the underwater welds into electrolytic anodes, resulting in rapid, highly detectable, corrosion of the weld metal. The damage may be corrosion pitting or more severe knife-edge slices (crevice corrosion) into the weld.

Finally, it is known that some of the first platforms installed in the North Sea have had problems with fatigue. In early North Sea designs fatigue was not explicitly analyzed and the severe environment (wave load spectrum) for fatigue led to cracking. Another problem for later platforms has occurred with the horizontal framing supporting the well conductors at the first level below the surface. In those designs, vertical wave forces probably were underestimated and repeated joint overloads also led to fatigue cracking, even though fatigue was considered.

2.4 Conclusions

It appears that there are two basic types of fracture problems. One type occurs because of poor workmanship or direct human error. Examples of this are significant crack initiations due to poor welding technique, construction overloads, and falling objects. Fracture control is achieved in these cases by preventing the errors from occurring.

The other type of problem relates to new technology or new frontier areas. In these cases, as experience is gained the problem diminishes in later designs. Examples are the weldability of new materials, lamellar tearing in thick plates, and fatigue in the North Sea. Experience has shown that the first generation of platforms to be installed in a frontier area has the most problems, the second has fewer, and by the third generation, most of the problems have been worked out. Fracture control is best achieved in these cases by first being aware of the unique characteristics and demands of a technology or area, and then by rapidly gaining experience and applying appropriate measures.

2.5 References

1. Telephone interview with Charles P. Royer and Nick Zettlemoyer, Exxon Production Research Company, Houston, Texas, on September 14 and 16, 1982.

2. Telephone interview with Peter Marshall, Shell Oil Company (USA) Houston, Texas, on August 17, 1982, from 12:30 - 2:00 p.m. PDT.

3. Rolfe, S.T. and J.M. Barson, Fracture and Fatigue Control in Structures, Prentice Hall, Inc., New Jersey, 1977.

3.0 CURRENT PRACTICES: MATERIAL SELECTION

Of the four major activities related to fracture control, the current practices used for material selection exhibit the most variation in the industry. There are several reasons for this; a major one is because there is disagreement over what material properties are needed to control fracture.

This section discusses the questions: What properties are selected and why? How are they specified? What tests are done to see that the materials have the desired properties? And, what are the current thoughts on how these practices may be deficient and how best improved?

3.1 Philosophy

The fundamental fracture control goal in material selection is to assure that the material will behave at least as well as assumed in design calculations. For tubular joints in offshore structures this means that the material must be able to accommodate large amounts of plastic deformation without fracture. Thus, there are two sub-goals: to limit material defects which might initiate fracture, and to avoid material susceptible to brittle fracture at the service temperature of the structure.

There is an important trade-off to be considered in material selection. To decrease the weight of the structure, a material with a higher yield stress, i.e., a stronger material, will often be chosen for the joints. There is, however, often an inverse correlation between the strength and the fracture resistance, or toughness, of a material. That is, a stronger steel is usually less tough. So when choosing a stronger material for the joints, it is possible a material less resistant to fracture is also being chosen. Therefore, the trade-off between strength and toughness should be carefully considered. One way to avoid the strength-toughness dilemma is to bear the expense of more costly steels for which both properties are adequate. This option creates a more complex trade-off among strength, toughness, and cost.

3.2 Current Practices

3.2.1 Desired Properties

General properties such as yield strength, ultimate strength, and ductility are standard. In special cases, through-thickness ductility may be needed to prevent lamellar tearing.

To limit defects which might initiate fracture, tolerance levels for porosity, inclusions, and laminations in the rolled plate are set. Since the presence of material defects is controlled by the steel manufacturing process, the process itself may be specified. The chemical composition of the steel is also controlled to assure the material's key mechanical properties and weldability. Carbon-equivalent is the most important relevant measure for weldability and some other key properties.

Brittle fracture is a frequently catastrophic failure mode in structural steels, initiated by a crack or crack-like defect, that occurs suddenly and with little or no warning, such as through prior plastic deformation. To avoid brittle fracture, material selection is based on the Fracture Analysis Diagram (FAD), of which the most important element is the nil ductility transition temperature (NDT). The NDT represents the temperature below which fracture is almost entirely brittle and the probability of ductile failure is negligible. The FAD plots the nominal dynamic stress required to propagate a given flaw size to failure in a Naval Research Lab (NRL) Drop-Weight Test plate, as a function of the test temperature, which is calibrated against the NDT (see ASTM Standard E208-69). This test, which dynamically bends a sharply-notched plate, closely simulates the strains and strain rates of a dynamic fracture initiation at the highest-stress locations (hot spots) of welds in tubular joints. Cracks are always initiated dynamically during this test; a specimen passes the test only if the crack is arrested before it can break the plate. A family of S-shaped, stress-versus-temperature curves is plotted for different initial flaw sizes. Based on these data, if the joint material is to withstand moderate flaws at stresses well above yield, the NDT of the material must be at least 45°F below the design temperature. The NDTs for materials in other applications can be similarly determined. Thus, to avoid brittle fracture, according to this philosophy, the NDT of the materials should be below temperatures less than, and defined in terms of, minimum operational temperatures.

3.2.2 Specifications

Standard mill tests are used to determine material defect levels, carbon-equivalent, strength, ductility, and so forth. The specification of brittle fracture properties such as toughness is less standardized. Traditional linear elastic fracture mechanics (LEFM or K_{IC}) fracture toughness testing methods are typically of little or no value except as conservative bounds. This is because most current practices dictate that, at critical joints, if K_{IC} can be determined using thicknesses less than or equal to structural details, brittle fracture resistance is already too low.

Given the usually unsatisfactory ability of K_{IC} tests to assure desired toughness levels, the standard practice is to specify notch toughness criteria for either NRL Drop-Weight Tests or Charpy V-notch absorbed energy impact tests. The API RP-2A gives the testing temperature conditions for underwater tubular joint material in its Table 2.9.3. For example, for joints with diameter-to-thickness ratios between 20 and 30, test on flat plates should be 54°F below the lowest anticipated service temperature. NRL Drop-Weight Test criteria call for no-break performance, i.e., cracks do not propagate to failure in the test plate, at the specified temperature.

Charpy V-notch energy criteria call for at least 15 ft-lbs. before specimen fracture at the specified temperature for low strength (Group I) steels, and at least 25 ft-lbs. for medium strength (Group II) steels. These Charpy energies are thought to be slightly above the lower shelf of the impact energy-versus-temperature curves (i.e., the energy corresponding to the NDT) for these materials. Thus the Charpy tests and Drop-Weight Tests are intended to assure that the NDT of the material is below the necessary temperature.

Some operators specify essentially the same criteria as the API, except the testing temperatures may be more or less severe. Other operators specify different Charpy energies. This implies either a different interpretation of the FAD (in terms of flaw size or stress level), or a different expectation for the material's lower energy at the NDT.

Some operators rely entirely on the supposed generic toughness of a material and do not perform toughness tests. The API RP-2A groups common steels, such as ASTM A36 or ASTM A572 Grade 42, into generic toughness classes, A, B, and C. Class A steels are supposed to have the highest generic toughness and Class C the lowest.

The ABS Rules contain similar classifications of steels by their toughness as a function of Grade (I, II, and III) and plate thickness. Both the ABS and API contain optional methods, qualitative (i.e., experience-based) and quantitative for assuring adequate toughness. The quantitative specifications are based upon the Charpy V-notch impact test, which is discussed in the next section. This inexpensive small-specimen test is used throughout the industry as a semi-quantitative toughness test for a variety of purposes but, especially, for quality control to assure adequate toughness over the encountered spectrum of materials, plate thicknesses, heats, loading directions, and proximities to the weld (that is, whether in base metal, weld metal, or heat-affected zone). The Charpy test energy results (CVE) cannot be used directly for design computations. However, CVE is sometimes used indirectly through correlation with more quantitative parameters such as described below.

Another way of specifying toughness is through the crack tip opening displacement, or COD (also CTOD), of the material. This is a fracture mechanics-based measure of the amount of plastic strain withstood at a crack tip in a ductile material before fracture occurs under static loading. Properly related to local stress and strain, the COD is suitable for design calculations. Thus, this test is more useful than the Charpy test for establishing quantitative relationships among loads, geometry, material properties, and crack size. It is, however, more expensive and employs larger specimens than the Charpy test, so that its use is normally restricted to material qualification, structural certification, and defect evaluation, rather than quality control. COD is the accepted measure of fracture toughness for British practice in fitness-for-purpose evaluation of weld defects in ductile steels. Its use is currently making its way into American practice, especially for fitness-for-purpose specifications and structural and defect evaluations.

3.3 Testing

Quality control and assurance for material selection is accomplished by testing samples of the material to be used in fabrication. There are standard tests, in particular, those specified by the American Society for Testing and Materials (ASTM), that cover composition, toughness, strength, and so forth.

3.3.1 Toughness Testing

Toughness values are used for quality assurance, as part of fracture control plans, and for detailed fracture assessment calculations. However, there is considerable debate as to the best test to use for these varying purposes. There are four basic types of toughness tests used for offshore structures:

- The Charpy V-notch (CVN) impact test
- The Drop-Weight Test (DWT), or the closely related Dynamic Tear Test
- The Crack Tip Opening Displacement (CTOD or COD) test
- Fracture mechanics tests to measure critical stress intensity factors (K_C or K_{IC}) or critical values of the J-integral (J_C or J_{IC}). Since COD results can be used (usually) more effectively in fracture mechanics analyses, and since current trends dictate that offshore materials should be tough enough to invalidate K_{IC} tests of specimens taken from the offshore structure, little description is provided below for K_{IC} and J_{IC} testing.

As described below, these tests vary in a number of ways: cost and difficulty, degree of familiarity, whether they measure crack initiation toughness or crack propagation toughness or both, and whether they are static or dynamic.

Charpy Test. This test is the simplest, most familiar, and most widely used toughness test. It is covered by an ASTM standard, A370-77. A small (10 mm square in cross section) notched specimen is broken dynamically by a swinging pendulum. The energy to break the specimen is recorded. This CVN energy (CVE) is the toughness parameter most commonly extracted from the test results, although the fracture appearance may also be used as a parameter. The CVN energy increases with test temperature from the lower shelf, through the transition region, up to the upper shelf at higher temperatures. A plot of energy versus temperature may be drawn.

The CVN test is essentially qualitative and the results cannot be directly related quantitatively to allowable stresses in the structure without extensive data demonstrating the correlation between CVE and such parameters as K_{IC}. Its use is based on satisfactory experience with materials that meet specified minimum standards for energy absorbed in the test. Fractures were never observed in Liberty ship plates during World War II when the CVN energy of the steel was 15 ft-lb or greater. This 15 ft-lb criterion is still commonly used, and is the specified minimum level for Class B, Group I steels in API RP-2A. However, it may provide an inadequate guarantee against fracture for some steels or for higher design stress levels. API RP-2A specifies a minimum of 25 ft-lb for Class B, Group II steels. Some operators may require higher levels.

The ABS Rules, Section 10.1.3, contains similar Charpy-based, optional specifications and "toughness criteria for steel selection." Specified minimum averages (for longitudinal-direction CVN specimens) also range from 15 to 25 ft-lbs depending on the Grade (I, II, or III) and plate thickness. The ABS Rules contain other material toughness controls. These include direct controls relating to transverse-direction Charpy properties and indirect controls such as on the maximum thicknesses (in Table A.3 for material selection guidelines) as a function of steel grade, service temperature, and defined criticality of material application areas.

The advantages of the CVN test are that the specimen is cheap and simple to fabricate and test, and that it is universally familiar. It is widely used for quality control purposes. The disadvantages of the CVN test include the fact that the rate of loading and the thickness of the specimen are usually not very similar to those experienced by the structure. The results of the test cannot be directly related to allowable stresses in the structure. Further, the energy absorbed includes both initiation energy and energy to propagate a crack through the specimen. It has been argued that this is a drawback on the grounds that the most important toughness property for hull steel is resistance to and arrest of dynamic crack propagation, since cracks will in any event initiate at weld flaws. In this argument (which conservatively assumes that such crack initiation can occur dynamically), the fracture control function of the base plate is to arrest dynamic crack propagation, not to prevent dynamic crack initiation. Hence, according to this argument, the test used should measure resistance to a dynamically propagating crack. This is the "fracture-safe" philosophy. The DWT test described below is such a test.

Drop-Weight Test. The DWT was developed at the Naval Research Laboratory by Pellini and co-workers (see, for example, NRL report 6957). Crack initiation energy is reduced to low levels by using a brittle starter weld (or, in the closely related dynamic tear test, by using a very sharp pressed notch). Thus the test measures, predominantly, propagation and arrest energies. The specimen is considerably larger than the Charpy specimen (ranging from 5/8 x 2 x 5 inches up to 1 x 3.5 x 14 inches). This is important since apparent material toughness generally falls as specimen size increases (all other factors being equal). The DWT test uses material thicknesses more representative of those used in offshore structures than does the Charpy test. The test is covered by ASTM Standard E208-69.

The main parameter extracted from the DWT test is the nil-ductility transition (NDT) temperature. This is the maximum temperature where the initial flaw propagates to at least one edge of the plate, at the plate surface, when the nominal stress in the surface is at yield. For temperatures higher than NDT, the crack will be arrested even at yield stress levels. The material is chosen so that the service temperature will always be above NDT. Any crack in a similar, monotonically-decreasing bending stress gradient should therefore be arrested. Those in the offshore industry who use this test consider that it is more representative of tubular joints, in terms of flexural loading, presence of a notched weld, limited yielding, realistic plate thickness, and lower strain rate, than the Charpy test. Furthermore they feel that it is a more realistic representation of the most dangerous failure mode in the structure, where a crack may be initiated in a weld and arrested in the plate.

The DWT has the disadvantages that the specimen is more costly to fabricate and test than the Charpy specimen. Correlations have been formulated between Charpy test results and NDT which allow the CVN test to be used instead of the DWT to measure NDT, although at some cost in accuracy. DWT test results can be approximately related to allowable stress levels in the structure using the Fracture Analysis Diagram. The correlation is both qualitative and approximate, however.

Crack Tip Opening Displacement. A further type of test which has been proposed to replace the CVN test is the crack tip opening displacement (CTOD or COD) test (see British Standard 5762). COD can be measured when the crack initiates in the specimen, or when the specimen reaches maximum load. Measurements made at or close to crack initiation are used in the design philosophy where reliance is placed on the static initiation barrier. COD measurements are popular in Europe, particularly Britain, and are rapidly gaining popularity in the American offshore industry. The COD test is normally a "static" test, i.e., it usually measures resistance to initiation or propagation under slow loading conditions. This is in marked contrast to the CVN, DWT, and DT tests, which all measure values only under dynamic, impact loading conditions. COD values in this context are used as "specification tests," i.e., a minimum allowable value is specified. However, as noted below, in a different type of fracture control approach, COD values can be linked quantitatively and directly to allowable stresses and crack sizes in the structure (although with some degree of uncertainty), unlike the results of CVN, DWT, and DT tests.

The British standard for this test calls for a notched three-point bending specimen to be slowly loaded until it fractures. The measured opening of the notch can be translated into the opening at the tip of a crack when fracture occurs. American standards for this test are being developed. Among the difficulties with interpreting the test results are: where is the crack tip? does "fracture" mean "fracture initiation" or "final fracture?" how are differences in stress gradient between specimen and structure best accounted for?

While COD is becoming a routine testing method and specification in North Sea practice, it is only now getting attention in this country. The authors are unaware of any American fixed offshore structure to be designed with this specification. However, COD testing has been used retrospectively to determine acceptance criteria for weld defects found in American fabrication yards and to specify a new material for one that has demonstrated inadequate toughness in an actual platform.

Failure Assessment Diagram (FASD) Procedure. The Failure Assessment Diagram Procedure (for which the published acronym is usually FAD which unfortunately matches that of the Fracture Analysis Diagram Method) is rapidly gaining acceptance as a practical competitor and/or supplement to such quantitative elastic-plastic fracture methods as the COD tests. The FASD procedure gains much of its practicality and generality from the fact that it addresses empirically two failure modes simultaneously and can be used in conjunction with almost any elastic-plastic fracture test ranging from ordinary unnotched ultimate-strength tensile specimens to COD specimens.

The FASD procedure, like the COD procedure, is considered to be a state-of-the-art technique for conservative evaluation of weld defects and has been formally validated in Supplement I to a Central Electricity Generating Board (CEGB) report by Harrison, et al. Figures 2 and 3 have been reproduced from Supplement I. These figures document the key FASD format and the validation results generated during the development of the FASD procedure. The procedure consists of evaluating the ratio S_r of the applied (σ) to plastic-collapse ($\bar{\sigma}$) stresses **and** the effective ratio K_r of applied (K) to critical (K_Q) crack toughness under the elastic-plastic conditions being evaluated. The inherent practicality, generality, and safety factors in the FASD procedure come from (1) the use of conservative characterizations of both applied loadings and material properties and (2) the conservative techniques used by Harrison, et al., to envelop their large experimental data base which includes a wide variety of different types of fracture specimens and full-scale (pressure vessel) structural simulators.

Note that one data point in each figure falls slightly within the assessment line. According to the Supplement authors, "These points are

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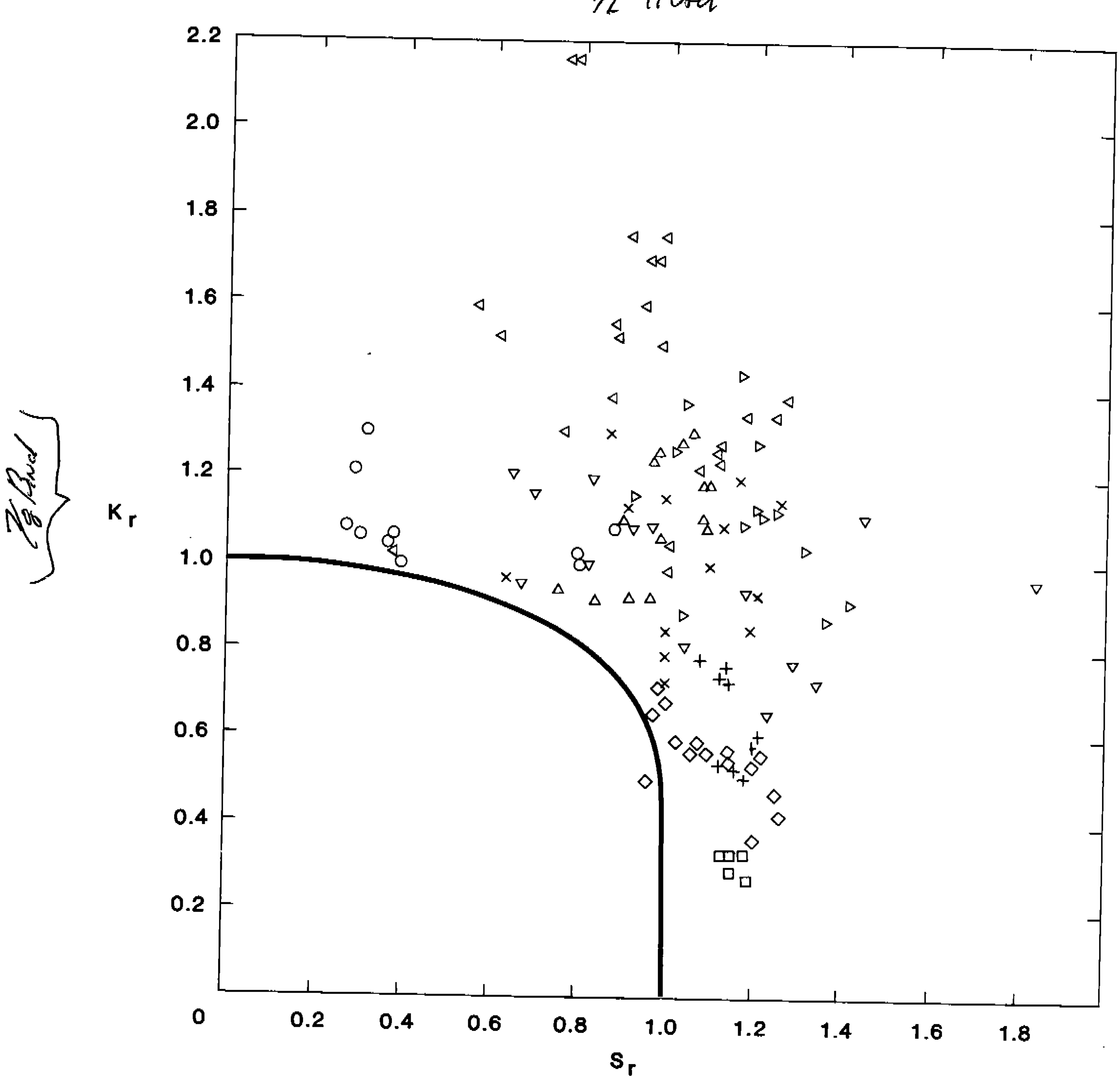

Results of analyses of data from test specimens.

Symbol	Section	Symbol	Section	Symbol	Section
△	A1	□	A4	▽	A7
+	A2	◇	A5	◁	A8
▷	A3	○	A6	×	A9

Figure 2. Taken from CEGB "Assessment of the Integrity of Structures Containing Defects," Supplement 1. Formerly Figure A.

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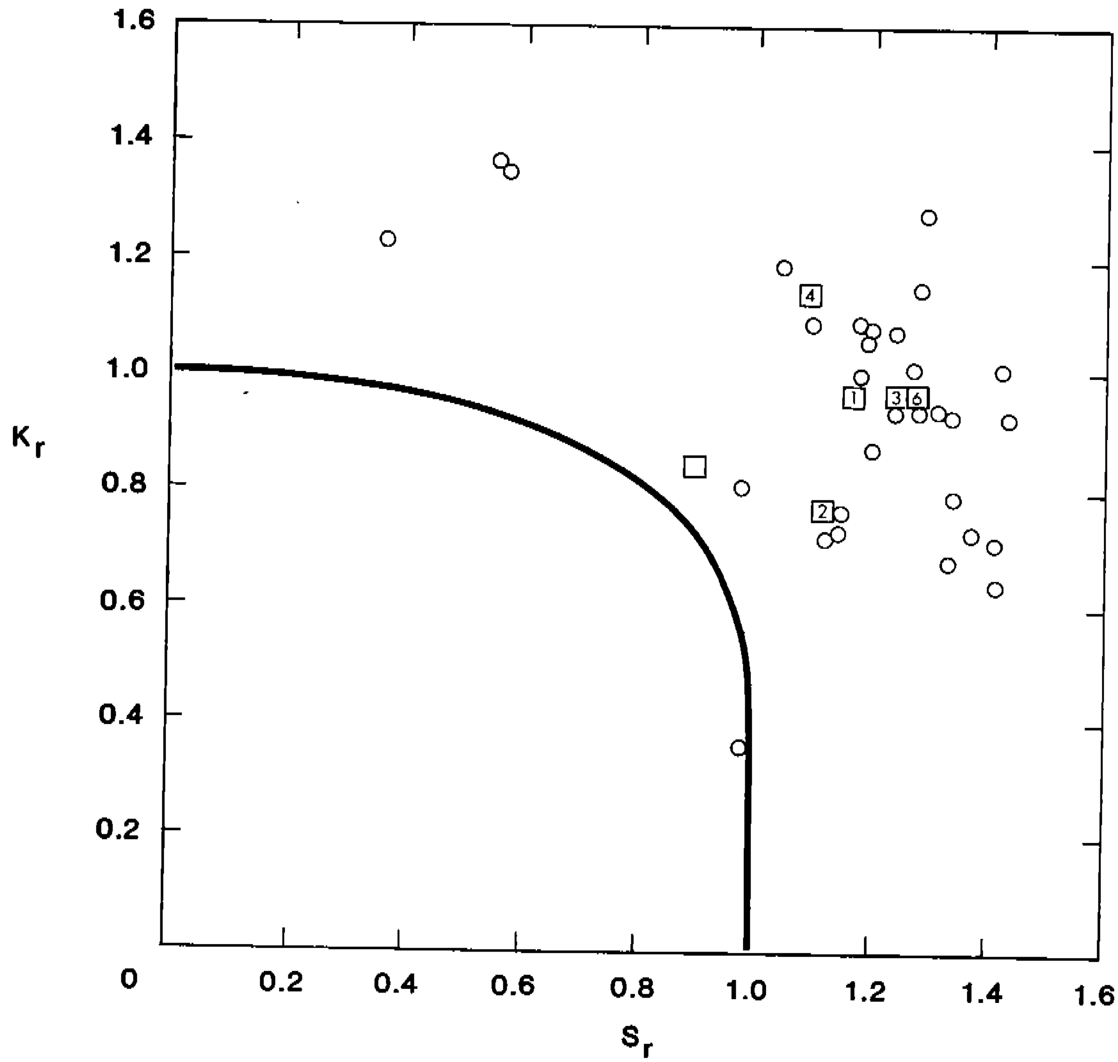

Results of analyses of data from vessel tests.

Symbol	Section
○	B1
1, 2, 3, 4, 6	B2
7	B3

Figure 3. Taken from CEGB "Assessment of the Integrity of Structures Containing Defects," Supplement 1. Formerly Figure B.

7/8" Bind

considered unreliable for reasons discussed in the text. It is concluded that these figures confirm that the Failure Assessment Diagram Procedure . . . provides an appropriate limit line for the avoidance of failure in ferritic structures."

3.3.2 Test Samples

In general, samples are taken from plates of each heat of manufacture. For special, critical applications, each piece of plate made is sampled. Samples of weldments, in general, are taken only from welding procedure qualification pieces. Rarely, during fabrication, samples may be taken of weldments made in the actual material to be used in a critical joint.

3.4 Discussion

It has been discussed that the purpose of Charpy or Drop-Weight Test requirements is to assure that the nil-ductility transition temperature of the material is below the required value determined from the Fracture Analysis Diagram. While this practice is well accepted, there are several serious limitations to this approach. First, the test results are not related to applied stress and strain (except indirectly through empirical correlations with such stress-related parameters as K_{IC} and COD), and therefore, the results are not directly usable for design purposes, or for fitness-for-purpose evaluation. Statistical correlations have been made between Charpy V-notch absorbed energies, CVE, and fracture mechanics fracture toughness, K_{IC}. The lower confidence bounds of statistically analyzed K_{IC} versus CVE data give extremely conservative values and are useful only as a lower bound on K_{IC}. Second, the small Charpy samples are not necessarily representative of the heavy sections actually used in tubular joints. For this reason the Drop-Weight and COD tests are preferred by most specialists in material toughness evaluations.

Third, testing at only one temperature does not define the entire toughness versus temperature transition curve. There is much scatter in test results, even for one piece of material. Were the transition curves to be determined for several pieces of similar material, i.e., the same ASTM specification and grade, several distinct curves would probably result. The actual NDTs would be different, as might be their absorbed energy lower shelves. And the S-shaped transition curves might have different slopes, some rising faster than others. The best piece of the sampled material would be the one that showed the most ductile behavior, that is, lowest NDT and briefest transition to fully ductile behavior above the NDT. This cannot be determined by tests at a single temperature.

Regarding the Fracture Analysis Diagram (FAD) -- while it is well accepted, not only in the offshore industry, but in others as well, there are those who disagree with its use. The FAD presents a family of curves for different flaw sizes for the nominal stress required to propagate the flaw to fracture (in the NRL Drop-Weight Test) versus the temperature of the test in terms of the NDT (e.g., NDT + 45°F). The same curves are supposed to be valid for various ship steels, no matter what their NDT. But, as just described, not only are NDTs different for different pieces of the same material, so are the transition curves. Why then should a single FAD be valid for the many different materials used in steel offshore structures?

Partly due to the above arguments, there is a trend toward COD testing for all purposes except for broad quality control, for which the CVN tests appear to be a fixture. COD material qualification specifications might reasonably be expected in the not too distant future. Of the various fracture mechanics fracture toughness measures, COD has the most immediate potential. As emphasized previously, the plane strain fracture toughness, K_{IC}, should not be measurable in the ductile steels and plate thicknesses used in offshore structures. If it is measurable, then the plate is often considered to be too brittle to be used in the first place. The J-integral, J_{IC}, could potentially be used. However, its use and applicability in the complex three-dimensional stress fields found in tubular joints is at the moment doubtful. The COD, on the other hand, is relatively easy to use (partly because it skirts the complexities of three-dimensional stress states through conservative bounds using surface stress) and there are important documented precedents for its use, most notably the British "Guidance on some methods for the deviation of acceptance levels for defects in fusion welded joints," BSI PD6493:1980.

Even with the use of COD testing there are still questions about what properties are needed. Most of the experience with COD testing is static. The loading of a tubular joint can be more dynamic. There is a disagreement among materials experts in the industry on whether a static toughness measure is enough, or if a dynamic measure is also needed. Under dynamic loading a material's strength increases, preventing plastic flow around a crack or a notch, and thus adding constraint. This constraint makes the material more susceptible to brittle fracture. Therefore, with increased strain rate, the toughness of the material decreases. This is especially true of low strength steels, and less true of high strength steels. Since critical crack extension in and some loadings of a tubular joint are dynamic, many experts are reluctant to give up the dynamic tests, Charpy and Drop-Weight.

There is also disagreement in the industry as to how much testing should be done on weldments and what criteria should be met. Should a weldment meet the same criteria as the parent plate? Some people feel that it is impossible to prevent crack initiation in a weld, and that once the crack has grown out of the weldment it is up to the parent plate to arrest the crack. For these experts, the toughness of the weldment is much less important than that of the plate. Needless to say, others disagree. One of their arguments is that the welding process puts heat into the parent plate and substantially changes the toughness of the heat-affected zone (HAZ). In their view the weld material or HAZ must arrest the dynamically-growing crack and should be tested.

Potentially, the Failure Assessment Diagram (FASD) procedure could eliminate some of the uncertainties described above with individual elastic-plastic fracture tests through its brute-force empiricism. The present authors and their colleagues have employed the FASD Procedure often and recommend its use strongly as a supplement to other methods of defect and structural fitness-for-purpose evaluations.

One final note, while fatigue is an important criteria for the design of offshore structures, there has not been much apparent concern, outside of long-term research, in the U.S. offshore industry with material S-N (stress vs. number of cycles to failure) curves and crack growth rates, "da/dt or da/dN" (for stress corrosion cracking or environmentally-assisted fatigue, respectively). Most of the published da/dN data for offshore steels comes from Europe, especially the UK. Materials are not selected for their environmental crack growth rate behavior. The reasons for this currently low emphasis on material subcritical crack behavior are apparently:

1. Fatigue has not been demonstrated to be a critical problem contributor in Gulf of Mexico applications.

2. Without environmental assistance and under a given fatigue loading condition, da/dN is not a strong function of the material.

It is believed that increased expansion into more hostile environments will result in more interest and effort in determining and modeling the subcritical crack growth properties of offshore structural materials.

3.5 Principal References

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4.0 CURRENT PRACTICES: DESIGN

Unlike the variations in material specifications, the nominal design practices used in the Gulf of Mexico are relatively uniform throughout the offshore industry. The API RP-2A recommendations form the backbone of the practice, each major design office implementing and executing the API provisions with its own procedures, analysis methods, and computer programs.

In this section the following questions are discussed with respect to fracture control. Where in the design process is fracture control considered, either explicitly or implicitly? What design procedures are used? How can the operator know if the design work is correct? What are the less well-understood design problems today that affect fracture control?

4.1 Philosophy

Traditionally, the designer is responsible for guarding against a structure's possible failure modes as well as producing a near-optimum functional and economic design. Before the occurrence of the previously mentioned Liberty ship failures, only two general types of failure modes were considered in typical design efforts: yielding, excessive plastic deformation, or ultimate failure under generally tensile or bending (i.e., plastic hinge) loads; and elastic or plastic buckling or other instabilities under compression loads. With the advent of higher strength steels under higher operational stresses, fracture, defined as unstable rapid crack extension--either elastic or plastic--leading to partial or complete failure of the member, is often considered along with subcritical crack growth under fatigue, environmentally accelerated fatigue, or stress corrosion, leading to loss of section and fracture.

There are other failure modes such as bulk corrosion and creep and complex load-related facets of all of the above failure modes such as complex residual, thermal, and dynamically induced stress fields. However, as discussed by Rolfe and Barsom, the first four failure modes mentioned are most often considered. The fracture and subcritical crack growth modes have only now started to receive attention approximating that accorded the general plastic deformation and buckling modes. It is self-evident that all high severity failure modes should be considered within the design stage, and the concentration upon subcritical and critical crack extension within this survey is due only to the relative difficulty of designing against these failure modes in comparison with designing against ultimate tensile and compressive loads of a sound, uncracked structure.

Fracture control is considered on two levels in the design process: local and global. One major concern at the local level is the design of tubular joints. Their detailed design for strength and sufficient toughness implicitly controls fracture by preventing fracture initiation. The most explicit consideration of fracture control in design is usually in the fatigue design of the joints.

On the global level, the concern is with the structure's tolerance to fracture, either due to fatigue or overloading. Some qualitative attention is paid to redundancy and other techniques for avoiding catastrophic failure in the presence of a fracture.

There are two main design trade-offs with inspection of the structure during its operation. First, if a tubular joint can tolerate a large, easy-to-find crack without significantly degrading its performance, then the inspection procedures do not have to be designed to locate small, harder-to-find cracks. Second, if the structure can tolerate a seriously damaged joint, then, again, the inspection procedures can be more relaxed. These points will be discussed both in this section and in the section on operation and inspection.

4.2 Current Practices

Structural design concerns itself with two aspects: the loadings placed on the structure by the environment and by its operation, and the resistance of the structure to these loadings. On the loading side of the equation, fracture control is implicit in the design for normal operating conditions, extreme environmental conditions (e.g., storm, earthquake, and ice), and forces due to installation (e.g., load out, transport, and launch). Fracture control is explicitly considered in the design for fatigue loadings, which for fixed offshore structures are usually dominated by the many repetitions of wave loadings.

On the resistance side of the equation, fracture control is implicit in tubular joint design for strength, and explicit in tubular joint design for fatigue. For the most part, when considering the structure's failure modes, fracture control is the main goal; however, many designers do not think of it as such in that they are simply meeting design codes, requirements, and constraints. These design rules are depended upon to have enough implicit safety factors and "forgiveness" to preclude serious failures. The following discussion focuses on the structure's resistance to loadings.

4.2.1 Tubular Joint Design

The design of the vast majority of tubular joints is controlled by consideration of their ultimate strength against the design loads. Most modern tubular joints are "simple," i.e., one tube, the brace, is cut to fit the other, the chord, which is continuous through the joints, and the brace is welded to the chord without any gussets, diaphrams, or stiffeners. The chord is often thickened at the joint, forming what is called a "can" (see Figure 4). The failure of these joints is usually by one of three modes. The can may buckle under compressive brace loads; with tension in the brace, failure may occur due to gross yielding of the joint and subsequent plastic instability; or the tension failure may be due to fracture.

The simplest basis for joint design is the concept of punching shear. Some early tubular joint designs failed by pull-out of the brace from the can. Thus, limiting the average stress along the perimeter of the connection normal to the chord, i.e., limiting the punching shear, was a useful concept. This design technique has evolved over the years, and now has provisions to account for load transfer between several braces acting simultaneously at a joint in the same plane. For example, in a K-joint two braces are attached to a joint on the same side, thus forming a "K." When one brace is in tension and the other in compression, the joint transfers load from one brace to the other in a shearing action. Compare this with the situation in a cross or X-

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2 9/16" Bread

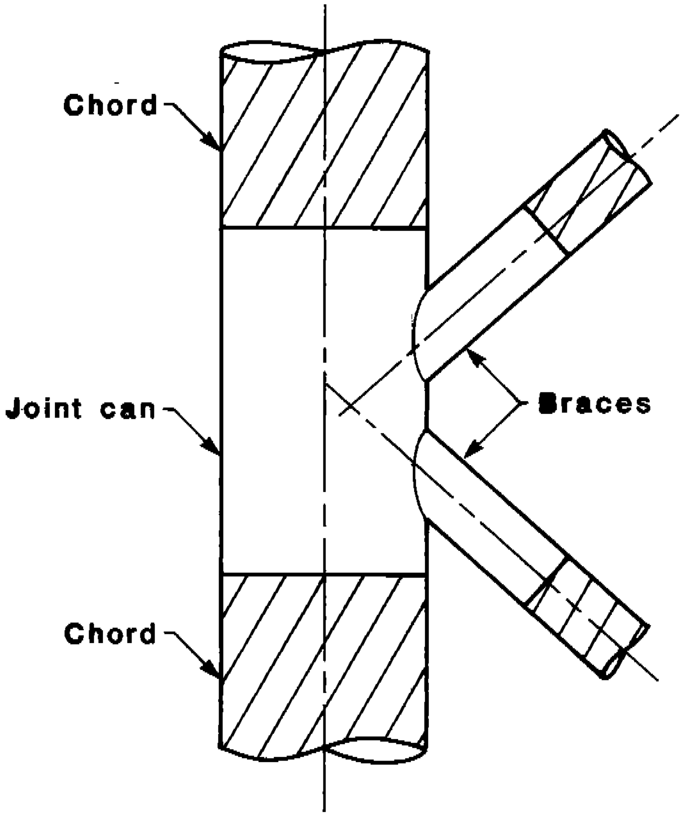


Figure 4. Simple tubular joint.
Note: The unshaded area is a node.

joint, in which both braces are, say, in compression. Then the joint transfers the load from one brace to the other in an action that ovalizes the can. Thus the X-joint is more prone to buckling than is the K-joint. The current punching shear design provisions of the API RP-2A include factors which account for these load interactions and effectively control the buckling as well as the pull-out modes of failure.

Researchers are currently investigating the interaction of loads in braces in different planes. For example, a corner leg is braced in two perpendicular planes, and sometimes a diagonal one. A compressive load in one brace may be transferred, at least partly, to out-of-plane bending in the other brace. One possible future approach is to consider directly the effects of such geometries and load transfer on "hot spot" stresses through extensive stress analysis execution and effective dissemination of results (e.g., through regression equations, tables, or nomographs) to designers.

Note that punching shear is an average stress over many square inches of cross-section. The magnitude and direction of the principal stresses vary around the joint, and in ordinary practice this distribution is not calculated. In fact, at the "hot spots," peak elastically-calculated stresses are often well above yield level. Thus, implicit in tubular joint design is the assumption that the material is able to withstand and contain large amounts of local plastic deformation.

More complex joints using gussets, stiffeners, or diaphrams are designed so that a reasonable magnitude and distribution of the stresses exist. For example, internal ring stiffeners may be designed to carry the entire brace load normal to the chord, each ring carrying a portion of the load times a safety factor (e.g., two rings, each carry half the load times a safety factor). The rings may be designed using a simple closed ring analysis. In more complex joints, or in critical joints, a finite element analysis might be used. Thin shell element analyses are the most common.

In all joints care is taken with details to provide smooth flowing transitions, so that large, highly constrained stress concentrations may be avoided. The gaps between members are controlled to minimize constraint of ductile behavior and avoid welds in close proximity which might increase the chances for restraint and shrinkage cracks. When judged necessary, special attention is paid to weld profiles to lessen the notch effect of the weld.

In complex joints special care must be taken to avoid stress concentrations and resultant cracking due to "redundant" elements. For example, if several internal rings are used, the placement of the rings is important to avoid inadvertent "hard spots." The inappropriate or excessive use of supposedly redundant elements can have negative effects. For example, unexpected cracks have occurred in brace and can welds to "redundant" plates.

4.2.2 Allowable Stress Fatigue Design

A very simple fatigue design procedure is allowed by the API RP-2A for template-type platforms with first dynamic mode periods of less than three seconds. For templates this is generally the case in water depths of less than about 400 ft. The procedure is to analyze the design extreme environmental loading (wind, wave, and current) and limit the maximum stress range (maximum stress encountered as the wave passes through the structure minus the minimum stress) to predetermined allowable values. The allowable stress range for the nominal brace-end stress is 20 ksi (e.g., +15 ksi to -5 ksi, or +25 ksi to +5 ksi). For sizing the joint can, punching shear allowables are 10 ksi for K-joints, 7 ksi for T-joints, and 5 ksi for X-joints. Alternatively, if the hot spot stress is known, it is limited to a 60 ksi range. Thus a stress concentration factor of 3.0 is assumed for the brace end, etc.

Therefore, using this procedure, only the effects of the design wave need be analyzed. The entire spectrum of different wave heights occurring throughout the life of the structure need not be analyzed. The justification for this is that a certain long-term distribution of wave heights is implied by the analysis (this being the distribution found in the Gulf of Mexico in about 400 ft. of water).

The 60 ksi hot spot stress range is based on prior generic analyses of typical structures in these environmental conditions and on a particular S-N curve. That is, complete fatigue analyses have been made, developing the full distributions of stress cycle occurrences. The fatigue damage due to these stress distributions and a particular S-N curve has been calculated in each case. And the design hot spot stress range that gives the desired fatigue life (service life times a factor of safety) has been back-calculated and specified as 60 ksi in API RP-2A.

The following factors are thus assumed:

- Hot spot stress concentration factors for the brace end and K-, T-, and X-joint cans:
- Template-type, static response to wave loads;
- Gulf of Mexico wave climate in about 400 foot water depth;
- Long-term stress cycle distribution resulting from the above;
- S-N curve.

Experience with this method in the Gulf of Mexico has shown that it is quite conservative in shallow water and less conservative as the water depth approaches 400 feet. In fact, on at least one occasion a designer has found it reasonable to conduct a full fatigue analysis for a structure which met these conditions, but which would have been too conservatively designed by this procedure. On the other hand, the procedure is so easy to use that it is attractive for even preliminary design of structures in deeper water.

4.2.3 Fatigue Analysis for Wave Loadings

For structures which do not meet the above conditions, especially if the dynamic response is thought to be an important factor, a full fatigue analysis is performed. All fatigue analysis techniques are based on the same fundamental principles, S-N curves and Miner's rule.

The S-N curves (stress versus number of stress cycles to failure) for tubular joints are based on constant amplitude load cycle tests on tubular joints in the laboratory. Under constant amplitude load cycling, fatigue cracks initiate and, upon reaching a reasonably large depth (such as 1/2 inch), grow at apparently constant rates. The test continues until failure occurs at N cycles, failure being either fracture, substantial loss of stiffness, too much displacement, or an arbitrary amount of cracking such that one of the above is imminent. The S-N curve is plotted for tests covering a wide range of stresses. For design purposes, an S-N curve which either bounds the test data or is the statistical mean curve minus two standard deviations is used. The statistical scatter in tubular joint fatigue test data is wide.

One of the assumptions inherent in S-N curves is that one stress cycle early in the test does the same amount of "damage" (not necessarily a measure of crack size) as one at the end. This may not reflect actual conditions and thereby may produce an over- or under-estimate of fatigue life.

Applying Miner's rule to accumulated damage, the damage due to n cycles of stress, for which N cycles would cause failure, is defined as n/N. The damage due to cycles of various stress amplitudes is the sum of the damage due to each amplitude independently, e.g., $\sum_i n_i/N_i = n_1/N_1 + n_2/N_2 + n_3/N_3 + \ldots$ Thus it is assumed, when applying Miner's rule, that fatigue failure occurs when the summation reaches 1 and that there is no interaction between the cycles of stress of different amplitudes.

The differences between the various types of fatigue analysis employed in the industry usually involve the treatment of loading history, structural response, stress analysis, stress cycle counting, and damage accumulation assumptions.

4.2.3.1 Loading History. Wave loading is the fundamental concern in fatigue calculations. In rare cases, the effects of current and wind are also considered. There are two basic ways to describe the long-term wave environment over the service life of the structure.

The first description is simply to count the expected number of waves of various heights (an assumed wave period is associated with each wave height). For example, of 1000 total waves, 600 are of heights from 0 to 3 feet, 300 from 3 to 6 feet, 99 from 6 to 9 feet, and 1 greater than 9 feet. The loading history is thus divided into wave-height groups or blocks.

The second description counts the number of occurrences of different sea states, rather than individual waves. A sea state is typically described by two parameters, the significant wave height and the mean zero crossing period. The significant wave height is the average height of the highest one-third of the waves in a sea state. The mean zero crossing period is a measure of the average wave period; more precisely, it is the average time between the occurrences of the water surface rising above mean sea level (zero) at a point. Typically, the environment is assumed to remain in the same sea state for about three hours. The number of occurrences of each sea state is then marked on a scatter diagram, which has significant height and mean period as its x- and y-axes. For example, there may be ten occurrences, i.e., 30 hours, of the sea state having a significant height of 4 feet and a mean period of 10 seconds. This is a more detailed description of the wave environment than the wave height count. In fact, the wave height count can be derived from the scatter diagram of sea states, but the reverse is impossible.

Refinements on the above are possible. With either description the directionality or heading of the waves can be considered by using a different wave height count or scatter diagram for each wave heading. More sophisticated descriptions, including the spreading of wave directions (in a sea) about an average general heading, or including the combination of waves arriving from a distant storm with locally generated waves, are possible with the sea state scatter diagram.

Whatever the description of the wave climate, wave forces are usually calculated according to Morison's equation (e.g., see ABS Rules, especially Section 4.5). That is, the wave force per unit length on a long slender cylinder is equal to the unit volume of the cylinder times the acceleration of water particles moving in the wave times a coefficient (which accounts for water density, cylinder shape, etc.), plus the unit area of the cylinder times the square of the velocity of the water particles times another coefficient. The procedure is the same as for storm wave loadings, except the coefficients might be different for the smaller fatigue waves and currents.

4.2.3.2 Structural Response. Even though wave loading is dynamic, in many cases it occurs slowly enough, compared to the structure's first dynamic mode period, that the dynamic effects may be neglected in an analysis. For platforms in the Gulf of Mexico, the general guideline used by the industry is that dynamic effects need not be considered unless the structure's period is greater than 3 seconds, or the water depth is greater than 400 feet.

In a static analysis, the structure's response is calculated at several points in time as the wave is stepped through, assuming that the load applied at that instant is the only load acting. That is, the inertial effects are neglected.

There are several methods of performing dynamic analysis. The most basic is to pass a series of identical waves through the structure and integrate the structure's response in time until a steady state is reached. Another possibility is to decompose the wave load into its Fourier series components, again assuming identical waves, and to directly solve for the steady state response. The two methods should give theoretically identical results. The response of structures under random, non-identical, waves is possible to compute; however, it has been only rarely used in design. Another refinement is to consider the effect of the relative velocity between the water and the moving structure on the loading. Since, according to Morison's equation, part of the wave force is proportional to the (relative) velocity squared, the effects can be substantial, especially for tall flexible structures.

It is appropriate to point out here that the velocity squared term makes Morison's equation non-linear. Water particle velocity and acceleration are linear functions of wave height according to the linear (Airy) wave theory used in certain (spectral) fatigue analyses. However, the wave force is not linear in wave height. Therefore, great care must be taken in choosing a wave height for the analysis for reasons to be discussed in Section 4.2.3.4: Stress Cycle Counting.

4.2.3.3 Stress Analysis. Using a static or a dynamic analysis, the calculation of stresses is fairly standard. The tubular space frame is analyzed using beam elements distributed within a three-dimensional "stick model." From this analysis the nominal stresses at the ends of (or along) each brace are found.

The next level of refinement is to compute hot spot stresses. As described earlier, the stress around the perimeter of the joint varies depending on many factors. The type of loading (axial, in-plane bending, or out-of-plane bending), and the way the load transfers through the can to other braces, are extremely important. Geometric factors include the diameter-to-thickness ratio of the can (D/T), the ratio of the brace diameter to the can diameter (d/D), the ratio of the brace thickness to can thickness (t/T), and the angle of the brace to chord intersection (θ). For braces acting as K-braces, the gap between braces is another factor.

The hot spot stress is defined as the stress that would be measured by a strain gage in a laboratory situation. Since strain gages have finite size, it is impossible to place them and measure surface stresses at a point where fatigue cracks initiate in tubular joints, i.e., at the weld toe. Typically, they are placed within 0.25 inch to 0.1 $\sqrt{Rt}$ of the weld toe (R and t being the radius and thickness, in inches, of the member being gaged). Note, however, that the stresses vary extremely rapidly in this region due to the notch effects of the weld. So variability in the experimental measurements would be expected. Also note that the stress being measured may not be the maximum principal stress, but the (weld-crack-driving) stress perpendicular to the weld toe.

The reason this stress is used is because the tubular joint S-N curves were derived this way. That is, the stress (or strain) used in the S-N curve is not the maximum principal stress at the crack, but the stress perpendicular to the crack a finite distance away. Thus, (if the inservice structure/geometry is similar enough to that used to produce the S-N curve) the next refinement in stress analysis, finding the stress at the weld toe, or crack, itself, is not necessary. The notch effects of the weld are already included in the S-N curve.

In light of the above, some disagreement over the correct value of hot spot stress in an experiment is to be expected. There is even more disagreement over the analytical calculation of hot spot stresses from nominal brace stresses. There are two primary accepted techniques: using finite elements, and using parametric equations.

Finite element techniques for tubular joints are fairly well established. The primary difficulty with using them is generating the element mesh for the rather complex geometries. Generally, thin shell elements are used and are placed on the mid-planes of the cylinders. Stresses from thin shell element models need to be corrected to get the "true" stress that would be measured on the surface of the plate at the weld toe. Thin shell elements also have difficulty modeling the extra thick region where the two cylinders join and are reinforced by the weld. For this reason, isoparametric thick shell and solid elements (with full 3-D elasticity capabilities) are presently being incorporated into tubular joint analysis programs.

The other accepted technique for hot spot stress analysis is to use parametric stress concentration factor (SCF) equations. The SCF so calculated, times the nominal brace stress, gives the hot spot stress. There are numerous sets of such equations. One of the most popular was derived by Kuang, et al. (1977). These equations are based on regression (curve fitting) of the results of numerous thin shell finite element analyses on various joint geometries and loadings (other analytical or experimental results could be fit as well). These equations are often used for comparing SCFs computed by other parametric equations, or from finite element analyses. So Kuang's equations are, in a sense, an industry benchmark.

Another popular set of parametric equations was derived by Wordsworth and Smedley (1978). These investigators measured hot spot strains in acrylic models of tubular joints. They have had success with the cheap acrylic material and were even able to model the weld reinforcement. But, while Kuang's equations are in the format of a series of factors raised to exponents (due to their derivation from exponential regression equation curve fits), the Wordsworth and Smedley equations are more similar to punching shear equations. Large discrepancies have been found to exist between the two for certain conditions. Apparently the same is currently true for any pair of the numerous sets of parametric equations that have evolved over the years. The computation of hot spot stresses, which ideally should be a straightforward exercise in stress analysis and presentation of results, is still viewed by many as a black art.

4.2.3.4 Stress Cycle Counting. With either a static or a dynamic analysis there are two methods of counting stress cycles. The simple method is known as the discrete wave or the deterministic method. This method is used when the wave climate is described by wave height blocks. The stresses due to a representative wave from each block are analyzed. The maximum stress range calculated is then used to calculate damage in the S-N curve. The number of cycles of that stress range is assumed to be the same as the number of waves in the block.

When using the discrete wave method it is important to use enough wave blocks to adequately define the peaks and valleys of the structure's response, which occur due to both geometric effects on the loading and dynamic effects on the response. The wave picked to represent each block should also be chosen carefully so that it is truly representative, not only of the range of wave heights in the block, but also the range of wave periods, especially if a peak or valley occurs within the block.

The above method is also known as the deterministic method because the number of stress cycles is known in advance, only the stresses need to be calculated from pre-determined waves. The second method is known as the probabilistic method, or the spectral method. In this method the stress ranges and the number of cycles are estimated using probability-theory-based equations. The method relies heavily on linear systems analysis techniques in the frequency domain.

The sea state description of the wave climate, i.e., significant height and mean period, is required. Given these parameters the sea state spectrum can be calculated, using the Pierson-Moskowitz formula or some other empirical formula. This spectrum is actually a power spectral density function, which is one way of representing a random process such as wave amplitude or wave-induced stress. The sea state spectrum is thus the input to a linear system, the structure. Multiplying the input spectrum by the square of the system frequency response function, or transfer function, produces the output spectrum. For fatigue analysis the transfer function relates wave heights or forces to hot spot stresses; thus, the output is the hot spot stress spectrum. (Transfer functions will be discussed below.) From the stress spectrum, the number of stress cycles and their distribution can be calculated probabilistically for each sea state. This calculation is repeated for each sea state, and the fatigue damage measured by the S-N curve is accumulated for all sea states. Note that since more than one stress cycle per wave can occur, the number of stress cycles calculated by this method is generally greater than the number of waves, as assumed in the discrete wave method.

Most of the computational effort in this method is to compute the transfer functions. A transfer function describes the response of the system to a unit harmonic loading over a range of frequencies. In this case, the response is the hot spot stress amplitude due to waves of unit amplitude over the relevant range of frequencies. Determination of the transfer function thus theoretically requires running many waves of unit amplitude through the structure at different frequencies (and, if under consideration, directions) and calculating the hot spot stress for each wave. About twelve frequencies are usually enough for each direction. (Thus, if eight directions are considered, then actually 96 wave analyses are needed for the fatigue analysis, versus the only eight or sixteen wave analyses used for strength design. If the wave analysis must be dynamic, the cost of the fatigue analysis skyrockets.)

As mentioned earlier, however, the wave force, and thus the hot spot stress response, is non-linear with respect to wave height. So the wave analysis is not performed with unit amplitude waves, but with waves of larger amplitude chosen to give the correct average response. The stresses due to the larger waves are then normalized back to unit amplitude wave responses. This technique is known as equivalent linearization.

However, there is still one problem with this linearization. That is, the velocity squared term also makes the wave force, and thus the hot spot stress response, non-linear in frequency as well as in amplitude with respect to wave height. That is, for waves of a single frequency passing through the structure, the resulting wave force is at that frequency and at higher harmonics of that frequency. The stress response, thus, also has higher harmonic components. The significance of this non-linearity is becoming apparent for deep water structures and new hybrid time-frequency domain transfer function techniques are being developed to handle it.

4.2.3.5 Damage Accumulation. Finally, there are two basic types of S-N curves. The curves based on hot spot stresses have already been discussed briefly. In American practice these are usually the API X and X' curves. Since the hot spot is away from the weld toe, the S-N curve must account for the stress riser at the weld toe, i.e., the weld's notch effects. The severity of the stress riser is a function of the weld profile. For this reason in bridge construction the weld is ground to a smooth curve for critical joints.

In offshore construction a less severe stress riser is accomplished by improving the weld profile by adding butter passes to the weld toes (buttering) and by grinding. This makes the transition smoother and may also improve the microstructure of the surface material near the weld toe. For joints with an improved profile, the X curve is used. For joints without an improved profile, the more stringent (pessimistic) X' curve is used. Due to the extra care and cost in welding required, designers generally try to avoid specifying that an "improved" profile be used.

The other type of S-N curve is the generic curve. In American practice these are the API D' and K curves. To use these curves, nominal brace stress range and punching shear range in the can are used instead of hot spot stresses. As with the allowable stress fatigue design method, this S-N curve assumes certain values for the stress concentration factors.

The S-N curves of the other American document covering tubular joints, the AWS D1.1, "Structural Welding Code," are essentially the same as the API. European curves are mostly similar, although the soon-to-be-released new UK DOE "Guidelines" will have S-N curves that are much more stringent for thick joints. This change was motivated by European research that indicates a degrading fatigue performance in thick plates. This will be discussed further in Section 4.4: Discussion.

One last note, all of the S-N curves described above are based on tubular joint tests in air. Left unprotected in a sea water environment, the fatigue performance would be expected to degrade. However, some continuing research in this area suggests that with proper cathodic protection the fatigue lives of submerged joints approach those of joints in air.

4.2.3.6 Fatigue Lives. All the variations of fatigue analysis described have as their goal the calculation of fatigue damage using an S-N curve, and the interpretation of that damage as fatigue life. Recall that the total fatigue damage is the sum of the damages due to each stress cycle range occurring during the life of the structure, $D_T = n_1/N_1 + n_2/N_2 + n_3/N_3 + \ldots$ Nominally, the total damage must be less than 1.0.

If D_1 is the average damage occuring during one year, its reciprocal, $1/D_1$, is the expected fatigue life. Obviously, the expected fatigue life of the structure must be at least the intended service life. Due to the many uncertainties involved, it is desirable to add a safety factor (SF) to the design fatigue life. For example, with a service life of 15 years and SF equal to 2.0, the design life should be 30 years.

When fatigue lives are computed at hot spots, generally either eight or sixteen points per brace-can joint are used. For eight points, the quarter points around the perimeter of the intersection (0°, 90°, 180°, 270°) are considered on both the chord and brace sides of the weld. For sixteen points, the eighth points (0°, 45°, ...) are considered. The standard parametric equations usually give hot spot SCFs for the quarter point locations, but not the eighth points. Those must be interpolated. By analyzing these locations, the spots susceptible to the most fatigue damage (due to axial load, in-plane bending, and out-of-plane bending) are covered. When finite element results are available, fatigue lives can be calculated wherever critical.

The fatigue lives thus calculated are generally listed in a design report to the operator. Usually the most critical joints are ranked in order of severity. Thus the operator is supplied with a list of fatigue-sensitive parts. North Sea operators are known to incorporate these fatigue results into their inservice inspection programs.

Note that fatigue lives are not calculated in the allowable stress fatigue design method. Note also that different parts of a structure will experience different stress cycle frequency distributions. Thus, even if two joints from different parts of the structure (say, near the top and near the bottom) are designed to the same 60 ksi hot spot allowable stress range, the frequencies of their various fatigue cycles can differ markedly and, therefore, their fatigue lives can be quite different. Thus, a ranking of the fatigue sensitive members is not possible with an allowable stress method.

Lastly, it is the consensus of industry experts that calculated fatigue lives of 20 years and 100 years do not mean that the joints will survive that long. There are so many uncertainties in the analysis that these numbers should be best interpreted as relative indicators. That is, a joint with a 20 year fatigue life is probably more susceptible to fatigue failure than one with a 100 year life.

Concern has been expressed by some experts that some designers take the fatigue life requirement too literally. For instance, if the design life requirement is 30 years, there may be a tendency to refine the analysis of a joint with a calculated 29.9 year life, but leave alone one with a 30.1 year life. Given the above reasons, both numbers are effectively the same, and both joints should be treated the same by the designer.

4.2.4 Fatigue Loadings Due to Transport and Vortex Shedding

Two other fatigue loadings are sometimes considered: those due to transport and to vortex shedding. Repeated loads occur during transport of template-type structures due to the motions of the barge, especially rolling. Self-floating towers experience these same motions, as well as wave loads on submerged or exposed members. Current Gulf of Mexico practices usually do not consider these loadings to be serious fatigue problems. This is because the tow from fabrication yard to location is relatively short, extra cribbing is sometimes used to reduce the effects, and weather conditions during the tow are generally good. As with inservice fatigue, the relative magnitudes of the design condition stresses and the numerous fatigue stresses play an important role.

More attention has been paid to transport fatigue in overseas practice, and lately in American practice. This attention is motivated by the need for longer tows in worse weather. For example, a number of Pacific Basin platforms have been fabricated in the Far East and transported across the Pacific in tows lasting longer than one month. In American practice, platforms have been towed from Singapore to California, and long tows are being considered for prospective platforms for the East Coast of the U.S. and Canada.

The other repeated loading that is sometimes considered is due to vortex shedding. Water passing by relatively long slender objects, particularly the caissons hanging off the deck of a platform into the water, tends to form (and shed) vorticies, or eddies, off the side of the object. These vorticies are periodic and cause pressure gradients which exert lateral forces that may cause the object to vibrate. If the object's supports are not properly designed, resonant vibration may occur. These vibrations can lead to premature fatigue damage of the supports.

Caissons, such as pipes for water and sewage, are particularly susceptible to this problem. Vortex shedding is now commonly investigated to see if resonance and fatigue will be problems, especially for critical slender members. Often caissons and other members subject to vortex shedding are nonstructural and their loss nominally does not affect structural integrity, but their failures may cause both cost increases and impact damage to structural members as they fall through the structure.

Repeated operational loads, such as the filling and emptying of tanks holding mud, water, or oil, and the operation of cranes lifting heavy loads, can cause fatigue damage. This may be a problem for the deck and supporting trusses. However, these load variations are usually too small and/or infrequent, compared to the total load, to cause problems in the tubular members of the jacket.

4.2.5 Failure Modes

The last line of defense a structure has against cracks is its ability to withstand their effects without a catastrophic failure. In offshore structures there are two components to this defense: the reserve strength of the structure against such a failure, and the redundancy of the system. Here, redundancy is used as a synonym for fail-safety, rather than as the mere existence of multiple load paths as in a statically indeterminate structure. That is, a redundant structure in the present context will be able to survive the failure of a major structural member.

The reserve strength of the structure is, in turn, due to two related reasons. The first is that individual members and connections normally do not fail brittlely once their design strength is reached. Due to the safety factors built into design formulas, the failure load of an average part is well above the design load. And when the "failure" load is reached, failure of tubular members and connections is normally ductile. That is, plastic deformation distributes loads throughout the cross-section rapidly enough to forestall catastrophic rupture and, therefore, some load carrying capacity remains. Such is the case, for example, in the fatigue failure of a tubular joint in a laboratory test. Thus, failure does not necessarily mean complete separation of the brace from the chord; it could mean too much displacement on the testing machine, or a significant loss of joint stiffness, or just significant cracking. Thus, the reserve strength of the parts of the structure helps to prevent immediate and catastrophic failure.

The second reason for structural reserve strength is that a fixed steel offshore structural detail is rarely stressed uniformly. So usually before the first part or cross-section reaches its ultimate load and fails, it redistributes some load to adjacent parts or cross-sections, again through plastic deformation and/or displacement control.

A characteristic failure mode of template-type structure frames is the "unzipping" of the lateral bracing, one level of bracing at a time. This mode involves both types of load redistribution discussed above, i.e., within the critical cross-section and into neighboring cross-sections and components. Thus, the structure has additional reserve strength beyond the capacity of its weakest parts.

The second line of defense is the fail-safe redundancy of the structural system. Redundancy (not to be confused with redundant stiffening elements in a joint, such as internal rings) implies that there are alternate load paths capable of sustaining the externally applied loads. For example, suppose that a brace were to fail due to a fracture at one of its ends. In a redundant structure, the load normally carried by that brace could be picked up by several other braces, possibly in other frames. Under normal loading conditions, the alternate load paths are adequate to carry the brace's load (including temporary dynamic loads during a sudden failure) without undue stress. For a typical Gulf of Mexico-type steel template, five or six braces need to fail before an extreme environmental loading causes collapse. The use of ambient vibration monitoring techniques to detect cracking damage in a particular component is made more difficult because of the structural redundancy. If the structure hardly feels the effect of a missing brace, ambient vibration measurements will have to be very sensitive to detect fatigue cracks reliably.

Due to reserve strength and redundancy, a fixed steel offshore structure can withstand a certain amount of cracking. The remaining problem is how to quantify this resistance. In normal Gulf of Mexico design practice such quantification is not even attempted. Platforms studied in the past indicate that substantial reserve strength exists against overloads due to severe storms and earthquakes, and against fatigue. So it is assumed that similar reserve strength exists in designs following the general patterns of those platforms.

The study of failure modes has probably received the most attention in designs for earthquake zones and arctic regions. For earthquake zone designs, "shakedown" analyses are routinely performed to evaluate structural ductility in the event of a larger-than-design earthquake. An industry-sponsored study of arctic platforms addressed their failure modes and stressed the maintenance of the integrity of the welds. But for fatigue and fracture, probably the most difficult problem in studying failure modes is in quantifying the strength of cracked tubular joints. Also, the tremendous number of joints involved may make a thorough investigation of the possible failure combinations during design prohibitively expensive.

4.3 Design Verification

Quality assurance for this fracture control activity means design verification. Verification must address scope, as well as accuracy. That is, the verifier must check to see whether or not the most probably damaging failure modes in the various structural components and locations have been addressed. As mentioned at the beginning of this section, the methods and tools of design are relatively similar in the offshore industry. Design criteria and methods, such as those described here, are well-documented in the API RP-2A, in Offshore Technology Conference proceedings, in the proceedings of other conferences, and in professional journals. The computer programs which implement these methods are "debugged" on simple problems, and are usually benchmarked against existing programs, if possible. The differences that are certain to exist between different implementations of similar procedures, such as dynamic deterministic fatigue analyses, are usually, but not always, considered to be of only minor significance from the fracture control perspective.

Verification of the design work itself is conducted by the operator's design representative, who is consulted on significant design decisions, such as the number of waves to use in a fatigue analysis. For Gulf of Mexico work, the designer and the operator are usually in the same area (typically, Houston or New Orleans) so contact between the parties is easy. For other work, e.g., California or abroad, the operator's representative either makes frequent visits to the design office, or is given in-house office space. In this way, the operator is assured that the design work meets all design criteria.

For the major platforms covered by the Minerals Management Service (MMS) Platform Verification program (in particular, for most new platforms in over 400 foot water depths in the Gulf of Mexico, and for all other platforms in U.S. operational areas outside the Gulf) another level of verification is used. The Certified Verification Agent (CVA) phase of the program requires that these platforms be checked by an independent third party. The CVA will run parallel analyses to check loads, dynamics, member and joint strength, fatigue lives, and other major design aspects. Thus, parallel efforts in the major analytical tasks are provided.

From this discussion it can be seen that the major deepwater structures are subject to the most fracture control attention in design. Deepwater platforms are the most likely to have all the most sophisticated tools used for their design, for example, a dynamic spectral fatigue analysis with special studies to examine non-linear effects. And the same platforms are subject to the most scrutiny from a verification perspective. Shallow water platforms, on the other hand, are more likely to be designed by the allowable stress method, which in the shallower range of its applicability should be quite conservative. And assuming that their design is conservative, the least fracture control attention is paid to shallow water structures.

4.4 Discussion

Many incompletely understood design problems have been mentioned. The following discussion will highlight the most important problems and trends in current practices.

4.4.1 Tubular Joint Design

It is generally agreed by designers that the single most important aspect of fracture control in design, beyond an understanding of loads and materials, is good detailing. Stress concentrations and close proximity welds should be avoided; this is universally accepted. However, there is controversy surrounding one important detail: the weld profile.

The API RP-2A makes special fatigue design provisions, i.e., a different S-N curve, available to the designer who uses an "improved" weld profile. This profile is described in API RP-2A paragraph 4.1.3c, "Joint Details for Shielded Metal Arc Welding:"

> A special effort should be made to achieve an as-welded surface which merges smoothly with the adjoining base metal, and approximates the concave profiles shown in Figure 4.1.3. "T" is the size of the diagrammatic weld exclusive of toe fillets added for this purpose.

Ideal profiles such as those depicted in API's Figure 4.1.3 (see Figure 5) are difficult to achieve in offshore construction without grinding, etc. So the "Commentary" to the fatigue section provides another diagram which shows small cap and butter passes on a weld to demonstrate what was intended. However, the API does not attempt to quantify the profile at all.

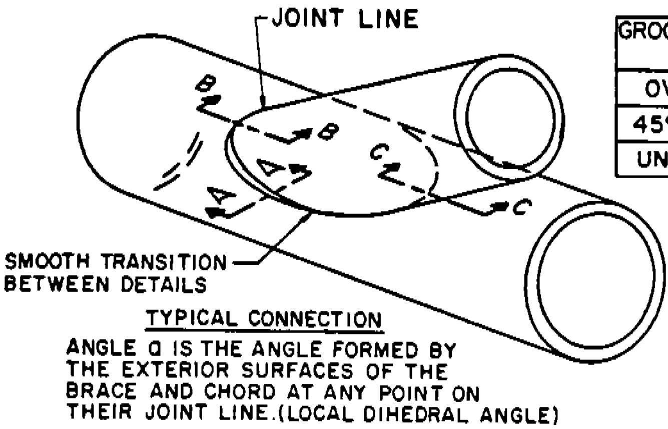
The question is then left for the designer to answer: when is a profile "improved" and when is it not? This has apparently been a point of dispute between the designers and the fabricators of offshore structures. Are the toe fillets, the butter passes, the only requirement? How high should they be?

How does the improved profile work? Nominally it reduces the notch effect of the weld, i.e., it reduces the surface stress riser. Recall that weld notch effects are included in the S-N curves: X for "improved" profiles, X' for unimproved. The additional welding and grinding may have three additional benefits associated with removal of the last, and presumably worst, weld bead. These are the probable removal of material with the worst defects, microstructure properties, and post-weld residual stresses. Detrimental effects of material removal are the cost and the possibility of surface damage (e.g., deep scratches along or misblending of a fillet radius) and significant loss of area in load-carrying cross-sections.

The effects of weld profiling on cracks growing in regions of large plastic deformation is currently an area of research in analytical and experimental fracture mechanics. While profiling is certain to affect fatigue

(3/4" Head)

1 1/2" Brace



GROOVE ANGLE "b"	ROOT OPENING, G	
	IN	mm
OVER 90°	0 TO 3/16	0 TO 4.8
45° TO 90°	1/16 TO 3/16	1.6 TO 4.8
UNDER 45°	1/8 TO 1/4	3.2 TO 6.4

NOTE: INCLUDES TOLERANCE

α	MIN."T"
50° TO 135°	1.25 t
35° TO 50°	1.50 t
UNDER 35°	1.75 t
OVER 135°	SEE SEC. B-B

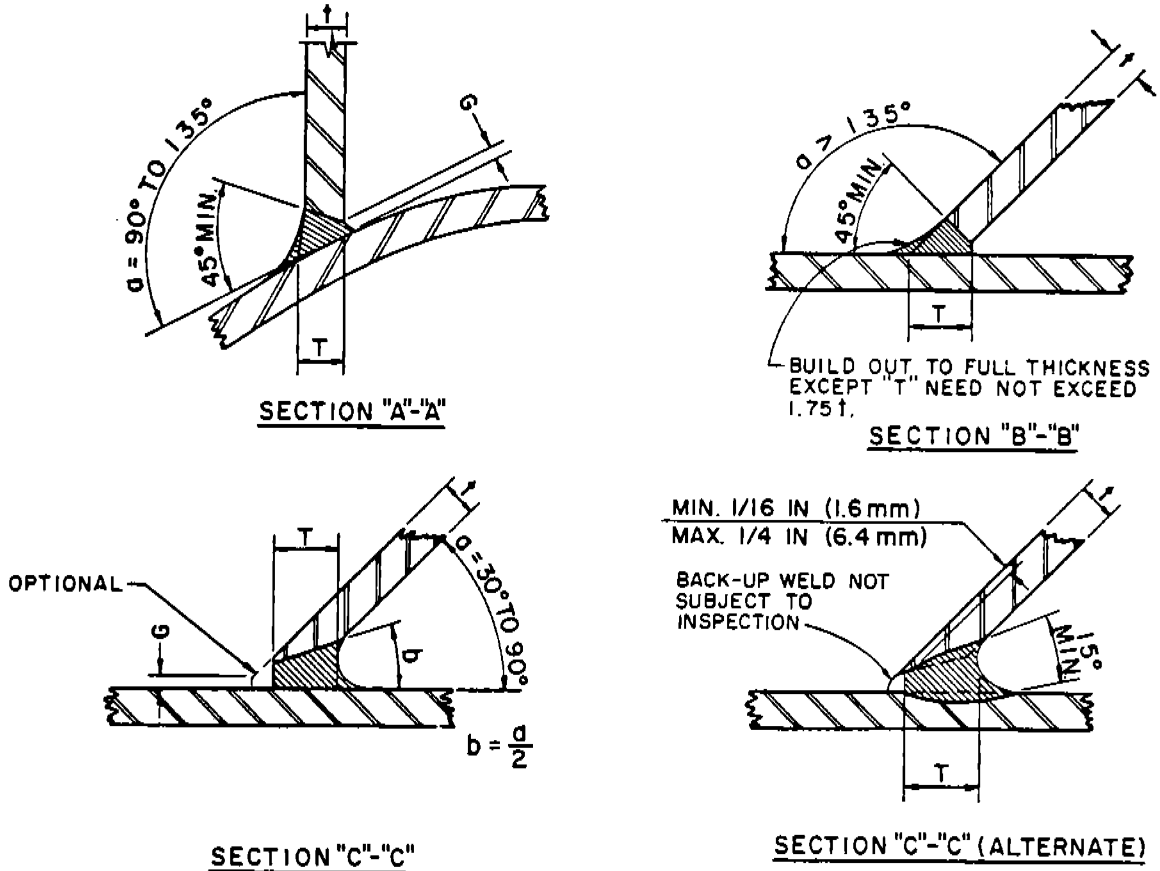


FIG. 4.1.3
WELDED TUBULAR CONNECTIONS
SHIELDED METAL ARC WELDING

Figure 5. Taken from API RP-2A, Twelfth Edition.

FaAA-83-6-2

initiation and growth of small cracks, it is probable that once the crack grows away from the surface, and stress redistribution around the joint occurs, the profile has little effect.

4.4.2 Fatigue Analysis

4.4.2.1 Uncertainties. There are many uncertainties in a fatigue analysis. There, of course, are questions about the proper dynamic analysis and other aspects of the global structural analysis. But the dominant contributions to uncertainty in a fatigue analysis come from the prediction of the long-term sea state distribution, the calculation of wave forces in a given sea state, and the computation of appropriate hot spot stresses for use with a given S-N curve.

The long-term sea state distribution may be the most significant uncertainty, especially for frontier areas. The wave climate in the Gulf of Mexico is fairly well known, but there is less data for the North Atlantic, particularly for severe storms, since shipping traffic tends to avoid bad weather. An oceanographer may have to attempt to forecast 100 years of waves from two years of data, for a remote location. While extrapolation of sea-state data is not an unusual practice, the accuracy of such extrapolation represents a source of error in the fatigue analysis. Thus, it seems that the least knowledge exists for the sea state conditions at the worst geographical locations for fatigue.

The current state-of-the-art methods for calculating wave forces relies on Morison's equation. The coefficients for the drag and inertial force terms are not constants but vary from one wave to another (i.e., with Reynolds number) and as a given wave passes; however, constants are assumed for analysis. The effects of marine growth on these coefficients are difficult to predict. The equation itself is empirical and developed for a single cylinder in relatively undisturbed flow and regular waves, instead of for a structure in a random sea state. With adjustments where appropriate for shielding and other flow-related structural-member interactions, this approach is agreed to give global forces on the structure (such as overturning moment) which are acceptably accurate for design purposes. However, the local wave forces on individual members which are important to fatigue are poorly estimated, and thus contribute large uncertainties to fatigue life estimates.

That the various hot spot SCF formulas available do not agree with each other has been discussed. There also is the problem that the hot spot often is not defined where the crack is, but where the strain gage is. And, in spite of the existence of appropriate stress analysis tools, the interaction of various combinations of loads in both in-plane and (especially) out-of-plane braces is poorly understood (or at least, poorly documented). (The authors are unaware of any fatigue analysis program that properly accounts for the different load paths taken through the joint under different wave loads.)

Then there are a host of comparatively minor uncertainties, but which taken together could have major impact upon a fatigue analysis. How valid is Miner's rule (or an equivalent rule, which involves linear summation of crack growth contributed by all transients) for predicting fatigue crack growth? What is the proper way to count stress cycles? What are the effects of residual and mean stresses? And what role does a sea water environment play?

Given all these uncertainties (especially when investigated in terms of quantitative effects upon life prediction), it is easy to see why fatigue lives are interpreted by experts only in a relative sense. What is the impact on fracture control plans?

4.4.2.2 Thickness Effects on S-N Curves. As American practice moves to deeper water, American operators may find themselves grappling with a problem currently before the Europeans, namely, plate thickness effects. Deep water structures, such as those found in the North Sea, have larger, thicker joints. European research indicates that the fatigue strength (i.e., stress level corresponding to a given fatigue life) of a joint configuration is approximately inversely proportional to the plate thickness raised to the one-fourth power, $t^{-0.25}$. That is, for two similar joints, one a scaled-up copy of the other, stressed to the same hot spot and nominal stress levels in a fatigue test, the thicker joint will have a lesser allowable stress in approximately the ratio of their thicknesses to the one-fourth power, $(t_2/t_1)^{-0.25}$, where $t_2 > t_1$. For example, if the thicker plate is twice the thinner, its allowable stress is reduced to about 84% of the thinner's.

The notch size effect of the weld, for which small notches enjoy a more rapid subsurface stress gradient than self-similar large notches, is thought to have the major effect on this phenomenon. Other effects, such as degrading material properties for large thicknesses and residual stresses due to rolling, fit up, and welding, and the relative size of the HAZ, may also play significant roles. European researchers are now looking to fracture mechanics approaches, with some apparent success, to help resolve this problem.

4.4.2.3 The Fracture Mechanics Approach. A goal of the fracture mechanics approach is to be able to derive S-N curves or similar design aides reliably, with a minimum number of fatigue tests of specimens or full-scale structural details. As a part of this goal, fracture mechanics is hoped to provide answers for such problems as the thickness effects described above.

Major problems face this approach. One is the analysis of the complex geometries and stress fields found in tubular joints, and then their reduction into simple design parameters such as diameter ratio, etc. Another problem is that, in a typical brace-chord joint, the growth rate of a surface crack deeper than, say, 25% of the cross-section's thickness in a constant amplitude load test appears to remain constant, rather than accelerating as would normally be predicted by a load-controlled-based fracture mechanics crack model or solution. This suggests that some displacement-controlled load shedding occurs as large cracks grow in typical joints. Fracture mechanics models must be refined--it is to be hoped--to the point of explaining how stress redistributes around a crack and inhibits crack acceleration.

A source of uncertainty shared by the fracture mechanics techniques with any other fatigue or subcritical crack growth analysis approach is the effect of environment on useful life of the structure. The most useful documents describing environmental effects upon crack propagation rates are Conference Proceedings organized by Smith, et al (20)., (Institution of Civil Engineers) and a series of progress reports by Burnside, et al (21). These references report a large amount of crack propagation data results as a function of stress intensity factor range and mean values (ΔK and R), cycling frequencies, environments, temperatures, levels of cathodic protection, and materials. The observed effects of environment upon fatigue crack propagation range from negligible (including, in some cases, improvements) for small cracks under cathodic protection tested at high frequencies and low temperatures, to crack propagation rates that were increased by factors of 6 under such detrimental combinations as freely corroding material, low frequencies, higher temperatures, and lower alternating stress intensity factors. This factor-of-six increase in crack growth rates must not be taken as an upper bound as little of the test data comes from the near-threshold, low crack growth rate levels of less than 10^{-8} m/cycle. There is a general consensus that more near-threshold testing must be done for the relevant frequency/environment conditions encountered in fixed offshore platform joints. (In fact, the effect of environment should be described in terms of change in the threshold level of ΔK rather than in terms of crack propagation rates.)

Of course all the uncertainties associated with loads, hot spot stresses, and subsurface stress distributions discussed above will impinge upon the fracture mechanics analysis. It is to be hoped that in spite of this impressive list of uncertainties, further research, calibration with inservice observations of fatigue crack growth, and the elimination of many geometrical and load and stress distribution parameters associated with fracture mechanics models at their best will increase the viability of this approach.

4.4.2.4 Fatigue Lives. Due to the uncertainties in the analysis, and as a standard conservative practice by engineers, the required design life of a joint is the service life of the structure times a safety factor, SF. SF is usually around 2.0 in Gulf of Mexico practice, a rather low nominal value compared to those used in other industries. However, it should be noted that, through the use of minimum-life (not mean life) design curves in API RP-2A and other conservative practices, the actual ratio of mean and "minimum" lives is usually much larger than 2.0.

As with any safety factor, SF relates to an accepted risk level, in this case developed for medium water depths in the Gulf of Mexico. This relationship implies, as do the allowable stress fatigue design criteria, certain loading conditions, structure type, and so on.

Two questions arise from this SF relationship. How appropriate is it to use this value of SF elsewhere, if loading conditions are different, or the structure is more or less redundant? And, what should the correct risk level be, relative to other hazards, such as earthquakes? To answer these it is necessary to be able to quantify the risk and reliability of offshore structures. Such research efforts are presently being conducted by, for example, individual and committee members of the API and the ASCE.

4.4.3 The Reliability of Offshore Platforms

As evidenced by the API and ASCE committees on the reliability of offshore structures, there is a long-term trend toward the implementation of reliability technology in the offshore industry. At least two design factors in the current API RP-2A are based on reliability. Design criteria for storm wave heights and earthquake magnitudes have been developed with these methods. It is possible that future development of reliability design factors will make quantitative trade-offs between fracture control options and practices possible.

There are at least two current efforts to quantify the reliability of a tubular joint against fatigue: one, sponsored by the API, "Probability-Based Fatigue Design Criteria for Offshore Structures," uses the safety index approach; the other, under development by CONOCO, Inc. and Det Norske Veritas, applies a more sophisticated analysis (the so-called Level II analysis), which computes an approximate probability of failure.

Reliability-based design and safety factors would be assigned to different practices, such as redundancy design in structures. Thus a redundant structural detail could be assigned a lower (more liberal) safety factor than its non-redundant counterpart, all other aspects equal. Another pair of options might be in the type of hot spot stress analysis, by parametric equations or by finite elements. In this case the lower-uncertainty finite element-based design could be awarded a more liberal factor of safety. Then the designer could make more informed decisions about what type of analysis should be performed for a critical joint. Given no variation in safety factors or "allowables," the exemplified combination of redundant design with finite element SCF results is obviously the most reliable, and the most costly. But perhaps this combination is at "the point of diminishing returns," i.e., perhaps a redundant structure combined with parametric SCF equations, or a non-redundant structure with finite element SCF computations, would be only slightly less reliable, but much less costly. Reliability-based, variable safety factor design could provide a rational basis for the decisions to make such trade-offs between resource allocations. Of course, for the present such variable safety factors are far away.

More current is the research into the specific contributions of fail-safe redundancy to structural reliability. How can redundancy be measured? How much exists in current designs? And how much is adequate? The most immediate result of the answers to these questions will most likely be the identification and improvement of fracture critical parts.

A fracture critical part can be defined as one whose failure by fracture seriously threatens the integrity of the structure. Fracture critical parts are not always identified as part of the design process. One may be identified later in the design should experience, inspections, or more detailed analyses indicate a problem exists with it.

Most present analyses of a part for fracture criticality are intuitive. A quick rule of thumb currently in use is that a lateral brace at the top of the structure is a primary load transfer path and is hence most likely fracture-critical. A brace at the bottom probably is not. As reliability and fail-safety techniques develop, more accurate quantification of part criticality will result.

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5.0 CURRENT PRACTICES: CONSTRUCTION

Although there are variations in the overall scheme of construction, such as different installation methods, the practices related to fracture control are quite similar in the Gulf of Mexico. These practices are documented by the American Welding Society (AWS), as well as by the API. Yet a wide range in the quality of construction, especially fabrication, exists in Gulf of Mexico fabrication yards.

This section examines only those construction practices related to fracture control, and discusses the following aspects: In general, how are construction practices related to fracture control? What specific practices are involved? What kinds of inspections are performed? And, why are some current trends in construction practices the subject of much concern and discussion?

5.1 Philosophy

In terms of fracture control, the main goal in construction is to limit built-in stresses, the size of initial defects, and large variations from specified material properties and structural dimensions. To this end, assembly and welding procedures are designed to minimize restraint and residual stresses, and inspections are performed to eliminate critical defects. Care is taken during construction of the structure to avoid accidental overloads which might cause cracking. And, of course, great care is taken to assemble the parts of the structure correctly, so that it behaves as it was designed to behave.

In choosing fabrication and installation methods, two main trade-offs related to fracture control are made. The first, the choice of fabrication method, relates directly to the cost of the two methods (frame or node, defined and discussed later). The second trade-off, the choice of installation method, controls, to a large degree, the design of the structure. For example, if it is decided to install the piles in groups around the corner legs, rather than in a skirt around the perimeter, then the tower-type structure (versus template-type) is likely to result (see Figure 1). For a tower platform, larger member and joint sizes are likely, and the fracture control problems related to size effects may result (see Section 4.4.2.2). The trade-offs related to the fabrication method are the main concerns addressed by this report, although transportation and installation are recognized as important issues and are addressed at some length as part of this section.

5.2 Current Practices

The construction of fixed steel offshore structures can be divided into two main phases, fabrication and installation. In the fabrication phase, fracture control is primarily concerned with quality assurance of incoming material and the welding of parts together. There is general agreement that it is difficult to overemphasize the importance of well designed and fabricated welds to fracture control. Welding involves controls on how welds are made, the inspection of these welds, the rejection or acceptance of weld defects, and the repair of defective welds. In the installation phase, fracture control is concerned with preventing and inspecting for damage to the structure. Following a brief overview of the construction of fixed steel offshore structures, welding of tubular joints and the treatment of fabrication defects are discussed. Inspections will be covered in Section 5.3.

5.2.1 Overview

A typical Gulf of Mexico template-type structure is fabricated on its side in a shipyard. Viewed from above, the completed structure usually has four lateral bracing frames visible, the center two frames being the launch trusses. These four frames are fabricated horizontally, then tilted up into position and joined together by more braces.

In what is commonly known as the frame method, a tubular joint between a brace and a chord is formed by cutting the end of the brace in the shape of a saddle to fit the chord. The brace is put into its position in the structure, in a frame or between frames, and welded to the chord. Special steel (either thicker plate or different material) may be placed in the chord at the joint by inserting a segment called a "can". Special steel is not usually used at the brace ends. An alternate joint fabrication method, known as the node method, will be discussed later, in Section 5.4.

Once the structure has been fabricated and outfitted with cathodic protection, installation equipment, and so forth, it is ready to be installed. If the structure is to be carried on a barge, it is jacked onto the barge, an operation called "load out". The barge carrying the structure is towed to the drilling site ("transport"), where it is launched off the barge. The structure will float on its side until it is set upright by selective flooding of its legs, and/or with the assistance of a large crane. Once upright, it is positioned on location and landed on the bottom. The piles and well conductors are installed, sometimes with a temporary work deck. And, finally, the deck and supporting trusses are placed on top of the platform.

If the platform is not a template-type structure, alternate installation methods may be used. For example, self-floaters do not require a barge; load out is replaced by flooding the dry dock and floating the structure, and no launch is necessary. Also, for gravity-type structures, no piles are needed.

5.2.2 Welding of Tubular Joints

Welding procedures for fixed steel offshore structures are described in detail in the American Welding Society's, "Structural Welding Code: Steel", AWS D1.1; the "Guide for Steel Hull Welding", AWS D3.5; the API RP-2A; and ABS "Rules for Building and Classing Offshore Installations," Section 11, and "Rules for Building and Classing Steel Vessels," Section 30. Most tubular joint welds are done manually, with hand-held welding rods (Shielding Metal Arc Welding, SMAW). In recent years semiautomatic welding, for example, using "flux core" wire (Flux Cored Arc Welding, FCAW), have been used, thus allowing faster weld metal deposition rates. And in special applications, gas shielded welding (Gas Metal Arc Welding, GMAW) has been used. All of these techniques are covered by the above documentation. Standard procedures are available for the choice of electrodes, polarity, voltage, current, etc.

Preparations are made for the weld to assure weldability and fusion. The base metal is preheated if necessary, and welding rods may be kept dry in special ovens (especially important for low hydrogen rods in humid Gulf of Mexico fabrication yards). The edge of the brace end is usually prepared without a root landing, so that the root weld can be made from the outside only. And the fit-up of the parts is watched closely, especially to control the root opening.

In the frame method, the root of the weld is accessible from only the outside of the joint. Special skill is required for this single-sided welding of complete penetration groove welds without backing. The root pass may thus be performed by a special welder, and other passes made by less skilled welders. Subsequent passes, to complete the weld and bring it to its required thickness, vary in number, size, and order. These parameters affect the residual stresses and distortion of the weld. Semiautomatic (or FCAW) procedures are often used because they are capable of filling the weld rapidly; however, the profile of the completed weld is then more difficult to control.

The weld profile should merge smoothly with the adjoining base material, without excessive undercut, etc. The weld has the effect of a notch on the stress distribution through the plate thickness, possibly causing a large stress riser at the weld toe. In fatigue sensitive joints the weld profile may be "improved" to decrease this notch effect. While the API does not quantify the profile so that the degree of "improvement" can be determined, it is generally accepted among fabricators that at least one small extra butter pass at each of the toes is called for. Sometimes extra cap passes are used to help form the weld to a convex profile. Grinding of the weld to control the profile is not common, although, given a nonaggressive environment, it substantially improves the fatigue performance of weld toes (e.g., see Appendix A).

Once the weld is complete, it is usually left alone until it is inspected. Post-welding treatments, such as post-weld heat treatment (PWHT), are not common in Gulf of Mexico practice. Joint sizes, i.e., thicknesses, are usually not large enough in American practice to warrant PWHT. Some work has also been done with grinding or peening the weld to reduce residual stresses.

5.2.3 Fabrication Defects

In terms of fracture control there are two primary types of defects of concern: welding discontinuities and gross errors. The gross errors are macroscopic errors such as member misalignment or insufficient gaps between braces in a joint. Such errors can lead to congested welds, undue residual stresses, cracking, and even inadvertent overlapping of braces. The structural engineer is usually consulted in these cases to assess the severity of the problem.

The principal welding discontinuities found in welded joints are: inadequate root penetration, incomplete fusion, undercut, slag inclusions, porosity, and cracking. These crack-like defects and cracks could compromise the strength of the weld, lead to brittle fracture, or initiate a fatigue crack. All of these discontinuities exist in tubular joint welds to some extent. Because of inspection system limitations, not all such defects are found by inspections, and those that are found may not be accurately characterized (e.g., sized). Of equal concern is the problem of defining the significance of cracks that are found and determining the disposition of a weld containing such a crack.

The decision to accept a weld with discontinuities, or to reject it, is based on the severity of the defect. In the past, strict limits have been placed on the size of acceptable defects, such as, no larger than 1/8 inch depth x 1 inch surface length. There is currently a trend away from such absolute standards and toward acceptance criteria based on the defect's impact on the fitness of the joint to serve the purpose for which it was intended; this trend is popularly known as "fitness for purpose," "fitness for service," or "Engineering Critical Assessment."

Current fitness-for-purpose evaluations are based on fracture mechanics models of the behavior of crack-like defects in the welded joint. The defect is checked against brittle fracture initiation, and other possible modes of failure, under the design and other critical loadings. If the modeled weld can withstand tests for failure under single extreme loads, the growth of the flaw in fatigue (multiple loading) is also considered to see if the critical crack size could be reached in the design life of the structure. If the flaw does not adversely affect the joint's fitness-for-purpose, it is acceptable. Otherwise, the weld is rejected and repaired.

As an example, consider a small crack found at the weld toe in the chord. The model of this crack is likely to consider a two-dimensional slice (plane strain) through the thickness of the chord, including the brace and the weld. The stresses around the crack might be determined by finite element analysis, or by conservative generic analyses (e.g., hot spot stress parametric formulas with stresses modified for the notch effect of the weld). The brittle fracture of this detail is then checked with respect to the fracture toughness of the material. Currently, the crack tip opening displacement (COD) of the material is the popular measure of fracture toughness in ductile steels for this purpose. The value of COD might be assumed from generic material values, derived from conservative correlations with Charpy tests, or actually determined by testing. The acceptance criteria for brittle fracture might then be based on methods such as those presented by the BSI PD6493:1980, "Guidance on Some Methods for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints".

If the example crack passes the applicable single loading tests, it is then checked for fatigue under multiple loadings. The propagation of the crack is considered using simple crack growth laws, and the expected stress cycle history, which may be available from the design fatigue analysis. The same two-dimensional* model as used above would be used, possibly with conservative assumptions to simplify the crack growth model or analysis. For instance, it is known that the displacement-limited, three-dimensional* stress redistribution occurring around the crack is beneficial in slowing down the growth rate. However, experiments show that, in many cases, once the crack goes through-thickness the growth rate rapidly increases, leaving only a little additional fatigue life of the joint. Assuming the two-dimensional*

*By the terms "two- or three-dimensional" we refer to the theoretical scope of the stress analysis used to estimate stress intensity factor and other near-crack tip stress parameters.

solution calculates faster crack growth rates, the modeled crack would conservatively reach the critical crack size sooner. Computer programs have been implemented to solve these problems automatically.

In addition to brittle fracture initiation, other possible modes of failure may be considered to determine the critical crack size. In tubular joints, yielding due to overloading of the remaining cross section, plastic instability, or leakage from a through-thickness crack might be considered. Even arbitrary limits might be chosen, such as a certain fraction of the joint thickness, since a through-thickness crack is often far more costly to repair than a part-through crack.

Should the weld be judged unfit, either by a fitness-for-purpose evaluation or by an absolute standard, it must be repaired. A weld repair consists of removing the defect from the weld, rewelding the joint, and reinspecting the work.

A defect is usually ground out under the close scrutiny of a team of inspectors. Their purpose is to assure that the defect "indication" found in the inspection corresponds to the actual size of the defect in the weld. Thus, defect removal is a very slow tedious process; only a thin layer of material is removed at one time, and then the exposed surface is inspected for the predicted defect. This serves as an important calibration of the inspection process, especially if embedded flaws are indicated by ultrasonic testing.

After the weld defect has been removed, rewelding proceeds according to the steps described for the original weld. However, more attention to following the correct procedures, such as preheating, etc., can be expected. The resulting weld should be as good as an original weld and, because of the extra attention, might even be above average. Inspection of this weld and other welds is described below.

5.3 Inspection

In the fabrication phase of construction the most effective inspection scheme is to prevent the introduction of defects into a weld, rather than to find them after they occur. To this end extensive qualification tests are required for both welders and welding procedures. Inspection of welds in the complex geometries of tubular joints is difficult, and special care is needed. Also, when defective welds are found, it is important to investigate the possibility of systematic error.

In the installation phase, inspections for fracture control are part of the overall quality control of construction. Special attention to fracture related aspects may be necessary.

The following discussion briefly describes the inspection procedures that are used, but does not go into the details of "how-to-do-it". Such details can be found in the references listed.

5.3.1 Welding Qualifications

As stated above, these qualifications are designed to prevent large weld defects from occurring in the first place. Since special skill is required to make one-sided full penetration groove welds, welders with this skill must be identified. The AWS D1.1 describes different skill levels to which a welder may be qualified. These skill levels are set by the type of weld (full or partial penetration, groove, butt, fillet, etc.), the position of welding (flat, horizontal, vertical, overhead, etc.), and the welding process (SMAW, FCAW, GMAW, etc.) necessary to the job. As in pipeline construction, special welders may be designated to do the root welds.

The welding procedures themselves must also be qualified. For example, the fabricator might propose to make the root weld using hand held welding rods (SMAW), and fill in the body of the weld using a semiautomatic procedure (FCAW). Since different procedures result in different heat inputs, cooling rates, chemistries, and microstructures, the toughness of the weld should be tested. The API RP-2A requires Charpy V-notch impact test specimens to be

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removed from the qualification welds and tested. A CVE (Charpy V-notch energy) of 20 ft-lbs at 0°F is required of the as-deposited weld material for welds in tubular joints. The test pieces should be representative of the actual plate thicknesses and diameters to be welded in the structure.

5.3.2 Inspection of Welds

The inspection of production welds is vitally important. Field inspections are of three kinds: observation of the welding process, visual examination of the weld, and non-destructive examination (NDE) of the weld.

The welding process is observed to assure that qualified welders and procedures are used. Sometimes, different colored hard hats are issued to welders of different qualification levels, to make it easy to see that a qualified welder is working. Critical welds are watched carefully.

Upon completion, the weld is inspected visually to check its profile and see that it merges smoothly with the adjoining base material without excessive undercut. Pocket gauges and magnifying glasses may be useful for this purpose. A visual examination may detect small surface cracks, such as in the weld or at its toe, or larger defects such as cratering. For fillet welds, a visual examination is likely to be the only inspection. For other welds, some sort of NDE is likely.

Non-destructive examination of tubular joints is very difficult. This is due to the complex geometry of a tubular joint and to the fact that the weld is only accessible from the outside of the joint. Under these conditions, meaningful radiographic inspections (gamma ray or x-ray) are impossible. So the burden of NDE inspection falls upon two techniques, ultrasonic and magnetic particle. A third technique using dye penetrants is sometimes allowed when one of the above cannot be performed.

Ultrasonic testing has become the most important inspection technique for tubular joints. In this test, the ultrasonic echoes of flaws are measured electronically by skilled technicians. Since the interpretation of the test results is difficult, especially for tubular joints, the API has published a

"Recommended Practice for Ultrasonic Examination of Offshore Structural Fabrication and Guidelines for Qualification of Ultrasonic Technicians," API RP-2X. The test results are best for flat plates, and least conclusive for the acute-angle brace-to-chord weld areas in K- and Y-joints. Because no single test is conclusive by itself, ultrasonic testing is often used in conjunction with another NDE technique.

For tubular joints the second major technique is magnetic particle inspection. Here an electric current is passed through the metal, creating a magnetic field. Flaws in the metal alter the current flow and distort the magnetic field; this distortion can be seen in magnetic particles dusted on the surface. One drawback to this technique is that it becomes less effective for detecting flaws the deeper the flaws are found in the plate. Typical inspection requirements call for 100% of tubular joint welds to be both ultrasonically tested and magnetic particle inspected.

In some instances, dye penetrants may be used in lieu of one of the above methods: For example, when the weld is inaccessible to the testing equipment. In this method, a dye is washed over the metal and penetrates surface cracks. Dye left in the cracks can be detected visually. However, dye penetrants cannot detect subsurface defects.

Besides tubular joint welds, pipe seam and girth welds must also be inspected. Here radiographic methods can be used (usually gamma radiation because of the equipment's portability). Typical inspection requirements call for these welds to be 100% radiographed and/or ultrasonically tested. Miscellaneous welds are inspected by a variety of methods.

5.3.3 Treatment of Defective Welds

In common practice, when a defective weld is found and rejected, the possibility of systematic error would be checked first. If not already done, the entire weld around the joint would be inspected to see if the problem is inherent in the joint. For example, the fit up may have been poor, or the welding process may be at fault. The welder himself may be at fault, so his work on other joints would be examined as well. The quality of a welder's work remains nearly constant, so if a defect is found in one of his welds, other defects are likely to exist. If too many defects are found in a welder's work, he would be disqualified (at least until retraining) for that type of welding.

When checking for systematic errors among different joints, it is useful to have records of who made which weld and how each was done. "How" should be identified on the drawings or specifications. On typical shallow water Gulf of Mexico platforms, the inspectors can usually remember who made each weld since the crews are small or they can refer to weld records, as available. Our interviews with a number of operators/fabricators indicated that detailed records of welders and welds are not always available.

5.3.4 Inspection of Installation

Once the fabrication phase is complete, inspection of the structure's construction concentrates on the proper execution of installation procedures. In terms of fracture control, the main goal of these inspections is to prevent damage due to accidents. Overloads causing crack initiation can obviously occur in the sensitive load out, transport, and launch processes.

There are also more subtle opportunities for cracks to initiate. A prime example is during offshore welding operations, such as welding the deck to the jacket. An improper or inadequate ground to a welding machine located on a barge can create a current flowing between the barge and the jacket through the water. Since the weld metal has a different chemical composition than the base metal, an electric potential is set up between them. This can cause the weld to behave like a sacrificial anode, resulting in rapid corrosion. The damage may be pitting of the weld, making local stress concentrations worse, or knife-edge slices into the metal, effectively initiating cracks.

Therefore, all inspections of the construction may affect fracture control, even if a direct correlation between the regulations and the fracture-related result is not apparent. Inspection of welds in tubular joints for defects is the most obvious fracture control measure. Procedures such as those which call for inspection of the grounding of offshore welding operations are equally important, but not as obvious.

5.4 Two Special Topics

Offshore construction technology is changing rapidly. The introduction of flux cored welding and ultrasonic testing have significantly advanced the state of the art. Yet the introduction in 1980 of the API RP-2X recommended practice for ultrasonic testing stirred a major controversy over weld root defect acceptance criteria. Closely related to this criteria is the frame method of joint fabrication. The following discussion examines this controversy.

A second topic is the recently increased attention to fracture control during transport. A current trend is toward longer tows from the fabrication yard to the installation site. Fatigue during transport has thus become a concern. The handling of this problem is also discussed.

5.4.1 Weld Root Defect Acceptance Criteria

Before the API RP-2X was first published in 1980, guidance on the acceptable size of defects in the root of full-penetration tubular joint welds came mainly from the AWS D1.1. Two levels of reject criteria are specified by the AWS D1.1. In bridges, the weld surfaces are ground smooth to improve their fatigue performance, and design fatigue life calculations assume a smooth surface and minimum weld defects. Thus, strict reject criteria are applied to bridges. In buildings, welds are usually left in their as-welded condition, as fatigue is less important. So more relaxed criteria apply to buildings. Recognizing that tubular joints in offshore structures are, loosely expressed, somewhere between bridges and buildings in regards to fatigue, the AWS D1.1 leaves the specific criteria up to the operator.

The API RP-2X was introduced to fill the gap in specifications between the bridge and building criteria, and quantifies the acceptable defect sizes in tubular joint welds for the operator. The criteria are based on experience with Gulf of Mexico type design and construction. That is, redundant template-type platforms are assumed, with typical as-welded surface profiles and notch tough materials. The frame method of joint fabrication is also assumed, i.e., welding and inspection are from one side. Thus, what have been quantified are the acceptable criteria for typical Gulf of Mexico practices.

A controversial aspect of these criteria is the greatly relaxed criteria applied to defects in the weld root. For example, outside of the root a planar defect is acceptable if it is less than 1/8" wide and 1/2" long; but, in the root area a 1/8" wide defect may be up to 2" long (i.e., 1/8" x 1/2" versus 1/8" x 2").

How is this relaxation of criteria justified? First of all, the AWS has long recognized, even before the API RP-2X was released, that root defects are less detrimental (and more difficult to repair) than defects elsewhere in the weld. A probable explanation is that all key crack-driving stresses in the root area are typically less than elsewhere in the weld. The notch effect of a weld profile is often restricted to the toe. When the brace is pulled in tension, the mean brace radius shrinks (Poisson effect), and then the weld root is actually placed in compression, or very low tension, due to shell bending. Second, residual stresses at the root also tend to be compressive or at least substantially lower than at the toe, since the root weld passes are effectively stress relieved by subsequently applied weld passes. And third, fatigue tests have shown that, as long as the root defect is not so gross as to significantly affect the overall weld area and stresses, toe defects, rather than root defects, control the fatigue strength of tubular joints.

So what is controversial about these criteria? First, there has been criticism that experience alone is not enough justification for relaxing the root defect acceptance criteria for all situations; these criteria should be backed up by further testing and analysis. For example, the shell bending effect mentioned above could make root defects more critical in compression braces. Second, there is a feeling that these criteria were designed more to protect the status quo in fabrication practices than to advance the state of the art in fracture control. Specifically, these criteria are based on typical quality levels achievable using the frame method of fabrication prevalent in Gulf of Mexico (rather than new frontier or North Sea) practice and benign wave load fatigue damage spectra.

To understand this second criticism, recall that, in the frame method, tubular joint welds must be made from one side, the outside, with no backing. This is very difficult to do, so weld root defects might be expected to occur rather frequently. In fact, the difficulty is so great that, should the weld be repaired, the repair weld may be no better. Another factor is that inspections conducted from the outside have extreme difficulty in correctly estimating the size of a root defect. There is large uncertainty in interpreting ultrasonic tests of this type of weld (due to the complex geometry), and a high probability of missing root defects completely.

Therefore, proponents of the API RP-2X argue that, (1) significant numbers of root defects of the API RP-2X acceptable size must exist in installed structures and experience with these structures indicates that they are all right; (2) even if all the root defects detected were repaired, the structure would still have numerous root defects of comparable size that were missed by the inspection (and the structure would still probably be all right); and (3) the repair of root defects is very costly, especially considering the large number of welds involved and a high probability that the repair will need to be redone. In short, they say that extensive experience, with sound qualitative stress-related explanations, has shown these criteria and current practices to be fine, so there is no need for stricter standards to be applied.

Actually this situation is not unusual to find in fracture control and in other fields. When a new or refined method of inspection is introduced, defects often will be found where they previously were not known to exist. The question of the significance of these defects is immediately raised. Are these defects something new, perhaps related to a change in practice? Or, have they been there all along? The position taken by the API RP-2X is that the root defects detected by ultrasonic testing have always existed in the past, but were not detectable by radiographic or magnetic particle inspection, and that experience has shown these defects to be acceptable.

So, what is the argument? The point would likely be moot were it not possible to fabricate tubular joints, especially those in critical load paths with high hot-spot stresses, without such large defects in the weld root. The technique making this possible is known as the node method.

The node method of fabrication originated in North Sea practice, in response to the need for post weld heat treatment (PWHT) of large tubular joints (i.e., large plate thicknesses). The solution to the problem of PWHT was to fabricate the brace-to-chord connections as a "node" separate from the main lengths of the braces and chord (Figure 4), and then to put the node into a large oven for PWHT. Thus, a node consists of a can and the brace ends, or stubs, which are welded to the can. Field assembly is then reduced to splicing the braces to the stubs and the chords to the can with simple girth welds. Complicated field fit ups and edge preparations are eliminated. One can imagine the assembly of the structure as building with "Tinker-Toys."

Several advantages result from this method. First, the nodes may be fabricated in locations other than the final assembly yard. Those locations may be chosen on the basis of steel availability, fabrication skill, etc. Second, special steel can easily be used in the stubs, as well as the can. Third, a higher level of control is possible over fit up, welding, and so forth, when a smaller assembly is fabricated on the ground, or in special jigs, than when the welder is working a hundred feet off the ground. Fourth, the location of the welds without PWHT is no longer at a cumbersome intersection of two cylindrical surfaces; instead these welds are made around the circumference of a cylinder, away from hot spot stresses. Fifth, and most important in this context, the most critical (brace-to-can) weld may be accessible from both sides for welding and inspection. (The less critical brace stub welds are only accessible from the outside.)

With the brace-to-can weld accessible from two sides it is possible to eliminate large root defects from the fabrication since welding from the back of the root and unambiguous inspection are possible. So, in North Sea practice, strict standards apply to root defects. The node method has one drawback, however; it is costlier than the frame method.

Thus, the stage is set for the controversy. Due to a natural dislike of weld defects, and knowing that a method of fabrication exists which can eliminate the largest weld defects with very high probability, opponents of the API RP-2X relaxed root defect rejection criteria argue against it. Its proponents argue that experience has shown these criteria to be all right. The rationale behind the criteria has been argued back and forth. So have alternate criteria.

The most important question to be asked here, which must be answered in the future, is how suitable are these relaxed criteria outside of the Gulf of Mexico? As discussed with respect to fatigue design and elsewhere, certain assumptions about the structure, its operation, and its environment have been made. Thus, built into these criteria are assumptions regarding acceptable risk levels, the "purpose" part of fitness-for-purpose, the rate of fatigue damage imposed by wave loads, and other aspects of fracture control which may not be suitable for areas outside of the Gulf of Mexico. The investigation and debate continue.

5.4.2 Fracture Control During Transport

In recent years this has been an area of increased concern and attention. Several factors have motivated this concern. Occasional failures in transport have occurred, involving fracture. Cracks have been found in some structures soon after installation, and crack initiation during transport was suspected. And, probably most important, there is a current trend in construction practices toward longer tows to (and, perhaps upon dismantling, from) the installation site, especially for frontier areas, thereby exposing the structure to greater fracture risk.

In the past, transport was considered as simply another part of installation for design, receiving roughly the same treatment as other construction loads, such as launch. That is, individual design loadings, the most extreme conditions expected (e.g., barge roll, pitch, and heave), were considered, but repeated loads, causing fatigue, were not. With the trend toward longer tows, this attitude has changed, and transport is recognized as an additional mission for the structure. A full design treatment may be given to the transport aspects of the structure, including fatigue analysis.

On the inspection end, fracture control has been low in priority during and after transport. During transport, the fracture control attention has been directed toward the sea fastenings tying the structure to the barge, rather than toward the structure itself. After transport (between the time the structure reaches its intended site and the time it is launched), generally more attention is paid to the installation equipment carried aboard the structure, such as hydraulic lines, valves, and instrumentation. And after it has been launched, the speed of the rest of installation is so important that an inspection for fracture control is "impossible" until installation is complete. So it is not until well after a series of potentially severe loadings, load out, transport, and launch, that the next inspection for fracture control can take place. And then such an inspection is likely to be only a quick visual check to see if the structure is intact.

An awareness of fracture control problems in this phase of a structure's life has been growing lately. This is particularly true of structures subject to long tows across rough water to Frontier areas, but it is also true for short Gulf of Mexico tows to some degree. A sophisticated example of the developing practice will now be described.

Consider a hypothetical platform to be installed on the U.S. West Coast. It is anticipated that the platform might be built in Japan, in which case a long tow, over one month, across the North Pacific would be necessary. A full fatigue analysis, including the dynamic response of the barge and platform combined, is performed as part of the design. The loading history is described by a scatter diagram of the sea states expected to be encountered along the tow route. A spectral fatigue analysis is performed for all hot spots plus the sea fastenings (alternatively, a deterministic analysis might be used). Damage due to transport fatigue is limited to a Miner's sum of 1.0 or less. In addition, the damage at each hot spot is carried over to the inservice fatigue analysis, and added to the damage expected over the life of the structure.

Such fatigue analyses have been performed for various platforms. Some important general conclusions from those analyses are as follows. It is important to conduct such an analysis for a long tow. Knowing the characteristics of the barge to be used is vital, and the barge flexibility and temporary structural supports should be considered. Transport fatigue may control the design of a significant number of joints in the structure, particularly those near the tie downs to the barge. However, since the transport loadings and the inservice wave loadings are resisted by different framing systems, there probably is little interaction between transport fatigue and inservice fatigue.

Finally, when long tows are involved, the structure may be taken to an intermediate protected area and inspected there. The inspections are most likely visual, but special attention is paid to important major joints and transport fatigue sensitive joints. After installation, a complete survey of the structure may be made to check its integrity and provide a baseline for comparison with future inspections. Post-installation surveys are treated further in the next section and a more detailed description of required and optional platform inspections is given in Section 9 of the "Requirements for Verifying the Structural Integrity of Outer Continental Shelf (OCS) Platforms."

5.5 Principal References

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10. Institution of Civil Engineers, Fatigue in Offshore Structural Steels, ed. by J. R. Smith, H. O. Crisp, N. A. Randall, and F. Sterry, Thomas Telford Ltd., London, 1981.

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6.0 CURRENT PRACTICES: OPERATION

The fourth major activity related to fracture control for fixed steel offshore structures is their operation after installation. Of the many aspects of operation related to fracture control, inspection and repair have received the most attention in the literature. Here, however, the subject of operation is considered in a wider sense. The principal elements of the practices described here are uniformly accepted by the industry and form the basis of a standard practice. However, the degree to which the standard practice is followed varies considerably from operator to operator and from structure to structure.

The following questions are addressed in this section: Why is fracture control an important activity during operation? What is done to prevent cracks from occurring? When they do occur, how are cracks assessed and repaired? How are cracks found? And what aspects of conventional fracture control during operation are being reconsidered due to recent experience and advances in technology?

6.1 Philosophy

The primary goal of fracture control during operation is to minimize the risk* of operating the structure in the offshore environment. Two conditions of the structure must be considered: routine conditions, when the structure exists as it was designed to exist, and damaged conditions, when cracks (or other damage) may be present. Under design conditions, fracture control is concerned with protecting the structure from damage, either due to accidents (e.g., boat collisions) or due to normal operating conditions (e.g., corrosion). In damaged conditions of the structure, fracture control is concerned with preserving the integrity of the structure: cracks must be found and their significance evaluated before they are dangerous, and if necessary, repairs must be made.

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*Risk equals probability of failure times the loss as a consequence of failure summed over all possible failure events.

To these ends there are three important trade-offs to consider. First, the inspection level (type and amount) chosen for periodic inspections may be high or low. The higher the inspection level, the more it will cost and the more likely cracks will be found while still small. But for redundant "fail-safe" structures, small cracks may not be dangerous, and low level inspections aimed at finding large cracks or even ruptured members may be more cost effective. Second, there are trade-offs between (1) doing a repair on the crack and (2) doing no repair on the crack, but changing the routine operation of the structure. Remembering that the goal is to minimize the risk of operation, a repair, in certain circumstances, may prove to be the riskiest option an operator has, and the choice of avoiding the risk by changing the routine operating mode may be best. The third trade-off is between the several types of repair that might be done. Besides the different repair procedures available, the operator can often chose between short-term and long-term fixes depending on his needs.

6.2 Current Practices

Fracture control practices during operation can be divided into the tasks: minimize the formation of cracks, find and monitor any cracks that may start, assess the crack's impact on the integrity of the structure, and take the necessary remedial steps. The task of finding cracks is discussed in Section 6.3, Inspection and Monitoring. The other tasks are discussed below.

6.2.1 Routine Operation

The fracture control aspects of the routine operation of a fixed steel offshore structure are mostly concerned with minimizing high stresses, cracks, and other damage from occurring. As discussed in Section 2, cracks can initiate during operation due to accidents or improper maintenance. Boat collisions and falling pieces of equipment are common examples of accidents initiating cracks. These can be avoided by closely observing the operating procedures written for the structure. Improper maintenance of the cathodic protection system can lead to corrosion damage, including crack initiations. Improper or inadequate maintenance of appurtenances, such as cathodic protection sleeves, can lead to these objects detaching from their supports, falling through the structure, and causing impact damage. Again such damage can be avoided by closely following the operating procedures.

Another important aspect of routine operation is the evacuation or "de-manning" of the structure for large storms. In the Gulf of Mexico the close passing of hurricanes can be predicted well enough in advance for the platforms to be safely evacuated. De-manning a platform substantially lowers the risk associated with structural failure by limiting the most serious consequences of failure. Other risk avoiding measures are also important. Not all aspects of fracture control during routine operation are specifically for minimizing the development of cracks.

The last aspect of routine operation is the monitoring of cracks after they have initiated. This is discussed below in Section 6.3, Inspection and Monitoring.

Suppose for the rest of this discussion that a crack has been found in the structure. The concern is now with the evaluation of the crack's impact on structural integrity and with remedial measures.

6.2.2 Evaluation of Cracks

There are four steps in the evaluation of a crack's impact on structural integrity. The size and location of the crack must be determined. The effect of the crack on the joint or structural member must be studied, as must the effect of the damaged element on the structure. Finally, a course of remedial action must be decided upon. A fifth step, which is often included in such evaluations, is to determine the cause of cracking, if not already known.

The size and location of the crack are of primary importance. The length of a surface crack can be determined with a photographic survey; however, crack depth cannot be measured from photographs. Non-destructive evaluation (NDE) techniques have been applied underwater. As is the case in construction inspections, ultrasonic testing has gained in popularity. With ultrasonic methods the crack depth can also be estimated. A recent innovation in NDE is the use of plastic molds to get an impression of the crack. Under certain circumstances, especially if tensile stress helps "open" the crack, both surface length and depth are measurable from the impression.

The assessment of the crack's effect on the joint or the structural member in which it has initiated is also known as a fitness-for-purpose analysis. The analysis steps are the same as described in Section 5.2.3, Fabrication Defects. The potential of the crack for brittle fracture may be evaluated by a fracture mechanics analysis. The fatigue life may also be estimated by a fracture mechanics analysis. However, note that the critical crack size might be determined by criteria other than brittle fracture; for example, a through-thickness crack may be judged very costly to repair and, therefore, critical. Also, the effect of a crack on the ultimate strength of a tubular joint is not yet understood. So the critical crack size for a fatigue life analysis may be merely a definition or conjecture for the purpose of performing the analysis. However, if the growth rate has accelerated rapidly at the defined size of a critical crack, the fatigue life, comprised mainly of crack initiation and slow growth while small, may be a very weak function of the critical crack size definition.

Due to the difficulties in predicting the critical crack size and the fatigue life of a crack, the analysis of the effect on the structure usually begins with the assumption that the joint, or the member, has separated. The strength of the "damaged" structure is then evaluated. Since most fixed steel offshore structures are highly redundant, they can usually stand the loss of one or more braces without much difficulty. So the structure is analyzed for overloadings (beyond design load levels) that push the structure to collapse. Then the relevant measure of the diminished strength of the redundant structure is the ratio of the diminished ultimate strength to the as-designed ultimate strength, or some other relative measure. In some circumstances a new fatigue life analysis for the "damaged" structure is in order.

Once the effect of the crack on the joint or structural member and the effect of the damaged element on the structure have been assessed, a decision must be made. Should the crack be repaired? If yes, then how should it be repaired? It is obvious that leaving the crack in the structure without repairs may add risk to the operation of the structure. That risk should be understood from the above analyses. It is less obvious that repairs may also add risk, which is more difficult to quantify. The decision to repair and the choice of repairs must therefore consider not only the cost of each choice, but also the risk of each. As commonly practiced, however, this decision is often more intuitive than analytical--"engineering judgement" being the vehicle for the decision analysis.

A failure analysis is sometimes included as a fifth step in the evaluation of cracks; that is, a determination is made of the cause of the crack, if not already known. Such an analysis could identify generic problems with the structure, and thus predict the locations of other possible cracks. This step is especially important if the crack appears in an unexpected spot. So, in this context, the appearance of a crack serves as an indicator of the structure's performance and calibrates the fracture potential for other spots in the structure.

6.2.3 Repair of Cracks

The repair of a crack offshore in an underwater joint is extremely expensive, potentially one or two orders of magnitude more expensive than the comparable repair done on dry land. There is thus great incentive for the operator to avoid such repairs when possible, either by preventing the cracks from starting (i.e., through design, material selection, etc.) or by justifying the operation of the structure without repairing the cracks. This incentive is greater for fixed platform operators than for the operators of mobile rigs, e.g., semisubmersibles, because the mobile rigs can be regularly drydocked, or at least elevated in calm shallow water, for repairs.

When a repair must be made, the repair procedure chosen depends on many factors. First, is the size of the crack small or large? If cracks are small enough, they are often repaired by simply grinding them out with a large radius, without rewelding. A functional definition of a small crack might thus be, "one that can be repaired by grinding." A large crack is generally considered to be anything bigger than a through-thickness crack. Large through-thickness cracks are significantly more costly to repair than small, part-through cracks.

Other factors include the cost of the repair, the time required to do the work, the diving conditions, the weather window, and the confidence that the repair can be made properly. This last point is especially important. For example, underwater rewelding is not unusual, but special precautions are required. However, given other options this is a less favorable repair because of the increased difficulty. Underwater rewelding is difficult to do, in part, because of the possibility of rapid quenching by the surrounding water. Thus, unless special precautions are required to prevent low quality and brittleness. Among the special precautions available is the opportunity to apply the underwater wet or wet-backed weld in such a way as to produce less geometric stress concentration and residual stress.

A more reliable repair requires that the entire problem joint (or node) be removed from the structure and raised out of the water. (This is not always feasible, especially if a leg joint is involved, and is not a normal operation.) The crack itself is then rewelded and inspected while dry. The repaired node is placed back into the structure to complete the repair. The underwater welds to reconnect the node are circumferential welds, which are easier to do than the tubular joint weld, and are far enough away from the highly stressed region so as not to be a problem themselves. However, the brace material toughness is often lower than that of the node material, necessitating perhaps more control of nodal rewelds than would otherwise be required. Of course, a high price is paid for the higher degree of confidence, not only in terms of money and time, but also in risk. While the node is out, the structure is left in a more precarious position than with the cracked joint in. Also, due in part to weather variability the risk of offshore repair operations is proportional to their duration: the longer the operation, the riskier it is.

A recent development in tubular joint repair is the use of grouted clamps. These clamps are prefabricated onshore to fit around the brace and chord of a cracked joint with good clearance between the inside of the clamp and the outside of the tubulars. The clamp is taken underwater in two pieces, which are bolted together around the cracked joint. Then the annulus between the clamp and tubulars is filled with high strength grout to complete the operation. This procedure was originally developed for North Sea repairs, where the diving conditions are poor and the weather window is short, making the speed of the repair operation most important. The immediate risk of this repair of a joint is consequently lower, and the confidence higher than node removal, repair, and replacement.

The grouted clamp repair is an advancement over the use of friction clamps, which are similar, but fabricated to snugly fit the tubulars without an annulus. These clamps are held in place by steel-on-steel friction. The advantage of grouted clamps over friction clamps is that they can be fabricated with much looser tolerances with respect to the geometry of the problem joint. Friction clamps are difficult to fit up due to out-of-roundness of the tubulars, etc. The use of clamps is still relatively new and research continues on long-term performance of clamped joints, how a clamp affects a joint's stiffness, and how the clamped joint can be inspected.

"Repair" does not always mean that the crack itself is fixed. It may be that the structure can live with a small crack as long as it doesn't grow larger in fatigue. Then it is appropriate to "repair" the crack by removing the cause of the cracking or of crack extension. Typically, this means removing sources of high stress concentration or high loads. For example, gusset plates may have been used in the original design and may now be seen to do relatively more harm than good. Another example, a redundant brace which may bring too much load into a joint might be removed without any problem, allowing the load to flow down another fail-safe load path.

Finally, some distinction should be made between temporary and permanent repairs. Should the failure analysis reveal a severe fatigue problem, rewelding the crack can only be a temporary solution. A permanent solution must also mitigate the cause of the cracking. Thus, the permanent repair may require, for example, that braces be added to reduce the cyclic stresses. An immediate temporary repair is often adopted to get the structure through a season of rough weather, to be followed a year or more later by the permanent solution.

6.2.4 Non-Routine Operation

Crack repairs are not the only remedial measures available to the operator. Non-routine operation, that is, changes to routine operations, may be chosen instead of repair or to supplement repair. In light of the high risks associated with offshore work and underwater repair (e.g., to divers), such options may occasionally be the best way to minimize risk. Even doing nothing at all might be the best course of action in some cases.

Removing the hazard associated with the operation of the cracked structure is a good way to reduce the risk. For example, oil storage might be removed from a cracked platform, thereby reducing the pollution hazard associated with platform failure. If danger to the operating personnel is an increased threat during storms, the platform might be de-manned more frequently (i.e., for smaller storms) than would be the case during routine operations. The hazard posed to any nearby platforms by the cracked platform must be a part of these considerations.

When the crack is small or otherwise tolerable, another remedial measure is to inspect the structure more closely and monitor the growth of the crack, rather than take any of the above actions. This approach can be especially valuable if the failure analysis is inconclusive. Examining the crack metallurgically and fractographically can also help to determine whether or not it is growing as the result of fatigue or whether it is a stable defect introduced sometime during construction. In this way, the crack may serve as another measure of the performance of the rest of the structure.

6.3 Inspection and Monitoring

The subject of inspection procedures and requirements is dealt with in detail in the National Research Council report, "Inspection of Oil and Gas Platforms and Risers" (1979) and the OCS Platform Verification Program, OCS Order No. 8, especially Section 9 under "Requirements". The emphasis of this discussion is, therefore, not on the "how to" aspects of inspection, but rather, on the integration of inspection with fracture control plans.

The task of finding cracks that may have started in the installed structure can be considered in four sub-tasks. First, the backbone of an inspection program is the periodic inspection of the structure specifically to find cracks. Second and third, more general inspections to check the condition of the structure may be conducted (1) soon after installation and (2) on special occasions, when warranted. And fourth, the structure might be continuously monitored to check its general health. Given the uncertainty connected with many inspections, it is good policy to combine several independent inspection types which can be used to check each other.

6.3.1 Periodic Inspections

The National Research Council report mentioned above concentrated on the periodic inspection of offshore structures. These inspections were considered the most important means for the operator to review the condition of a structure. In some cases, some underwater inspection is accomplished annually, but all critical components and joints are not inspected every year. Instead, there is a rotated inspection schedule such that each critical joint or component is inspected at appropriate intervals (e.g., five or more years).

There are two different fracture control philosophies followed by Gulf of Mexico operators for these inspections. One philosophy approaches the inspections with a "fine-toothed comb," while the other uses a "broad brush." Both have independent merits and, as implied above, may provide beneficial synergism, if combined.

The "fine-toothed comb" approach is designed to find small cracks in critical joints before they can become dangerous. That is, the attempt is made to catch the cracks early in their development. These cracks can then be repaired by grinding or other minor repair methods.

In order to find "small" cracks, the surface of the joint being inspected must first be cleaned of marine growth (down to bright metal), usually with a water jet and wire brush. Then, according to some experts, cracks at least 100 mm (~4") long on the surface can be detected visually, and cracks at least 30 mm (~1") long can be detected reliably by non-destructive examination (NDE) (magnetic particle inspection is used for this in the North Sea). Other practitioners are more optimistic or pessimistic on the crack size that is detected with high probability. Such examinations are extremely time consuming; therefore, only a few, twenty to thirty, joints can be examined during a typical annual inspection. The particular joints examined during each inspection may be rotated each time so that all critical joints are eventually examined, for example, every five years. The operator may decide which joints to inspect each time based on the importance of the joints, their fatigue lives, the convenience of their inspection, or other criteria.

The "fine" approach to inspection has been adopted by North Sea operators and regulators. It has the advantage of early warning, which makes the repairs less expensive. But, it also assumes that the operator knows which joints to inspect and when. This is a drawback.

The second approach is more of a "broad brush" approach. It is designed to find relatively big cracks which are easily detected by visual examination alone. These cracks must generally be through-thickness cracks, and are generally more costly to repair. The approach assumes that the joint has a great tolerance for cracks and that the structure is safe with a severely cracked joint. Since a visual examination can be done fairly quickly, as compared to other NDE techniques, the entire structure can be checked during every inspection period.

The "broad" approach might wrongly be considered to merely be a continuation of historic Gulf of Mexico practices. Before the sophisticated underwater NDE methods were developed, typical practice might have been to send divers down periodically to "count the braces." However, the "broad" approach is based on sounder reasoning than just to avoid expensive inspections: one, typical Gulf of Mexico redundant structures can tolerate big cracks without much difficulty, so it may not be absolutely necessary to find the smallest cracks possible. And two, experience has shown that cracks usually occur where they are not expected, so the "fine-toothed comb" approach might not examine the cracked joints at the right time, if at all.

These two operational inspection approaches are the dominant philosophies in Gulf of Mexico practice today. The potential middle ground between the two appears sparsely populated. At the moment there is no comprehensive rationale for deciding how the two approaches should be mixed. It does seem clear, however, that both have advantages and disadvantages and could be combined optimally. Indeed, most North Sea inspection programs have elements of both the fine and broad approach in that each inspection interval a full visual inspection is conducted and only some of the joints are subjected to magnetic particle and other NDE inspection techniques.

6.3.2 Special Inspections

Special inspections in addition to the usual periodic inspections may be warranted when there are indications that damage might have occurred. For example, an accident such as a boat collision may have occurred. Or the structure may have experienced an earthquake, a mudslide, a particularly severe storm, or some other overloading. Or a potential for cracking may be indicated by the detection of cracks somewhere else in the structure (by the periodic inspection), or by cracks found on another, "similar" structure.

When a special inspection is warranted, the inspection method and procedure used should be whatever is appropriate to find the kind of cracking suspected. This basically is a common sense measure, and is commonly practiced in the Gulf of Mexico.

6.3.3 Post-Installation Survey

An important recent trend is the survey of the structure as soon as possible after installation. (A very broad inspection during load out, tie down, positioning at the site, installation, and final field erection is required by Section 9.2.7 of the OCS Platform Verification Program. However, unless foregoing inspections indicate that overstressing has occurred, this inspection is far less complete than the inspections described above at the construction site (see OCS Section 9.2.7.5).) Divers examine the structure for its general condition and may closely inspect some critical joints. Such a survey is useful because it helps establish a baseline condition of the structure as-built. This in turn helps answer the question of, when a crack is found, when it initiated. Cracks initiated during transport, launch, and installation can be identified as such. As noted before, the treatment of a crack initiated during transport should be different from one initiated by fatigue while in service; the later being a more serious (i.e., ongoing) problem.

Thus, this recent trend fits well into a comprehensive fracture control plan. It provides a baseline against which the periodic inspections can be compared. The initial appearance and growth of a crack can be monitored with reasonable confidence. Of course, the examination techniques used in the post-installation survey should be compatible with those used in the periodic inspections if the crack indications are to be compared.

6.3.4 Monitoring

A number of structural monitoring techniques are currently being developed with the goal of providing a continuous review of the "health" of a structure, versus the periodic "snapshots" available today. Monitoring techniques also have the potential to reduce costly and risky diver activities.

Of the various techniques being studied, the most work has been done on ambient vibration methods. In these methods, the natural vibration modes are measured to detect any changes over time which might be due to a loss of structural stiffness resulting from cracks. One problem with detecting cracks in this way is that small changes in the general structure's stiffness must be measured as a crack grows until the joint separates. This difficulty is due to the same properties that protect the structure against cracks, i.e., tolerance, arising from displacement control, of the joint to the cracks and structural redundancy. The small signal to be detected may be masked by equipment operating noise and vibration. So while ambient vibration monitoring is potentially a useful tool for checking the general health of a structure, the application of this technique to small crack detection is still in development.

A related technique is to measure the local vibration modes of the individual braces. Each brace has its own characteristic "ring" when struck, and a change in its ringing will result when cracks degrade the stiffness of its end restraints, the joints. This is a relatively new technique which has not been studied as much as the more global ambient vibration method (some early tests indicate that equipment reliability is still a limiting factor of this technique). Because it checks one brace at a time, it is less sensitive to structural redundancy; also, it is still uncertain how large a crack would have to be to cause a confidently detectable change in the ringing.

A third technique is to measure acoustic emissions. When a crack grows, it makes noises (acoustic emissions) which are detectable with sensitive listening devices. The quality of the signal created, the rate and level of emissions, depends on many factors, including the type of material and the rate of crack growth. At the moment, the low signal-to-noise ratio is a major obstacle, even after filtering. As with the ambient and local vibration techniques, this one also struggles to overcome equipment reliability problems as well as interference from normal production and drilling noise.

An innovative monitoring technique which could reduce, if not eliminate, diver activities is the use of pre-cracked specimens (see Figure 6) directly welded to platform structure near critical hot spots. These specimen coupons may be constructed of the same material, including welds, as the monitored region and ideally should be attached to the structure so as to pick up the full load and corrosive environment spectrum without affecting the fatigue performance of the structure to which it is attached. As can be seen from Figure 7, the connection procedures are complex. It is important to ensure that the placement of such a coupon does not affect the integrity of the supporting member.

The major difference then between the coupon and the structure is that the pre-crack is purposely set so as to be larger and much more likely to grow than the maximum weld defects expected in the structure. The reliability of monitoring equipment is another problem which must be overcome. In theory, through use of coupons of varying crack size, a very accurate reading of

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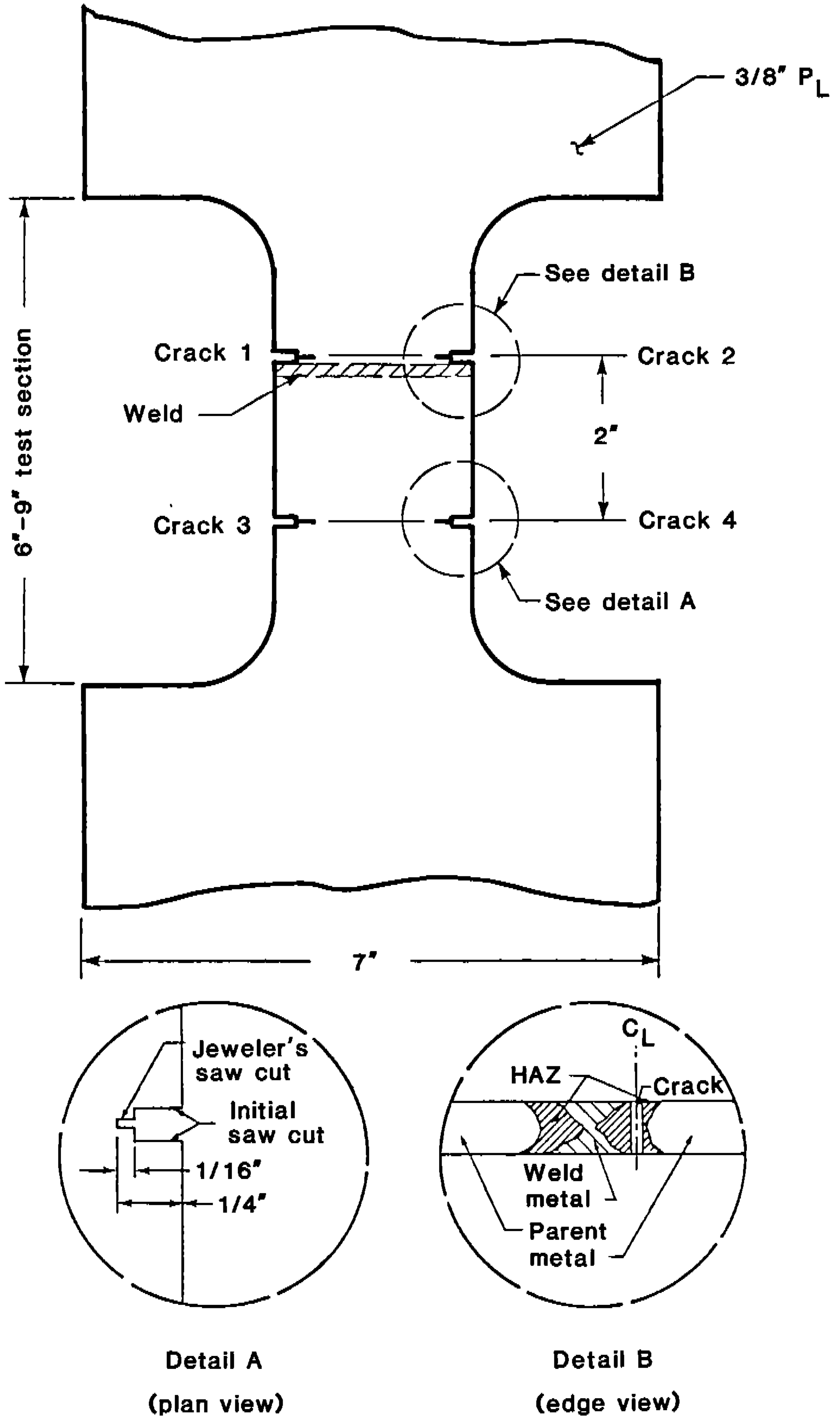

Figure 6. Location of starter cracks in in-situ precracked panel specimens. From Failure Analysis Associates report, "Development, Design, and Installation of In-Situ Corrosion Fatigue Gage."

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7/8 Blind

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13/16 Bind

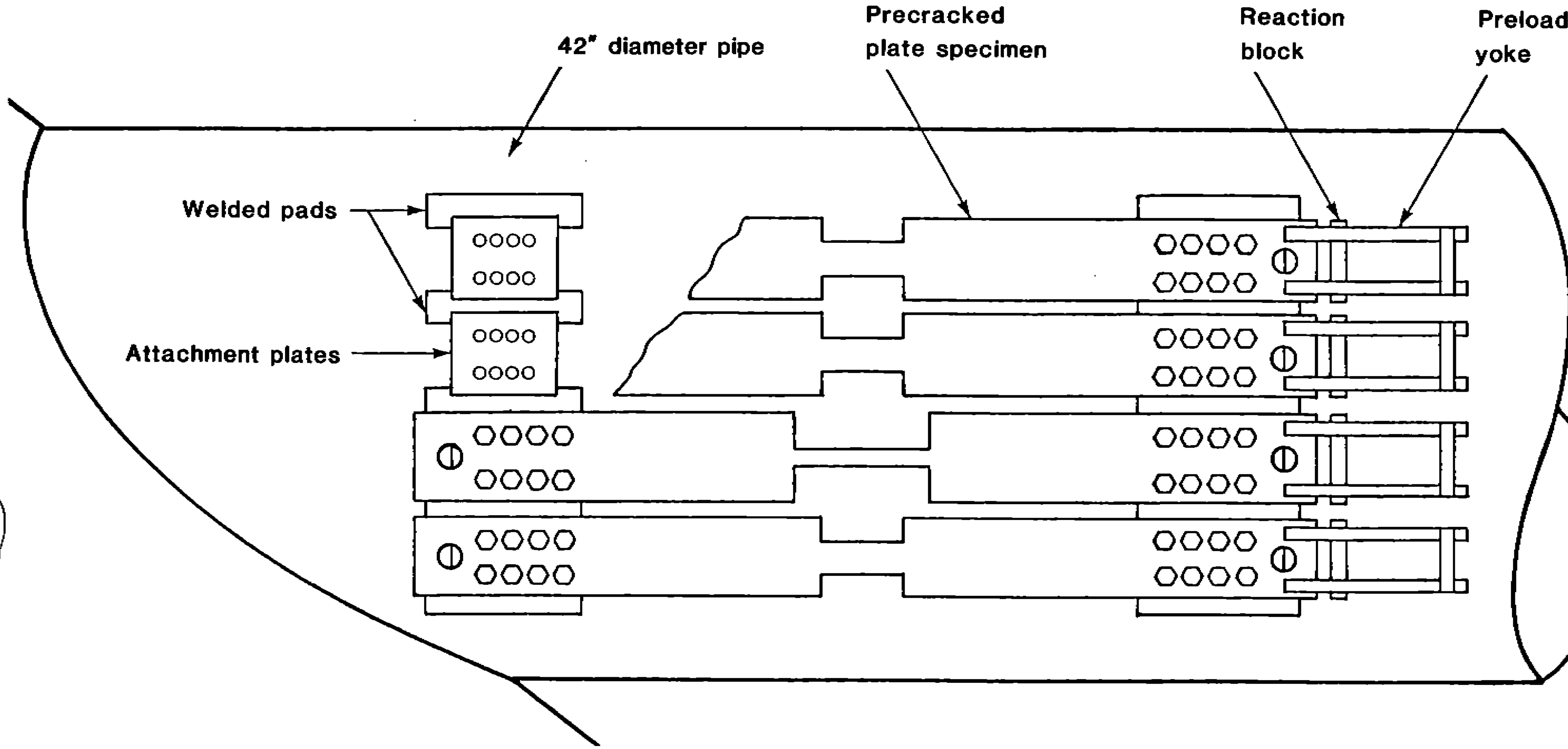

Figure 7. Schematic of precracked plate specimens. From Failure Analysis Associates report, "Development, Design, and Installation of In-Situ Corrosion Fatigue Gage."

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damage accumulation could be achieved. It is our understanding from informal interviews, however, that when this technique was tried by a consortium of oil companies on Gulf of Mexico platforms, the initial results indicated no cracking in the coupons. It is speculated that this lack of cracking is due to a combination of a relatively benign wave load spectrum in the Gulf and/or the use of cracks in the coupons of less than optimumal severity. Thus, the idea may still be practical and good although additional information would be needed to separate the individual effects upon fatigue damage of loading spectrum components, corrosive environment, and, unless several materials were used, of material properties. (Even some of these variables could be separated by clever placement of the crack coupons so as, for example, to minimize one load component while maximizing another. Possibilities for estimating the environmental effect would include greater-than-normal protection against corrosion for selected specimens or, even the use of a material unaffected by the environment for selected specimens, i.e., stainless steel.)

Most other monitoring techniques being studied emphasize the limitation or removal of diver activities; for instance, divers might be replaced by remotely operated submersibles or remote sensing devices. However, from the fracture control perspective, all monitoring techniques share the same important aspects: the continuous (or almost continuous) scrutiny of the structure and the capability to survey the entire structure.

6.4 Discussion

As considered in this report, the operation of the installed fixed steel offshore structure is the fourth and last major activity in a fracture control plan. Recall that the other three activities identified are the selection of material, the design of the structure, and its construction. All four activities are interrelated in terms of fracture control and must be considered together in a comprehensive fracture control plan. Therefore, some of the issues raised by recent reconsideration of operating practices bring in question some long-held tenets which formed the bases of many fracture control plans. The following discussion attempts to tie together a few of the interrelated aspects of the four major activities. The discussion will address these aspects in terms of the evaluation and repair of a discovered crack and the inspection of the structure to find such cracks.

6.4.1 Evaluation and Repair of Cracks

The four steps in the evaluation of a crack's impact on structural integrity (see Section 6.2.2) are performed to varying degrees depending on the situation and the operator. A survey of the crack must be performed in all instances, but the visible surface length is probably sufficient information for most operators. The evaluation of the crack's impact on the joint and on structural integrity is often based on experience, and rules of thumb, not analysis. And the decision to repair is influenced by "external" factors, most notably liability and insurance, not just the "internal" engineering factors. So, in many cases, if not most, the analytical process described in Section 6.2.2 is followed only in outline, at best. Few cases will see full analytical treatment.

The newness of the fitness-for-purpose analysis and industry's lack of experience with it are partly responsible for its lack of popularity. As experience is gained, more of a trend toward its use is expected. Perhaps a more serious drawback is the uncertainty of the calculations, which makes interpretation of the results difficult. The technology is currently relatively unsuccessful at predicting the ductile failure and ultimate strength of a cracked tubular joint. The fracture toughness (COD) of the materials is not specified directly or inspected for, adding to the uncertainty. And the growth of cracks in tubular joints is not understood to a sufficient degree. So, the fracture potential and fatigue life calculations for cracked tubular joints are basically engineering judgements at this time and are, therefore, difficult to interpret properly. These judgements can be improved with more research.

In light of the above, the engineer would be likely to go immediately to the structural integrity analysis: the crack is assumed to cause joint separation, and a strength analysis can be performed. But then the question is, what is the necessary strength of the structure? This echoes the question asked by the designer: How much redundancy is enough? So again, the interpretation of the results of an integrity analysis is uncertain. The engineer is likely to resort to engineering judgement and rules of thumb. For example, braces near the waterline are primary shear transfer members; a crack in one of these is probably serious and should be repaired. But, braces near the mudline or at depth are fundamentally redundant; cracks here are less serious and could probably be tolerated.

So, a crack is often repaired automatically because of "good engineering judgement" and a formal risk analysis is not performed. But "external" factors also influence the decision to repair a crack. These are, specifically, the influence of regulations, insurance, liability, and litigation. In terms of liability and litigation, it seems likely that a court would find the operator more liable for an accident involving a structure with a known crack, than one without; the "act of God" accident is easier to defend than one stemming from an unlikely, but arguably foreseeable, fracture, even if both would have been judged _a priori_ by state-of-the-art analyses to have the same likelihood. These "external" factors contribute to a decision-making environment which heavily favors the automatic repair of the crack as a remedial measure.

This attitude favoring automatic repair is unfortunate because poor decisions are often the result. Not only are repairs made when other remedial actions (e.g., non-routine operation) might be more economical, but the total risk picture might be worse with the repair than with other actions. To illustrate, consider an incident related to the authors by one of the survey's interviewees. A crack was discovered in an offshore platform and it was decided to repair the crack. No risk analysis was performed (or less formal consideration given) to compare the risks of operating the structure with the crack unrepaired to the risks of repairing the crack. The type of repair chosen was to cut the node out of the framing, raise it to the surface with a crane working over the side of the platform, and reweld the crack on the deck. By luck or design, this turned out to be an unfortunate choice, because the crane was overloaded and pulled off the deck into the water. As the crane fell, it hit the structure and knocked out at least one brace. The result of the "repair" operation was a structure in much worse condition than before. Either no action, a less risky repair, or some other remedial action should have been taken. But, apparently, the rapid reflex reaction to the crack influenced the operation negatively. Admittedly this is an extreme example, but it illustrates the potential risk that must be considered in any decision to repair a crack.

In terms of a comprehensive fracture control plan, the objectives and the problems of the evaluation and repair of cracks and of the design process are nearly the same. What is the residual strength of a cracked tubular joint? What is the residual/total fatigue life of a tubular joint? How much fatigue life is necessary? How much strength is enough? How much redundancy is enough? These are all questions relevant to both evaluation and design. A comprehensive fracture control plan must address these questions and provide answers consistent with the fracture control philosophy.

6.4.2 Inspection

A comprehensive fracture control plan should also integrate the development of an inspection scheme with all other fracture control activities, especially design. In developing an inspection scheme, it is important to determine what size cracks the inspection should be designed to find.

As described earlier, there are two periodic inspection philosophies, designated here as the "fine-toothed comb" and "broad brush" approaches. The success of the "fine" approach depends on the ability of the operator to correctly predict where cracks are likely to initiate at any given time and upon the reliability of the inspections. Recent experience has demonstrated that operators are not very successful at making these predictions. Furthermore, the authors have received comments from the American Bureau of Shipping to the effect that they do not generally accept the reliability of ultrasonic testing for underwater crack detection, but recognize its use in determining crack depth after a crack has been located. In fact, in the North Sea magnetic particle inspection has performed better than ultrasonic techniques for underwater crack detection, since the typical crack has a surface or near-surface location and because of the difficulty in cleaning inspected surfaces to the level required by current ultrasonic devices. During an interview we were told that improved methods are underway (funded by the MMS) which may increase the applicability of ultrasonic inspection for underwater crack detection as opposed to crack sizing.

The experience with the conductor bracing of North Sea platforms, mentioned in Section 2.3, is an example of the inability to predict where cracks might occur. In this case, the fatigue loads were not predicted well enough and the anticipated fatigue lives were over-optimistic. In retrospect, the cracking might have been predicted with the proper analysis had current design practices been applied. However, using overly optimistic fatigue lives as a guide for inspection schedules, the conductor bracing was not inspected soon enough to catch the fatigue cracks while they were still small, thereby defeating the purpose of the "fine" inspection.

The general experience of offshore operators is that cracks often form where they are not anticipated. "Fine" inspections, as the example illustrates, often catch these unanticipated cracks only after they are already large or not at all. Some operators are therefore reconsidering the use of such inspections. Instead of concentrating the inspection on only a few joints each time, they reason, it would be better to look for the larger, easily detectable cracks over the entire structure. If large cracks are at least temporarily tolerable, then would not a "broad" inspection, which would find the unanticipated cracks, be preferable? Perhaps a blend of the two approaches would be appropriate: "fine" inspections for locations identified as "fracture critical," and "broad" inspections for the rest of the structure.

A comprehensive fracture control plan should thus identify where "fine" inspections are necessary and where "broad" inspections would suffice. The design phase is the logical point at which to identify fracture critical parts. The material and construction of such parts should be carefully controlled. In designating a part "fracture critical," both the likelihood of fracture and its consequences should be taken into consideration. All four fracture control activities must then be integrated into the comprehensive fracture control plan.

6.5 Principal References

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2. National Research Council, "Inspection of Oil and Gas Platforms and Risers," Marine Board, Washington, D.C., 1979.

3. Marshall, P. W., "Strategy for Monitoring, Inspection, and Repair for Fixed Offshore Platforms," Proceedings of the Conference on the Behavior of Offshore Structures (BOSS '79), London, 1979.

4. Marshall, P. W., Crick, H. F., and Marks, P. T., "Welding and Inspection," Chapter 27 in The Design of Fixed Offshore Platforms, ed. by B. McClelland, to be published by Van Nostrand Reinhold, New York, 1982.

5. Tebbett, I. E., and Robertson, D. A., "Novel Underwater Strengthening System for Tubular Joints," Proceedings of the Offshore Technology Conference, OTC 4110, Houston, Texas, 1981.

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8. Wade, B. G., J. L. Grover, and G. R. Egan, "Development, Design, and Installation of In-Situ Corrosion Fatigue Gage," Failure Analysis Associates for Shell Oil Company, January 1979.

7.0 COMPARISON OF CURRENT PRACTICES

The development of offshore petroleum resources in the North Sea became an important influence on worldwide offshore practices during the 1970's. Since fatigue was such a major problem during the early development, there has been considerable interest in fracture control among North Sea operators. Much of the full-scale fracture-related research in the world is conducted by European laboratories. Through documentation, codification, and research publications, the North Sea standard of practice has become established as one of two main approaches to fracture control of fixed steel offshore structures, the other being the Gulf of Mexico standard of practice.

International offshore practices tend to fall then into two types: a Gulf of Mexico type and a North Sea type. The type of practice followed in a particular location is affected by the type of offshore environment (Gulf type versus North Sea type), who the operators are (American versus European), and the time at which offshore development began (before versus after the 1970's). For instance, in the Persian Gulf, the Gulf of Mexico type standard can be expected: the environment is mild, the operators have American ties, and development began before the 1970's. While in the Tasman Sea (New Zealand), the North Sea type of standard can be expected: the environment is severe, the major operators are European, and development began in the 1970's. Local ties to classifying agencies (e.g., DNV, Lloyds, ABS) also influence the type of practice.

This final section of the summary of current practices compares the Gulf of Mexico type of standard practice with the North Sea type for those aspects that affect fracture control. Other relevant aspects of worldwide practice not typical of the Gulf of Mexico or the North Sea will be mentioned where appropriate. The section is divided into three major parts. The first deals with differences in the offshore and operating environments. The second treats the current practices in the four major fracture control activities, and the third discusses the selection of fracture control plans for frontier areas.

7.1 Offshore and Operating Environments

As summarized in Figure 8, the environments, both the physical offshore environment and the financial and regulatory (philosophical) operating environment, have played the major roles in establishing the different fracture control practices. The severe fatigue loading of the North Sea has already been mentioned. Other contributing factors in the North Sea offshore environments include the great water depths, the cold temperatures, the large distances from land, and the short weather window for offshore construction and inspection activities. In other offshore environments, other hazards, such as earthquakes, mudslides, and ice loadings, may affect the fracture control plans.

The physical environment aside, there are two aspects to the operating environment that have affected North Sea fracture control practices. The first aspect is related to the risk of operations and the second to regulations.

First, the risk aspects: Compared to the Gulf of Mexico where most of the thousands of offshore structures are in relatively shallow water (less than 300 feet), many North Sea structures are major deepwater installations. These structures are expensive to build and to replace. Thus, the economic consequences of a single platform failure, or even of a major repair, could be devastating to a North Sea operator. Also, compared to the Gulf of Mexico, the length of experience operating in the North Sea is much shorter. The uncertainties are therefore higher, increasing the probability of failure at a given level of loading. Thus, the total risk (cost of failure times probability of failure) could be much greater were not the North Sea operating companies extra conservative in their designs.

Second, the regulations: the conservatism of the operators is compounded by the conservatism of the North Sea regulators. In American waters, the Federal government requires verification of a platform's design, fabrication, and installation through the OCS Platform Verification Program. This program requires the platform to be designed and constructed to acceptable standards of practice; for instance, tubular joints are to be designed by a

OPERATING ENVIRONMENT

NORTH SEA

- European Operators
- Offshore Development: post 1970

PHYSICAL

- Severe fatigue loading from wave spectra
- Deep water
- Cold temperatures
- Far from land
- Short weather window

PHILOSOPHICAL

- Deepwater installations are expensive to build and to replace. (Can't afford loss).
- Shorter length of experience = higher uncertainty = greater design conservatism
- Specifications (DNV Rules and U.K. DOE Guidance) are required by government and insurers
- Certification and periodic recertification is required for insurance

GULF OF MEXICO

- American Operators
- Offshore Development: pre 1970

PHYSICAL

- Relatively benign environment and fatigue damage from wave load spectra.
- Shallow water
- Warm temperature
- Close to land (for demanning)
- Operation and inspection is possible all year

PHILOSOPHICAL

- Cheaper frame construction is possible. (Loss is more affordable).
- Years of operating experience = less uncertainty = less design conservatism
- API, MMS, ABS rules, etc., are not binding regulations. (However, OCS platform verification program does contain binding regulations.)

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Figure 8. Differences between the operating environments of fixed offshore platforms in the North Sea and the Gulf of Mexico.

procedure comparable to that set forth in the API RP-2A recommendations. A third party reviews the design, verifying the design process. The operator is required to submit general information to the government, such as a summary of the fatigue analysis, and the government, through the Minerals Management Service, issues a drilling permit. The MMS requires periodic inspection of the structure during its life.

In comparison, in the North Sea adherence to the much stricter Det norske Veritas's "Rules" and/or the UK Department of Energy's "Guidance" is required. Acceptable design practices for these waters are specified in much greater detail by these documents than by their American counterparts. Further, a certificate of fitness is issued by the government (i.e., either the UK or Norway) after the platform has been installed, which must be renewed periodically (every five years, or sooner). Rigorous inspection requirements are at present made for the recertification, although this practice may be changing in favor of one more like that required by the MMS. Thus, government regulators and their agents currently play a much more active role in the building and operation of North Sea platforms than in the Gulf of Mexico platforms.

Thus, the extreme conditions of the offshore environment, the higher potential risk, and the strict regulatory environment have combined to help develop a cautious approach to fracture control in the North Sea. The discussion continues next with the major differences between current Gulf of Mexico practices and current North Sea practices and describes how the environment has helped create these differences.

7.2 Major Differences in Current Fracture Control Practices

Figure 9 summarizes the subject differences in practices between the North Sea and the Gulf of Mexico platforms.

7.2.1 Material Selection

It was recognized early in North Sea development that the toughness of the materials used is important in controlling fracture. A low nil-ductility transition temperature (NDT) is especially important because of the low ser-

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FRACTURE CONTROL

NORTH SEA

- Emphasis on material toughness (selected for COD properties)
- Heavy, large-diameter legged towers
  - 4-legged pile type foundation (can be installed quickly within short weather window)
  - 4-legged tower is less redundant
- Tower has larger, more fatigue-sensitive joints
  - PWHT necessary
  - Node method of construction
- "Fine-Toothed Comb" inspections
  - Platform is permanently manned
  - Inspections are limited by environment (weather, water depth, sea conditions).

GULF OF MEXICO

- Less experience with COD testing (and material fabrication), since material toughness is not as important in the Gulf environment.
- Lighter, template-style platforms
  - 8-legged pile foundations (Long predictable weather window; no need for speedy installation)
  - More legs offer more redundancy
  - Cheaper to fabricate
- Joints are smaller, less fatigue-susceptible
  - PWHT not necessary
  - Allows frame method of construction
- "Broad Brush" inspections
  - Platform can be demanned
  - Environment rarely limits inspection or inhibits repair.

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Figure 9. Differences between current fracture control practices in the North Sea and the Gulf of Mexico.

vice temperatures experienced there. It is significant that the most severe storms occur in the North Sea when the water temperatures are the coldest, but in the Gulf of Mexico the hurricane season occurs during warm months. Thus, the most demand for toughness (for the North Sea) is placed on a material when its supply is lowest, while the reverse is true in the Gulf of Mexico.

European research and development of fracture toughness measures in ductile materials has resulted in the selection of materials for crack tip opening displacement (COD) properties. Recent platform designs for the North Sea have seen COD testing explicitly required by specifications and regulations.

To obtain these material properties on a regular basis, the close cooperation of the steel making industry has been required. European steel makers supplying North Sea fabricators have the necessary experience with COD testing to satisfy this requirement, as have the Japanese. American steel makers have had less experience in this, but are gaining. In contrast, some U.S. operators have reported difficulty in getting even simple Charpy impact tests when contracting with steel makers in some developing countries; assurance of toughness then must be attempted through other means--for example, through correlations with strength testing.

The wide spread use of COD testing is one of the most explicit fracture control measures used in North Sea practice.

7.2.2 Design

Fixed steel structures designed for the North Sea tend to be heavier than their Gulf of Mexico counterparts. For platform designs, North Sea operating companies seem to favor large diameter legged towers over the templates found in the Gulf region. These differences affect fracture control through the redundancy of the structure and the size of the joints.

Foundation design is one of the main reasons towers are favored for North Sea environments. Due to the short weather window, installation time is limited. Pile groups clustered around the four corner legs can be installed quickly, because the driving equipment does not have to be relocated for each pile. This leads to a four-legged tower-type design and, in some cases, to self-floaters. Other considerations, such as fabrication costs, are also important.

The framing of a four-legged tower tends to be less redundant, as there are fewer braces, than an eight-legged Gulf of Mexico template. Thus, the loss of a single brace in the structure has a more severe effect on the tower's structural integrity. The tower is therefore inherently less tolerant of cracks.

The large diameters of a tower's legs necessitate large tubular joints. These joints are thickened further by the effects of dynamics and fatigue. The resulting joints are both large in diameter and in thickness. Detrimental size effects then come into play: the fatigue strength (measured in units of stress) of tubular joints decreases as their size increases. They are also more difficult to fabricate.

Fracture control is therefore affected by the typical design of North Sea platforms. Tower-type designs result in lower structural redundancy and, in combination with more fatigue content in wave load spectra, larger, more fatigue-sensitive joints. These structures are less tolerant of cracks than are the template type structures typical of the Gulf region.

7.2.3 Construction

The large joint sizes used in North Sea structures require post-weld heat treatment (PWHT). As discussed earlier, this requirement led to the development of the node method of fabrication. From the fracture control viewpoint, this has several advantages. First, the node can be fabricated in a more controlled environment, assuring a higher quality of fabrication for the critical joints. Second, access to both sides of a tubular joint weld for welding and for inspection is possible, allowing better control over weld defects at the root. Third, special material can easily be used for the brace-end stub when extra fracture resistance is necessary. And fourth, the node method shifts the weld stress away from the node intersections.

Thus, the predominant use of the node method of fabrication, especially for critical joints, has several advantages in limiting initial defect size.

7.2.4 Operation

The inspection philosophy for the periodic inspections of North Sea structures is to find small cracks before they can become dangerous. The "fine-toothed comb" approach to inspections is followed, and, in fact, required by regulation.

There are two major operational reasons for this inspection philosophy. One is that the platforms are permanently manned, and with much larger contingents than those in the Gulf of Mexico. Evacuation of the platforms for large storms is often impossible because of the short notice before a storm occurs and the large distances to land bases. So the consequences of structural failure are much higher than in the Gulf of Mexico. The second reason is that inspections are limited by the environment. The water depth limits the accessibility of critical joints to diver inspections, and the short weather window for diver activities limits the duration of those inspections. So the operator must make use of very limited resources.

Under these circumstances, it is logical that an inspection philosophy emphasizing a careful inspection of the joints most likely to develop cracks is used in the North Sea.

7.3 Discussion

North Sea practices have thus evolved in an environment that places severe demands on materials (crack resistance), limits inspection opportunities and precision and necessitates the use of structural designs that are not particularly tolerant of cracks. In the face of devastating failure consequences, a very cautious attitude towards fracture control prevails. Gulf of Mexico practices, on the other hand, have evolved in a more benign environment, enabling the design of structures that are very tolerant of cracks in a region that produces little stress and low failure consequences.

Both practices have advantages and disadvantages, but it is important to remember that each is a product of its environment, physical and philosophical.

Perhaps the most exciting question in fracture control today is, what is the best practice for new frontiers? As mentioned before, the current international practice is to adopt one of the two main approaches, either in whole or with small modifications. This can clearly be inappropriate if the choice is not made wisely, and could in fact be dangerous, especially if fracture control provisions are taken out of important context.

For example, consider a region where earthquakes are an important consideration. If the fatigue environment is relatively benign, it may be tempting to follow the Gulf of Mexico practice. But earthquakes, unlike hurricanes, occur without warning, so evacuations are not possible. Therefore, a risk analysis would show the risk of platform failure to be more like that of the North Sea situation. The effect of earthquakes on fracture control plans depends on the individual platform's location and response and is an area which requires further study.

The choice of which fracture control practice to follow, or the design of a comprehensive fracture control plan, must address all the aspects of fracture control mentioned in this report. Starting with the basics of fracture and fatigue, the fracture control plan should integrate the practices in material selection, design, construction, and operation. Ultimately, fracture control must be considered as a part of the entire risk of an offshore project; the risk of fracture must be weighed against all other risks.

7.4 Principal References

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2. United Kingdom Department of Energy, Petroleum Engineering Division, "Offshore Installations: Guidance on Design and Construction," Her Majesty's Stationery Office, London, 1977.

3. U.S. Geological Survey, Requirements for Verifying the Structural Integrity of OCS Platforms, especially Section 9, U.S. Geological Survey Conservation Division-OCS Platform Verification Program-Order No. 8, October 1979.

III. DISCUSSION OF AND RECOMMENDATIONS FOR IMPROVEMENTS AND FUTURE RESEARCH

1.0 INTRODUCTION

Most of the recommendations made in this section for new and follow-on research and technological development derived from the literature survey of current practices performed for the Summary (Section II). In stating the current state of affairs or reviewing present technology, many of the authors interjected critical comments and suggested new work and directions. Early in the project these "recommendations" and identified trends were marked and filed for future reference.

Added to these, as the project progressed, were comments and suggestions made by the designers and fracture control "generalists" contacted during the telephone interviews. Here the authors of this report had an opportunity to discuss, often "off the record," the reasons and concerns behind many of the recommendations prevalent in the literature. The interviewees directed the authors to other literature and specialists in the field for further verification and discussion, and out of this process and their own experience the authors have come up with the recommendations presented in Sections 3 through 8, following.

2.0 ELEMENTS AND RATIONALE FOR A FRACTURE CONTROL PLAN

2.1 Scope and Method of Documentation

In this section a summary of Survey Tasks 2, 3, and 4 identified in the Introduction to the report (Section I) is presented. For convenience we restate these tasks below:

Task 2: Identify the essential elements and rationale of a fracture control plan to provide a framework which could eventually evolve to a fracture control plan for fixed offshore structures.

Task 3: Identify areas where existing technology would suggest cost-effective improvements in current practices.

Task 4: Identify promising areas of technical research which would provide a sounder basis for fracture control of fixed offshore structures.

Based upon discussions with and suggestions from the Ship Structures Subcommittee and the Committee on Marine Structures, documentation of the above three tasks will comprise the following outline form.

2.2 Outline

The fracture control plan element will be identified, briefly described, and, if necessary, justified. Elements will be technical subspecialties, such as materials and design, rather than functional categories, as detailed, for example, by Rolfe and Barsom in their extensive discussion of fracture control. Those authors identify the basic functional elements of fracture control as: (1) **identification** of factors contributing to fracture; (2) **establishment** of their relative contribution; (3) **determination** of effectiveness of various design methods to minimize the chance of fracture; and (4) **recommendation** of specific design considerations to ensure structural safety and reliability against fracture. We might employ such a breakdown of functional elements for a specific application but have found it more convenient to define elements as technical subspecialties for the current broad survey.

A. Summary of Status

A short statement of the current status of the fracture control element is given with reference to the Task 1 summary, as appropriate.

B. Relevant Documentation

Reference is made to codes, specifications, and other documentation concerning the identified element in general usage by designers, builders and operators of U.S. fixed steel offshore structures.

C. Recommendations for Use of Existing Technology

The authors' recommendations for cost-effective improvements in current practice related to the identified fracture control element are given. Emphasis will be placed on those areas where existing technology has evolved from efforts to control and prevent failures.

D. Recommendations for Future Research

Technical research areas which may provide a sounder basis or a more effective or less expensive procedure for fracture control of offshore structures will be identified. As opposed to the recommendations section, emphasis in this future work section will be on development of new technology rather than application of existing technology.

Distinction between C and D is not always easy. For purposes of this report, those items that could be invoked unilaterally by a platform operating company or could be implemented by consensus (e.g., API RP-2A) or regulation change (e.g., USGS "Requirements") are considered "Use of Existing Technology". Those items requiring further development before implementation is practical are considered "Future Research". With these distinctions, those recommendations that seem appropriate for sponsorship by research organizations (e.g., Ship Structures Committee) fall into the future research category.

The above outline is applied in Sections 3 through 8. Section 3 discusses the integration of all fracture control elements as an element in itself. Sections 4 through 8 break down fracture control into its technical elements: material selection, design, construction, inspection, and operation. Within these sections, the recommendations fall into one or more of six categories: 1) data base development/evaluation; 2) experimental research, testing; 3) analytical evaluation/development; 4) procedures/guidelines, specialists; 5) education, training; and 6) detailed inspection/analysis for impact. These categories sometimes overlap, and in these cases the recommendation is placed in the most general category or the categories are combined. Of course, not all of the categories are needed for every fracture control element. Each recommendation is first stated simply and then elaborated upon. In many cases the elaboration results in a set of closely related recommendations that support the main.

For ease in future reference, a three-character cataloging scheme has been devised for the recommendations. The first character identifies the technical element (F for integrated fracture control, M for materials selection, D for design, C for construction, I for inspection, and O for operation). The second character identifies whether the recommendation is for use of existing technology (E) or for future research (R), and the third character (1, 2, . . .) identifies the specific recommendation.

2.3 Reference

1. Rolfe, S. T. and J. M. Barsom, Fracture and Fatigue Control in Structures:Applications of Fracture Mechanics, Chapters 14 and 15, especially the list of four basic elements of fracture control on page 415, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1978.

3.0 INTEGRATED FRACTURE CONTROL

The definition and method of documenting a fracture control plan appears to be an issue almost as large as any one of the single technical elements within the plan and has, therefore, been isolated as an element unto itself. Our best short definition of fracture control has already been given in Section 1.2 and is repeated here for convenience. Fracture control is the rigorous application of those branches of engineering, management, manufacturing, and operations technology dealing with the understanding and prevention of crack initiation and propagation and member failures leading to catastrophic failure of the structure.

3.1 Summary of Status

The above definition of fracture control was accepted or "tolerated" by a consensus of those interviewed. One level down from a global definition, the five technical elements (material selection, design, construction, inspection, and operation) in Section 2.2 are identified as being part of a fracture control plan. Further, an overall goal or philosophy of fracture control has been identified in terms of three lines of defense against catastrophic failure:

1. Prevent cracks when possible.
2. Contain or tolerate growth of those cracks not prevented.
3. Contain a fracture within a part or tolerate the loss of the part if a crack should grow critically.

Explicit documentation of fracture control, as defined above, has no clear-cut status. Aside from some feeling that API RP-2A, the ABS Rules, portions of the OCS Platform Verification Program, and other more specialized references provide an excellent start to documenting some of the elements of fracture control, only one entity, a major oil company, appears to have an explicit written fracture control plan. However, the elements of an integrated fracture control plan exist implicitly within the offshore industry through two media:

1. Use of experienced, competent engineers who may be called fracture control generalists. Such engineers, who may or may not also specialize in one of the elements of fracture control, take it upon themselves to ensure that any aspect of one of the elements of fracture control is examined for its impact upon other fracture control elements.

2. Team efforts of engineers in the various fracture control subspecialties responsible for ensuring that all aspects of their specialties are considered in the context of the other technical elements of the overall fracture control plan.

Although the participants in these media may come from the operator, designer, or fabricator, a key factor in how vigorously fracture control is pursued appears to be the attitude of the operator (who eventually bears the cost).

3.2 Relevant Documentation

The following U.S. documents have been cited as containing either rules or recommendations that encompass several fracture control elements:

American Bureau of Shipping, "Rules for Building and Classing Offshore Installations," Special Committee on Offshore Installations, New York, 1983 (The 1982 Draft report was used in preparation of this report).

American Petroleum Institute, "API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms," API RP-2A, Thirteenth Edition, Dallas, Texas, January 1982.

United States Geological Survey, Conservation Division, "OCS Platform Verification Program," Department of the Interior, Washington, D.C., 1979.

Publications which make specific recommendations for the development of industry-wide fracture control planning (or plans) include the following:

Bristoll, P., "A Review of the Fracture Mechanics Approach to the Problems of Design, Quality Assurance, Maintenance, and Repair of Offshore Structures," Proceedings of the European Offshore Steels Research Seminar, Welding Institute, Abington, Cambridge, November 1978.

McClelland, B. (ed.), The Design of Fixed Offshore Structures, with specific reference to Chapters 18 and 19 ("Tubular Joint Design" and "Steel Selection for Fracture Control") by Peter Marshall, and Chapter 27 ("Welding and Inspection") by P. W. Marshall, H. F. Cricks, and P. T. Marks, to be published by van Nostrand Reinhold, New York, 1982.

Pellini, W. S., "Criteria for Fracture Control Plans," Naval Research Laboratory, NRL Report 7405, May 1972.

Rolfe, S. T. and J. M. Barsom, Fracture and Fatigue Control in Structures, Chapters 14 and 15, Prentice-Hall, Inc., New Jersey, 1977.

McHenry, H. I., and S. T. Rolfe, Fracture Control Practices for Metal Structures, National Bureau of Standards IR79-1623, January 1980.

3.3 Recommendations for Use of Existing Technology

Only a minority of engineers in the offshore industry want to immediately create a written integrated fracture control plan for general usage. Many in the industry are averse to any sort of official fracture control document in the form of a regulation or widely-used recommended practice. This aversion is due to their fear that the document would not contain sufficient generality and freedom for competent structural engineers to optimize all aspects of their structures including safety and fracture control, and there is a voiced concern that the recommendations would begin to take on the "cook book aspects now seen in the nuclear power industry". Rolfe and Barsom, in the broadest of the recent surveys of fracture control plans we have reviewed, do not advocate an industry-wide document for a generic class of structures. Rather, they advocate a document for each critical structure. In spite of this reluctance and aversion to a fracture control "Bible", there is a general feeling in the offshore engineering community that some additional integration of the subspecialties of fracture control is necessary and desirable.

In Rolfe and Barsom's book, several pages are devoted to the general comments of Dr. George Irwin on the subject of fracture control plans. In turn, we would like to repeat two quotations that most influenced our recommendations in this section, and which stand as recommendations on their own:

- ". . . .. It is necessary to point out that the concept termed comprehensive fracture control plan is quite recent and cannot yet be supported with completely developed illustrations. We know in a general way how to establish plans for fracture control in advance of extensive service trials. However, **until a number of comprehensive fracture control plans have been formulated and are available for study, detailed recommendations to guide the development of such plans for selected critical structures cannot be given** . . ." [Emphasis is ours.]

- ". . . .. One can see that efficient operation of a comprehensive fracture control plan requires a large amount on inter-group coordination. If a complete avoidance of fracture failure is the goal of the plan, this goal cannot be assured if the elements of the fracture control plan are supplied by different divisions or groups in a voluntary or independent way. **It would appear suitable to establish a special fracture control group for coordination purposes.** [Emphasis is ours.] Such a group might be expected to develop and operate checking procedures for the purpose of assuring that all elements of the plans are conducted in a way suitable for their purpose. Other tests might be to study and improve the fracture control plan and to supply suitable justifications, where necessary, of the adequacy of the plan."

Since fracture control practices, though not always explicitly stated as such, are reasonably well established within the offshore industry, most recommendations can be expressed as changes to an existing system. The following recommendations then, some of which are repeated and discussed in more detail within the technical subspecialties, exemplify such changes.

Recommendation FE1

Encourage Fracture Control Integration.

Encourage the two areas of fracture integration identified under Status--namely the use of fracture control generalists and of engineering teams inherently capable of providing sufficient integration. Encouragement could come through appointment (early in the design stage) of an individual or small group as the fracture control focal point for each installation.

Recommendation FE2

Document the anticipated effects of every major structural decision or change upon all fracture control elements.

As a compromise between what is done now (generalists and informal teams) and what might be feasible or done in future, comprehensive, documented fracture control plans, introduce a minimum level of documentation to improve and ensure integration. For every major decision or change involving a structure's fracture control, ask the most cognizant engineers to identify the reason for the change and the fracture control element most involved and to list any possible or probable impact on other fracture control elements. Such a document could turn into a major report with many quantitative calculations or could take a short, qualitative form. An example of the latter is included in Appendix A in which a hypothetical change in a tubular joint, involving grinding to improve the stress concentration at the toe of the weld, is described qualitatively in terms of its effects upon the other elements of an integrated fracture control effort.

An effort like this could be expensive, both in dollars and in time spent by key engineering talent. Therefore, at present this kind of documentation may only be justifiable for truly fracture-critical parts.

Recommendations 1 and 2 exemplify a strongly recommended approach: that of working to optimally **modify the existing fracture control system** rather than to tear it down and build anew. Recommendations 3 through 5, which could be listed in the following sections within technical subspecialty elements, are included below to exemplify more specific ways of **optimizing a sound existing system.**

Recommendation FE3

Modify punching shear criteria to prevent other failure modes.

> For design against overload, attempt to make modest changes within the punching shear criteria that will minimize the impact of failure modes other than punching shear. For example, see the changes proposed by Marshall in "A Review of American Criteria for Tubular Structures -- and Proposed Revisions."

Recommendation FE4

Use a calibrated fracture mechanics model to address tough fatigue and fracture problems.

> For non-routine fatigue and subcritical crack growth evaluations, start with the S-N approach, build a fracture mechanics model consistent with all known facts, such as typical defect sizes in weld toes, etc., and use this model only to extrapolate from the original S-N curve to account for improvements or detriments in the structure. In this manner, the comfort and tradition of the S-N curve approach can be combined with the special capabilities of the fracture mechanics procedure to account for the complex stress distribution and notch and part size effects.

Recommendation FE5

Apply structural reliability models to optimize design and operational decisions.

The probability of fracture and other risks related to structural design can be minimized by applying structural reliability models to choose an optimum combination of design, material selection, inspection specifications, and structural redundancy. Marshall refers to the study of these trade-offs with the acronym DIRT, for "design-inspection-redundancy triangle." Optimization can be simply a minimization of cost subject to meeting or exceeding traditional safety constraints. While reliability estimates can be strong functions of uncertain input to the analysis, the optimization process can still be accurate and robust. Such accuracy is due to weaker dependencies upon input of historically calibrated relative costs and probabilities which influence tradeoff decisions more than do absolute probabilistic estimates.

3.4 Recommendations for Future Research

Recommendation FR1

Survey industries using more formal fracture control documents than does the offshore industry.

It is not clear how comprehensive an integrated fracture control document is feasible for various projects and applications within the offshore industry. We recommend that a survey (mostly interviews) be conducted, using Rolfe, Barsom, and McHenry's work as a starting point, for those industries, notably aerospace and nuclear power, which have already formulated and used such documents. The survey should include such representatives as the document's drafters, regulators, and users. If, after such a survey, the idea of an integrated plan is dropped, continuous discussion and improvements should be encouraged for the three fracture control integration methods already identified: namely, the use of competent engineering generalists, teams, and case-by-case "effect statements" as exemplified in Appendix A.

Recommendation FR2

Prove that Charpy tests are meaningful for new situations.

Starting with generic fracture toughness material grades and Charpy tests, do only enough quantitative fracture testing to learn whether the Charpy-based correlations will stand up to some new situations, such as the increase of brace and can wall thicknesses.

Recommendation FR3

Calibrate structural reliability models to field experience.

Recognizing that accurate fundamental estimates of structural reliability are not yet possible, strive for worthwhile sensitivity studies and extrapolations to be made from a known baseline condition using calibrated probabilistic models. These models should contain enough deterministic and stochastic relationships to estimate the effects of changes in design, inspection procedures, redundancy, and material properties. That is, calibrate a probabilistic model to field experience.

Recommendation FR4

Build a data base of failure, accident, and success experience for feedback to those who influence fracture control.

Since many of the recommendations involve calibration against inservice experience, a formalized failure/accident feedback system, as described in Carlsen, et al., is strongly recommended. The entire spectrum of people who might have influence on failures and accidents would benefit from such a system. Examples are given in Carlsen, et al., ranging from the operator who is expected to act "normally" in the face of such abnormal events as a fire, blow-out, impending structural failure, or evacuation (in spite of the fact that he probably has no personal experience with these rare events), to the researcher who may need to be kept in touch with reality through feedback of inservice experience. This would provide a definition of important research areas and, as called for throughout these recommendations, a means for "real life calibration of theoretical models."

Examples of documentated feedback given in Carlsen, et al., include the detailed reports of the Alexander Kielland incident and the broad data associated with accidents reported in Lloyd's List and other similar sources.

4.0 MATERIAL SELECTION AND SPECIFICATION

The first step in designing against fracture is to select and specify a material for each location/application within the structure to meet its intended purpose without suffering one of the five modes of failure covered in our summary of design practices (Section 5.2).

4.1 Summary of Status

Materials selection for various applications in the steel jackets of fixed offshore platforms is typically a matter of choosing from among the few dozen steel alloy/grade combinations to fit the intended application and design envelope. Standard mill tests are used to determine material defect levels, carbon-equivalent, strength, ductility, and other "standard" properties. Notch- or crack-toughness is most often determined by the Charpy V-Notch test, which is used almost exclusively for any extensive quality control studies of material, occasionally even including weld metal and heat-affected zones. Other fracture toughness tests used for such purposes as initial material qualification, defect evaluation, and fitness-for-purpose studies are NRL Drop-Weight tests, which focus on the ability of the base alloy to arrest a rapidly propagating crack; crack-tip opening displacement (COD) specifications; and, most often, reliance on generic toughness of prequalified materials (e.g., per API RP-2A Classes A, B, and C). Standard plane-strain brittle fracture toughness tests, as for example in ASTM E399, are only rarely applicable since, for most critical jacket locations, standard practice is to ensure toughness levels such that even full thickness specimens will not fail by brittle ($K_{applied} > K_{IC}$) fracture.

One of the most important tradeoffs to be considered in material selection is the relationship between strength, fracture toughness, and cost of the steel. In U.S. practice, there is currently a low emphasis on material subcritical crack behavior. By subcritical crack behavior we refer to fatigue crack propagation, with and without environmental assistance, and stress corrosion cracking. The apparent reasons for the low emphasis are that fatigue crack propagation has not been a critical contributor to overall structural unreliability in Gulf of Mexico applications, and under typical

Gulf conditions (including cathodic protection) crack propagation in steels is not a strong function of the material/environment.

4.2 Relevant Documentation

Relevant source materials, standards, specifications, and industry or university studies are listed at the end of the Material Selection section of the Section II Summary. Another key reference is:

1. Pellini, W.S., Criteria for Fracture Control Plans, Naval Research Laboratory, NRL Report 7405, Washington, D.C., May 11, 1972.

4.3 Recommendations for Use of Existing Technology

Analysis/Procedures

Recommendation ME1

Make routine and extensive use of simplified analysis procedures, such as the FASD.

> Simplified analysis procedures for quantitative fracture analysis which connect both the mechanical and metallurgical aspects of fracture should continue to be developed. We believe that the FASD procedure (which has the twin benefits of being a brute-force empirical procedure and having a reasonable, and rapidly improving theoretical basis) can be both a valid and safe fracture criteria and a handy repository for fracture data base information of various kinds as mentioned above. Examples of the use of the FASD procedure are given by both the CEGB and Chell (Volume 2).

Recommendation ME2

Designate a materials fracture control specialist for each application for which a correlation between standard specifications and quantitative fracture properties has not been established.

The burden is on the materials fracture control specialist to account for the statistical variability of toughness data in making material specifications. This typically involves statistically valid correlation between standard specifications, by means of generic toughness grades or Charpy tests, and quantitative fracture properties. We recommend that such a specialist be designated for each fixed-platform application for which this correlation has not been established, and that guidelines be identified for his/her use to ensure that this aspect of fracture mechanics is not overlooked.

4.4 Recommendations for Future Research

Data Base Development/Evaluation

Recommendation MR1

Start a materials data base for all important measured fracture parameters of offshore structural steels.

A materials data base for offshore structural steels should be started (published literature) for all important measured fracture parameters. Mainly, the basic fracture properties should be described in terms of mean and design (e.g., "-2s"; where s is an appropriate standard deviation reflecting material property variations in the structure) values. Ideally, enough information could be collected to add data points to such brute-force, empirical, general quantitative techniques for defect evaluation as the failure assessment diagram procedure (Section II:3.3). A committee could propose standards by which all contributions to the data base could be qualified. Data not meeting the standards, but potentially useful for fracture control specialists, could be included and identified as such.

Recommendation MR2

Use a data base such as suggested in MR1 to identify programs for closing the "data gap."

Comments made by W. S. Pellini, regarding the state of engineering fracture data in 1972 are nearly as applicable now. To quote:

> Unfortunately, the literature on fracture research is highly specialized and the notable agreements which exist on fracture-state criteria are obscured by masses of detail. Moreover, the processes of metal property surveys and the sources of this information are not considered in adequate detail. Serious concern must be expressed for the paucity of statistically reliable engineering fracture data for standard grade metals that is provided by the existing literature. Developing this information is of foremost consequence at this time.

We agree with the need to collect, organize, and unambiguously express valid and statistically reliable engineering fracture data. Then, what is available can be matched up with what is required for offshore applications and cost-effective fracture tests can be devised to close the "data gap." As with our first recommendation under existing technology above, the data should be expressed in terms of properties the investigator was measuring <u>and</u> in terms of some global brute-force quantitative fracture criterion, if possible, such as the FASD procedure, as exemplified by Figures 2 and 3 (in Section II:3.3.1), or COD.

Experimental Research, Testing

Recommendation MR3

Fund quantitative toughness testing using specimens which simulate the physical characteristics at the crack border of the structure.

The most serious source of error in addressing the fracture problem in a complex fixed offshore steel-jacket structure is to interpret data from comparatively simple laboratory specimens. The two most widely encountered problem areas are differences in near-crack-tip constraint between specimen and structure and, a related matter, differences in section size, especially thickness. Specifically, severe interpretation problems can arise if plastic flow at crack tips, especially including constraint associated with the developed triaxial stress fields and shear lips, are not similar between specimen and structure. This problem is compounded in the offshore current practices by the extensive use of inexpensive Charpy tests, sometimes to the exclusion of the use of larger specimens. Pellini points out notable examples where steels exhibiting superb Charpy properties (greater than 50 foot-pounds CVNE) had inadequate fracture toughness for their intended, very large thickness, application. Thus, it is imperative that some quantitative toughness testing be done, using specimens which simulate the physical characteristics at the crack border of the structure, along with Charpy tests. These supplementary toughness tests could be added to any extensive Charpy testing program or, more likely, could be conducted in industry-wide research efforts for generic material classes. The final step would be the demonstrated correlation between Charpy impact data and quantitative measures of fracture toughness, at least in a bounding sense, so as to provide assurance of some minimum value of fracture toughness for the structural application.

Recommendation MR4

Collect existing data and define and execute an experimental program to evaluate constant amplitude fatigue, overload, and underload effects upon crack growth. Ensure that an adequate range of crack propagation rates is covered.

Collect existing fatigue crack growth data applicable to joint weld cracking and generate additional data as necessary. Insofar as is practical, a wide range of inservice parameters should be enveloped in the experimental program. To save money, tests and reliable extrapolation should be developed to focus upon the boundaries of the "envelope" rather than upon conducting a large matrix of many combinations of test variables. Key test variables should be adjusted to reflect previous experimental results by designing test programs with feedback loops rather than blind execution of tests fully specified before the first specimen was tested.

Included in the envelope of data collected and generated should be (1) frequencies associated with wave loading and other excitation of the structures; (2) environments reflecting both submerged and near-surface (wet/dry) conditions, with and without various levels of cathodic protection (including detrimental "overprotection"); (3) a full range of R*-ratios--from high R values associated with the presence of full-yield residual stresses to the lowest R values arising from compressive loads or compressive residual stresses that might be caused by beneficial overload effects; and (4) specimen geometries simple enough to model the in-service interaction of material and environment but varied enough to test whether or

*For a given cyclic stress intensity factor versus time K(t) excursion from a minimum value, K_{min}, to a maximum level, $K_{max} > 0$, R is defined as K_{min}/K_{max}.

not the fracture mechanics model can account for geometry analytically, as it is supposed to. In addition:

- Define the experimental program necessary to evaluate overload and underload (compressive overload) effects upon subsequent crack growth in offshore structures. Bounding experiments can be made to determine where load interaction effects can be ignored and where proof-test logic can be used for screening of flaws.

- Ensure an adequate range of crack propagation rates is covered in both of the above recommendations. We recommend a range between 10^{-7} and 10^{-4} inches per cycle at least, and, more ideally, an expanded range of 10^{-8} to 10^{-3} inches per cycle and similar da/dt ranges, as practical, for stress-corrosion cracking.

- Statistically analyze all variability generated in the experiments to provide input to probabilistic fracture mechanics approaches discussed in Section 4.2.3, following.

- Compare these distributions with those in Engesvik and other sources and try to resolve or explain differences.

- Design experiments reflecting <u>worst-case scenarios</u> to see if such expensive-to-simulate test variables as the environment can be eliminated or greatly simplified. As an example of the potential for simplification, consider the following quote from Carlsen, et al., which gives the impression that environmental acceleration of subcritical crack growth can be well controlled using existing technology:

  > With respect to corrosion/fatigue, considerable research for the last years has been carried out . . . From this work it appears that although offshore structures under free corrosion will have fatigue strength lower than in air, cathodic pro-

tection with a normal potential close to -800 mV will restore the in-air fatigue strength.

Recommendation MR5

Set up a "devil's advocate" testing program to evaluate fracture criteria.

There is always going to be much controversy between the pragmatists who wish to use inexpensive screening tests such as the Charpy test for providing lower bound toughness properties and the "purists" who hold out for use of specimens which can be used for quantitative defect evaluation and can simulate precisely the dynamics and triaxiality of stresses at the crack-like structural defect. As mentioned above, one recommendation to reduce the detrimental impact of this controversy is to mix the two kinds of tests and investigate data correlations.

A second idea, admittedly untried except as it occurs naturally in an engineering or scientific field, is to set up "a devil's advocate" testing program in which a noted fracture-test purist could be funded to design and demonstrate a worst-case scenario in which the Charpy criterion would fail for an important inservice application. If a simplified fracture criterion can be defeated (to the satisfaction of the funder or perhaps a neutral technical reviewer) with an experimental set-up that simulates in-service conditions, that criterion probably should be discarded or improved. Similarly, if a seemingly oversimplified criterion resists the attempts to discredit it by knowledgeable people who have something to gain through its discreditation, it (the criterion) deserves more respect and credibility. A few good experimental examples which showed the ability or inability of a simplified fracture criterion to guarantee an adequate minimum toughness level would probably be more convincing to the technical community than volumes of literature containing detailed theoretical and qualitative arguments.

5.0 DESIGN

The designer is responsible for guarding against the structure's possible failure modes as well as for producing a near-optimum functional and economic structure. Five relevant failure modes are listed below in order of decreasing emphasis given by the authors in the fracture control survey:

1. Fracture, defined as unstable rapid crack extension--either elastic or plastic--leading to partial or complete failure of the member.

2. Subcritical crack growth, under fatigue, environmentally accelerated fatigue, or stress corrosion cracking, leading to loss of section and fracture.

3. Yielding, excessive plastic deformation; or ultimate failure under tensile or bending (plastic hinge) loads.

4. Elastic or plastic buckling or other instabilities under compression loads.

5. Bulk corrosion, leading to loss of cross section.

Structural design against fracture concerns itself with two aspects: The loadings placed on the structure by the environment and by its operation, and the resistance of the structure to these loadings.

5.1 Summary of Status

The nominal design practices used in the Gulf of Mexico (primarily from API RP-2A) are fairly uniform. To account for loadings placed on the structure, fracture control is explicitly considered in the design for fatigue loadings and is implicit in the design for normal operation in extreme environmental conditions and forces due to installation and transport. Due to reserve strength and redundancy, a typical steel jacket structure can withstand a certain amount of cracking. In normal Gulf of Mexico design practice, quantification of this resistance is not attempted. Verification of design work is conducted by the operator's representative, who is also consulted on significant design decisions. The MMS Platform Verification Program requires that the design of platforms for US operations outside the

Gulf, or new Gulf platforms which will be located in over 400 feet of water (among other qualifications), be checked by an independent party--resulting in additional verification of the major analytical design tasks.

5.2 Relevant Documentation

Relevant source materials, standards, specifications, and industry or university studies are listed at the end of the Design section of the Section II Summary. Other key references include:

1. Pellini, W.S., Criteria for Fracture Control Plans, Naval Research Laboratory, NRL Report 7405, Washington, D.C., May 11, 1972.

2. Carlsen, C.A., T. Kvalstad, H. Moseby, E.M.Q. Rørn, T. Wiik, "Lessons Learned from Failure and Damage of Offshore Structures," Eighth International Ship Structures Congress, Gdansk, 1982.

3. Fisher, P.J., "Summary of Current Design and Fatigue Correlation," Fatigue in Offshore Structures, Institute of Civil Engineers, Conference Proceedings, London, February 24-25, 1981.

4. Rolfe, S.T. and J.M. Barsom, Fracture and Fatigue Control in Structures, Prentice Hall, Inc., New Jersey, 1977.

5. Telephone interview conducted with Robert G. Bea and Ashok Vaish, PMB Systems Engineering, Inc., San Francisco, California, on September 16 and 23, 1982.

6. Gurney, T.R., "Revised Fatigue Design Rules," Metal Construction, revision of UK DOE Guidance, January 1983.

7. Failure Analysis Associates, "BIGIF--Fracture Mechanics Code for Structures," Electric Power Research Institute, EPRI NP-1830, April 1981.

5.3 Recommendations for Use of Existing Technology

Analytical fracture mechanics methods assist a quantitative determination of the significance of fatigue cracks in offshore structures and aid the task of designing against fatigue and other forms of subcritical crack growth. Many of the recommendations listed under "Analysis" are suitable for both applications and, therefore, for many fitness-for-purpose evaluations of cracks found in fabricated structures, either in service, or during loadout, transport, and launching operations. The remaining recommendations cover other aspects of the design element of fracture control.

Analytical Evaluation/Development

Recommendation DE1

Use first-order bounding fracture mechanics models to determine relative effects of toughness and fatigue-design control.

It is believed that the U.S. fracture control effort, because of the relatively low fatigue damage content of Gulf wave loading spectra and water depths, has concentrated more on the monotonic-loading failure modes associated with fracture toughness and arrest of critical, rapid crack growth and "pop-in". As frontier areas which, in combination with new, innovative structural designs, approach and perhaps surpass the fatigue damage potential of the North Sea are encountered, it is recommended that first-order bounding fracture mechanics models, which take advantage of the fact the the majority of the useful life of welded structures is spent propagating rather than initiating a crack, be used to ascertain the relative effects of toughness control as compared to fatigue-design control. Many situations may arise in which the fracture toughness of the steel would have a negligible effect on the useful life of the structural joint.

Recommendation DE2

Supplement S-N curves with deterministic fracture mechanics approaches.

There is a general consensus that the use of S-N failure data will remain the main design tool against fatigue. Crack growth data and fracture mechanics methods should continue to be developed mainly to provide support for fitness-for-purpose evaluation and extrapolation of S-N data to situations that cannot be or have not been simulated in experimental work.

Recommendation DE3

Model size/shape of crack and transition behavior in brace or leg.

Where necessary, model the transition from partial- to through-thickness cracks in the brace or leg. Concentrate analytical efforts in flaw size/shape ranges for which most of the joint's fatigue life will be expended.

Education, Training

Recommendation DE4

Teach engineers to review their thinking on safety factors in order to avoid dangerous design assumptions which may actually reduce the structure's reliability.

To quote Pellini (Criteria for Fracture Control Plans, page 45):

> In developing fracture control plans, the engineer must develop completely new thinking with respect to factors of safety. Adherence to past conventions is dangerous . . . . [For example,] . . . the added "safety" assumptions [for "beefing up the structures" by] increasing wall thickness are not [always] justified.

Pellini goes on to give an example, based on data for a 100 ksi yield strength pressure vessel steel, where a thickness increase actually weakened the welded structure because of its susceptibility to moderately-sized weld defects. Such examples should be useful for educating designers that such "tried and true" fixes as beefing up the structure might actually weaken it in the presence of defect-related failure modes such as fracture and subcritical crack propagation. Potential weaknesses of the resulting thicker cross-sections are more defect-prone welds, lower toughness joints, and reduced member and joint flexibility.

Recommendation DE5

Reduce the human error factor through education and minor modification of the MMS Platform Verification Program.

Effort and research is needed to reduce the problem of the direct impact of human errors in design (as well as in fabrication, inspection, maintenance, etc.). The best vehicle for implementing desired error control techniques may be minor modification of the MMS Platform Verification Program and through education programs (one of Peter Marshall's recommendations) to improve the designer's application of API RP-2A.

Detailed Inspection/Analysis for Impact

Recommendation DE6

Survey the entire structure for critical elements.

As emphasized by T. R. Gurney ("Revised Fatigue Design Rules," UK DOE Guidance): "It should be noted that in any element or member of the structure, every welded joint or other form of stress concentration is potentially a source of fatigue cracking and each should be considered." Gurney then makes the point that the Guidance Notes' intention is to consider every joint and that the most insignificant-appearing attachments may be vital in the context of fatigue and structural reliability. It should be possible to avoid quantitative evaluation of every weld in a structure by adopting standard details that have been generically evaluated in detail.

5.4 Recommendations for Future Research

Data Base Development

Recommendation DR1

Develop a data base of service and repair histories.

Develop an industry-wide data repository for service experience on fixed structures and for repair histories on same.

- The use of repair welding and other repair procedures introduces complexities into the estimation of both critical and subcritical crack growth. There is therefore a need for data on the toughness and fatigue performance of repaired joints.

- Catalog observations of cracks, failures, and nearly as important high-severity situations which did not lead to cracking. These observations would both challenge and calibrate improved design developments.

Analytical Evaluation/Development

Recommendation DR2

As a long-term goal, it would be desirable to develop accurate stress intensity factor solutions for all stress fields and crack geometries of concern. This would include evaluation of displacement control exhibited by most tubular joint crack geometries. As a starting point, develop a handbook

or software library of stress intensity factor solutions for often occurring geometries and load cases.

The state of the art may be such as to allow some numerical, accurate, full three-dimensional stress intensity factor solutions to be developed as a practical matter. However, a more cost effective approach based on existing technology would be the use of variable (cross-sectional) thickness two-dimensional solutions and approximations for many of these geometries.

Implicit in a recommendation to develop stress intensity factor solutions for all stress fields and crack geometries of concern is an evaluation of the displacement-control exhibited by most tubular joint crack geometries. The theoretical developments should have the full capacity to account for such load redistribution effects as (1) unbending of a brace wall due to growth of a crack through the wall at the brace-can intersection; (2) effect of critical or subcritical crack growth around the brace into regions of lower stress, and, possibly, differing principal stress directions; and (3) load redistribution along the brace leg and to other members in the structure. While rigorous models of these three types of load redistribution may be neither currently feasible nor cost effective, some accurate approximations are well within the state of the art. The accuracies can be evaluated through both sensitivity studies and comparisons with observations of experimental and inservice crack propagation. Additional suggestions include:

- Run full parametric studies for developing stress intensity factor solutions which include simultaneously such local factors as the ability to handle any stress gradient in the uncracked structure, the ability to handle all credible variations of weld profile geometry, and the ability to

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characterize residual stress fields. To obtain such generality, the weight or influence function method is a useful tool for the analytical developments for most geometries.

- Verify all solutions for general stress distributions by using an independent, state-of-the-art, finite element program to solve the crack problems for certain specified "benchmark" stress distributions.

- Create a handbook and/or software library of stress intensity factor (K) solutions for geometries and load cases that occur often in design and fitness-for-purpose calculations. This would be an extension and/or specialization of such K handbooks as those of Tada, et al.; Sih; and Rooke, et al.

Recommendation DR3

Develop deterministic design and fitness-for-purpose approaches for routine analysis of significance of defects and for development of examples and guidelines.

Develop both methods and software for deterministic design and fitness-for-purpose systems in a form suitable for routine analysis of the significance of cracks in offshore structures. As noted by Carlsen, et al., in "Lessons Learned":

> Due to uncertainties on fatigue life predictions, . . . it is very important to calibrate design requirements against in-service experience, and to develop tailor-made in-service inspection programs to follow up critical parts in service.

From this:

- Exercise the system for both hypothetical and practical problems which envelop geometric, stress, material, and environmental combinations to be expected in the field. The fifteen to fifty analyses created can serve as modeling examples and guidelines for the offshore engineering community.

- Present in graphical and tabular form the effects of variations of key input parameters, individually and in combination, upon the dependent variables, fatigue life or static strength. These will provide guidelines and input to develop a probabilistic fracture mechanics system as described below.

Recommendation DR4

Develop a probabilistic fracture mechanics approach for routine crack analysis.

Develop a probabilistic fracture mechanics (PFM) method and software for routine analysis of cracked offshore structures. The software should probably employ realistic and computationally practical Monte Carlo methods although less general numerical procedures can be devised which employ variance-covariance statistical approximations for computing the impact of independent variable scatter on dependent variable scatter.

- Develop a procedure for determining when a PFM analysis should and should not be employed. Stress the use of deterministic (DFM) bounding calculations to avoid needless implementation of PFM. Specifically PFM should normally be used with reliability analyses, cost optimization studies, and when DFM is inconclusive (i.e., when worst-case DFM assumptions predict structural failure but nominal DFM assumptions predict success).

- Implicit in setting up a PFM system will be recommended probability distributions for certain input variables, such as the coefficients used to relate material crack propagation as a function of stress intensity factor. Each suggested probability distribution should be qualified by a description of its range of validity and indication of what changes might be expected under worst-case conditions. Note that high accuracy is not usually needed for these input probability distributions--even if different input distributions lead to significant differences in reliability estimates, the use of conservative bounds of distributions may still permit much to be gained from a PFM analysis. This potential gain arises from the fact that deterministic worst-case models assume that all input variables will be at their most unfavorable values <u>simultaneously</u> while worst-case PFM models can easily avoid this unrealistic assumption. Note also the rapidly growing literature on PFM-related data and methods, as exemplified by Engesvik.

- Execute the PFM analysis for several of the hypothetical and practical cases analyzed with deterministic fracture mechanics (DFM). Pick some examples which will benefit and some of which will fail to benefit from PFM to illustrate the optional character of this analysis technique.

Recommendation DR5

Establish design loads for and protection against impact damage (collisions, explosions, etc.)

More research is required to establish design loads and methods for protecting the structure against damage due to collisions, dropped objects, fires, and explosions. Among the technical areas to be explored are the establishment of realistic impact forces, energy dissipation methods and other protection means for offshore structures. Some of the elastic-plastic buckling work being carried out should help significantly in this effort by establishing, for example, the residual buckling strength of a compressive member as a function of the size of its impact dent.

Recommendation DR6

Define applications suitable for use of higher-order-average alternating-stress methods for life prediction.

For some variable-amplitude stress histories, replacement of the history on the basis of a root-mean-square (RMS) or higher-order-average (e.g., cube root of mean cube) alternating stress appears to offer a reasonable method for life prediction under variable amplitude loading. Further work is necessary to define which applications will not suffer inaccuracies due to this higher order averaging approximation and to define optimal cycle-counting methods from stress histories. The effects of severe overloads or underloads require particular attention.

Recommendation DR7

Formalize the statistical approach to defining the variability of S-N and subcritical crack growth data for any given material or environmental combination.

There is a need to provide a more formalized statistical approach to defining the variability of S-N and subcritical crack growth data in the presence of endurance limits and stress intensity factor thresholds, respectively. Relatively simple mathematical techniques exist to handle this statistical evaluation (and similar ones involving fracture properties) routinely. Two steps are required and recommended:

- Analysis of variance to determine which quantities maintain a constant variance over the entire S-N or da/dN (K) curve. For example, at the endurance limit, it would no longer be proper to consider the standard deviation of "log cycles" for each lab-specimen data point. A more appropriate parameter might be the standard deviation of stress or log stress or, of greater complexity, the standard deviation of perpendicular distance of the data points from the mean-trend S-N curve in a specified type of plot (e.g., log S versus log N).

- Having established the parameter which exhibits constant variance (and under what situations this is true), use standard regression methods to analyze it and calculate the "-2s or -3s line" to be recommended for design use.

Recommendation DR8

Estimate the effect of multiple crack-site origins at the weld toe.

More work is needed to estimate the effect of multiple defect- and crack-site origins at weld toes and their interaction and linking characteristics as they grow.

Recommendation DR9

Define stress gradients and other characteristics of the subsurface stress distribution.

The need to define the subsurface stress distribution for fracture mechanics applications is amplified by the presence of joints with large shear transfer. A common example of such transfer would be a K-joint with adjacent braces of which one is in high tensile and the other in high compressive loading. Among researchers that have developed detailed fracture mechanics models there is consensus that more work in general is needed to define the stress gradients and other characteristics of the subsurface stress distribution. Some of this work may require the use of three-dimensional numerical stress analysis techniques or, at the very least, analytical models which do not employ the simplifying assumption that all load transfer between brace and can walls occurs at the intersection of their mid-thickness surfaces.

Recommendation DR10

Develop accurate, versatile crack analysis methods.

While the finite element method is the most versatile for analyzing both uncracked and, to a lesser extent, cracked tubular joints, it can be quite expensive, time consuming, and of questionable accuracy for the most difficult problems. Thus, there is a real need to come up with accurate, nearly-as-versatile, methods to be used by the researcher and design system developers if effective, everyday application of advanced fracture mechanics is to be realized. This need is the basis for the recommendations above to use the weight function method and to formulate handbooks of useful stress and stress intensity factor solutions of tubular joints subject to cracking.

Recommendation DR11

Consider the effect of greater-than-predicted wave loadings upon the fatigue life of a structure.

The unpredictability of environmental loadings is a primary cause for uncertainty in fatigue stress predictions. This is especially true for frontier locations where long-term data are scarce or non-existant. Sea state scatter diagrams must often be constructed with only two years of wave recordings. Thus, we recommend that the impact of departures from the design wave environment upon the fatigue life of a structure should be considered.

Recommendation DR12

Study methods for determining hot spot stresses and tubular joint behavior outside the standard case.

Tubular joints have been classified as T, K, or X based on standard load paths through the joints. Studies should be done to investigate the proper way to interpolate between the standard cases to find the hot spot stresses.

Also, the behavior of tubular joints has to date been studied mostly in two-dimensions. The effect of three-dimensional interaction of braces out of plane needs further study. The effects of joint flexibility and eccentricity also need further study.

Recommendation DR13

Study wave loading and associated phenomena more closely and develop guidelines for application.

It is recognized by the industry that the calculation of wave loads on a structure is very imprecise. In particular, it is recognized that local wave force effects may be seriously miscalculated, while the integrated effect on the entire structure is adequately calculated for design. Industry-sponsored studies of the wave loading and associated phenomena need to be continued.

- Guidelines should be developed to aid the designer in the choice of wave periods corresponding to chosen wave heights for the discrete wave fatigue analysis approach. It is not sufficient for fatigue analysis purposes to just choose the average wave period for a given wave height, because in a fatigue or other life computation the stresses above some threshold are raised to a large power and those below the threshold are ignored and thus choosing the average wave period is non-conservative. For each wave height, the analyst should consider either a spectrum of periods or the average period corresponding to the high-stress waves.

- Guidelines should be developed to aid the designer in computing the effective damping of the structure required as input for a dynamic analysis. This is particularly true for longer period structures in deep water, where damping has a significant effect on the dynamic amplification of member stresses.

- Guidelines for the inclusion of simultaneous current loading in fatigue analysis should be developed. Current loads are often only added when calculating the maximum stresses in structure in combination with a design wave. It should be noted that superposition of current and wave changes the amplitude of the stress cycle as well as the mean. This occurs because the drag term in Morison's equation includes a nonlinear (velocity-squared) term.

- With the proliferation of framed structures computer codes for analyzing offshore structures, some now available on microcomputers, designers working on certain applications need to be warned against the use of oversimplified codes which do not properly handle the nonlinear wave loads. Typical simplifications include linearization of the drag term in Morison's equation and using water particle velocity rather than relative water particle velocity.

Recommendation DR14

Determine the feasibility of determining approximate effects of stress gradients in estimating elastic-plastic crack tip stress parameters.

Investigate the feasibility of handling stress gradients approximately (in the uncracked structure at the crack locus) in estimating elastic-plastic crack tip stress parameters such as COD and the J-integral. If analytical solutions are beyond the state of the art (which may be true in many cases), the extensive data base of COD and J experiments that is evolving could be used. For example, the experimental data now used to set lower bound design and failure assessment curves in BSI PD 6493:1980 can be employed to approximate the effects of stress gradients due to the many tested combinations of axial, bending, and residual stress levels.

Recommendation DR15

Develop algorithms for the problem of contained plasticity in notches.

Develop and apply algorithms, such as key Neuber-based methods and solutions as employed in BIGIF (EPRI NP-1830), to handle the frequent problem of contained plasticity in notches and its effects on subsequent subcritical fatigue and stress corrosion crack propagation.

Recommendation DR16

Develop additional design data for steel "shell" components.

We recommend development of additional design data for ultimate design capacity of the stocky steel "shell" structural components of fixed offshore platforms which often fail due to a combination of elastic and plastic shell and column buckling. Comprehensive research in this area has apparently already led to design method improvements, according to Carlsen, et al., page 23.

Recommendation DR17

Assess effects of uncertain hot spot stresses and incorporate into a PFM model.

The effects of uncertain hot spot stresses due to uncertainties in the wave environment, wave loading, dynamic response, and joint behavior should be assessed and incorporated into a PFM model.

Recommendation DR18

Determine the accuracy of "identical wave" DAFs in variable wave spectrums.

The dynamic amplification factor (DAF) for a given wave is computed from a dynamic analysis assuming steady-state conditions (i.e., a continuous series of identical waves). It needs to be determined how accurate this "identical wave" DAF is for a variable-wave spectrum. This determination would require two types of work. First, one would need to obtain actual time histories for typical sequences of waves. Second, one would perform a dynamic analysis with a step-by-step time integration with loads calculated at each step from the actual time history. The stress cycles for this time history could then be compared with those computed by the usual techniques involving DAFs.

Recommendation DR19

Evaluate the neglect of larger wave periods in fatigue analyses.

Waves with periods approximately two or three times the fundamental period of the structure often cause two or three stress cycles in the structure. This effect is usually neglected in fatigue analyses. Research should be conducted to evaluate this nominally non-conservative assumption.

Recommendation DR20

Study effects of soil-structure interaction and, particularly, long-term foundation degradation.

The effects of soil-structure interaction and, particularly, long-term foundation degradation need further study. This is particularly true for many areas of the Gulf of Mexico where platforms stand on deep deposits of weak soils (for example, on deposits from the Mississippi River). This effect should include both analytical work and instrumentation of appropriate existing and future structures.

Recommendation DR21

Develop a more accurate finite element program for the global analysis of structures using both joint and member elements.

With the proliferation of studies on tubular joints, it is now possible to better understand joint flexibilities due to shear deformation and member ovalization. The feasibility and necessity of developing joint elements which could account for this flexibility should be investigated. The result would be a more accurate finite element program for the global analysis of structures using both joint and member elements.

Recommendation DR22

Employ natural load shedding and displacement control features to help design crack arrest features.

The natural load shedding and displacement control features of complex tubular joints and fixed offshore platforms, when better understood and analytically modeled, can be employed to help design crack arrest features. Such features could add substantially to the fail safety and resistance to catastrophic fracture at the welded joint "level". This improvement supplements the brace-level fail-safe redundancy discussed elsewhere.

Experimental Research, Testing

Recommendation DR23

Expand the range of tubular joints tested and used to set S-N curves.

Since the S-N approach is still the major tool used to prevent fatigue failures, we recommend that the range of welded tubular joints that have been tested and used to set the S-N curves be significantly expanded beyond what has been done to date; namely, almost entirely simple T-joints. Aside from the needs to obtain data on a wider range of joint types and to adjust the design curve when appropriate, such tests would provide an ideal data base upon which to benchmark candidate fracture mechanics models for designing against fatigue in welded tubular joints.

6.0 CONSTRUCTION

In terms of fracture control, the main goal in construction is to limit built-in stresses, the size of initial defects, and (most basically) large variations from specified material properties and structural dimensions. In choosing fabrication and installation methods, two main trade-offs related to fracture control are made. The trade-offs are the choice of fabrication method (frame or node) and the choice of installation method.

6.1 Summary of Status

The construction of fixed steel off-shore structures can be divided into two main phases, fabrication and installation. In the fabrication phase, fracture control is primarily concerned with quality assurance of incoming material and the welding of parts together. Both of the two primary fabrication methods, frame and node, involve the welding of tubular joints. However, the node method offers advantages of potential post-weld heat treating and welding under more favorable conditions. Most welds are made manually, although semiautomatic welding, such as Flux Core and Gas Metal Arc Welding have specific applications. Emphasis is placed on producing a weld profile that merges smoothly with the base material to reduce the stress concentration effect.

Fabrication defects can be divided into gross errors, such as member misalignment, and weld discontinuities, which all welds have to some extent. Nondestructive inspection techniques are used to detect these cracks or crack-like defects in the welds. Disposition of the defects is based on a "fitness for purpose" evaluation, including a fracture mechanics analysis of the defect. A decision to use as is or repair is made and an investigation of potential systematic error in the welding process is conducted. Fabrication defects are prevented by employing qualified welders and welding procedures, by closely observing the welding process, and by performing visual and other nondestructive inspection of the welds.

Fracture control during installation concentrates on proper execution of the installation procedures to prevent damage due to accidents. Installation of some types of platforms includes "load-out" (loading on a barge), transport to site, launch off the barge, erection, and final assembly. In other cases, the platform is floated to the site, which modifies the installation conditions. The trend toward longer tows has made evaluation of the transport process more critical to sound fracture control.

6.2 Relevant Documentation

Relevant source materials, standards, specifications, and industry or university studies are listed at the end of the Construction section of the Section II Summary. Other key references include:

1. Haagensen, P.J., "Improving the Fatigue Performance of Welded Joints," Offshore Welded Structures Conference, Trondheim, Norway, 1982.

2. Fisher, P.J., "Summary of Current Design and Fatigue Correlation," Fatigue in Offshore Structures, Institute of Civil Engineers, Conference Proceedings, London, February 24-15, 1981.

3. Telephone interview conducted with Robert G. Bea and Ashok Vaish, PMB Systems Engineering, Inc., San Francisco, California, on September 16 and 23, 1982.

4. Marshall, Peter W., "Fracture Control and Reliability for Welded Tubular Structures in the Ocean," Shell Oil Company, presented at the Ninth NATCAM, Ithaca, New York, June 1982.

5. National Research Council, "Inspection of Offshore Oil and Gas Platforms and Risers," Marine Board Assembly of Engineering, Washington, D.C., 1979.

6. Telephone interview with Peter Marshall, Shell Oil Co., Houston, Texas, on August 17, 1982.

7. Gurney, T.R., "Revised Fatigue Design Rules," Metal Construction, revision of UK DOE Guidance, January 1983.

6.3 Recommendations for Use of Existing Technology

Procedures/Guidelines

Recommendation CE1

Establish the level of cathodic protection necessary at all fatigue-critical welded joints.

It is important to establish control of the level of cathodic protection at all fatigue-critical welded joints. This is because crack growth rates of the order of 6, and even more, times faster than in air are possible given significant deviations either well below or well above the -800 mV optimum level of cathodic protection. Variables to be considered include the material, weld, and environment.

Detailed Inspection/Analysis for Improvement and Repair of Welded Joints

Recommendation CE2

Determine the condition of the weld root before improving the weld toe performance.

The improvement techniques recommended are effective mainly through the reduction of weld toe defect size. Care must be taken to determine whether or not fatigue life improvement might be negated by the mode of failure involving crack growth from the weld root. It would clearly be unfruitful to dramatically improve the weld toe performance if the weld root was "scheduled" to fail soon after the unmodified toe. The failure site depends on the relative sizes and stress distributions of the governing toe and root (e.g., lack of penetration) defects.

Recommendation CE3

Apply the principles of integrated fracture control to the design and execution of repair procedures.

An especially fruitful field of application of the principles of integrated fracture control is the design and execution of repair procedures. The need for repair usually connotes some sort of problem has arisen and therefore the design and fabrication decisions associated with the repair have higher stakes. When this is combined with the typically hurried atmosphere in arriving at a decision and implementing it on the structure, fracture control problems can be compounded. Therefore, the use of a formal or partially formal method of documenting the impact of the repair upon all elements of fracture control, as exemplified in Appendix A, is even more important than in the more leisurely design stage and decreases the probability that the final repair strategy will impair the function of the platform or cause any added risk.

6.4 Recommendations for Future Research

Experimental Research, Testing

Recommendation CR1

Undertake large-scale component testing to determine the effectiveness and applications of ways to improve weld toe fatigue performance.

As examples of fatigue performance improvement schemes, hammer peening and shot peening owe their effectiveness, in part, to reduction of residual stresses at the weld toe. We recommend that large-scale component tests and other tasks be undertaken to determine whether or not the residual stress improvements will last in certain situations (e.g., high compressive loads can shake down the compressive residual stresses introduced and even produce detrimental tensile residual stresses), the effect of cathodic protection on the fatigue strength of improved joints in sea water must be established, and the efficiency of improvement techniques on large scale structures should be verified. Large scale tests are also needed to estimate both the effect of decreasing the severity and frequency of micro defects in welds through the techniques discussed in Recommendation CR2.

Procedures/Guidelines

Recommendation CR2

Develop guidelines for the use of available techniques for improving welded joints where fatigue performance is marginal or inadequate.

There are several effective and reliable methods for improving the fatigue performance of welded joints in offshore structures. These costly techniques are recommended only where fatigue performance has been demonstrated to be marginal or inadequate. These include many techniques, investigated by Haagensen, which improved the weld primarily by decreasing both the residual stresses and micro-defects at weld toes. Except for "improved profile welds," all techniques listed below can be expected to improve the fatigue strength by at least 30% (measured in units of stress at a given fatigue lifetime). Guidelines for their use should be developed, based on research already performed or additional testing, as appropriate.

- Grinding Techniques. Provided they result in smooth profiles, these avoid deep scores or misblends oriented perpendicular to the highest stress components, and remove material of a depth of at least 0.5 to 1 mm in order to remove the deepest and most harmful defects associated with "typical" weld toes.

- Weld-Toe Remelting Techniques. Such techniques as TIG (tungsten-inert-gas) and plasma dressing, properly applied, can significantly improve fatigue lifetime by removing fatigue cracks of depths up to 3 millimeters and by lowering the hardness and improving the properties of heat-affected zones.

- Improved Profile Welds. Quantitative evaluation of the improvement due to specifying an overall concave weld profile and a smooth transition at the toe is somewhat inconclusive although the latest modification to API RP-2A discourages the use of non-profile welds through use of a lower S-N curve. Of all the improvements listed, improving the profile appears to be the least sure to substantially improve fatigue performance.

- Use of Special Electrodes. Designed mainly for higher strength steels, these electrodes produce a final weld pass at the toe of joints with good wetting, flow, and material characteristics and therefore a smooth transition profile that normally avoids costly weld improvement treatments.

7.0 INSPECTION AND MONITORING

The fracture control-related task of finding cracks during fabrication and in the installed structure requires the capability to find, size, and otherwise define the extent of cracking. This task can be broken down into four sub-tasks: (1) monitor the condition of the structure during fabrication; (2) check the condition of the structure soon after installation; (3) check the condition of the structure on special occasions, when warranted; and (4) if appropriate, continually monitor the structure to check its general condition.

7.1 Summary of Status

Given the uncertainty connected with the many inspections in the sub-tasks defined above, it is good policy to combine several independent inspection types which can be used to check each other. The subject of inspection procedures and requirements is dealt with in detail in primarily two documents: a National Research Council report, "Inspection of Oil and Gas Platforms and Risers" (1979) and the OCS Platform Verification Program, OCS Order #8, especially Section 9 under "Requirements". Given the criticality of welds, most of the effort in field inspections involves weld inspection at some level: observation of the welding process, visual examination of the welds, or NDE of the welds. NDE of welded tubular joints typically requires both ultrasonic and magnetic particle testing. For welds inaccessible to these methods, dye penetrants are sometimes used. Following fabrication, inspection focuses on the proper execution of installation procedures--the goal being to prevent damage due to accidents and avoid overloads during the sensitive load out, transport, launch, and dismantlement processes.

7.2 Relevant Documentation

Relevant source materials, standards, specifications, and industry or university studies are listed at the end of the Inspection section of the Section II Summary. Other key references include:

1. Marshall, Peter W., "Fracture Control and Reliability for Welded Tubular Structures in the Ocean," Shell Oil Company, presented at the Ninth NATCAM, Ithaca, New York, June 1982.

2. National Research Council, "Inspection of Offshore Oil and Gas Platforms and Risers," Marine Board, Assembly of Engineering, Washington, D.C., 1979.

7.3 Recommendations for Use of Existing Technologies

Experimental Testing, Research

Recommendation IE1

Determine the suitability of proof testing as an inspection procedure for joints known to have seen stresses at or near their design envelope.

Of all the common "inspection" techniques, proof testing is most notably deemphasized in or lacking from the general literature concerned with fracture control of offshore platforms (one exception is leak testing of members which store fluids or provide buoyancy). A good reason for this lack of emphasis would be the extreme, and in some cases, insurmountable, difficulties in proof testing selected joints in extremely large and structurally complex steel jackets. On the other hand, certain joints will be effectively proof tested before the operational phase by the load out and other transport operations. While we are not necessarily advocating taking credit in the design process for this effective proof testing, we do advocate careful inspection and analysis of those joints known to have seen stresses at or near their design envelope before placing the structure into operation. In general, if only because proof testing is such a big part of fracture control of components and structures of lesser complexity than a fixed platform's steel jacket, we feel that more consideration should be given this valuable inspection tool, whether or not such proof loads are ever to be applied independently of the normal transport of the platform.

Guidelines and Detailed Inspection/Analysis for Impact

Recommendation IE2

Combine independent inspection methods.

The varying strengths and weaknesses between the three types of inspections: 1) global/visual, "to count the braces"; 2) NDE, to find and size cracks; and 3) operational monitors, to measure any degradation in the structure in time provides an opportunity to use several different inspection procedures simultaneously and synergistically to dramatically improve the inspection resolution and false alarm rate over that associated with a single type of inspection. Combination of independent inspection procedures from these three categories is strongly recommended, tailored to the needs of each platform (see Recommendation IE3).

Recommendation IE3

Tailor the inspection procedures to the intended application.

Given the redundancy and use of forgiving, tough materials in fixed offshore platforms, we believe it is very important to tailor the inspection discrimination, sensitivity, and false alarm characteristics to the intended application. Specifically, if "counting the braces" every year is sufficient to provide adequate structural reliability of a platform, it makes no sense to demand supersensitive crack detection or sizing or small uncertainty of, say, an underwater ultrasonic inspection used to monitor the joints. As stated in a prior recommendation, the key is the simultaneous use of independent inspections which, in aggregate, provide strong protection against the highest risk failure modes with an acceptably low level of false alarms. For most fixed offshore platform applications, it would be a mistake to spend large research funds to, say, increase the resolution of an inspection procedure so it can find half the cracks of depth 0.25 mm rather than half the cracks of depth 0.5 mm (perhaps at the cost of additional false alarms). This money would probably be better spent in improving local monitoring devices which can reliably detect significant loss of load carrying capacity of a brace.

Recommendation IE4

Make inspection plans site-specific.

One of the recommendations stressed by the National Research Council (1979) report is that inspection plans be site-specific. Each type of structure, each tow and installation process, each operating environment has its own characteristics and each involves separate inspection considerations.

Education, Training

Recommendation IE5

Ensure that divers, platform operators, and inspection personnel are adequately trained.

Ensure that divers, platform operators, and inspection personnel are adequately trained. Monitoring equipment is often only as reliable as the people operating it. These people should have the associated education, attitude, and career expectations that such a level of responsibility and commitment demands. This is an idea that has recently gained acceptance by the nuclear power industry, which is now upgrading the control room operator from a technician to an engineer. The attendant aggregate increase in understanding of the system is expected to result in increased reliability and safety for the industry.

7.4 Recommendations for Future Research

Analytical Evaluation/Development

Recommendation IR1

Further develop monitoring systems to be portable, be discriminating, minimize the use of divers, and have an acceptable rate of false alarms.

Several structural monitoring systems have the potential to signal the distress of the structure well before the most catastrophic events can occur. This distress could involve a higher-than-expected fatigue damage, large cracks, or a failed member. Emphasis should be given to the further development of these monitoring systems to make them portable, minimize the use of divers, produce a level of discrimination commensurate with the structure's redundancy, and have an acceptably low rate of false alarms.

8.0 OPERATION

The primary goal of fracture control during operation is to minimize the risk of operating the structure in the offshore environment. Two conditions of the structure must be considered: routine conditions, when the structure exists as it was designed to exist, and damaged conditions, when cracks (or other damage) may be present. Under design conditions, fracture control is concerned with protecting the structure from damage due either to normal operating conditions or such accidents as boat collisions. One technique for lowering the risk associated with structural failure during routine operation is to evacuate a platform prior to a large storm. Under damaged conditions, fracture control is concerned with preserving the structural integrity.

8.1 Summary of Status

Fracture control practices during operation can be divided into four tasks: minimize the formation of cracks, monitor any cracks that may start, assess the crack's impact on the integrity of the structure, and take the necessary remedial steps. The fracture control aspects of the routine operation of a fixed steel offshore structure are mostly concerned with minimizing the occurrence of high stresses, cracks, and other damage. Cracks can initiate during operation due to accidents, such as falling pieces of equipment, or improper maintenance, especially maintenance of the cathodic protection system. This damage can be avoided by closely following specified operating procedures for the structure. Crack detection is based on scheduled inspections and structural monitoring. Once a crack is found, its size and location are determined using various nondestructive examinations. An evaluation is made of the effect of the crack on the joint or member and the effect of the damaged element on the structure. A risk analysis is performed to decide whether to repair the crack and, if so, a suitable repair method is selected. Alternatives to repair include non-routine operations to reduce the risk inherent in the presence of the crack.

8.2 Relevant Documentation

Relevant source materials, standards, specifications, and industry or university studies are listed at the end of the Operation section of the Section II Summary.

8.3 Recommendations for Use of Existing Technology

Recommendation OE1

Spell out available crack repair schemes in operation, emphasizing their effects on fracture control and safety risk.

> In order to make rational decisions concerning the remedial treatment of cracks the different alternatives should be spelled out and considered in turn, including various repair schemes, de-rating the structure, and "do nothing." Safety risk should be a primary factor in the choice of remedial action. (See Recommendation under "Education, Training" in Section 5.3).

8.4 Recommendations for Future Research

Recommendation OR1

Consider redundancy more quantitatively in undertaking risk-based remedial actions.

> A study of structural redundancy and the qualification of a structure's tolerance to cracks should be performed for typical designs so that a measure of risk can be computed for risk-based remedial action decisions.

9.0 OVERVIEW AND PRIORITIZATION

9.1 General Conclusions

As stated in Section 3, the elements of an integrated fracture control plan already exist within the offshore industry, from rules and guidelines such as API RP-2A and the ABS Rules to the use of fracture control generalists and engineering teams who consider fracture control through the design, construction, and operation phases. To our knowledge, one major oil company has an explicit, written fracture control plan. While such a detailed plan may not be the answer, and, on an industry-wide basis, could not be expected to cover every case, a more uniform application of existing technology is recommended.

The recommendations in this report are most often expressed as modifications to or applications of fracture control practices that are already reasonably well established. The major themes in these recommendations can be stated as follows: (1) improve and optimize the existing system (rather than trying to start anew), and (2) encourage communication among the various disciplines and the many organizations and individuals impacting fracture control.

9.2 Prioritization of Recommendations

Because of the large number of recommendations, it is clear that not all can be implemented at once. Therefore, it is desireable to have a ranking of the relative importance of the recommendations. Such a ranking is given in this subsection, based solely on the opinions of Failure Analysis Associates' staff, in view of the survey results. It is expected that others will have different opinions.

The recommendations naturally fall into two groups: (1) those for which existing technology is sufficiently developed so that they can be implemented by designers, builders, and operators (in some cases via regulations, rules, or codes), and (2) those directed toward future research. With these distinctions, engineers interested in upgrading fracture control on immediate projects would refer to the first group, and organizations interested in research to advance the state of the art would emphasize the second group in their planning.

The most important features of recommendations for use of existing technology are believed to be (in order) effect on control of fractures, ease of (or probability of successful) implementation, and cost of implementation. A ranking based on these factors is given in Table 1. A three-point rating system is used for each feature, with higher rating corresponding to greater motivation to implement the recommendation.

In rating each recommendation for its effect on fracture control, the tendency was to give higher rating to those that draw attention to the need for fracture control. The reasoning is that the most critical step is to ensure that the responsible engineers are actively focusing on fracture control issues. The midlevel rating was given to those activities of direct involvement with specific fracture problems, and the lower rating to activities which primarily supply more or better general information.

In rating ease of implementation, those recommendations simply requiring management decision or education were given highest rating, those requiring quantitative application of existing methods were rated in the midrange, and one requiring a multidisciplinary approach was rated difficult.

Cost of implementation was visualized in terms of engineering manpower required for a platform over its life cycle. Thus, activities requiring multidisciplinary teams over extended periods were regarded as expensive. Creation of permanent or semi-permanent small groups or focal points were viewed as moderately expensive. Activities of specific problem evaluation were thought to be less expensive.

After each recommendation was assigned a rating for each desirable feature, an overall ranking was established to a first order by "point count" and to a second order by giving highest weight to effect on fracture control, second highest to ease of implementation, and lowest weight to cost.

Table 1

Ranking of Recommendations for Use of Existing Technology

		Recommendation	Effect on Control of Fractures	Ease of Implementation	Cost of Implementation
			1-Small 2-Moderate 3-Large	1-Difficult 2-Moderate 3-Easy	1-High 2-Moderate 3-Low
1.	ME1	Make routine and extensive use of simplified analysis procedures, such as the FASD.	3	3	3
2.	FE1	Encourage Fracture Control Integration.	3	3	2
3.	DE6	Survey the entire structure for critical elements.	3	3	2
4.	FE3	Modify punching shear criteria to prevent other failure modes.	2	3	3
5.	IE2	Combine independent inspection methods.	3	2	2
6.	IE3	Tailor the inspection procedures to the intended application.	2	3	2
7.	FE2	Document the effects of every major structural decision or change upon all fracture control elements.	2	3	2
8.	DE1	Use first-order bounding fracture mechanics models to determine relative effects of toughness and fatigue-design control.	2	2	3
9.	DE2	Supplement S-N curves with deterministic fracture mechanics approaches.	2	2	3
10.	FE4	Use a calibrated fracture mechanics model to address tough fatigue and fracture problems.	2	2	3
11.	DE4	Teach engineers to review their thinking on safety factors in order to avoid dangerous design assumptions which may actually reduce the structure's reliability.	2	2	3
12.	DE5	Reduce the human error factor through education and minor modification of the MMS Platform Verification Program.	2	2	3

Table 1 (Cont'd)

		Recommendation	Effect on Control of Fractures	Ease of Implementation	Cost of Implementation
			1-Small 2-Moderate 3-Large	1-Difficult 2-Moderate 3-Easy	1-High 2-Moderate 3-Low
13.	CE3	Apply the principles of integrated fracture control to the design and execution of repair procedures.	2	2	2
14.	IE4	Make inspection plans site-specific.	2	2	2
15.	IE5	Ensure that divers, platform operators, and inspection personnel are adequately trained.	2	2	2
16.	CE2	Determine the condition of the weld root before improving the weld toe performance.	1	2	3
17.	FE5	Apply structural reliability models to optimize design and operational decisions.	3	1	1
18.	ME2	Designate a materials fracture control specialist for each application for which a correlation between standard specifications and quantitative fracture properties has not been established.	1	2	2
19.	DE3	Model size/shape of crack and transition behavior in brace or leg.	1	2	2
20.	CE1	Establish the level of cathodic protection necessary at all fatigue-critical welded joints.	1	2	2
21.	IE1	Determine the suitability of proof testing as an inspection procedure for joints known to have seen stresses at or near their design envelope.	1	2	2
22.	OE1	Spell out available crack repair schemes in operation, emphasizing their effects on fracture control and safety risk.	1	2	2

For future research recommendations, the desirable features were deemed to be the effect on control of fractures (assuming the research would be successful), the probability of success of the research, and the cost of performing the research. The first two features were rated on a three-point system and the third on the basis of estimated personhours to perform the research as indicated in Table 2. (Personhours are escalated to account for additional costs in computer or test intensive research.)

In rating research recommendations for effect on control of fractures, the authors considered the likelihood that the results would be actively used as well as the more obvious consideration of what effect the method would have if used. An important aspect was consideration of what is presently used; that is, what <u>increment</u> over present technology would the research provide? There was also a tendency to give higher rating to research which would likely result in specific improved design or construction features. An attempt was also made to rate these research recommendations (with respect to effect on control of fractures only) on the same scale as the existing technology recommendations in Table 1. No such attempt was made for the other features, since the correspondence between other features in the two groups is not one-for-one.

Ratings for the probability of success feature were influenced for most items by our judgement of the technical feasibility. This was in turn influenced by how definitively the final work product of the recommendation could be visualized. The only low probability of success rating was given to failure data base development, not because of technical feasibility concerns, but because of our knowledge of the reluctance of people who have access to such information to record, collect, and supply the data. This has been true even in the nuclear power industry where motivations for such activities are considerably greater.

Our estimates of personhours for research are tentative at best and would need to be refined if serious intentions to fund a project develop. We believe the estimates are reasonable for comparison of research opportunities. The estimates generally represent the smallest increment of work that has a reasonable chance of satisfying the recommendation.

Table 2

Ranking of Recommendations for Future Research

		Recommendation	Effect on Control of Fractures	Probability of Success	Cost
			1-Small 2-Moderate 3-Large	1-Low 2-Moderate 3-High	Person-hours of Research
1.	CR2	Develop guidelines for the use of available techniques for improving welded joints where fatigue performance is marginal or inadequate.	3	3	5000
2.	IR1	Further develop monitoring systems to be portable, be discriminating, minimize the use of divers, and have an acceptable rate of false alarms.	3	2	6000
3.	CR1	Undertake large-scale component testing the effectiveness and applications of ways to improve weld toe fatigue performance.	3	2	8000
4.	MR2	Collect reliable fracture data to be matched up with offshore needs in order to produce recommended programs for for closing the "data gap."	2	3	2000
5.	DR15	Develop algorithms for the problem of contained plasticity in notches.	2	3	2000
6.	DR3	Develop deterministic design and fitness-for-purpose approaches for routine analysis of significance of defects and for development of examples and guidelines.	2	3	3000
7.	DR9	Define stress gradients and other characteristics of the subsurface stress distribution.	2	3	3000
8.	DR10	Develop accurate, versatile crack analysis methods.	2	3	3000
9.	MR1	Start a materials data base for all important measured fracture parameters of offshore structural steels.	2	3	4000

Table 2 (Cont'd)

		Recommendation	Effect on Control of Fractures	Probability of Success	Cost
			1-Small 2-Moderate 3-Large	1-Low 2-Moderate 3-High	Person-hours of Research
10.	DR2	Develop accurate stress intensity factor solutions for all stress fields and crack geometries of concern. Include evaluation of displacement control exhibited by most tubular joint crack geometries. In addition, develop a handbook or software library of stress intensity factor solutions for often occurring geometries and load cases.	2	3	5000
11.	DR22	Employ natural load shedding and displacement control features to help design crack arrest features.	2	3	5000
12.	MR5	Set up a "devil's advocate" testing program to evaluate fracture criteria.	2	2	1000
13.	DR14	Determine the feasibility of determining approximate effects of stress gradients in estimating elastic-plastic crack tip stress parameters.	2	2	1500
14.	DR1	Develop a data base of service and repair histories.	2	2	2000
15.	DR4	Develop a probabilistic fracture mechanics approach for routine crack analysis.	2	2	2000
16.	DR12	Study methods for determining hot spot stresses and tubular joint behavior outside the standard case.	2	2	2000
17.	DR16	Develop additional design data for steel "shell" components.	2	2	2000
18.	DR13	Study wave loading and associated phenomena more closely and develop guidelines for application.	2	2	2000
19.	OR1	Consider redundancy more quantitatively in undertaking risk-based remedial actions.	2	2	3000

Table 2 (Cont'd)

		Recommendation	Effect on Control of Fractures	Probability of Success	Cost
			1-Small 2-Moderate 3-Large	1-Low 2-Moderate 3-High	Person-hours of Research
20.	MR3	Fund quantitative toughness testing using specimens which simulate the physical characteristics at the crack border of the structure.	2	2	4000
21.	DR20	Study effects of soil-structure interaction and, particularly, long-term foundation degradation.	2	2	4000
22.	DR21	Develop a more accurate finite element program for the global analysis of structures using both joint and member elements.	2	2	4000
23.	FR3	Build improved structural reliability models capable of calibrating to and extrapolating from field experience.	2	2	5000
24.	DR23	Expand the range of tubular joints tested and used to set S-N curves.	2	2	8000
25.	FR1	Survey industries using more formal fracture control documents than does the offshore industry.	1	3	1500
26.	DR19	Evaluate the neglect of larger wave periods in fatigue analyses.	1	3	1500
27.	FR2	Prove that Charpy tests are meaningful for new situations.	1	3	2000
28.	DR6	Define applications suitable for use of higher-order-average alternating-stress methods for life prediction.	1	3	2000
29.	DR18	Determine the accuracy of "identical wave" DAFs in variable wave spectrums.	1	3	2000
30.	MR4	Define and execute an experimental program to evaluate constant amplitude fatigue, overload, and underload effects upon crack growth. Ensure that an adequate range of crack propagation rates is covered.	1	3	6000

Table 2 (Cont'd)

		Recommendation	Effect on Control of Fractures	Probability of Success	Cost
			1-Small 2-Moderate 3-Large	1-Low 2-Moderate 3-High	Person-hours of Research
31.	FR4	Build a data base of failure, accident, and success experience for feedback to those who influence fracture control.	2	1	8000
32.	DR11	Consider the effect of greater-than-predicted wave loadings upon the fatigue life of a structure.	1	2	1000
33.	DR7	Formalize the statistical approach to defining the variability of S-N and sub-critical crack growth data.	1	2	1500
34.	DR8	Estimate the effect of multiple crack-site origins at the weld toe.	1	2	1500
35.	DR5	Establish design loads for and protection against impact damage (collisions, explosions, etc.)	1	2	2000
36.	DR17	Assess effects of uncertain hot spot stresses and incorporate into a PFM model.	1	2	3000

In combining the three features to obtain an overall ranking, cost was used only as a second order consideration. This is justified on the basis that none of the costs are significant compared to the enormous potential cost avoidances associated with successful completion. These potential cost avoidances include a reduction in the number of premature service cracks, repairs, and failsafe component failures, as well as the possibility of reducing the already low rate of more serious platform failure modes. Effect on control of fractures was given slightly more weight than probability of success, partly for the same reasons.

In Table 3, the recommendations for future research are listed according to their subject matter. The eleven categories are presented in order of decreasing cost. As shown in the table, almost half of the program costs are in the areas of materials and component testing (28%) and fracture mechanics (18%). If the recommended programs with the lowest effect on fracture control or the lowest probability of success are deleted, then the number of programs is reduced from 36 to 24 (a 33% reduction) and the cost decreases from 118,500 hours to 86,500 hours (a 27% reduction). The result is presented in Table 4. As in Table 3, a majority of the total cost is expended in testing and fracture mechanics. However, the order of the programs, in terms of cost, is different from that of Table 3 and two categories, impact and fracture control systems, do not appear at all. Tables 3 and 4 are intended to provide the reader with a better picture of the recommended programs in terms of their application and cost.

Table 3

Recommendations by Subject

Subject	Recommendation	Ranking[2]	Cost-1000 hrs
Material & Component Testing	CR1	3-2	8.0
	MR2	2-3	2.0
	MR3	2-2	4.0
	MR5	2-2	1.0
	DR16	2-2	2.0
	DR23	2-2	8.0
	[1]FR2	1-3	2.0
	[1]MR4	1-3	6.0
			33.0 (28%)
Fracture Mechanics	DR2	2-3	5.0
	DR3	2-3	3.0
	DR10	2-3	3.0
	DR15	2-3	2.0
	DR4	2-2	2.0
	DR14	2-2	1.5
	[1]DR8	1-2	1.5
	[1]DR17	1-2	3.0
			21.0 (18%)
Data Base Enhancement	MR1	2-3	4.0
	DR1	2-2	2.0
	[1]FR4	2-1	8.0
			14.0 (12%)
Fatigue	DR13	2-2	2.0
	[1]DR7	1-2	1.5
	[1]DR11	1-2	1.0
	[1]DR6	1-3	2.0
	[1]DR18	1-3	2.0
	[1]DR19	1-3	1.5
			10.0 (9%)
Stress Analysis	DR9	2-3	3.0
	DR22	2-3	5.0
	DR12	2-2	2.0
	DR21	2-2	4.0
			14.0 (12%)

[1] Recommendations having either a low effect on fracture control or a low probability of success.

[2] Numbers refer to effect on fracture control--probability of success.

Table 3 (Continued)

Subject	Recommendation[1]	Ranking[2]	Cost-1000 hrs	
Risk Analysis & Reliability	OR1	2-2	3.0	
	FR3	2-2	5.0	
				8.0 (7%)
Nondestructive Examination	IR1	3-2	6.0	
				6.0 (5%)
Welding Improvement	CR2	3-3	5.0	
				5.0 (4%)
Foundations	DR20	2-2	4.0	
				4.0 (3%)
Impact	[1]DR5	1-2	2.0	
				2.0 (2%)
Fracture Control Systems	[1]FR1	1-3	1.5	
				1.5 (1%)[3]
		TOTAL		118.5(100%)

[1] Recommendations having either a low effect on fracture control or a low probability of success.

[2] Numbers refer to effect on fracture control--probability of success.

[3] Cost of all recommendations in each subject expressed in hours and as a percentage of the total cost.

Table 4

Most Significant Recommendations By Subject

Subject	Recommendations	Ranking[1]	Cost	
Material & Component Testing	CR1	3-2	8.0	
	MR2	2-3	2.0	
	MR3	2-2	4.0	
	MR5	2-2	1.0	
	DR16	2-2	2.0	
	DR23	2-2	8.0	
				25.0 (29%)
Fracture Mechanics	DR2	2-3	5.0	
	DR3	2-3	3.0	
	DR10	2-3	3.0	
	DR15	2-3	2.0	
	DR4	2-2	2.0	
	DR14	2-2	1.5	
				16.5 (19%)
Stress Analysis	DR9	2-3	3.0	
	DR22	2-3	5.0	
	DR12	2-2	2.0	
	DR21	2-2	4.0	
				14.0 (16%)
Risk Analysis & Reliability	OR1	2-2	3.0	
	FR3	2-2	5.0	
				8.0 (9%)
Nondestructive Examination	IR1	3-2	6.0	
				6.0 (7%)
Data Base Enhancement	MR1	2-3	4.0	
	DR1	2-2	2.0	
				6.0 (7%)
Welding Improvement	CR2	3-3	5.0	
				5.0 (6%)
Foundations	DR20	2-2	4.0	
				4.0 (5%)
Fatigue	DR13	2-2	2.0	
				2.0 (2%)
			TOTAL	86.5(100%)

[1] Numbers refer to effect on fracture control--probability of success.

[2] Cost of all recommendations in each subject expressed in hours and as a percentage of the total cost.

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IV. CONCLUSIONS AND GENERAL RECOMMENDATIONS

A survey of experts and the open literature was conducted to determine the current fracture control practices for fixed offshore structures. The essential elements of fracture control were identified as materials, design, construction, operation, and inspection. Each of these areas was summarized and evaluated to identify areas where use of existing technology would suggest cost-effective improvements and to identify promising areas of technical research.

This survey revealed that the more advanced fracture control methods used in the United States offshore industry closely parallel those used by other high-technology industries such as aerospace. Sophistication of the best methods used considerably surpasses analysis requirements of typical codes used in several other industries (e.g., nuclear power). However, the best methods do not appear to be as uniformly applied and/or documented as they should be. Thus, it is recommended that emphasis for the foreseeable future be placed first on more widespread and uniform use of the best existing methods and second on steady improvements in the methods. The first emphasis could be accomplished voluntarily under leadership of the platform operators. (The survey revealed that typically, designers and constructors look to the operators for guidance.) The second emphasis should be addressed by research organizations.

An operator who wishes to take positive steps toward more uniform fracture control should do so by using the fracture control checklist provided in Appendix B and documenting efforts explicitly pointed toward fracture control in a format such as recommended in Appendix A. This list and documentation, used in conjunction with the recommendations for use of existing technology in Section III of this report, would place an operator at the forefront of fracture control in the industry. Since instantaneous changes in several areas at once are not usually feasible, the operator should make use of the priority ranking provided in Table 1. It is believed that the economic benefit gained in problem avoidance would greatly exceed the cost of implementation. The particular gain would depend on how much this recommended approach differs from the operator's present approach.

A need for substantial future research at a minimum cost of about $8- to $12 million was identified. Unless sources for this order of funding (over about three years) are already available, the first step should be toward identifying such sources. Although not specifically addressed in this report, it is believed that this research cost is quite small compared to the economic benefits that would accrue from avoidance of cracking, repair, and failure problems. Our basically positive assessment throughout this report of the state of the art of fracture control of offshore structures (e.g., as compared to fracture control practices in other industries) certainly does not imply that cost-effective improvements are not obtainable.

We do not believe that technology transfer from ongoing research in support of other industries will greatly influence the needs identified here. Most of the recommendations are too closely associated with specific problems encountered in offshore structures to gain other than a general benefit from other research.

To the extent that full funds cannot be obtained, Table 2 should be used to establish research priorities. Design recommendations dominate the list numerically, but more certain and effective immediate payoffs may come from construction and inspection advances. Some materials tasks are also strong contenders for high priority funding. In the spirit of an integrated fracture control improvement, a balanced approach is recommended, where one or more tasks are selected from at least the design, materials, construction, and inspection fracture control elements.

Appendix A
FRACTURE CONTROL: STATEMENT OF EFFECTS

The following exemplifies a recommended compromise between the development and use of a comprehensive fracture control plan "Bible" and no fracture control plan documentation at all. For the purpose of illustration, the example has been stated qualitatively; although, as will be indicated, in an actual application extensive quantitative information could be included.

A.1 Description of Problem

New oceanographic data for a frontier location indicates a more severe fatigue environment than anticipated in the design of a fixed offshore platform which is already in an advanced phase of fabrication. A careful design audit reveals that with the important exception of eight nominally identical tubular-joint brace-can intersection hot spot weld-toe locations, the original design will be adequate for the harsher loading/environmental conditions. A fatigue analysis of the eight hot spot locations reveals that they are marginally unacceptable due to the greater fatigue damage associated with the more severe wave load spectrum.

After careful consideration of several alternative measures (which may in some cases have included a fracture control effect statement for each measure), it has been decided to grind the critical weld-toe locations to increase adequately the fatigue performance of the eight hot spots in question. (Assume that the weld root performance is already adequate.) As part of the effort to both select and justify this fatigue performance improvement method, the following illustration of a fracture control plan statement might have been offered.

A.2 Primary Impact on Fracture Control of Weld-Toe Grinding Improvement

Both relevant S-N literature data and a fracture mechanics-based weld fatigue analysis reveal that weld-toe grinding will improve the fatigue life under a given spectrum by at least a factor of three. (The most recent U.K.

DOE fracture design rules permit the equivalent assumption of at least a factor of 2.2 life increase without a supporting analysis.) This improvement is accomplished by reduction of the weld-toe (notch) geometry's stress concentration and inherent crack-like defects. Life improvement credit from grinding should not be taken without cathodic protection or the corrosive action may pit the surface and negate most of the benefits of grinding. This improvement has been calculated to be adequate to handle the more hostile wave loading spectrum associated with the new platform location. (If the uncertainties and/or controversy engendered by the above analysis and literature search were large, a structural simulation experiment, with and without weld-toe grinding could be performed to "prove" the fix, if time permitted.)

This primary effect on fracture control is nothing more than the reason for the design change. What follows is a more comprehensive survey of the impact of this change that good engineering practice dictates should be followed in some form. The point of our illustration is to show how this "common-sense, good engineering practice" could be documented in the form of a fracture control effect statement.

A.3 Secondary Influences of Weld-Toe Grinding on an Integrated Fracture Control Plan

Material: The last welding pass, which contains the most suspect microstructure and hardest weld metal, will be removed by the specified grinding operation. Furthermore, the effective initial crack size should decrease due to grinding. With no other significant impact of grinding upon material properties, the secondary effect of this change on the material element of fracture control can only be positive.

Design: The primary design effect of reducing the surface and relevant stress concentrations at the hot spot have already been addressed in Section III:4.2. There are, however, several secondary effects on local geometry and stress fields, and hence upon design, which might be detrimental.

A worst-case tolerance analysis of the new weld profile indicates that the brace and can cross-sections themselves could be reduced by the grinding. Specifically, it is determined that the local thickness of the brace wall could be reduced by 5% and of the can, 3%. Rather than performing a detailed finite element analysis to model this local thickness reduction, the brace and can wall bending and membrane stresses have been multiplied by the following tabulated factors.

Factors for Worst-Case Reduction Of Section Properties By Grinding

"Nominal" Maximum Principal Stress Component (perpendicular to Weld-Toe Defect)	Increase in Finite Element Stress Closest to Hot Spot Brace	Can
Membrane	1.053 $[(1-0.05)^{-1}]$	1.031 $[(1-0.03)^{-1}]$
Bending	1.108 $[(1-0.05)^{-2}]$	1.063 $[(1-0.03)^{-2}]$

Assume for this example that these factors have been incorporated into and are discounted within the primary analysis mentioned before which revealed the overall factor-of-three improvements of fatigue life performance. Thus, the secondary impact associated with this local thickness reduction has already been conservatively bounded within the fatigue analysis.

Three geometrical effects of grinding upon the weld profile have been considered. First, grind depth should be at least 40-mils below the original surface to be reasonably sure of removing weld-toe fabrication defects. Second, it is standard practice that the grinding direction should be parallel to the maximum principle stress direction. (That is, most likely, from brace to can rather than around the brace.) Thus, any crack-like scores due to grinding would not be oriented in a direction likely to cause premature fatigue cracking. The third geometrical feature that has been accounted for as a secondary impact upon fracture control is the possibility of misblended radius due to a difficult weld geometry or poor workmanship. Experience (feasibility studies could be another possibility) has shown that with proper inspection (see below) and use of qualified technicians for the grinding operation, the worst case deviations from an ideally ground surface would not cause nearly as much fatigue performance reduction as introduction of a 5-mil deep crack. Since such an initial crack depth corresponds to the average fatigue performance of well-made weld-toes (ground or not) in general, this worst-case weld-toe profile error should have a tolerable impact. In other words, grinding can be used to help ensure that the welds behave as if they had a 5-mil (rather than a much deeper) crack.

The local residual stresses due to local weld shrinkage have been shown to be maximum tension in the last one or two weld passes. Thus, the subject grinding fix can only improve the state of residual stress. However, no analytical credit has been taken for such improvement because there are no plans to actually verify through residual stress measurement 1) that a stress decrease has taken place due to grinding, and 2) that the maximum compressive stress excursions expected during launch and operation of the platform would not reintroduce yield-level tensile residual stresses. Thus, while some fatigue performance improvement might arise from residual stress reduction, due to grinding, no specific quantitative estimate or credit has been taken for this potential positive effect upon fracture control.

Construction: Other than the original feasibility study to show that the weld profile grinding could be achieved (given qualified workmen and inspectors) as a primary effect, the grinding of the eight weld-toe locations has no known effect upon the fabrication of the as-built platform.

Inspection: The weld profile has been chosen to provide a smooth, clean surface which will only improve the crack-detection and sizing inspections and measurement of the profile itself to ensure that the ground geometry is within tolerance. Therefore, it has been decided to prepare the jacket for load out before the grinding operation. The resulting loads on the joints should apply a net tension in the hot spot locations and allow any preexisting large weld-toe cracks to open up and reveal themselves as material is ground away. A qualified inspector has been assigned to work with the grinders to attempt to detect and size such cracks that might be revealed. A repair weld/grinding procedure has been devised in case such cracks are found beyond a certain fracture mechanics-based maximum size.

<u>Operation</u>: Beyond the primary aspect of the increased wave loading spectrum already discounted in the initial fatigue analysis, a special inspection schedule for these eight locations should be used to verify the benefits of the grinding.

Appendix B
FRACTURE CONTROL CHECKLIST

B.1 Introduction

In order to execute a fracture control check and "semiformal" documentation, as outlined in Appendix A, some guidelines should be available such that fracture control specialists can select from a relatively comprehensive list those items to emphasize in their fracture control checks. An initial version of such a checklist is outlined below:

B.2 Initial Checklist for Fracture Control Execution

B.2.1 General Policy

A statement of policy should be made to minimize accidents due to fracture in the structure under study. Then a more focused and specific statement of policy could be made for the specific area under study.

B.2.2 Objective

State the responsibilities, criteria, and procedures to be used for fracture control project under study.

B.2.3 Scope

State which platforms and substructures and activities are to be covered with the focused fracture control plan. State which activities are to be emphasized among design, analysis, testing, material selection and control, fabrication, nondestructive evaluation, operations, maintenance and inservice inspection. State whether the plan is for information only or is an internal guideline or code.

B.2.4 Prerequisites and Assumptions

It is often very difficult to define where basic engineering practice stops and where specialized fracture control calculations and checking begin. Any written fracture control document should clearly delineate prerequisites and assumptions based on information outside the scope of that document. For example, a rather broad set of prerequisites and assumptions might be as follows:

- Assume that basic materials data, loads and environmental definition, and comprehensive structural analysis are available as a matter of good engineering practice.

- Assume a comprehensive test program to verify unique designs and conditions.

B.2.5 Organization and Responsibilities

Each organization involved in the specific offshore structural detail under study (designer, builder, operator) could appoint a fracture control specialist or committee (possibly with advisory rather than decision-making powers) within which are represented at least the following engineering disciplines:

- Structural design
- Structural analysis
- Materials engineering
- Maintenance
- Operation
- Inspection

If appropriate, each fracture control committee would develop an operating plan (could be informal written document) which defines the specific responsibilities of each specialist.

B.2.6 Fracture Critical Parts Selection Criteria

A systematic criteria should be devised to determine which parts and activities are fracture critical and therefore subject to stringent fracture control measures. Certain parts could be automatically designated fracture critical parts.

B.3 Specific Requirements, Procedures and Documentation

B.3.1 Sources of Crack, Defect and Damage Initiation

Cracks, crack-like defects, or other damaging imperfections such as crevice corrosion sources or impact dents, may initiate during the construction, transport, installation, operation, or dismantling of a fixed offshore structure. The following defect types and causes should be considered in a fracture control effort.

- Defect in the original material. These include steel plate porous regions, nonmetallic inclusions, or lamination. The largest and most significant of these defects should be detected and rejected or repaired before the plate is used.

- Cracks initiating from welding:

  - Large crack-like defects in the weld due to poor weldability of the materials or poor welding technique
  - Cracks caused by overrestraint in the welds and associated high residual stresses (e.g., through improper pre-heat and other welding procedures)
  - Lamellar tearing near welded joints

- Overload of a joint

- Fatigue cracks

- Impact dents, gouges, tears, or complete joint separations

- Corrosion cracks or pits, or crevice corrosion (severe knife-edge slices into the weld or other structural detail).

B.3.2 Material Selection and Specification

Assure that the material will behave at least as well as assumed in design calculations.

- Limit material defects which might initiate fracture.

- Avoid materials too susceptible to subcritical cracking and brittle fracture at the service temperature of the structure.

- Produce near-optimum tradeoff among material strength, toughness and cost.

- Depending upon the defined scope of the fracture control plan (see Section B.2.4, Prerequisites and Assumptions), assure such general properties as yield strength, ultimate strength, ductility, and lamellar tearing resistance are up to defined standards.

- Set tolerance levels for porosity, inclusions, laminations, and other rolled-plate defects.

- Specify those aspects of material process that help meet the above tolerance levels.

- Control carbon-equivalence and any other important chemical composition properties to assure weldability.

- Specify materials and processes for fracture-related properties.

- Obtain adequate fracture toughness, crack arrest capacity, dynamic load resistance, crack growth rate resistance, threshold stress intensity factor, stress corrosion and environmentally-accelerated fatigue susceptability, effects of temperature and other environmental considerations.

- Define, as far as possible, effects of processes, size effects (e.g., thickness), grain orientation, and geometric configuration.

- Guard against such corrosion-related failure modes as stress corrosion cracking, environmentally-accelerated fatigue or fracture, and bulk corrosion thickness loss through a combination of paint, other coatings such as metallic wrap, and, most likely, cathodic protection.

B.3.3 Design

While producing a near-optimum functional and economic structure, guard against the five failure modes: fracture; subcritical crack growth caused by a combination of cyclic and steady loads and environment; yielding, including excessive plastic deformation modes such as ultimate failure or plastic-hinge bending; elastic or inelastic buckling or other instabilities under compression loads; and bulk corrosion leading to loss of cross-section.

- General Design:

  - Minimize stress concentrations.

  - Provide access for inspection and maintenance

  - Select stress levels so that life can be verified by analysis combined with nondestructive inspection.

  - Clearly identify fracture critical parts on drawings as appropriate.

- Fatigue and Fracture Mechanics Analysis:

  - Account for impact of possible initial flaws on all relevant failure models.

- Perform nondestructive inspection or, less likely, proof test to screen flaws.

- Evaluate residual stress effects.

- Loading. Account for the many sources of loading that might become important to the five failure modes listed above. These include:

  - Wave loads. Determination of wave loads includes specification and prediction of maximum wave heights and associated frequencies, characterization of wave spectra as functions of location and water depth, statistical analysis and prediction efforts necessary to specify and justify chosen parameters for wave sizes and spectra, proper computation and application of hydrodynamic forces, including vortices, treatment of wave spectra, and nonlinear combinations of wave and current.

  - Wind loads (involving proper computation of aerodynamic forces and vortices). Work is similar to that involved in specifying waves in that extreme once-in-a-lifetime winds and hurricane models must be specified.

  - Tides and currents

  - Submarine mudslides

  - Marine fouling

  - Where applicable, ice

  - Earthquake loads

  - Installation forces during loadout, transport, launch, and dismantling

  - Operational loads associated with platform equipment used for drilling and lifting supplies and personnel.

- Design Analysis:

  - Perform standard space-frame analysis of steel jacket and associated structure.

- Perform quasistatic and dynamic analysis for design load cases.

- Perform local analysis of tubular joints using an appropriate combination of stress analysis tools such as finite element and shell theory, experimental results, and regression (equational or nomographical) fits to analytical or experimental results.

● Fatigue Analysis. Including load spectrum analysis described above; analysis of most critical structural details from global, local, and crack propagation viewpoint; proper cycle counting using both deterministic and spectral models; and appropriate cumulative damage rule.

● Standard design calculations:

  - Check for local and global buckling of tubular members including the effects of inelastic behavior and hydrostatic collapse. Check for static strength of tubular joints (1) using proven punching shear formulas with appropriate corrections for simpler classes of joints, and (2) designing appropriate experiments for more complex joints.

  - Compare fatigue analysis results described above with known experimental results in the fatigue of tubular joints. If appropriate, introduce fracture mechanics model, calibrated against all known data, for extrapolation to different section thicknesses and other situations.

● Complex failure modes:

  - Investigate combined or common failure modes such as caused by progressive degradation due to corrosion and fatigue.

  - Investigate the role of fail-safe redundancy including appropriate dynamic effects, such as dynamic load amplification and dynamic effects on resistance (e.g., the structure might be fail-safe against static failure modes of a given member but not against sudden dynamic fracture).

- Pilings and Foundation. Standard design load cases often cause significant tensile loads in piling structures so that foundation structures should be considered when controlling fracture. Some of the more important fracture control aspects of foundation design include determination of axial and shear loads from space frame analysis of the structure, displacement control loads due to mudslides and earthquakes, maximum bending combined with compression to produce maximum tensile stresses at piling welded details, and for long slender pilings such nonlinear loading effects as the "P-Δ" effect, and effects of overloads.

If deterministic design analyses, such as those in the checklist above, are inconclusive, consider a probabilistic approach to either perform a structural optimization or to more realistically model a "worst-case scenario".

B.3.4 Construction

- Understand and control the effects on fracture of processes such as material removal, forming, joining (especially through welding), thermal treatment, and chemical cleaning.

- Meet specified structural dimensions and material properties or assume worst-case effects of variations from specifications upon the control of fracture. Minimize residual stresses, especially in welding.

- Maintain tolerances and surface finishes.

- Ensure qualifications of personnel involved in fabrication.

- Ensure traceability of materials, personnel, and procedures used to fabricate fracture-critical parts.

- Perform state-of-the-art fitness-for-purpose evaluations of unusual fabrication defects.

- Use inspection liberally in locating weld defects and, during repair, calibrate the inspection by measuring the depths of defects repaired.

- Learn from the occurrence of weld and other defects. Attempt to determine the root cause of such defects and avoid the same during repair welding. Inspect other joints which may have been subject to the same root cause.

- See that welds merge smoothly with the adjoining base material without excessive undercut.

- Consider the advantages and disadvantages of use of extensive prefabrication processes such as the nodal method of construction.

- Concentrate inspection upon those joints known to have been exposed to the largest fabrication-induced loads and residual stresses.

B.3.5 Operation and Inspection

- Generally protect the structure from damage either due to such accidents as boat collisions or due to normal operating conditions (e.g., corrosion).

- Under damage conditions of the structure, fracture control must concentrate upon preserving the integrity of the structure. Serious imperfections must be found and their significance evaluated before they are dangerous, and if necessary repairs must be made.

- Under nondestructive evaluation practices, perform tests to understand sensitivity and reliability of possible techniques. Select the most appropriate technique or, much more likely, combination of NDE techniques.

- Review quality and report nonconformance.
  - Report incidence and characteristics of defects.
  - Report departures from prescribed properties and dimensions (presumably occurring during operation).
  - Record any failures, their causes and corrective actions.

- Inspect structures periodically.
  - Define inspection scope, frequency, and intensity on basis of knowledge of design and operation. Consider stress levels, NDE capabilities, and level of fail-safe redundancy.
  - Require formal item-by-item checklist to confirm proper execution of inspection.

- When combining inspection procedures, try to choose techniques that complement each other. For example, it may be appropriate to combine a needed "fine-toothed-comb" crack detection technique with a structural monitoring technique capable of continuous review of the "general health" of an important section of the structure. Consider timing of inspections. For example, use intervals based upon worst-case scenarios of stress corrosion or fatigue crack growth. Base certain inspections upon event-related phenomenon to take advantage of field experience feedback.

- Prior to actual damage, plan actions to repair whatever types of damage could be found. This will avoid the need for hasty decisions under surprising operational events. Among those types of damage that should be considered, in approximate decreasing order of importance, are (1) ruptured, buckled, and missing members, (2) large cracks anywhere in the structure but especially at welded joints, (3) severe bulk corrosion accompanied by loss of cross-sectional thickness, (4) accelerated local corrosion, especially in the form of crevices or pits near welds or heat-affected zones, (5) dents, punctures, and abrasions, (6) small cracks, and (7) corrosion in non-critical members.

- Safety-risk should be the prime consideration in choosing a repair procedure for operational abnormalities or unusual events. The do-nothing option should always be considered in order to balance the risks associated with various repair schemes and to consider the role of fail-safe redundancy and alternative safety measures, such as evacuation.

- Assure a strong feedback loop to designers and other fracture controllers in order to take full advantage of the lessons learned from operational experience.

Strip Impact