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Final Report

Assessment of the Feasibility of the Application of Threaded Connections in Offshore Platform Caissons

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FINAL REPORT

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EXECUTIVE SUMMARY

This report provides the results obtained in the first phase of a two-phase study aimed at providing the Minerals Management Service (MMS) with an assessment of the technical feasibility of applying threaded connections to offshore caisson platforms. The study, motivated by the potential economic benefits associated with reductions in offshore installation times and opportunities for retrieval and reuse, is necessary for two reasons. First, specific guidelines for the design, validation, and testing of threaded connections for caisson applications are virtually non-existent. Second, considerations for the retrieval and reuse of the connection that may have been driven and allowed to freely corrode in a marine environment must be defined.

To address these issues, preliminary work was conducted in phase one of this study to outline a general guideline for conducting the design, analysis, and validation of a threaded connection for offshore caisson applications. Technical activities performed in phase one and reported herein included the independent evaluation of existing practices for the design of caisson structures and threaded connections, emphasizing the outer continental shelf regions of the United States. Overall, many of the existing guidelines outline the fundamental requirements for successful design of caisson structures and of threaded connections. Many may be readily applied to the design of connections for caissons, and some may require only small modifications. However, the results of the evaluations indicated key portions of the existing design protocols that are deficient or inappropriate when applied to caissons with threaded connections. One example is the current lack of any specific requirements for tubular-connection (global-local) structural analyses that couple the local behavior of the connection to the overall, or global response of the structure. A second example is the suitability of the direct application of established fatigue assessment approaches to the evaluation of connections subjected to high static compression. Recommendations for the performance of these analyses, and guidelines for the treatment of other special considerations are given in this report. Once validated by phase two work, these recommendations, when used in conjunction with principal requirements of the existing documents, will be useful in the development of successful designs.

Also in phase one, a survey was performed to assess the potential for industry acceptance and support of the proposed application of threaded connections. In general, moderate interest from both caisson designers and caisson operators was received; although, each believe that proof of the technical feasibility and economic benefits must be first established. To this end, the phase two work activities have been defined to provide validation of the special considerations recommended for further design evaluation, but will exclude any validation efforts that are necessarily the responsibility of the designer or manufacturer. The effect of global-local structural response when subjected to caisson-type loading will be specifically addressed since there is currently no requirement for the design or validation of structures based on these effects. Conversely, the behavior in fatigue, which is heavily regulated for offshore structures and is primarily the responsibility of the designer, will not be evaluated. Thus, upon completion of phase two, results of the elemental validation activities needed to establish basic technical feasibility can be used to develop more formalized guidance for the use of threaded connections in caisson structures.

Assessment of the Feasibility of the Application of Threaded Connections in Offshore Platform Caissons

Report Organization

This document summarizes the findings for phase one of a two-phase study assessing the feasibility of applying threaded connections in offshore platform caissons. Please note that the report is not structured in accordance with the work task breakdown defined in the program scope of work. Rather, existing caisson and threaded connection design practices are addressed independently of each other in two separate sections, while a third section integrates these into a discussion of their application to threaded connection designs for caisson structures. Following this discussion, recommendations are made for development of a general guideline, and an accompanying scope of work is outlined for the second phase of the feasibility study.

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1. INTRODUCTION

In recent years, the operational demands placed on offshore structures and related equipment has increased with industry interest in reducing the costs associated with installation and retrieval time offshore, and with improving the safety of retrieval processes. As a result, designers are seeking increasingly efficient and cost effective means by which their designs can be more easily implemented in an offshore operation, and safely withdrawn. Moreover, because of the often-high initial costs of design and fabrication of such structures, operators would like to optimize or extend the useful lifetime by re-using the structure at a number of locations. The later condition requires that the in-situ structure withstand the deleterious effects of structural loads imposed during installation and service in free-corroding environments, and that the structure be easily removed from service and re-certified prior to installation at a second site.

The benefits of using threaded connections in tubular structural components for reducing installation times offshore and to avoid complications with girth welded members has been recognized by various members of the offshore industry [EMAS, Gerwick]. Most current applications of threaded connections today have been in both critical and non-critical components in drilling, workover, and production risers, conductors, casing, and tension leg platform (TLP) tendons where loading derived from fixed structural and dynamic service loads (e.g., wind, wave and current loading, vortex shedding, and temporary loadings) generates complex static, dynamic, and cyclic stresses that must be resisted. When applied to tubulars driven into the seafloor, static and cyclic axial loading arising from large compressive and pile driving loads sustained within the connection and tubular body must also be well understood by the designer and accommodated in the resulting design.

To date, a great deal of work has been performed on the structural capacity determination of continuous tubular members, both critical and non-critical, subjected to high axial tension, compression, bending, pressure, or a combination of these loadings. Structural tubular studies that consider individual joint connections, threaded or otherwise, have focused on casing, tubing, line pipe, risers, and TLP tendon connections, and usually consider only application-specific loadings that typically include high tensile forces. One proposed application of threaded tubular members is in caissons, where the tubular body typically provides the sole support for the structure (monopod), and may be required to resist large axially compressive forces coupled with bending and fatigue loads. For such structures, the penalty of a failure is quite severe, resulting in the loss of a supported platform, attendant equipment, or personnel.

In an effort to better understand the specific use of threaded connections in primary structural applications involving tubular members subjected to combined compression and bending, Southwest Research Institute (SwRI) initiated a study for the Minerals Management Service (MMS) to determine the feasibility of applying threaded connections in the fabrication of offshore free-standing caisson platforms. SwRI worked under the guidance of MMS, who provided sole support for the study, to assess both the technical feasibility and potential for industry acceptance of applying threaded connections within the caisson body as an alternative to welded girth connections. The first phase of the two-phase study, reported herein, included generalized analytical assessments of the structural performance of standard thread designs, a review of commercially available high performance thread designs, manufacturing to decommissioning issues, and an evaluation of current technical practices and existing regulatory guidelines for the design, analysis, and validation of caissons structures and threaded connections. To define direction for the second phase of the study, elemental technical guidelines for the application of threaded connections in caisson assemblies, and recommendations for validation of the approach were also developed. The validation work to be performed in phase two of the study is planned for the 1999 fiscal year.

1.1 MOTIVATION

As discussed in Section 1, motivation for the current study was derived from potential economic advantages related to the installation and removal of threaded caisson structures, and, subsequently, from the need to better understand technical performance characteristics required to implement such designs. Each of the motivating factors is further described in the following paragraphs.

1.1.1 Economic

The principal economic motivation is a possible reduction in installation and eventual removal costs. The welding of large girth connections on site, as is often required with most caisson assemblies, is costly due in part to the expense of attendant equipment needed. Additionally, when complete structures are assembled onshore, towing to the installation site and righting can also be costly, especially when the expense of large floating rigs necessary to perform the installation is considered. The ability to easily retrieve a design from service can reduce costs associated with attendant equipment.

Re-certification of the structure for use at an alternate location is appealing since it avoids the necessity for, at a minimum, fabrication of a new structure. Moreover, it is envisioned that following successful retrieval of the structure, damaged components in a threaded connection design can be simply removed from the assembly and replaced by a newer component. Thus, the need to fabricate an entire structure due to failure of an individual component is averted.

1.1.2 Technical

Having realized the possible economic benefits, the technical feasibility of using threaded connections in caisson structures must be addressed. Technical concerns related to their use are primarily focused on ascertaining that the resulting structural performance and reliability of the connection meets or exceeds that of in-service girth welds. The ability to conduct this evaluation without the exacting guidance, which is available for common tension driven design codes, requires that some criteria be developed and proven effective for caisson applications.

Ultimately, the ability to actually retrieve a design from service and re-certify its use must also be considered.

1.2 PROGRAM OVERVIEW AND OBJECTIVES

The program has been structured to accomplish two primary objectives: (1) to perform the complete evaluation of technical aspects related to the design, analysis, and verification of caisson structures with threaded connections, and (2) to provide a preliminary appraisal of current practice and the potential for industry acceptance and use of threaded connections in caisson construction following establishment of proven design guidelines. Work task descriptions for the phase one program are given in the following sub-sections (Sections 1.2.1 through 1.2.5). Phase two tasks descriptions are given in Section 6 of this document. A program overview is provided in Figure 1-1.

1.2.1 Literature Search and Review

An exhaustive search and review of technical literature was performed to determine current practices for caisson and threaded connection design and evaluation. An abbreviated listing of the literature reviewed in contained in section 7. The review included design guidelines (provided by API and others), numerous proceedings of pertinent technical conferences and published texts related to many aspects of design, analysis, and validation of threaded connections. The review focused on the definition of current practices related to the development of both caisson structures and threaded connections, which was provided primarily by the guidelines and open literature. Text books provided fundamental engineering models and assessment procedures that assisted the development of generalized guidelines for the extension, or enhancement of existing practices to the proposed use of threaded connections.

1.2.2 Survey of Current Practice

To supplement information obtained in the literature search and review, personal interviews with caisson designers and threaded connection manufacturers were performed. In all, three caisson design firms, three threaded connection manufacturers, and two operators were interviewed. Useful information gained is reported in Section 3 through Section 6.

In addition to the personal interviews, a written survey was developed and distributed to multiple caisson operators and designers. (A copy of the survey form is contained in Appendix A.) Information requested by the survey included existing design geometries and loadings, installation methods, numbers of current installations, and personal comments related to the potential implementation of threaded connections in future installations. Existing caisson data obtained was used to guide the development of recommendations for phase two work, and general design guidance (Section 6). Personal comments were most useful in assessing industry interest in the continued development of technical guidelines.

1.2.3 Define Analysis Methodology and Considerations

Results of the work tasks described in Sections 1.2.1 and 1.2.2 were used in the evolution of a comprehensive index of design parameters, loadings, and special considerations, and analysis and validation protocols for caissons and threaded connections. Also included in this index are existing codes which may be directly applied or extended to the development of threaded connections for caisson structures. Various aspects of the index are reviewed in detail in Sections 3 through 6.

1.2.4 Threaded Connection Design and Analysis

Following development of the design index described in Section 1.2.3, each element of the design, analysis, and validation of caisson structures and threaded connections were technically reviewed to assess accuracy and applicability of the techniques when applied to caissons with threaded connections. Any deficiencies in the current procedures when extended to the proposed application were identified, and recommendations developed for their inclusion in general guidance. Section 5 outlines the additional considerations to be addressed for caisson designs employing threaded connections.

1.2.5 Validation Scope of Work Preparation and Recommendation for a Code or Standard

The final task in phase one of the program outlined a general and preliminary plan for the design, analysis, and validation of threaded connections for caisson structures that can be further verified through the completion of phase two activities. Each of these topics is discussed in Section 6. Key elements needed to complete the technical evaluation of the proposed application for threaded connections are outlined for the phase two validation scope of work. When complete, verification information will be available for the development of more formalized guidance, likely based on the preliminary plan.

1.3 FOCUS OF PROJECT WORK

The feasibility assessment focused on the development of general considerations for the use of non-specific threaded connections in offshore structural caissons. To this end, *worse case* engineering assumptions were employed in most design considerations, to provide a lower bound evaluation of the performance that could be anticipated for a given design, although some effort was expended on reviewing improved designs. (Section 1.3.1 discussed the assumptions used.) Therefore, preliminary guidelines for the design, analysis, and validation of threaded connections for the proposed application are necessarily general, and focus solely on the evaluation of design performance. Specific guidance regarding safety factors used in design is to be assigned by regulatory agencies. No effort to provide design failure criteria was attempted. Section 1.3.2 further discusses the guidance provided.

1.3.1 Technical Considerations

Offshore platforms that incorporate a single structural caisson member are categorized as minimum structures, where manning is infrequent. Such a structure consists of the caisson itself and usually includes a boat landing and some type of deck structure, upon which wellhead equipment is placed. They may be guyed, braced, or free-standing. The structure typically encompasses one large tubular member, usually 3-6 feet in diameter, that supports one or more wells, and is often installed in relatively shallow water. Caisson members may also be used in the construction of multi-leg platforms, where three or more caissons are used to support a large offshore operation. Because of the structural redundancy, or added structural capacity present in guyed, braced, and multi-leg designs, the current study has focused on the evaluation of free-standing, or monopod, caisson structures where the associated loading demands generally represent a “worst case” scenario. For this condition, all pressure, axial, and bending static and cyclic loading must be supported by the single tubular without the assistance of support structure, and without redundancy. Failure of the caisson in this case results in catastrophic failure of the entire structure. A typical monopod caisson structure is shown in Figure 1-2.

Various mechanical connections are commercially available for use with tubular goods offshore. These connections are used to join individual lengths of the tubular goods and include connections of the following types [API Spec 16R, Buitrago 1998]:

- threaded or grooved pin and box assembled by torque and radial interference,
- flanged connectors assembled by threaded fasteners,
- dogged connectors that use radial wedges between the pin and the box, and
- collet connectors assembled by impinging friction or grip.

In addition to these, intrusively threaded pipe has been used successfully in casing applications and has been proposed for caisson applications. During the study, connections of the “threaded or grooved pin and box assembled by torque and radial interference” (referred to in subsequent discussions as an external coupling), as well as intrusively threaded pipe connections, were used to provide basic information on the design, analysis, and verification of threaded connections for caisson applications.

Currently, high performance thread manufacturers conduct testing and analysis of their own proprietary designs for customers. Based on industry surveys, caisson manufactures and designers are unlikely to design their own threaded connections for an individual application due to the cost of proof testing and analysis. However, the guidance developed in the study (discussed in Section 1.3.2) should be widely applicable to all threaded connections designed and evaluated by a commercial high performance thread manufacturer or otherwise. Thus, lower bound standard thread designs, that excluded highly optimized thread patterns, were assessed. High performance designs, such as those commercially available, were only cursorily reviewed in the study.

Only the threaded connections of the two types discussed above were considered for caisson applications in the study. (See Figure 1-3.) Collet type connections, which are most similar to the threaded connections reviewed, were only cursorily examined due to their generally more complex design, sometimes proprietary nature, and their noted nonlinear behavior. Flanged and dogged connections were not included in the study, although they can be designed to withstand loadings offshore.

1.3.2 Guidance Provided

As stated in the introductory comments to Section 1.3, the guidance to be provided in this document is intended to be general and preliminary, and strictly focuses on computations and considerations for the design effort. Specific guidance regarding safety factors used in design is to be assigned by regulatory agencies. Failure criteria, such as that provided in American Petroleum Institute Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms [API RP 2A] is not addressed in this document. Such design codes strictly specify the criteria that must be met by the design for use in a particular application. Hence, following verification activities in phase two of the program, more formalized guidance may be evolved which can be used to develop a design, and the existing codes or standards employed to determine acceptability of the design.

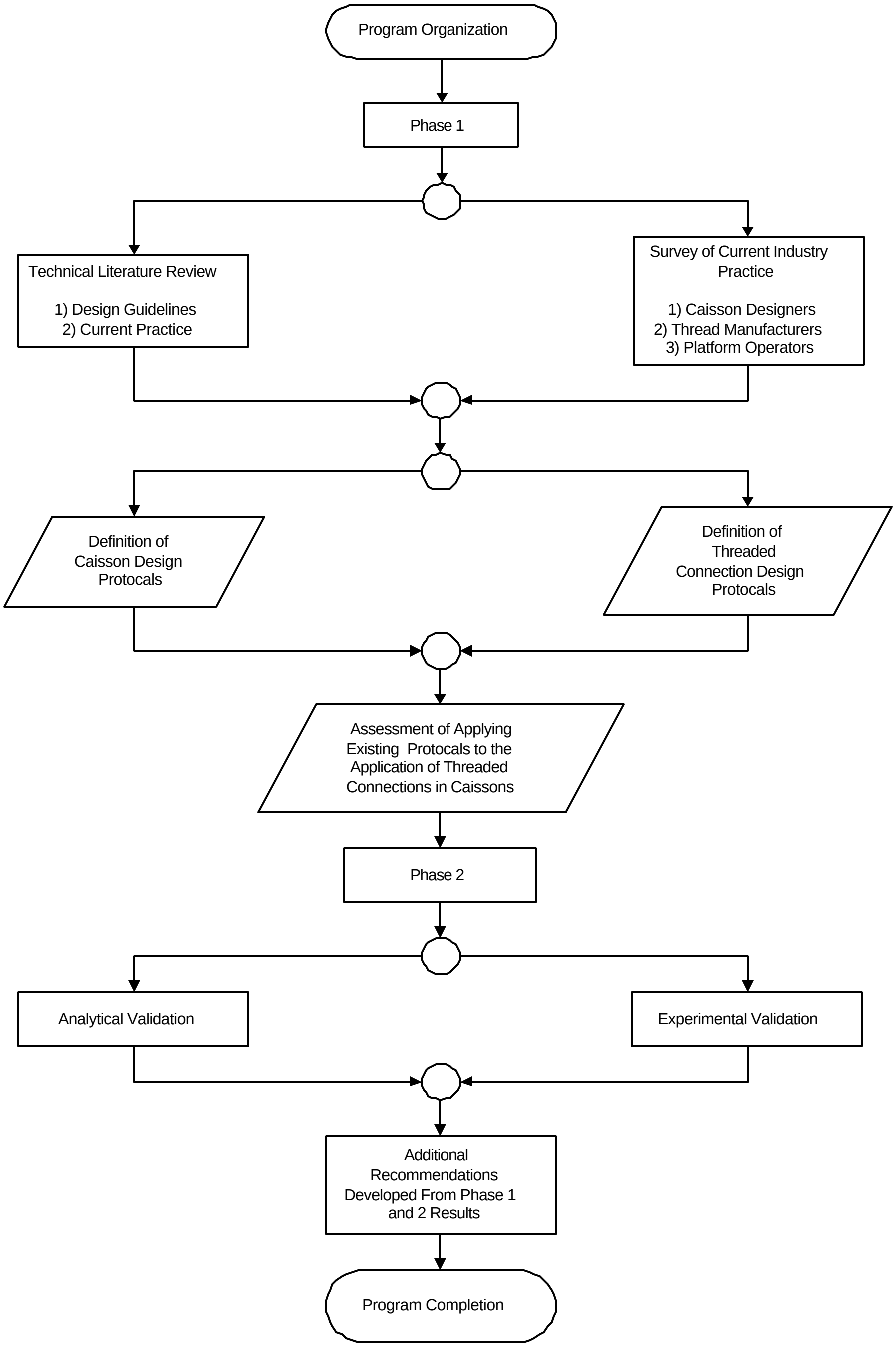

Figure 1-1. Overview of program organization.

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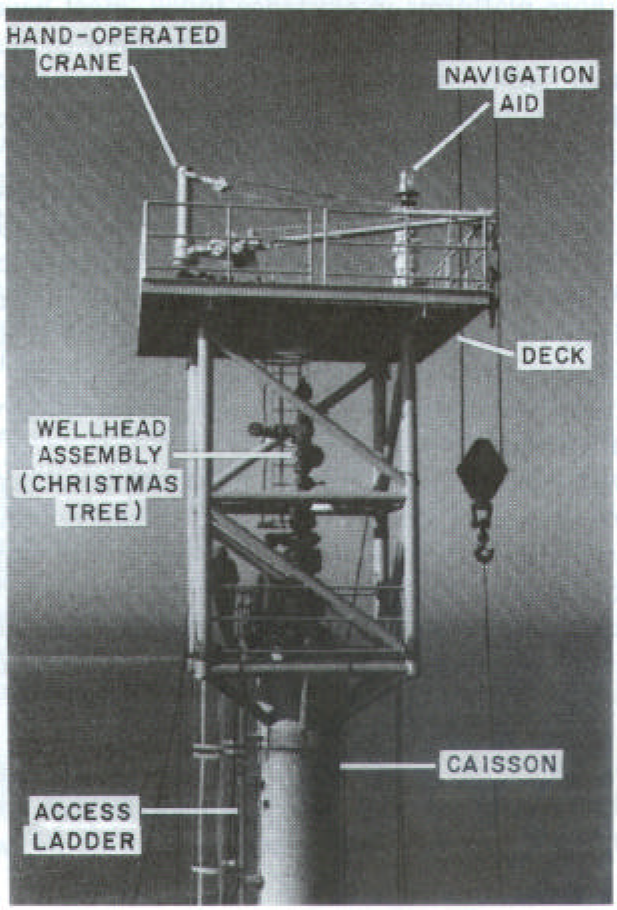

Figure 1-2. Typical caisson well-guard platform. [Drawe and Riefel, Ed. McClelland and Riefel, Copyright © 1986 by Van Nostrand Reinhold Co., Inc.]

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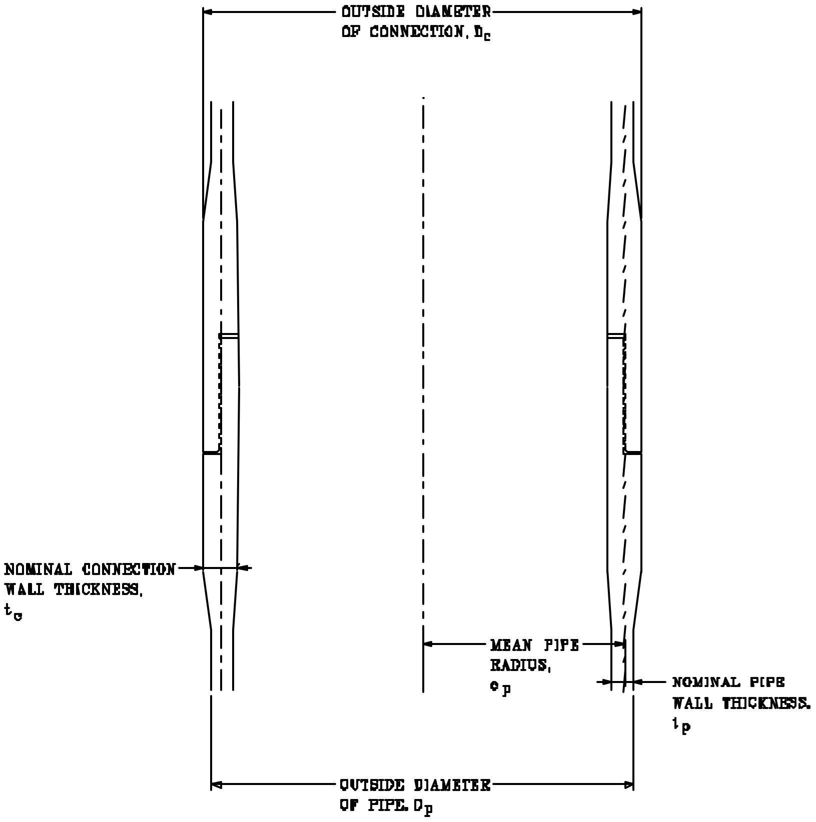
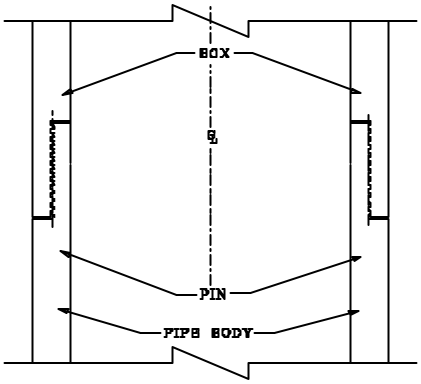


a. External coupling threaded connection.



b. Intrusively threaded pipe connection.

Figure 1-3. Threaded connections considered in feasibility study.

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2. REPORT TERMINOLOGY AND NOMENCLATURE

All terms and units (in parenthesis) used in the discussions, equations, figures, and tables within this document are defined in the following sections.

2.1 LOADING AND RELATED PARAMETERS

F_A	Total applied axial force, tensile or compressive (kips), see Figure 2-1
W_P	Platform weight, see Figure 2-1
F_P	Connection axial pre-load (kips)
W_W	Wave, wind, and current loading (kips), see Figure 2-1
M_B	Bending moment (kip-ft)
M_C	Bending moment at connection (kip-ft)
F^M	Membrane load acting a thread root (ksi)
$\mathbf{d}$	Column eccentricity (inches)
P_I	Internal pressure for design (ksi)
P_E	External pressure for design (ksi)
P_F	Friction capacity of pile (ksi), see Figure 2-2
P_B	Bearing capacity of pile (ksi), see Figure 2-2
d	Depth of water (ft), see Figure 2-1
d_P	Depth of piling (ft), see Figure 2-2
x	Caisson location (grid number)
P_{EQV}	Equivalent axial load simulating bending moment (kips)

2.2 PIPE BODY AND THREADED CONNECTION PARAMETERS

straight profile	Thread form protrudes from a cylindrical surface
tapered profile	Thread form protrudes from a conical surface
SCF	Stress Concentration Factor: Ratio describing an elevated (maximum) stress level relative to an average (nominal) stress
FCL	Fatigue Critical Location
external upset	Variation in outer diameter between the nominal pipe body and a welded on connection, see Figure 2-3a
internal upset	Variation in inner diameter between the nominal pipe body and a welded on connection, see Figure 2-3a
pin	Connection member having external threads, see Figure 2-3a
box	Connection member having internal threads, see Figure 2-3a
shoulder	Load bearing surface adjacent to threaded region
lead	Axial distance a threaded part travels when rotated one turn in its mating thread
pitch	Axial distance measured between corresponding points on adjacent threads, see Figure 2-3a
root	Surface of a thread defined along the cylinder or cone from which the thread protrudes that joins the flanks of adjacent thread forms, see Figure 2-3a
flank angle	The angle made between a given flank and the perpendicular to the axis of the thread as measured in the axial plane, see Figure 2-3a
helix	A three dimensional curve with one or more rotations about an axis

runout	Circular variation of the major and minor cylinders with respect to the pitch cylinder caused by factors such as eccentricity and out-of-roundness
axisymmetric	A geometry defined in a cylindrical coordinate system that has no dependence on the circumferential direction

D_P	Outside diameter of pipe body (inches), see Figure 2-3b
t_P	Nominal wall thickness of pipe body (inches), see Figure 2-3b
c_P	Mean pipe body radius (inches), see Figure 2-3b
A_P	Pipe body cross sectional area (in^2), see Figure 2-3a
I_P	Moment of inertia of pipe body (in^4)
$\acute{o}_{YP}$	Yield strength of pipe body (ksi)
S_X, S_Y, S_Z	Linearized stress components in global X, Y, and Z directions
$\boldsymbol{T}_{XY}$, $\boldsymbol{T}_{YZ}$, $\boldsymbol{T}_{ZX}$	Average shear stress components in global X, Y, and Z directions
$\overline{S}$	Von Mises equivalent stress (based on linearized and averaged stress components)
S_P	Stress in pipe body (ksi), see Figure 2-4
S_{Pr}	Stress range (between maximum and minimum stress levels) in the pipe body (ksi)
S_{Pr}^{A}	Stress range between maximum and minimum axial stress levels in the pipe body (ksi)
S_{Pr}^{B}	Stress range between maximum and minimum bending stress levels in the pipe body (ksi)
S_{Pr}^{P}	Stress range between maximum and minimum pressure levels in the pipe body (ksi)
e_P	Nominal strain in the pipe body (in/in)

D_C	Outside diameter of connection (inches), see Figure 2-3b
t_C	Nominal wall thickness of connection (inches), see Figure 2-3b
σ_Y	Yield strength of connector material (ksi)
σ_U	Ultimate strength of connector material (ksi)
σ	Local stress at critical location in connection (ksi)
σ^M	Membrane component of stress at critical location in connection (ksi)
σ^B	Bending component of stress at critical location in connection (ksi)
σ_{ij}	Stress tensor at critical location in connection (ksi)
σ_{ij}^{MAX}, σ_{ij}^{MIN}	Local stress tensors at minimum and maximum load application at critical location in connection (ksi)
$\Delta\sigma_{ij}$	Change in stress tensors (between minimum and maximum load applications) at critical location in connection
$\sigma_1, \sigma_2, \sigma_3$	Principal stress components at critical location in connection (ksi)
$\Delta\sigma_1, \Delta\sigma_2, \Delta\sigma_3$	Change in principal stress components (between minimum and maximum stress levels) at critical location in connection (ksi)
$\bar{\sigma}$	Equivalent stress at critical location in connection (ksi)
σ_{MAX}	Local stress at critical location in connection under maximum applied load (ksi)
σ^P	Local stress at critical location in connection under applied pre-load load (ksi)
σ_{MAX}^P	Local stress at critical location in connection under pre-load and maximum applied load (ksi)

ó_{r}	Range in local stress (between maximum and minimum stress levels) at the critical region in the connection (ksi)
ó_{m}	Mean local stress (average of maximum and minimum stress levels) at the critical region in the connection (ksi)
ó_{a}	Amplitude of local stress (from mean value to maximum or minimum) at the critical region in the connection (ksi)
ó_{a1}, ó_{a2}, ó_{a3}	Amplitude of principal stresses (from mean value to maximum or minimum) at the critical region in the connection (ksi)
$\bar{\text{ó}}_{a}$	Amplitude of local stress (from mean value to maximum or minimum) at the critical region in the connection based on effective stress calculation (ksi)
$\bar{\text{ó}}_{aREV}$	Fully reversible amplitude of local stress (from mean value to maximum or minimum) at the critical region in the connection based on effective stress calculation (ksi)
$\bar{\text{å}}_{aREV}$	Fully reversible amplitude of peak local strain (from mean value to maximum or minimum) at the critical region in the connection (ksi)
ó_{m1}, ó_{m2}, ó_{m3}	Mean principal stresses from static loading at the critical region in the connection (ksi)
$\bar{\text{ó}}_{m}$	Effective mean stress from static loading at the critical region in the connection (ksi)
ó_{r}^{e}	Elastic local stress range (between maximum and minimum applied stress levels) from finite element analyses (ksi)
ó_{r}^{ep}	Elasto-plastic local stress range (between maximum and minimum stress levels) from transformation of local elastic stress range (ksi)
ó_{p}	Peak local stress at maximum or minimum applied stress level, see Figure 4-7
ó_{p}^{e}	Elastic peak local stress from finite element analyses (ksi)

ó_{p}^{ep}	Elasto-plastic peak local stress from transformation of elastic local stress (ksi)
ó_{m}^{ep}	Elasto-plastic local mean stress from transformation of elastic local stress (ksi)
ó_{m}^{e}	Elastic local mean stress finite element analyses (ksi)
S	Nominal stress in the critical thread root cross section (includes membrane and bending contributions) (ksi)
S^{M}	Membrane stress in the critical thread root cross section (ksi)
S_r	Stress range (between maximum and minimum stress levels) in the critical thread root cross section (ksi)
S_r^{M}	Membrane stress range stress (between maximum and minimum stress levels) in the critical thread root cross section (ksi)
A_C	Cross-sectional area at critical thread root (in^2), see Figure 2-4
K_t	Stress concentration factor at critical location in connection based on pipe body stress
K_t'	Stress concentration factor equal to ratio of local stress in critical thread region and membrane stress in cross section of critical root region
K_t''	Stress concentration factor equal to ratio of local stress in critical thread region and nominal stress in cross section of critical root region (includes membrane and bending)
K_t^{D}	Dynamic stress concentration factor due to cyclic loading, and based on nominal pipe body stress
$K_t^{D,A}$	Dynamic stress concentration factor due to cyclic axial loading, and based on nominal pipe body stress
$K_t^{D,B}$	Dynamic stress concentration factor due to cyclic bending, and based on nominal pipe body stress
$K_t^{D,P}$	Dynamic stress concentration factor due to cyclic pressure loading, and based on nominal pipe body stress
k_t	Stress concentration factor based on Neuber's Rule

k_s	Stress amplification factor for Neuber’s Rule
k_e	Strain amplification factor for Neuber’s Rule
e	Local strain at the fatigue critical location
K_f	Fatigue notch factor
q	Notch sensitivity factor
ρ	Notch radius (inches)
α	Material constant for fatigue notch sensitivity factor calculation
N_f	Number of cycles to failure
N_i	Total number of cycles at incident *i*
N_{fn}	Number of cycles to failure at incident *i*
E	Modulus of elasticity for connection (ksi)
b	Fatigue strength exponent for connection
c	Fatigue ductility exponent for connection
$\acute{o}'_f$	Fatigue strength coefficient (ksi)
$\tilde{\tilde{o}}_f$	True fracture strength (ksi)
$\mathring{a}'_f$	Fatigue strain coefficient
H'	Cyclic strain hardening coefficient for the connection
n'	Cyclic strain hardening exponent for the connection
a	Instantaneous crack length (inches)
a_d	Minimum detectable crack length (inches)
a_c	Critical crack length (inches)
DK	Change in stress intensity
F	Dimensionless function of the ratio of crack length to width of component in direction of crack

K_{max}, K_{min}	Stress intensity a maximum and minimum stress levels
$\frac{da}{dN}$	Cyclic crack growth rate (inch/cycle)
C	Constant used in regression curve for $\frac{da}{dN}$ versus DK
m	Slope of the log-log plot of $\frac{da}{dN}$ versus DK
S_c	Strength of cracked region

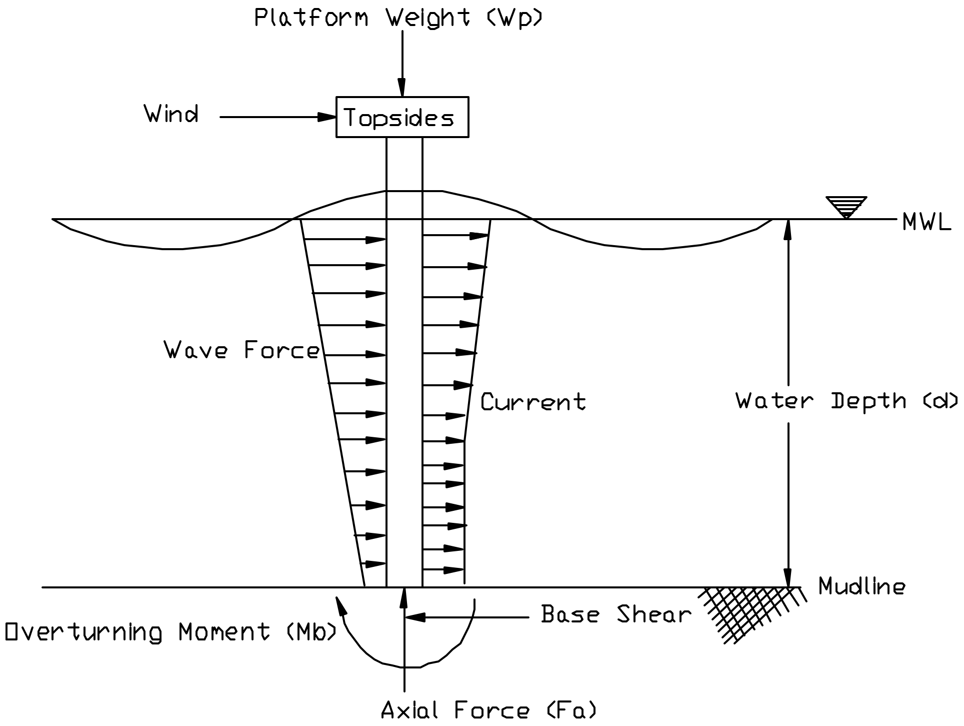

Figure 2-1. Minimal structure geometry and applied loads above mudline.

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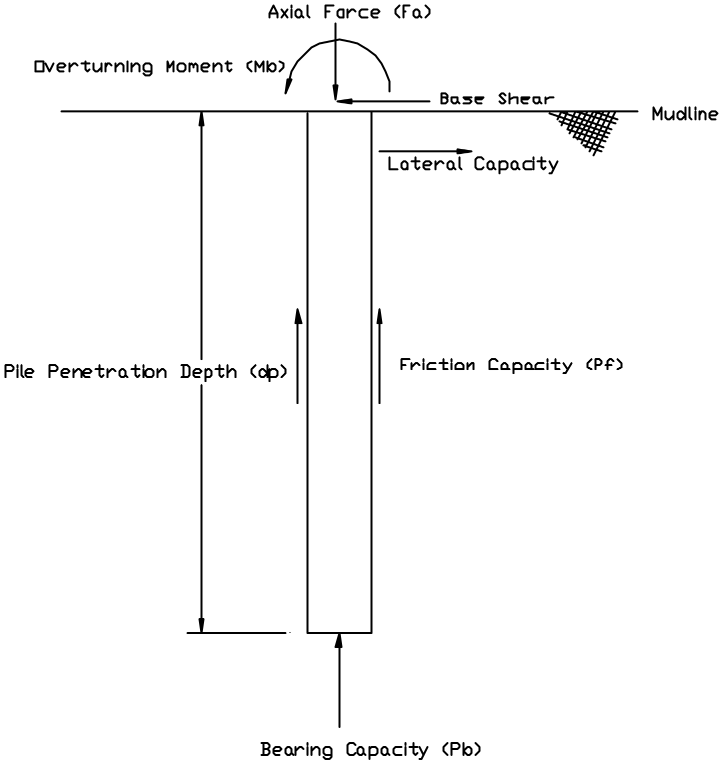

Figure 2-2. Minimal structure geometry and applied loads below mudline.

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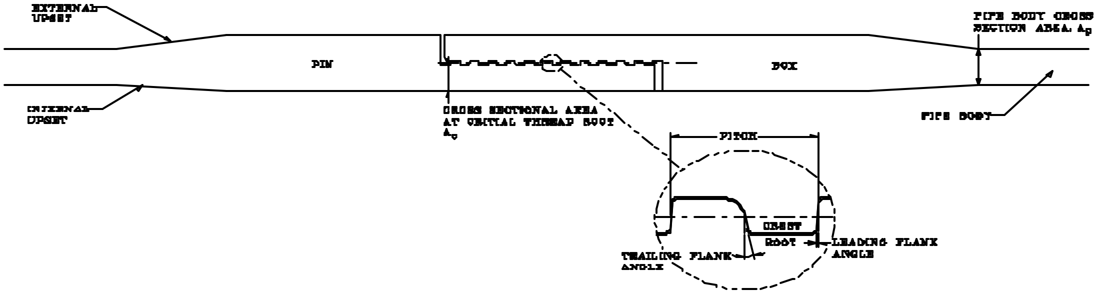
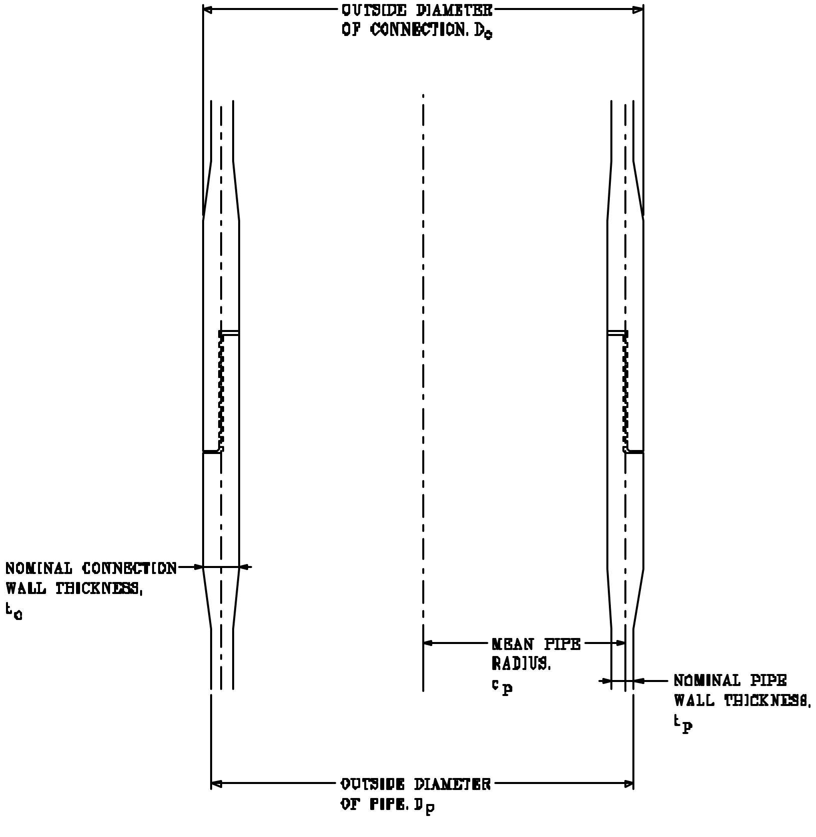


a. Thread details.



b. Nominal section details.

Figure 2-3. Threaded connection and nominal pipe geometry description.

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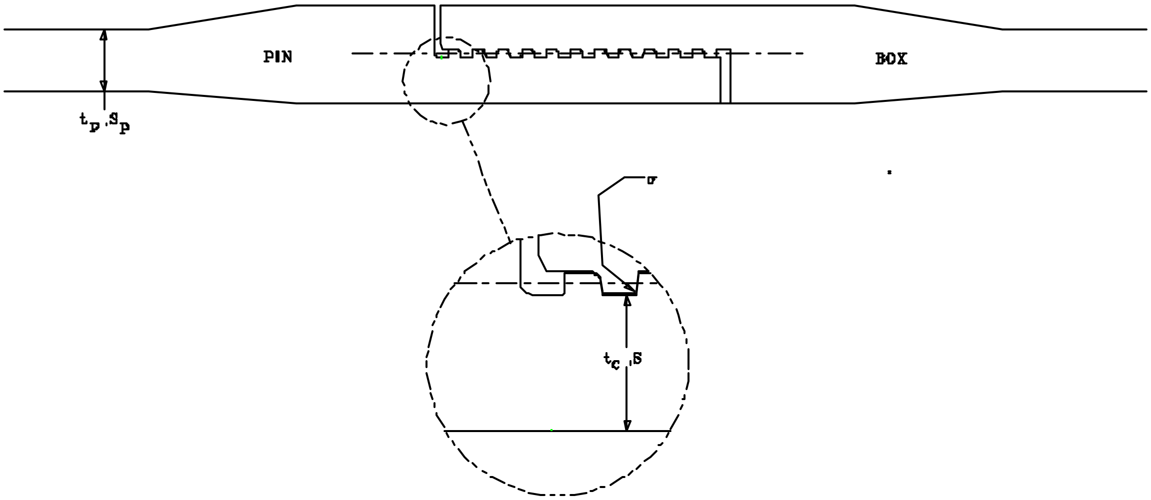

Figure 2-4. Important stress locations.

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3. EXISTING CAISSON DESIGN PRACTICE

Existing caisson design is well proven offshore. In fact, many of the existing regulations that govern design of such structures are based on experience gained over time. What follows is a discussion of general caisson design issues, existing regulations and guidelines, other related areas, such as analysis and validation, and a survey of actual in-service practice.

3.1 DESIGN

As in the design of any structure, geometric and material parameters govern the adequacy of the design to resist imposed loads and constraints. For offshore structures, these design parameters must be clearly identified and matched to the anticipated application and location, which ultimately define the load type, magnitude, and cyclic loading action. In addition, offshore installation requirements, such as transportation and pile driving, must be considered since the in-service life of the structure could be affected by installation loads and cyclic stress waves produced during driving. Finally, reuse of the structure may necessitate additional fatigue considerations and a thorough assessment prior to removal and reinstallation. Figure 3-1 outlines the stages used in the development of a caisson design, as presented in this section.

3.1.1 Offshore Caisson Applications

An offshore caisson typically defines a large diameter tubular member that may or may not be flooded. The caisson usually provides protection to more vital piping and tubing and it may provide structural strength to an offshore platform in relatively shallow water. In some instances, a smaller diameter structural well conductor may provide sufficient protection and some load-bearing capacity. In this case, the annulus between the conductor and the internal piping is usually grouted. A platform employing such a conductor would likely have some type of supporting structure to assist in carrying loads. Otherwise, the conductor (and/or casing) would be housed and protected on the inside of the caisson.

A minimum structure is characterized by a lower consequence of failure and a corresponding reduction in structural redundancy. Free-standing caisson platforms, occasionally called monopods or well-guard platforms (One is shown in Figure 1-2.) where the caisson forms the primary structure and protects one or more wells, are specifically identified by API RP 2A as minimum structures. These platforms may support well head and limited production equipment on their deck, a heliport, and a boat landing.

In addition to free-standing configurations, caisson platforms may also be guyed or braced for added lateral support. From a structural standpoint, though, design of a free-standing caisson platform will be considered “worst-case” due to the lower structural stiffness provided by the sole load-bearing member, the caisson. To increase structural integrity and possibly access deeper water depths, multileg platforms may incorporate multiple caissons.

3.1.2 Design Philosophies

As mentioned, most caisson platform designs are built upon prior in-service experience with minimum structures. However, special consideration of connection strength, connection flexibility, increased structural dynamics, and generally reduced design redundancy must be made. This is weighed against the consequences of failure, which are usually less with minimum structures. Specific characteristics of free-standing caisson platforms that also factor into the design philosophy are discussed below.

3.1.2.1 Single and Tapered Diameters

Most early caisson designs, and particularly those in shallower waters, employed a uniform diameter throughout the caisson length. This type of caisson can simplify the design. However, to reduce environmental loading in the wave zone, a tapered caisson design has often been adopted. This is commonly seen in deeper water applications, where a wider, supportive caisson base is also needed at the mudline. Tapered design will produce stress concentration in the tapered region and varying structural stiffness, and, hence, should be considered during the design effort.

3.1.2.2 Connections

As in most large tubular steel structures, individual pipe sections—often referred to as joints—are formed into a long tubular member by circumferential girth welds. This type of weld is typically assumed to be of equivalent strength to the body of the tubular through a process of weld certification, which includes filler rod material specifications, welder qualification, and non-destructive evaluation of critical welds. No other analysis of the welded connection or its effect on structural stability is performed. Of the caisson-related applications mentioned above, only well conductors and casings exhibit widespread use of non-welded connections between the individual tubular sections.

3.1.3 Caisson Design Parameters

Figure 2-1 displays some of the key design parameters and loads that are involved in the design of a free-standing caisson platform. Location is a major factor that determines all of the environmental loads, the water depth, and the seafloor soil characteristics. Thus, location drives the selection of design parameter values, which are somewhat interrelated themselves, as shown in Table 3-1. A discussion of these parameters follows.

3.1.3.1 Water Depth, d

The water depth at the location, rarely more than 100 feet for a free-standing caisson, and the height above mean water level determine the unconstrained length, upon which environmental loads act. The unconstrained length has a direct effect on global static and dynamic response.

3.1.3.2 Penetration Depth (of Caisson into Seafloor), d_P

The penetration depth, usually greater than 100 feet, is dependent on the seafloor soil characteristics and the loads experienced by the structure at the installed location. The total length, which equals the unconstrained length plus the penetration length, may factor into decisions regarding fabrication and installation methods and may also have an effect on installation loadings, such as lifting.

3.1.3.3 Nominal Outside Pipe Diameter, D_P

Nominal outside diameters of caissons typically range from 3 to 6 feet. Selection of the diameter will be influenced primarily by global response limitations, such as dynamic behavior. Other dependencies are the service application and associated equipment requirements, characteristics of the location, and installation protocol. Moreover, any geometric restrictions (e.g., size and number of well conductors to be contained within the caisson) must be considered, as well as the ability to manufacture the selected size within required tolerances.

3.1.3.4 Nominal Pipe Wall Thickness, t_P

Similar to the caisson diameter, wall thickness selection is also a function of location characteristics, service application, installation protocol, and geometric restrictions. Additionally, wall thickness is dependent upon material strength and the ability to fabricate large diameter pipe because of limitations on rolled plate materials.

3.1.3.5 Yield Strength of Pipe Body, s_{YP}

Pipe material yield strength and thickness can be varied inversely to achieve similar pipe body strength characteristics. Though, one concern with high strength steels is fracture toughness. Generally with steel, as yield strength increases, fracture toughness decreases. Yield strength of the pipe body also governs the ultimate strength of the caisson platform.

3.1.4 Caisson Design Loads

In general, the caisson platform should be designed for loading conditions, including the combination of loads, which produce the most severe effect on the structure. These include loads imposed during installation, such as driving loads, and after installation, such as environmental, operating, and eventual removal loads.

3.1.4.1 Installation

Significant loading can be experienced when transporting the newly assembled structural components to the installation site. These loads may be due to towing and lifting. In addition to transportation loads, actual installation loads themselves, which might include additional lifting and pile driving, must be considered. The installation process will be discussed further in Section 3.1.5.1.

3.1.4.2 Environmental

Wind loading is focused upon the deck structure of the platform. This can lead to significant bending moments and possibly torsional loads during storm conditions because of the unconstrained length of the caisson.

Wave loading acts toward the end of the unconstrained length of the caisson, again leading to significant bending moments. In addition, wave action creates near-surface currents that can load a caisson laterally below the waterline. The time-varying nature of the wave loading can lead to dynamic response and fatigue.

Current loads act laterally on the caisson. These loadings are mostly constant and taper off with depth. Large-scale thermally-driven eddy currents, called Loop Currents, can develop in areas such as the Gulf of Mexico, generating strong subsurface currents that may be a consideration; although, these currents are usually encountered in deeper water, where caisson platforms are not employed.

3.1.4.3 Operating

Live (dynamic) operating loads can be generated when the platform is manned, especially during boat landings and helicopter transfers. Therefore, impact loads may be a concern during these specific actions. Dead (static) loads, such as platform weight and topside equipment, are primarily due to the weight of the structure and supported equipment. Both of these loads are relatively minor compared to the environmental loads, especially in deeper waters.

3.1.4.4 Removal

Loads associated with removal of the platform are generally only a concern if the platform is to be reused or if lifting large components, where failures of a partially assembled caisson could lead to damage, injuries, or loss. Removal is discussed further in Section 3.1.5.3.

3.1.5 Other Design Considerations

Specific considerations during the design process must be made to account for infrequent occurrences, such as during installation, any type of required inspection or assessment, and removal.

3.1.5.1 Method of Installation

Two scenarios are most common for caisson platform installation. The first involves construction of the total caisson length in the construction yard. The complete caisson is then sealed at both ends and towed to the installation site. The second scenario involves connecting relatively short sections, or joints, which are typically 40 feet or less, together at the installation site until the total caisson length is formed. Additionally, a combination of the two approaches may be taken, where a length equivalent to the penetration depth and some of the water depth is assembled in the yard and the total length is completed on site. Care should be taken during the transport of the caisson to the site so that mechanical damage of the pipe body or connections does not occur.

Once at the site, the caisson may be installed by driving it into the seafloor or by jetting the mud from the inside of the caisson, allowing it to progressively settle into the seafloor. Fully assembled caissons are flooded in a controlled manner and allowed to sink to the seafloor prior to driving or jetting. Partially assembled caissons are built up from the seafloor. As the driving or jetting occurs, additional joints must be added to achieve the total length of the assembled caisson. These installation procedures must be accounted for in the design of the caisson.

3.1.5.2 Inspection

In addition to standard inspection of critical welds during fabrication, usually with radiography, consideration should be given to the potential for in-service inspection, and/or post-service assessment prior to reuse. Focus should be upon corrosion and cracking, if evident.

3.1.5.3 Removal

Essentially the reverse of installation, removal plans should included disassembly, removal of the deck, removal of the structure from the seafloor, and transportation. If eventual reuse is planned in advance, the initial caisson design should consider the structural response to removal loadings. In addition, an assessment prior to removal and following post-mortem examinations of future expected life should be conducted.

3.1.6 Existing Regulations Pertaining to Caisson Design

The Code of Federal Regulations, Title 30, Part 250 [30CFR250] provides requirements for the design, fabrication, installation, operation, and removal of offshore platforms and structures in U.S. territorial waters, and refers to American Petroleum Institute Recommended Practice 2A, Working Stress Design [API RP 2A] for additional requirements, insofar as they do not conflict. These two documents—the latter, generally used by industry worldwide—were central in the evaluation of existing regulations pertaining to caisson design and also provided the design basis for the evaluations performed in this study. The use of other design methods for steel platforms and their associated safety criteria are allowed if it can be successfully demonstrated that such alternative methods will result in a structural safety level equivalent to that provided by the direct application of the requirements found in 30CFR250 and API RP 2A. A summary of existing regulations is provided in the following sections.

3.1.6.1 Design Loads

Design code specifications for loading scenarios are discussed in the paragraphs that follow. Unless otherwise noted, discussions outline specifications directly given by the governing documents, API RP 2A and 30CFR250.

3.1.6.1.1 Static Strength

In addition to static dead weight and equipment weight loads, the global structural forces acting upon the platform are calculated by a vector summation of the drag forces due to waves and currents and the force of the wind on exposed portions of the platform. (See Figure 2-1.) Particular consideration should be given to wave kinematics, current blockage, the effects of marine growth, and interaction with platform appurtenances.

3.1.6.1.2 Fatigue

Analyses should be performed to determine the stress range and dynamic effects of anticipated loads over the design life of the platform. Structural members and connections for which past experiences are insufficient to ensure safety from possible cumulative fatigue damage shall be analyzed fully. Additionally, emphasis shall be given to joints in the splash zone, those that are difficult to inspect and repair after the platform is in service, and those susceptible to corrosion-accelerated fatigue. For structural members and connections which require a detailed analysis of cumulative fatigue damage, and where structural redundancy to prevent catastrophic failure on the platform as a result of member or connection failure does not exist, the results of a fatigue analysis shall indicate a minimum calculated life of three (3) times the design life of the platform.

The primary source of cyclic loading is due to wave action. However, possible vortex induced vibration and live operating loads should also be considered. When a minimum structure, such as a free-standing caisson platform, is designed, the natural frequency of the structure must not correspond with that of the wave action. To assure this, minimum structures with natural periods equal to or greater than 3 seconds must be fully analyzed, taking into consideration extreme wave conditions.

3.1.6.1.3 Driving

For a driven caisson, the wall thickness should be adequate to resist stresses during pile driving. If the behavior of the soil, caisson, and hammer are known, it is possible to approximate the forces and resistances involved in driving—and, thus, the caisson stresses—using the principles of a one-dimensional elastic stress wave. A detailed discussion of this can be found in E.A.L Smith's "Pile-Driving Analysis by the Wave Equation" [E.A.L. Smith]. Installation forces shall not affect the integrity of the structure or the design life.

3.1.6.1.4 Combined Bending and Axial Loading

For tubular members subjected to axial compression and bending, allowable stress limits shall be set in accordance with a defensible formulation based on full scale testing or analysis, such as nonlinear finite element analysis followed by experimental validation. Tubular members should be proportioned to satisfy both strength and stability criteria at all points along their length. Additionally, the effects of initial stresses and geometric imperfections or discontinuities shall be considered in structural stability since the stress-strain history and imperfections can contribute to premature and catastrophic failure of the structure. For example, tubular structures subjected to highly compressive longitudinal and bending loads may exhibit localized buckling (and resultant global buckling) at the location of extreme out of roundness, extensive corrosion, or weld mismatches. Sensitivity analyses which consider the effects of geometric imperfections or discontinuities and ovality on buckling capacity can be used to define tolerances for manufacture.

3.1.6.2 Material Definition

In general, materials shall be suitable for their intended service as demonstrated by testing under relevant service conditions or previous satisfactory performance. Steels, in fracture critical members, shall exhibit sufficient toughness to guard against brittle fracture. All material used in the construction of a platform shall be described and designated by a material specification. For detailed areas of high stress concentration, consideration shall be given not only to safety against brittle fracture but also to material quality-control procedures.

According to the Commentary on Minimum Structures in API RP 2A, a freestanding caisson platform can be built out of Class C steel, where no fracture toughness requirements are imposed. This reduced material requirement has been developed from experience gained over the years with these types of structures. However, primary connections used to join tubular steel, where failure of which would cause significant loss of structural strength, should be made of Class A steel, where specified fracture toughness requirements are imposed.

3.1.6.3 Manufacturing

Fabrication of caissons by a means other than welding shall be performed in accordance with the American Institute of Steel Construction Specification for Structural Steel Buildings, Allowable Stress Design and Plastic Design (AISC ASD). In critical connections where high stress concentrations can be found, manufacturing tolerances can dictate the connection functionality and structural integrity. As mentioned in Section 3.1.6.1.4, testing and sensitivity studies can be performed to determine the effect on functionality and integrity.

3.1.6.4 Installation

The structural strength and integrity of a platform shall not be reduced or otherwise jeopardized by the performance of the activities required to install the platform on site, such as transporting to the site, lifting, and pile driving or jetting. Analyses shall be performed to determine the type and magnitude of the loads and load combinations to which the platform will be exposed during installation, and to ensure that the structural design is sufficient to withstand the loads without loss or degradation of structural integrity.

Overall dimensional tolerances, forming tolerances, and local alignment tolerances shall be commensurate with those considered in developing the structural design. Quality control inspections shall ensure that the dimensional tolerance criteria are met.

3.1.6.5 Removal

In cases where platforms are intended to be reused, the design must consider removal, transportation, and reinstallation. In addition to reuse considerations, the integrity of all platforms must be assessed prior to removal and reinstallation. Many issues relating to end-of-life assessment are contained in Supplement 1 to API RP 2A, involving a complete review of the design and assessment of the existing condition.

Plans for platform removal should be developed to describe procedures for removal of decks, appurtenances, and pilings. Emphasis should be on the prevention of damage if the platform is to be reused.

3.1.6.6 Other Design Guidance

Allowance for more complex design methods that include nonlinear effects, scale modeling and subsequent extrapolation of results to support analytical studies, and ultimate strength designs is discussed below.

3.1.6.6.1 Nonlinear Analysis

Any method of analysis that involves geometric or material nonlinear effects shall be conducted in a defensible manner. Additionally, plastic methods of design shall be employed only when the properties of the steel exclude the possibility of brittle fracture, allow sufficient plastic rotation, and provide fatigue resistance. Additionally, the effects of buckling and other destabilizing nonlinear effects shall be taken into account in the plastic analysis.

3.1.6.6.2 Model Studies and Extrapolation of Results

In many instances, full-scale testing of the large structural components associated with caisson design is too costly and difficult to perform. In addition, due to the complexity of some classical and analytical techniques, particularly fatigue life assessments, reliable data used to predict behavior is difficult to achieve. As an alternative, scale model studies shall be performed to supplement ill-defined or non-existent analytical studies, where the acceptability of the model studies depends on enumeration of possible sources of error, limits of applicability, and extrapolation to full-scale data. The ability to appropriately scale tolerances and defect sizes may be limited, and, thus, great care should be used in conjunction with good engineering judgment when designing the models and interpreting results.

3.1.6.6.3 Ultimate Strength Designs

Whenever the ultimate strength of the platform is used as the design basis of its members, the capability of the primary structural members to develop their predicted ultimate load capacity shall be demonstrated. Accordingly, material specifications for such designs should include definition of the minimum anticipated ultimate strength of the material.

3.2 ANALYSIS

Detailed analyses, particularly finite element analyses, may be performed to provide input to the design, evaluate a potential design, and to generate needed design verification information in the absence of physical test data. An example of the latter is the use of finite element and classical analytical techniques to determine the fatigue strength of a new design where physical test data is non-existent and difficult to obtain possibly due to the size of the component.

In general, beam-type analyses performed using software such as StruCAD*3D [Zentech] are used to determine the global response of the structure to the applied loads. Such analyses may be used to determine the effect and magnitude of constraint provided at the seafloor, deflected shapes, natural frequencies, and location of maximum axial and bending stresses. Once critical factors related to the design are defined in global analyses, detailed local analyses studying specific behavior of a high stress region or connection can be performed. The following paragraphs describe both the global and local analyses that may be performed.

3.2.1 Global Response

A prediction of the global response is required to assure accurate representation of the static and dynamic behavior of the overall structure. Most global analyses involve a three-dimensional finite element model composed of beam elements to characterize the static, modal, and dynamic response under wind, wave, current, and operational loadings. These analyses can later serve as the foundation for local stress analyses and fatigue life predictions. Additionally, global analyses provide the only means of determining the structures natural frequency and dynamic behavior under cyclic loads.

3.2.2 Local Response

Once the global behavior is known in terms of forces and moments or displacements and curvatures, a local three-dimensional finite element model can be constructed and analyzed for more detailed local stress levels. Typically, solid two-dimensional or three-dimensional elements are used instead of beams. This type of analysis would be used on connections to determine critical regions of stress concentration, or at critical bending and fatigue locations.

3.3 VALIDATION

Adequate validation of design predictions is necessary, unless prior evidence of successful design implementation can be proven. Thus, for new designs some type of validation is usually required. Additionally, if critical information is being obtained from local finite element analyses, validation of the analytical effort shall be obtained by measuring critical strains during testing.

3.4 EXISTING CAISSON DESIGNS (SURVEY RESULTS)

Twenty-one industry surveys were delivered to designers and operators in the Gulf of Mexico area. (See Appendix A.) Contact was initially made over the telephone to establish appropriate company personnel prior to sending the survey via facsimile. Additionally, visits to three caisson designers, three pipe threaders, and two operators in the Houston area were made. What follows is a summary of the findings.

3.4.1.1Design Parameters

As a part of the industrial survey to determine actual in-service practices (contained in Appendix A), designers and operators were requested to provide minimum, maximum, and typical values of design parameters. Table 3-2 below is similar to Table 3-1 in Section 3.1.3 and summarizes the industry values obtained from the survey.

3.4.1.2 Other Survey Design Information

Mostly free-standing caisson platforms were addressed; however, some of the information is representative of guyed caisson platforms as well. Approximately half of the caissons incorporated a tapered design with a reduced diameter in the wave zone.

All caissons were driven during installation. Installation techniques varied somewhat, but mostly paralleled what was discussed in Section 3.1.5.1. For deeper depths, most of the fabrication occurred on-shore. The large tubular was towed to the site and righted with a large lifting vessel. Additional sections were then added as the caisson was driven into the seafloor.

Survey results also yielded information regarding loading. Topside weight (i.e., deck dead weight) ranged from 5 to 370 kips, with an average of about 65 kips, acting as a static compressive force on the caisson. Pile driving hammer sizes ranged from 35 to over 300 ft-kips, with an average of about 130 ft-kips. (Note that the hammer size determines the amount of energy exerted on the caisson during each blow.) The number of hammer blows per foot ranged from 10 to 500 blows/ft, with an average of 100 blows/ft.

API RP 2A, 19th and 20th editions provide design guidance for all current designs. The American Institute of Steel Construction was also cited as a source of guidance.

Table 3-1. Key Design Parameters

Parameter	Description	Dependencies
d	Water depth	Location
d_P	Penetration depth of caisson into seafloor	Water depth, soil characteristics, loads
D_P	Nominal pipe outside diameter	Water depth, soil characteristics, loads, dynamic response and structural stiffness limitations
t_P	Nominal pipe wall thickness	Loads, yield strength
s_{YP}	Yield strength of pipe body	Loads, wall thickness, fracture toughness

Table 3-2. Industry Survey Design Values

Parameter	Description	Average	Range
d	Water depth	60 ft	5-300 ft
d_P	Penetration depth of caisson into seafloor	150 ft	70-350 ft
D_P	Nominal pipe outside diameter	48 in.	20-120 in.
t_P	Nominal pipe wall thickness	1.5 in.	0.5-2.5 in.
s_{YP}	Yield strength of pipe body	40 ksi	35-80 ksi

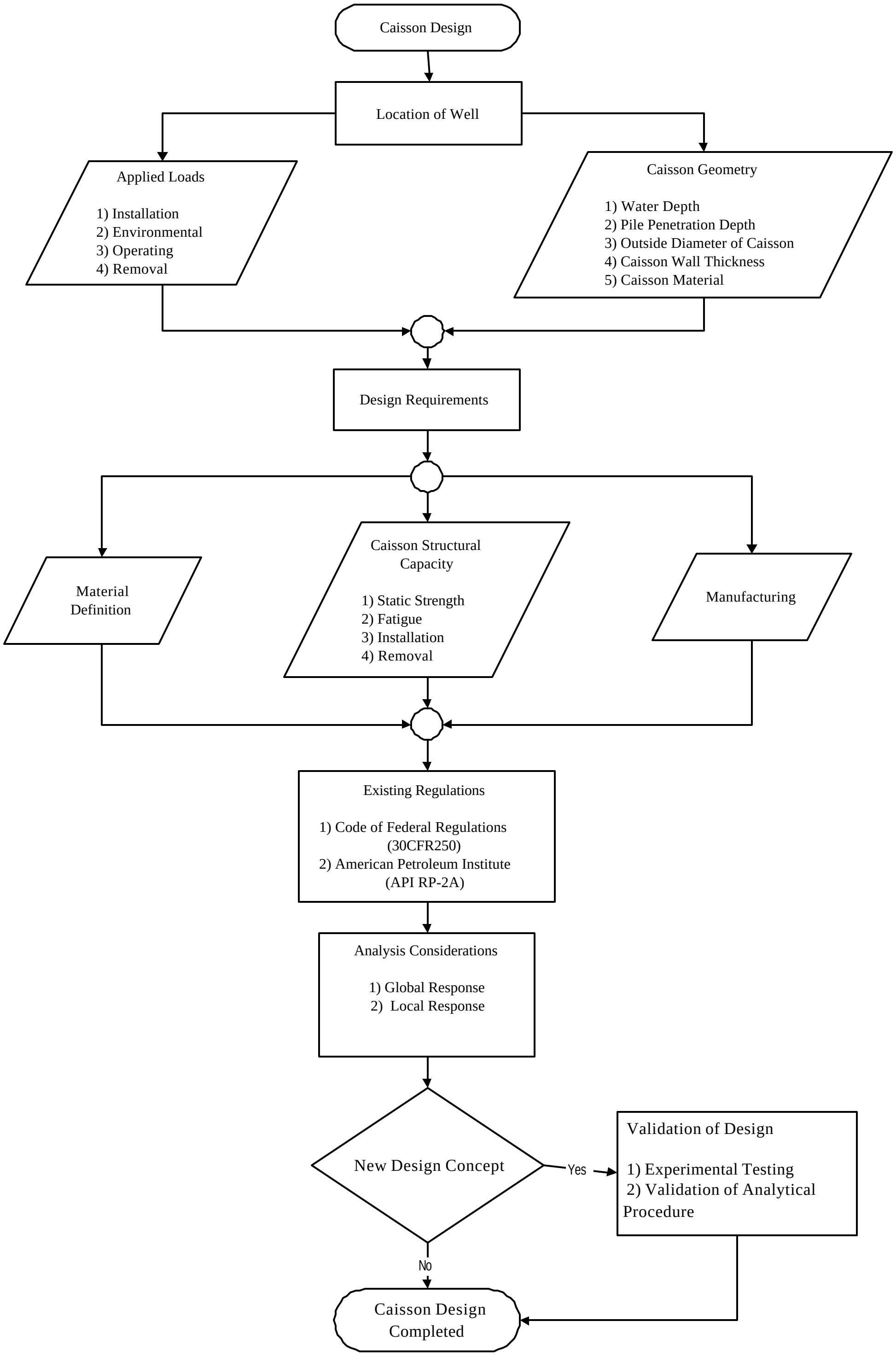

Figure 3-1. Caisson design development.

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SECTION 4 LIST OF FIGURES

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4. EXISTING THREADED CONNECTION DESIGN PRACTICE

The safety and integrity of tubular structures and structural components is dependent on the capacity of the threaded connection that may be used in their construction. With regard to offshore applications, the coupling of high static, dynamic, and cyclic loadings imposed during offshore service with the often large geometric discontinuities in the threaded region, typically leads to fatigue dominated failures, and hence, has limited the widespread use of threaded connections in primary components of marine structures.

Threaded connections designed for offshore applications have been successfully implemented by various operators for drilling and production risers, conductor and casing, and TLP tendons, as well as general tubing and line pipe applications. Although specific guidance for the design, analysis and validation of threaded connections for caisson applications is non-existent, general requirements related to the design and validation of connection capacity are given by API RP 2A. More specific guidelines and proven techniques for the evaluation of threaded connections are provided by API and open literature [API RP 5C5 and Buitrago 1998], and can be used in conjunction with the general requirements to successfully design connections for caisson applications. General requirements given by API RP 2A and applicable portions of the specific threaded connection design guidelines and practices are discussed in this section. Section 5 reviews extension of the existing guidelines and practices for threaded connections to caisson structures and presents special considerations for their successful implementation.

In addition to the review of existing guidelines and techniques for threaded connection design, analysis, and validation provided in this section, an analytical review of standard thread designs (as opposed to commonly used high performance thread designs) is outlined, as well as in Appendix B. This review provides insight into fundamental differences in performance achieved with standard designs, and helps to identify specific aspects of the thread profile, which can be optimized for improved response. Such optimizations are generally applied in the development of the existing commercially available high performance thread designs, which are also discussed in this section. Figure 4-1 provides an overview of the discussions within this section.

4.1 DESIGN

In addition to internal and external pressure, connections intended for offshore applications must be designed to withstand axial loads and bending from wave and current action, and other temporary loadings imposed by the structure, which it supports. For caisson applications, capacity of the connection must be shown sufficient to withstand large compressive loads, wind loads and temporary loading on the platform, driving loads for pile driving installations, and removal operations. Detailed consideration of the connection’s fatigue performance is paramount to successful implementation and service since known stress concentrations exist at the connection-pipe boundary (for welded mechanical connection designs) and thread roots, which may develop fatigue cracks well in advance of those produced in the pipe body subjected to similar cyclic stresses. Such locations are termed *fatigue critical locations* (FCLs), and any given design may exhibit multiple FCLs that must be evaluated for fatigue performance.

Special consideration should also be given to makeup and breakout, galling of contact surfaces, installation and decommissioning, inspection, manufacturing, sealing requirements, and the potential for strength and functionality loss from service in a free-corroding sea water environment. All loadings and special considerations for the design of threaded connections for offshore service are outlined in the following sections. Some current applications of threaded connections offshore are also reviewed.

4.1.1 Applications of Threaded Connections Offshore

Due to the complexity of loading experienced offshore, existing connection designs for such applications typically employ high performance thread profiles, which have been optimized for improved behavior in fatigue, installation, and/or decommissioning. High performance designs are reviewed in Section 4.5, and are typical of the types used in the current applications discussed in the following paragraphs.

4.1.1.1 Risers

According to API Specification 16R, a marine riser coupling provides a quick means of connecting and disconnecting riser joints. The coupling pin and box provide support to transmit the weight of the suspended riser string to the riser handling equipment while running or retrieving the riser. In addition, the coupling may provide support for choke and kill, auxiliary lines, and buoyancy. There are many different connection designs besides threaded: breech-block, collet-type, dog-type, and flange-type [API Spec 16R].

4.1.1.2 Conductors and Casing

Much of the guidance provided on conductors, casing, and tubing connections can be found in API Bulletin 5C2, 5C3, and 5C4, Recommended Practice 5C5, and Specification 5CT. These couplings are primarily threaded, using a buttress or round thread form. A large amount of experimental information exists on the strength of these connections in axial loads and under pressure loads. These connections are widely used for the smaller diameter application and benefit from a great amount of in-service experience.

4.1.1.3 TLP Tendons

Like risers, there exists a variety of connection types. Two of the most common are threaded pin and box and dog-type, which usually requires a hydraulic tool to provide the high axial makeup force needed to achieve the interference fit. Extensive analytical work and prototype testing is also performed to verify the design. Tendon connectors are usually designed to be significantly stronger than the tendon itself. Installation methods for tendons are similar to caissons — the entire length is assembled onshore (if the assembled length is not too large), or individual sections are joined at the installation site.

4.1.2 Design Philosophies

Tubular structures that employ the connection designs considered for the current study (i.e., threaded pin and box assembled by torque and radial interference, and threaded pipe connections), each adopt specific, differing design philosophies, and subsequently, failure assessment protocols. The design of connections of the first type, threaded pin and box connectors externally affixed to the pipe body, is governed by the pipe body strength, requiring that the connection be at least as strong as the adjoining components for all loading cases. Alternatively, designs utilizing threaded pipe connections are inherently weaker in the threaded region than in the pipe body, and thus, strength of the assembled structure is governed by the strength of the weakest section in the threaded region. Fundamental considerations applying each of the two design philosophies follows.

4.1.2.1 Failure in Pipe Body

For most tubular structural design applications, strength of the threaded connection must be shown to meet or exceed that of the connection for each load acting on the assembled structure. For example, when considering axial loading, the tensile (or compressive) strength of the threaded connection must meet or exceed that of the tubular components it joins. This philosophy is commonly adapted for the design of connections employing an external coupling connection, and has been successfully employed in risers, TLP tendons, and other structures subjected to axial, bending, and pressure loads.

The static and fatigue strength of the connection is based on the capacity of the critical section, typically located at the root radius of the thread adjacent to the shoulder of the pin or box, or the diameter thickness transitions between the box and the pipe. Figure 4-2a identifies the critical sections for an external coupling. If, following the initial design of the connection, the resulting static or fatigue capacity is less than that of the pipe body, the designer may chose to utilize higher strength materials to meet capacity requirements, within the limits discussed in Section 4.1.3.4, or to further optimize the connection geometry. Key features of the thread profile (e.g., thread root radii, pitch, flank angles, and initial axial and/or radial interference), the amount of preload, and thickness transition region(s) can be optimized to reduce stress concentration, and improve the capacity of the design. Section 4.2.4 discusses issues related to the optimization of threaded connections.

4.1.2.2 Failure in Threaded Connection

In addition to external coupling designs, intrusively threaded pipe sections have been used to join tubular components for offshore applications. For connection designs in which the pin and box is machined into the pipe wall, the standard design philosophy does not apply. Instead, failure of the structure is dictated by the strength of the critical section within the threaded region, typically the root radius of the thread adjacent to the shoulder in the pin or box. Hence, the intrusive threaded connection, fabricated from the same material as the pipe body, must prove capable of withstanding the maximum loading applied to the structure. Figure 4-2b displays potential failure locations for the threaded pipe connection.

For tubular structural designs employing threaded pipe connections, the adjoining tubular diameter and wall thickness is dictated by the capacity of the connection, based on computations of the strength in the critical thread region. To accommodate the demands imposed by loading on the assembled structure, the capacity of the critical region is improved through optimization of the thread profile, or by increasing the adjoining pipe body strength, diameter, or wall thickness. (Note that unlike externally affixed mechanical connector designs, diameter upsets are not used, and thus, they are given no consideration in threaded pipe designs.)

It is important to note that scaling of the material strength and nominal pipe dimensions of the threaded region will require that, at a minimum, the strength and geometry of the two adjoining members will also be scaled. This increase in strength and dimensions is usually accompanied by an increase in cost of the members and the connection.

4.1.3 Connection Design Parameters

Recent research [Sato, Buitrago, Glinka, and others] has shown that threaded connectors can be successfully used to resist typical offshore loadings, and if designed correctly, can develop fatigue lives that exceed that of the pipe body [Chen]. As in the design of the primary structural members, the offshore location of the assembly and production requirement will define loading parameters to be considered in the design of the structure, and subsequently, of the connection. The primary parameters to be considered in the design are discussed in the following sections. Refer to Figure 2-2 for identification of the parameters for the threaded connections.

4.1.3.1 Diameter, D_C

The connection diameter is influenced by the diameter of the pipe (D_P) or tubular body to which it will be attached in external coupling designs. In threaded pipe designs, the diameter in the threaded region required to sustain the design loadings may dictate the pipe diameter. In addition, the wall thickness of the pipe (t_P), the anticipated type and magnitude of the loads that the connection must sustain, material strength, and the thread profile will affect diameter selection.

4.1.3.2 Wall Thickness, t_C

As in selection of the connection diameter (D_C), the nominal wall thickness of the connection is influenced by the pipe or tubular geometry, the applied loads, the thread profile needed for effective distribution of the loads, and the material type employed.

4.1.3.3 Thread Profile and Geometry

Selection of a *straight* or *tapered* thread profile for the design will influence the distribution of loading transmitted through the connection. In general, a tapered profile allows for more uniformity of loading (and therefore stress) through the connection. Moreover, a tapered design improves the ease of stabbing of the connection, and usually improved tooth contact at full makeup when compared with a straight design. Tooth geometry also affects load transfer, stabbing efficiency, and the amount of preload needed to maintain integrity during service. The pitch, thread height-to-base ratio, radial and axial interferences, and leading and trailing flank angles can be designed to produce improve load transfer and hence, functionality of the connection in service.

4.1.3.4 Material Selection

The strength of the connector should be selected to provide acceptability of the connection as related to the design loads (Section 4.1.4). Of primary importance is the fatigue strength, which is approximately related to the tensile strength of the material in that the fatigue limit in reversed alternating stress for steels is about one-half of the tensile strength [Jones]. However, higher tensile strength may lead to manufacturing difficulties, increased notch sensitivities, and decreased ductilities and fracture toughness, and hence, fatigue strength of the connector may not increase proportionally with increasing tensile strength. In general, medium strength alloys may be more suitable for connection designs, since good tensile and fatigue strengths can be achieved without introducing manufacturing difficulties or other problems related to high tensile strength materials.

Other factors, such as corrosion resistance, cost, and weight may also be of concern to the designer. Plain carbon steels tend to corrode more rapidly in marine environments. The connection may be made more corrosion resistant with the use of stainless steels, or copper or nickel alloys, although such alloys will increase the cost of the design, and the potential for galvanic corrosion assessed.

4.1.4 Design Loads

Loading on the connection will be dictated by the design application. In general, connections currently used offshore are exposed to combinations of pressure, axial, bending loads, and are imposed either by direct application, such as pressure and makeup torque, or transmitted by the structural components that it joins, such as axial and bending loads. Moreover, because some connection designs may allow for local plastic deformation in the threaded region, and the sequence of application of these loads in-service is difficult to predict, the connection design should be shown to perform consistently irrespective of the loading sequence; i.e., the connection should behave nominally elastic and independent of the load path. General descriptions of the load types affecting design of the connection are discussed below.

4.1.4.1 Pressure

Depending on the service application, the connection may be required to withstand internal and/or external pressures, the magnitude of each may change along the length of the assembled tubular structure. The magnitude of the pressure loadings applied will influence selection of the connection diameter, wall thickness, thread profile, makeup requirements, and preloads.

4.1.4.2 Axial Loads

Axial loading on the connection is typically imposed by the adjacent structural components it connects and their response to dead and live, installation, fatigue, and removal loadings, and the designed initial preload of the connection. As with the pressure loads, the magnitude of axial loads will influence selection of the connection diameter, wall thickness, thread profile, makeup requirements, and preloads.

4.1.4.3 Bending Loads

Bending stresses in the connection result from the global bending loads applied to the assembled structure. These bending loads may include pure moments resulting from transverse loading at sections along the length of the assembled structure (M_B), and axial loading coupled eccentricity of the column ($F_A \cdot d$). Significant bending may cause thread jump-out or gross deformation in the connection that reduces preloads and the load carrying capacity of the connection, or local buckling that leads to collapse of the assembled tubular. Hence, the magnitude of bending loads will influence selection of the of the connection diameter, wall thickness, thread profile, makeup requirements, and preloads.

4.1.4.4 Fatigue

Because cyclic stresses in the connection are derived from irregular fluctuations in wave loading, vortex shedding and vibration, installation, design, preload, and other variable service loadings, nominal cyclic load histories and resulting connection peak stresses are not well defined. (Accurate load histories may be defined by installing a monitoring system that tracks variations in cyclic service loadings to provide information for a complete fatigue assessment.) However, API RP 2A provides general guidance on wave, wind, and current loadings for a given installation location which may be used to characterize loading on the assembled structure, and ultimately, on the connection. Such loading characterizations, coupled with a global response analysis of the assembled structure will generate sufficient information for the conservative fatigue assessment of a given connection design. Section 4.2.3 describes general methods of the fatigue evaluation of threaded connections.

4.1.4.5 Preload

Several researchers have discussed the benefits of imposing an initial preload (pre-torque) to extend the fatigue life of the connection [Glinka, Buitrago 1988, Chen]. Briefly, the presence of axial preload on the connection serves to reduce the stress range that can be developed during cyclic loading, and hence, for a material exhibiting typical *S-N* fatigue behavior, (i.e., increasing fatigue life with exponentially decreasing stress range), a longer fatigue life is produced. However, local stresses and strains in the critical thread regions are increased under preload, and if the preload is too high, will offset any potential benefits to be realized. Moreover, definition of the stress concentration factor in critical regions is complicated by the preload since both membrane and bending stresses are present at the thread root and contribute nonlinearly to the local stress. (Section 4.2.2 provides further details on this topic.) Hence, the design of preload should carefully and accurately examine local stress distributions and magnitudes, and be cognizant of the potential for diminishing the fatigue (and static strength) capacity of the design under excessive initial preloads.

4.1.4.6 Torque

Temporary and cyclic loading, such as yaw of any supported structures, may produce torque at the connection in a direction that tends to loosen the preload. In anticipation of such loads, anti-rotation pins or devices may be installed to prevent backdriving of the connection during torsional loading. Such loads will affect the amount of makeup torque needed to maintain integrity of the connection.

4.1.4.7 Makeup and Breakout

The required torque for full makeup of the connection is highly dependent on the design of the connection (including radial and axial interference quantities), preload requirements, thread compounds, sealing requirements, and capacity of equipment available to perform the makeup. Careful consideration must be given to each of these parameters so that the connection will remain fully assembled during all loading applications, including temporary and cyclic loading.

Evaluation of the required torque and method of breakout of the connection should consider the deleterious effects of service in a free-corroding environment, the thread compound used, and the available equipment for this action. In some cases, heating of the box will be required to assist breakout. The potential for degradation of the ductility of the box should also be addressed for re-used designs. Buitrago recommends a factor of safety applied to the disassembly torque to account for in-service degradation (and required initial breaking torque) equal to 1.5 [Buitrago 1988].

4.1.5 Other Design Considerations

In addition to static and cyclic strength, the connection must be assessed for its ability to withstand loading imposed during installation, and an in-service inspection protocol must be designed. Moreover, the ability to manufacture the connection within the design tolerances must also be assured. Such considerations, as they apply to the design process, are also discussed in this section.

4.1.5.1 Installation

The method of installation of the connection and the assembled structure should be addressed in the design stage. For example, in pile applications, the assembled structure will be subjected to dynamic driving forces (e.g., hammer energy) which must be efficiently transmitted through the connection without diminishing the structural capacity [Buitrago 1988]. The ability for easy stabbing and quick makeup with capacities of the attendant equipment should also be considered.

4.1.5.2 Inspection

The method and frequency of inspection should be considered prior to finalizing and installing the design. Preliminary analyses of the threaded connection can identify, *a priori*, critical locations for in-service and post-service inspections, as well as the needed frequency of inspection based on predicted fatigue and damage growth modeling. Selection of the connection design will be influenced by the need to perform frequent inspections, such as in TLP tether applications where quick assembly/disassembly is required, or infrequent inspections such as in pile applications where inspections are performed following decommissioning and prior to reuse [Buitrago 1988].

In addition to visual inspection, NDE (Non Destructive Evaluation) methods may be used to inspect connections at critical locations usually after retrieval. Such methods include x-ray photography, ultrasonic or acoustic methods, and magnetic techniques. Electrical techniques such as Alternating Current Field Measurement

(ACFM) and Alternating Current Potential Drop (ACPD) have also been used in recent years to accurately define detectable crack sizes [Dover].

4.1.5.3 Manufacturing Considerations

The ability to manufacture and inspect a given thread design has improved in recent years with the advent of CNC (Computer Numerically Controlled) machines. Tolerances for most high performance thread designs applied in medium size diameter ranges are well within the capacity of such machines, and help to alleviate the difficulties previously encountered with the mass production of complex thread patterns [Chen]. However, for larger diameters, machines and inspection protocol capable of producing and evaluating the complex geometry is less common [Buitrago 1988].

During the design and manufacture of the connection, attention should be given to the method of manufacture, the needed design tolerances (including the pipe body), and the procedure to be used in the quality control and assurance of the resulting connection.

4.1.5.3.1 Methods

Three methods of manufacturing threads are commonly used: (1) machining, (2) grinding, and (3) rolling. Of these, machining of the threads is most common. Threads manufactured by machining profiles into the pipe or connection wall may introduce surface microcracks, which when loaded in fatigue, may coalesce into larger cracks that fail the connection. Grinding of threads causes rapid heating of the surface, which alters strength and ductility, and if excessive, leads to local expansion of the material that may cause yielding. Rolling of threads cold works the metal surface, thus locally increasing the yield strength and hardness, and in general, good surface finish, thus improving fatigue strength [Jones]. Irrespective of the manufacturing technique employed, effort should be expended towards the production of a good surface finish the avoid microcracking and improve fatigue performance.

4.1.5.3.2 Tolerances

Pipe ovality and thickness variations will affect the fit-up between forged and machined rings in mechanical coupling designs, and accuracy of the thread installation in threaded pipe connections. The later of these often requires tolerances on ovality (and an understanding of thermal effects on ovality changes) that are at least compliant with API 5L line pipe tolerances. For large diameters, more stringent requirements on ovality and thickness variations, limitations of the forging sizes, machining tolerances, and the capability of machines to produce the desired tolerances within the thread profile may be needed, and can influence the ability to develop a reliable design.

4.1.5.3.3 Quality Control and Quality Assurance

Quality assurance must be shown to effectively control, on a mass production basis, the dimensional tolerances required by the design [Buitrago 1988]. For forged ring designs, the thread form, lead, pitch and diameter must be inspected with gauges capable of measuring dimensions within the needed tolerances. To evaluate quality of the thread features, including geometry and surface finish, plastic replicas of the threaded region can be developed and measured. For large diameter connections, the availability of measurement gauges is limited.

4.1.5.4 Thread Compounds and Sealing

The primary reasons for applying thread compounds to threaded connections and couplings is to achieve a leak-tight seal and to prevent damage of the connection during makeup, running, and breakout of the pipe [McDonald]. Additionally, proper use of thread compounds provides protection against metal to metal contact and galling at high bearing stresses. The addition of a thread compound makes possible high connection preloads during makeup. Some connections also incorporate an integral sealing mechanism in addition to the thread compound to ensure a leak-tight connection.

4.1.5.5 Corrosion

Hostile chemical environments accelerate the growth of fatigue cracks, thus reducing fatigue strength [Dowling]. Figure 4-3 shows the reduced *S-N* (stress versus number of cycles to failure) fatigue behavior for a typical material exposed to a saltwater environment. In addition, corrosion initiated at a critical thread region could amplify the stress concentration factor in the region due to metal loss. In marine applications, corrosion resistant coatings, cathodic protection, seal welds, or alloyed steels (as discussed in Section 4.1.3.4) can be used to minimize corrosive action.

4.1.6 Existing Regulations for Threaded Connection Design

Design guidance related to threaded connections is provided by API for casing, tubing, line pipe, risers, and TLP tendons offshore. A summary of special considerations used in connection design and evaluation for such systems is given in the following paragraphs. As indicated in the discussions, some of the guidelines may be suited for assessments of threaded connections used in caisson structures, and may be adapted for use when applied in conjunction with the additional design considerations outlined in Section 5.

4.1.6.1 Riser Systems

Some of the most detailed guidance, concerning design of offshore connections and couplings is provided in API Spec 16R. This regulatory document provides guidance on global and local design and analysis of risers couplings. In particular, it provides very applicable information on the design and analysis of a complex coupling. As mentioned in Section 4.1.1.1, many different types of riser couplings exist; however, guidance provided is general enough to be applicable to all. Of most importance is the method of determining coupling stresses and stress concentrations under load.

Information concerning the stress state in a coupling should be obtained with the finite element method and validated with prototype strain gage testing. Attention during the finite element analysis shall be paid upon friction and preload effects and proper analytical techniques, which require consideration of the mesh discretization, accurate material properties, and correct loading and constraints. Experience has shown that cracks develop at stress concentrations. As such, particular attention shall be given to obtaining accurate values of stress concentration under combined loading, including preload and incremental load steps to determine if a dependency on loading exists. Additionally, the effect of manufacturing tolerances shall be accounted for in the analyses. Prototype testing shall be conducted to verify any assumptions made during the analyses and to validate strain/stress results.

Other issues such as material requirements, welding, testing, and quality control for marine riser couplings are also addressed in API Spec 16R. Some of the discussion pertaining to allowable stresses, found in Appendix C of API Spec 16R, will be considered in more detail in the following sections. Incorporation of some of the information found in Appendix A of API Spec 16R, concerning finite element stress analysis, has been made in Appendix B of this report, where standard thread analyses are reviewed.

4.1.6.2 Casing, Tubing, and Line Pipe

American Petroleum Institute Specification for Casing and Tubing, API Specification 5CT, calls out for fracture toughness requirements on connection material only if the grade of steel is greater than 40 ksi yield strength. Additionally, in casing and tubing manufacture, the connection must be certified to be the same design and manufactured to the same dimensions and tolerances as those used in the evaluation tests [API RP 5C5]. Of further significance, extrapolation of casing and tubing connection test results to other sizes and materials is the responsibility of the end user. Line pipe connections are similar to casing and tubing connections.

4.1.6.3 TLP Tendons

Typically, only tubular tendons employ connectors. Because of their complexity, extensive engineering development and prototype testing may be warranted to determine the fatigue, fracture, and corrosion characteristics and the mechanical capabilities. These connections are similar to riser connections.

4.2 ANALYSIS

Analysis of a connection design for specific response characteristics is almost always conducted using finite element analyses of the local threaded region. Input to the local analysis of the connection is extracted from a global analysis (finite element or structural models) of the assembled structure, from which the generalized static, dynamic, and cyclic load transfer from the structure to the connection is quantified. With this information, a detailed analysis of the local behavior of the connection, including highly accurate modeling of the thread profile, internal and external diameter upsets, radial and/or axial interference, and machining tolerances, is performed. Data from the local analyses is then used to perform additional evaluations of the static strength and fatigue performance used in the final design selection and to guide validation testing.

When assessing the connection's response to the applied loading, local regions displaying a high concentration of stress should be identified. It is common to define a stress concentration factor for these regions, usually relative to the pipe body stress, so that static strength and fatigue analyses of the assembled structure can be performed. Techniques used in calculation of the connection performance, including definition of the stress concentration factors and fatigue life are discussed in the sections that follow.

4.2.1 Finite Element Analysis Techniques

The successful use of finite element analysis techniques in the evaluation of threaded connection designs is generally well understood, and well documented [Glinka, Buitrago, et al]. For most assessments, linear elastic analyses are used to provide basic information on the magnitude and distribution of stresses in the threaded region. Such analyses can be used to identify critically loaded regions or the areas of highest stress concentration for subsequent fatigue assessments, and to define the method and path of load transfer through the connection to assist with initial design evaluations and optimization studies. Other considerations are addressed in API Spec 16R and summarized in Section 4.1.6.1 of this report.

A brief discussion of the procedures used in the finite element analysis of a standard set of thread patterns is given in Section 4.4. Appendix B contains further detail on the analyses and the corresponding results. The general approach, including global loading application, element selection, and contact surface modeling for the analyses is given to provide insight into the procedures used in local connection analyses, and to provide general information on the response characteristics of standard thread designs. The following paragraphs provide information on the primary considerations for analysis of a given threaded connection.

4.2.1.1 Model Characteristics

Many commercially available programs exist that are suitable for the local analysis of threaded connection designs [ANSYS, ABAQUS, NASTRAN]. To fully utilize the capabilities of finite element analysis techniques, the modeling and analysis package selected for the evaluation should be capable of implementing the following tools:

- axisymmetric and/or three-dimensional elements,
- non-linear material and geometry capabilities,
- large deformation assessment,
- generalized contact simulation,
- initial imposed displacements, and load path definitions, and
- a fairly large number of elements.

As discussed in the sub-sections that follow, any or all of these capabilities may be employed for accurate assessment of the localized behavior of the connection.

4.2.1.1.1 Element Selection (Axisymmetric vs. 3-Dimensional)

Axisymmetric assessment techniques preclude the exact representation of the 3-dimensional (3-D) helix of a thread profile. However, researchers [Glinka] have successfully shown that for some connection geometries, the use of an axisymmetric model consisting of parallel rings, to approximate the 3-D helical thread generated no appreciable difference in the analysis results. This approach can significantly reduce analytical time and effort. The axisymmetric approach is generally accepted when the diameter of the threads is large compared to the pitch and helix angle [Liebster].

If the connection will be subjected to large bending loads, a more complex 3-D model is best suited for the analysis since axisymmetric models, in general, do not allow for proper bending load definitions. However, bending of the connection can be simulated in an axisymmetric analysis by equating the bending moment to an equivalent axial load, P_{EQV}, and assessing the connection under compressive and tensile loading equal to P_{EQV}. The equivalent axial load may be conservatively estimated from the bending stress relation for the section as [Buitrago 1998]:

$$P_{EQV} = \pm\left(\frac{M_B \cdot c_P}{I_P}\right)A_P = \pm M_B\left[\frac{32t_P\left(D_P - t_P\right)^2}{{D_P}^4 - \left(D_P - 2t_P\right)^4}\right] \qquad (4\text{-}1)$$

where c_P is the mean pipe radius, I_P is the moment of inertia of the pipe body, and A_P is the cross-sectional area of the pipe body. D_P and t_P are the nominal pipe diameter and thickness, respectively. Some specialized finite element formulations allow the application of non-axisymmetric loads, but these loads are defined in terms of a harmonic function about the circumference and may not accurately simulate bending loads.

Additionally, an axisymmetric model will not capture any reaction torque from the helical thread form. A simplified 3-D model of a sector of the tubular cross-section is an alternative. This type of model takes advantage of some axial symmetry, but still retains the 3-D nature of the model, and it can significantly reduce the solid model size.

For new designs, or significant modifications to existing designs, comparison analyses aimed at quantifying the difference between model predictions using an axisymmetric approximation of the 3-D helical thread form should be performed. In addition, such analyses may help in optimizations and critical assessments of designs, which are marginal with respect to capacity requirements.

4.2.1.1.2 Model Geometry and Mesh Density

The geometry and mesh density of the local analysis model is dependent on the connection geometry, the desired accuracy of results, and computational capabilities of the analysis package and supporting hardware. An ideal analysis would include a three-dimensional model of the connection, a large number of elements at and adjacent to each thread root, and corresponding contact elements at the pin and box surfaces. However, such models are not always economically feasible or needed to produce accurate results. As discussed in Section 4.2.1.1.1, elimination of the need for a 3-D representation of the connection can help to significantly reduce run times and associated costs, without appreciably reducing accuracy of the model predictions for many load cases.

If possible, the entire connection should be modeled, and a sufficient axial length of the connecting components so that end and localized stress effects from boundary conditions and load application regions can be avoided. The mesh applied to the model should be more refined in the highly stressed thread regions as well as the internal and external upset areas. Appendix B contains an axisymmetric model for standard thread profiles.

To determine the mesh density needed for accurate results, incremental refinement and analysis of the mesh from an initial “course” discretization to “fine” discretization should be conducted. Whenever possible, all regions of the model should be refined to ensure accurate load transfer to critical regions. Key results (e.g., stress or strain at critical regions, and relative displacement of the pin an box) should be reviewed for each increment of refinement to identify the optimal mesh for a converged result. Convergence of the analytical result is crucial to accurate definition of local stress amplification, and hence, to determination of the critical stress concentration factor for the design.

4.2.1.1.3 Material Properties (Linear versus Non-Linear)

In some threaded connection designs, some amount of localized plasticity in the threaded region is allowed, provided that behavior of the connection remains nominally elastic and such plasticity does not lead to failure of the connection. For these designs, the best approach is to define the nonlinear material behavior for the connection so that localized plasticity and the corresponding redistribution of stress throughout the connection and into the adjacent connecting body can be closely predicted. However, this level of analysis may be too costly to perform, and the inability to precisely model inherent material variations throughout the connection (imposed during forming) may lead to some inaccuracy of the analysis predictions. The analyst should therefore be aware of such limiting conditions in the interpretation and application of results, and be sure to always apply conservative estimations of material behavior.

Most current analysis procedures employ linear-elastic material definitions, which are easily obtained from the material manufacturer. Such analyses are less sensitive to the variation in material properties and specifically, strain hardening behavior, at different points within the connection. Elastic stress-strain results from the linear-elastic analyses can then be used to develop elasto-plastic stress-strain response for subsequent *strain-based* fatigue analyses incorporating localized plasticity using Neuber's Rule or the Equivalent Strain Energy Density method (ESED). (See Section 4.2.3 for details.)

4.2.1.1.4 Large Deformation and Contact

Large deformation analyses, which employ contact elements, must be used to evaluate the deformation characteristics of the design. Deformation within the connection will identify any propensity for thread jump-out or disengagement during makeup or service loading, which affects the functionality of the connection. Large deformation of the connection, such as at failure, can be modeled using the large deformation capabilities of the analytical program. Although such analyses are computationally intensive, accuracy of the finite element predictions used in subsequent fatigue, capacity, and preload assessments hinges on the ability to precisely prescribe local deformation (and resulting stress-strain response). Therefore, it is generally recommended that large deformation and contact algorithms be employed in all finite element analyses of threaded connections.

4.2.1.2 Strength Determination

The ultimate tensile (or compressive) and bending strengths of the assembled connection may be difficult to ascertain through experimental methods. Often times the ability to test the connection to failure is limited by the size of the connection and the equipment or facilities available for testing. In such cases, scale testing and well-validated analytical procedures are needed. In addition, because external coupling designs employ a *failure in the pipe body* design philosophy (Section 4.1.2.1), it may be difficult to produce actual operating conditions in test set-up since pipe bodies stronger than the actual design pipes are required.

Large deformation and inelastic (plastic) analyses of the connection can provide a good estimate of the static strength of the connection. Analyses that incorporate contact algorithms to simulate sliding at the pin-box interface and thread jump out are needed. The static strengths (and associated stresses and strains) will be dictated by the ability of the connection to maintain coupling strength under the applied loads.

API Spec 16R and ISO Standards [Buitrago 1998] recommend the linearization of model peak local stresses to eliminate stress concentration effects in critical thread root regions, and account for global section behavior. Linearization of the model stresses results in an average, or membrane stress, and a differential, or bending stress. Stresses in the region must also be classified as *primary* (stresses developed to maintain equilibrium with the applied loading), *peak* (highly localized stresses occurring at a discontinuity in the load path), and *secondary* (any stress which is not primary or peak, and is self-limiting and self-equilibrating). Any of these may be further classified as *membrane* (normal stress averaged over an area, such as F_A / A_P), *bending* (stress induced by a bending moment), *pure shear* (shear stress from a force transverse to the section), and *bearing* (normal stress acting on contacting surfaces).

As shown in Figure 4-4, the actual stress distribution, usually determined via finite element analysis, varies nonlinearly over the section under a given external load (e.g., axial or bending). The dashed line in the figure represents the linear distribution of the stress, assessed for each significant stress component (excluding bearing and shear stresses), and classified as a membrane or bending stress. The linear stress representation of the three normal (S_X, S_Y, and S_Z) and three shear stress components ($\boldsymbol{T}_{XY}$, $\boldsymbol{T}_{YZ}$, and $\boldsymbol{T}_{ZX}$) for a given loading mode are then used to calculate the von Mises effective stress for the local region:

$$\overline{S} = \frac{1}{\sqrt{2}} \left[\left(S_X - S_Y \right)^2 - \left(S_Y - S_Z \right)^2 - \left(S_Z - S_X \right)^2 + 6 \left(T_{XY}{}^2 + T_{YZ}{}^2 + T_{ZX}{}^2 \right) \right]^{\frac{1}{2}} . \quad \text{(4-2)}$$

Note that the linearization of shears is not recommended by API or ISO Standards, and instead, should be averaged over the region. The effective stress $\overline{S}$ is then compared to the allowable strength of the connection for the given loading mode. ISO Standards [Buitrago 1998] suggests an alternate representation for the stress components which includes membrane plus bending stress representations in determination of the primary stress components for Equation 4-2.

4.2.1.3 Dynamic Loading

Typically, dynamic analyses performed on the connection focus on pile driving forces. The primary purpose of performing a dynamic analysis on the pile driving of a threaded connector is to ensure that the structural integrity of the connector is maintained throughout the entire driving procedure. Whereas, dynamic loadings that are experienced by the structure globally are usually treated as static loads locally. Structural integrity includes both the capacity of the connection after driving and the ability to breakout the connection upon completion of a service period. The connection must have sufficient strength following the driving to withstand the applied loads during the remaining operation and decommissioning phases. A successful breakout requires that permanent deformation of either the thread form or connector body not be present after the driving.

Performing a detailed analysis of a stress wave propagating through a threaded connector is inherently difficult to achieve with the results in the critical thread region being especially hard to validate through a full-scale test. As such, a typical analysis will consist of a stress wave model similar to that described in Section 3.1.6.1.3 with the threaded connector modeled as a uniform body and a 1-2 percent energy loss assumed at the connection [Buitrago 1988]. The resulting stress in the critical region will then be calculated using the nominal stress from the simplified model in conjunction with the static SCF relating the critical stress to the nominal stress in the connector.

4.2.1.4 Fatigue Behavior

Data for fatigue analyses is extracted from the finite element results to predict the fatigue life of the connection. In particular, the peak local stress at the critical location, s, for the applied loads is used to define stress concentration in the region that may be used in *stress-based* (Section 4.2.3.2) or *strain-based* (Section 4.2.3.3) fatigue assessments. Local elastic stress predictions, including the stress range, amplitude, and mean stress levels, in fatigue critical locations (FCLs) are used in the assessments to define the fatigue limits of the connector.

4.2.1.5 Preload

The effect of an initial preload on the relative tooth displacement and local stress levels can be used to determine an optimum preload magnitude for the connection. Applying a preload to a finite element model can be achieved simply in the first load step. In fact, such a load step may be necessary to achieve convergence when using contact elements needed to capture the interface between the coupling pin and box. The effect of the preload on the stress concentration or amplification factor is discussed in detail in Section 4.2.2.3.

4.2.1.6 Makeup and Breakout

Required makeup and breakout torques are influenced by the requirement for preload. Analyzing for makeup and breakout torque requirements will prove to be very difficult. The difficulty exists in modeling the friction forces involved, especially after use and during breakout. More accurate information can likely be achieved through physical testing.

4.2.2 Definition of the Stress Concentration Factor

Of paramount importance to evaluation of the cyclic capacity of the connection, and ultimately, the assembled design, is accurate definition of the stress concentration factors at critical locations within the connection. Most designers choose to identify a “target” stress concentration factor for the FCL that defines acceptability of the design, and/or the need for additional optimization. The following sections discuss the various relations and approaches for definition of stress concentration factors (SCFs) and the applicability of linear SCF assumptions in threaded connection designs.

4.2.2.1 Stress Amplification Parameters

The stress amplification within the threaded region is highly dependent on the geometry of the thread profile, and subsequently, its ability to efficiently transfer load throughout the connection. For a threaded connection like those included in this study, stresses will be concentrated at a thread root, and/or the internal or external diameter upsets for mechanical threaded connections. The critical region for fatigue assessments is that which exhibits the highest stress range. In order to accurately interpret and apply the results of analyses aimed at defining the magnitude of stress concentration, individual loading components contributing to the peak local stress s in the critical region must be defined, and their effects well understood.

4.2.2.1.1 Local Stress, s

Within the critical region, membrane stresses from the applied axial loads will be produced that are amplified due to connection geometry. Once engagement (full contact) of the threads is achieved, tooth loads are generated which tend to alter the stress magnitude within the critical region. Considering an FCL at the thread root region, the local stress will be equal to the summation of the contributing components:

$$\acute{o} = \acute{o}^{M} + \acute{o}^{B} \tag{4-3}$$

where s is the local stress in the thread root, s^M is the membrane stress contribution attributed to pipe loading, and s^B is the bending stress contribution attributed to loading on the adjacent tooth. (The quantities s^M and s^B represent the primary, secondary, and peak stresses at the critical thread root region.) The nominal thread root cross-section stress (*S*) will also consist of membrane and bending stresses from axial membrane and thread bending loads.

When examining membrane and bending action at an internal and/or external diameter upset, geometry of the connection and load transfer are again important. As in the evaluation of the thread root local stress, membrane stresses are generated at the upset attributed to the axial loads. Bending stresses in this case are produced by the local bending moment induced by the discontinuity in the wall thickness.

The local stress at any increment of loading can be expressed as a stress tensor, s_{ij} that must be converted to an equivalent uniaxial stress for static strength and fatigue assessments. The stress tensor defines the normal and shear components needed to fully describe membrane and bending contributions, and the principal stresses s_1, s_2, and s_3. Once the principal stresses in the critical thread root have been determined, the local stress can be defined by the von Mises effective stress relation given below.

$$\bar{o} = \frac{1}{\sqrt{2}}\left[\left(\acute{o}_1 - \acute{o}_2\right)^2 + \left(\acute{o}_2 - \acute{o}_3\right)^2 + \left(\acute{o}_3 - \acute{o}_1\right)^2\right]^{\frac{1}{2}} \qquad (4\text{-}4)$$

Alternatively, maximum-shearing stress theory can also be used to define the an effective local stress of the critical thread root region.

$$\bar{o} = \frac{1}{2}\left[\max\left(\left|\acute{o}_1 - \acute{o}_2\right|, \left|\acute{o}_2 - \acute{o}_3\right|, \left|\acute{o}_3 - \acute{o}_1\right|\right)\right] \qquad (4\text{-}5)$$

It is commonly accepted to define the stress concentration factor, K_t, as the ratio of the local stress in the critical region either at the critical thread root, or the internal or external pipe diameter upset, to the nominal pipe body stress. That is,

$$K_t = \frac{\acute{o}}{S_P} \qquad (4\text{-}6)$$

where K_t is the stress concentration factor the critical region (maximum value in connection), and S_P is the nominal stress in the pipe body. Under pure axial loading, the stress in the pipe body is defined as:

$$S_P = \frac{F_A}{A_P}$$

(4-7)

where all quantities related to the nominal pipe body are indicated by the subscript P. Typical values of K_t range from 2.0 to 4.0, although, through careful design optimization, values less that 2.0 can be achieved [Buitrago 1988].

For critical thread regions, the stress concentration factor can also be defined as the ratio of the local stress to the average membrane stress in the corresponding thread root cross section. Specifically,

$$K_t' = \frac{\text{ó}}{S^M} \tag{4-8}$$

where, for assumed pure membrane loading of the cross section, the membrane stress in the thread root cross section, S^M, is:

$$S^M = \frac{F^M}{A_C} \tag{4-9}$$

and F^M is the membrane load acting at the critical thread root cross-section. Note that the nominal stress, S, in the critical thread root cross section will contain some contribution of bending stress from the adjacent tooth loading which is localized in the area of the thread root in addition to membrane components. Thus, some error in the calculation of the stress concentration factor may be developed if pure membrane action is assumed.

To improve accuracy of the SCF calculation, a third designation of the stress concentration factor may be developed which relates the local stress to the nominal stress in the thread root cross section, comprised of both membrane and bending stress; i.e.,

$$K_t'' = \frac{\text{ó}}{S^M}\ . \tag{4-10}$$

Local and nominal cross-section stress magnitudes for the definition of K_t'' can be accurately determined via finite element techniques.

Selection of the stress concentration factor designation is dependent on the geometry of the connection and potential design optimizations, as well as the design basis. For example, K_t may be chosen where definition of strength capacities for the assembled structure are in terms of the pipe body strength (mechanical connector designs), while K_t' or K_t'' may be reserved for use when capacity is defined in terms of a critical thread region, or when evaluating local stress validations during design optimizations [Turner]. As applied to the current study, K_t' or K_t'' is likely best suited for assessment of the intrusively threaded pipe, where failure will be dictated by the strength of the critical thread region. If failure in the region is dictated by the onset of plasticity, the use of K_t'' in design assessment is most suitable since it includes the membrane and bending stresses contributions to the peak and nominal stress quantities in the critical threaded region. However, if either K_t' or K_t'' is used, a function which relates this value to the nominal pipe body stress must be additionally defined since global stress distributions from static and dynamic analyses will usually be related to the assembled structure or pipe body.

4.2.2.2 Linear Versus Non-Linear Behavior Of The SCF

Most design protocols for threaded fasteners allow for nonlinearity of the stress amplification factor (SCF) provided that: (1) the stress concentration factor is shown to behave linearly over the anticipated design load range, or (2) a defensible methodology for the design assessment accounting for the nonlinearity can be provided. In either case, a clear definition of SCF relationship to the applied loading should be obtained.

As discussed in Section 4.2.2.1.1, the local stress in the thread root is comprised of primary, secondary, and peak membrane and bending stresses that can be solved for in terms of the principal stress quantities, s_1, s_2, and s_3 (Equation 4-3). Clearly, relating the complex stress state at the thread root to the pipe body stress (S_P) or the thread cross section membrane stress (S^M), both of which are purely membrane, does not precisely capture the contribution of bending action that is included in the local stress quantity s. Hence, as the loading on the connection is linearly increased, a non-proportional change in the local stress is produced attributed to the coupling of bending and membrane actions. The result is a non-linear relationship between the load and the local effective stress, which varies as prescribed in Equation 4-4.

The designer should perform analyses to quantify the magnitude of SCF non-linearity for a given design. As previously stated, the magnitude of the stress concentration in the local region is highly dependent on the profile geometry and it's ability to effectively transfer load through the connection. If appreciable non-linearity of the SCF exists, a defensible method for its treatment in fatigue and static strength assessments should be implemented. In the design of riser couplings for marine drilling operations, it is required that the SCF be evaluated at 20, 40, 60, and 80 percent of the rated load (plus nominal or minimum values of preload) to quantify non-linearity of the SCF with axial loading [API Spec 16R].

4.2.2.3 Effect of Preload On The SCF

Tubular connections applied in offshore applications typically include the application of an initial preload during assembly to increase resistance of the connection to fatigue, shock, and vibration loads, and to activate initial metal-to-metal sealing surfaces [Turner]. The effect of the initial preload is to impose compression in the connection, resulting in compressive loading of the box teeth, counter-balanced by tensile loading of the pin teeth. For the critical thread root region at the trailing edge of the first fully-loaded tooth furthest from the pin free edge and adjacent to the pin shoulder, local stress from the preload is largest and tensile, and defines the initial local stress value, s^P, from which the local stress will vary as the axial load is applied.

For a connection subjected to an increasing tensile axial load, F_A, without an initial preload, local stresses in the thread root will increase from zero to some maximum value, s_{MAX} , at full load. Figure 4-5a displays an assumed linear relationship between local stress at the thread root and an applied tensile axial load for the case of no applied preload. Imposition of a preload on the same connection forces initial contact and load transfer between the mating pin and box surfaces. This action produces localized stresses in the threaded region at zero axial load, shown as the point s^P in Figure 4-5a. After applying tensile axial load, F_A, the local stress in the thread root increases from the initial value s^P to a maximum value, s^P_{MAX} , at full load, which is only slightly greater than that of the connection with no preload, s_{MAX}. (Again, the relationship between the local stress and the applied tensile axial load for the preloaded connection is assumed linear.) The important fact to note from Figure 4-5a is that the rate of increase of the local stress with increasing tensile axial load is less in the preloaded connection than in the connection with no initial preload. This behavior is attributed to the relief of the initial local preload stresses with the application of axial tensile loading [Glinka].

The potential for nonlinearity of the stress concentration factor for critical regions at varying levels of preload should also be investigated. Analytical study using the methods described in Section 4.2.2.2 can be used to quantify any nonlinearity by varying the initial preload level, and applying the given percentages of design load. The result of such study will be a clear definition of the SCF under preload, and the relationship of the SCF at that preload to increasing load. Ultimately, this information can be used to define an optimal value of the preload, which should be applied at installation.

Note that while the concept of preloading of the connection to increase fatigue life is well understood and widely practiced, there exists a practical limitation to the amount of preload that can be applied without negating the potential positive effects (i.e., smaller cyclic stress range) [Glinka]. If the initial preload is too high, local stress in the region will be driven to a level, which exceeds yield of the material when axial loading is applied. This occurs because the rate of stress relief provided by the increasing axial load is not large enough to reduce local stresses from the initial preload before yield is reached. Figure 4-5b displays this behavior for a tensile axial load. Conversely, if the initial preload is too low, it will be overcome by the applied axial load before reaching the design maximum, the connection will open, and integrity of the structure is compromised. The solid lines in Figure 4-5b shows this trend.

4.2.2.4 Cyclic Loading SCF

The basic definitions of stress concentration factors presented can be applied directly for fatigue assessments, as is typically the goal of SCF evaluation studies, by defining the local and nominal stress range for the connection under the assumed cyclic loading. The local elastic stress range, s_r , at the critical region may be defined from finite element analyses, as can the nominal stress ranges for the pipe body (S_{Pr}) and thread cross-section (S_r). However, nominal stress ranges may also be known input quantities to the analyses, or can be derived through simple formulations. Given the stress range corresponding to a specific set of loading conditions, the dynamic stress concentration factor, K_t^D , based on nominal pipe body stress becomes:

$$K_t^D = \frac{\acute{o}_r}{S_{Pr}}. \qquad (4\text{-}11)$$

Alternate definitions of K_t^D can be defined by the ratio of s_r to alternating membrane stress, S_r^M , or membrane plus bending stress, S_r, in the critical thread root cross-section. For convenience, subsequent discussions of the dynamic stress concentration factor have adapted the conventional designation where local stress is normalized by the pipe body stress, S_{Pr} , directly relating global structural loads to the critical location.

Dynamic stress concentration factors can be calculated for each cyclic load type applied to the connection for which a cyclic capacity must be determined, although, specification of an axial SCF is usually sufficient for design [Buitrago 1998]. Specifically, for axial loading, F_A:

$$K_t^{D,A} = \frac{\acute{o}_r}{S_{Pr}^A} \text{ and } S_{Pr}^A = \frac{\Delta F_A}{A_P}, \qquad (4\text{-}12)$$

for bending, M_B:

$$K_t^{D,B} = \frac{\acute{o}_r}{S_{Pr}^B} \text{ and } S_{Pr}^B = \pm\frac{\Delta M_B \cdot c_P}{I_P}, \qquad (4\text{-}13)$$

and finally, for pressure, P_I or P_E:

$$K_t^{D,P} = \frac{\acute{o}_r}{S_{Pr}^P} \text{ and } S_{Pr}^P = \pm\frac{\Delta P \cdot D_P}{2t_P}. \qquad (4\text{-}14)$$

Such definitions are typically used in fatigue assessments as discussed in Section 4.2.3. (Considerations for the calculation of the local stress range for fatigue life evaluation are given in Section 4.2.3.1.1).

The change in principal stresses in the thread root is derived from the difference in the stress tensors at the upper and lower bounds of the applied loading. That is,

$$\Delta\acute{o}_{ij} = \acute{o}_{ij}^{MAX} - \acute{o}_{ij}^{MIN} \qquad (4\text{-}15)$$

where σ_{ij}^{MAX} and σ_{ij}^{MIN} are the maximum and minimum stress tensors at the thread root for successive load increments. Principal stress ranges $\Delta\sigma_1$, $\Delta\sigma_2$, and $\Delta\sigma_3$, derived in terms of the tensor $\Delta\sigma_{ij}$, can be used to define an effective local stress range, σ_r , and a corresponding equivalent stress amplitude.

Consideration of the preload in definition of the stress concentration factor for fatigue assessment is crucial since the magnitude of the initial preload (and corresponding stress) will define the allowable stress range for the critical region. For a connection without an initial preload and subjected to a loading environment which produces an upper bound local stress, σ_{MAX} , at the critical thread root, the stress range will be:

$$\sigma_r = \sigma_{MAX} - 0 = \sigma_{MAX} . \qquad (4\text{-}16)$$

For a connection subjected to the same loading environment and preload producing local stress σ^P in the critical region, the stress range will be:

$$\sigma_r^P = \sigma_{MAX}^P - \sigma^P .$$

(4-17)

(Note that Equation 4-17 is truly valid only if the principal stress axes do not rotate during the application of external loads.)

As shown in Figure 4-5b, for a preloaded connection, the stress range is reduced, leading to increased fatigue life. Hence, exclusion of the preload stress magnitude from the fatigue assessment, and calculation of the SCF would lead to an excessively conservative result. Again, potential nonlinearity of the SCF with loading should be quantified to ensure a suitable level of conservatism exists.

4.2.3 Fatigue

As indicated in the introductory comments for Section 4, complex loadings in the threaded connection, coupled with the known propensity for fatigue failure at threaded regions containing large stress concentrations, precludes the widespread acceptance of the use of threaded connections in primary structural applications. However, technically defensible methods exist for fatigue assessment of complicated thread profiles that include the effects of stress concentration at the critical thread root, variable amplitude loading, and preload on the connection.

Three major approaches are: (1) the *stress-based* approach, where the nominal (average) stress that can be resisted under cyclic loading is determined by considering mean stresses, (2) the *strain-based* approach, which accounts for localized plasticity in the thread root, and (3) the *fracture mechanics* approach, which predicts the initiation of growing cracks in the thread root [Dowling]. The most commonly used approaches are *stress* and *strain* based, and hence, will be detailed in Sections 4.2.3.2 and 4.2.3.3. The *fracture mechanics* approach is only briefly outlined in Section 4.2.3.4, but is discussed with applications to threaded connections for tubular structures in Buitrago 1998, and Chen.

4.2.3.1 Definition of Parameters

In both the *stress-based* and *strain-based* techniques, a clear definition of the cyclic stress range, mean stress, stress amplitude, and the connection (preferred) *stress versus number of cycles to failure* (*S-N)* behavior, analytically predicted or physically determined, must be provided. Variable loading amplitudes, and their affect of fatigue life must also be considered. General descriptions of the key elements of fatigue assessments for the two dominant approaches are given in the sub-sections that follow.

4.2.3.1.1 Local Stress

When performing a fatigue strength assessment of the threaded connection, failure is assumed to occur at the most highly stressed region (FCL). Total stress in the critical region resulting from cyclic loading may be derived from finite element analyses, or from the product of nominal stresses in the pipe body (S_P) or thread root cross-section (S) and the appropriate stress concentration factor (K_t or K_t'', respectively). Local stress values developed in either manner can then be presented in terms of the stress range

$$\sigma_r = \sigma_{MAX} - \sigma_{MIN}, \tag{4-18}$$

the mean stress

$$\sigma_m = \frac{\sigma_{MAX} + \sigma_{MIN}}{2}, \tag{4-19}$$

and the peak stress

$$\sigma_p = \sigma_m + \frac{\sigma_r}{2}. \tag{4-20}$$

Each of the local stress quantities is shown graphically in Figure 4-7, where t is the time. Use of "peak" in fatigue calculations refers to the maximum total stress in the critical region as shown in the figure.

While finite element methods for the direct determination of elastic-plastic local stress response do exist, they are typically more computationally intensive and hence, the total stress quantities in Equations 4-18 through 4-19 are usually defined by the elastic response. In *strain-based* techniques, the elastic local stress can be converted to elasto-plastic stress to improve accuracy of fatigue life predictions. The procedures used in the conversion are discussed in detail in Section 4.2.3.3.

It is important to note that if local stress values are calculated via the SCF technique using nominal pipe values and K_t, and K_t is not linearly related to the pipe body stress, the local mean stress σ_m can not be precisely calculated. Additionally, nonlinearity of the SCF to pipe stress may be the result of a preload, in which case initial stresses at the thread root are produced that are unrelated to pipe body stress. If significant nonlinearity does exist (from preload and/or geometric effects), an instantaneous SCF may be used, equal to the dynamic stress concentration factor K_t^D as calculated in Section 4.2.2.4, to relate the pipe stress range to the local stress [Buitrago 1998].

For fatigue calculations, the local stress quantity used for comparison with uniaxial fatigue life curves is the stress amplitude, σ_a. If no static loads are present in the fatigue curve or analyses (i.e.; $\sigma_m = 0$), and the loading mode is uniaxial, then σ_a is simply the stress range divided by 2 ($\sigma_a = \sigma_r/2$). If mean stresses are present, then a fully reversible stress amplitude σ_{aREV} must be calculated for comparison with a fatigue curve excluding mean stress effects. The Goodman relation,

$$\sigma_{aREV} = \frac{\sigma_a}{1 - \dfrac{\sigma_m}{\sigma_U}} \tag{4-21}$$

where σ_U is the ultimate strength of the material, is one popular method of relating mean and amplitude stresses to the fully reversible amplitude needed for comparisons.

If local stresses have been developed from multiaxial loading conditions, then an equivalent uniaxial stress amplitude, $\bar{\sigma}_a$ must be calculated if the results are to be compared with fatigue strength relations that have been developed for uniaxial loading conditions. If mean stresses are not present in the analysis $\bar{\sigma}_a$ is calculated from the maximum and minimum principal stress amplitudes, σ_{a1}, σ_{a2} and σ_{a3} that have been determined from the stress tensors (σ_{ij}^{MAX} and σ_{ij}^{MIN}) or finite element analyses, and the von Mises relation is used.

$$\bar{\sigma}_a = \frac{1}{\sqrt{2}}\left[(\sigma_{a1} - \sigma_{a2})^2 + (\sigma_{a2} - \sigma_{a3})^2 + (\sigma_{a3} - \sigma_{a1})^2\right]^{\frac{1}{2}}. \tag{4-22}$$

Again, Maximum-shearing stress theory may be used instead of Equation 4-22.

For applications where the principal axes rotate during cyclic loading, the applicability of Equation 4-22 and the Maximum-shearing stress theory is questionable, and alternate approaches for determination of $\bar{\sigma}_a$, such as the *critical plane* approach, may be pursued [Dowling]. For most fatigue calculations of threaded connections, it is assumed that principal axes remain unchanged during cyclic loading, which may be the case for specific load types, thereby justifying the use of Equation 4-22.

If static loads are present, an effective mean stress can be calculated from the mean stresses in the three principal directions from static analyses [Dowling]:

$$\bar{\sigma}_m = \sigma_{m1} + \sigma_{m2} + \sigma_{m3}. \tag{4-23}$$

Then, the equivalent fully reversible uniaxial stress for comparison with a corresponding uniaxial *S-N* curve may be expressed as

$$\bar{\sigma}_{aREV} = \frac{\bar{\sigma}_a}{1 - \dfrac{\bar{\sigma}_m}{\sigma_U}}. \tag{4-24}$$

Similar relationships exist relating a stress range (or amplitude) and mean stress to equivalent fully reversible stress amplitudes such as that suggested by ISO Standards [Buitrago 1998], relating stress amplitudes to mean stress at constant life. (See Section 4.2.3.2).

It is important that the designer understand the implications associated with each representation so as to ensure conservatism of the design. Section 5 outlines some deficiencies related to application of Equation 4-24 in the assessment of compressive mean stresses for caisson structural design.

4.2.3.1.2 Notch Sensitivity Factor, Kf

The elastic stress concentration factor K_t remains valid only up to yielding. Hence, for fatigue analyses that include inelastic stress or strain contributions in the development of local stresses or fatigue-life relations, the use of K_t may not provide the most accurate results. To improve the accuracy of fatigue calculations, a fatigue notch factor, K_f, can be substituted for the elastic stress concentration factor K_t in *stress-based* calculations and *strain-based* calculations employing Neuber's Rule (Section 4.2.3.3.2). This factor essentially relates the fatigue strength of an unnotched member to its notched fatigue strength at a given life [Bannantine], and considers the effects of notch sensitivity. One empirical relation for K_f, proposed by Peterson [Peterson], is

$$K_f = 1 + q(K_t - 1), \tag{4-25}$$

where K_t is the elastic stress concentration factor, and q is the notch sensitivity factor equal to

$$q = \frac{1}{1 + \dfrac{\boldsymbol{a}}{\boldsymbol{r}}}\,. \qquad (4\text{-}26)$$

Here, $\boldsymbol{r}$ is the notch radius, and $\boldsymbol{a}$ is a material constant. For relatively high strength steels, Dowling suggest a value for $\boldsymbol{a}$ equal to

$$\alpha = 0.001\left(\frac{300\,ksi}{\acute{o}_{U}}\right)^{1.8}. \qquad (4\text{-}27)$$

Other values of $\boldsymbol{a}$ have been suggested by ISO Standards as outlined in Buitrago 1998. Peterson [Peterson] defines various value of K_f for many materials and notch sensitivities.

In general, differences between K_t and K_f become almost negligible as the notch radius increases. Conversely, if $\boldsymbol{r}$ is small, the difference between K_t and K_f may be large, and the use of K_t will lead to conservative life predictions, attributed to the overestimation of notch effects based in elastic stress concentration. For simplicity, the following discussions on the *stress*- and *strain-based* approaches include use of the elastic stress concentration factor, K_t.

4.2.3.1.3 Variable Amplitude Loadings

For variable amplitude loading such as that shown in Figure 4-8, the Palmgren-Miner rule (commonly referred to as Miner's Rule) may be used to determine the cumulative fatigue damage imposed on the structure during the entire load history. Miner's rule states that the sum of the ratios of the number of cycles at a given amplitude N_i to the number of cycles to failure for that amplitude N_{fi}, will equal unity (1) at failure. Stated mathematically for a total of n incidents,

$$\frac{N_1}{N_{f1}} + \frac{N_2}{N_{f2}} + \frac{N_3}{N_{f3}} + \ldots \frac{N_n}{N_{fn}} = \sum_{i}^{n} \frac{N_i}{N_{fi}} = 1\,. \qquad (4\text{-}28)$$

Note that some cycles of variable amplitude loading may include mean stresses, for which a fully reversible stress amplitude must be calculated [Dowling].

To relate the complex cyclic loading history found offshore to available constant amplitude test or analysis data, some method of cycle counting must b performed. The most common approaches to cycle counting include:

- level-cross counting,
- peak counting, and
- simple-range counting.

One of the most popular techniques currently employed for counting highly irregular loading cycles is *rainflow cycle counting*.

Considering the peak counting method, local maximum and minimum strain levels (or stress or load levels) are identified, and these peak value are then used to form complete cycles for fatigue assessment. For example, the first cycle may be performed by combing the maximum and minimum peak magnitudes to define a single large cycle. Subsequently cycles are then formed by combining sequentially decreasing maximum and minimum magnitudes into full cycles. Other methods of combining counts exist [Bannantine], and usually, the most damaging combination of cycles is represented in fatigue assessment.

4.2.3.2 Stress-Based Fatigue Analysis

Stress-based fatigue assessment is widely used in the evaluation of a variety of metals, and materials which contain notches or geometric discontinuities. Simply stated, the *stress-based* approach involves the calculation of local total stress quantities as in Section 4.2.3.1.1, and the comparison of these stresses to a *S-N* curve for the connection (preferred), or the connection material.

Several presentations of the of the *stress versus number of cycles to failure* (*S-N*) behavior for materials exist, as do curves for specimens with geometric discontinuities and some threaded connection designs. Such curves typically represent the *S-N* behavior in terms of a uniaxial local stress amplitude (s_a or s_{aREV}) versus cycles to failure (N_f), at various levels of mean stress (s_m) as shown in Figure 4-9. (Fatigue life data may also be presented in terms of the *strain versus number of cycles to failure* for strain-based assessments.) For the fatigue life evaluation of a given design, curves such as those shown should be obtained for each of the anticipated load types (e.g., axial tension or compression, and/or bending).

The effects of mean stresses can also be presented in the form of a constant life, or amplitude-mean diagram. Figure 4-10 displays the relation between stress amplitude and mean stress and constant life increments. A qualified *S-N* curve for a given connection design can be developed through physical fatigue testing of the connection to failure. Such curves are preferred since they include the effects of local stress concentration, relative displacement throughout the connection, and load redistribution. (Localized plasticity at the thread root region is also included.) Since local stress analyses attempt to include each of these effects, comparison of the analysis results with the qualified fatigue curve for the connection provides the most accurate results. However, often times the cost and scale (large diameter) of the connection disallows such physical testing. In those cases, unnotched fatigue curves developed for the connector material, which are more readily available, may be used. In cases where fatigue curves for either the connection or the material are nonexistent, the *strain based* approach may be used to analytically derive the relationship between local strains and fatigue life (N_f). (See Section 4.2.3.3.)

Following identification of the appropriate fatigue life curve(s), the corresponding fully reversible uniaxial stress amplitude, calculated as in Section 4.2.3.1.1, is compared with the fatigue life curve to determine the number of cycles to failure N_f. Note that the uniaxial stress amplitude may be that due to uniaxial loading analyses (s_{aREV}), or an equivalent value ($\bar{o}_{aREV}$) from multiaxial loading analyses. In either case, the effects of mean stress must be included in both the fatigue curve and fully reversible uniaxial stress amplitude.

Fatigue life computations should be made for each load type experienced, and for variable amplitude loading. The procedure described above is applied to determine the fully reversible uniaxial stress (or effective stress) at the FCL, for a given loading mode that can include axial, bending, and pressure loading (or combinations thereof if effective stress amplitudes are used). Once variable load amplitudes have been identified and the ratios N_i / N_{fi} defined, Miner's Rule is used to define cumulative fatigue damage for the connection.

4.2.3.3 *Strain-Based Fatigue Analysis*

A strain-based approach (also defined as Initiation Life) is usually more appealing than a *stress-based* fatigue assessment since it accounts for localized plasticity in the critical thread root region. This approach is also more easily implemented than a *fracture mechanics* approach, which generally requires sophisticated modeling techniques to determine crack propagation behavior.

Using finite element analysis to determine local stresses in the critical region, and detailed static and cyclic properties material descriptions, the Smith, Watson, and Topper (SWT) Parameter [Dowling] can be solved for the number of cycles to failure, N_f,

$$\acute{o}_{aREV}\varepsilon_{aREV} = \frac{\left(\acute{o}'_f\right)^2}{E}\left(2N_f\right)^{2b} + \acute{o}'_f\varepsilon'_f\left(2N_f\right)^{b+c} \qquad (4\text{-}29)$$

where s_{aREV} and e_{aREV} are the fully reversibly local stress and strain amplitudes, and the quantities $\acute{o}'_f$, e'_f, E, b and c are material constants (for connection material) as defined in Section 2. Note that for multi-axial loading equivalent stress and strain quantities, $\bar{o}_{aREV}$ and $\bar{e}_{aREV}$, may be used. The SWT parameter ($s_{aREV}e_{aREV}$) includes the effect of non-zero mean stress, and usually provides good estimates of fatigue life for a number of materials, but may give non-conservative results for mean compressive stresses [Dowling]. Alternate relations, such as strain-life curves based on the Manson-

Coffin method may be used to conveniently display the *strain versus number of cycles to failure* behavior. In such a formulation, employing the parameter σ'_f,

$$\varepsilon_{aREV} = \frac{\sigma'_f}{E}\left(1 - \frac{\sigma_m}{\sigma'_f}\right)\left(2N_f\right)^b + \varepsilon'_f\left(1 - \frac{\sigma_m}{\sigma'_f}\right)^{\frac{c}{b}}\left(2N_f\right)^c \qquad (4\text{-}30)$$

ε_{aREV} is directly related to the material properties and mean stress, and provides a method of graphically estimating the fatigue life. In Equation 4-30, the Morrow parameter, σ'_f, is the fatigue strength taken from the uniaxial *S-N* curve of an unnotched specimen. Selection of the method that best represents the actual behavior of the connection should ultimately be based on physical test verification.

For either of the methods presented, the equivalent fully reversible stress and strain amplitudes (σ_{aREV} and ε_{aREV}), or their equivalents must be determined. A relation for the effective fully reversible stress, which includes mean stress effects, is proposed by ISO Standards (and Buitrago 1998),

$$\sigma_{aREV} = \left[\frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma'_f}}\sqrt{\left(\sigma_m + \sigma_a\right)\sigma_a}\right]^{\frac{1}{2}} \qquad (4\text{-}31)$$

and is similar to the relation expressed in Equation 4-24. Selection of the formulation used to calculate σ_{aREV} should be based on knowledge of the limitations and potential for nonconservative results for a given formula, and on the accuracy of predictions when compared with physical test data.

By applying the cyclic stress-strain relation for the material, the fully reversible strain amplitude is:

$$\varepsilon_{aREV} = \frac{\sigma_{aREV}}{E} + \left(\frac{\sigma_{aREV}}{H'}\right)^{\frac{1}{n'}}. \qquad (4\text{-}32)$$

The values H' and n' are the material strain hardening coefficient and exponent, respectively.

For strain-based methods, Equations 4-31 and 4-32 represent the fully reversible and equivalent elasto-plastic stress variations at the FCL. Elasto-plastic behavior is developed from the transformation of elastic response quantities in the FCL, derived from finite element analyses, and applying: (1) Equivalent Strain Energy Density (ESED, Section 4.2.3.3.1), or (2) Neuber's Rule (Section 4.2.3.3.2).

Once the elasto-plastic response is determined by either ESED or Nuerber's Rule, Equations 4-29 or 4-30 can be solved at varying levels of stress to develop an analytical *S-N* curve for the connector. As in the *stress-based* analysis approach, fatigue life computations should be performed for each loading mode present, and variable amplitude loadings addressed by Miner's Rule.

4.2.3.3.1 Equivalent Strain Energy Density (ESED)

Given the elastic stress range and peak stress in the FCL, the elastic strain energy is equated to elasto-plastic strain energy by the relation for cyclic stress-strain behavior of the material [Buitrago 1998]:

$$\frac{\left(\sigma_r^{ep}\right)^2}{2E} = \frac{\left(\sigma_r^{e}\right)^2}{2E} + \frac{\sigma_r^{ep}}{n'+1}\left(\frac{\sigma_r^{ep}}{H'}\right)^{\frac{1}{n'}} \tag{4-33}$$

where σ_r^{e} is the elastic stress range at the critical thread root region from finite element analysis. Equation 4-29 is solved for the transformed elasto-plastic stress range, σ_r^{ep}. (Note that this definition of the stress range differs from that previously given for elastic behavior (Equation 4-18) only in that some plasticity is contained the current computation for *strain-based* fatigue analyses.)

Substituting the peak local elastic stress value σ_p^{e} from finite element analyses for the stress range in Equation 4-29 results in definition of the fully reversible elasto-plastic peak stress σ_p^{ep}. Definition of the transformed elasto-plastic mean stress σ_m^{ep} for Equations 4-30 and 4-31 becomes

$$\sigma_m^{ep} = \sigma^{ep} - \frac{\sigma_r^{ep}}{2}. \tag{4-34}$$

The number of cycles to failure N_f is then determined by solving Equations 4-31 and 4-32 for elasto-plastic stress and strain quantities $\boldsymbol{\sigma}_{aREV}$ and $\boldsymbol{\varepsilon}_{aREV}$, respectively, and substituting these values directly into Equation 4-29.

4.2.3.3.2 Neuber's Rule

Neuber's rule offers a closed-form solution for definition of the local strain occurring in the FCL during plastic deformation. The rule states that the geometric mean of the stress and strain concentration factors remain constant during plastic deformation [Dowling]. For a stress concentration factor relative to the pipe body stress k_s (equal to $\acute{o}/S_p$), and strain concentration k_e factor defined as

$$k_{\varepsilon} = \frac{\varepsilon}{e_p} \tag{4-35}$$

where ***e*** is the local strain at the FCL and e_P is the nominal strain in the pipe body, Neuber's rule defines the stress concentration factor during loading (and plasticity) as

$$k_t = \sqrt{k_{\sigma} \cdot k_{\varepsilon}} \tag{4-36}$$

and by substituting definitions for k_s and k_e into the above equation, Neuber's rule becomes

$$\acute{o}\varepsilon = \frac{(k_t \cdot S_P)}{E}. \tag{4-37}$$

This relationship remains valid up to fully plastic yielding [Dowling].

Elasto-plastic local stresses at the FCL can be calculated by combining the relation for cyclic stress-strain behavior with Neuber's rule, yielding

$$\acute{o}_r^{ep}\left[\frac{\acute{o}_r^{ep}}{E} + \left(\frac{\acute{o}_r^{ep}}{H'}\right)^{\frac{1}{n'}}\right] = \frac{k_t^{\,2}}{E}\left(\frac{S_{Pr}}{2}\right)^2 \tag{4-38}$$

which can be solved for the elasto-plastic stress range $\acute{o}_r^{ep}$. The elasto-plastic peak stress $\acute{o}^{ep}$, accounting for pipe body mean stress, is similarly calculated as

$$\acute{o}_r^{ep}\left[\frac{\acute{o}_r^{ep}}{E} + \left(\frac{\acute{o}_r^{ep}}{H'}\right)^{\frac{1}{n'}}\right] = \frac{k_t^{\,2}}{E}\left(S_{Pm} + \frac{S_{Pr}}{2}\right)^2. \tag{4-39}$$

Note that Equations 4-38 and 4-39 require knowledge of the pipe body stress range, and the stress concentration factor k_t. It is generally sufficient to assume the elastic stress concentration factor calculated in Section 4.2.2 provided that nonlinearity between the SCF and the applied loads is negligible. However, if significant nonlinearity does exist, the dynamic stress concentration factor K_t^D may be used (Section 4.2.3.1.1).

If the local elastic mean stress at the FCL is known, Equation 4-39 becomes

$$\acute{o}_{r}^{ep}\left[\frac{\acute{o}_{r}^{ep}}{E}+\left(\frac{\acute{o}_{r}^{ep}}{H'}\right)^{\frac{1}{n'}}\right]=\frac{k_{t}^{\,2}}{E}\left(\acute{o}_{m}+\frac{S_{Pr}}{2}\right)^{2}. \qquad (4\text{-}40)$$

Again, the elasto-plastic mean $\acute{o}_{m}^{ep}$ stress is calculated as in Equation 4-34, Equations 4-31 and 4-32 are solved for the fully reversible equivalent stress and strain quantities $\boldsymbol{s}_{aREV}$ and $\boldsymbol{e}_{aREV}$, and N_f is determined from Equation 4-29.

4.2.3.4 Fracture Mechanics Based Fatigue Analysis

In addition to the *stress-based* and *strain-based* approaches, which predict the life to initiation of a fatigue crack, a *fracture mechanics* approach can be applied to predict propagation of the crack to some critical length, and ultimately, fracture of the connection. One benefit of such an analysis is the ability to define the frequency of inspection based on crack growth considerations. However, such methods are often difficult to implement since detailed material definitions and crack growth and propagation characteristics are needed.

Fundamentally, the fracture mechanics approach involves assuming an initial crack of some length, say the minimum detectable length or nominal size of flaws from manufacturing, a_d, is present in the connector. Under cyclic loading, the crack grows until reaching a critical crack length, a_c, at a number of cycles N_f, and failure occurs. Growth of the crack to this critical length is controlled by the nominal stress range S_r in the FCL. They are related mathematically through the stress intensity range, ΔK, as

$$\Delta K = F\,S_r\sqrt{\boldsymbol{p}\;a} \qquad (4\text{-}41)$$

where F is a dimensionless function of the ratio of the crack length to the width of the component in the direction of the crack. Note that the stress range S_r is usually based on the nominal stress range in the *uncracked* cross-section of the FCL. Resolving the stress range in to maximum and minimum quantities, ΔK can be more clearly defined as

$$\Delta K = K_{max} - K_{\min} \qquad (4\text{-}42)$$

where

$$K_{max} = F\,S_{max}\sqrt{\boldsymbol{p}\;a}\,,$$

(4-43)

and

$$K_{min} = F\,S_{min}\sqrt{\boldsymbol{p}\;a}\,. \qquad (4\text{-}44)$$

To determine the number of cycles to failure N_f, the stress range (through the stress intensity range) is related to the cyclic crack growth rate, expressed as the change in crack length over the change in the number of cycles. Simplistically, that is,

$$\frac{da}{dN} = C(\Delta K)^m \tag{4-45}$$

where da/dN is the crack growth rate, C is a constant and m is the slope of the log-log plot of da/dN versus ΔK.

Cracking continues until failure occurs at the critical crack length a_c, which occurs a maximum stress S_{max}, and when K equal K_c, the fracture toughness of the material. Or

$$a_c = \frac{1}{\pi}\left(\frac{K_c}{S_{max}\,F}\right)^2 . \tag{4-46}$$

With the initial and final crack lengths now known, Equation 4-45 is integrated between these lengths to determine the number of cycles to failure, N_f.

The “whole life” of the connection under fatigue loading can be determined by summing the initiation life (calculated in the previous approaches) with the propagation life outlined here. More detail on a “whole life” approach is given in Buitrago 1998 and Chen.

4.2.4 Design Optimization

Finite element analyses are a valid and economical means by which initial designs can be evaluated and the results used to identify key design details, which may be modified to improve connection performance. Initial connection designs that fail to meet the specified acceptance criteria often exhibit excessive stress concentration in the threaded region and/or diameter upsets, a propensity for excessive deformations, or disengagement under the applied loads, thus limiting the connection capacity. Other considerations, such as the required tolerances on manufacture of the connection can also be cursorily addressed. Most improvements required for success of the design are related to the geometry of the threaded region, and hence, optimization of the connection focuses on key features of the thread profile, which can be altered to improve uniformity of loading (and stress and deformation) throughout the connection. Some of the design features examined in typical optimization studies are briefly discussed in the following paragraphs.

It is important to again emphasize that the design and corresponding performance of the connection is highly dependent on the connection geometry, and the load types and magnitudes to be resisted. While the discussions that follow highlight some of the primary considerations for design optimization, they constitute only a partial listing of the many features that can be modified for a design. Current manufacturers employ design optimizations like those discussed, as well as the optimization of many other features, which are specific to their proprietary designs.

4.2.4.1 Thread Profile

As shown in Appendix B, selection of the thread profile governs the effectiveness of load transfer and strength of the connection. Whether or not the profile is tapered or straight will dictate the uniformity of load distribution through the connection. A more uniform load distribution is desirable since tooth loads will be roughly equal, and hence, stress concentration factors are essentially equal. The benefit here is that one highly stressed tooth position does not drive failure of the entire connection, while adjacent teeth stresses remain well below yield. Instead, all teeth can be loaded to a level nearer to yield, resulting in a higher strength design. A tapered profile with a straight load path (no eccentricity) usually allows for increased uniformity of loading when compared with a straight profile. Optimization of the thread height-to-base ratio, by specifying lower ratios (stouter) in highly loaded region may also help to equalize tooth loads.

The profile selected will also affect the procedures and time required for makeup of the connection. Tapered profiles allow for easy stabbing of the pin into the box, which lessens alignment restrictions. Many current tapered designs also provide for full makeup (complete sealing and tooth/shoulder contact) with only a minimum of turns (or fraction of a single turn) through multiple thread starts. These designs usually provide quicker makeup times when compared with their straight profile counterparts.

4.2.4.2 Differential Tooth Pitch

A differential tooth pitch can be used to improve uniformity of load transfer through the connection teeth. The designer may specify an increased number of teeth adjacent to the region of highest load, and transcend to a smaller number of teeth away from the load — a higher concentration of teeth available to absorb loading helps to more evenly distribute the tooth loading throughout the connection. A differential pitch may also be used to compensate for the Poisson’s ratio effect induced by radial straining during makeup [Gunderson].

4.2.4.3 Flank Angles

Flank angles may be optimized in any given design to assist with stabbing, makeup, and breakout of the connection. For most high performance designs, negative flank angles may be used to help reduce separation of the pin and box under radial loading or bending. Again, optimization of the leading and trailing flank angles will be highly dependent on the connection configuration.

4.2.4.4 Root Radius and Thickness Transitions

Stress concentrates in regions of geometric discontinues. As discussed earlier, complex membrane and bending stresses exists at the thread root that are imposed not only by axial loading on adjacent teeth, but by the dramatic geometric discontinuity which serves to amplify nominal membrane stresses. Altering the radius at the thread root may reduce the local stress magnitude to an acceptable level for the design. Similarly, the transitions at internal and external diameter upsets can be optimized to produce minimal stress concentration.

4.2.4.5 Stress Relief Grooves

Stress relief grooves may be installed between the trailing tooth (tooth furthest from the pin or box free end) and the shoulder to relieve stress on the tooth, which is usually most highly loaded, and help to improve uniformity of loading throughout the connection.

4.2.4.6 Interference

Initial interference in the made-up connection can be used to generate some preload in the connection, and insure mating of pin and box teeth. Although axial preloading from makeup torque will dominate axial displacements in the connection, a radial preload from an initial radial geometric interference may considered. Gunderson reports that a radial preload from radial interference may eliminate the need for preload shoulders, resulting in longer thread length and thinner taper runout. The increased thread length will result in lower load per thread, and the thinner runout improves uniformity of the thread load [Gunderson].

4.3 VALIDATION

Validation of the connection design though physical testing is generally required; although, for large diameter connections, availability of test equipment capable of producing failure loads on the connection may be limited. Wherever possible, physical testing using either full or scaled specimens should be performed to:

- verify design strengths predicted by classical and finite element analyses,
- ensure makeup and breakout performance and predicted load levels, and
- assess the effects of scale, surface defects, metallurgical and environmental conditions, which can not be accounted for in any analysis [Buitrago 1988], on the predicted design strength.

Because of practical limitations to physical testing (e.g., size of connection, capacity of equipment, and expense), scale testing, and the feasibility of extrapolating scale test results to connection designs must be considered.

4.3.1 Testing

Assessment of the connection response in a physical test environment usually involves measurement of an accurate loading history, using load cells and pressure transducers (to measure loading ram hydraulic pressures that can be later converted to load), and corresponding strain measurements at critical and nominal positions, using strain gages or photoelastic methods. Other measurements, such as specimen deflection under axial loading or bending, and rotation of the specimen during axial bending, may provide additional information that can be used to verify key modeling assumptions (e.g., boundary conditions, simplistic model geometries, and material properties). Moreover, some redundancy of primary measurements, such as load and strain, should be included to confirm the accuracy of measurements, and to provide back-up measurements should failure of primary instrumentation occur.

The ability to use strain gages in highly loaded thread regions is somewhat limited by the geometry of the connection and durability of instrumentation when subjected to high loadings. However, their use is ideal since a direct measurement of highly localized straining can be made. Some caution should be used in the interpretation of test strains and ensuing comparison of the results with finite element analyses. In most cases, strain obtained at the model nodes will exceed those measured, and some averaging of the strains over multiple nodes or element areas is required for reasonable comparisons.

To obtain premium validation data for comparison with analyses, every effort should be made to exactly duplicate, to the extent possible, the loading and boundary conditions applied in the analytical procedure. (Note that if the physical test can not duplicate such conditions, the finite element model should be modified to reflect any discrepancies.) Exact levels of preload, to the tolerances that can be measured, should be applied, and although the connection should be designed to prohibit load path sensitivity, the sequence of loadings in the test should duplicate those of the analyses. During the interpretation of results, some thought should be given to the inherent difficulties with duplicating the analysis conditions, and further, to the inability to exactly duplicate conditions for two identical tests. If desired, probabilistic structural analyses can be used to quantify the degree of anticipated scatter.

General guidance on the number of tests to be performed for validation of each design parameter is given by API [Turner]. It is usually appropriate to perform three identical tests to improve the confidence level of the results, as is recommended by ASTM and others. However, for large diameter connections, cost and size considerations precludes testing of a large number of connections. In such cases, new methods based on probabilistic structural analysis and verification techniques may be applied. These methods are used to define a test matrix based on assessment of only the key design parameters influencing structural performance. This technique is most useful for cases in which a failure, considering a large number of design parameters and their combined effects, must be assessed.

4.3.1.1 Strength

Determination of the static strength of the connection usually involves the application of static loads (e.g., pressure, axial, bending, and preload) to failure of the connection. Depending on the design philosophy used, failure of the connection under the static service load may occur in the pipe wall, as in coupling designs, or in the threaded region, as in threaded pipe connections. Hence, during physical testing, the test specimen for coupling design evaluations must be configured such that failure occurs in the connection and not in the pipe wall. Most researchers [Buitrago 1989] will install the connection within nominal pipe sections with increased thickness (and capacity) to force failure to occur within the connection. For the purposes of model validation, some analysis of the actual test configuration, with increased nominal pipe geometry, should be considered. Such difficulties may not be encountered with threaded pipe connections since the design is based on failure within the connection.

If the assembled tubular structure will be driven during installation, testing to simulate driving should be performed. The connection must be shown to successfully withstand driving forces without impairing its structural performance, and to provide an efficient means of transferring hammer energy [Buitrago 1988]. In addition to strength evaluation, a driven connection should be used to assess breakout torque needed for retrieval.

In all physical tests, the specimen should be made-up using conditions identical to those anticipated during in field installation.

4.3.1.2 Fatigue

Ideally, fatigue testing should be performed to ascertain accuracy, or at least trends, of the finite element model and fatigue calculations (Section 4.2.3). The test specimen, with special configurations as discussed in the previous section, should be loaded to fatigue failure under each of the anticipated fatigue loading modes. These may include bending fatigue, which may be rotating bending, and/or axial, to simulate vessel motions. For complete validation of fatigue predictions, static design loads (including preload) should also be imposed during fatigue testing to evaluate predictions of the fatigue life as a function of mean stresses.

The effects on fatigue strength due to loading in a free-corroding environment should also be investigated. Results of such tests can be used to confirm a reduced capacity when compared with in-air fatigue strengths, which can not be modeled in analyses.

Following testing, such post-mortem examination of the failure location should be performed to determine if surface or microstructural defects, such as hard inclusions, initiated failure. The mode of critical cracking, be it the coalescence of many microcracks or the formation of a single critical crack can also be assessed post-mortem. Grain elongation measurements and crack lengths can also provide useful information on the suitability of the material for the given application.

Note that there will typically be a large scatter in fatigue results, which may not provide reliable validation of analytically developed fatigue curves, or fatigue life predictions. It is well documented that such scatter may be attributed to differences in actual test loadings when compared with modeling assumptions, and to surface and microstructural variations, imposed by manufacture or quality of the material, that can not be accounted for in analyses. Thus, physical testing results usually provide qualitative information, which can be used to verify general stress levels, trends in behavior, and modeling assumptions.

4.3.1.3 Make-Break Tests

The required torques for full makeup and breakout can be assessed in make-break tests. The designer usually has an initial estimate of the required torques from design calculations and analyses, and may need to verify these predictions on prototype connections where manufacturing tolerances become important. It is also desirable to perform break tests on specimens that have been allowed to freely corrode in a saltwater environment, and/or connections that have been driven, so that initial breakout torque, can be defined.

4.3.1.4 Manufacturing Considerations

The ability to manufacture a functional and reliable connection can be assessed through fabrication of a prototype connection. The prototype, which may be used in subsequent physical testing, should be measured to assure dimensional tolerances are within specification. Measurements should include both the profile features and surface finish.

4.3.2 Extrapolation of Testing and Analysis Results

As emphasized throughout this section, connection performance under static, dynamic, and fatigue loadings is highly dependent on the connection geometry, and some difficulty in producing reliable and repeatable results (attributed to limitations on testing conditions) may be encountered. When considering large diameter connections, test equipment capable of generating severance load levels is extremely unique, or the tests may become far too costly to perform in full-scale. In such cases, validation testing may require the use of scale models, which can then be correlated with corresponding scale analysis models in an effort to supplement and/or validate analytical predictions.

The underlying assumption in scale model testing is that analytical procedures and results, if well validated against corresponding scale tests, can be used to reliably predict the behavior of the full-scale connection of a variety of conditions. Researchers have addressed the use of scale testing of connections, and have demonstrated that reasonable correlation between models scaled to differing proportions of the same connection exists [Buitrago 1989]. However, further complicating the inherent difficulties of physical testing of scaled designs, is the inability to scale fatigue critical effects such as the surface finish, microstructure (and associated defects), and manufacturing tolerances that may complicate accurate interpretation and application of the results.

When developing a scale model for testing and analysis, the geometry should be developed in exact scale proportion with the full-size design. For example, a half-scale model of a 40-inch diameter connection with a 1-inch thread pitch would be 20 inches in diameter and possess a 0.5-inch thread pitch. All other thread profile dimensions in the half-scale model would be scaled as well. This includes thread engagement length, the ratio of diameter-to-thickness (D/t) of nominal pipe sections and the connector region, and all dimensional tolerances. Simply applying a design validated with a 20-inch diameter test connection to a 40-inch diameter connection, without direct scaling of the entire thread profile is invalid.

Scale modeling may not always be appropriate. The potential for development of alternate failure modes should be considered when extrapolating results to the full-scale design. Additionally, testing that is somewhat qualitative in nature, such as make-break testing, if possible, should be performed in full scale.

4.4 STANDARD THREADS

During this study, the design and analysis of threaded connections subjected to caisson-like loadings was performed. The analyses employed standard thread designs, using both straight and tapered profiles and *failure in the threaded connection* philosophy (i.e., where the threaded connection strength is less than the pipe body) to assess the general feasibility of using threaded connections in caisson applications. Selection of the standard profile designs, as opposed to highly optimized designs and coupling configurations, was based on the premise that the unmodified, widely available thread forms would provide a lower bound performance, adding conservatism in the assessment. Moreover, guidelines and recommendations regarding the use of threaded connections in caisson applications are intended to be generally applicable for all threaded designs, and existing standard thread patterns could potentially be used for coupling or threaded pipe configurations.

In all, four standard thread profiles were examined. The results of these analyses, detailed in Appendix B, validated the need for some optimization of the thread profile, particularly the thread height and root radius. This information provided valuable insight into the sensitivity of the threaded connection geometry and loading on stress concentrations.

4.4.1 Straight Threads

Three common straight thread profiles were selected to conduct stress analyses. The intent was to investigate the effects of thread height and flank angle. The three profiles that will be discussed are shown in their respective finite element model form, contained in Appendix B, and as schematics referenced in the sections that follow.

4.4.1.1 Acme

The General Purpose Acme profile is characterized by a 29 degree angle between the sides of the thread and a flat crest. The basic thread height is one half of the pitch, which is equivalent to the amount of axial distance covered by the thread form in one revolution. They are typically utilized in assemblies where the inner threads are fixed and the outer threads traverse axially while supported laterally by bearings [Oberg]. A General Purpose Acme thread profile is shown in Figure 4-11.

4.4.1.2 Stub Acme

The Stub Acme profile is very similar in profile and application to the General Purpose Acme; however, as the name suggests, the basic thread height is 30% of the pitch [Oberg]. The Stub Acme profile is shown in Figure 4-12.

4.4.1.3 Buttress

The buttress thread form has certain advantages in applications involving exceptionally high stresses along the thread axis in one direction only. This is attributed to the contacting flank, which takes the thrust, and its perpendicular orientation to the thread axis to reduce radial loading [Oberg]. A straight buttress profile is shown in Figure 4-13. API buttress thread profiles are usually tapered; however, to make a fair comparison with other straight thread forms, the taper was neglected in this portion of the modeling effort. The API buttress is characterized by unsymmetric 3-degree and 10-degree flank angles and a relatively low profile similar to the Stub Acme [API Spec 5B].

4.4.2 Tapered Threads (Tapered Buttress)

For comparative purposes with the straight threads, a tapered buttress design was modeled, and is shown in Figure 4-14. The conical taper was 1 inch over 1 foot [API Spec 5B]. Specifically, the API buttress thread form that has been adopted for casing sizes 16-inches and larger was used. The thread form was scaled up to create a 0.5-inch pitch.

4.4.3 Design and Analysis Approach

Standard thread performance is often analytically treated with empirical formulas based on a large database of test results or simple closed-form solutions that assume the load is distributed over a critical area. For example, the load needed to fail a threaded connection in shear is equal to the shear area multiplied by the yield stress of the material, or if tensile failure in the critical thread is assumed, the yield stress is then multiplied by the cross-sectional area at the critical thread. These formulas have been shown to work satisfactorily for all types of fasteners, from screws to bolts to relatively small diameter pipe. API Bulletin 5C3 provides formulas such as these for casing joint strength. More exact design calculations are often not required if the loading and failure mode are known.

4.5 EXISTING HIGH PERFORMANCE THREADED CONNECTIONS

High performance threaded connectors are available explicitly for use in risers, conductors, and TLP tendons. The primary difference between the thread forms, or profiles, present in these connectors and those described in Section 4.4 is that the high performance thread forms have been refined in an effort to more uniformly distribute the loading between all of the teeth. Naturally, a more uniform load distribution will reduce the stress concentrations present at the critical tooth or other discontinuities. By reducing the stress in the critical regions, a greater load capacity can be achieved for the same grade and amount of material present in the connector.

Two types of high performance threaded connections have been identified: (1) external couplings, and (2) intrusively threaded connections. The following sections discuss the general design characteristics and behavior of each type.

4.5.1 External Couplings

The first type of high performance threaded connector is designated as an external coupling due to the upset (or built up) pin and box design. As suggested, the design is comprised of pin and box sections that have been machined out of over-sized forged annuli. Upon completing the machining process, each section will be welded onto desired pipe joints. Once this is done, it is possible to thread the pin and box together thereby connecting the pipe joints.

As stated before, these proprietary connections have been thoroughly modified in an effort to reduce the stress concentration factor at the critical tooth. While each design is unique, there are common characteristics among the group of external couplings. The first is that a coarse, buttress-type tapered thread form is typically used. The relatively large nature of the thread form allows a wider range of geometric parameters to be optimized in an effort to reduce the critical SCF. For instance, since the critical location is typically at the thread root, a greater range in acceptable thread root radius should permit a lowering of the SCF. Also, negative flank angles are typically employed in an effort to improve the loading behavior of the connection and better maintain thread engagement. Another common characteristic of the couplings is that relatively large stabbing angles are employed that not only provide a more uniform load distribution but also aid in aligning the joints during assembly.

External couplings overcome the local stress concentrations at the thread root by using a thicker cross section, stronger material, or a combination thereof to reduce the stress in the critical tooth region below that of the nominal pipe body. As such, failure will occur in the pipe body and not the connector itself.

4.5.2 Intrusively Threaded Connections

The second alternative for a high-performance threaded connection is to intrusively thread the pipe body. This type of design eliminates the need for welding couplings onto a pipe by directly machining a thread form into the pipe wall. Once the threads have been machined, the pipe sections can be assembled in the same manner as the external couplings.

The overall development of the thread form is similar to that described in Section 4.5.1. The primary concern with machining a thread form into a pipe versus a forging is that the pipe must be sufficiently round initially and maintain its roundness after machining to prevent excessive runout and enable proper threading of the completed parts.

Unlike the external coupling that uses a built-up section to ensure that the pipe body will fail prior to the connector, the intrusively threaded coupling assumes that the failure occurs in the threaded region. As such, to achieve greater strength in the threaded connection, it is necessary to increase the wall thickness, steel grade, or some combination thereof, for the entire pipe.

4.5.3 Design, Analysis, and Validation of High-Performance Threads

The design, analysis, and validation approach adopted by most manufacturers is consistent with the associated API requirements and standard practices. As such, a program combining finite element analyses with validation and proof testing is employed for each new design. The applied loads generally consist of bending, axial, and pressure applied either individually or in combination with each other. In addition to static strength proof tests, fatigue, driving, and make-break tests may also be performed.

The testing and analysis program required for assessing small design changes, such as slightly increasing the diameter or nominal wall thickness, is generally determined using "engineering judgment." This means that the individual manufacturer will determine if it is realistic to scale an existing design or if a complete re-evaluation of the design must be performed. The factors defining "small change" and "new design" will vary between manufacturers, and, therefore, so will the extent of subsequent validation procedures.

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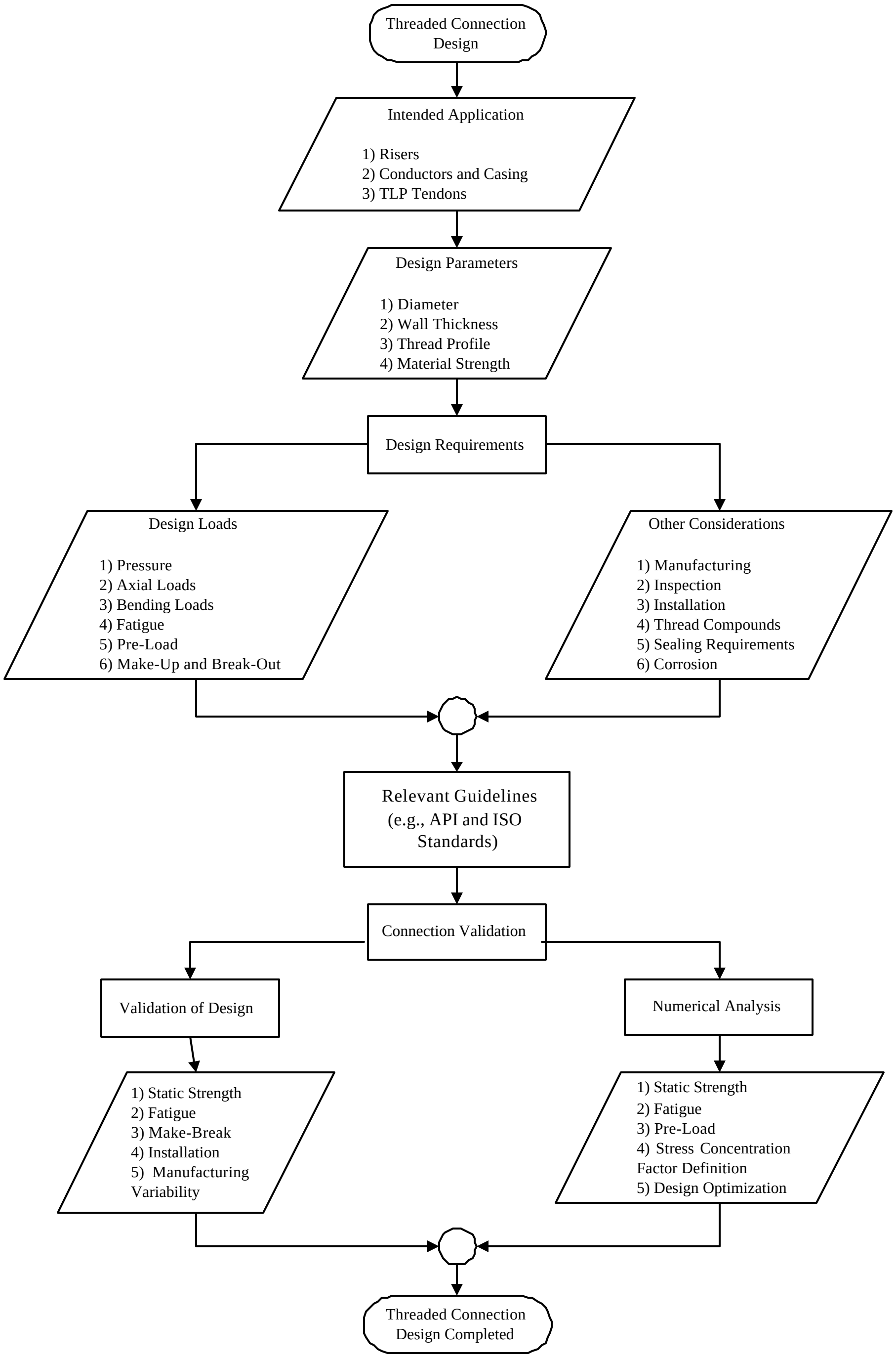

Figure 4-1. Overview of Connection Design

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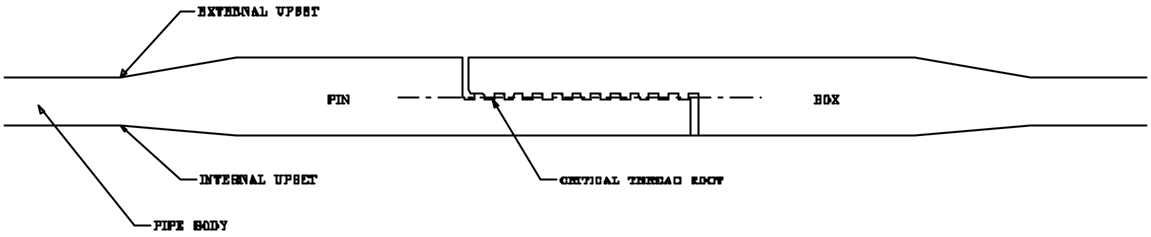
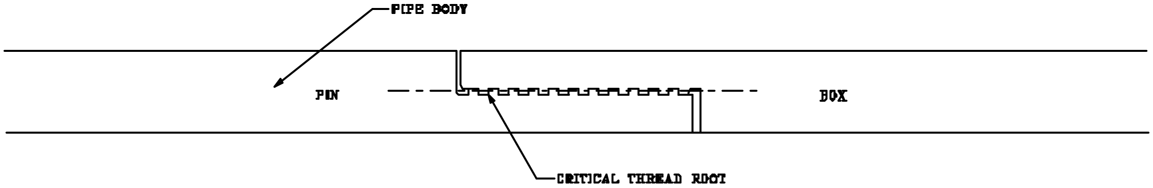


a. Critical locations for external coupling.



b. Critical location for intrusively threaded pipe.

Figure 4-2. Critical locations in threaded connections.

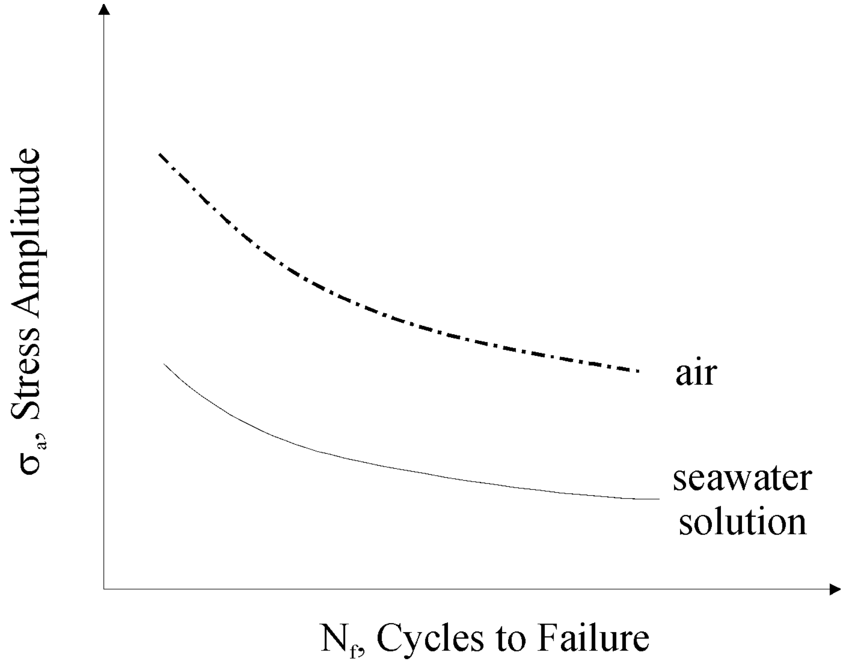


Figure 4-3. Seawater effect on fatigue.

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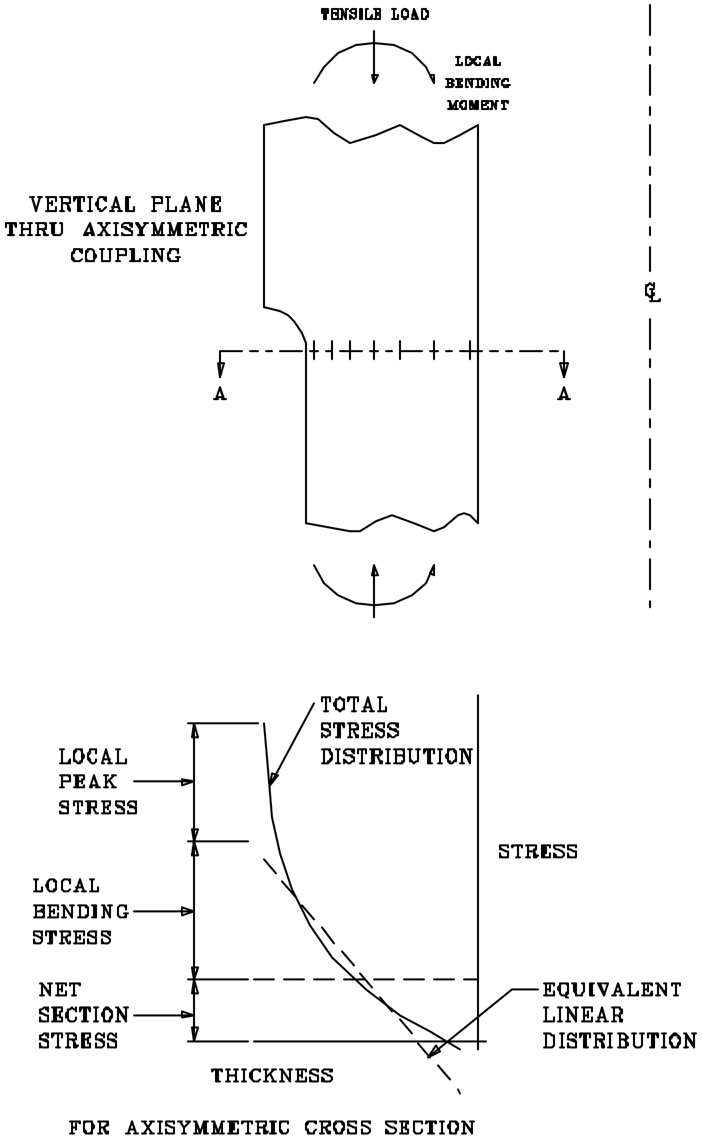

Figure 4-4. Stress linearization in critical region.

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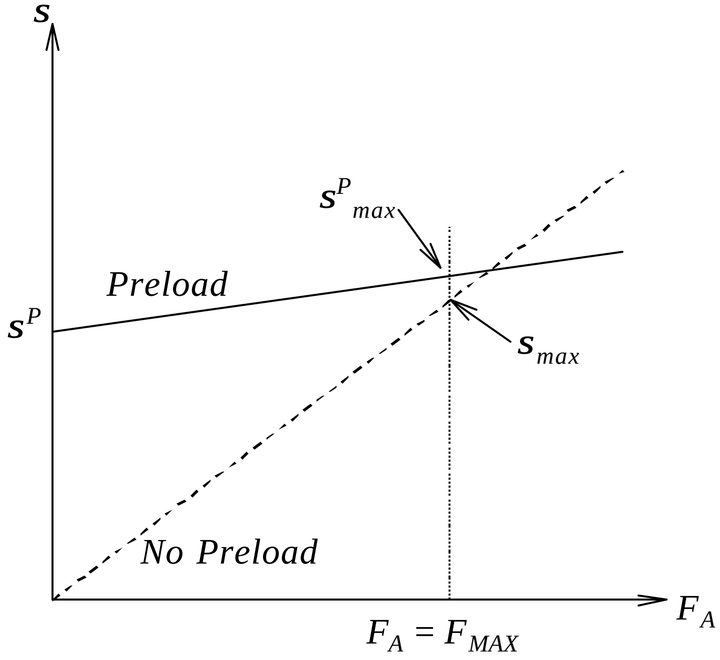
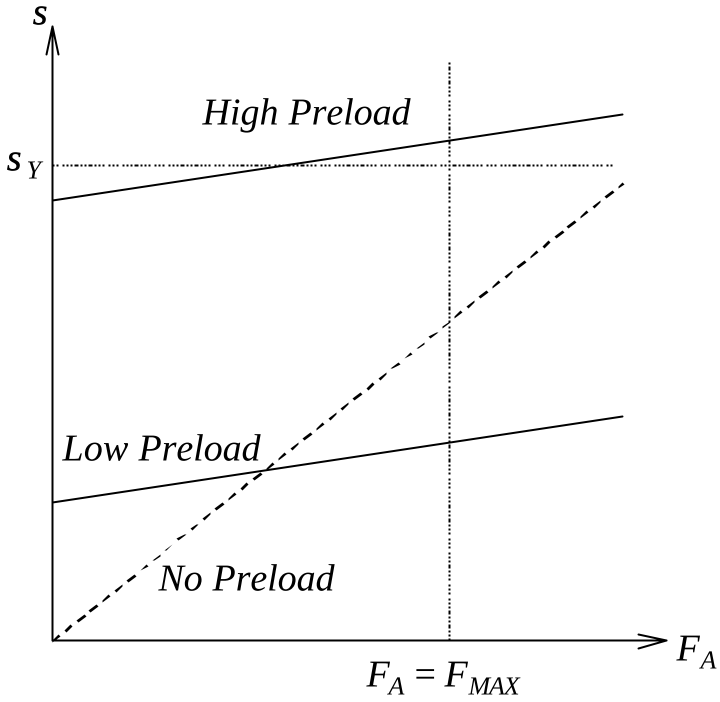


a. Preload Effect on Local Stress



b. Preload Effect on Cyclic Stress Range

Figure 4-5. Preload effect on local stresses in critical region.

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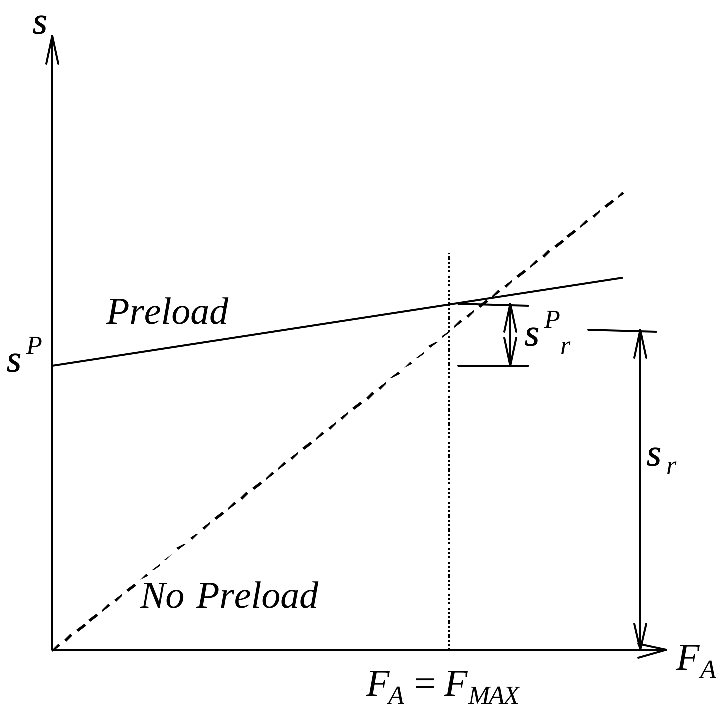

Figure 4-6. Preload effect on stress range.

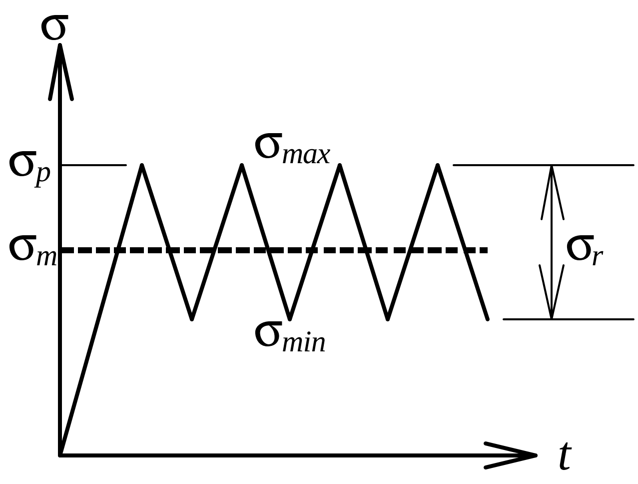

Figure 4-7. Local cyclic stress quantities.

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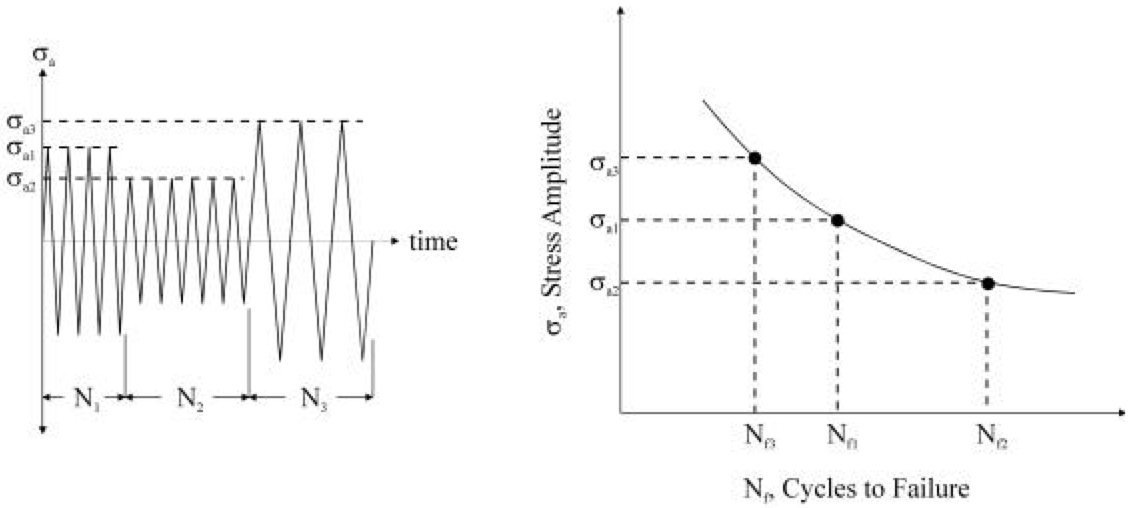

Figure 4-8. Palmgren-Miner Rule.

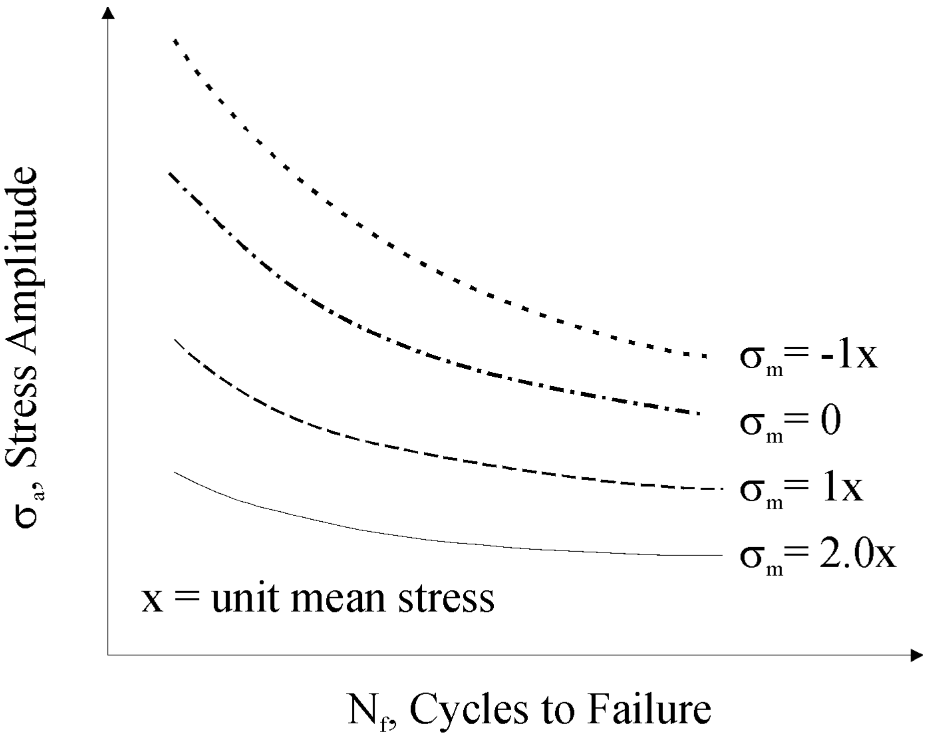

Figure 4-9. Mean stress effect on *S-N* curve.

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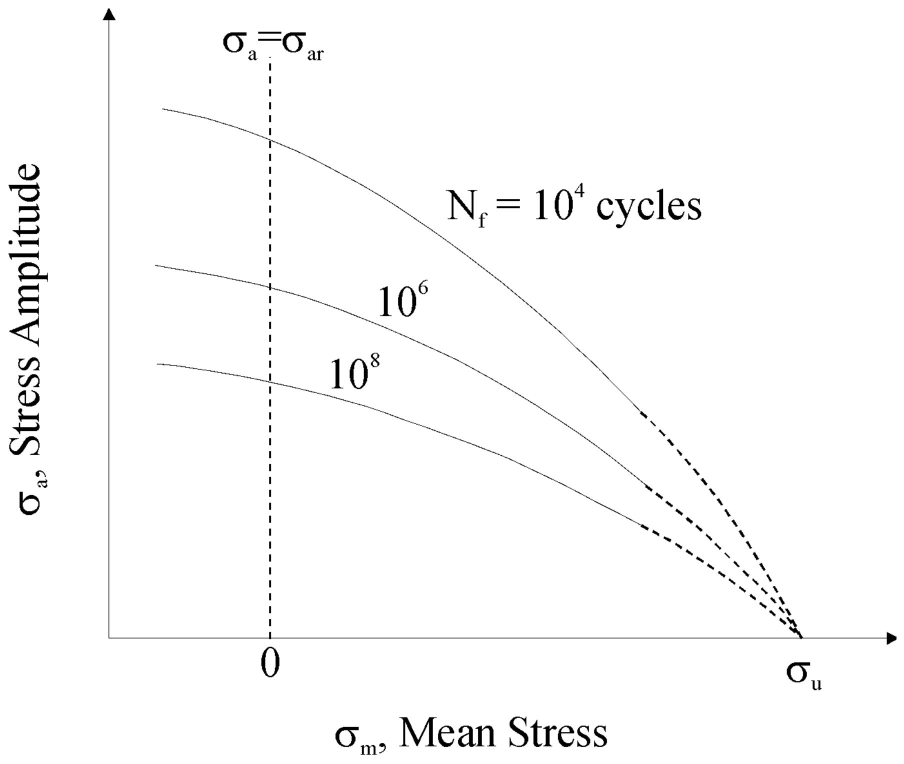

Figure 4-10. Typical Constant-Life Diagram.

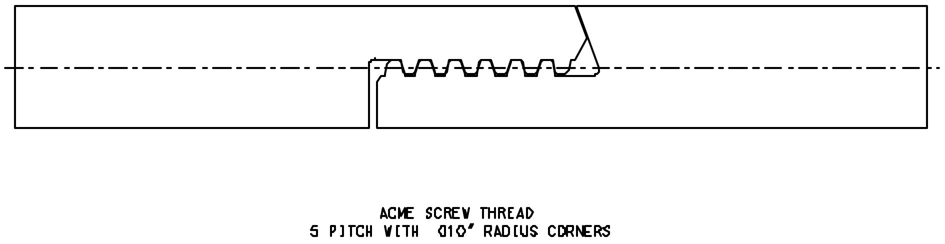

Figure 4-11. Acme thread profile.

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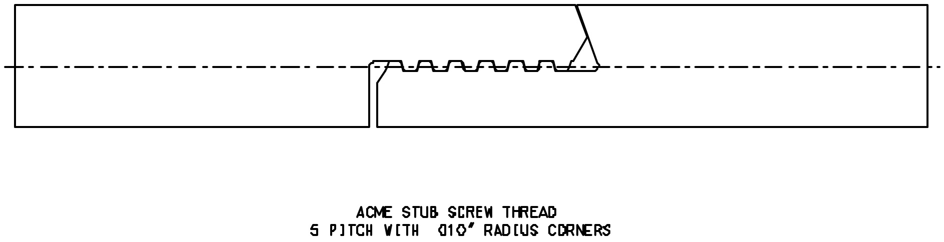

Figure 4-12. Stub Acme thread profile.

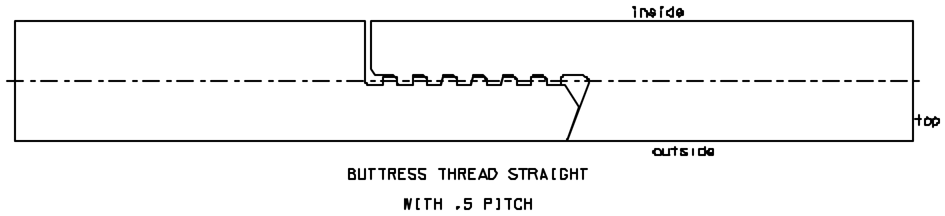

Figure 4-13. Straight Buttress thread profile.

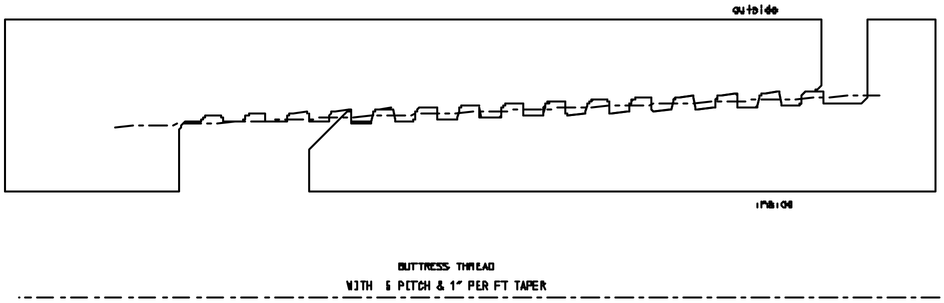

Figure 4-14. Tapered Buttress thread profile.

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5. APPLYING THREADED CONNECTIONS TO CAISSONS

As stated in the opening comments of this document, the intent of the study is to assess the feasibility of applying threaded connections to caisson structures. Thus far, existing protocols for the design, analysis, and validation of caisson structures and threaded connections have been considered independently. The combination of these protocols, and other relevant technologies, form the basis of the feasibility assessment of threaded caisson connections discussed in this section.

Unless otherwise noted, it is appropriate to assume that the guidance reviewed in Section 3 (Existing Caisson Design Practice) and Section 4 (Existing Threaded Connection Design Practice) is relevant to the evaluation of threaded connections in caisson applications. Any guidelines that are not well suited to the evaluation, or special considerations that have not been addressed are discussed in this section. A general overview of the design of caissons employing threaded connections has been extracted from the following discussions, and is presented in Section 6 with additional recommendations for further study aimed at verifying some of the unproven aspects of the design.

5.1 DESIGN

Following the review of design protocols discussed in Sections 3 and 4 of this report, it was discovered that, with the exception of casual and non-explicit references in texts and guidelines, detailed design guidance pertaining to threaded connections used in large diameter caisson-like applications is nonexistent. Thus, the design approach detailed in Figure 5-1 and discussed in the following sections is primarily based on good engineering judgment and in-depth technical evaluations, and not on previous field experience in the area. Subsequently, any connection design will likely require thorough analysis and validation through testing, and some level of in-service qualification.

5.1.1 Applications

By most estimations, threaded caisson connections may provide a timesaving, cost-effective method of constructing a caisson in relatively shallow water and would be especially useful if the availability of large lift vessels needed to install the fully assembled design were cost prohibitive or nonexistent.

5.1.2 Design Philosophies

Based on the detailed assessments performed, either of the two design philosophies evaluated in Section 4, *failure in the pipe body* or *failure in the connection*, can be used in the design of threaded connections for the proposed application provided that appropriate design protocol and validation is completed, and all potential modes of failure are considered. Note that while the connection considered in this study may perform essentially identical in tension driven designs, when subjected to high compressive loadings, different failure modes should be expected. (Section 5.2.2.2 provides more specifics.)

5.1.3 Threaded Caisson Considerations

Specific considerations that are unique to the use of threaded connections in offshore caisson applications are outlined in the following sub-sections. The majority of loads and design parameters discussed are consistent with those discussed in Sections 3 and 4 unless otherwise noted.

5.1.3.1 Combined Axial Compression and Bending

Many studies have been performed on the evaluation of girth welded tubulars, tubulars with mechanical damage (corrosion), or structural repair sleeves when subjected to combined internal pressure, large axial compression, and axial bending loads [Zhao, Bouwkamp, Smith 1998, Grigory, SSD]. In work performed by Zhao and Bouwkamp, tubulars without geometric discontinuities were subjected to combined loading scenarios resulting in buckling collapse of the structure initiating in the maximum compression region. Studies performed by Smith, Grigory, and SSD on tubulars with geometric discontinuities (e.g., girth weld mismatch, local thinned regions, and repair sleeves) subjected to combined loading produced localized bucking that led to a loss in bending stiffness and subsequent collapse of the structure.

When applying a large geometric discontinuity, such as an external coupling, to a caisson structure subjected to high axial compression, local buckling adjacent to the connection (diameter upset) may be developed as a result of thickness transitions and the inherent stiffness mismatch. The extreme bending moment applied to the section is the result of the coupling of axially compressive and bending loads, and may be mathematically expressed as:

$$M_C = M_B + F_A \cdot \delta \qquad (5\text{-}1)$$

where M_C is the moment in the region of the connection. Corresponding stresses are positive or negative depending on the side of the connection that is under consideration and its relation to the applied loads. M_B and F_A are the bending moment, and the total applied force, respectively, and are as defined in Section 2, and δ is the eccentricity, or displacement of the centerline of the tubular-connection cross-section. Each of these quantities is shown in Figure 5-2. For worst case considerations (at the compression side of the coupling), the applied bending moment M_B is the same sign as the product of $F_A \cdot \boldsymbol{d}$.

Intrusively threaded pipe may be treated in a somewhat similar fashion to an external coupling under bending loads. However, it is likely that failure for this type of connection would occur in the threaded region. The threaded region of an intrusively threaded pipe may more accurately mimic a locally thinned area, reducing the bending stiffness of the joined sections particularly if large threaded displacement or thread jump-out occurs during application of the bending loads.

Internal pressure, when combined with axially compressive and bending loads, may allow for increased eccentricity and curvature in the region, and at extreme magnitudes, dramatically reduce the moment-carrying capacity. However, this is an unlikely loading scenario for offshore caissons. Perhaps more seriously impacting the structural response is external pressure. Various researchers have investigated the effects of external pressure applied in combination with axial and bending loads to define collapse pressures and failure modes for tubulars. While most of this research has focused on small diameter tubulars without defects, they have shown that under such conditions, rapidly propagating collapse and buckling of the structure can be produced. Again, some analysis of the potential for this type of failure should be investigated in the design and analysis phases. In any stability analysis, the onset of buckling should be considered the failure point, as opposed to the ultimate collapsed shape. This simplifies the analytical effort and provides conservatism of the results.

In addition to the stability failure phenomena described above, localized failure of the threads should be evaluated. Under high compressive loads, shearing of the threads can initiate a compression failure of the connection. When coupled with bending, teeth on the compression side of the connection will be forced together, while those on the tension side will be pulled apart. On the tension side, disengagement of the threads may occur, affecting integrity of the connection. Such effects should be considered in the thread profile design.

5.1.3.2 Fatigue and Fracture

An in-depth discussion of fatigue strength assessment protocols for threaded connections was presented in Section 4.2.3, and provides insight into specific areas that should be addressed when applied in caisson structures. In general, definition and behavior of the stress concentration factor and stress ranges as a function of large compressive and bending loads must be addressed. Furthermore, the applicability of existing fatigue assessment guidelines for connections subjected to large compressive mean stress is uncertain, requiring that detailed analyses and physical testing be performed. Typically, compression does not lead to fatigue failure. However, compression of a threaded connection should not be disregarded due to the complex stress distributions, some of which may remain tensile in preloaded connections. (See Section 5.2.2.1.)

The attainment of accurate values of stress concentration factors (SCF) is vital to the assessment of structural integrity under cyclic loading, such as pile driving and wave action. These values must be obtained through analytical modeling and validation testing, using methods similar to those discussed in Section 4. Additionally, assurance that the in-service connection performs as predicted by analyses, particularly when scale testing and modeling is applied, is essential for any reliable assessments. This includes makeup and tolerances.

As in all fatigue failures, the ultimate failure mode is from fracture of the remaining ligament. With threaded connections, external couplings or intrusively threaded, it is likely that the initiation of fatigue and ultimate fracture will occur in the threaded region or diameter upsets. Inspection of these areas, in-service or otherwise, may prove difficult, and thus, adequate safety margins must be accounted for in the design.

5.1.3.3 Backdriving

The potential for backdriving of the connection from torque loadings transmitted through the caisson should be considered. Additionally, cyclic loading may also lead to incremental backdriving over the caisson life and should also be evaluated. Special techniques or mechanisms may be implemented to lock the connection in place and provide resistance to additional torsional loadings. For example, a non-structural seal weld may be used following make-up of the connection that precludes rotation of the connection, and also provides a barrier against seawater intrusion. Such a weld is usually only a single pass and is not intended to penetrate the thickness as in a fully-penetrating girth weld. Upon caisson removal, the seal weld is simply ground off, and the connection is broken loose as usual.

In addition to seal welds, special locking mechanisms, such as an anti-rotation pin and slot, can be designed to resist torsional loadings. Initial evaluations of the mechanism performance can be accomplished through local analyses of the connection (Section 5.2.2), although validation of the final design will require physical testing that includes the effects of friction, make-up, preload, service loadings, and subsequent removal. In addition to these, the effects of corrosion over the life of the caisson should be considered for any locking mechanism.

5.1.3.4 Installation

Each detail of the installation for the connection should be addressed in the design phase. Required makeup torque, sealing requirements, handling, and the method of installation should be preliminarily addressed, and ultimately validated through full-scale (preferred) testing. Special considerations for each of these issues follows.

5.1.3.4.1 Makeup Torque

Applying makeup torque can alter the stress range that a connection experiences (refer to Section 4.2.2.4) and reduce the possibility of backdriving from torsional loads that tend to loosen the connection. For large diameter connections, the ability to properly apply the needed torque during installation may pose serious problems. As a possible alternative, matched markings on the connection pin and box may assure proper makeup torque has been achieved during installation, provided that the connection tolerances can be held relatively tight during manufacture. As such, a matched set of marks helps to ensure that the connection is made up properly, and that the correct amount of preload exists.

5.1.3.4.2 Sealing

In addition to the discussion in Section 4.1.5.4, a non-structural seal weld to resist torque loading may also provide added sealing capability.

5.1.3.4.3 Handling

Thread protectors may be needed to prevent damage to the threaded region during any handling of any unassembled connection. Additionally, lifting limits should be established to define the maximum weight of connected pipe sections that can be supported without damaging the connection, or initiating buckling of assembled members under bending loads.

5.1.3.4.4 Pile Driving/Jetting

Since gross deformation in the hammered region is developed during pile driving, it is unlikely that a costly connection will be directly hammered on, or will be located in any region where large deformation from hammer forces are anticipated. The grossly deformed region where the hammer impacts is usually trimmed and disposed of, and a new section to be driven is added. Since a cut is made, the new section must be welded on. The new section may contain a threaded connection, but it must not be positioned adjacent to the hammering location. The process is then repeated until the full string has been assembled and installed. Thus, threaded connections can not be used exclusively for driven applications as some welding will be required. Some thought should be given to the development of a sacrificial piece for hammering, or modification of the hammer to reduce deformation. Hence, jetting (sometimes referred to as drilling) a caisson may be more attractive for caissons with threaded connections.

5.1.3.5 Removal

The likely removal scenario is to retrieve the caisson in one piece and break it down on shore. Again, limits should be set on the length of connected pipe sections that can be supported during lifting. Full consideration of these lifting forces for assembled caisson connections should be made during the design process.

Two additional complications in the removal process are: (1) controlling which connection is broken loose first, and (2) ensuring that corrosion over the caisson life does not prevent disassembly or promote premature disassembly during retrieval. A detailed plan should be developed that considered these complications, and appropriate protection from corrosive elements should be provided. Protection can be supplied in the form of corrosion resistant coatings and thread compounds, seal welds, cathodic protection, and/or the use of materials less susceptible to corrosive elements.

5.1.3.6 Manufacturing Considerations

In addition to concerns regarding material grades and their selection (Section 5.1.4.3), issues associated with the ability to reliably produce a threaded connection within the needed tolerances must be addressed. Additionally, the ability to inspect threaded connections for large diameter applications is difficult since often times gauges in such sizes are virtually non-existent. Other significant concerns related to manufacturing of the connection are outlined in the sub-sections that follow.

5.1.3.6.1 Tolerances

Ovality of the caisson tubular material must be controlled very closely for both structural stability, proper manufacture of the thread profile and connection, suitable makeup. In addition, poorly designed and loose threading tolerances can lead to a girth mismatch at the joining region that further compounds makeup alignment and structural stability problems.

5.1.3.6.2 Quality Assurance and Quality Control

By developing new methods to gauge large diameter, large pitch thread profiles, and inspecting connections as well as pipes for ovality, assurance of design performance can be met. Makeup inspections should also take place after installation to assure that the design requirements at installation have been achieved.

5.1.3.7 Maintenance and Inspection

Because of the likelihood that a critical fatigue crack would develop within the threaded region, an inspection protocol should be developed to inspect for these cracks *during* service. Most often, critical cracks may not be evident unless the connection is disassembled and visually inspected, or inspected with NDE methods (Section 4.1.5.2). Once the caisson platform is installed, disassembly of the connection for inspection becomes impossible. Thus, non-destructive techniques that can “peer” into the threaded region should be considered for in-service inspections. Such techniques already exist in the form of radiographic inspection, and would be well suited to in-service inspections if adapted for marine applications. Following detection of the crack, fracture mechanics techniques (Section 4.2.3.4) may be used to assess the remaining fatigue life, and the need for and frequency of follow-on inspections.

5.1.4 Applicable Guidance from Existing Regulations

Sections 3 and 4 provide detailed descriptions of the relevant design guidance for caissons and threaded connections, respectively. Additional guidance as it relates to the design of threaded connections for caisson applications is given below, and is fundamentally based on information echoed in API RP 2A or 30CFR25.

5.1.4.1 Strength and Considerations for Stress Concentration

In Section 16 of API RP 2A, special considerations for bolted connections, such as shear, lamellar tearing, friction factors, relaxation, stress corrosion cracking, fatigue, brittle failure, and combinations thereof, has applicability in threaded caisson connections. Additionally, where primary members rely on friction to transfer load, it should be demonstrated, using appropriate analytical methods or experimental testing, that adequate load transfer will be developed and maintained during the life of the structure.

"Stress concentrations at critical structural joints shall be specifically addressed." According to AISC ASD, connections shall be proportioned so that the calculated stress is less than the allowable determined by structural analysis for: (1) loads acting on the structure, or (2) as a specified proportion of the strength of the connected members, whichever is appropriate. For stresses of highly localized nature, local yielding of the structure is acceptable if it can be demonstrated that such yielding does not lead to progressive collapse of the overall platform, and that general structural stability can be maintained.

5.1.4.2 Validation of Connection Behavior

In Section 4 of API RP 2A, other complex joints that are not specifically covered, including threaded connections, may be designed on the basis of appropriate experimental evidence, or an appropriate analytical check verifying that a distribution of stress can be assumed that satisfies equilibrium without exceeding the allowable stress of the material. Reference to validation activities is also made in Section 16 of API RP 2A.

5.1.4.3 Materials Definition

For intrusively threaded pipe, the allowance for Class C steel to be used in caissons is in conflict with the requirement that primary connections for minimum structures, where failure would cause significant loss of structural strength, be made of Class A steel. However, for external couplings, this allowance and requirement can be achieved.

5.1.4.4 Installation and Removal

Add-on pile sections should be provided with guides to facilitate proper stabbing and alignment. A tight, uniform fit by the guide should be provided. The guides should be capable of safely supporting the full weight of the add-on pile section prior to welding (or assembly). While specifically addressing welding, this requirement may also be appropriate for thread makeup.

5.1.4.5 Inspection

Where connections are designed to be field installed, inspection methods should be developed to ensure that no damage has occurred to the threaded region during handling, and that proper installation in accordance with specified design assumptions is achieved. Inspection procedures are also discussed in Section 5.1.3.6.2 of this document.

5.1.4.6 Manufacturing Considerations

Structural steel pipe specifications found in American Petroleum Institute Specification 2B [API RP 2B] call for out-of-roundness tolerances not to exceed 0.5 inch for large diameter pipe. These specifications should be fully considered in the design of large diameter threaded connections, where out-of-roundness tolerance requirements will be predominantly dictated by the tolerance needed for proper design, manufacturing, and installation of the thread profile.

Threaded connections should be gauged as discussed in Section 4.1.5.3.3 to ascertain that thread form, pitch, diameter, and runout can be produced within the tolerances required by the design. Again, the availability of inspection gauges for large diameter thread designs is limited, and may pose some difficulty to the ability to provide adequate assurance of the design.

5.1.4.7 Validation Analyses

Lloyd's Register, Rules and Regulations for the Classification of Fixed Offshore Installations, Structural Steel Requirements [Lloyd's], generally requires primary structural members to be analyzed by a three-dimensional finite element method. Alternate means of analysis can be used if shown to be adequate for the design. The finite element model and the element types used are to be sufficiently representative of the primary components of the structure so as to enable accurate determination of forces and displacements. Sections 3 and 4 discuss specifics of the applicable finite element analyses and their use in design validation.

5.2 ANALYSIS

Offshore experience with the connections under consideration is limited, therefore, connection performance and reliability is of concern especially when utilized in a low redundancy structure. Consideration of the characteristics of the connection, such as flexibility and localized stress concentrations, during global structural analysis may ultimately dictate the failure mode(s) produced.

5.2.1 Global Response Analyses

When combining threaded connections and caisson structures, the allowance should be made for not only applying global analysis results locally in the connection but also returning results of the local response to a second iteration of the global analysis; i.e., global-local interaction analyses should be performed. Figure 5-1 displays this interaction.

5.2.2 Local Response Analyses

Local analyses, using the finite element analysis procedures described in detail in Section 4.2, should be performed to evaluate the effects of global loading on the connection performance. (See Figure 5-2.) While static and dynamic strength, piling, and thread jump-out evaluations are directly applicable to the proposed application of threaded connections, the suitability of direct application of fatigue strength assessment procedures described is uncertain. Moreover, additional failure modes may be produced which should, at a minimum, be investigated with analytical techniques.

5.2.2.1 Fatigue Strength Determination

Calculation of the stress concentration factor for fatigue strength assessments is identical to the procedures described in Section 4.2.2.1. The potential for nonlinearity of the SCF with applied loading must be quantified, and a defensible method for either assuming linearity in fatigue assessment (i.e., SCF is linearly related to load over anticipated load range), or treatment of any nonlinearity in the evaluation should be provided.

When considering the effect of a preload on the design, which is typically applied to prevent inadvertent breakout but can reduce the cyclic stress range and extend fatigue life, the analyst will note that local tensile stresses at the previously established fatigue critical location (FCL) will decrease under increasing axial compression. This behavior, shown graphically in Figure 5-3 for an assumed linear relation between local thread root stress and applied load, also depicts the more rapidly declining slope of the non-preloaded connection. The observed behavior is essentially identical, for both the preloaded and non-preloaded connections, to that observed for the tensile loading mode, and is attributed to the tendency for loaded flanks to open (decreasing tensile loading) and alternate flanks to become loaded as the connection is forced into compression. (See Figure 2-4.)

In previous tension dominated designs, local stress at the trailing root radius of the tooth furthest from the pin free-end was often higher than other regions within the connection, as is the assumed location in Figure 5-3. However, during compressive loading, as the local tensile stress in this thread root region declines, that on the opposite side of the tooth may begin to rise, as will stresses in the shoulder. Note that when the preloaded connection curve in the figure intersects the load axis (x-axis), the initially loaded and contacting flanks will have separated. The gradually decreasing slope of the preloaded curve accounts for the fact that at the time it intersect the load axis in the figure, significant deformation will have occurred at shoulder regions. Hence, it is appropriate that for all connection designs, some effort be expended on the identification of critical regions for compressive loading that may not have been critical in the tension loading mode. Comparison of the figures in Appendix B for the different loading modes provides some insight into understanding the change in the critical region.

Considering once again the critical thread root region from previous tension designs, Figure 5-4 displays how a cyclic compressive axial loading may affect the stress ranges in the preloaded and non-preloaded connections. As shown, while the non-preloaded connection's cyclic stress range remains compressive, the preloaded connection will have a corresponding cyclic stress range that is tensile. The root radius on the other side of this same tooth will experience yet another cyclic stress range, which may or may not be more critical than that shown in the figure. And further still, shoulders, which will resist the major portion of all compressive loading, may exhibit even more critical conditions. Such variation in the thread stresses observed in compression, with or without initial preloads, emphasizes the need for thorough examination of the connection under anticipated loading conditions so that the appropriate critical locations and corresponding stress can be identified.

Once the SCF (based on pipe body stress or thread root cross-section stress) for the connection has been accurately defined, the fatigue assessment of the connection can be initiated. Regarding the procedures discussed in Section 4.2.3, a reliable approach for the proposed application is *stress-based*. In this approach, a qualified fatigue curve (S-N) for the connection or material exists that includes compressive cyclic loading, geometric effects, and preferably, compressive mean stress, and geometry effects, and elastic finite element predictions of the stress range at the FCL are converted to fully-reversible and equivalent axial stresses ($\overline{s}_{aREV}$) for comparison with the actual S-N curve. Miner's rule may be applied for variable amplitude loadings, following counting, and the number of cycles to failure (N_f) can be directly assessed.

Accurate fatigue strength determination using the *strain-based* approach for connections subjected to high compressive loads (compressive mean stresses) should be cautiously approached. The Smith, Watson, Topper parameter (SWT, equal to $\bar{s}_{aREV}\bar{e}_{aREV}$) commonly used to relate the fully reversible and equivalent stresses and strains at the FCL may produce nonconservative predictions of the fatigue life for compressive mean stresses [Dowling]. Figure 5-5 depicts a comparison of actual test data with predictions developed using the SWT parameter, and shows overestimation of the calculation. Hence, it may be more appropriate to apply an alternate method, such as the Manson-Coffin technique, to directly relate the fully reversible and equivalent uniaxial strain ($\bar{e}_{aREV}$) to the number of cycles to failure.

Because compressive loading on the connection installed in a caisson structure will be largely static, accurate treatment and representation of compressive mean stresses is crucial. As discussed above, the commonly accepted SWT parameter relating local stress/strain amplitudes to the fatigue life is nonconservative for compressive mean stresses. In addition, some mean stress representations based on amplitude-mean diagrams (introduced in Section 4.2.3.1.2) may be nonconservative when applied to compressive mean stresses in either a *stress*- or *strain-based* approach. If the amplitude and mean stress for the FCL region are known, and an equivalent uniaxial, reversible stress amplitude is needed ($\bar{s}_{aREV}$), the following equation, rearranged from the Goodman expression in Equation 4-21, may be solved for $\bar{s}_{aREV}$.

$$\frac{\bar{s}_a}{\bar{s}_{aREV}} + \frac{\bar{s}_m}{s_U} = 1 \tag{5-2}$$

When large compressive mean stresses are present, this calculation will overestimate the fatigue life as shown in Figure 5-6. Accuracy of the calculation can be improved if the true fracture strength ($\tilde{s}_f$) or the fatigue strength coefficient (s'_f) is substituted in Equation 5-2 (or similar forms) for the ultimate material strength. Other representations, such as the Gerber Parabola also plotted in Figure 5-6,

$$\frac{\bar{s}_a}{\bar{s}_{aREV}} + \left(\frac{\bar{s}_m}{s_U}\right)^2 = 1 \tag{5-3}$$

similarly generate nonconservative results when compared with actual test results at compressive mean stress. (Note that Equations 5-2 and 5-3 take the form of Equations 4-21 and 4-31 used in *stress*- and *strain-based* approaches, respectively.)

5.2.2.2 Additional Failure Modes Introduced

Results of the technical evaluation and industry survey indicate the potential for two additional failure modes that should be addressed: (1) local buckling of the caisson, and (2) backdriving of the connection during service. Local analysis approaches for each of these are given in the following sub-sections.

5.2.2.2.1 Local Buckling

Local buckling of a tubular occurs when a peak in the moment (M_C) versus deflection (δ) behavior is produced, as shown graphically in Figure 5-7, and the point of local buckling is usually defined by the moment-curvature relation also shown. (Curvature, unlike moment, can be directly measured. Thus, definition of a buckling, or critical curvature for in-service evaluations is standard.) For most axial tension dominated designs, like those currently employed in drilling risers and TLP tendons (with and without connectors), local buckling at the connection may not be a significant concern for moderate applied bending moments (M_B) since the bending contribution of the $F_A \cdot d$ term in Equation 5-1 tends to reduce the moment applied at the connection M_C. However, as discussed earlier (Section 5.1.3.1), large tubular structures with and without geometric discontinuities may experience local buckling at or adjacent to the diameter upset, as well as a stiffness mismatch region, when subjected to high axial compression and/or axial bending loads.

Many factors can initiate a buckle in a tubular body — the magnitude of applied loads and their sequence of application, ovality of the cross-section (that increases with increasing bending moment), axial camber of the tube, girth weld mismatches, thickness transitions and their length, and size of local thinned regions. Considering the work performed by Bouwkamp, Grigory, SSD, and others, the peak moments and corresponding critical curvatures of pipes with sleeves were less than those of pipes without sleeves for the same load path, material grade, and nominal pipe diameter-to-thickness (D_P/t_P) ratio. Similar effects were observed for local thinned regions in work performed by Smith [Smith 1998].

When comparing study results for different ratios of D_P/t_P, pipes with and without sleeves exhibit lower peak moments at lower ratios than do corresponding pipe configurations at high ratios. For curvature, the inverse was observed. This fact is troublesome since, in general, tubulars used in caisson construction have lower D_P/t_P ratios (< 50). Additionally, some sensitivity to the axial length of the geometric discontinuity has also been observed in the studies. For sleeved pipe configurations at a given D_P/t_P, longer sleeve lengths generally reduce the peak moment and critical curvature due to the greater extent of stiffness mismatch.

Extending these concepts to the evaluation of threaded connections for caisson structures, where high axial compressive loads are coupled with bending, there exists a strong possibility that local buckling failure initiated by the presence of a connection could occur. For an external coupling, the buckle may form at or adjacent to the diameter upset attributed to the change in bending stiffness and the thickness transition. For a threaded pipe connection, the buckle may form within the threaded region, initiated by any ovality or thread disengagement, in addition to the geometric discontinuity of the threaded region itself.

Given the above discussions, there clearly exists a need to evaluate a caisson design containing threaded connections for local buckling behavior. Analyses should be both global and local to identify any contribution of connection displacement, ovality, and plasticity, if present, on the overall structural response. An encouraging fact from the previous studies is that advanced finite element analyses have been successfully employed, and verified, to assess the onset of local buckling in sleeved pipe configurations and pipes with local thinned regions [SSD, Smith 1998]. Such analyses of connection behavior, although likely more sophisticated, may include:

- detailed modeling (including contact and refined mesh) of the connection and some portion of adjacent connecting bodies,
- symmetry modeling, assuming effects of 3D helix can be accurately evaluated in this manner,
- nonlinear material definitions, including any anisotropy between hoop and longitudinal material directions, and
- the specification of multiple load paths to insure load-path insensitivity of the connection and the effects of preload.

Note that if the connection is designed in accordance with existing protocol (Section 4), the connection should remain nominally elastic during the entire load history, although highly localized plasticity at critical thread regions is likely. Thus, the connection should not exhibit any load path sensitivity. However, some effort to verify this aspect of the design is initially required.

Global analysis results (for the entire structure) can be used to define loads imposed on the local connection region. To investigate local buckling behavior in subsequent local analyses, the connection should be positioned between equal lengths of the adjacent connecting tubulars, and centered about the region of maximum bending. The length of connecting tubulars to be modeled should be sufficient to preclude the interaction of end-effects at the free-end boundaries with the connection response. Load magnitudes defined by the global analyses are then applied at the free-end boundaries, and the adjacent tubulars will transmit this load to the connection. (Note that a plane of symmetry can be placed at the connection axial mid-plane for thread models, taking into account some assumptions regarding the 3D helix.) Ultimately, the local response characteristics should be compared with global predictions of loading (and stress/strain, if possible) at local model boundaries to verify modeling assumptions.

To reduce the modeling effort, initial local analyses of the connection to insure the validity of modeling assumptions should be performed. In addition, any design optimizations should be conducted prior to performing the local buckling analyses.

Once satisfied with the analytical procedure, the connection configuration can be further modified to optimize peak moment and curvature capacities. Such optimizations may include variation of the axial length of the connection, an increase in material strength, or modification of the connection diameter, upset, and/or nominal wall thickness. If such optimizations are performed, re-analysis of the new configuration for static and fatigue strengths, and functionality should be pursued.

5.2.2.2.2 Backdriving of the Connection During Service

Torsional loading may be imposed on the caisson body (and threaded connection) from the lateral loading of platform that it supports. Wind forces on the platform, and temporary loadings from boat landings can generate torsion which may tend to "unscrew" the connection in service. If significant rotation of the connection is developed, the loss of preload and make-up torque, and ultimately, integrity of the connection, results. The diminished integrity of the connection may subsequently lead to local buckling or a loss of critical strength capacities.

Global analyses can be used to define the magnitude of torsional loads acting at the connection, which can then be applied to a local connection model to evaluate the capacity of any anti-rotation device implemented in the design. Initial sizing and capacity of the seal weld and/or anti-rotation pin and slot can be assessed in the local models that simulate the make-up toque, preload level, and service loadings. However, physical validation, which includes frictional effects, is needed for validation of the modeling assumptions.

5.3 VALIDATION

Validation of the overall design should primarily focus on the connection response, and in general, will be identical to the techniques described in Section 4.3. However, because of the potential for error in fatigue strength computations, local buckling, and loss of functionality due to driving, long term exposure to corrosive elements, and torsional loading, additional physical testing aimed at defining these effects should be initiated. Specifics on the extended validation requirements, and potential difficulties in testing of large diameter connections follow.

5.3.1 Additional Testing Requirements

Static and dynamic strengths of the connection can be determined using the test sample configurations and protocols given in Section 4.3, and should include determination of the compressive capacity of the connection. (Note that if tension loading will be experienced during the service life of the structure, the tension capacity must also be established.) Considerations for the manufacturing of the connection, through the development of a prototype that is gauged for fabrication tolerances and make-up characteristics are also assessed as before.

5.3.1.1 Fatigue Strength

Fatigue testing should be performed as discussed in Section 4.3.1.2, for each cyclic loading mode. However, a sufficient number of tests at various levels of mean compressive stress should be conducted to assess applicability of the fatigue strength computation to compressive mean stresses. At a minimum, these tests should include fatigue testing with a compressive mean stress and preload equal to the design value.

5.3.1.2 Local Buckling

To assess the local buckling capacity of the connection under combined loadings, the connection should be loaded such that both bending and axial compression (and external pressure) can be applied. The specimen geometry should include appropriate lengths of nominal pipe joined by the connection to be tested, and installed in the test facility with the connection positioned at the maximum bending region. To obtain peak moment information, axial compression and bending moment magnitudes (applied by hydraulic loading rams) should be measured using load cells, premium resolution pressure transducers to measure hydraulic fluid pressure at the ram, or a combination of these. Critical curvature can be measured using inclinometers to measure rotation over a known gage length, or displacement transducers at multiple axial locations from which a displacement profile, and ultimately, the curvature at buckling can be obtained.

If analyses predict failure due to excessive ovalization of the nominal pipe or connection cross-section, ovality measurements can be made using a combination of vertically and horizontally oriented displacement transducers positioned about the circumference of the presumed critical cross-section.

Note that buckling tends to occur rapidly in the test environment, and thus, loading should be applied incrementally and measurements taken at each increment up to and slightly beyond the peak moment value. For these conditions, continual measurements are best. Test data developed in either manner will be useful in validating each load step of the analysis.

5.3.1.3 Functionality

Two additional areas of concern regarding the functionality of the connection have been identified. The first considers break-out of the connection which has been driven, subjected to service loadings, and allowed to freely corrode in a seawater environment. The second focuses on backdriving of the connection under caisson torque loadings which is perhaps more of a concern in caisson applications than in risers, TLP tendons, and other similar applications. Proposed validation procedures for the additional functionality concerns are given in the following sub-sections.

5.3.1.3.1 Break-Out

The assembled structure will be subjected to large driving forces at installation, possible damage due to unforeseen incidents, and corrosive environments during service that may impair long term integrity of the connection. Thus, break testing of a driven, corroded connection should be performed to validate breaking torque predictions. Achieving the desired full-scale sample for testing will, however, be difficult since loadings imposed during service may influence the growth of any inelastic deformations or microcracks initiated during driving, or increase/decrease the rate of corrosion. Hence, accurate validation may be delayed until an appropriate sample can be removed from service. The alternative involves initial driving of a connection that is then stored in a saltwater environment and allowed to corrode for a pre-determined period of time under accelerated corrosive conditions (e.g., current, salt fog, and other methods), and possibly under cyclic loading as well.

Following the break test, mating surfaces in the threaded region should be examined to determine if any gross deformation of the threads has occurred, corrosion is more extensive than anticipated, and if any surface defects have developed which may be of critical proportions. This examination will provide information on the effectiveness of corrosion coatings, and general information on the deformation capacity of the connection.

5.3.1.3.2 Backdriving

Much of the information needed for the prevention of backdriving, with the exception of cyclic loading, which could lead to backdriving, can be obtained in breakout testing. Ideally, backdriving tests are performed on the full-scale specimen (or prototype), madeup in accordance with design specifications (Section 5.1.3.4.1). The prototype connection should also include any anti-rotation devices and/or installation techniques so that their effectiveness in resisting backdriving of the assembled connection can be established.

5.3.2 Extrapolation of Results

The industry survey performed indicated an average caisson diameter of 48 inches. Hence, the threaded connection to be used in such designs will be a large diameter, requiring tremendous loads to evaluate in full-scale. In most cases, testing of the connection to failure will require the use of scale modeling techniques and the extrapolation of analytical results to obtain full-scale connection capacities.

Every effort to replicate the full-scale connection in a scale model for testing and analysis should be expended. This includes scaling of the threaded pattern and nominal pipe D_P/t_P ratio, surface finish, and manufacturing tolerances, although the later two parameters are much more difficult to achieve. If, upon development of the scale test sample, deviations from the full-scale design are noted, analytical models of the scale test sample should be updated to reflect the deviations, and the effects of such discrepancies should be quantified.

Because of the need for extended fatigue assessment to verify applicability of existing evaluation formulas, exacting measurements of any surface defect prior to and following physical tests should be obtained. Such defects, the size and effects of which are difficult, if not impossible to scale, may lead to scatter in the test results, or results which appear questionable when compared with predictions. For instance, initial defects present on the full-scale design prior to service may be less threatening to connection capacity than the same size initial defect in a scale model design. Detailed examination of the threaded connection surface can therefore assist in the identification of potential fatigue failure initiation sites and actual failure sites and modes, and in the interpretation of results.

The number of tests and corresponding analyses of scale models should be sufficient to provide confidence in the ability to extrapolate results to the larger full-scale design. Aside from the non-scaleable design features, key parameters affecting the failure point may or may not be linearly extrapolated to the full-scale design. A minimum of three scale models can be used to provide qualitative information on any nonlinear relationships.

5.4 INDUSTRY ACCEPTANCE

Various caisson designers and operators were interviewed and surveyed in an effort to determine the potential for industry acceptance of the proposed application for threaded connections. Responses to questions concerning the feasibility and willingness to apply threaded connections to caisson designs were useful in both directing the technical evaluation, and assessing the potential for industry support in verification of the proposed concepts.

5.4.1 Designers

Currently, the caisson design organizations consulted exclusively employ welded connections in their designs attributed to the belief that a welded connection will provide capacities that meet or exceed those of the connecting tubular bodies. This belief is based on a long history of the successful use of welded connections in caisson designs, and well-validated procedures for their design and implementation. Furthermore, the versatility of welded connections in the development of tapered diameters, which will be difficult to implement with some threaded connections, is an added benefit to their use.

Regarding the use of threaded connections in caisson applications, designers primarily expressed concern in the following areas.

- capacity of the connection and structural soundness
- ability to apply tapered diameter design philosophy
- the potential for backdriving of the connection under torque loadings
- fatigue and fracture of the connection
- corrosion and its affect on connection integrity
- the lack or insufficient capacity of installation equipment required to make-up and break-out the connection
- true potential for retrieval and reuse
- potential costs associated with structural failure compared with the costs to be gained through implementation of threaded connections

With the exception of long-term corrosive effects on a loaded connection and retrieval and reuse considerations, each of these concerns can be addressed through proper design, analysis, and validation of the connection (as described in the preceding sections) *prior* to installation. Long-term effects and the true potential for retrieval and reuse, however, must be assessed in the service environment and following decommissioning.

In the view of some designers, the perceived risks associated with the loss of a platform from failure of the connection outweigh the potential for actual cost savings that can be realized from their use in caisson designs. Moreover, the costs associated with the proper design, analysis, and validation of threaded connections for caissons are thought to be much greater than potential cost savings. Hence, it is apparent that in addition to the development of proven technical guidelines, an in-depth cost/benefit analysis will be needed to establish the economic advantage of the use of threaded connections relative to a welded connection.

5.4.2 Operators

The majority of all operators reviewed were moderately interested in the potential for cost savings, and believe that designers are burdened with the responsibility of proving the effectiveness of threaded connection caisson designs.

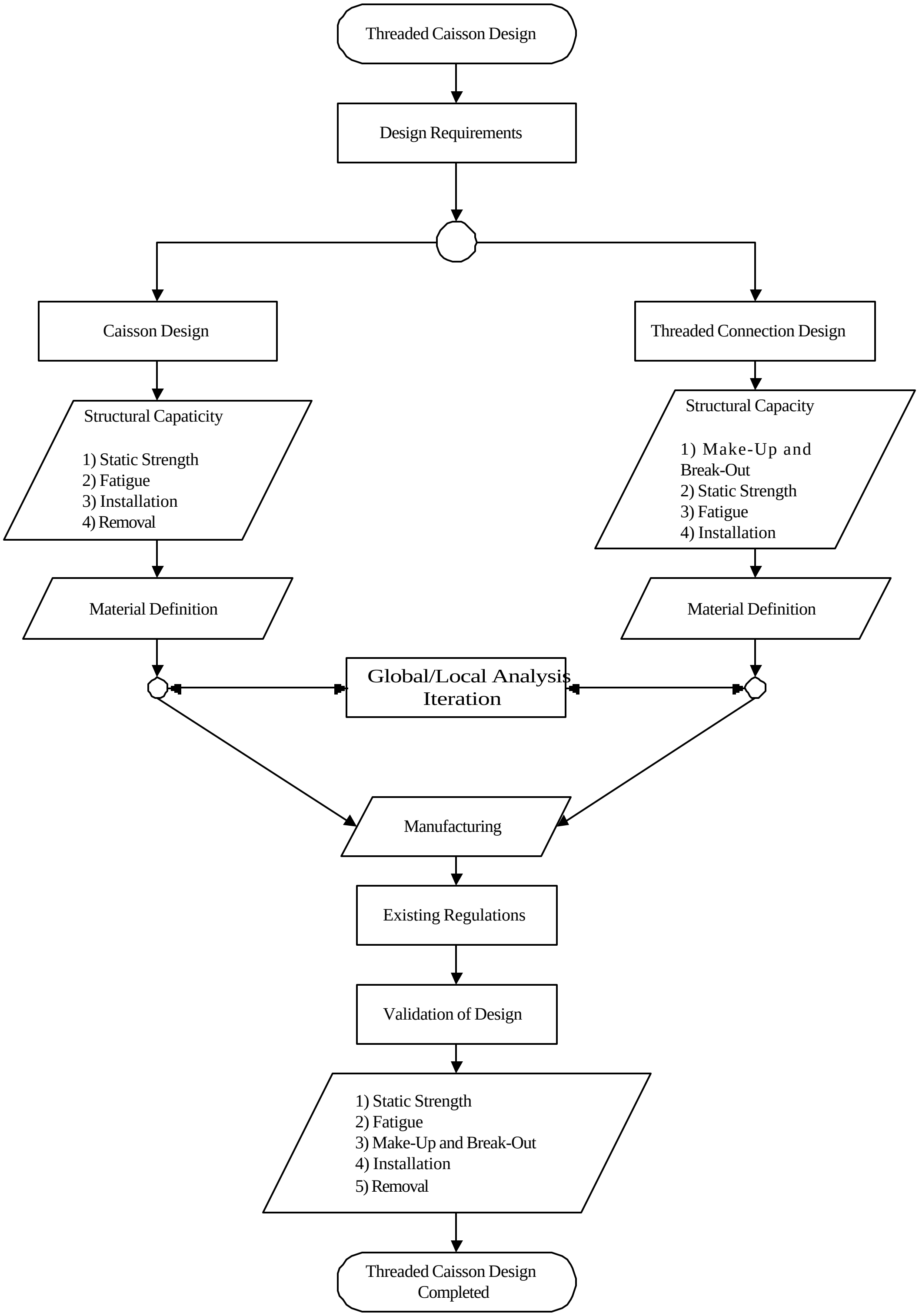

Figure 5-1. Applying threaded connections to caissons.

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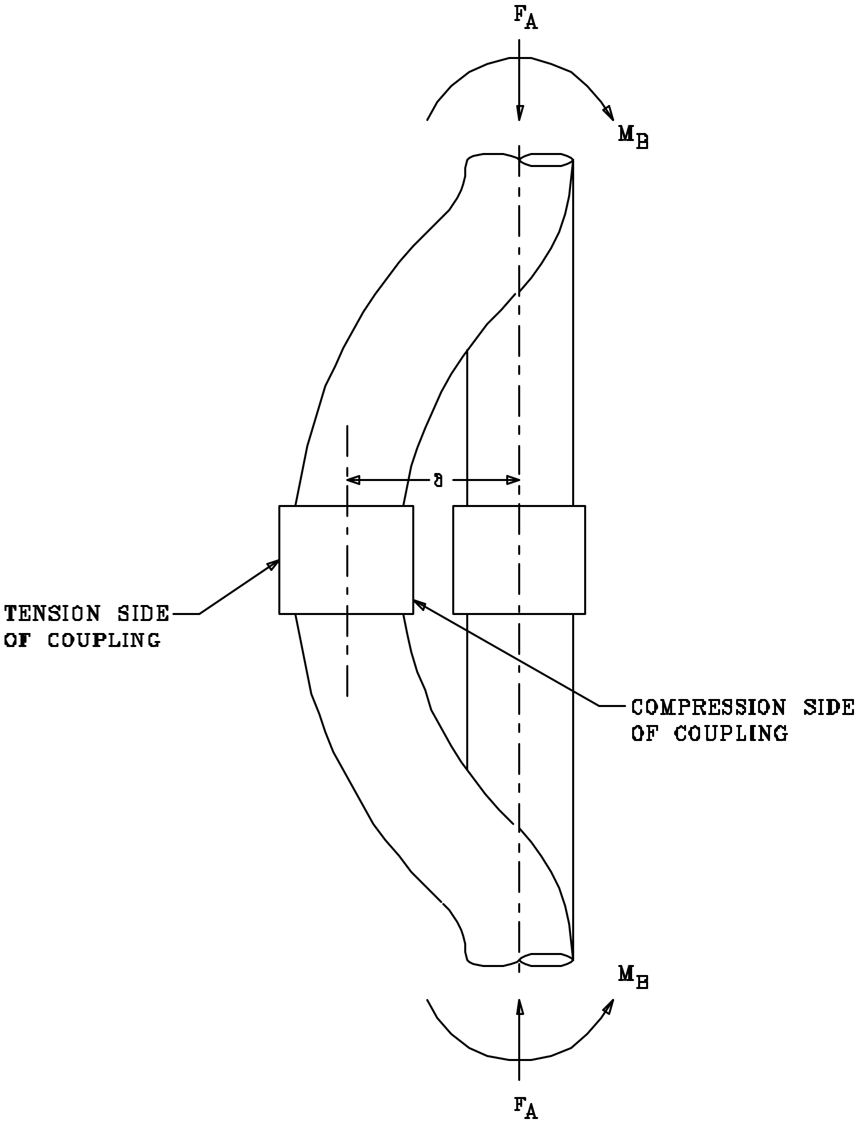

Figure 5-2. Interaction of bending loads on caisson structure.

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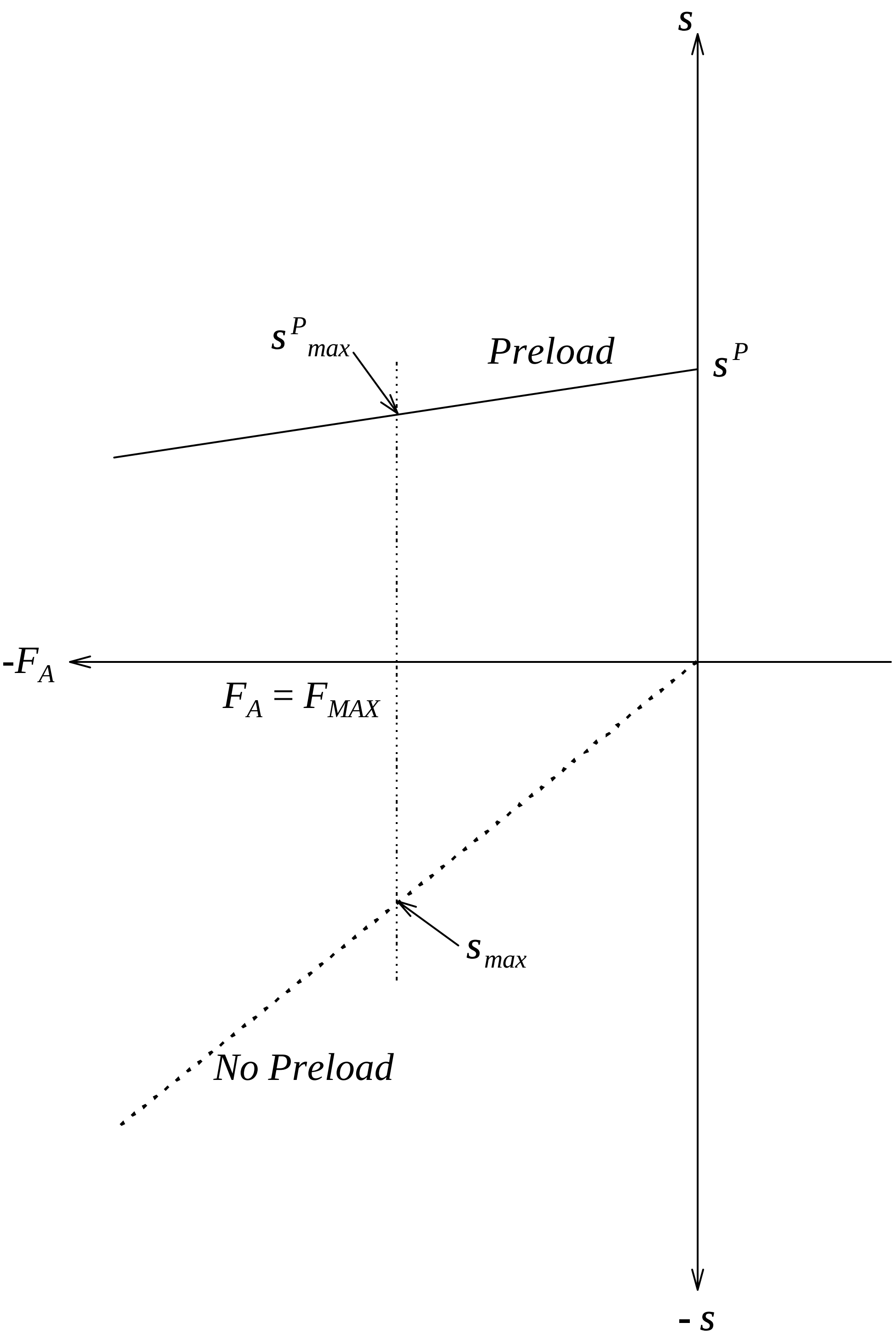

Figure 5-3. Effect of preload on local stress with increasing axial compression.

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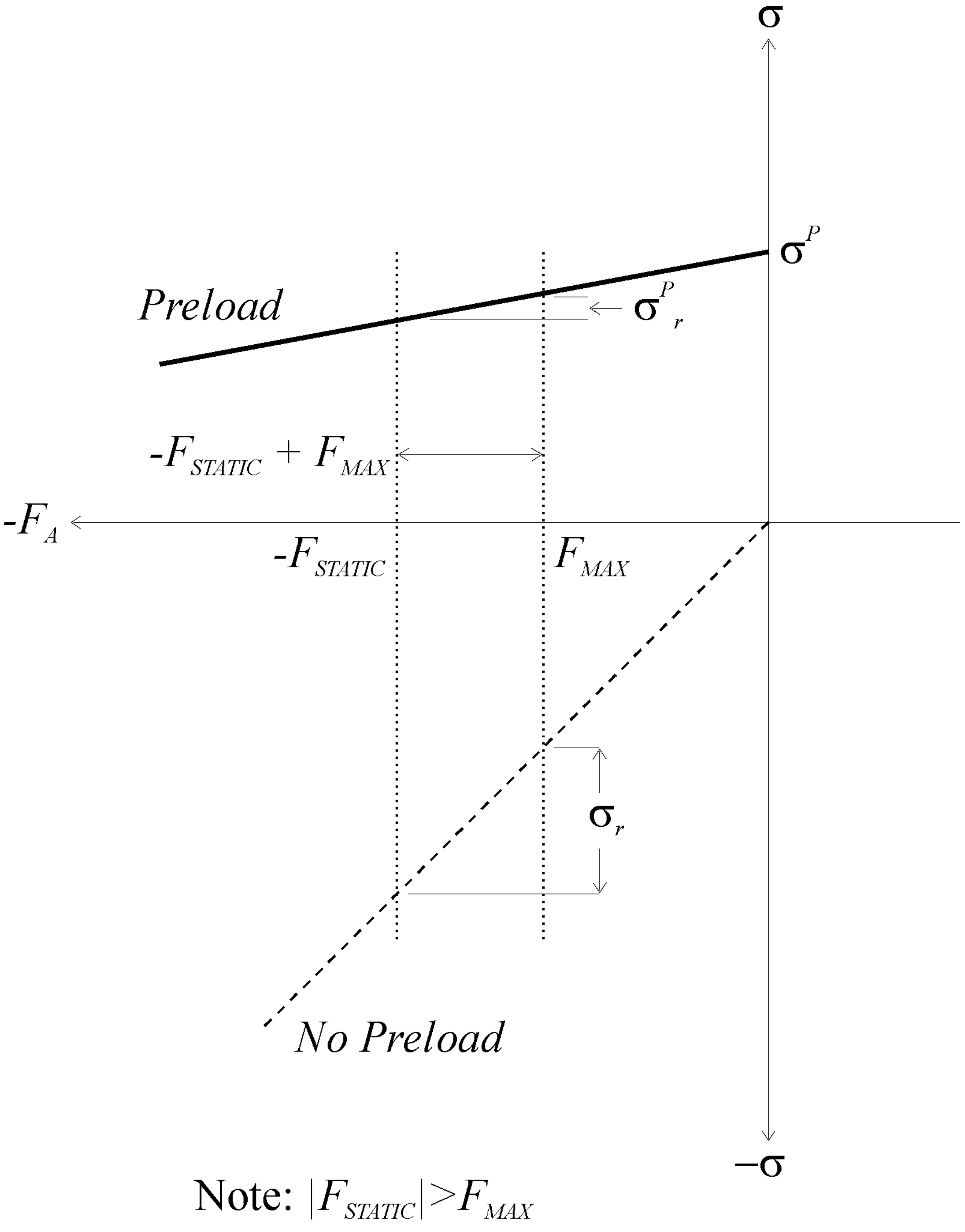

Figure 5-4. Effect of preload on cyclic stress range.

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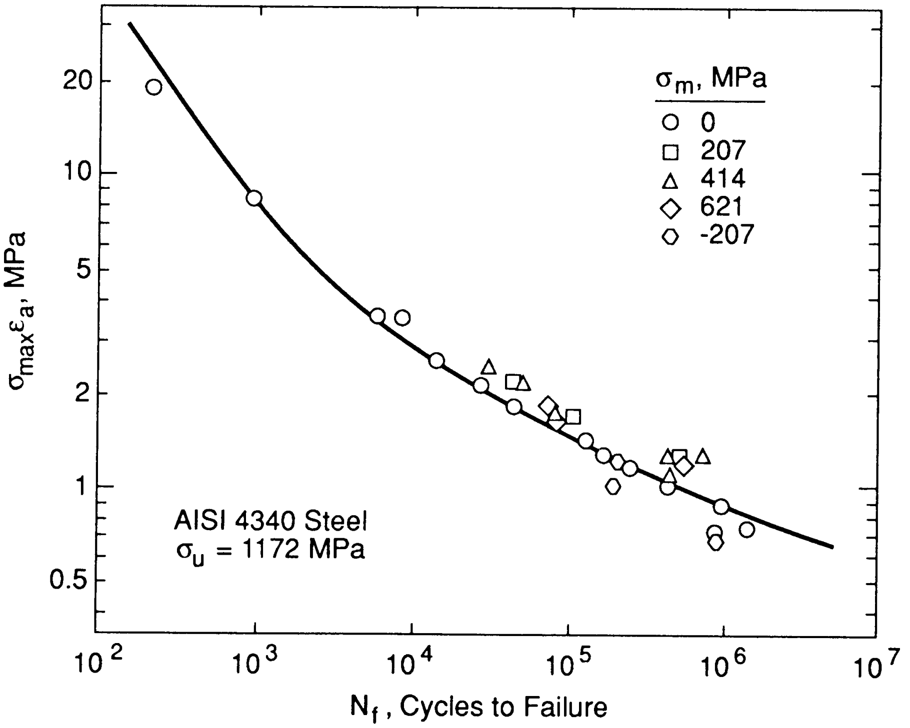

Figure 5-5. Plot of Smith, Watson, Topper Parameter ($s_{\max} e_a$ in the figure) showing non-conservatism of predictions for compressive mean stresses.

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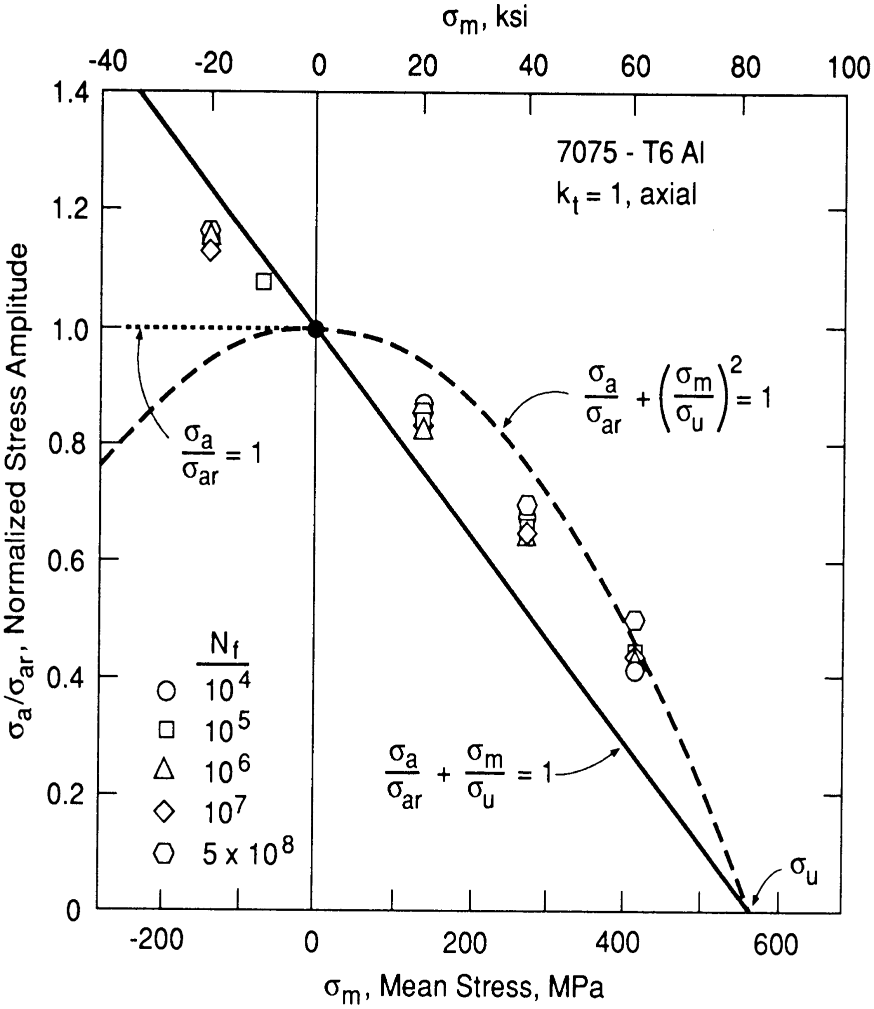

Figure 5-6. Amplitude-mean diagram for Aluminum material showing non-conservatism of predictions by Goodwin and Gerber Parabola relations.

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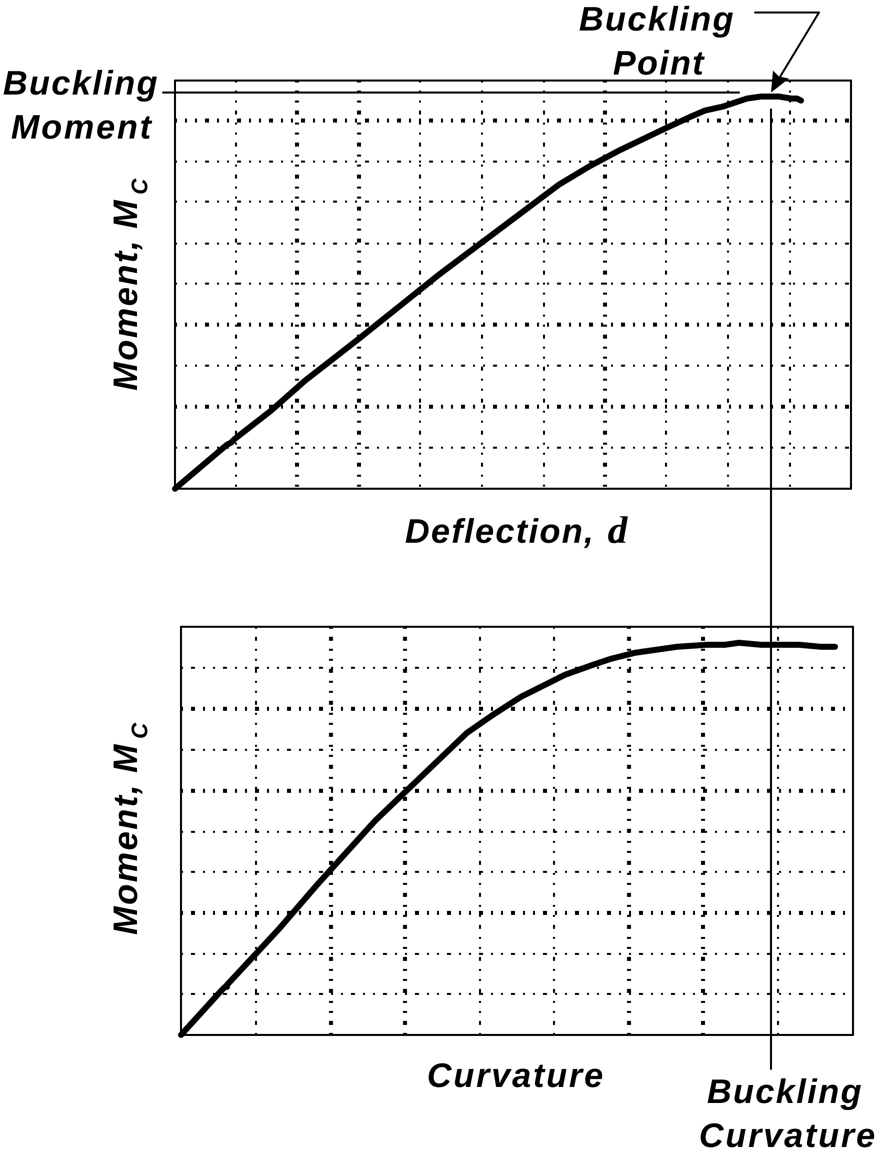

Figure 5-7. Moment-deflection and moment-curvature behavior of pipe section at buckling.

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6. RECOMMENDATIONS

The in-depth evaluation of existing caisson and threaded connection design practices executed during this study revealed key technical aspects that should be considered prior to the use of threaded connections in caisson structures. For example, the effect of pre-load and variations in both the stress concentration factors and stress ranges in critical regions as a function of high *compressive* loading is not well defined. Such behavior must be assessed if existing regulations and assessment protocols, which have been well-validated for connection designs subjected to dominant tensile loadings, are to be adapted for caisson threaded connection designs.

As noted previously, the controlling design guidelines for caisson structures, API RP 2A, does not provide specific guidance for the design or use of threaded connections in minimum structures. In fact, while API RP 2A does provide a list of connection types other than welded, including threaded connections, that may be employed in the design, general considerations on their use are provided only for the bolted, pinned, clamped, grouted, and doubler-plate types. Thus, there exists an obvious omission of any guidance or design considerations pertaining to the use of threaded connections (as well as swaged connections) for caisson structural design. It therefore appears evident that the results of this study, when complete, may be used to provide input to the currently deficient guidance.

Overall, though, many of the guidelines in existence provide a basic approach to the procedures needed to design, analyze, and validate a threaded connection for caisson applications (Section 6.1.4). This fact is encouraging since existing guidelines are typically well founded on basic engineering principles and historical records of performance, and subsequently, are familiar to many designers. However, the study did reveal some aspects related to structural assessment and performance that have not been considered in regards to caisson structures, and may prove significant in the structural design.

At this stage in the study, the recommended treatment of threaded connection designs for caissons is only cursory, but has been developed based on good engineering judgment and in-depth knowledge of fundamental design, analysis, and validation techniques. As such, the considerations outlined in Section 6.1 do not constitute a *recommended practice*, but rather, preliminary and general guidance. Specific guidance regarding safety factors used in design is to be assigned by regulatory agencies. Following the completion of phase two of the program, discussed in Section 6.2, data will become available that will help to confirm cursory evaluations, and from which, more formalized guidance can be drawn.

6.1 PRIMARY CONSIDERATIONS FOR DEVELOPMENT OF A CODE OR STANDARD

A general guideline for the design, analysis, and validation of caisson structures using threaded connections is provided in the sub-sections that follow. More specific guidance is supplied only where existing protocol was deemed inadequate, or where previous procedures are non-existent.

6.1.1 Design

Existing design guidance related to caissons and threaded connections, considered independently, are generally applicable, although they should be extended to specifically consider large static compressive loadings, significant driving forces, and behavior of the structure when subjected to fatigue loadings. Some specific design guidance is needed, however, which details the procedures for evaluation of the coupled structure, and the potential for global failures induced by local effects. For example, the possibility of local buckling at the girth weld connecting the mechanical coupling to the nominal pipe joint appears not to have been quantified by API RP 2A or API specific guidelines. Subsequently, no guidance on the design to avoid this failure mode has been adequately developed. It is therefore appropriate that some specific guidance related to global-local interaction be provided for any connection within a caisson.

6.1.2 Analysis

Standard protocol for structural and finite element analyses is applicable for caisson designs with threaded connections. This includes: (1) global analysis of the structure to define all loads acting at the connection, and (2) local analyses of the connection to insure adequate strength and functionality, and a cursory assessment of the make/break requirements. Local analyses should include:

- static strength determination as it relates to the global response of the structure,
- a detailed evaluation of the potential for nonlinearity of the relationship between local stresses at critical regions and pipe body (or thread root section) stress, and the variation of the SCF with pipe body (or thread root section) stress,
- the effects of pre-load on the local stresses, the stress ranges, and the SCF in the critical region,
- fatigue evaluation considering potential nonlinear local stress versus pipe body stress, stress ranges, and mean stresses.

Results of the analyses would be used to define potential design improvements, critical load levels, and guide the development of validation protocol.

As discussed in Section 5, the SCF in the critical region(s) may behave dramatically different when subjected to high compressive loadings. A specific plan to assess this behavior should be outlined, and may be similar to that presented in API Spec 16R, on the design and assessment of Riser Couplings for Marine Drilling Operations. Such guidance may include analysis of the connection for:

- no initial pre-load plus 20, 40, 60, 80, and 100 percent of the rated load capacity,

- nominal or design pre-load plus 20, 40, 60, 80, and 100 percent of the rated load capacity,
- sensitivity of the design to initial pre-load.

The results of such analyses will be used to quantify non-linearity of the SCF with loading, and should be documented in design records.

Following the SCF analyses, fatigue assessment of the connection should be performed in accordance with an appropriate *stress-based*, *strain-based*, or *fracture mechanics* approach, or a combination of these. Analyses, in conjunction with physical testing, should include varying levels of mean compressive stress to address the suitably of standard assessment techniques to large compressive static loadings. For example, the popular SWT parameter may produce nonconservative fatigue life predictions for compressive mean stresses, and thus may be rendered inappropriate for the current application. As shown in Figure 5-4, use of the parameter when compressive mean stresses are present leads to an over prediction (nonconservative) of the fatigue life. Other approaches, such as the Coffin-Manson approach with substitution of the true fracture strength ($\tilde{o}_f$) or Morrow parameter ($\acute{o}'_f$) may be better suited for caisson applications.

Finally, some direction for the evaluation of failure modes that may not be experienced in existing axial tension driven designs is needed. With regard to the local buckling mode considered in Section 5, analyses to determine the onset of buckling may be performed, although successful evaluation usually requires an experienced analyst with thorough knowledge of the analytical program employed and key modeling features, (e.g., material anisotropy, contact, mesh density, element type, connection geometry), that must be included. Following detailed study and validation of a given design for potential local buckling, a simplistic computation or criterion may develop that can be readily used for future assessments of similar caisson designs.

6.1.3 Validation

As in the design of tension dominated structures employing threaded connections, validation testing must be performed to assess the structural capacity of the connection when subjected to static, dynamic, and cyclic caisson-type loads. Such tests should include:

- ultimate strength determination which includes testing of the connection to severance or collapse
- pile driving to define the maximum driving force and number of blows that can be sustained without negatively affecting integrity of the connection
- fatigue testing (in air and in seawater) with variable compressive mean stress levels

Section 4.3 provides details on the testing procedures which are currently employed in the validation of non-caisson related designs, which may be readily adapted for evaluations of threaded connections for caisson applications. Briefly, test samples should be configured with full consideration of the design philosophy applied. For coupling designs, which require failure in the pipe body, ultimate strength of the connection can be developed by increasing the capacity (usually wall thickness) of the connecting tubular. (See Section 4.3.1.1.) Detailed instrumentation (e.g. load cells and strain gages or photoelastic templates, at a minimum) should be used to accurately define the load versus strain/stress behavior at critical regions and nominal pipe sections to verify modeling assumptions. Again, the number of samples to be tested for verification of any design parameter, although usually dictated by the physical size of the sample and cost of testing, should be sufficient to provide reasonable confidence in the results.

Section 3 defines the upper and lower bound, and average diameters used in caisson designs. Considering a 48-inch average diameter and 1.5-inch average wall thickness, it is clear that some limitations on the availability of test equipment capable of producing ultimate failure will be encountered. Ultimately, physical testing of scale models will be required. Scale model testing can be successfully used to validate analytical models that will be employed to predict full-scale behavior, provided that satisfactory scaling of the connection geometry and manufacturing tolerances in the tests and analyses is achieved. Because most large diameter designs will never be tested in full-scale, and failure of a minimum structure can result in significant losses, conclusive evidence of the accuracy of scale modeling approaches is needed. Such evidence may be achieved through the testing and analysis of a minimum of three scale models so that any nonlinearity in the scaling of a given model result can be quantified and dealt with appropriately in the design validation.

As indicated in Section 6.1.2, the suitability of applying existing fatigue assessment technologies must be confirmed though physical testing. Considering applicability of the popular SWT parameter in fatigue strength prediction, fatigue testing with various levels of *compressive* mean stress should be pursued. Note that some scatter of test results may be observed, attributed to the difficulty of physical testing and the random nature of small surface or microstructural defects which incite fatigue cracking, and the direct application of results should be executed cautiously. Additionally, the direct application of fatigue results produced in scale model tests may be questionable, considering the inability to scale surface or microstructural defects. To aid in the interpretation of results, post-mortem fractography may be used to identify the source and mode of fatigue failures.

The ability to manufacture the connection within the required design tolerances will be proven through the fabrication of a prototype connection. Following inspection and approval of the prototype, make/break testing can be performed to define installation and retrieval torques needed to ensure that suitable equipment exists and can be made available at the installation site. Torsional capacity of the connection, that may include anti-rotation mechanism of specialized installation procedures, should also be assessed with the full-scale prototype.

For driven caisson designs, pile driving tests should be performed to assess the ability of the connection to effectively transfer driving forces to adjacent tubular bodies, and to ensure that the capacity of the connection is not diminished during driving. In addition, the ability and torque required to break a driven connection should be addressed.

Finally, the deleterious effects of seawater environments on any of the structural performance characteristics outlined for the connection should be addressed through testing in saltwater solution or post-service evaluation. In particular, the fatigue performance (which degrades in free corroding environments), and breaking requirements (which generally increases in free corroding environments) should be evaluated to determine the long-term integrity and retrievability are suitable for the design. Some validation of the effectiveness of thread compounds and corrosion resistant coatings should also be performed in a saltwater environment.

6.1.4 Applicable Design Codes

Some of the most applicable design guidance for incorporation of threaded connections in caisson applications can be found in API publications that discuss marine riser design and the design of marine riser couplings. (See Section 4.1.6.) Additionally, discussions on minimum structure design in API RP 2A may provide focus and design objectives. Ultimately, though, very little specific guidance exists on the incorporation of threaded connections in offshore caisson applications.

6.2 PROPOSED WORK FOR PHASE 2

As discussed in Section 5, results of the technical review of existing caisson and threaded connection design practices indicated four primary areas that strongly influence the structural performance considerations discussed above, and which demand extended study. They are:

- stability of the structure under high compressive loadings,
- the possible harmful affects of driving on connection integrity and retrieval,
- the influence of corrosion on long term structural performance and retrieval, and
- the effectiveness of existing fatigue assessment criteria to caisson-type loadings.

Recall that the study is motivated by the potential economic advantages of reducing installation and retrieval times, and the re-use of a given design at multiple locations. Thus, in order to obtain an accurate assessment of the feasibility of applying threaded connections in caisson designs, the technically lacking areas should be further investigated.

The program proposed for phase two of the study, which requires both analytical and physical testing activities, has been designed to provide fundamental insight into the key portions of the guidelines currently lacking any approach to a validated design or assessment protocol. This differs from the initial program proposal [SwRI] in that the need for analytical work was not anticipated. However, as determined in phase one of the study, some analytical assessment will be required in order to accurately determine the feasibility of the proposed use for threaded connections. Exclusion of the analytical work program at this stage may lead to inappropriate acceptance and application of existing guidance when employed in caisson design.

While the evaluation of fatigue assessment techniques is a primary consideration for any threaded connection design, the actual fatigue strength (and *S-N* behavior) is highly dependent on the thread geometry, materials, manufacturing tolerances, and surface or microstructural propensity for defects. While performing full-scale fatigue tests to examine the effects of large compressive mean stresses is essential for evaluating fatigue assessment methodologies, such an undertaking exceeds the limits of the current program, and may prove futile given that current connection designs can produce vastly different trends. Moreover, as noted in Section 5.4, current manufacturers generally perform detailed fatigue examinations of their specific and proprietary designs, and will be required to conduct similar examinations for caisson-type loadings prior to use in related structures. Therefore, no fatigue specific issues other than an analytical examination of the SCF for such loads, which can be applied in fatigue assessments, is proposed.

6.2.1 Analyses

Two analytical studies aimed at the general definition of response trends for caissons with threaded connections are proposed. The first study includes a preliminary assessment of the local buckling failure mode, which will be later validated through full-scale experimentation (Section 6.2.2). The second focuses on definition of the SCF behavior when subjected to preload, high static compression, and cyclic stress, which can then be used by designers in their detailed fatigue evaluations. Each of the analytical studies proposed are discussed in the following sub-sections.

6.2.1.1 Local Buckling

One key result of previous programs focused on buckling of tubular members (discussed in Section 5.2.2.2) was that advanced finite element techniques validated through physical testing can be used to accurately predict the onset of local buckling that leads to collapse of the structure. Such procedures are proposed for the initial evaluation of caisson-type structures using a single pipe with no connection, pipe with a single intrusively threaded joint, and pipe with a single mechanical coupling. The first analysis of a plain pipe with no connection will provide a baseline for comparison with the subsequent analyses with threaded connections to quantify, globally, the propensity for local buckling due to the presence of a threaded connection. Only those analyses including the connection will be verified in full-scale testing.

6.2.1.2 Evaluation Of The Stress Concentration Factor For Preloads and High Compressive Loads

Because extensive study of the variations in stress concentration factors and cyclic stress ranges with high compression loadings has not been pursued, an analytical study of these effects is proposed. Using the standard thread model of the tapered buttress profile developed in phase one of the study and discussed in Section 4.4 and

Appendix B, with the addition of a shoulder, finite element analysis techniques and SCF determination methods (described in Section 4.2.2), will be applied to define the effects of preloads and high compressive loadings. Data from the analyses will be used to confirm anticipated reductions of the static capacity, and variations of the SCF with preloads and caisson-type loadings. In future work programs, not proposed herein, results of these analyses can be applied to evaluate the predicted fatigue strength of the connection when subjected to preloads and high compressive loadings.

6.2.2 Validation

Physical testing in the proposed program will be limited to validation of the local buckling behavior predicted in the analytical study (Section 6.2.2.1), and breaking a previously driven connection that has been removed from service. (Note that the proposed program assumes samples for the physical test program will be donated or obtained through purchase, the cost of which has not been included in the proposed program.) Each of the physical testing activities proposed is discussed in the following sub-sections.

6.2.2.1 Buckling Capacity Determination

The facility used to perform the combined loading tests of pipes with geometric discontinuities [Smith 1998, Grigory, SSD] is shown in Figure 6-1, and will be used to perform the local buckling tests of large diameter pipe sections joined with: (1) an intrusively threaded design, and (2) a external coupling. In each test, the connection will be subjected to high axial compression and 4-point bending loads sufficient to produce local buckling within the structure. Connections will be located at the axial mid-span (where bending moments are largest) as shown in the figure.

Note that internal pressurization of the assembled structure is not currently proposed since most caissons are not required to sustain significant internal pressures which tend to enhance structural performance. Therefore, its exclusion from the tests and analyses will provide an indication of the lower bound estimate of buckling capacity. In future efforts (not proposed herein), small-scale test specimens may be used to address the effects of external pressure, bending, and axial compression on buckling capacity and propagating buckling.

No larger than 30-inch nominal pipe geometries with a 1-inch wall thickness, and their appropriately sized connections, will be tested in the facility shown in Figure 6-1. If larger sample sizes are desired, the use of an alternate test facility at SwRI can be investigated. Accordingly, the costs associated with larger scale testing will impact the test program, and are not currently considered in the estimate for phase two activities (Section 6.2.4). At the request of MMS, SwRI will prepare revised estimates for the increased scale tests.

6.2.2.2 Break Test

The breaking torque required to retrieve a caisson from service will be assessed using a connection that has been previously installed *by driving* offshore and allowed to freely corrode in a saltwater environment. The requirement for obtaining a driven connection is included since it is believed that driving forces and their potential effect on connection deformations will affect breaking torque requirements.

The connection may be a threaded pipe joint or external coupling, (preferably both) that has been donated to the program from a supporting organization (Section 6.2.4). Following full separation of the joint, thread surfaces and shoulders (if present) will be examined to identify any wear patterns, local surface defects, or evidence of significant localized deformation that would preclude its use in subsequent designs.

Design, installation, service, and removal documentation for the connection must accompany the donated specimen. This information will be used to assess accuracy of initial estimates of the breaking torque requirements and potential failure mechanisms assumed in the original design. Moreover, connections may include corrosive resistant coatings and thread compounds that can be cursorily evaluated, and knowledge of their initial design parameters used in the interpretation of results.

6.2.3 Reports and Recommendations for A Code or Standard

Following completion of the phase two technical activities, a report documenting the findings of the analytical program and validation testing will be developed. Results reported, in full detail, will include:

- local buckling analysis results, comparing plain pipe (pipe without connections) to pipes with external couplings and pipes with threaded connections
- SCF evaluation results including the analytically predicted variation of local stress concentrations with preload and high compressive stresses for later use in static, dynamic, and fatigue assessments
- local buckling test results, including comparisons with corresponding finite element analyses, and
- break test results, including review of original design expectations, and results of post-mortem inspection of mating surfaces

Also included in the report will be general protocol for the design, analysis, and validation of threaded connections for offshore applications enhanced to account for the findings of phase two technical program tasks. Any outstanding issues related to the development of formalized guidelines will also be identified.

6.2.4 Financial Support

The estimated cost for completion of the second phase is $234,000, and will be completed during the 1999 fiscal year. Note that this is more than twice the amount that was initially proposed, primarily due to testing of two different connection designs and corresponding analytical work. This estimate is based on the assumption that specimens for physical testing activities will be donated to the program, in testing configuration, through external supporting organizations. Regarding the break test, a donated specimen(s), previously installed and removed from service is required since only a used connection(s) will provide information needed to assess breaking torque and long-term deleterious effects.

Please note that the rough order of magnitude (ROM) estimate does not constitute a bid or quote for competitive evaluation. However, it does contain proprietary pricing information that we request not be disclosed to any third party. This estimate is intended for budgeting and planning purposes only, and upon request, a formal proposal for consideration will be provided.

6.2.4.1 Level of Effort

The estimated costs for each program task are given in Table 6-1, and are scheduled for execution during the 1999 fiscal year. The costs have been developed based on labor and materials estimates needed to complete the work tasks as defined. Again, the estimated costs do not include procurement or development of test samples for the physical test program. Costs associated with retrieval of the specimen(s) for break testing of the used threaded connection, or the related break equipment needed to perform the test have not been included. The current estimate for break testing is based on the performance of two break tests (i.e., two individual specimens).

6.2.4.2 Funding Sources

As stated previously, results of the industry survey indicated only moderate interest in the use of threaded connections in caisson structures. This response is primarily due to technical concerns (discussed in Section 5.4) weighted against the potential economic advantages. Most designers have adopted a position that requires proof of the concept and economic benefits prior to giving full consideration to the feasibility of the proposed use of threaded connections. Hence, support for advancement of the technology and completion of the feasibility assessment will likely rely on interested thread manufacturers, supportive owner/operators, and on the MMS.

6.2.4.2.1 Potential For JIP Funding

At this time there is no conclusive evidence that a Joint Industry Program (JIP) to complete the phase two program can be assembled. In general, only a single thread manufacturing organization has been identified which has a strong interest in the success of this study, and others have only a detached interest in the application of threaded connections in caisson designs. During the personal interviews (Section 5.4), only small dollar amounts (less than $10,000) were tentatively committed by two operators.

Hence, the costs associated with the development of a JIP with individual contributions in such small allotments and varying dollar amounts do not, at this time, warrant further pursuit of JIP supporters.

Upon initiation of the phase two program, however, the technical program now proposed may incite some interest on local buckling behavior of threaded connections that could potentially lead to increased industry support, given that threaded connections are now being used in insert piles offshore [Buitrago 1988]. However, no additional effort toward soliciting possible industry support will be pursued prior to MMS approval of the proposed scope of work is obtained.

6.2.4.2.2 *MMS*

As can be surmised from the preceding commentaries, completion of the phase two program will rely heavily on the ability of MMS to secure the necessary funding. Although designers, at the current time, are reluctant to commit funds towards the development of the proposed technologies, it is believed that upon completion of the feasibility study they will be more willing to employ threaded connections in their designs. Ultimately, some guidance and approval by the MMS for such designs will be required, and completion of the feasibility study as proposed will be needed.

6.2.4.2.3 *Other Sources*

It is likely that the extent of support for phase two activities from other sources will be through the donation of test articles and equipment. It is believed that at a minimum, an intrusively threaded connection can be obtained from one threaded pipe manufacturer. Following acceptance of the proposed program, threaded coupling manufacturers will be requested to donate equivalent test articles, so that comparative evaluations can be performed. Note that the inability to obtain equivalent test articles from a coupling manufacturer will reduce the total cost of the program in that only one local buckling test and one break test will be possible. For completeness of the analytical work program, local buckling analyses of each connection type will be performed, irrespective of the number and types of donated samples obtained.

Table 6-1. Estimated Program Costs By Task

Task	Description	Estimated Cost
6	Local Buckling Analyses	$28,000
7	SCF Analyses	$44,000
8	Local Buckling Tests	$92,000
9	Break Test	$26,000
10	Reports and Recommendations For A Code or Standard	$44,000
TOTAL		$234,000.00

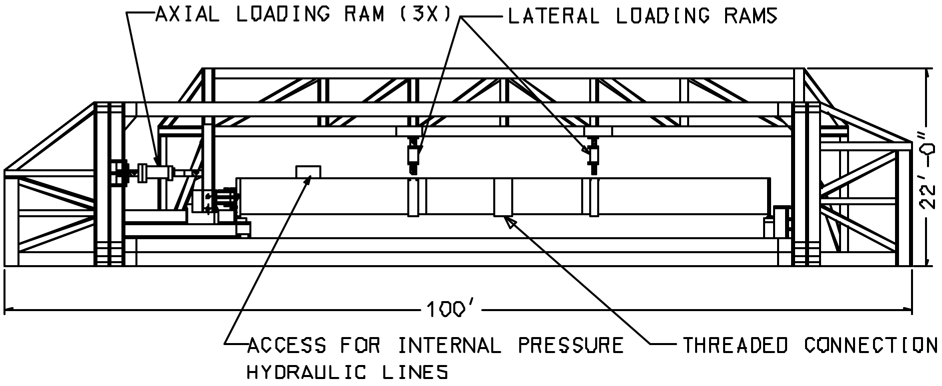

Figure 6-1. Facility used to perform the combined loading test of tubulars.

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7. REFERENCES AND LITERATURE REVIEW

A comprehensive search and review of technical literature was performed to determine current practices for caisson and threaded connection design and evaluation. An abbreviated listing of the literature reviewed in contained in the section. The review included design guidelines (provided by API and others), numerous proceedings of pertinent technical conferences and published texts related to many aspects of design, analysis, and validation of threaded connections. The review focused on the definition of current practices related to the development of both caisson structures and threaded connections, which was provided primarily by the guidelines and open literature. Textbooks provided fundamental engineering models and assessment procedures that assisted the development of generalized guidelines for the extension, or enhancement of existing practices to the proposed use of threaded connections.

The last 13 years of OTC (Offshore Technology Conference) proceedings and the last 6 years of the OMAE (Offshore Mechanics and Arctic Engineering) proceedings were reviewed. A great deal of information was found on loading scenarios, much of which pertained to various environmental conditions. Many of these studies were either experimental or theoretical in nature. Standard practices, as outlined in the accepted API standards, were believed to provide enough information to determine most loads in general terms. As a result, current and applicable API publications were obtained. Many of the API standards also appeared to provide the basis of international ISO standards.

Sufficient information was obtained to develop an accurate understanding of pile driving forces. Additionally, references were also obtained on thread analyses to provide detailed analytical examples, which could be used to guide development of the finite element mesh discretization and methods employed for the standard thread model analyses. Also, many of the references on thread analysis focused on areas of concern that have been addressed in this report.

BIBLIOGRAPHY

[30CFR250] Code of Federal Regulations, Title 30--Mineral Resources, Chapter II--Minerals Management Service, Department of the Interior, Part 250--Oil and Gas and Sulfur Operations in the Outer Continental Shelf (30CFR250).

[ABAQUS] Hibbitt, Karlsson, & Sorensen, Inc. Pawtucket, RI, 1997

[AISC ASD] American Institute of Steel Construction (AISC) Specification for Structural Steel Buildings, Allowable Stress Design and Plastic Design, June 1, 1989, with Commentary.

[ANSYS] SAS IP, Inc., Houston, Pennsylvania, 1996.

[API RP 2A] API, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design, American Petroleum Institute, API Recommended Practice 2A-WSD (RP 2A-WSD) Twentieth Edition, July 1, 1993 (with Supplement 1, February, 1997).

[API RP 2B] API, Specification for the Fabrication of Structural Steel Pipe, American Petroleum Institute, API Specification 2B, Fifth Edition, May, 1996.

[API Spec 5B] API, Specification for Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads, American Petroleum Institute, API Spec 5B, Fourteenth Edition, August 1996.

[API BUL 5C2] API, Bulletin on Performance Properties of Casing, Tubing, and Drill Pipe, American Petroleum Institute, API Bulletin 5C2 (BUL 5C2), Twentieth Edition, May, 1987.

[API BUL 5C3] API, Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties, American Petroleum Institute, API Bulletin 5C3 (BUL 5C3), Sixth Edition, October 1, 1994.

[API BUL 5C4] API, Bulletin on Round Thread Casing Joint Strength with Combined Internal Pressure and Bending, American Petroleum Institute, API Bulletin 5C4, Second Edition, May 31, 1987.

[API RP 5C5] API, Recommended Practice for Evaluation Procedures for Casing and Tubing Connections, American Petroleum Institute, API Recommended Practice 5C5, Second Edition, November, 1996.

[API Spec 5CT] API, Specification for Casing and Tubing (U.S. Customary Units), American Petroleum Institute, API Specification 5CT, Fifth Edition, April 1, 1995.

[API 5L] API, Specification for Line Pipe, American Petroleum Institute, API Specification 5L, Forty-First Edition, April 1, 1995.

[API BUL 16J] API, Bulletin on Comparison of Marine Drilling Riser Analyses, American Petroleum Institute, API Bulletin 16J (BUL 16J) First Edition, August 1, 1992 (Formerly BUL 2J).

[API RP 16Q] API, Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems, American Petroleum Institute, API Recommended Practice 16Q (RP 16Q), First Edition, November 1, 1993 (Formerly RP 2Q and RP 2K).

[API Spec 16R] API, Specification for Marine Drilling Riser Couplings, American Petroleum Institute, API Specification 16R, First Edition, June 1, 1997.

[API List] API, Composite List of Manufacturers Licensed for Use of the API Monogram, On Products Manufactured to API Exploration and Production Department Specifications, American Petroleum Institute, Volume 4, Number 3, October, 1996.

[ASME V116] Photoelastic Measurements, Transactions of the ASME, Vol. 116, November, 1994, p. 228.

[Bannantine] Bannantine, J. A., Comer, J. J., Handrock, J. L. *Fundamentals of Metal Fatigue Analysis*, Prentice-Hall, 1990.

[Bouwkamp] Bouwkamp, J. G., Stephen, R. M. Full-Scale Studies on the Structural Behavior of Large Diameter Pipes Under Combined Loading, Report No. UC-SESM 74-1, University of California at Berkeley, prepared for Alyeska Pipline Service Company, January 1974.

[Broadbent] Broadbent, T.P. and H. Fessler, Stress Analysis of Screwed Tubular Joints, International Conference on Fatigue and Crack Growth in Offshore Structures (1986:London), Mechanical Engineering Publications Limited, 1986, pp 171-186.

[Buitrago 1988] Buitrago, J., “Validation of Large-Diameter Connector Designs,” Proceedings of an International Seminar Organized by the NDE Centre, University College, London, September, 1988, pgs. 87—118.

[Buitrago 1989] Buitrago, J., Gunderson, R., “Experimental Validation of a Large-Diameter Tether Connector,” OTC 5939, Proceedings of the 21st Annual Offshore Technology Conference, pgs. 555-565.

[Buitrago 1998] Buitrago, J., Sele, A., “Strength and Fatigue Provisions for Mechanical Connector Design: New ISO Standard for Offshore Structures,” Proceedings of the 17th International Conference on Offshore Mechanics and Arctic Engineering, Vol. III — Materials Engineering, 1998.

[Chen] Chen, W-C, “Fatigue-Life Predictions for Threaded TLP Tether Connector,” OTC 5938, 21st Annual Offshore Technology Conference, Houston, Texas, May 1-4, 1989.

[Dover] Dover, W., and Dharmavasan, S., "Inspection of Threaded Components Using ACFM," Proceeding of an International Seminar organized by the NDE Centre, University College, London, 1988, pp. 57-70.

[Dowling] Dowling, N., *Mechanical Behavior of Materials — Engineering Methods for Deformation, Fracture, and Fatigue*, Prentice Hall, 1993.

[Drawe] Drawe, W. J. III, Reifel, M. D. “Platform Function and Type,” *Planning and Design of Fixed Offshore Platforms*, Edited by B. McClelland and M. Reifel, Van Nostrand Reinhold Company, 1986.

[E.A.L. Smith] Smith, E. A. L., Pile-Driving Analysis by the Wave Equation, Transaction of the ASCE, Paper No. 3306, Vol. 127, 1962, Part I, pp 1145-1193.

[EMAS] EMAS, *Fatigue of Large Diameter Threaded Connections*, Proceedings of an International Seminar organized by the NDE Centre, University College London, 21-22 September, 1988, Engineering Materials Advisory Services, Ltd, West Midlands, UK.

[Gerwick] Gerwick, B., *Construction of Offshore Structures*, Wiley & Sons, 1986.

[Glinka] Glinka G., Newport, A., “Stress Concentration in Threaded Tubular Connection Under Cyclic Load,” Transactions of the ASME, Vol. 188, June, 1996, p. 274.

[Grewal] Grewal, A. S., and M. Sabbaghian, “Load Distribution Between Threads in Threaded Connections,” Journal of Pressure Vessel Technology, February 1997, Vol. 119, p. 91.

[Grigory] Grigory, S. C. Experimental Stress Analysis of 48-inch Diameter Pipe with a Sleeve Repair, Final Report SwRI Project No. 07-3758-600, prepared for Alyeska Pipeline Service Company, June 1994.

[Gunderson] Gunderson, R. H., J. Buitrago, S. A. Fox, and J. Q. Burns, A Large-Diameter Threaded Connector for Tension Leg Platform Tendons, OTC 5937, 21st Annual Offshore Technology Conference, Houston, Texas, May 1-4, 1989.

[Jones] Jones, W., “Materials Selection for Threaded Connections With Particular Reference To Corrosion-Fatigue Strength,” Proceedings of an International Seminar Organized by the NDE Centre, University College, London, September, 1988, pgs. 71—85.

[Lewis]	Lewis, D.B., J. F. Chappell, and A. T. Katsounas, Effect of Makeup and Internal Pressure on the Structural Strength of API Buttress and 8 Round Threaded Connections, OTC 7558, 26th Annual Offshore Technology Conference, Houston, Texas May 2-5, 1994.
[Lloyd's]	Lloyd's Register, Rules and Regulations for Classification of Fixed Offshore Installations, Part 4, Steel Structures.
[Liebster]	Liebster, T., and Glinka, G., "Development of a Numerical Model for Predicting Fatigue Lives of Tubular Threaded Connections," Case Studies for Fatigue Education, ASTM STP 1250, American Society for Testing and Materials, Philadelphia, 1994, pp. 156-173.
[McDonald]	McDonald, H.B., "Overview of API Research Projects on Thread Compound Performance Properties," OTC 7343, 25th Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1993.
[NASTRAN]	MacNeal-Schwendler Corporation, Los Angeles, CA, 1996.
[Oberg]	Oberg, Erik, Franklin D. Jones, and Holbrook L. Horton, Machinery's Handbook, A Reference Book for the Mechanical Engineer, Draftsman, Toolmaker and Machinist, Industrial Press, Inc., New York, 1976.
[Peterson]	Peterson, R. E., Stress Concentration Factors, Wiley & Sons, Inc., 1974.
[Percy]	Percy, J. L., and A. Sato, Analysis of Threaded Joints by Finite Element Methods, 1989 ANSYS Conference Proceedings, Pittsburgh, Pennsylvania, May 1-5, 1989.
[Sato]	Sato, T., S. Sano, K. Ishikawa, and T. Nakano, "Finite Element Analysis and Fatigue Evaluation of the Threaded Marine Riser Connector," Journal of Energy Resources Technology, Vol. 110, June 1988, p. 85.
[Smith]	Smith, E. A. L., Pile-Driving Analysis by the Wave Equation, American Society of Civil Engineers Transactions, Paper No. 3306, (Vol. 127, 1962, Part I)
[Smith 1998]	Smith, M., Nicolella, D., and Waldhart, C., "Full-Scale Wrinkling Tests and Analyses of Large Diameter Corroded Pipes," Proceedings

of the ASME 1998 International Pipeline Conference (IPC'98), 1998.

[SSD] Experimental and Analytical Evaluations of Sleeve Pipeline Configurations, SSD Engineering Consultants and Berkeley Engineering and Research, prepared for Alyeska Pipeline Service Company, June 30, 1994.

[SwRI] Assessment of the Feasibility for the Application of Threaded Connections in Offshore Platform Caissons, SwRI Proposal No. 06-20479, submitted to Minerals Management Service, December 1996.

[Tafreshi] Tafreshi, A., and W. D. Dover, "Stress Analysis of Drillstring Threaded Connections Using the Finite Element Method," Int J Fatigue 15, No. 5 (1993) pp 429-438.

[Turner] Turner, W., Mackie, M., and Duxbury, J., "Design Methodology for Mechanical Connectors," Proceedings of an International Seminar Organized by the NDE Centre, University College, London, September, 1988, pgs. 189—212.

[Warrington] Warrington, D. C., A Proposal for a Simplified Model for the Determination of Dynamic Loads and Stresses During Pile Driving, OTC 5395, 19th Annual Offshore Technology Conference, Houston, Texas, April 27-30, 1987.

[Zentech] Zentech, Inc., StruCAD*3D Engineering Solutions, Ver 3.7, ES Notices-1, Houston, Texas, 1997.

[Zhao] Zhao, Hua, "A Numerical Method for Load Distribution In Threaded Connections," Transactions of the ASME, Vol. 188, June, 1996, p. 274.

APPENDIX A INDUSTRIAL SURVEY

Twenty-one industry surveys were delivered to designers and operators in the Gulf of Mexico area. Contact was initially made over the telephone to establish appropriate company personnel prior to sending the survey via facsimile. The following four pages contain a cover letter explaining the survey and the survey itself.

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Materials and Structures Division
May 27, 1998

[Contact Person]
[CONTACT COMPANY]
[Contact Company Address]
[City, State   zip code]

Subject: Assessment of the Feasibility for the Application of Threaded Connections in Offshore Caisson Structures

Reference: Telephone conversation on [Date Contacted]

Dear [Contact First Name]:

Southwest Research Institute (SwRI) is performing a study for the Minerals Management Service (MMS) to determine the feasibility of applying threaded connections in the fabrication of offshore free-standing caisson platforms. The attached survey has been generated to determine the range (minimum and maximum) and "typical" design criteria for installations overseen by your organization. The information you provide will be used by SwRI to the benefit of MMS to outline the range of design parameters, which must be considered in the study, and to assess the need for guidelines regulating the use of threaded connections in future caisson designs.

SwRI has been working under the direction of MMS, who has provided sole support for the study, to assess both the economic and technical feasibility of applying threaded connections within the caisson body as an alternative to welded girth connections. MMS initiated the study based on the perception that industry may pursue using threaded connections for offshore caisson structures as a method of reducing installation and decommissioning costs. Thus far, this work has included generalized analytical assessments of the structural performance of standard thread designs, a review of commercially available high performance thread designs, manufacturing and installation/decommissioning issues, and a review of current technical practices and existing regulatory guidelines for the design, analysis, and validation of caissons structures and threaded connections.

To appropriately complete the feasibility study, industry guidance, through the completion of the attached two (2) page survey and any additional comments, is needed. Economic and technical concerns, suggestions, or criticisms are of most importance to the study. Moreover, some indication as to whether [Company Name/Abbrev.] would be willing to adopt, as an added option, the practice of using threaded connections in primary structure caisson designs. This will help guide continued research and development of threaded connections for offshore caissons. The final page of the survey form allows space for your individual comments which are maintained confidential within SwRI.

Design criteria results of the industry survey will be reported to MMS in the form of a table defining the upper and lower bounds of each parameter, and, where possible, any weighted distribution of these parameters. Additional comments and suggestions will be generally summarized in a final report to MMS. The survey will be presented without reference to the responding organization. You can obtain results of the survey when complete by sending your request to the postal or e-mail address given below.

If possible, the survey should be completed by **June 12, 1998**. However, all surveys arriving later than the informal deadline stated will be accepted and used in the study if received prior to June 30, 1998. The survey should be returned, preferably by facsimile, to:

Marina Q. Smith — MMS/SwRI. Project No. 06-8955
Southwest Research Institute - Building 71
6220 Culebra
San, Antonio, Texas 78228
Fax: (210) 522-3042
E-mail: msmith@swri.edu

Should you have any questions or comments about the survey, or require any additional information with regard to the feasibility study, please contact me at (210) 522-2143. If you are unable to complete the survey, please feel free to forward the survey to other individuals in your organization. Your input is important to our study, and I thank you in advance for your time and consideration in completing the survey.

Best Regards,

Marina Smith, Senior Research Engineer
Structural Engineering Department

INDUSTRY SURVEY FOR:

“Feasibility of the Application of Threaded Connections in Offshore Platform Caissons”

Minerals Management Service

Southwest Research Institute

SURVEY CONTACT INFORMATION

Name

Title

Company

( ) Phone

( ) Facsimile

E-mail Address

DESIGN CRITERIA (BEST ESTIMATE)

Parameter	**Minimum**	**Maximum**	**Typical**†	**Units**
Caisson Diameter				inches
Wall Thickness				inches
Material Yield Strength				ksi
Water Depth				feet
Penetration Depth(from mudline)				feet
Topside Weight				kips
Hammer Size (if driven)				kips
Number of Blows (if driven)				blows

† Please indicate parameter value most common to current and planned installations. If none, leave blank.

DESIGN GUIDES

Please list guidelines used in design.

ADDITIONAL DESIGN AND OPERATIONAL CONSIDERATIONS

Number of free-standing caisson platforms your company installs/operates in the Gulf of Mexico:

Number of planned installations for free-standing caisson platforms in the Gulf of Mexico in 1998:

Percentage of tapered caissons with a reduced diameter in the wave zone:

Preferred method of fabrication (check one):

- Weld individual members offshore ☐
- Weld in yard, tow out, large single lift ☐
- Other (please describe)

All funding for this survey provided by *MMS*

INDUSTRY SURVEY FOR:

"Feasibility of the Application of Threaded Connections in Offshore Platform Caissons"

MMS Minerals
Management
Service

Southwest
Research
Institute

ADDITIONAL DESIGN AND OPERATIONAL CONSIDERATIONS (CONTINUED)

Typical method of installation (check one): Driven ☐ Jetted ☐

Please list caisson installation locations (general area or lease block names).

GENERAL INTEREST

Would your company be interested in using threaded connections to assemble caissons in lieu of current methods? (check one): Yes ☐ No ☐

Who at your company could SwRI contact to discuss the feasibility of such an application?
(Please provide contact information if different survey respondent)

Name

Title

(   )
Phone

(   )
Facsimile

E-mail Address

COMMENTS (CONCERNS, SUGGESTIONS, CRITICISMS)

Please give any additional comments.

All funding for this survey provided by *MMS*

APPENDIX B STANDARD THREAD ANALYSIS

During this study, the analysis of threaded connections subjected to caisson-like loadings was performed. The analyses employed standard thread designs, using both straight and tapered profiles and *failure in the threaded connection* philosophy (i.e., where the threaded connection strength is less than the pipe body) to assess the general feasibility of using threaded connections in caisson applications. Selection of the standard profile designs, as opposed to highly optimized designs and coupling configurations, was based on the premise that the unmodified, widely available thread forms would provide a lower bound performance, adding conservatism in the assessment. Moreover, guidelines and recommendations regarding the use of threaded connections in caisson applications are intended to be generally applicable for all threaded designs, and existing standard thread patterns could potentially be used for coupling or threaded pipe configurations.

In all, four standard thread profiles were examined. The results of these analyses are contained in this Appendix and validated the need for some optimization of the thread profile, particularly the thread height and root radius. This information provided valuable insight into the sensitivity of the threaded connection geometry and loading on stress concentrations.

Using accepted thread design standards as a guide, (e.g., Oberg and API Spec 5B), four thread profiles were chosen. Straight thread profiles of the ACME, Stub ACME and API Buttress designs, and a tapered thread profile for the API Buttress design were scaled from the standards to accommodate an assumed pitch of 1/2-inch for the 48-inch diameter pipe.

Simplistic two-dimensional local finite element models of each of the four thread profiles were developed. To evaluate the relative efficacy of each of the profiles, axisymmetric models of the joint were developed and analyzed under a nominal axial loading of 1000-psi. Each model, which focused on the thread engagement, did not include shoulders so the effects of varying thread geometry can be precisely determined. Details of the axisymmetric finite element analyses follow.

- ANSYS, revision 5.3, finite element software was utilized and executed on a personal computer (PC).

- Approximately 2600 total elements were used in each thread model, of which about 280 were point-to-surface contact elements at the thread engagement boundaries, four were compliant springs, and the remainder were four-noded axisymmetric quadrilateral elements.

- A symmetrical contact surface was utilized between the joint's box and pin thread profiles to allow for relative sliding between the pin and box surfaces of the connection.

- Loading was either 1000 psi axial compression or tension on the box, with the pin fixed rigidly in the horizontal (X) and vertical (Y) directions.

For each profile, the region at the thread roots was highly discretized to effectively capture the almost immediate transition from high to lower stress levels at this location. Density of the mesh decreased away from the thread roots to a course mesh at the inner and outer surfaces of the connection. The mesh used for the Stub ACME analyses is shown in Figure B-1, with the pin on the left and the box on the right, and is typical of those used for all axisymmetric analyses.

By applying a nominal load of 1000-psi to each model, resulting axial, radial, and von Mises equivalent stresses obtained for each thread profile were compared. The analysis procedure utilized is outlined below.

1. After the model was created in the "just touching" position, the four compliant springs were used to add structural stiffness and aid convergence.

2. The first load step either held the box and pin in the touching condition, or forced contact by imposing a slight radial displacement on the box as shown in Figure B-2. (This constraint is an initial requirement for all contact analyses using ANSYS.)

3. During the second load step, the imposed displacement was removed from the box and an axial loading was imposed on the box as shown in Figure B-3.

Note that geometric symmetry of the thread profile in the straight Stub and Stub ACME designs allowed for the analysis of a single compression load case. However, for the unsymmetric straight and tapered API Buttress designs, the joint was loaded in tension and compression to define maximum stress locations and magnitudes for each loading condition.

The von Mises equivalent stress contours for each of the thread designs (and each load case for the API Buttress designs) are shown in Figures B-4 through B-9. When comparing maximum equivalent stress values, the tapered API Buttress thread profile results in the lowest stress magnitude in tension and compression, followed by the straight API Buttress, Stub ACME and ACME designs. Based on this comparison, the following conclusions can be made.

- Lower profile threads, such as Stub ACME when compared with ACME, reduce the stress concentration at the thread root.

- Reduced leading and trailing flank angles, such as API Buttress when compared with ACME, also produces a slight reduction in the stress concentrations at the thread root.

- The tapered thread profile evaluated, API tapered Buttress, reduces thread loading when compared with straight thread profiles. This effect has also been documented in other studies.

In addition to von Mises effective stress comparisons, the radial (X) and axial (Y) stresses for each joint were reviewed to further assess the performance of each joint and to verify accuracy of the models used. As shown in Figures B-10 through B-15, the first fully-loaded tooth is consistently the most highly stressed, and an immediate parabolic transition of the stresses from this high level to lower stress was observed when traversing from tooth to tooth. This effect is well documented in the available literature. When comparing axial stress contours for the Stub ACME straight thread (Figure B-10 and B-11) and the API Buttress tapered threads (Figures B-12 and B-13), a more uniform distribution of stresses though the tapered thread joint is achieved which results in nearly homogenous behavior of the joint under tension and compression (Figures B-14 and B-15).

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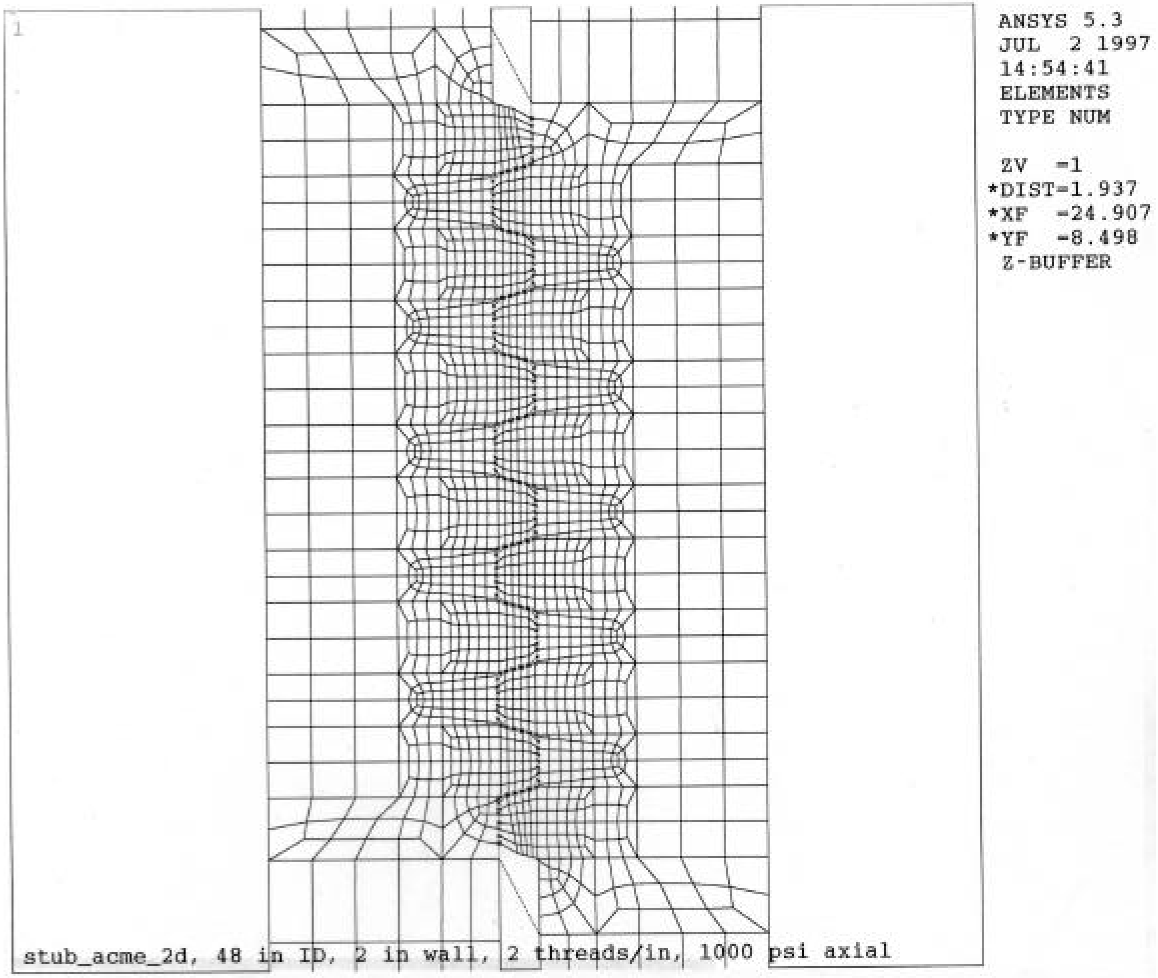

Figure B-1. Local Mesh Discretization

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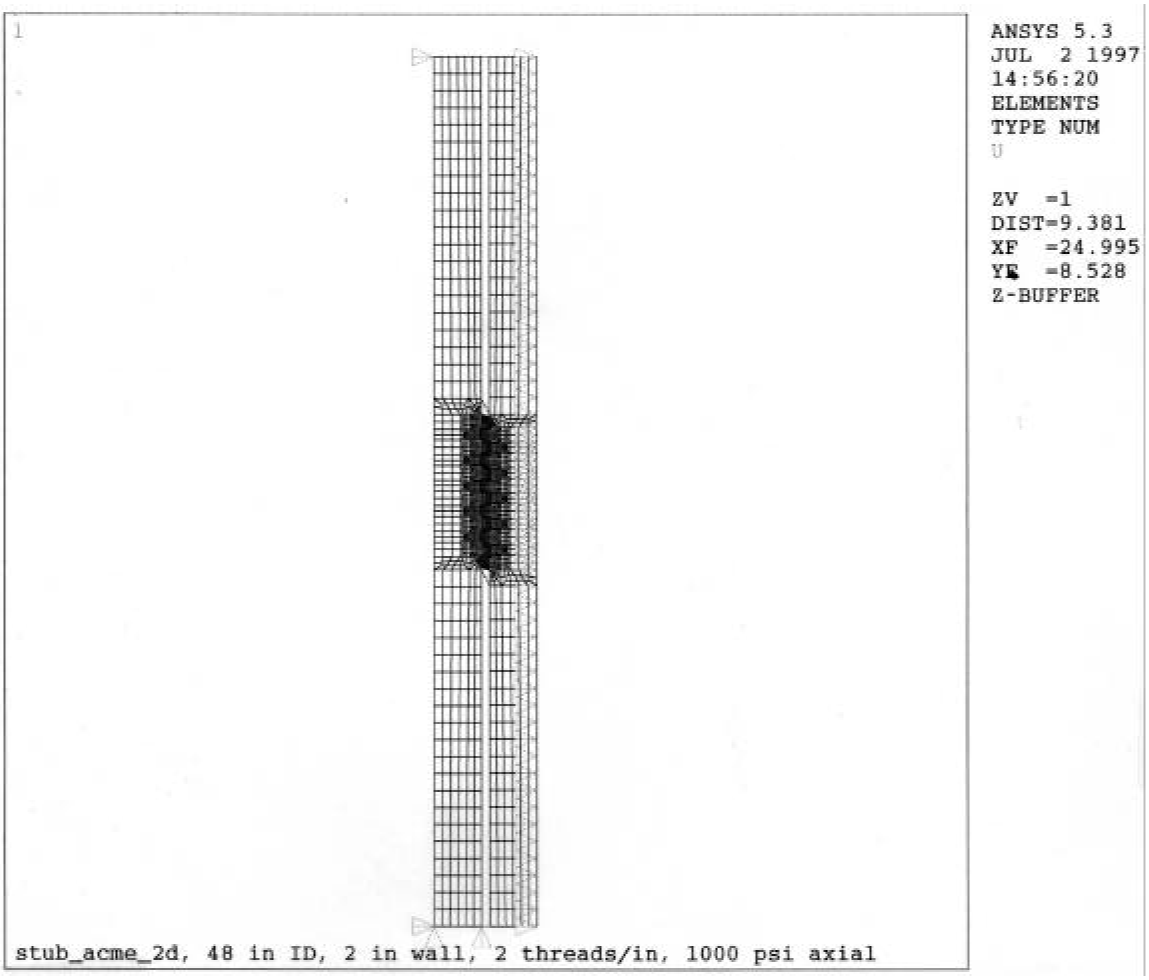

Figure B-2. First Load Step (Initial Radial Contact)

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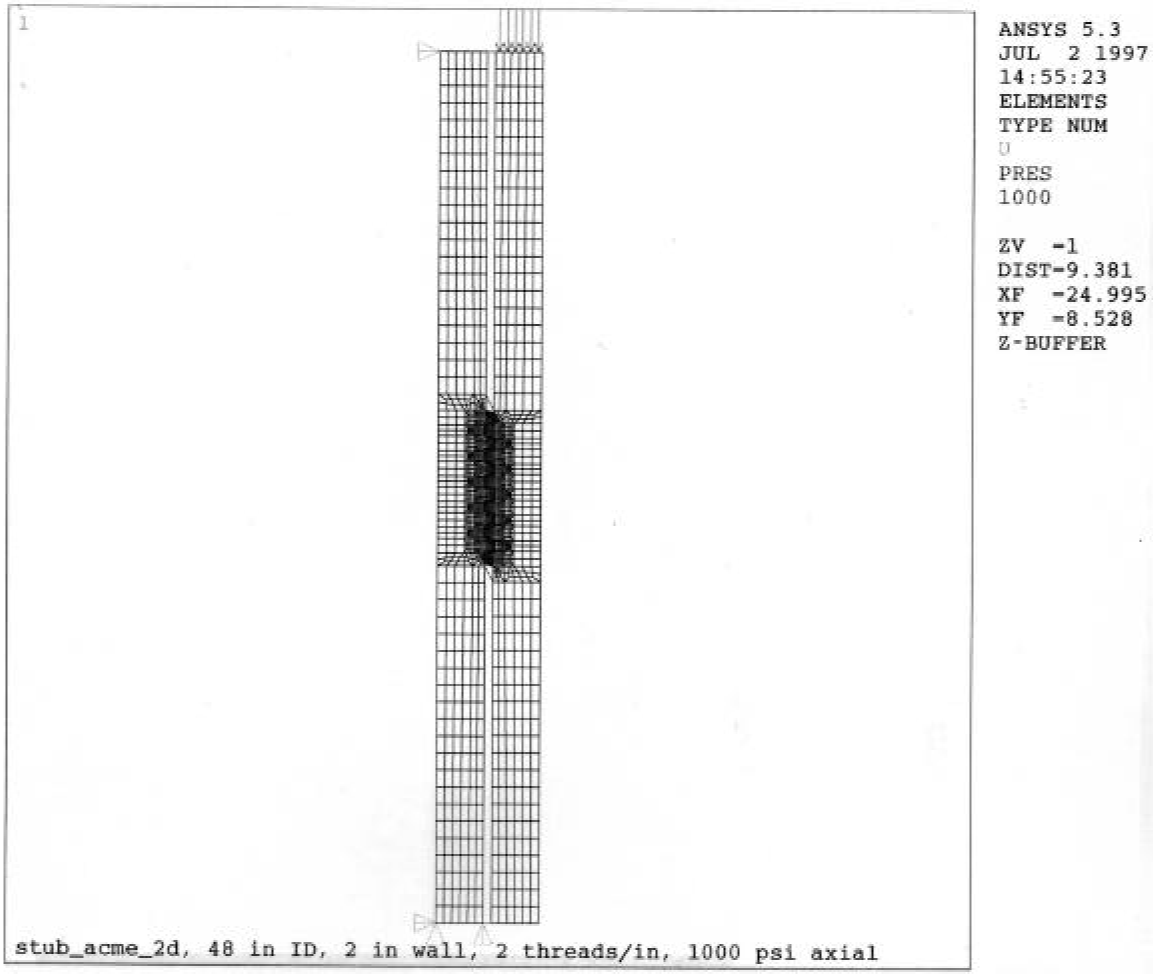

Figure B-3. Second Load Step (Axial Loading)

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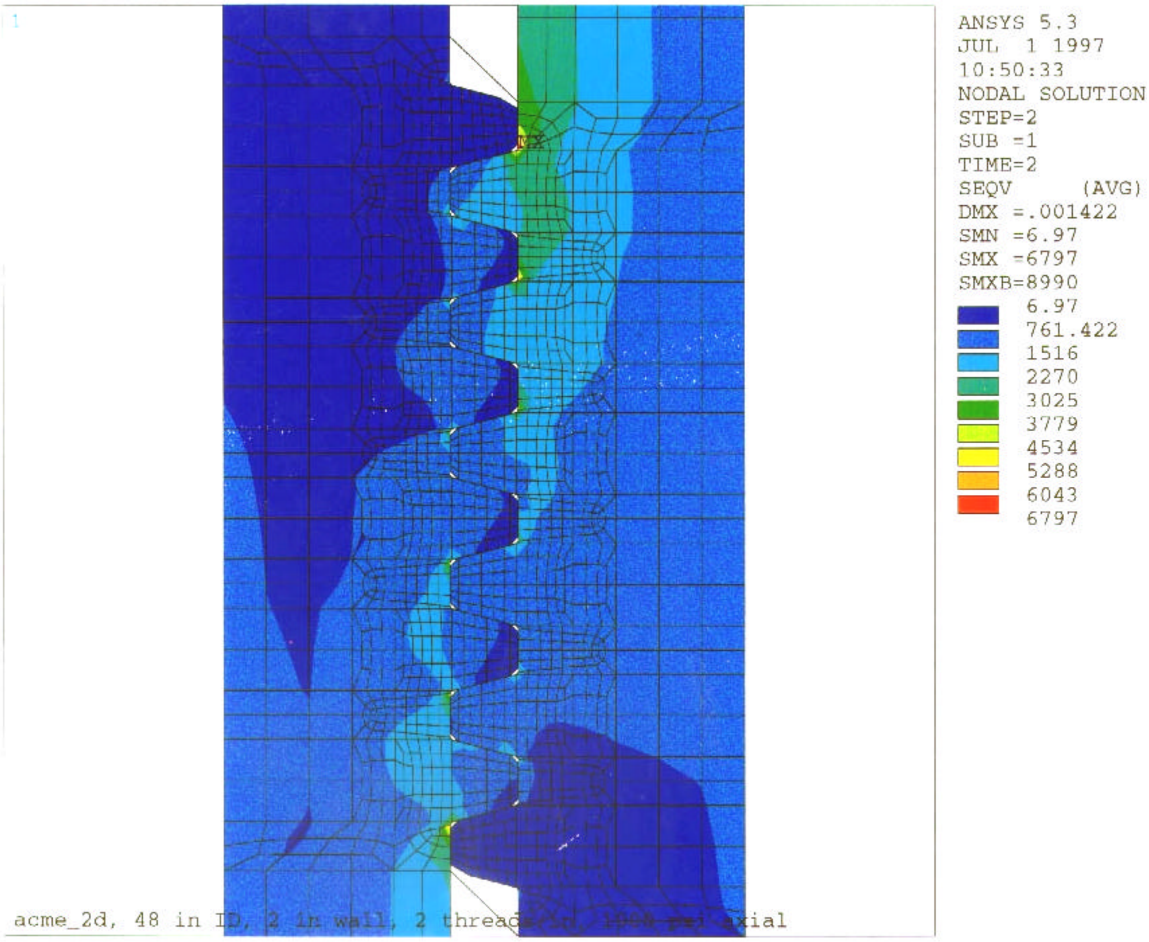

Figure B-4. Standard ACME in Compression (Equivalent Stress)

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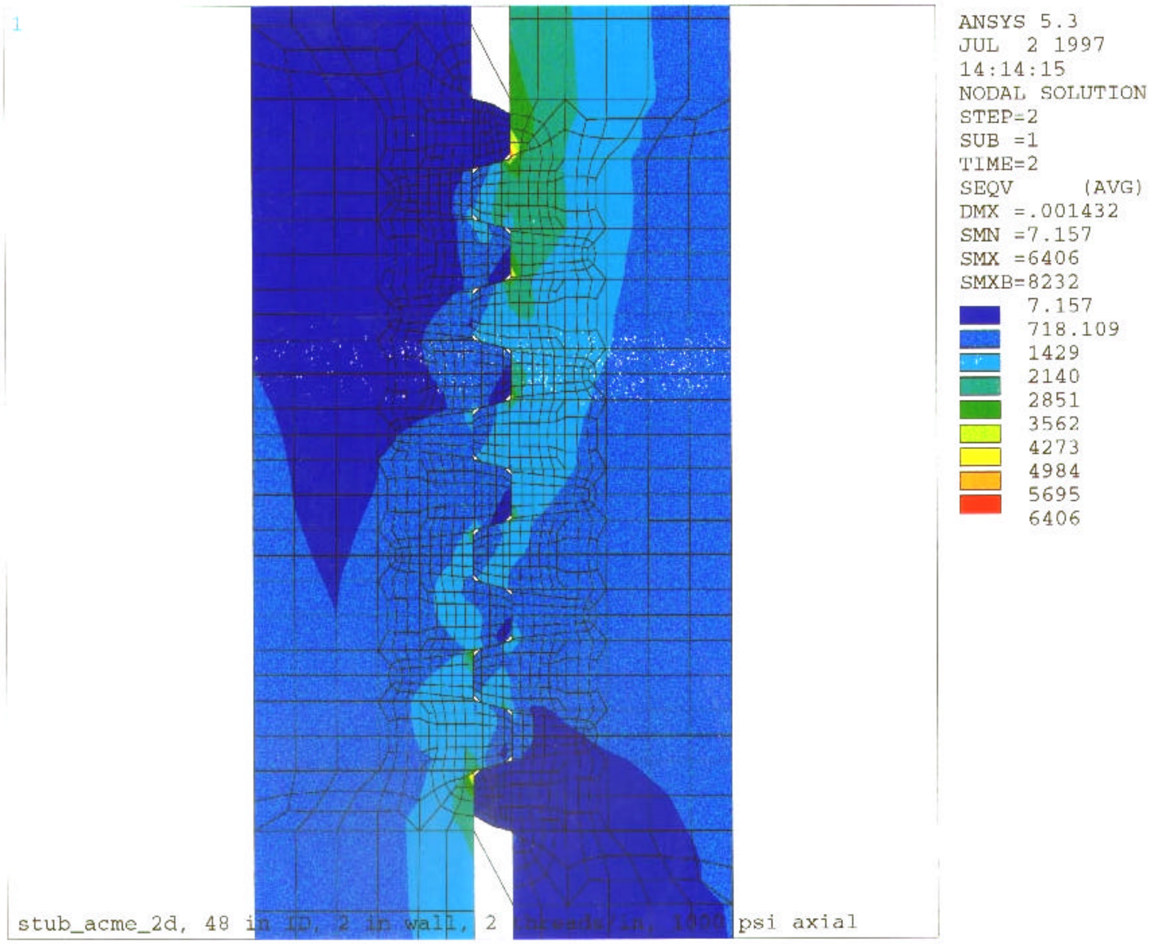

Figure B-5. Stub ACME in Compression (Equivalent Stress)

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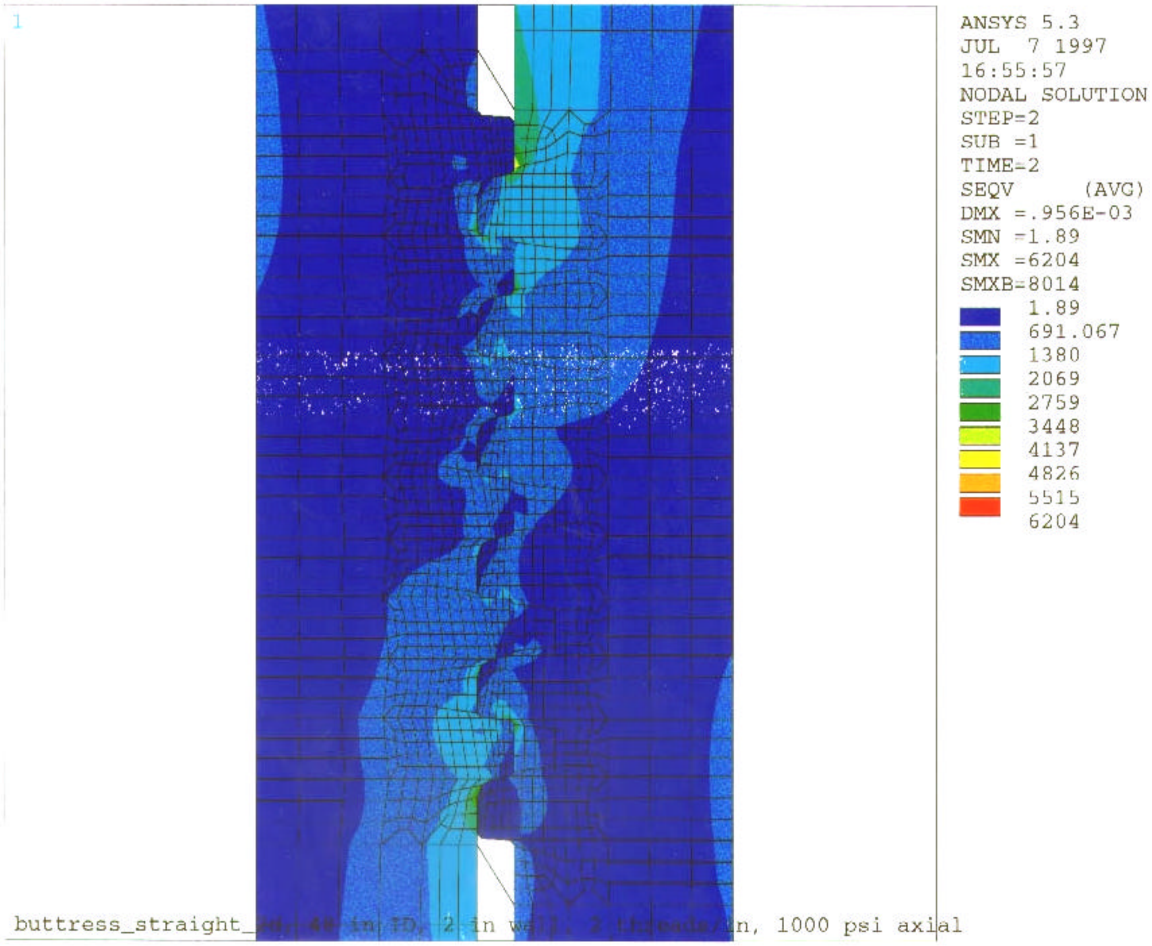

Figure B-6. Straight Buttress in Compression (Equivalent Stress)

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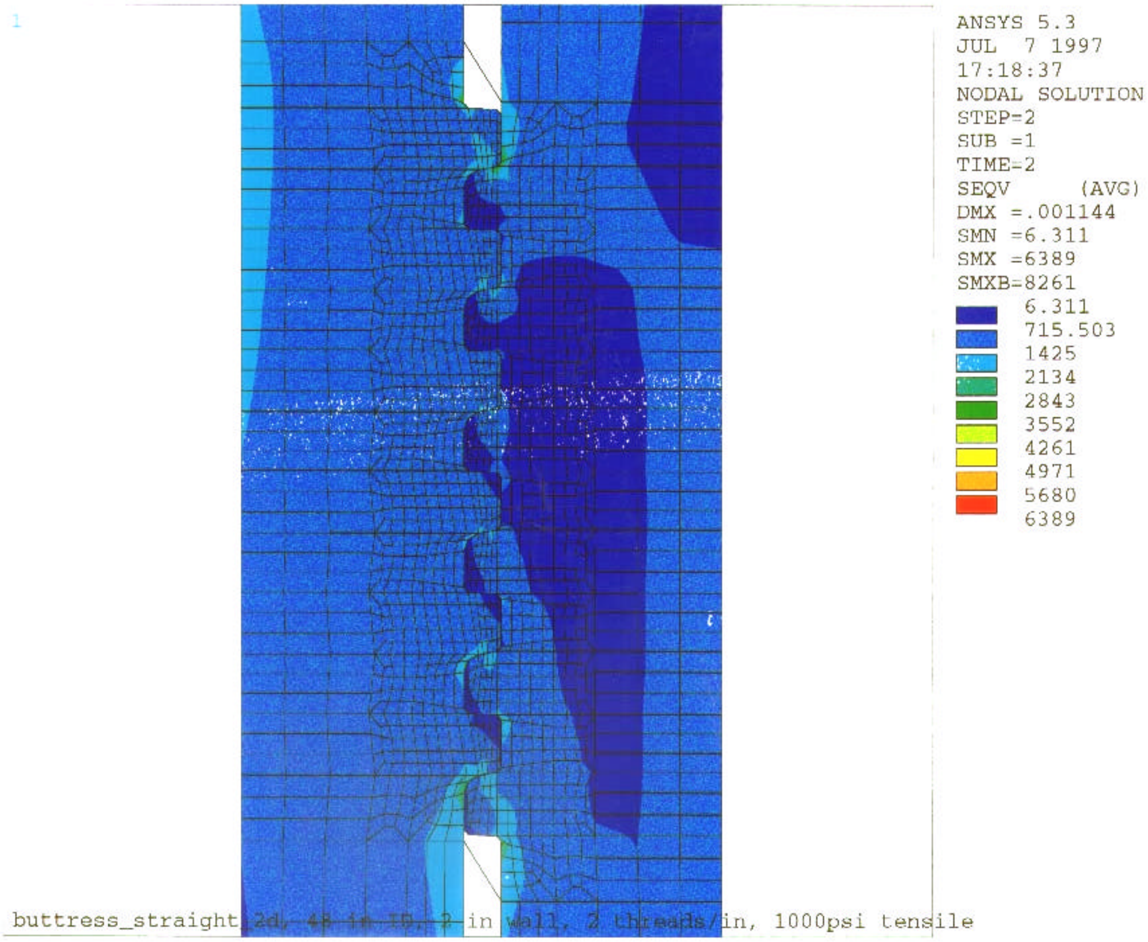

Figure B-7. Straight Buttress in Tension (Equivalent Stress)

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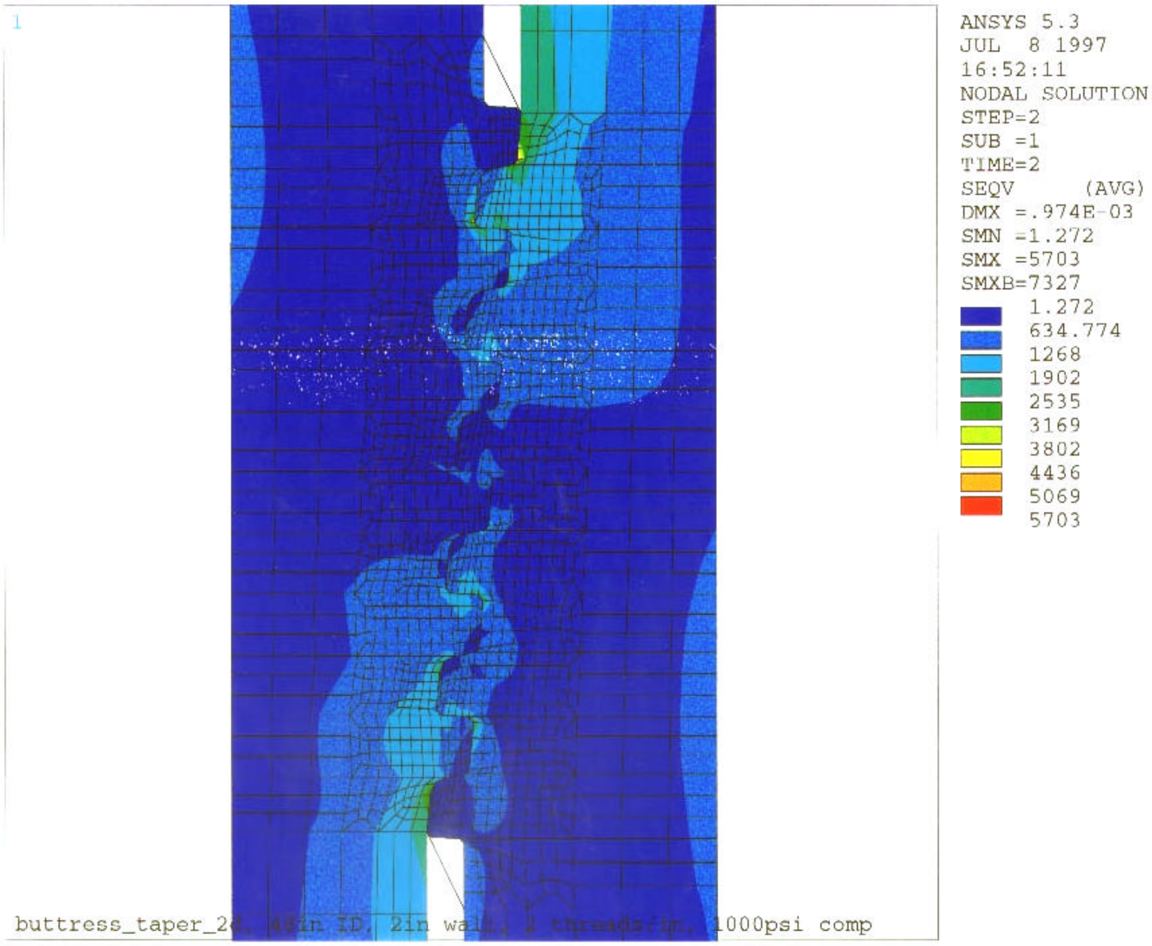

Figure B-8. Tapered Buttress in Compression (Equivalent Stress)

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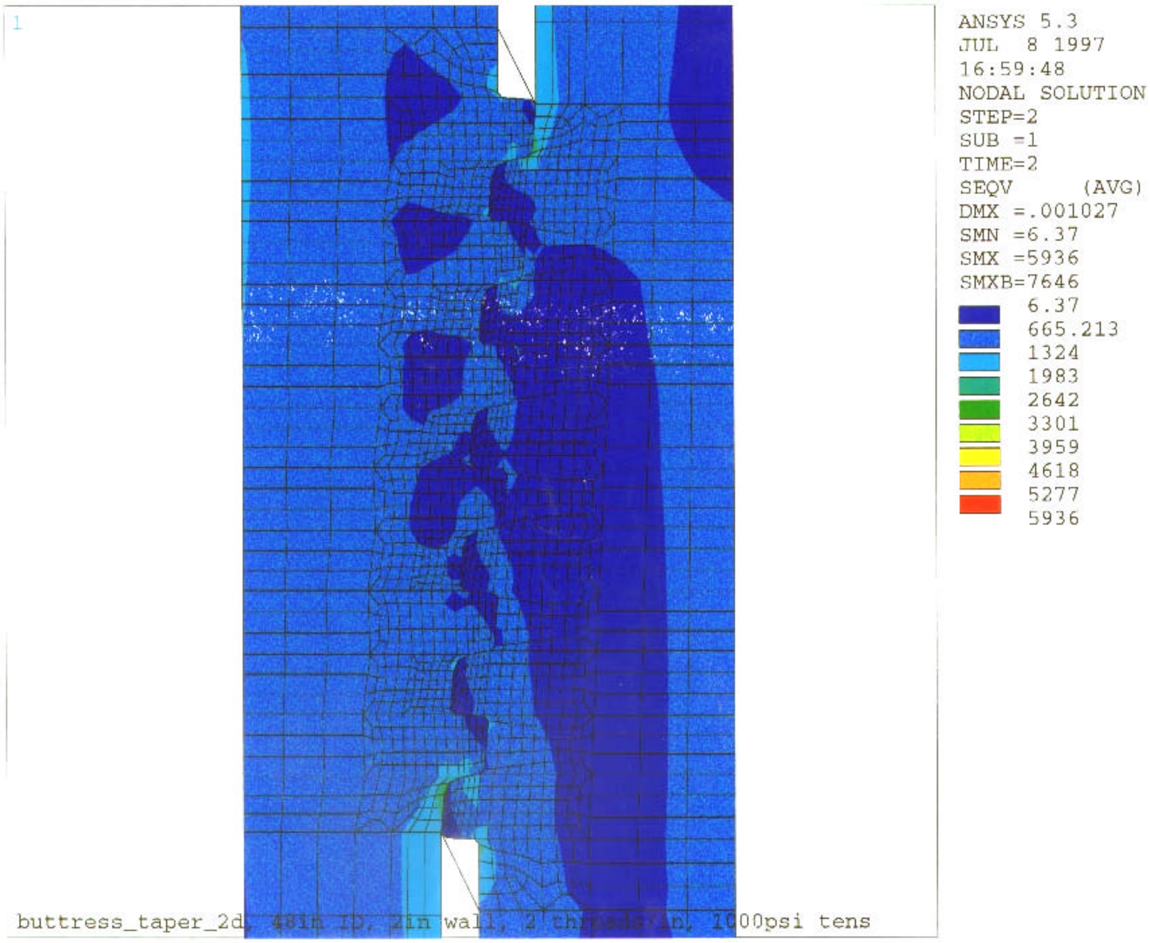

Figure B-9. Tapered Buttress in Tension (Equivalent Stress)

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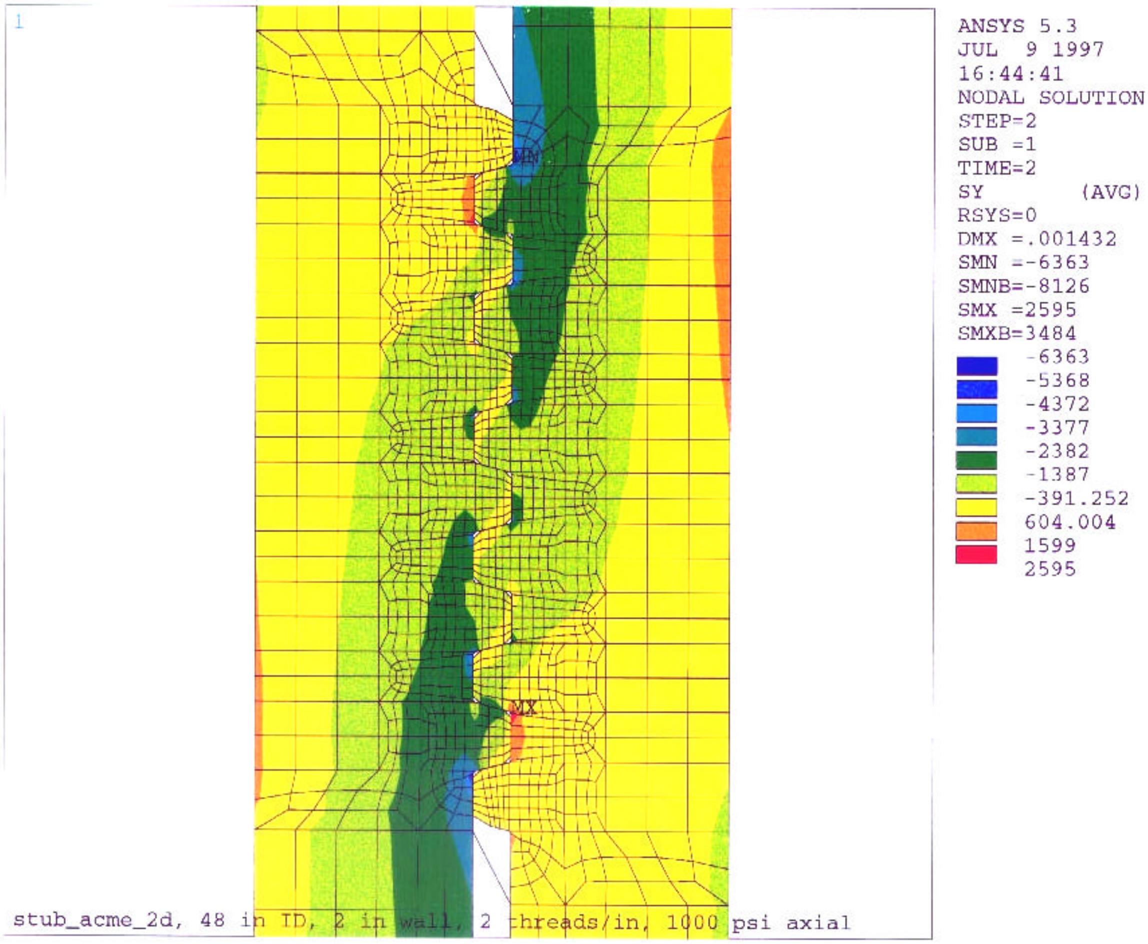

Figure B-10. Stub ACME in Tension (Axial Stress)

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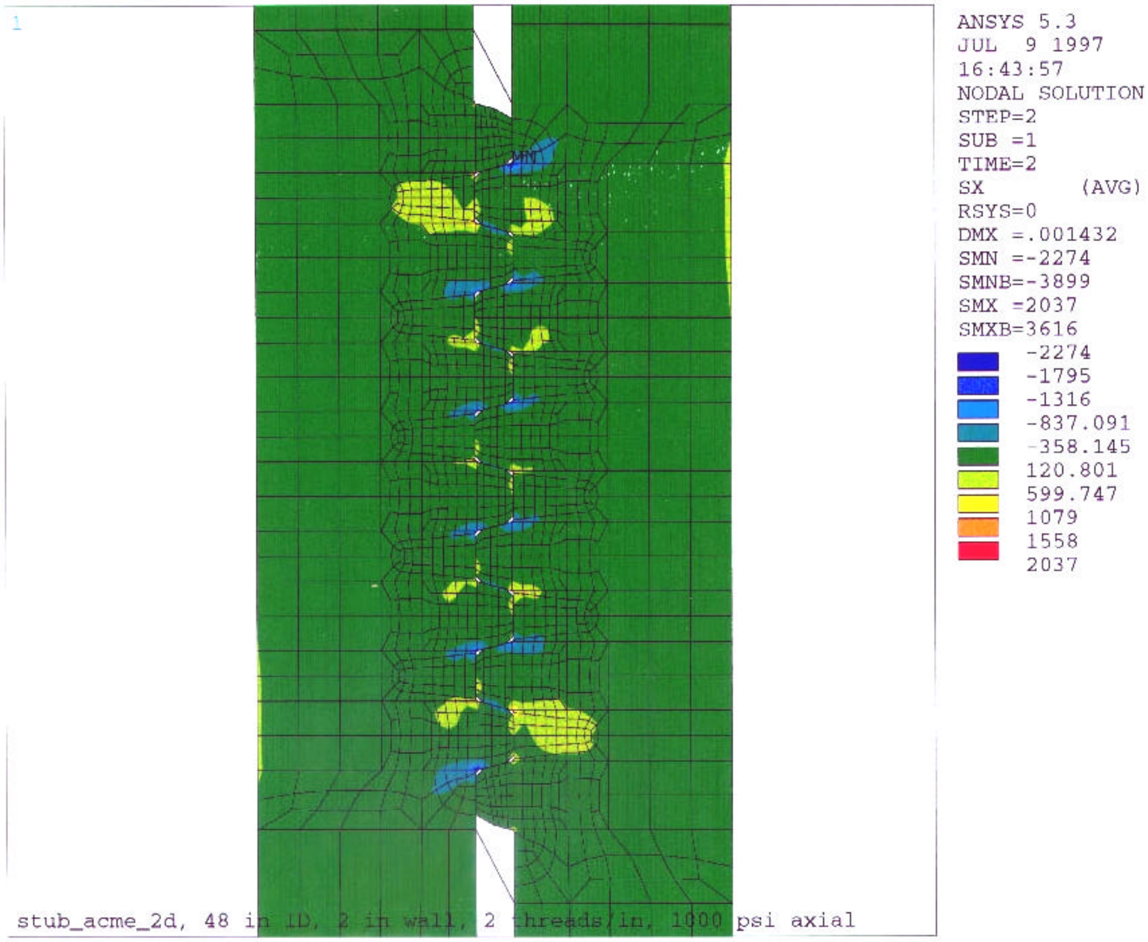

Figure B-11. Stub ACME in Tension (Radial Stress)

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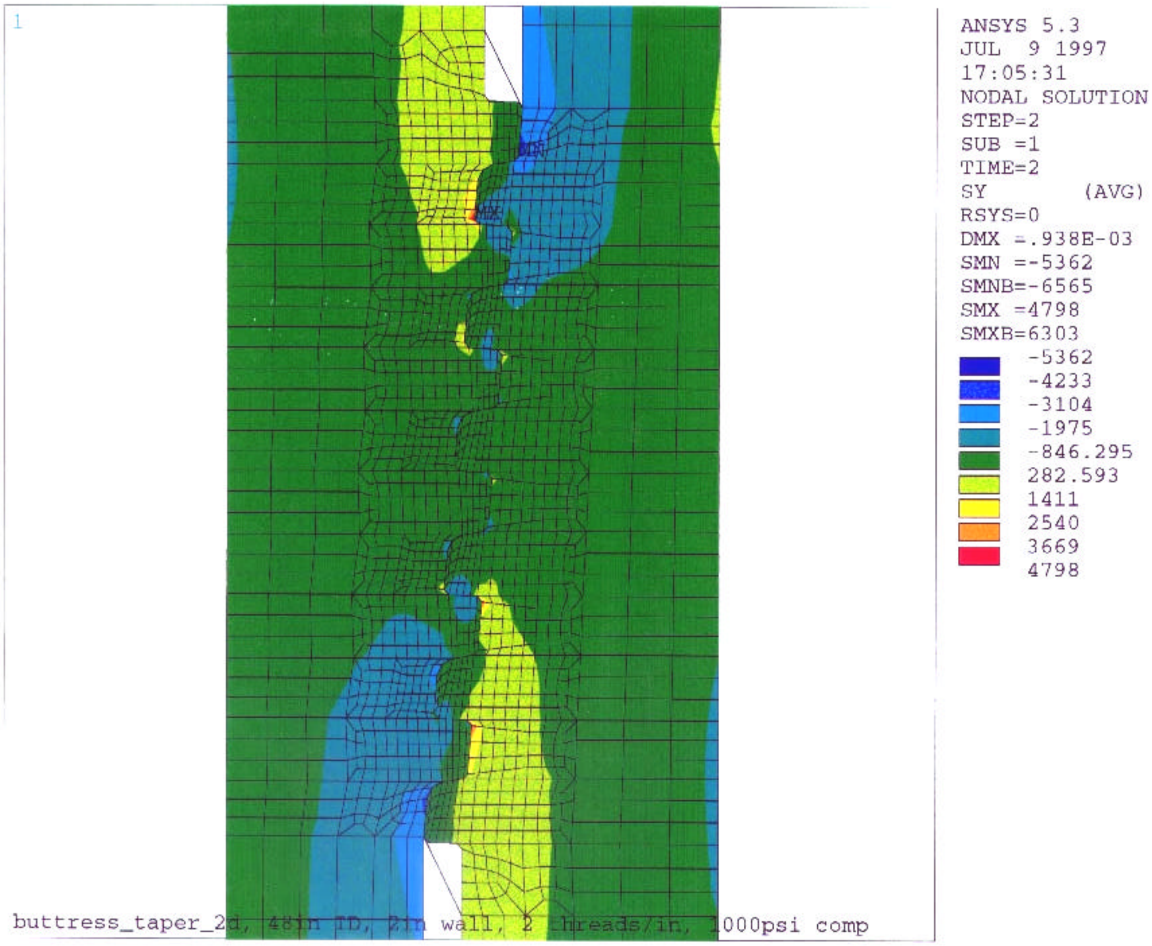

Figure B-12. Tapered Buttress in Tension (Axial Stress)

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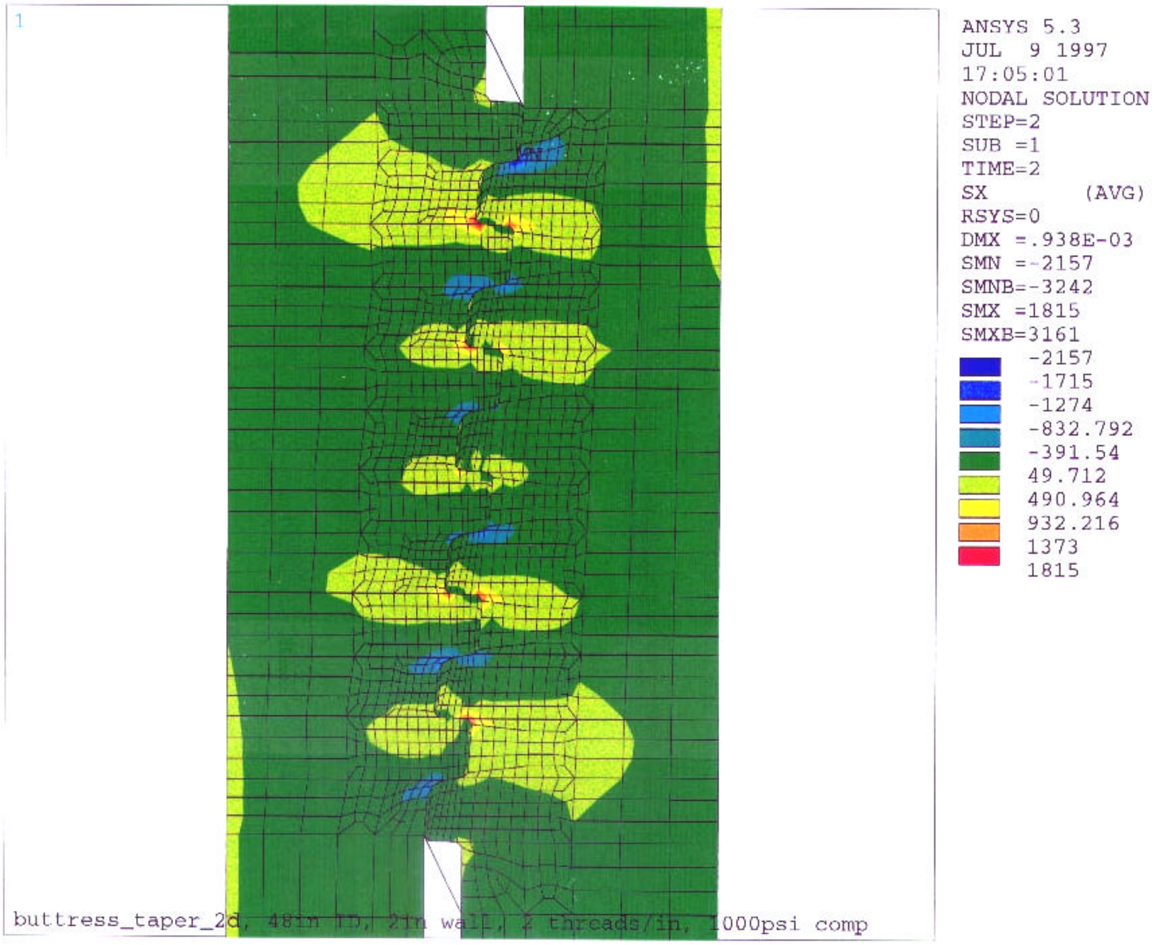

Figure B-13. Tapered Buttress in Tension (Radial Stress)

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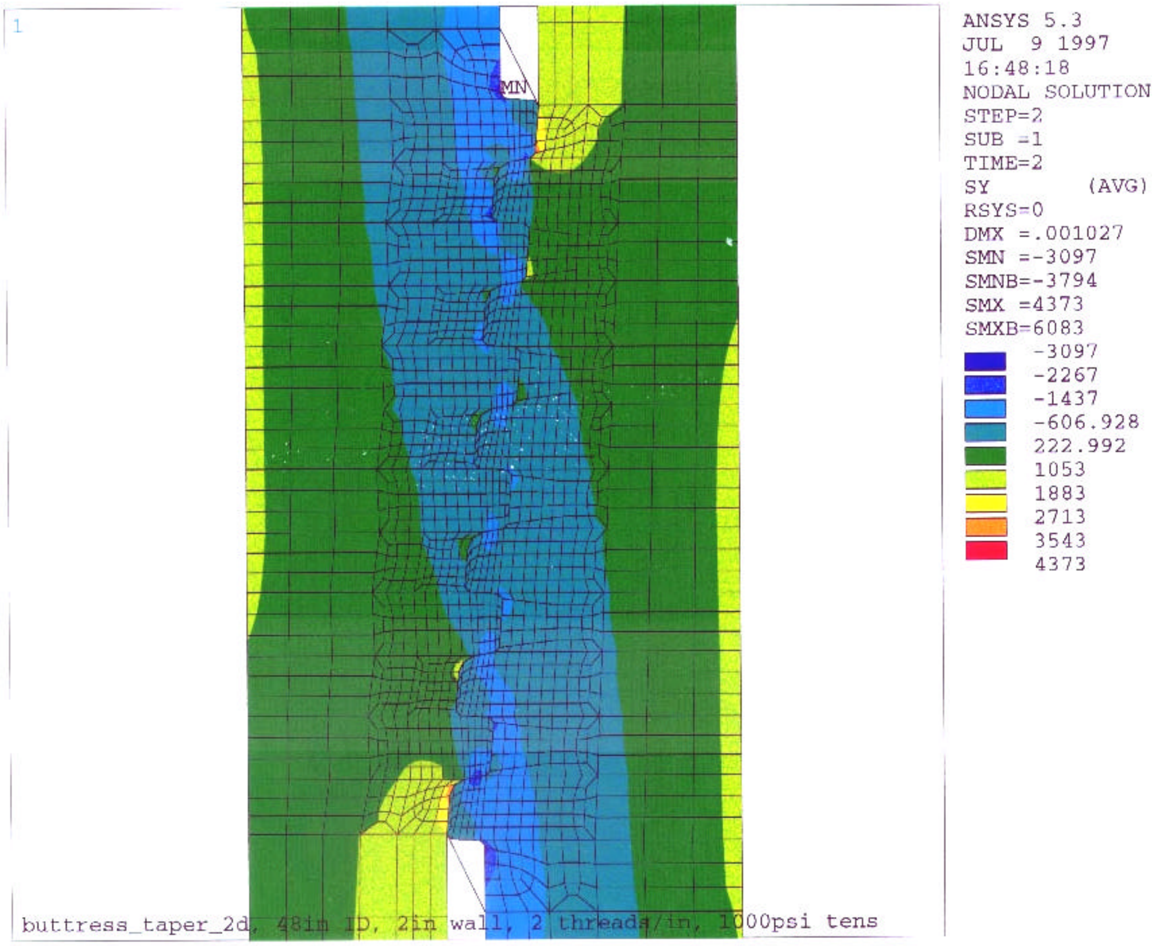

Figure B-14. Tapered Buttress in Compression (Axial Stress)

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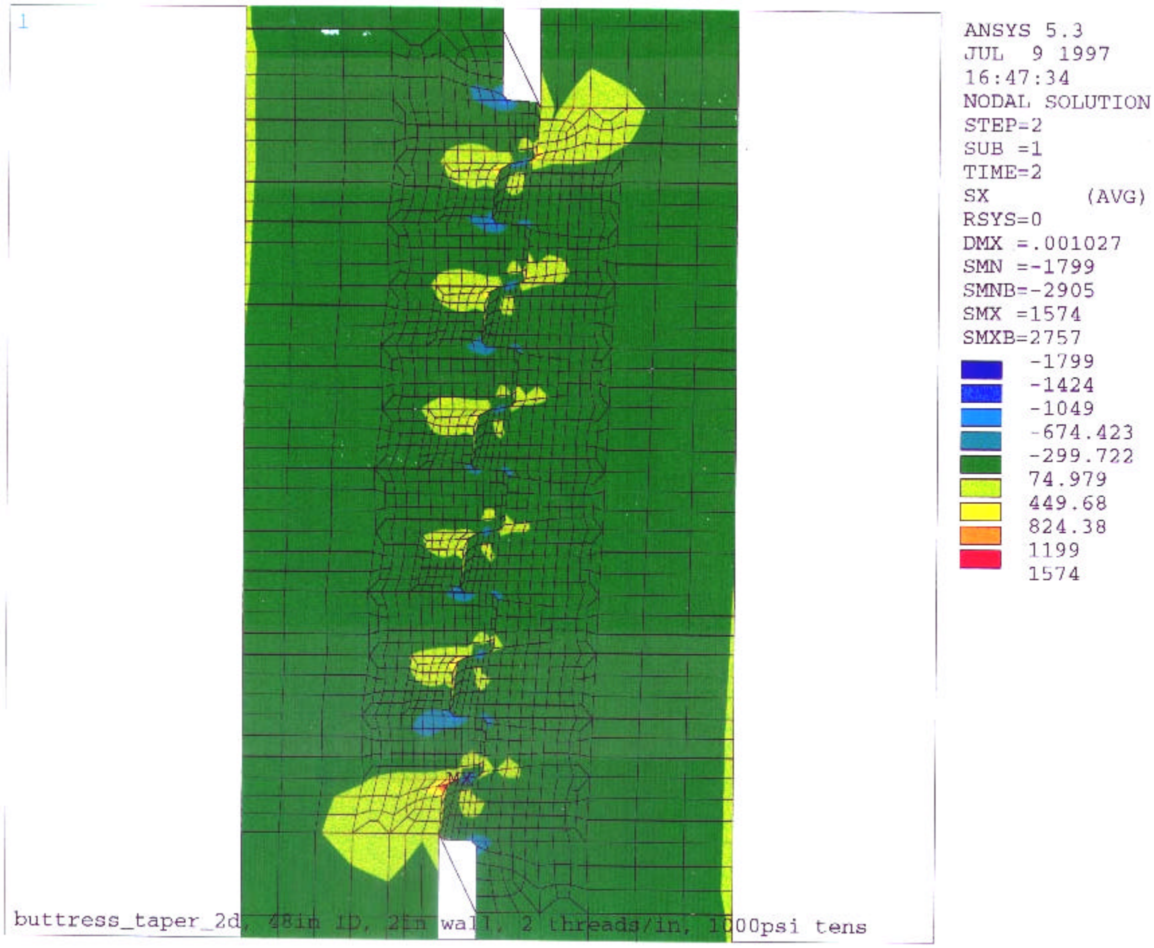

Figure B-15. Tapered Buttress in Compression (Radial Stress)

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